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# Late Paleozoic and Mesozoic Deformations in the Southwestern Primorye Region

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**Abstract**—Two types of tectonic deformations indicating different geodynamic settings are defined in the southwestern Primorye region. Near-latitudinal compression forces were responsible for the oldest, Late Paleozoic deformations. The Permian stratified complexes host a near-meridional system of folds and zones of dynamothermal metamorphism, cleavage, and foliation oriented orthogonally relative to the compression. Late Proterozoic (?) mafic–ultramafic rocks are characterized by similar deformations. In the Late Permian, the deformations were accompanied by granitoid magmatism controlled by fold and cleavage structures. The younger, Mesozoic deformations produced by near-meridional compression are represented by NE-trending sinistral strike-slip faults and their structural parageneses: an ENE-trending system of folds and downdip–thrusts both superimposed on Paleozoic protostructures and manifested in Mesozoic and Cenozoic sequences. It is inferred that, at the Paleozoic–Mesozoic boundary, near-latitudinal compression was replaced by near-meridional compression, probably, in response to the corresponding change in direction of the lateral displacement of the interacting Asian continent and (or) Pacific Plate.

**Key words:** *Deformations, structural paragenesis, geodynamic regime, destruction, strike-slip faults, folds, cleavage, granitization, Primorye region.*

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## INTRODUCTION

The southwestern Primorye region representing the eastern flank of the latitudinal Jilin-Laoelin Fold System (JLFS) up to 100 km wide (and wider) extends for hundreds kilometers between the North China and Amur geoblocks [9]. Similar to the entire eastern margin of Asia, the eastern flank of the JLFS, together with the Sikhote Alin fold system (SAFS), belongs to the Pacific mobile belt [9 and others]. The kinematic uncertainty of the term “mobile belt” for the Mesozoic–Cenozoic stage of its development was specified by recognizing dominant NNE-trending sinistral strike-slip faults constituting the East Asian global strike-slip zone (EAGSSZ) [18, 21]. The latter is considered as resulting from synchronous or successive motion of the Asian continent and (or) Pacific plate relative to each other.

The continent–ocean transition zone is characterized by systems of folds, strike-slip faults, thrusts, pull-apart structures, and normal faults, whose regular subordination in space and time reflects the sinistral strike-slip geodynamic settings of the transition zone in the Mesozoic–Cenozoic. At the same time, while the NE-trending SAFS corresponds entirely to fold parageneses of sinistral strike-slip dislocations that formed under near-meridional compression, the Paleozoic stratified sequences of the southwestern Primorye region were deformed in near-latitudinal compression settings, as follows from mapped fragments of near-latitudinal folds. There was a dilemma: either the southwestern Primorye region and old Khankai Massif were located beyond the EAGSSZ or Mesozoic dislocations superimposed on Paleozoic structures were missed during previous studies. To solve this problem, we continued searching for facts that would confirm previous conceptions [18, 21], according to which the Asian–Pacific transition zone was developing in changeable geodynamic settings determined by variations in the motion directions of joint continental and oceanic lithospheric superblocks: from frontal (thrust–upthrow) to oblique (strike-slip faults) and vice versa. The study of differently oriented dislocations, those superimposed on protostructures included, makes it possible to distinguish different-age regional lithosphere compressions of different directions and, thus, establish the geochronology of presumably repeated changes in the geodynamic settings of the continent–ocean transition zone.

## STUDY METHODS AND APPROACHES TO SOLUTION OF THE PROBLEM

It is known that dynamics (or geodynamics) that characterizes the direction and character of the stress impact on a particular geological space are primarily reflected in the regular combination of tectonic structures or structural parageneses determined by the tectonic load [10 and others]. Methods of paragenetic structural analysis, which is largely aimed at deciphering local and regional geodynamic regimes, are developing and widely used by many Russian and foreign geologists [1, 6, 10, 12, 16, 19, 23, 26, 28, and others]. One of the modifications of this method was applied in the study of Mesozoic–Cenozoic tectonic dislocations and coeval magmatism in the eastern Primorye region [17, 19] and is used in this work for the study of its southwestern part, where similar problems remain unsolved so far.

The study of the structural parageneses was carried out by analyzing maps, plans, sections, and field materials on the morphology, the spatial and temporal relationships of different-rank folds and faults, as well as their structural and kinematic constituting elements: bedding, fractures, striation, tectonic slickensides, banding, gneiss and taxitic patterns, cleavage, and others. Wulf nets were used for statistic generalization of observations with compilation of particular and total diagrams. Based on the known regularities of the most widespread deformation types and using methods of the dynamic analysis [5, 7, 13, and others] and the method of morphogenetic analogies between different-rank structures developed specially for the tectonic study of poorly exposed mountainous–taiga Primorye areas [19], the compression directions were determined with account for the dominant positions of elements of structural parageneses.

Materials were obtained during the geological mapping by G.M. Vlasov (in 1944), B.I. Vasil'ev (in 1957, 1960), A.A. Asipov with colleagues (in 1960), V.M. Chmyrev with colleagues (in 1965), A.A. Vrzhosek with colleagues (in 1968), A.I. Burde with colleagues (in 1969), and N.G. Mel'nikov with colleagues (in 1991). We carried out the field structural study during the additional geological mapping on a scale of 1 : 200 000 (GDP-200) by the Primorskaya prospecting–mapping expedition (T.K. Kutub-Zade with colleagues in 1998, 2000; A.A. Syas'ko with colleagues in 1999, 2001). Materials of original structural studies that can be found in GDP-200 reports are partly published elsewhere [22].

## STRUCTURES OF THE PRE-MESOZOIC DEFORMATION STAGE

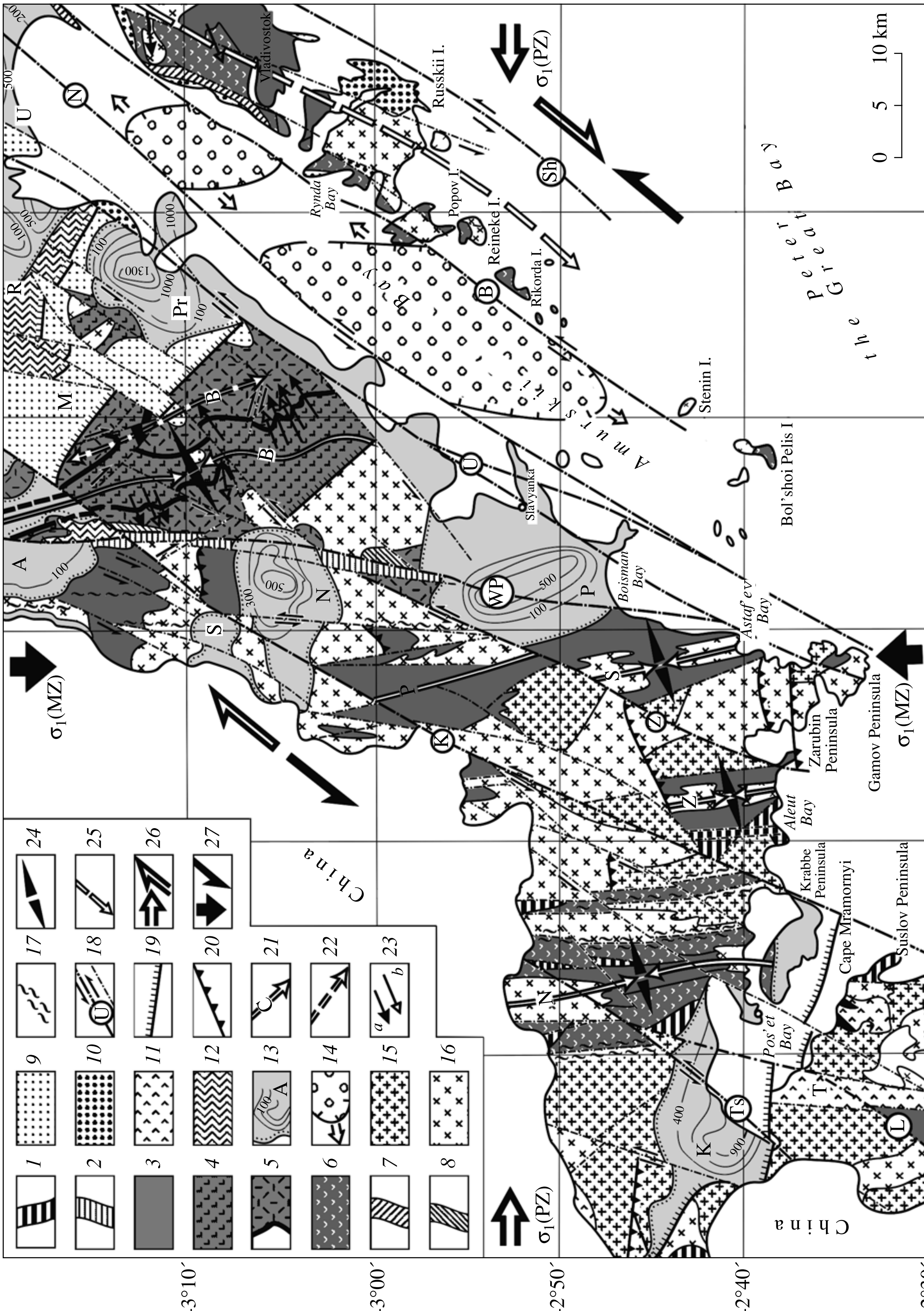
The following lithologies are defined among pre-Mesozoic rocks: Upper Riphean (?) metamorphic (Kubansky) and igneous (Suslov) sequences, which are united here into a single gabbro–pyroxenite complex (Fig. 1); Lower–Upper Permian terrigenous and Upper Permian terrigenous–volcanogenic and carbonate–terrigenous–volcanogenic rocks; Late Permian granitoids that include the different-depth Sedanka granophyre granite and Gamov tonalite—granite complexes. According to geological mapping, the latter also comprises the presumably Jurassic Gvozdevo granite–leucogranite complex. However, as was established in [2], all the granitoids formed in the Late Permian immediately after mafic and ultramafic intrusions.

### *The Structure of the Late Riphean (?) Blocks*

The dominantly meridional gabbro–pyroxenite blocks are located on limbs of some anticlines and in zones of dynamothermal metamosphism (dynamometamorphic zones), where they contact along faults with Permian rocks (Fig. 1). During geological mapping, their Late Riphean age was inferred from the compositional and visual similarity with rocks developed in China near its boundary with Russia and dated by the U–Pb method back to 690 Ma (Kutub-Zade and others, 2001). The gabbro–pyroxenites were subjected to several stages of tectonic–metamorphic transformations. The most intense of them was the Late Permian stage, which masked signs of previous alterations. This is evident from the dominant orientation of structural elements within gabbro–pyroxenite blocks, which demonstrate similarity with deformation patterns in Lower–Upper Permian stratified sequences.

**Fig. 1.** Geological–structural map of the southwestern Primorye region.

(*1*) Late Riphean (?) gabbro–pyroxenite complex; (*2–8*) Permian stratified complexes: (*2*) volcanogenic rhyolitic ($P_1$), (*3*) terrigenous ($P_{1-2}$), (*4*) terrigenous–volcanogenic ($P_2$), (*5*) carbonate–terrigenous–volcanogenic ($P_2$) with a limestone member (black band), (*6*) the same, undivided ($P_2$), (*7*) carbonate–terrigenous ($P_2$), (*8*) terrigenous, developed in near-fault troughs ($P_2$); (*9–13*) Mesozoic–Cenozoic stratified complexes of superimposed depressions: (*9, 10*) terrigenous $T_3$ (9) and $T_{1-3}$ (*10*) of the Mongugai (M) Depression, (*11*) volcanogenic ($T_3$) of the Talmi (T) Depression, (*12*) coaliferous–terrigenous ($K_{1-2}$) of the Razdol'naya (R) Depression, (*13*) Cenozoic volcanogenic–terrigenous complex filling in depressions (isohypses (m) of the basement surface): Kraskino (K), Poima (P), Narva (N), Sinii Utes (S), Amba (A), Provalovsky (Pr), Razdol'naya (R), Uglovoe (U); (*14*) starved extension structures associated with strike-slip faults (arrows indicate the directions of extension synchronous with movements along strike-slip faults); (*15, 16*) Late Permian granitoid complexes: Gvozdevo granite–leucogranite (15), Sedanka granophyre granite and Gamov (west of the West Primorye Fault) tonalite–granite (*16*); (*17*) dynamic zones; (*18*) principal faults (arrows indicate Mesozoic–Cenozoic strike-slip displacements): (WP) West Primorye, (U) Ussuri, (K) Kubansky, (Z) Zarubin, (N) Vol'no-Nadezhdinskoe, (B) Beregovoi, (Sh) Skotovo, (Ts) Tsukanovka, (L) Lebedinyi; (*19*) normal faults; (*20*) updip–thrusts; (*21*) axes of Paleozoic anticlines: (B) Barabash, (P) Poima, (S) Sukhanovka, (Z) Zarubin, (N) Novgorodskaya (arrows indicate directions of arch dipping); (*22*) axis of the Barabash Syncline (B); (*23*) dip directions of hinges of small superimposed alternating anticlines (*a*) and synclines (*b*); (*24*) axes of large Mesozoic superimposed synclines; (*25*) axis of the Murav'ev-Amurskii horst anticline and direction of its dip; (*26, 27*) directions of Late Paleozoic (*26*) and Mesozoic (*27*) regional lithospheric compression that determined respective dextral and sinistral activation of a system of NNE-trending strike-slip faults and corresponding structural parageneses.


Vladivostok
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Popov I.
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Bol'shoi Pelis I
Boisman Bay
Astaf'ev Bay
Zarubin Peninsula
Gamov Peninsula
Aleut Bay
Krabbe Peninsula
Cape Mramornyi
Suslov Peninsula
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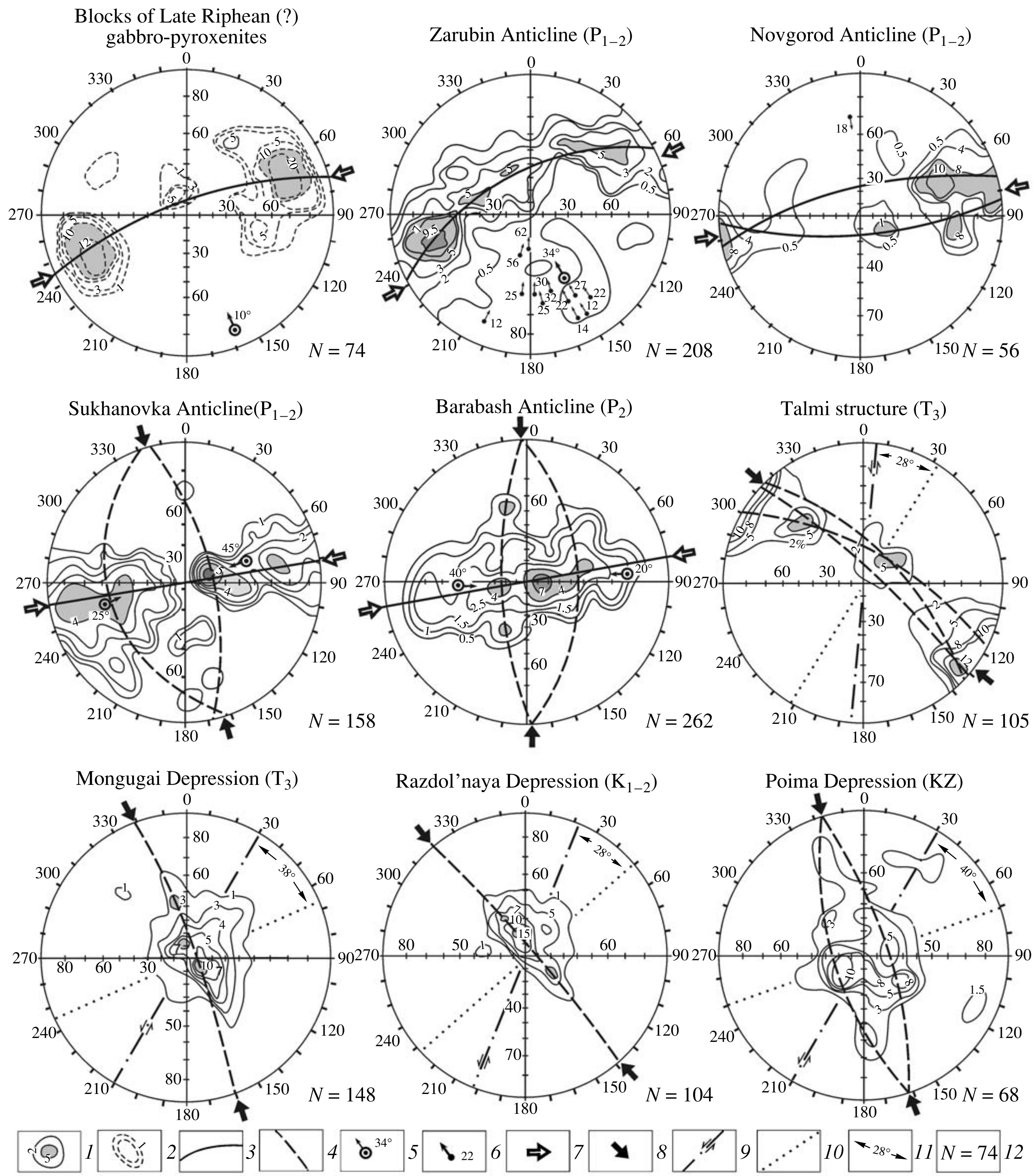


**Fig. 2.** Diagrams illustrating orientation of planar and linear textural elements in different-age sequences (Wulf net, upper hemisphere).

(*1, 2*) isolines of bed (*1*), cleavage, and foliation (*2*) dips; (*3, 4*) zones of bedding and cleavage of structures resulting from Paleozoic near-latitudinal compression (*3*) and bedding of structures resulting from Mesozoic–Cenozoic near-meridional compression (*4*); (*5, 6*) outcrops, directions, and dip angles of zone axes (*5*) and hinges (*6*) of high-rank folds; (*7, 8*) directions of regional Paleozoic (*7*) and Mesozoic–Cenozoic (8) compression; (*9*) orientations of sinistral strike-slip faults bounding depressions; (*10, 11*) strikes of fold systems in depressions (*10*) and angles between folds and strike-slip faults (*11*); (*12*) number of measurements.

Gabbroids are frequently layered into leuco- and melanosomes, gneissose and foliated to acquire banded and taxitic structures. The melanosome is largely represented by amphibolites and pyroxenites, while the leucosome is composed of plagioaplites and plagiodiorites. Both of them are characterized by elongated bedded to lenticular shapes parallel to the block strike. Orientation almost parallel to lenses (NW-trending) is characteristic of foliation and cleavage, which are accompanied by granitization. The latter is reflected in the formation of elongated thin serrated (along cleavage) aggregates of taxitic and banded biotite granites, granodiorites, plagiogranites, and aplites, which envelope elongated gabbro fragments that extend parallel to cleavage (Fig. 3). Based on these elements, five NNW-trending cleavage syn- and antiforms with limbs from 500 m to 1.5 km wide are defined in the section between capes Mikhel'son and Lukin (Fig. 4). The folds are steep, keel-shaped, with dip angles of 60 to 80°, and gradually dipping in the NNW direction. The perfectly ordered arrangement and almost parallel near-meridional orientation of the fold–cleavage textures imply intense structure-forming compression that was oriented in the near-latitudinal direction and slightly advanced the granitization or was synchronous with the latter.

### *Protostructures of Permian Rocks*

The structural study of Permian stratified sequences located among the spacious distribution area of Late Permian granites revealed their largely anticlinal structure.

The NNW-trending **Zarubin anticline** (Figs. 1, 4) is traceable for a distance of 15 km and composed of the flyschoid Reshetnikovo Formation ($P_{1-2}$). On its flanks, the structure is bounded by NNW-trending faults and represents a narrow antiform. Its limbs are steep (Fig. 4) and an arch dips in the NNW direction at an angle of 34°, which is evident from the position of the axis of the belt with maximums in the diagram of the bed orientation (Fig.2). Hinges of small folds that complicate the anticline limbs dip in the same direction (Fig. 2).

In the course of compression and deformation, flyschoid rocks experienced different-intensity dynamothermal metamorphism of muscovite facies that likely accompanied intrusion of Late Permian granites. It is known that metamorphism of greenschist facies is characterized by contrasting primary structures of sedimentary rocks resulting from the replacement of poorly distinguishable clayey layers by newly formed mineral assemblages [15]. Effects of interlayer sliding that appear during folding stimulate, probably, such a replacement as well. In the rocks under consideration, such layers are subjected to micatizaion and silicification, which determined the relatively distinct structure of additional folds that likely resulted from viscous flow of material toward arches of small anticlines (Fig. 5). In other situations, additional folds of the western Zarubin Anticline limb are strongly compressed and

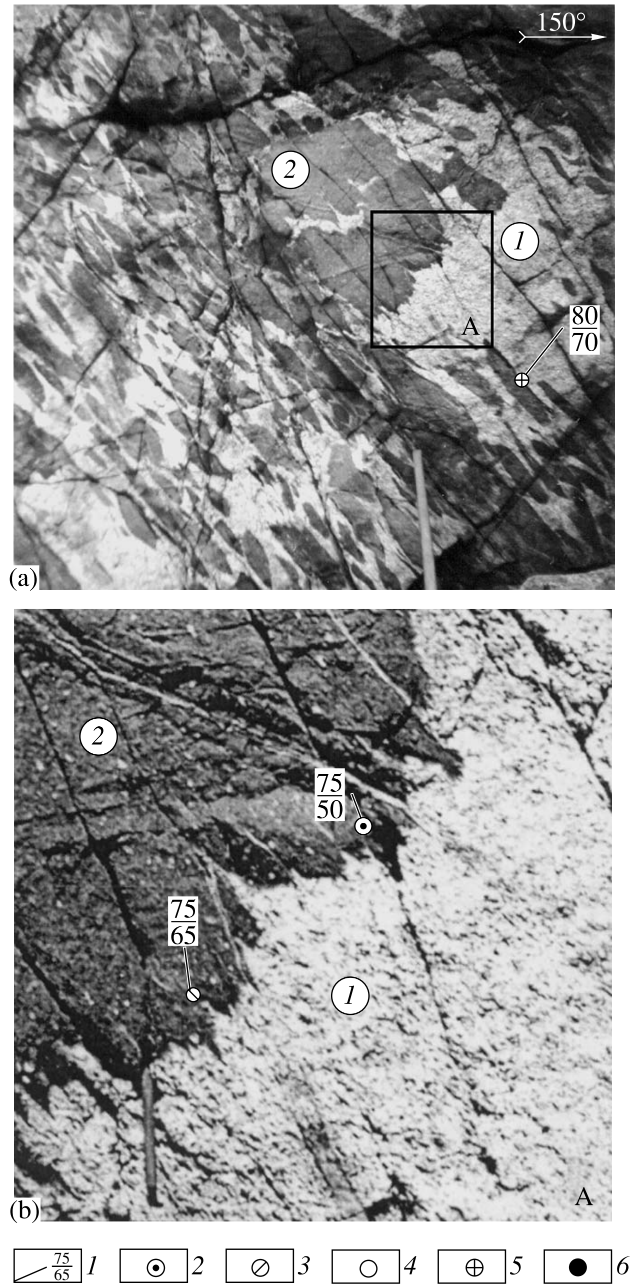


**Fig. 3.** Granitization in foliated Late Riphean gabbroids (for location, see Fig. 4).

Encircled numbers: (*1*) biotite–hornblende granites, (*2*) dark gray gabbro with plagioclase phenocrysts.

Hereinafter: (*1*) numerals in the upper row indicate azimuths of dip, the lower angle is a dip of the tectonic plane (*2*), foliation and cleavage (*3*), bed (*4*), boundary of intrusive body or dike (*5*), and fold hinge (*6*).

overturned eastward (Fig. 6), in contrast to similar folds of its eastern limb that are overturned westward (Fig. 7). No less than four orders of geometrically similar folds are distinguished. All of them are characterized by the convergent structural patterns, which imply their formation in line with the mechanism of deformation of a

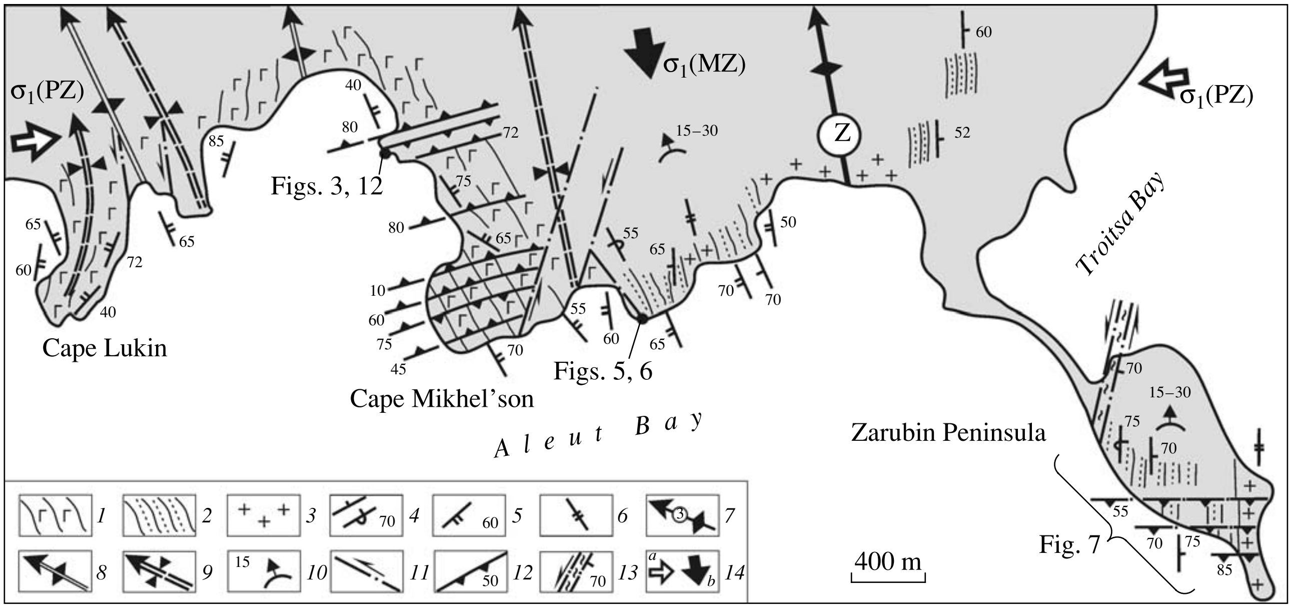


**Fig. 4.** The structure of the Zarubin Anticline and cleavage syn- and antiforms.

(*1*) Layered, foliated, and tectonized gabbro–pyroxenites; (*2*) foliated, tectonized, and folded flyschoid sediments of the Reshetnikovo Formation ($P_{1-2}$); (*3*) biotite granites ($P_2$); (*4*) orientation of flyschoid beds in normal and overturned occurrences; (*5*) orientation of cleavage and foliation;(*6*) strike of steeply dipping taxitic textures in granites; (*7–9*) axes of folds resulting from near-latitudinal compression (pre-Mesozoic deformations): (*7*) Zarubin Anticline, (*8, 9*) cleavage antiforms (*8*) and synforms (*9*) and direction of dip of their axes; (*10*) directions and dip angles of hinges of small folds; (*11–13*) fractures resulting from Mesozoic near-meridional compression: (*11*) strike-slip faults, (*12*) thrusts, (*13*) Zarubin Fault (strike slip-fault) zone; (*14*) direction of the main vector of Pre-Mesozoic (*a*) and Mesozoic (*b*) compression.

solid body occurring inside soft matter under longitudinal (near-latitudinal in the considered case) compression [14, 24, 25].

The folds are universally accompanied by cleavage, which is almost parallel to axial surfaces of different-rank folds and has slightly different dip angles. It is largely characterized by similar orientation with beds on fold limbs, although being steeper. There are transitional forms of cleavage from imperfect rhombic via near-parallel brittle to the most perfect foliation cleavage. The cleavage of the Zarubin anticline is almost parallel to that observed in Late Riphean (?) gabbroids (Fig. 2), which suggests that both of them formed in similar dynamic settings of near-latitudinal compression.

Similar to other structures, granitization of rocks in the arch of the Zarubin Anticline is its important feature (Figs. 1, 4). At the same time, the eastern limb of the anticline hosts a large granite body extended in the meridional direction parallel to the bed strike of Permian stratified rocks (Fig. 7). Widespread in these rocks are also interstratal largely basic dikes (probably comagmatic with granitoids). In addition to interstratal dikes, the western limb of the anticline demonstrates granitization of sedimentary rocks (Fig. 5), which involves mainly sandstone elements of their flyschoid rhythms. Owing to such selective patterns, granites preserve relicts of primary flyschoid textures (Fig. 6a). It seems that spacious fields of Late Permian granites (Fig. 1) could be developed after dominant sandy rocks.

**The Novgorod Anticline** 10–15 km wide is traceable in the NNW direction for a distance of 35–40 km from the eponymous bay to the state boundary with China (Fig. 1). Its sections were examined in the northern coast of the Krabbe Peninsula and in the Cape Mramornyi area. The fold structure has many features in common with the Zaurbin Anticline. Its core and limbs are composed of Reshetnikovo Formation flyschoid rocks ($P_{1-2}$) and an Upper Permian Barabash Formation ($P_2$), respectively. The latter is represented by andesites, dacites, rhyolites, rare basalts and ultramafics, and silicified siliceous–clayey shales with interbeds of marbled limestones. The rocks were subjected to regional metamorphism of the muscovite facies. In addition, alternating wide and narrow dynamometamorphic zones (up to 3 km wide) developed on the anticline limbs demonstrate relatively intense thermodynamic transformations up to greenschist and, rarely, amphibolite facies. The fold is strongly compressed, symmetrical, and has steep limbs (Fig. 2), which are complicated by numerous small disharmonic folds frequently characterized by extrusion patterns and flat near-meridional hinges. The anticline core comprises additional symmetrical folds (Fig. 8).

**The Sukhanovka Anticline** 10–12 km wide and 15–20 km long is traceable in the NNW direction from the Astaf'ev Bay area to the middle reaches of the Ryazanovka River, where it is bordered by the Zarubin strike-slip fault (Fig. 1). The fold is composed of the Reshetnikovo Formation flyschoid sediments ($P_{1-2}$). In contrast to the Zarubin and Novgorodskaya anticlines, it is less compressed and slightly asymmetrical (the eastern limb is gentler as compared with the western one) (Fig. 2). Small complicating folds developed near the anticline core are characterized by simple forms.

B.I. Vasil'ev was the first to map the **Barabash Anticline** in 1957. Subsequently, its structure was specified by A.A. Vrzhosek in 1965 and ourselves. The anticline core is distinctly marked by the member of limestones and limy sandstones (Fig. 1), and its limbs are composed of terrigenous–basaltic and terrigenous–rhyolitic sequences of the Barabash Formation ($P_2$), respectively. The anticline approximately 10 km wide and 35 km long is symmetrical, box-shaped, and extends in the near-meridional direction. The dip angles are 10–20° in the hinge part of the fold and frequently up to 40–50° in its limbs (Fig. 2). The anticline limbs are complicated by additional meridional folds of higher orders. In its eastern limb, some additional folds are overturned eastward due to development of upthrows, which implies the horst mechanism of the Barabash Anticline uplifting under near-latitudinal compression.

Relicts of NNW-oriented Paleozoic folds are observed in Rynda Bay of Russkii Island (Fig. 1), where the limb of the anticline composed of Permian foliated volcanogenic–terrigenous rocks hosts flat (25°) schists lacking additional folds and packets of similar schists intensely deformed into small folds vergent toward the anticline axis (Fig. 9).

The presented features indicate that folds composed of pre-Mesozoic rocks are characterized by structural similarity. They also demonstrate similar parageneses of the internal structure of different-rank folds that consist of systems of rhombic and parallel cleavage, foliation, and additional strongly compressed, vergent folds with flat hinges. Parageneses of these elements represent regular patterns of flattening deformation in response to longitudinal compression. Deformation of pre-Mesozoic rocks was accompanied by their granitization in the Late Permian. It should be noted that the deformation patterns and granitization of Permian and Upper Riphean (?) rocks provide no grounds for an assumption that deforming forces were related to intruding granite magma. Otherwise such ordered convergent shapes of different-rank folds, which result only from longitudinal lateral compression that has nothing to do with intruding magmas, have never been observed in these rocks. The near-meridional orientation of the above-mentioned elements of parageneses and folds themselves suggests a near-latitudinal compression vector of 240–260° (Fig. 2). Variations in the compression direction for each of the fold structures under consideration are insignificant and explained probably by some local dynamic peculiarities. It is of importance also that superimposed Mesozoic deforma-

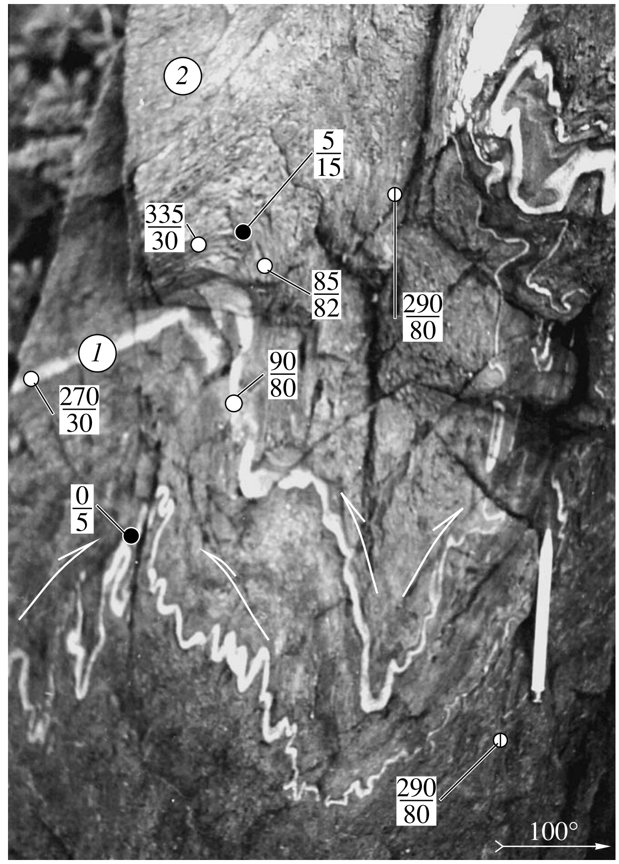


**Fig. 5.** High-rank folds resulting from plastic flow in foliated siltstones (Reshetnikovo Formation, $P_{1-2}$).
Encircled numbers: (*1*) fine-grained sandstones replaced by cyptocrystalline quartz, (*2*) siltstones altered up to quartz–chlorite–actinolite schists. Arrows indicate directions of differentiated displacement at limbs of folds.

tions that resulted from meridional compression with the formation of a system of NE-trending sinistral strike-slip faults could rotate the Paleozoic fold system counterclockwise to change its primary meridional strike for the northwestern one. Consequently, it can be stated that the vector of regional compression in the Paleozoic was nearly latitudinal.

## STRUCTURES OF THE MESOZOIC DEFORMATION STAGE

Tectonic processes that commenced probably in the Triassic transformed primary structures of the Late Paleozoic deformation stage by new superimposed fractures and folds, which are best manifested in Mesozoic sequences.

### *Fold Structures Superimposed on Paleozoic Protostructures*

Near-latitudinal synclinal troughs superimposed on the Paleozoic near-meridional anticlines are the largest

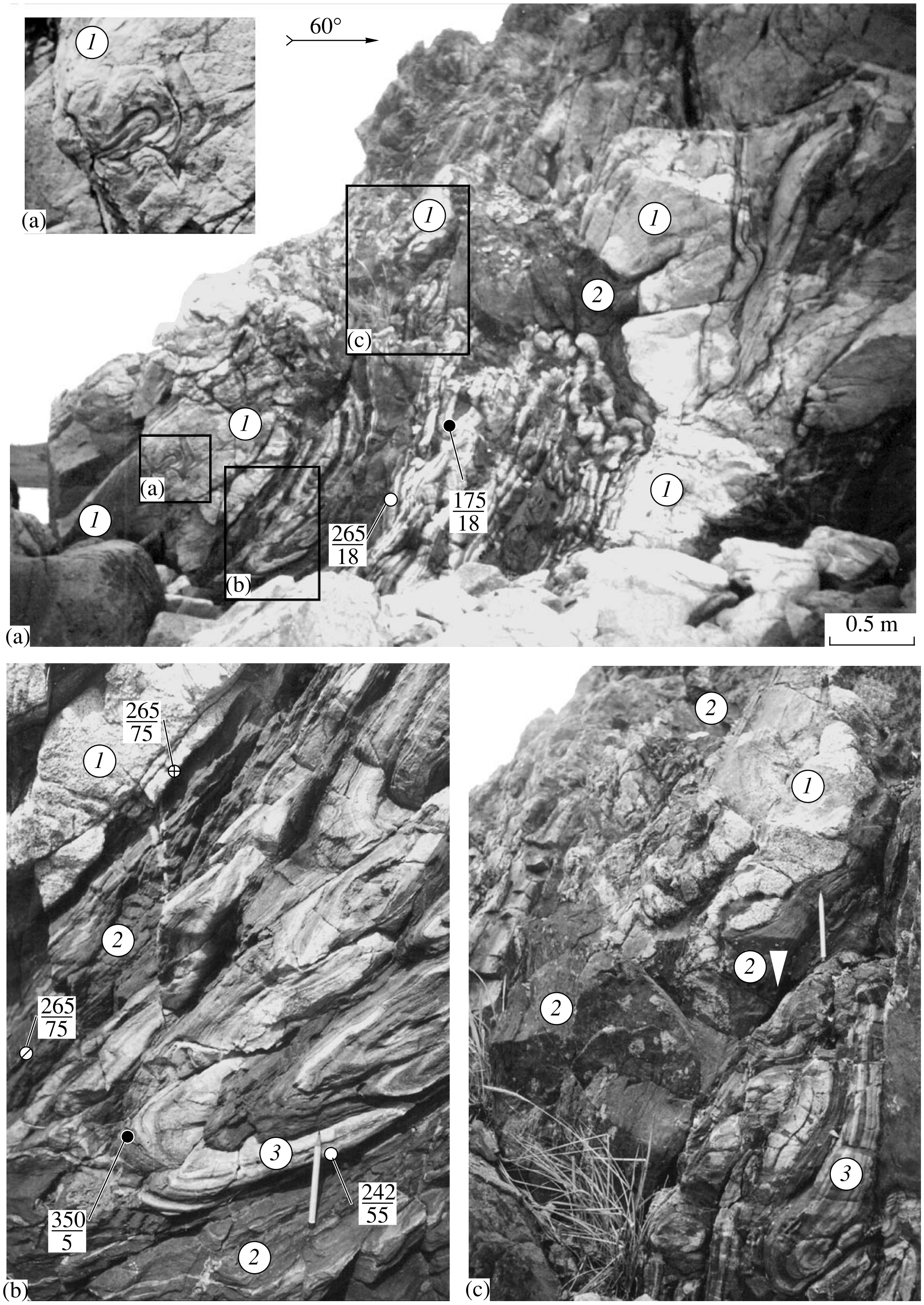


**Fig. 6.** Folds and local ganitization of flyschoid deposits ($P_{1-2}$) in the western limb of the Zarubin Anticline (for location, see Fig. 4). Encircled numbers: (*1*) biotite granites, (*2*) siltstones, (*3*) alternating siltstones and sandstones. For other symbols, see Fig. 3.

among the recognized fold structures of the Mesozoic deformation stage (Fig. 1). The figure demonstrates that granitoids localized in cores of Paleozoic structures pinch out in troughs that complicate the Sukhanovka, Zarubin, and Novgorodskaya anticlines. The synclinal trough superimposed on the Barabash Anticline retains fragments of Triassic sequences (Fig. 1). The descending movements determined subsidence of arches of

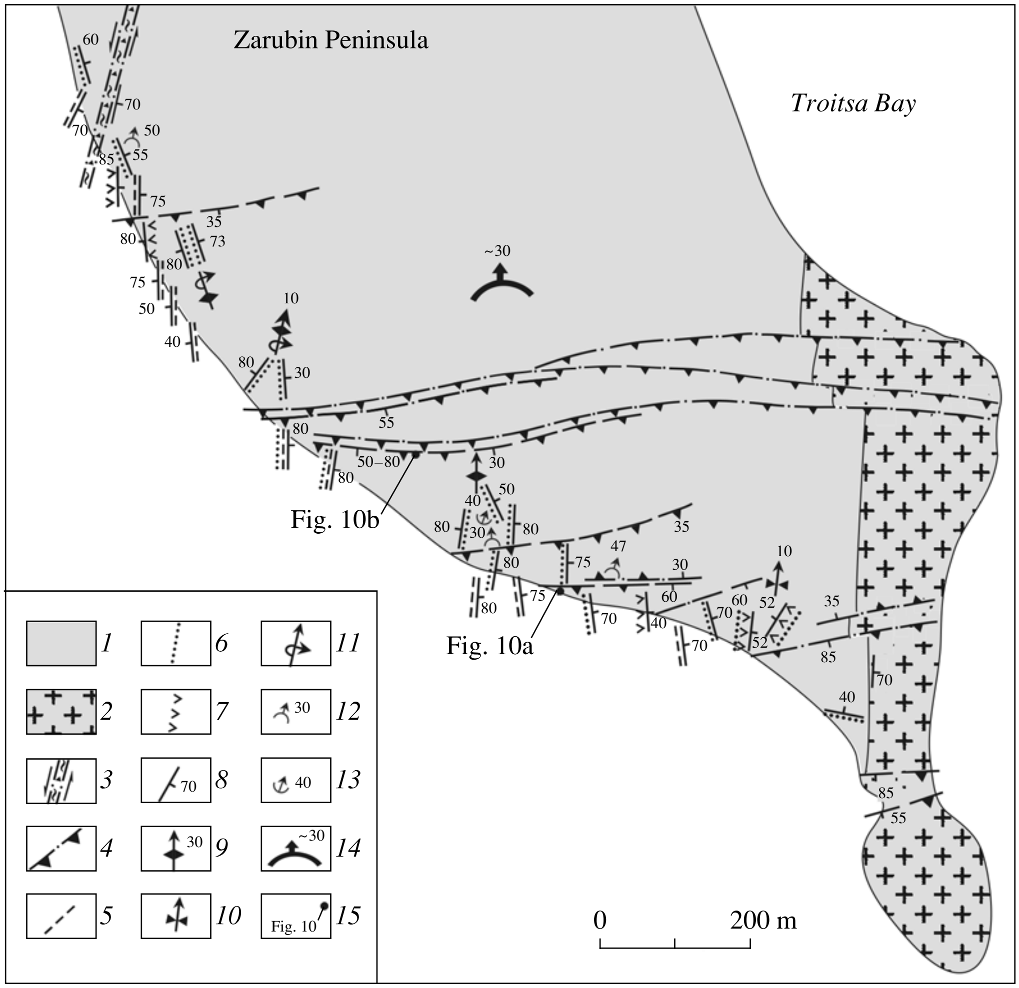


**Fig. 7.** Spatial relationships between folds, fractures, cleavage, and granitoid dikes and bodies in the eastern limb of the Zarubin Anticline.

(*1*) Sandstone–siltstone flyschoid deposits of the Reshetnikovo Formation ($P_{1-2}$); (*2*) granites ($P_2$); (*3*) zone of the Zarubin strike-slip fault; (*4*) thrusts and reverse faults; (5–8) attitude elements: cleavage and foliation (*5*), beds (*6*), dikes of intermediate composition (*7*), direction and angle of their dipping (*8*); (*9–11*) directions and dip angles of hinges of second-order folds: anticlines (*9*), synclines (*10*), overturned anticlines (*11*); (*12, 13*) orientation and dip angles of hinges of third-order folds; anticlines (*12*), synclines (*13*); (*14*) generalized dipping direction of hinges of Paleozoic fold structures; (*15*) location of photos.

Paleozoic anticlines, which is confirmed by similar dips of hinges of small conform folds. The NNW dip of their hinges is established at the southern flanks of the Zarubin (Figs. 2, 4, 7) and Novgorodskaya (Figs. 2, 8) anticlines, where it characterizes limbs of superimposed troughs averaging 15–30°.

Relatively small folds that complicate limbs of the Barabash Anticline are an important element indicating development of secondary (superimposed) deformations. The superimposed near-latitudinal folds are readily traceable owing to the marker limestone member (Fig. 1). The hinges of these folds dip northeast- and southwestward conformably with the dip of the Barabash Anticline limbs. The secondary folds are relatively gentle being from a few to hundreds of meters wide and several tens of meters high.

Development of superimposed nonconform folding is confirmed by the analysis of diagrams illustrating the orientation of the dominant bedding. Both the Barabash and Sukhanovka anticlines are characterized by distinct near-meridional zones, which are developed against the background of dominant near-meridional bedding (near-latitudinal zone) and reflect superimposed near-latitudinal folding resulting from near-meridional compression (Fig. 2). In addition, this compression trend is indicated by a system of conjugate sinistral NE-oriented and dextral NW-oriented strike-slip faults with corresponding displacements (amplitudes up to 3 km) of marker limestone members of the Barabash Anicline (Fig. 1) that reflect in integrity the so-called pure strike-slip fault complicating this structure.

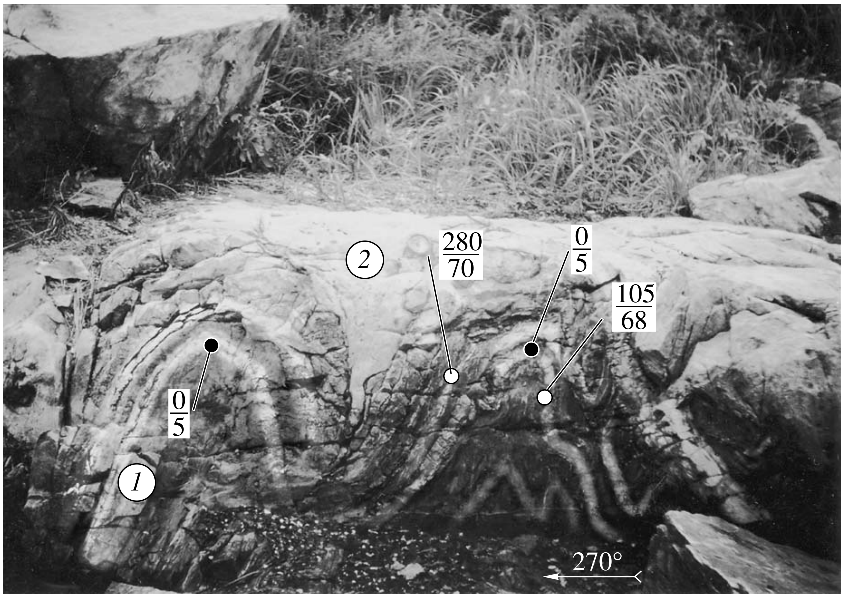


**Fig. 8.** The hinge of the Novgorod Anticline (northern coast of the Krabbe Peninsula, for location, see Fig. 1). Encircled numbers: (*1*) beds of gray marble, (*2*) calcitized limestones. For other symbols, see Fig. 3.

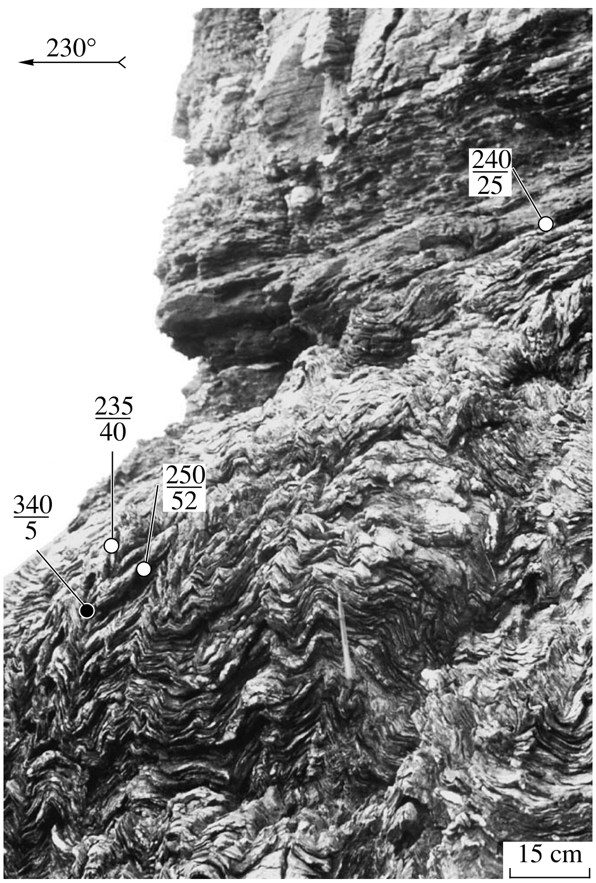


**Fig. 9.** The structure of the Paleozoic anticline limb. Gently dipping schists are underlain by their quartz–chlorite–sericite varieties deformed into small disharmonic folds. Russkii Island, eastern coast of Rynda Bay (for location, see Fig. 1, legend as in Fig. 3).

*System of Latitudinal Updip Fault–Thrusts*

Latitudinal updip–thrusts (Fig. 1) are also distinct indicators of meridional compression. They are largely observed in Paleozoic and Riphean (?) sequences, where they are numerous, although being usually truncated by NE-trending strike-slip faults. Latitudinal displacements are frequently characterized by reverse fault- and thrust-related striation and locally accompanied by congruent dragging folding. Reverse and thrust faults form zones 1 m to a few tens of meters wide traceable sometimes for 5 km and more. Such zones characterized by gentle and listric planes with slickensides are particularly well manifested in the eastern limb of the Zarubin Anticline, where they orthogonally cross Paleozoic fold structures (Figs. 7, 10). Latitudinal thrusts superimposed on Paleozoic meridional fold structures are also observed in the Khasan area southwest of the study region (Fig. 11). The near-latitudinal systems of reverse faults also cross Upper Riphean (?) gabbroids with cleavage and near-meridional bodies of Permian granitoids developed along the latter (Fig. 12).

*Deformations of Mesozoic and Cenozoic Sequences*

Mesozoic and Cenozoic folds and fractures are observable in the Triassic Talmi and Mongugai, Cretaceous Razdol'naya, and some Cenozoic depressions.

**The Talmi Depression** is bounded by meridional faults (Fig. 1). It is composed of stratified Late Triassic basalts and rhyolites with fragments of Permian granites. Andesite and rhyolite flows experience warping with the formation of NE-oriented folds (azimuth 30–40°). Their limbs dip northwest- and southeastward at angles of 30–85°, while their hinges dip northeastward

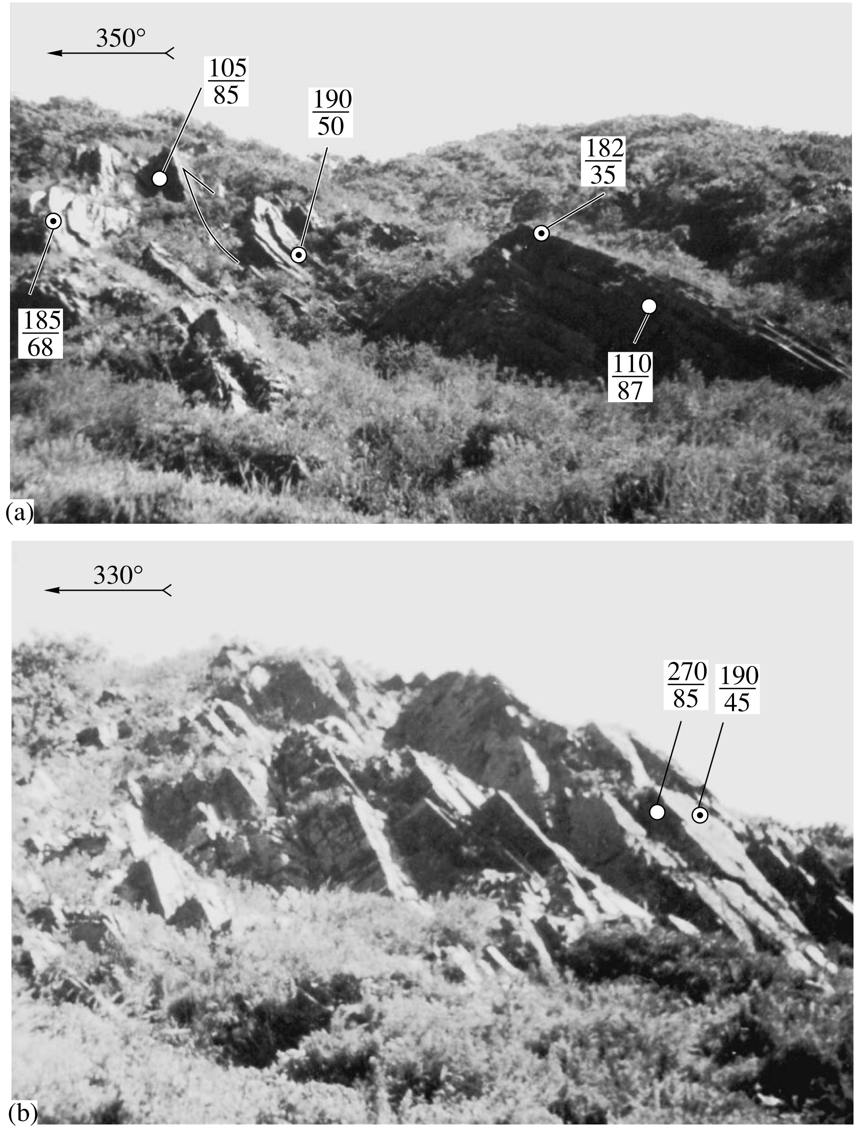


**Fig. 10.** Zones of near-latitudinal updip–thrusts with low-angle planes (b) and of the listric type (a), transversely crossing the eastern limb of the Zarubin Anticline. The Zarubin Peninsula (for location, see Fig. 7, legend as in Fig. 3).

at angles of 5–30° (Fig. 2). The folds are up to a few tens of meters wide.

**In the Mongugai Depression,** Upper Triassic coal-bearing sequences are deformed into simple, frequently brachyform NE-trending folds with dip angles of 10–35 up to (locally at limbs) 50—60° (Fig. 2). These are the NE-trending Fillipovka and Borodinsky synclines and Malyutinka Anticline [4].

In the study region, the **Razdol'naya Depression** represents a southwestern flank of a large sedimentary basin filled in largely by Cretaceous rocks deformed into NE-trending gentle brachyform folds similar in shapes and strike to their counterparts in Triassic sequences of the Mongugai Depression (Fig. 2). The northwestern part of the spacious Razdol'naya Depression (beyond the limits of the study region) comprises a system of NE-trending anticlinal and synclinal uplifts bounded by uniform synsedimentation thrusts [3]. Similar folding is also characteristic of Cenozoic alternating sediments and andesites, for example, in the Poima Depression, where dip angles of limbs in NE-trending folds amount to 80° and their hinges dip largely southwestward at angles of 10–30° (Fig. 2).

Thus, Mesozoic and Cenozoic sequences characterized by a system of NE-trending largely brachyform folds conform to the strike of the Sikhote Alin fold system in eastern Primorye. The structures related to latitudinal compression are missing. Consequently, Mesozoic–Cenozoic sequences were deformed under NNW-oriented compression synchronously with systems of near-latitudinal troughs, folding, and updip–thrusts superimposed on Paleozoic protostructures.

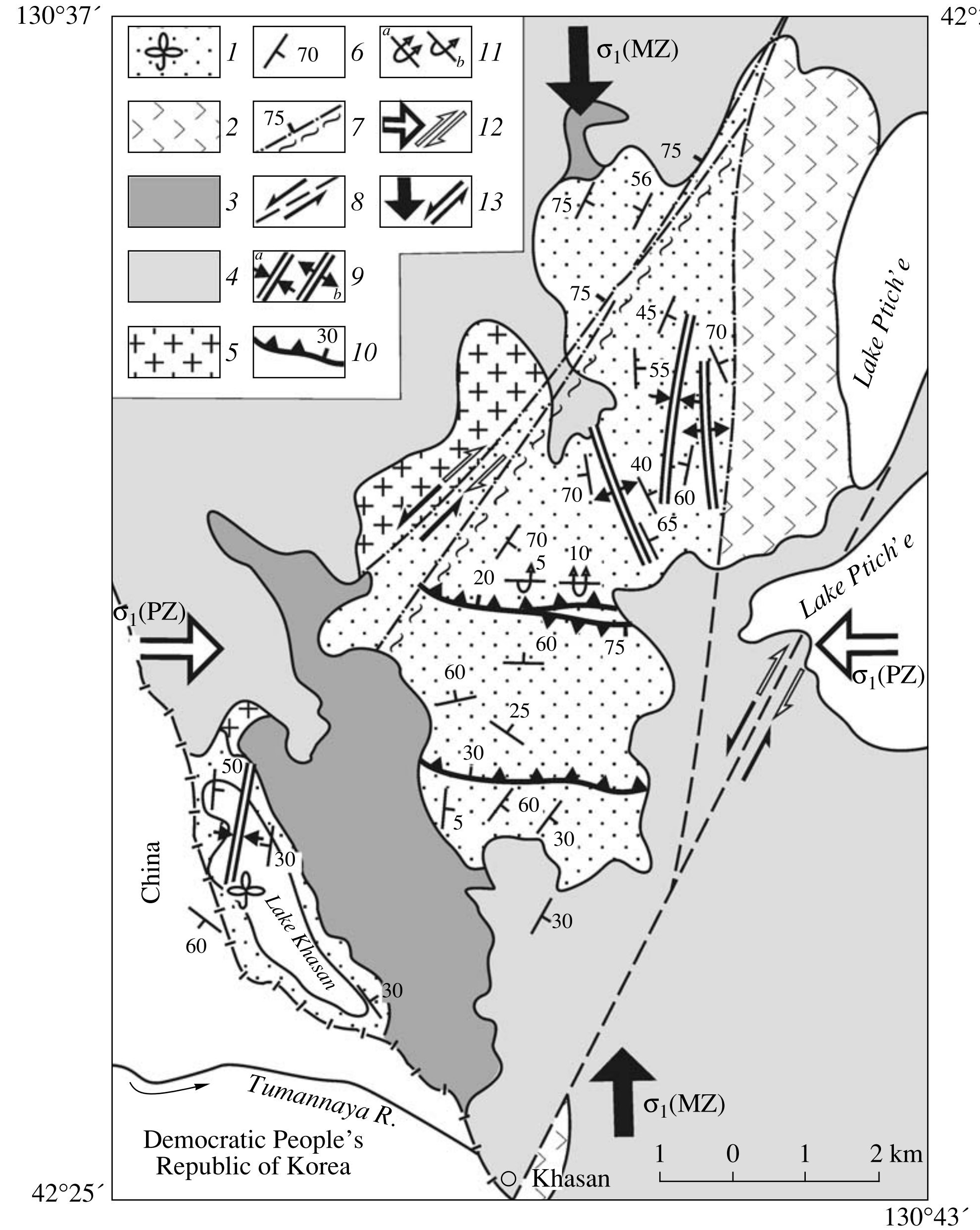


**Fig. 11.** Two orientations of deformations in terrigenous sequences ($P_{1-2}$) of the Khasan block.
(*1*) Terrigenous sediments with plant remains ($P_{1-2}$); (*2*) rhyolites, andesites ($T_3$); (*3, 4*) Paleogene (*3*) and Neogene (*4*) sediments; (*5*) multiphase granitoid complex ($P_2$); (*6*) orientation of beds; (*7, 8*) proven (*7*) and assumed (*8*) strike-slip faults; (*9*) synclines (*a*) and anticlines (*b*); (*10*) thrusts and reverse faults; (*11*) overturned folds (*a*) and beds (*b*); (*12*) dextral strike-slip faults resulting from latitudinal compression; (*13*) sinistral strike-slip faults activated in response to meridional compression.

### *System of NNE-Trending Strike-Slip Faults*

Even based on morphological features (rectlinearity), this system of through faults should be attributed to strike-slip faults (Fig. 1). Moreover, by its strike, the latter is identical to the fault system of eastern Primorye with a proven sinistral strike-slip component [8, 17]. In the examined territory, the strike-slip faults that are characterized below are mapped for distances of tens of kilometers as boundaries between rocks of different ages and compositions (Fig. 1); locally, their structures and kinematic characteristics were studied.

**The Ussuri strike-slip fault** [19] that is traceable in the region under consideration along the northwestern coast of the Amur Bay extends in the northeastern direction at least for 500 km, being almost continuously marked by rectilinear segments of river valleys (from the north southward): Ussuri, Ilistaya, and Razdol'naya (lower reaches) (Fig. 1). This fracture corresponds to a distinct gravity step. In fact, it represents a zone of

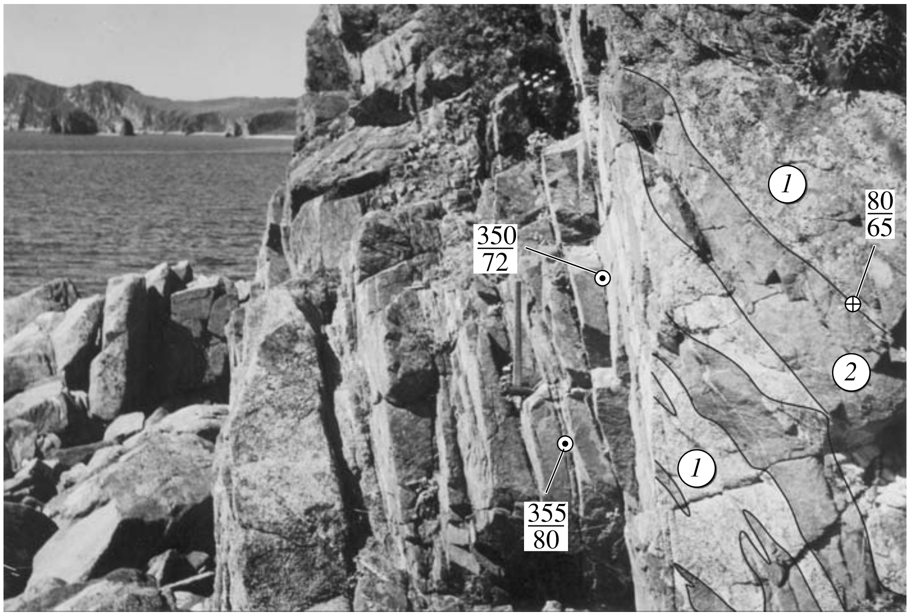


**Fig. 12.** Zone of latitudinal reverse faults crossing gabbroids in the western limb of the cleavage synform (for location, see Fig. 4; legend as in Fig. 3).
Encircled number: (*1*) biotite granites, (*2*) gabbroids.

strike-slip faults up to 2–3 km wide. Northerly in the Lake Khanka area (Ilistaya River), Cambrian sequences are displaced along the Ussuri strike-slip fault for 50 km in the sinistral direction [19]. The strike-slip fault also controls the Poima, Provalovsky, and Razdol'naya depressions and truncates the Barabash Anticline on the southeast (Fig. 1). In the Cape Gamov and Boisman Bay areas, the strike-slip fault is marked by zones of gauge clays, brecciation, and a system of steep planes with low-angle tectonic striation and feathered by relevant extension-induced NW-trending fractures that enclose dikes of different lithologies.

The eastern limb of the Sukhanovka Anticline is crossed by a system of closely spaced NE-trending fractures (Fig. 13a) representing elements of the Ussuri strike-slip fault. Judging from the development of echelon extension fractures and extension duplexes of out-of-line strike slips (Figs. 13b, 13c), they are sinistral strike-slip faults. In the zone of the Ussuri strike-slip fault, Triassic sequences show intense cleavage, foliation, and microfolds. The fault zone is also characterized by relevant folds and fractures in Paleogene–Neogene sedimentary and volcanogenic rocks.

**The Kubansky, Zarubin, Tsukanovka, Beregovoi, Shkotovo,** and other less extended (as compared with the Ussuri) strike-slip faults are reflected in the topography largely as negative structures being frequently traceable along the general direction of the sea coast for tens of kilometers (Fig. 1). The strike-slip faults usually border Paleozoic fold structures and Cenozoic depressions along the strike or cross them displacing in the sinistral direction for a distance up to 0.5 km (Fig. 1). Their zones up to 0.5 km wide are formed by systems of closely spaced fractures (planes). Displacements along particular planes are insignificant, while their integral amplitudes may be high. In addition, there are thick (up to 5 m) members of gouge clays, brecciation, and foliation located in these zones of the diffused displacement, which result undoubtedly from significant and repeated strike-slip displacements. Strike-slip kinematics are reflected in low-angle tectonic striation developed on steep planes that border narrow sheets composed of differently brecciated and grinded rocks. The strike-slip zones locally host small folds with steeply dipping hinges, while beds of sedimentary rocks are rotated counterclockwise in a flexure manner relative to the general northwestern strike, which points to sinistral strike-slip kinematics. Sinistral displacements along some strike-slip faults (up to 3 km) are recognized due to separated contacts and marker members of Permian formations (Fig. 1).

**The Western Primorye Fault** over 200 km long is oriented in the meridional direction and, according to geological mapping, serves as a boundary between different lithotectonic zones (LTZ) [11]. The southern segment of the fault separates the Pogranichnaya and Barabash LTZs composed of terrigenous ($P_{1-2}$) and substantially volcanogenic ($P_2$) sequences with the respective Gamov and shallow Sedanka complexes of Late Permian granoitoids (Fig. 1). Its northern segment, which is interpreted to represent the eastern boundary of the Early Silurian intracontinental rift, separates the Grodekovo LTZ and Kantei Massif in the Chinese territory [11]. The fault was initiated no later than in the Early Permian. It is accompanied by narrow depressions filled in with terrigenous sediments, products of

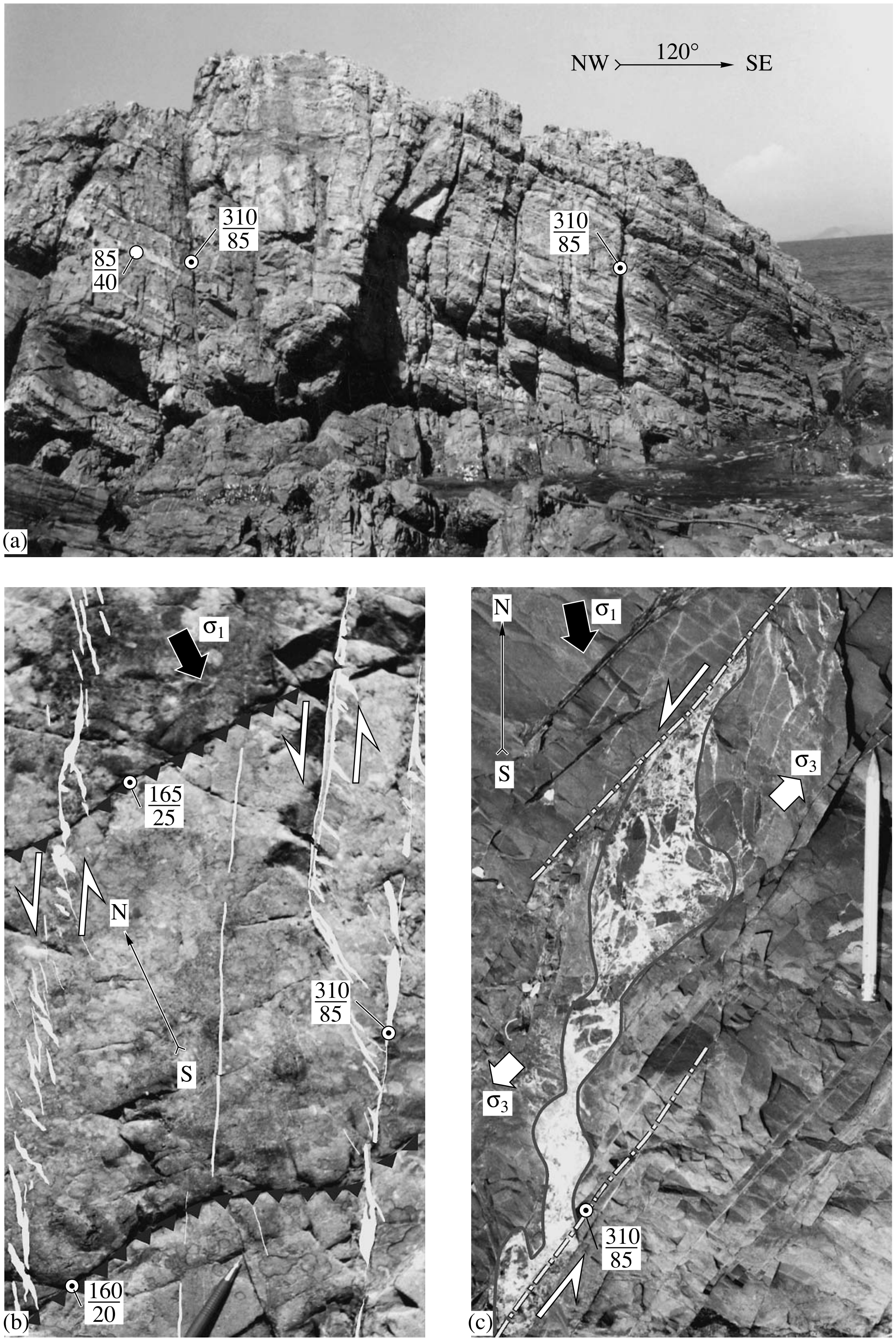


**Fig. 13.** System of closely spaced sinistral planes in the zone of the Ussuri strike-slip fault crossing the eastern limb of the Sukhanovka Anticline. Western coast of Boisman Bay (for location, see Fig. 1).

Sinistral displacements along strike-slip faults are manifested in plan as echelon quartz veinlets (b) and as an extension duplex of out-of-line strike-slip faults filled in with breccia cemented by quartz (c). The denticulate line indicates thrusts: direction of main compression ($\sigma_1$) and extension ($\sigma_3$).

Early and Late Permian fault-line volcanism, and Cretaceous coaliferous–terrigenous formations (Fig. 1.). The Cenozoic Amba, Narva, and Poima depressions are also confined to this fault (Fig. 1); crossing the last two structures, it displaces them sinistrally for a distance of 1 km. The fault zone up to 1 km wide consists of a system of closely spaced planes accompanied by intense cleavage, foliation, and mylonitization. The planes bear largely sinistral strike-slip tectonic striation and are accompanied by axonoclinal folding. The fault zone is also characterized by signs of repeated strike-slip activation with different kinematics (dextral and sinistral strike-slip faults).

## GEODYNAMIC FORMATION SETTINGS OF DIFFERENT-AGE DEFORMATIONS

As is shown, the Paleozoic and Mesozoic stages in the tectonic development of the southwestern Primorye region are characterized by different structural parageneses. Their analysis allows geodynamic settings to be defined for development of different-age deformations. For the Paleozoic stage, these are near-meridional compression structures: different-rank, congruent, largely compressed folds accompanied by intense cleavage, foliation, single-plan updip–thrusts with folds, and zones of dynamothermal metamorphism extended along fold structures. Under near-latitudinal compression, development of fold–cleavage structures in the Late Permian was accompanied by granitization with the formation of different-size granite bodies controlled by these structures. There are successive stages established in the formation of the fold–cleavage structures and synchronous mineralization, which indicate discrete near-latitudinal compression.

The confinement of near-meridional compression structures to pre-Mesozoic sequences allows the inference that the Mesozoic deformation stage in the southwestern Primorye region was characterized by different geodynamic settings. It is also hardly valid to extrapolate near-latitudinal compression to the Riphean, since the concordance between the Late Riphean (?) and Paleozoic structures is probably determined by Paleozoic stresses, due to which protostructures reflecting the Late Riphean geodynamic settings could be masked by superimposed deformations. In addition, the Late Riphean age of gabbro–pyroxenites in the region under consideration is ambiguous; it is conceivable that they correspond to the earliest stage of the Late Paleozoic intrusive magmatism [2].

As for possible development of NE-trending faults in the Paleozoic, it should be noted that, in the near-latitudinal compression settings, they could form as dextral strike-slip faults. This assumption follows from the near-meridional orientation of Paleozoic compression structures, which correspond entirely to structural parageneses of NE-trending dextral strike-slip faults. In response to the change of the geodynamic setting in the Mesozoic, dextral strike-slip faults could be transformed into sinistral varieties; thus, they are presumably considered as faults with alternating kinematics.

The Mesozoic stage of deformations was characterized by development of tectonic systems of NNE-trending sinistral strike-slip faults, near-latitudinal updip–thrusts, and NE-trending folds. The system of such folds developed in Mesozoic–Cenozoic sedimentary sequences is oriented obliquely (at angles of 28 to 40°) relative to strike-slip faults bordering and crossing sedimentary basins (Figs. 1, 2), which indicates that folding associates with them. Folding in Paleozoic sequences is less intense, being manifested in the formation of synclinal troughs transverse to protostructures and small folds superimposed discordantly on limbs of these primary structures. It is conceivable that Paleozoic sequences deformed into near-meridional folds and even more brittle Permian granitoids were unfavorable for the fold formation during the Mesozoic stage of tectonic deformations. Therefore, near-meridional compression resulted largely in wide development of near-latitudinal updip–thrusts.

The systems of Mesozoic–Cenozoic compression structures formed synchronously with activation of NE-trending sinistral strike-slip faults. At the same time, blocks of consolidated Paleozic rocks bordered by faults experienced Mesozoic and Cenozoic destruction with the formation of pull-apart structures that were oriented transversely relative to strike-slip faults and determined localization of sedimentary basins. This is primarily true of Cenozoic depressions controlled by strike-slip faults, which is not incidental (Fig. 1). The pull-apart nature of these structures is best exemplified by the Kraskino and Narva coal-bearing depressions [19, 20] extended in the WNW direction transversely to their bordering strike-slip faults (Fig. 1). Similar to others, these depressions were characterized during the Cenozoic by intermittent volcanism represented by basaltic and acid lavas, which indicates discrete extension of the consolidated basement beneath sedimentary basins synchronously with movements along strike-slip faults. Uncompensated extension structures associated with strike-slip faults likely determined the formation of the linear Amur Bay that is bordered by strike-slip faults (Fig. 1). The Murav'ev–Amurskii horst anticline bounded by the Beregovoi and Shkotovo strike-slip faults was also involved into relevant extension, which resulted in the formation of bays (Zolotoi Rog, Novik, and others) and straits separating the Russkii, Popov, and other islands from the continent. These structures are oriented transversely to strike-slip faults and characterized by southwestward stepwise dipping of their bottom (Fig. 1). Destruction of the continental crust associated with movements along strike-slip faults that commenced in the Triassic to reach the maximum in the Cretaceous was in progress during the Pleistocene. This is evident from inherited subsidence of the spacious Triassic–Cretaceous Razdol'naya sedimentary basin bordered by the Kubansky and Ussuri strike-slip faults, where Triassic deposits are overlain by Cretaceous strata in the northeastern part of the Mongugai Depression (Fig. 1). The basin subsidence was accompanied by development of NW-trending normal faults transverse relative to strike-slip faults. Planes of these normal faults dip steeply in the northeastern direction toward the pull-apart structure of the consolidated basement under the Razdol'naya basin, which was repeatedly activated in response to movements along strike-slip faults (Fig. 1). Synchronous or successive development of compression and extension structures is a characteristic feature of the geodynamic regime associated with strike-slip faults.

The structural analysis allows the following main inference: the Paleozoic–Mesozoic boundary was marked by a sharp change in the geodynamic settings in response to the replacement of near-latitudinal compression by the near-meridional one. This resulted in the formation of shear (strike-slip faults), compression (updip–thrusts and folding), and extension (pull-apart structures associated with strike-slip faults) structures in the southwestern Primorye region during the Mesozoic and Cenozoic. They are characterized by regular spatial and temporal subordination and are similar to Mesozoic–Cenozoic structural parageneses of sinistral strike-slip dislocations in eastern Primorye [17, 19]. The concordance between Paleozoic and Mesozoic structures observed in the last region should probably be considered as resulting from intense transformation of Paleozoic protostructures by superimposed Mesozoic dislocations related to development of the Sikhote–Alin system of sinistral strike-slip faults under near-meridional compression.

In some short periods of the Mesozoic, near-latitudinal compression could have probably developed in the Primorye region, although it left unchanged the structural patterns of the latter formed by movements along the sinistral strike-slip faults. Inasmuch as the Primorye region represents a large fragment of the eastern Asian margin, it can be assumed that the established change in the geodynamic settings is characteristic of the entire Asian–Pacific transition zone. Consequently, the replacement of the geodynamic regimes should be considered as resulting from changes in the direction of the lateral motion of the Asian continent and (or) Pacific Plate, which is consistent with our previous conceptions [18, 21, 29].

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