ISSN 1819-7140, Russian Journal of Pacific Geology, 2013, Vol. 7, No. 2, pp. 107–123. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © P.L. Nevolin, V.P. Utkin, A.N. Mitrokhin, S.A. Kasatkin, 2013, published in Tikhookeanskaya Geologiya, 2013, Vol. 32, No. 2, pp. 44–62.

Role of Latitudinal Compression in the Formation of Paleozoic Intrusive Structures in the Southern Primorye Region in the Far East

P. L. Nevolin, V. P. Utkin, A. N. Mitrokhin, and S. A. Kasatkin

Far East Geological Institute (DVGI), Far East Branch, Russian Academy of Sciences, pr. Stoletiya Vladivostoka 159, Vladivostok, 690022 Russia

E-mail: val-utkin@yandex.ru, stakhor@yandex.ru

Received January 17, 2011

Abstract—The structural–geodynamic features of the Anna, Gaidamak, Dunai, Tinkan, and Tafuin gabbroid and granite intrusions are analyzed. They are recently considered as elements of the basite Sergeevka terrane, which was previously known as the Sergeevka metagabbroid inlier (or massif). At the same time, their outcrops mark the ENE-trending Tafuin anticlinorium, which, being conjugate and synchronous with the northerly adjacent Petrovka depression, was formed in the Mesozoic as a constituent of the long-living Sergeevka structure. Therefore, these intrusions are considered in this work along with Cretaceous massifs, which occur among Mesozoic sediments, as resulting from tectonic-magmatic pulses transforming the basic substrate. These pulses mark the Proterozoic–Early Paleozoic, Late Paleozoic, and Mesozoic geodynamic periods with each being characterized by particular directions of the lateral compression with the Late Paleozoic one being the most intense. The latter was responsible for the near-meridional elongation of the structures and the dominant directions of their elements: the layering, banding, taxitic textures, cleavage, and foliation. All of them were determined by the cleavage formation and thrusting (in form of counter thrusts) of the same direction. The intrusions exhibit shear-type pseudofolds, which are considered as produced by flattening and warping.

Keywords: structural patterns, geodynamic periods, nonisostatic strain field, longitudinal compression, banding, layering, cleavage, pseudofolded structures, intrusive massifs, southern Primorye region

DOI: 10.1134/S1819714013020061

INTRODUCTION

Reconstructions of regional paleostrain fields and block movements derived from the terrane and plate tectonics analyses, which are based to a significant extent on the compositional features of igneous rocks, lead to the concepts of the dominant role of longitudinal compression in the earth crust [3]. On the other hand, based on these compositional properties of the magmatic chambers, it is traditionally believed that large and small intrusions are characterized by autostructuring under intense transverse (vertical) dynamic influence on the host medium of the "emerging" magmatic column. In our opinion, the contradiction between these two gnoseologic approaches may be eliminated by conducting structural–geodynamic investigations of the geological position and structures of the intrusions. Such investigations carried out in the Albian Uspenka [12, 13] and Cambrian Tafuin [15] intrusions of the southern Primorye region revealed the inheritance of the host structures by these massifs and the dominant role of lateral compression in the formation of their architecture and structure.

Previously, such investigations involved mostly granite massifs. The main purpose of this work consisted in the sampling and analysis of the factual material concerning the structures of the basic intrusions, the comparison of their structural features with those of the granite massifs, and revealing the consistencies in structural patterns of the gabbroid bodies and deformations corresponding to three geodynamic periods [14].

The investigational methodology corresponds to the level of the meso- and macro structural studies, or small- and large-scale geological mapping. It includes several traditional methods of structural investigations developed in the works by E. Cloos, B. Sander, A.A. Polkanov, N.A. Eliseev, A.V. Luk'yanov, A.I. Suvorov, V.S. Burtman, S.I. Sherman, V.P. Utkin, and many others. The main attention was paid to the study of the strain field indicators such as the structural parageneses and patterns [2, 9, 17, and others] formed by the directions of the bedding, foliation, banding, layering, and other elements.

The structural paragenesis is an association of tectonic elements, the formation of which was determined by the same geodynamic factor; i.e., they were formed synchronously. Every element and geodynamic impact are characterized by a genetic connection, while the elements are connected by paragenetic relationships. The parageneses of elements as reflections of tectonic events serve as a main tool for interpreting the paleogeodynamic environments: strain fields (the deviator stress is meant) and block movements. Knowing the impact type, we may forecast a missing element of the paragenesis during, for example, investigations of ore-bearing structures. The parageneses are named after the corresponding dynamic settings (paragenesis of longitudinal or transverse compression or extension) and types of deformations (reversed-fault, strike-slip-fault, fold, pure- or simple-shear, and others). The knowledge of the parageneses is continuosly improved owing to experimental, theoretical, and natural modeling. Every type of parageneses may belong to different levels of structural organization of the geological space. In natural environments, the researcher, in fact, deals almost always with the integrity of different-order parageneses. For example, the paragenesis of the pure shear (conditionally of the first order) surely includes the simple-shear parageneses of the second (and higher) order. The latter contains unavoidably thrust and pull-apart parageneses of the third and fourth orders, which, in turn, may include normal-fault parageneses of the fifth order. The same is true of different-order parageneses of fold deformations, where the first-order structures resulting from the longitudinal compression may include hierarchically subordinated folds and disjunctive elements related to transverse compression that indicate the formation of a similar hierarchically of subordinate strain fields. Proceeding from the interpretation principles in [9], it would likely be more correct to name different-order paragenetic integrities as structural patterns. At the macro- and microlevels, the researcher deals usually precisely with patterns defining dominant paragenetic associations of tectonic elements among them. Further, cells of domains should be determined [5]. In this work, the cell is a space area where the structural pattern is dominated by a certain type of single or several parageneses that mark the same geodynamic setting. Such areas are usually characterized by different sizes. In mesolevel constructions, domains are usually defined using graphical and statistical analyses. In this case, the main role belongs to the graphical analysis and statistics in the orientation of structural elements proper, which serve frequently as indicators of tectonic movements. The graphical analysis comes mostly to the construction and interpretation of different-scale plans, sections, and maps for revealing structural patterns and parageneses. The statistical analysis consists largely in obtaining of the generalized statistical orientation picture of structural and kinematic elements. For this purpose, circular diagrams are constructed by the traditional method using many measurements of dip azimuths and angles of elements. These methods are considered in many works [e.g., 26]. Our diagrams are constructed on the upper hemisphere of the Wulff equiangular projection. This equiangular stereographic projection allows more correct comparison of angles between probable systems of conjugate shears, and its upper hemisphere is significantly more convenient for plotting poles of planar elements. Clouds of poles form different-intensity maximums. In the end, the diagram represents a statistical model of the structural pattern or paragenesis [17]. The more regular the distribution of the measurement points in the space, the more objective the diagram is. The statistical analysis is in fact performed simultaneously with the geometrical one. Their results supplement each other.

Let us recollect also the paragenesis of pure-shear deformation, which represents a reliable indicator of the strain field. Under the load of the pure-shear deformation, the anisotropic strain field is characterized by the formation of conjugate shears, which are expressed as a system of intersecting fractures [18, 28, and others]. The intersection of shears forms two pairs of opposite dihedral angles. Moreover, the maximal stress σ_1 is directed along the bisector plane of a pair of opposite angles orthogonally to the conjugation (intersection) of the shears. The angle between the axis of the main compression and the one of the conjugate shears is termed as a shear angle (θ). The angle between two conjugate shears is termed as an angle of conjugation (2θ). Under brittle deformation, the angle θ never exceeds 45°. At the same time, in case of plastic shearing in the crust, for example, at shallow and medium depths [18], the angle θ may be as large as 70°–80° [18]. The minimal compression stress σ_3 is directed along the other bisector plane of another pair of opposite angles. In this case, the intermediate strain axis σ_2 is parallel to the conjugation line.

MATERIALS

Geodynamic Structure-Forming Periods

Three structural styles of interfering successive deformations that correspond to three geodynamic periods [14, 20, 21] lasting in total from the Late Proterozoic to the initial Cenozoic are definable in the western and southwestern Primorye region. The investigations of the structural patterns and parageneses reveal that the dominant structure-forming compression during each of these periods was practically unidirectional. The Anna, Gaidamak, Dunai, and Tinkan intrusive massifs, the structures of which represent the main objects for this study, became elements of the structural plans corresponding to these geodynamic periods.

Late Proterozoic–Early Paleozoic period. The compression vector during this period is interpreted from the gentle folds observable in rocks constituting the basement, for example, of the Khanka massif. In this intrusion, gentle hinges of folds are usually oriented at ≈255°–285° orthogonally to the direction of the main compression vector confined to the sector between ≈345° to 15°. This is exemplified by the position of the Tafuin massif.

Middle–Late Paleozoic period. This period was characterized by the dominant sublatitudinal compression vector, which determined the structural flattening in reliably dated (by faunal assemblages) stratified Silurian and Lower and Upper Permian sections (the Kordonka (S_1), Kazachka (P_1), Reshetnikovka (P_{1-2}), and Barabash (P_2) formations) with the development of narrow strongly compressed folds, cleavage, and counter-thrusts [14, 21], as well as in the Gamov and Grodekovo granite batholiths. The collected material shows that precisely the principal regional sublatitudinal compression during this period was responsible for the formation of the structures of the basic and leucogranitic intrusions under consideration.

Mesozoic period. This period was marked by NNW-oriented lateral compression, which determined the Sikhote-Alin deformation plan [19]. Its resulting structures include large and small folds of the northeastern strike, meridional and NNE-trending sinistral strike-slip faults, northeastern thrusts, and northwestern normal faults. In the western Primorye region, Mesozoic deformations were superposed on Late Paleozoic structures bending, displacing, renewing, and transforming them. The different-order folds of the northeastern strike are also observable in the general system of integral folding. The main of them are represented by large warping fold deformations, which control the magmatic processes and mineralization.

Structures with many intrusions produced during different geodynamic periods are variably expressed in the southern Primor'e region as well. In this work, the main attention is paid to the Anna, Gaidamak, Dunai gabbroid, and Tinkan granite massifs, which were formed during the Middle–Late Paleozoic geodynamic period.

Geological Position of Intrusions

The Paleozoic Anna, Gaidamak, Dunai, Putyatin gabbroid, Tafuin, Tinkan granite (Fig. 1), and other smaller massifs crop out in the axial part of the Tafuin anticlinorium [4] (Fig. 1b). This anticlinorium was formed during the Mesozoic geodynamic period simultaneously with the neighboring (in the north) Petrovka depression filled with Triassic–Cretaceous sediments.

The anticlinorium was previously considered as the Sergeevka inlier of the ancient ophiolitic substrate [6, 10], which is better known now as the Sergeevka terrane (Fig. 1a) accreted owing to subduction [22, 23] or obduction [8] to the continental block (Fig. 1). The main terrane-constituting complex was subjected to several pulses of tectonomagmatic activity [6, 11]. Its separate easterly located block represents a complex composite structure termed the Sergeevka metagabbroid massif.

The following complexes are definable with different confidence in the Sergeevka terrane-forming massif: (1) the Avdokimovka (PR–?) composed of meta-amphibolites, paragneisses, metasedments, metavolcanics, and marbles constituting relicts (including shadow structures) in orthometamorphites; (2) the Sergeevka (PZ_1–?) represented by layered gneissoze gabbroamphiboltes and diorites; (3) the Partizansk (PZ–?) consisting of oval gneiss–granite and gneiss–plagiogranite bodies usually with obscure boundaries; (4) the Vladimiro-Aleksandrovskoe (Є–?) peridotite; and (5) the Taudemi (Є), which includes microcline hybrid granodioritic plagiograntes [6]. The alternation of the contrasting bodies of the Sergeevka, Partizansk, and Taudemi complexes is considered as resulting from the transformation of the mafic substrate during the subsequent palingenesis and migmatization [6]. Developing this viewpoint, we defined preliminarily four tectonic-magmatic stages of mega-layering. Each of these stages is represented by a pair of near-synchronous contrasting (leuco- and melano-) complexes [11].

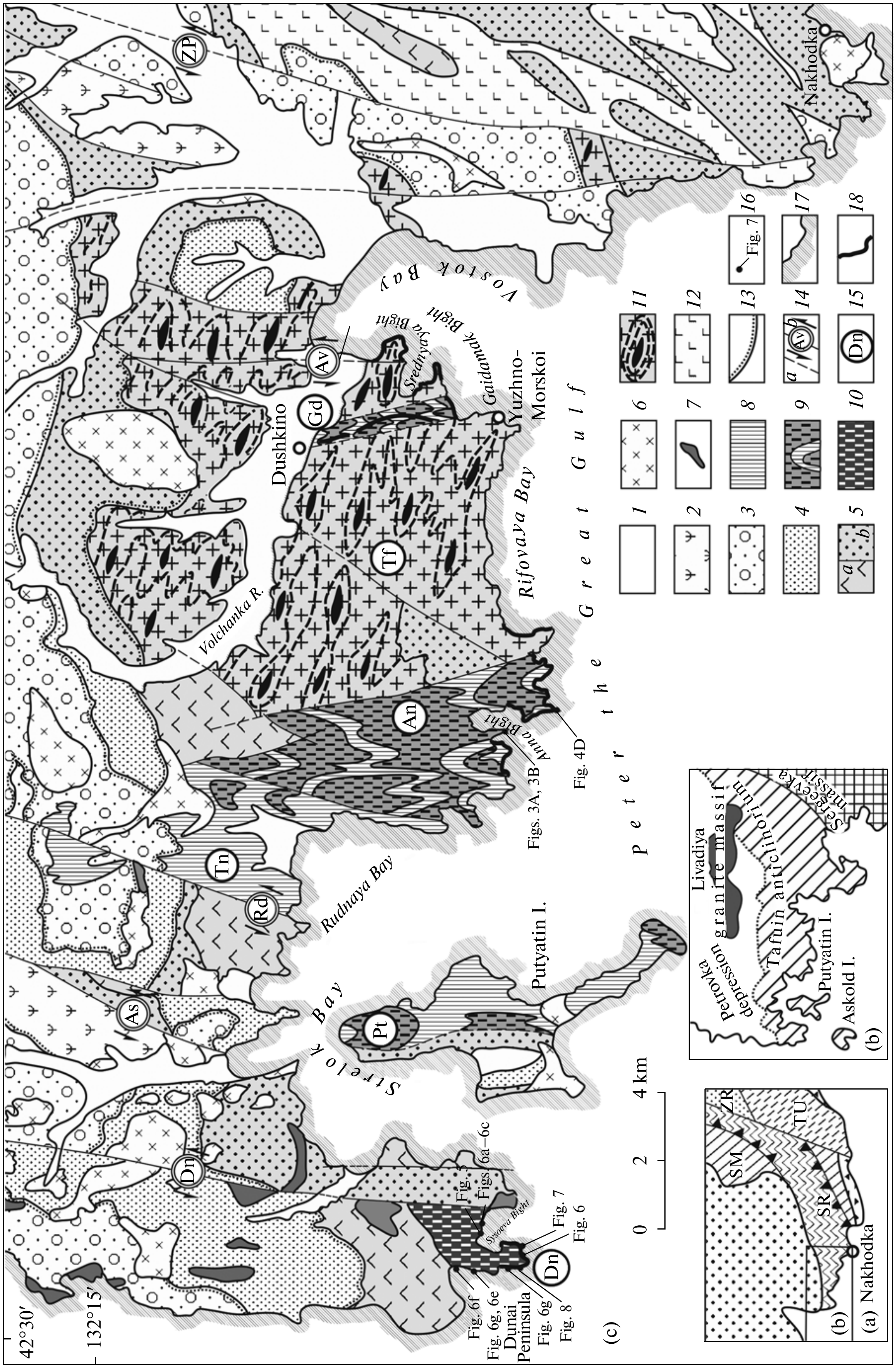
The examined intrusions of the Tafuin anticlinorium are spatially and temporarily interrelated with each other so closely that they may together be considered as a composite massif resulting from the transformation of the mafic substrate. It is conceivable that their above-mentioned structural properties have analogs immediately within the parental block proper and may help in interpreting the relatively complex stucturization of both the Sergeevka terrane and the southern Primorye region as a whole.

The intrusive structures considered in this work experienced the variable impact of geodynamic processes during all three periods. Nevertheless, the latitudinal compression during the Middle–Late Paleozoic geodynamic period was the principal structure-forming factor for all the intrusions except the Tafuin one.

Structurization of Intrusions

The Tafuin Granite Intrusion

The brief characteristics of the Tafuin massif are given only for the comparison with the basite massifs considered below. The massif is located on the Livadiya Peninsula, where it is composed of bimicaceous granites. It represents an ESE-extending inlier among younger rocks, and its configuration is interpreted from erosional windows. The structure of the massif is in detail considered in [15], where it is shown that the structures of the Cambrian Tafuin massif are consistent with the deformations produced by the Late Proterozoic–Early Paleozoic NNE-oriented compression. This compression resulted in the formation of the main folds belonging to two types.



ZP
Nakhodka
Vostok Bay
Srednyaya Bight
Gaidamak Bight
Yuzhno-Morskoi
Gd
Av
Dushkino
Rifovaya Bay
Peter the Great Gulf
Tf
Volchanka R.
An
Anna Bight
Fig. 4D
Figs. 3A, 3B
Tn
Rd
Rudnaya Bay
Putyatin I.
As
Strelok Bay
Pt
Dn
Figs. 6a–6c
Fig. 5
Sysoeva Bight
Fig. 7
Fig. 6
Fig. 6f
Fig. 6g, 6e
Dunai Peninsula
Fig. 6g
Fig. 8
42°30′
132°15′
(c)
0 2 4 km
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
a b
Fig. 7
Av
Dn
(a) Nakhodka
(b)
SM
SR
ZR
TU
Petrovka depression
Livadiya granite massif
Tafuin anticlinorium
Sergeevka massif
Putyatin I.
Askold I.
(b)

Fig. 1. Tectonic position of the intrusions in the southern Primorye region.

(a) The terranes (hachured) and overlying complexes (dots) after [23] and simplified; the terranes: (SR) Sergeevka, (TU) Taukha, (ZR) Zhuravlevka, (SM) Samarka. (b) the principal tectonic units after [4] slightly modified. (c) the positions of the intrusions.

(*1*) Quaternary sediments; (*2–5*) stratified sequences: (*2*) sedimentary, volcanosedimentary, and volcanogenic K_{1-2}, (*3*) sedimentary (J_{1-2}), (*4*) sedimentary (T_{1-3}), (*5*) volcanogenic (P_1) (*a*), terrigenous (P_1) (*b*); (*6*) granitoids (K_2); (*7*) gabbroids (K_2); (*8*) granitoids of the Tinkan massif (P_2); (*9*) gabbroids of the Anna and Gaidamak intrusions with meridional cleavage and pseudofolds emphasized by *beds* of the Tinkan granites (Є?); (*10*) gabbroids of the Dunai intrusion with dominant meridional banding (Є?); (*11*) bimicaceous granites (Є) of the Tafuin massif with relicts of ancient rocks (PR?); (*12*) Sergeevka gabbroids (PR–PZ?); (*13*) unconformity; (*14*) faults, mostly strike-slip faults: (*a*) assumed, (*b*) proven (the double circle corresponds to the fault index and the arrow, to the direction of the displacements): (Dn) Dunai, (As) Askold, (Rd) Rudnaya, (Av) Avangard, (ZP) Zapadno-Partizansk; (*15*) the intrusions: (Gd) Gaidamak, (Tf) Tafuin, (Tn) Tinkan, (Pt) Putyatin, (Dn) Dunai; (*16*) points corresponding to graphical and photo illustrations; (*17*) Peter the Great Gulf coast; (*18*) lines of detailed observations.

The folds of the first type were formed prior to the intrusion's emplacement in the host section. This folding type is reflected in the foliation trajectories of the undisturbed (not reoriented) relicts and the morphology of the shadow bands that remain visible and also not reoriented among the granites after the partial granitization of the host rocks. In diagrams, its folding patterns are represented by main belts 1 and 2, the equators of which unite the main maximums (I, II, III) of the bedding and foliation in the relicts (Fig. 2a), which are almost parallel to each other. The orientation of the belt axes is emphasized by the position of the hinges in the natural folds (Fig. 2a). The belt-like distribution of the bedding and foliation poles points to the horizontal position of the axis of the principal structure-forming strain σ_1^1 orthogonal relative to the hinges of the small folds, the gentle position of the intermediate strain axis σ_2^1 (along hinges), and the vertical position of the minimal compressive strain σ_3^1 (in diagrams, σ_2 and σ_3 are not shown).

Thus, the principal compression was gently oriented in the ENE direction. Small folds observable in

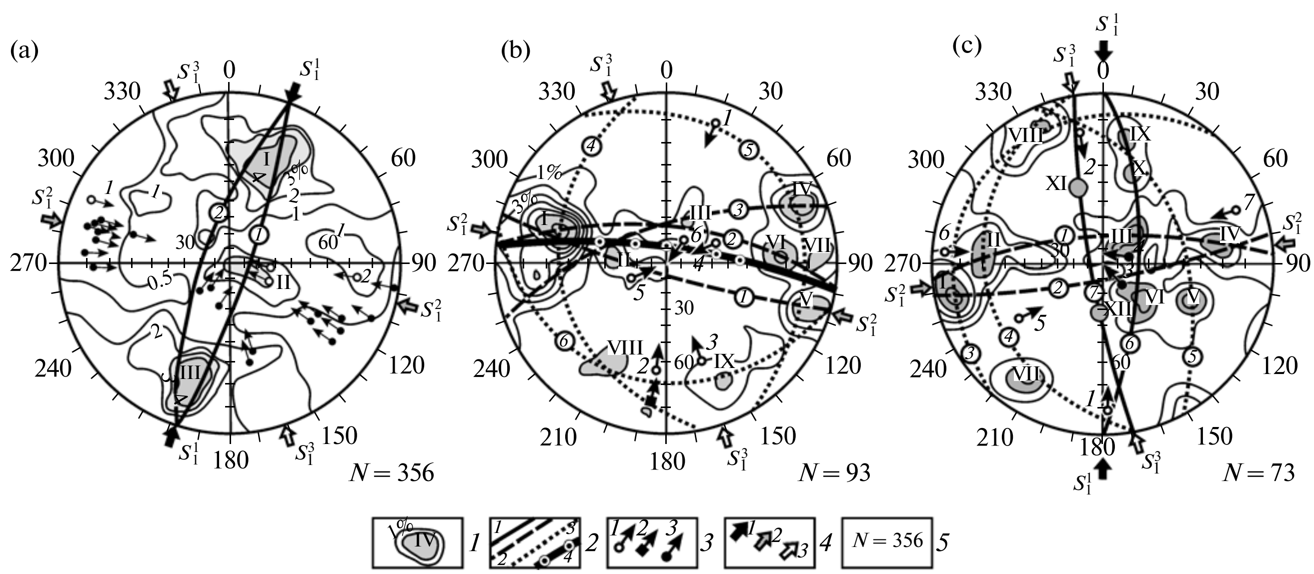


Fig. 2. Orientation of the structural–dynamic elements.

(a) Bedding and foliation in relicts of the Tafuin massif; (b) foliation and thin banding along shears that form pseudofolds in gabbro and gabbrodiorites of the Anna intrusion; (c) taxitic textures, foliation, and banding in gabbroids of the Dunai massif. The diagrams were compiled using the Wulff projection (the upper hemisphere).

(*1*) Lines of isoconcentrations of poles, reference maximums (indicated by Roman numerals and gray-colored); (*2*) equators of belts of elements produced by the Late Proterozoic–Early Paleozoic (1), Late Paleozoic (2), and Mesozoic (3) compression and the belt of the natural pseudofold of the Gaidamak massif (4); (*3*) projections of the belt and natural hinge axes (the scale of the axis dip angles is reversed), the numbers of the projections of the belt axes in the diagram are identical to the numbers of the corresponding belts with the arrows indicating the dipping direction (1), the axis of the belt of the real pseudofold (2), and the hinges of the small natural folds in the relicts of the primary framework and their shadow counterparts in the granites of the Tafuin massif (3); (*4*) the azimuthal direction of the compression during the Late Proterozoic–Early Paleozoic (1), Late Paleozoic (2), and Mesozoic (3) geodynamic periods; (*5*) the number of measurements.

natural outcrops, which complicate the limbs of larger folds, converge opposite to their dips, which is consistent with the structural patterns in the experimental [30] and graphical [27] models. This consistency serves as additional evidence in favor of the dominant lateral compression.

The second, pseudofolding type marks the next, syngranite compression pulse of the same direction, although slightly reoriented clockwise (by 10°–20°). Despite the fact that the patterns caused by such compression are distinctly emphasized by the granite and aplite substrate, they were formed in granites connected by systems of gentle conjugate shears (counterthrusts). It is noteworthy that the structural patterns of the pre-Paleozoic and Early Paleozoic blocks of the Khanka massif were caused by compression of the same direction. The compression that was responsible for the formation of the Tafuin massif is temporally and spatially well consistent with the compression that determined the structures of Khanka massif terranes (for example, the Matveevka–Nakhimovka and other smaller blocks), which "float" in the form of cores among the younger magmatites of the Grodekovo massif. Such a situation indicates at least the structural similarity between the Tafuin massif and the oldest rocks of the Primorye region, let alone its Cambrian age determined by the U–Pb method for zircons [22]. It should be noted, however, that, in the earlier geochronological scale, these dates corresponded to the Ordovician. In the recent geochronological scale (GTS 2004), the date of 493 Ma is attributed to the Cambrian; consequently, the massif also automatically became the Cambrian in age. This age is consistent with its structural patterns correlating the massif with the Late Proterozoic–Early Paleozoic geodynamic period.

The Middle–Late Paleozoic latitudinal compression, which played a dominant structure-forming role during the corresponding geodynamic period in the Anna, Gaidamak, Dunai, and Tinkan intrusions, is reflected in the Tafuin massif only by exclusively postgranite brittle deformations. In the diagram (Fig. 2a), the vector of this compression is designated by the arrow σ_1^1. The brittle properties of the granite material and the lateral direction of the horizontal sublatitudinal compression σ_1^1 along the steeply dipping heterogeneous foliation prevented the formation of new submeridional folds oriented orthogonally relative to such a compression. The latter was able only to provide gentle undulation of hinges of the folds from the first and second pattern types. This undulation is probably illustrated by the counter dip of such hinges in the diagram (Fig. 2a). In addition to the undulation, the latitudinal compression was responsible for the formation of a system of meridional counter thrusts or, less commonly, reverse faults represented in outcrops by planar to, occasionally, gently curved surfaces with thrust and upthrow striation. In some areas, they exhibit insignificant thrust amplitudes (a few centimeters or decimeters). The thrust planes alternate with fractures without visible displacements. The alternation step is 1–3 m. These thrusts cross all the earlier structural patterns.

The Mesozoic NNW-oriented compression is reflected in the Tafuin massif exclusively by the meridional and NNE-trending shear deformations.

Anna and Gaidamak Gabbro–Diorite Massifs

The Anna massif extends from the Anna and Rudnaya bay coasts in the northern direction and is characterized by tectonic contacts with the Tafuin and Tinkan granitoid intrusions (Fig. 1). Its eastern contact with the Tafuin massif is partly overlain by Lower Permian terrigenous rocks. The Anna massif is largely composed of fine- to coarse-grained banded amphibolites–pyroxene gabbrodiorites with subordinate gabbro and pyroxenites. The rocks are intensely altered. The K–Ar ages available for the Anna gabbro–amphibolites are 615, 533–537, 400–500 (according to E.S. Ovcharek), and 200–250 Ma (according to A.V. Oleinikov with colleagues, 2002). The U–Pb method for the zircons yields an age of 526 Ma [23].

Despite the older geochronological dates obtained for the Anna massif as compared with that of the Tafuin one, the whole set of structural elements of the former indicates its structural formation during the Late Paleozoic geodynamic period and the corresponding latitudinal orientation of the lateral compression.

The Anna massif has a "younger twin" represented by the dike-shaped Gaidamak gabbrodiorite intrusion, which is characterized by a similar structure and composition. Gabbroid massifs, which are established in the Gaidamak Bay area, where they are traceable in road excavations, also cross the Tafuin intrusion (Fig. 1).

The structural patterns of the Anna and Gaidamak intrusions indicate that the **Late Paleozoic sublatitudinal compression**, the impact of which is vague in the Tafuin massif, is widely reflected in them as a structure-forming factor. The principal structural features of the Anna and Gaidamak intrusions pointing to the external dynamic impact are primarily the practically meridional cleavage, the foliation parallel to the latter, and the shear pseudofolds. This set of indicators is similar to a significant extent to that characterizing the dynamic environments of the Tafuin massif's formation. The sole difference consists in the different orientations of these structural elements in the Anna and Gaidamak massifs as compared with the Tafuin pluton. The shear folding is defined by analogy with the structure of the Tafuin massif, where such structures are widely developed particularly in the form of aplite bodies [15, 16].

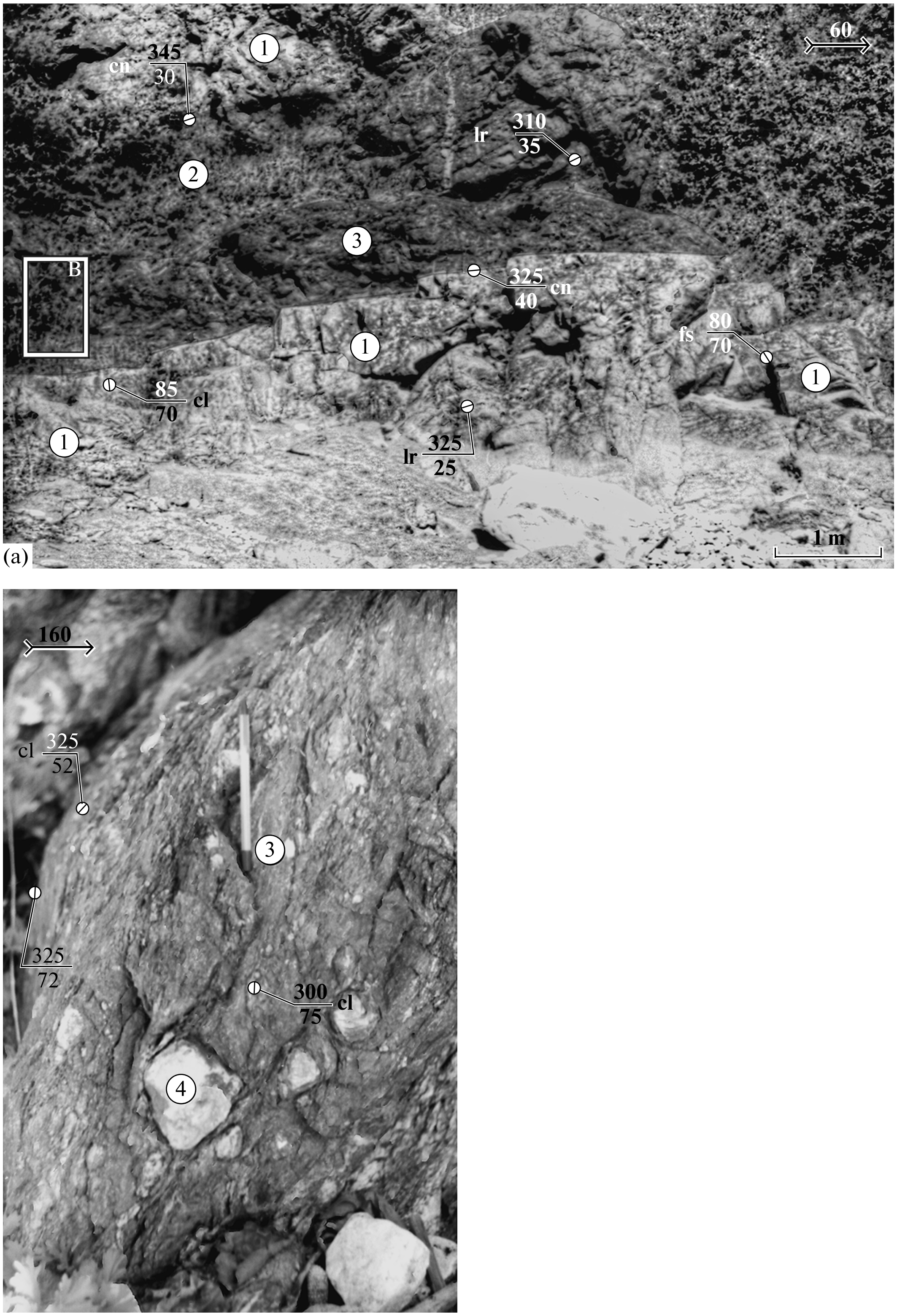


Fig. 3. An example of the stratiform inclusion of altered clastic rocks (2 and 3) among gabbro (1) in the Anna massif (a); a “bed” of dark gray fine-grained rocks with cleavage, foliation, and flattened subangular silicified inclusions (b).

The encircled numbers: (1) massive light greenish gray fine- to coarse-grained gabbro with cleavage and foliation mostly along the cleavage; (2) dark gray fine-grained gabbro with an admixture (up to 5%) of inclusions; (3) the same as (2) but with more abundant (up to 10%) inclusions; (4) inclusions of silicified rocks.

Hereinafter, the small circles indicate the measurement points of the structural elements’ orientation, the fraction designates the azimuth (numerator) and the dip angle (denominator) of the structural element in degrees; the line in a small circle corresponds to the position of the structural element in the plane (here and in Fig. 4): the cleavage (cl), the contact between the bodies (cn), the fold limb (lm), the banding (bn), the layering (lr), the taxitic textures (tx), the fissure (fs), and the fold hinge (hn).

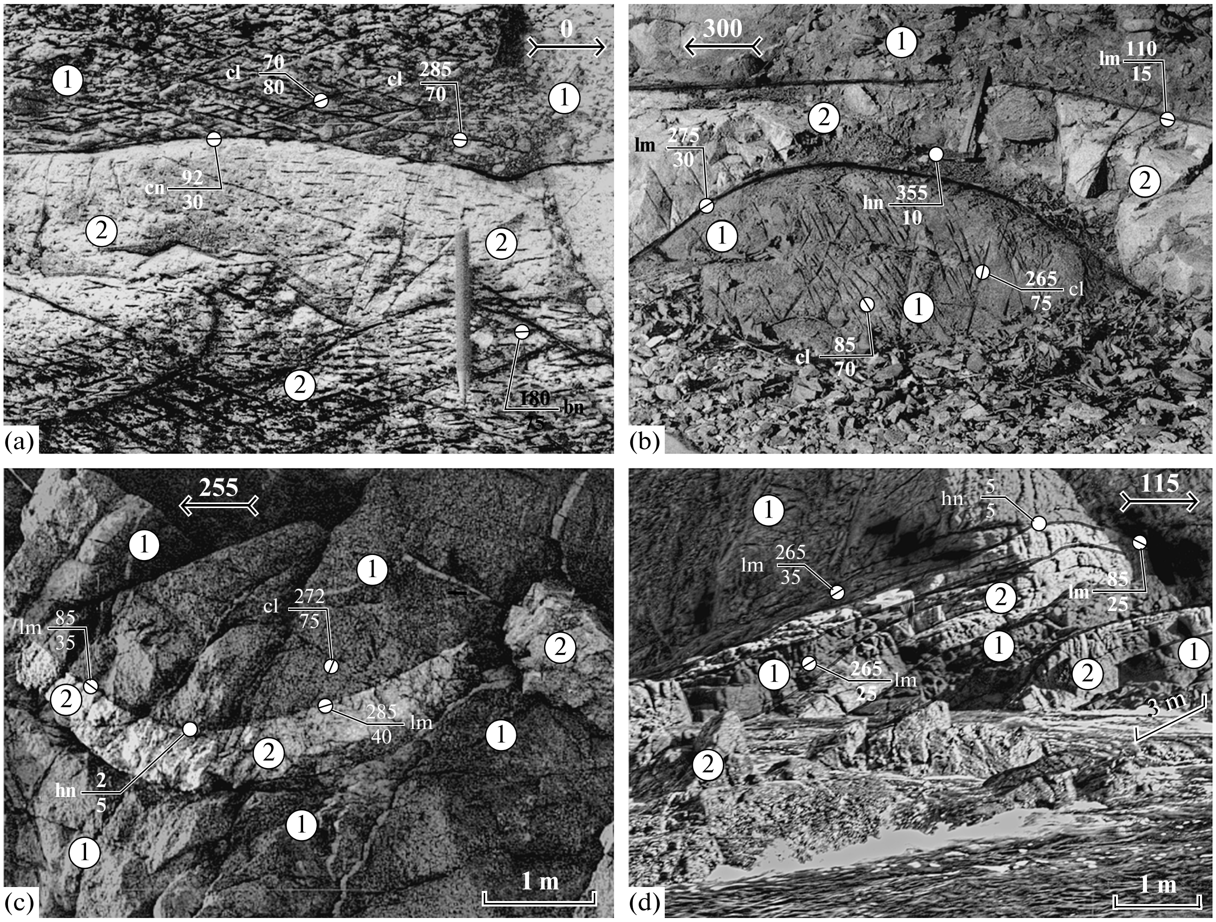


Fig. 4. Small structural forms in the Gaidamak (a, b, c) and Anna (d) gabbroid massifs.
(a) Meridional (along the chord) rhombic cleavage in gabbrodiorite (1) and a “bed” of granites (2) in the Gaidamak massif; (b, c) shear pseudofolds of the meridional strike in gabbro with taxitic and cleavage textures (1) emphasized by pinkish fine-grained leucogranites (2) in the Gaidamak massif; (d) an antiform fold in gabbroids (1) outlined by beds of pinkish granites (2) in the Anna massif. For the photographing point, see Fig. 1.
(1) Dark gray fine-grained gabbro; (2) “beds” of light pinkish fine-grained granites.

In the Anna massif, the gabbro include the protolith substrate that forms large lenses and beds with inclusions (10–15%) of presumably detrital origin. Clasts are silicified, isometric or subangular in shape, and from fractions of a millimeter to 2–4 centimeters across (Figs. 3a, 3b). The lenses could primarily be volcanogenic (?) in origin probably representing relicts of bedded varieties of the Avdokimovka complex, although with primary textures entirely masked by cleavage and foliation.

The cleavage formation involves approximately two-thirds of the Anna and almost the entire Gaidamak intrusion, being developed with variable intensity (Fig. 4a). The available factual material is consistent with the standpoint expressed in [7, 24, 29, and others) on the tectonic nature of the cleavage in contrast with the alternative although rightful opinion that this structural phenomenon may be explained by the fluid activity [5 and others]. According to [24], the further development is accompanied by the replacement of the cleavage by cleavage foliation and banding.

Indeed, the cleavage observable in the Anna and Gaidamak massifs is formed similar to pure shear deformations by systems of conjugate closely spaced shears [30] intersecting in plan at conjugation angles of ≈140°–160°. The length and thickness of the cleavage shears are variable. The large continuous fissures and microfractures are several tens of centimeters and up to <1 mm long, respectively. Large fractures (dislocation zones) are up to 1 mm thick and short (a few centimeters and millimeters) fissures are characterized by their microscopic thickness. Correspondingly, small cleavage fissures are abundant, while their larger counterparts occur less commonly. The planar sizes of the rhombs (lithons) fringed by cleavage shears are also variable. The rhombs with the following long diagonals (the long diagonal is the chord of the cleavage) are definable: 70–60, 25–20, 4–3, 2–1 cm, 3–1 mm, and smaller (Fig. 4a). The cleavage chords extend in the meridional direction. Precisely the chord orientation is usually considered as the orientation of the whole cleavage system. It is believed that cleavage is the most characteristic attribute of the plastic deformations. It means that, in our case, it was also formed in a plastic medium; therefore, the conjugation angles between the cleavage shears along the principal strain axis are regularly obtuse, which represents a property of the system of conjugate shears in the plastic and brittle–plastic media [25, 26].

It is remarkable that the orientations of the cleavage fissures bordering the rhombs (lithons) and fault-ranked fractures bordering the Anna massif are similar to each other. The massif is shaped as half of a large rhombic lithon. It is conceivable that its second half buried under the waters of the Peter the Great Gulf supplements its rhombic configuration. The meridional position of a large diagonal coincides with the cleavage chords.

The primary folded structures in the protorocks of the Anna and Gaidamak intrusions are indefinable in contrast with the secondary forms: the shear pseudofolds are emphasized by undulating granite bodies. From the viewpoint of the formation dynamics of both intrusions, these secondary pseudofolds are analogous to their counterparts in the Tafuin massif, where they are filled with material of the granite and aplite phases. In both massifs, the pseudofolds are formed by systems of gentle conjugate shears (pure shears), which serve as their limbs. Therefore, large areas of limbs located away from hinges exhibit a planar form and, judging from the sliding striation, are characterized by low displacement amplitudes and terminal curvatures of the structural elements and represent counter thrusts. The surfaces of the counter thrusts are marked by light pinkish gray granites corresponding in their appearance and composition to varieties of the first phase in the younger Tinkan massif and visually emphasizing pseudofolds (Figs. 4b–4d). Some folds are marked by fine dotted banding and foliation. Owing to such features, it is well seen that the hinges are characterized by rounded outlines due to the bending of the shears or the flattening of the angles under the subsequent movements. The maximal width of the continuously traceable fragments of hinges in some pseudofolds slightly exceeds 50 m (Fig. 4d), and its minimal value varies from a few meters to tens of centimeters. The flattened hinges of pseudofolds (or lines of fold-forming shears emphasizing limb conjugation) extend in the near-meridional direction similar to conjugations of cleavage shears, which serve as reliable indicators of the position of the intermediate deviatoric stress (or intermediate strain axis). Inasmuch as the fold-forming conjugate shears represent counter trusts, the principal strain axis occupied the near-latitudinal subhorizontal position orthogonal to the direction of the fold hinges and conjugations of cleavage systems. Judging from the shapes of the folds, their formation mechanism in longitudinal compression environments proposed for explaining the structure of the Tafuin massif [15, 16] is also applicable to the structures of the Anna, Gaidamak, and other basic intrusions.

The trends of the shear elements of the pseudofolds observable in the coastal outcrops of the Anna and Gaidamak bays are plotted in the main diagrams constructed for the massif under consideration (Fig. 2b). The groups of the main maximums (I, IV–VII) in the peripheral part of the diagram illustrate the steep position of most of the cleavage elements and parallel foliation. Maximums II and III in the central part of the diagram characterize the positions of gentle shear elements of pseudofolds. The patterns of the pole isoconcentations with maximums I, II, III, IV, V, VI, and VII form three main belts (1–3), which reflect with a certain confidence the principal strain axes. The intermediate axis s_2, which corresponds to the axes of the above-mentioned belts (arrows 1–3), occupied the gentle submeridional position. Correspondingly, the variations in the sublatitudinal compression axis s_1 were characteristic of areas along equators of these belts (in other words, dynamic planes s_1s_3). At the same time, variations in the extension axis s_3 as a normal to planes s_1s_2 were oriented in this case subvertically reflecting the dynamics of the uniaxial sublatitudinal compressive stress. Let us pay attention also to the fact that the belt in Fig. 2b with the axis corresponding to the hinge of the real pseudofold in the Gaidamak massif (Fig. 4c) is incorporated into a group of belts of "pseudofolded" shears 1–3. The above-mentioned natural pseudofold reflects, as a typical example, the styles and positions of most of the small pseudofolds in the Anna and Gaidamak intrusions. Such a coincidence between the statistical and real situations is hardly incidental. It allows us to speak in this situation about the distinct dynamic similarity between the in fact different-order and different-scale folds. The structural and dynamic consistencies between the statistical and natural structural patterns support an assumption of the dominant role of the gentle sublatitudinal compression.

The Mesozoic NNW-oriented compression is a postintrusive phenomenon that took place after some temporal break in the massif's formation, since it is largely reflected in brittle shear dislocations. As in other areas, the shears are oriented in the NNE and NE directions and represent sinistral strike-slip faults accompanied by slickensides and small-scale axonoclinal folds of the corresponding type. The dextral NNW- and NW-trending strike-slip faults, which develop usually in such dynamic situations under the regional compressive strain, are less frequent. Several strike-slip faults up to >5 km long are definable. Small-scale sinistral strike-slip faults occur at distances of a few hundred meters from each other. Dextral strike-slip faults are observable only in the form of small fractures. Depending on the types of strike-slip faults, they are accompanied by small oblique en ech-

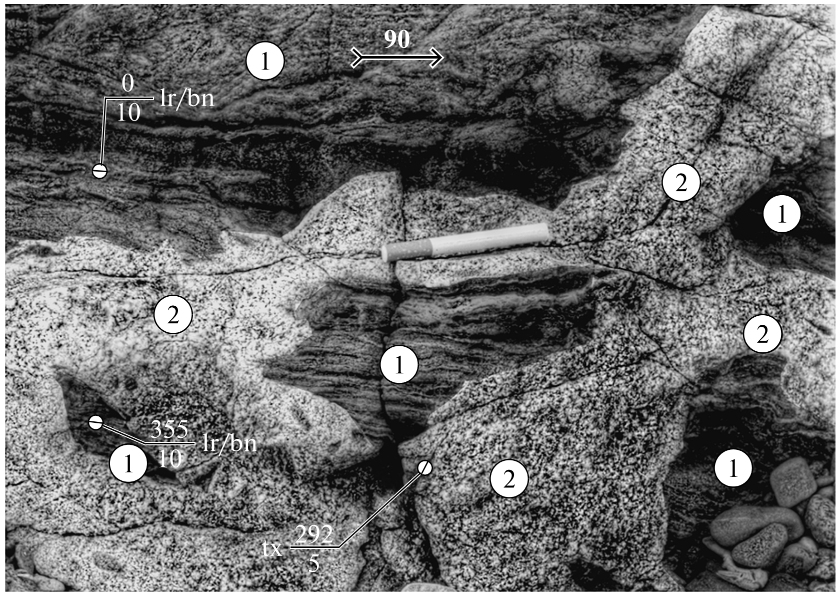


Fig. 5. Subdetrital inclusions of foliated and thin-banded gabbro with relict latitudinal orientation (1) and gabbrodiorites (2) with meridional taxitic textures in the Dunai massif. For the photographing point, see Fig. 1.

elon fault-line S-shaped break-away faults with right- or left-lateral steps. The break-away faults are usually filled either with quartz or red aplite-like granites almost similar to granites of the second intrusive phase in the Tinkan massif.

The combination of fold–cleavage structural patterns in the gabbroids that resulted from the sublatitudinal compression and the superposed typical shear structures formed by the NNW-oriented compression implies the formation peak of the Anna and Gaidamak gabbroid massifs most likely closer to the Late Paleozoic period.

Dunai Massif

The massif is located on the eponymous peninsula (Fig. 1c). Based on the similar composition and presumable age, its rocks are attributed to the Vladimiro-Aleksandrovskoe gabbro–peridotite complex. The following K–Ar dates are available for the Dunai and other similar massifs: 572 ± 14, 563 ± 15, and 610 Ma (according to E.S. Ovcharek and A.V. Oleinikov and others, 2002). Based on these dates, the rocks are considered to be the Early Silurian in age (G.S. Belyanskii and others, 2006).

Despite its small size, the Dunai massif is heterogeneous. It exhibits structural patterns characteristic of strain fields corresponding to all three defined geodynamic periods. At the same time, they are dominated by structures produced precisely by latitudinal compression during the Late Paleozoic geodynamic period. The massif includes separate relicts of ancient rocks with unclear contacts, which are attributable, based on their lithological and structural properties, to the Avdokimovka and Sergeevka complexes. By the same features, other rock types are very similar to the younger Anna gabbrodiorite complex.

The Late Proterozoic–Early Paleozoic meridional compression is reflected in the structure and positions of large and small inclusions in the form of thickened lenses among the gabbrodiorites. Frequently, small lenticular and angular inclusions occurs together (Fig. 5). Large inclusions usually have no distinct contacts with the host rocks. The banded structures of these inclusions are emphasized by the thin (up to 1 mm) frequently alternating (every ≈1–5 mm) white (plagioclase–quartz) and black (pyroxenite) discontinuous “laminae.” In some laminae sections, they look like bands against the background of fine-grained dark gray gabbro (probably, metagabbro) structurally resembling relicts of garnet-bearing metagabbroids of the Avdokimovka and Sergeevka complexes among structurally Tafuin granites [15]. Such a similarity is also evident from the sublatitudinal strike of structurally structural elements. This feature allows the rocks to be confidently considered as relicts of the ancient host framework. It is noteworthy that large fragments of such rocks confined mostly to the eastern part of the Dunai massif (Figs. 6a–6c) exhibit small folded structures emphasized by banding. The folds are characterized by relatively gentle shapes. They are from 1–2 to 20–30 m wide and structurally dip angles at their limbs amount to 20°–40° and, less commonly, 60°. The folds demonstrate notably dominant SSW vergence. The hinges of these folds usually dip gently (10°–15°) in the ESE (110°–120°) and opposite directions. The axial surfaces of the folds are accompanied by steep parallel cleavage. The folds also involve large quartz–

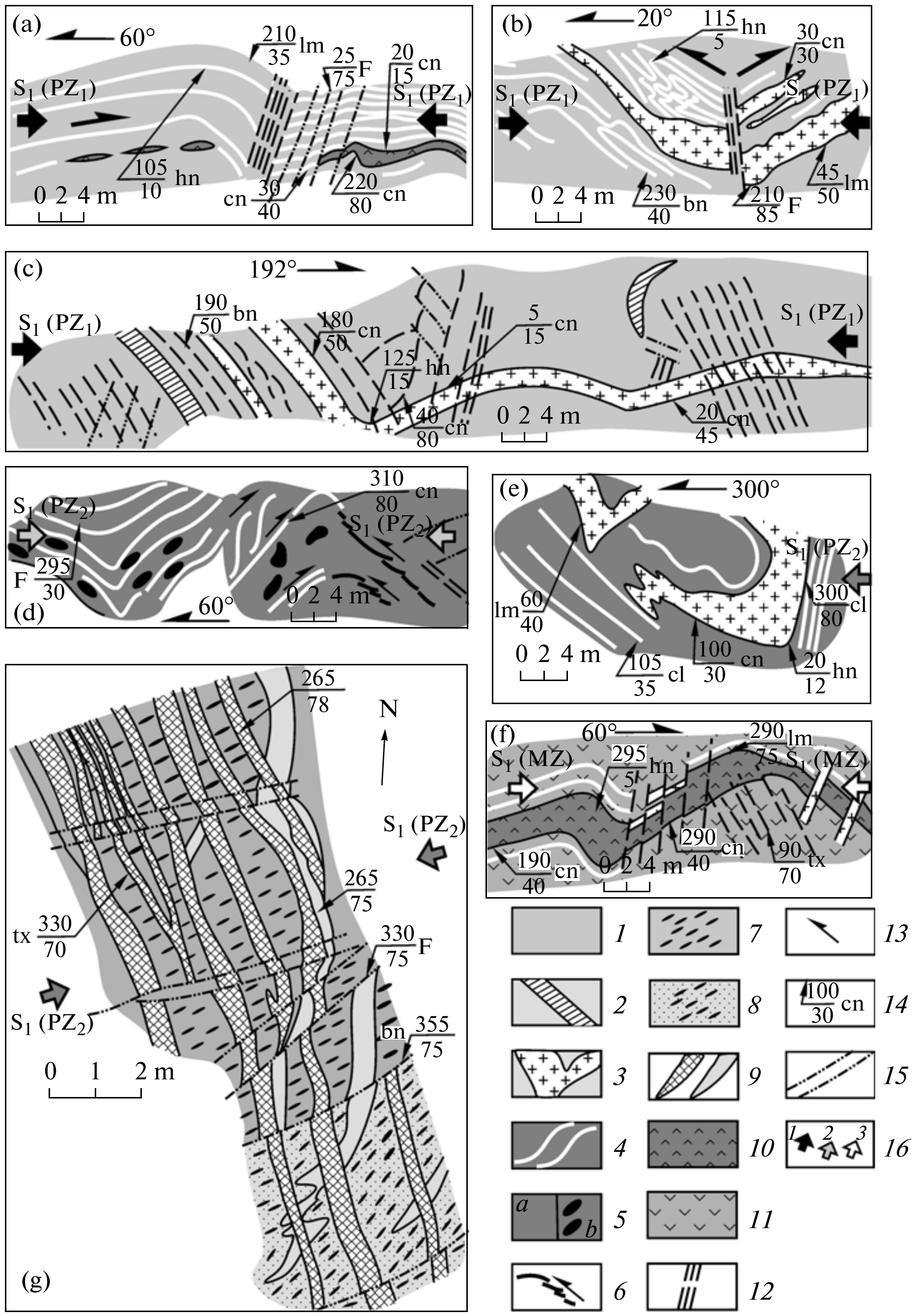


Fig. 6. Small structural forms in the Dunai gabbroid massif.

(a, b, c) Pseudofolds and cleavage produced by the meridional Late Proterozoic–Early Paleozoic compression; (d, e) pseudofolds emphasized by banding and stratiform granite inclusions produced by the sublatitudinal Late Paleozoic compression; (f) pseudofolds produced by the NNW-oriented Mesozoic compression; (g) pseudofolds and subcleavage dike-shaped banding.

(*1*) Dark greenish gray fine-grained banded and foliated gabbro; (*2*) large quartz–plagioclase bands; (*3*) granite–granodiorite bodies among gabbro and gabbrodiorites; (*4*) abundant narrow quartz–plagioclase bands; (*5*) fine- to coarse-grained taxitic gabbrodiorites (*a*) with amphibolite schlieren (*b*); (*6*) en echelon quartz veins conformable with banding; (*7*) taxitic gabbrodiorites; (*8*) taxitic granites; (*9*) veins of andesites (1) and dacites (2) developed after cleavage; (*10*) fine-grained to aphyric gabbro; (*11*) fine-grained diorites; (*12*) cleavage; (*13*) direction of the material flow; (*14*) point of measuring the orientation of the structural elements: the azimuth (numerator) and dip angle (denominator): (cn) the contact between the two rock varieties, (lm) fold limb, (hn) fold hinge, (tx) taxitic textures, (bn) banding; (*15*) fractures (F) with displacement features; (*16*) direction of the principal normal compression σ_1 with the index of the presumed age: (1) PZ_1, (2) PZ_2, (3) MZ.

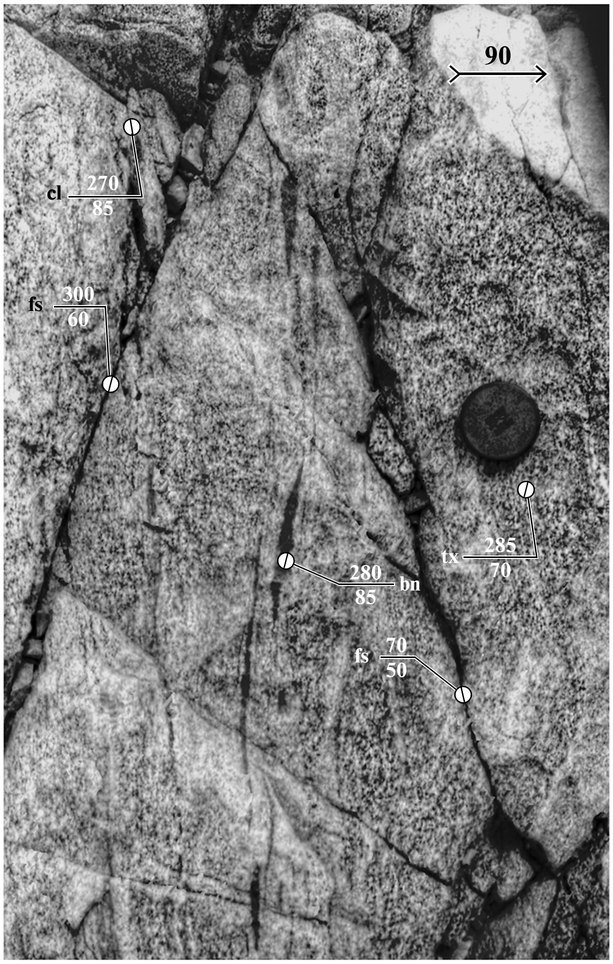


Fig. 7. Taxitic and gneissic textures expressed by short and long narrow amphibole lenses in diorites of the Dunai massif.

plagioclase bands (layers). It is conceivable that these folds were formed synchronously with the banding, since some hinges demonstrate an increased thickness of the quartz–plagioclase bands. The dominant orientation of the banding and foliation in the inclusions is reflected statistically in the maximums of poles III, VI, IX, X that form belt 6 and poles XI and XII of belt 7 (Fig. 2c). The axes of these belts, which coincide with the orientation of the hinges in the natural folds, imply the latitudinal position of the intermediate strain axis and, in addition, the meridional direction of the compression σ_1^1, which is consistent with the compression trend during the Late Proterozoic–Late Paleozoic geodynamic period.

Unfortunately, no distinct relationships between the large inclusions of the older foliated gabbroids and the younger host magmatites are observable in the Dunai massif. The host gabbro and gabbrodiorites enclosing small inclusions demonstrate meridional taxitic textures, while the inclusions are characterized by latitudinal foliation and small-scale banding. Therefore, proceeding from the available factual data on the orientation of the different deformation elements in the massif that were formed during the Late Proterozoic–Paleozoic and Late Paleozoic geodynamic periods [14], such features may be interpreted as documental indicators of the strains characteristic of both these periods with the replacement of the meridional compression vector by the latirudinal one.

The Middle–Late Paleozoic latitudinal compression was responsible for the structural patterns of the whole Dunai massif. This is primarily evident from the folds (probably, pseudofolds) and the structures emphasized by the rough banding probably similar in genesis to the intercalations of the Tinkan granites among the Anna gabbrodiorites. In this massif, the banding is accompanied by meridional taxitic textures expressed in diorites by small amphibolitic lenses (Fig. 7) and cleavage fractures that form with folds a regular paragenesis. Large fragments of folds (usually limbs and, less commonly, hinges) are observable in the cliffs of the Peter the Great Gulf (Fig. 8). The width of the folds estimated from the banding dip angles on their western and eastern limbs is 500–600 m, and their height never exceeds 100 m. Small folds up to several tens of meters wide and up to ten meters high were observed immediately in outcrops (Figs. 6d, 6e). The folds are composed of bedded or foliated dark gray fine- to medium-grained taxitic gabbro, gabbrodiorites, and subordinate diorites. All the rocks are characterized by rough banding, which is represented by beds (?) of leucocratic and subordinate melanocratic material. The thickness of the bands alternating every 50–10 cm to a few meters varies from a few centimeters to several meters.

The folded patterns are emphasized by the statistical distribution of the poles of the foliation and banding elements, which form pseudobedding (or "subbedding"). Indeed, the poles of these elements form the most distinct maximums I, II, III, VI, and VI in the corresponding diagram (Fig. 2c). These maximums are grouped into belts 1 and 2, which characterize, similarly to the above-mentioned situations, the idealized model of cylindrical folding under the latitudinal compression vector σ_1^2 (Fig. 2c). As was mentioned, the latter was characteristic, in our opinion, of the Late Paleozoic geodynamic period [14]. The intermediate strain axis occupied a gentle position and was meridionally oriented at that time corresponding usually to the directions of the belt axes (belts 1 and 2).

The large folds are geometrically similar to their smaller counterparts (Figs. 6d, 6e). Being compared with traditional folding (Fig. 6d), the pseudofolds formed by bands point to moderate to strong compression. Recumbent folds of dominant western vergence are also frequent (Fig. 6e). The small pseudofolds are complicated by microforms. Combined with the terminal curvatures, their vergence reflects the upward-oriented movements at limbs of larger folds. Such

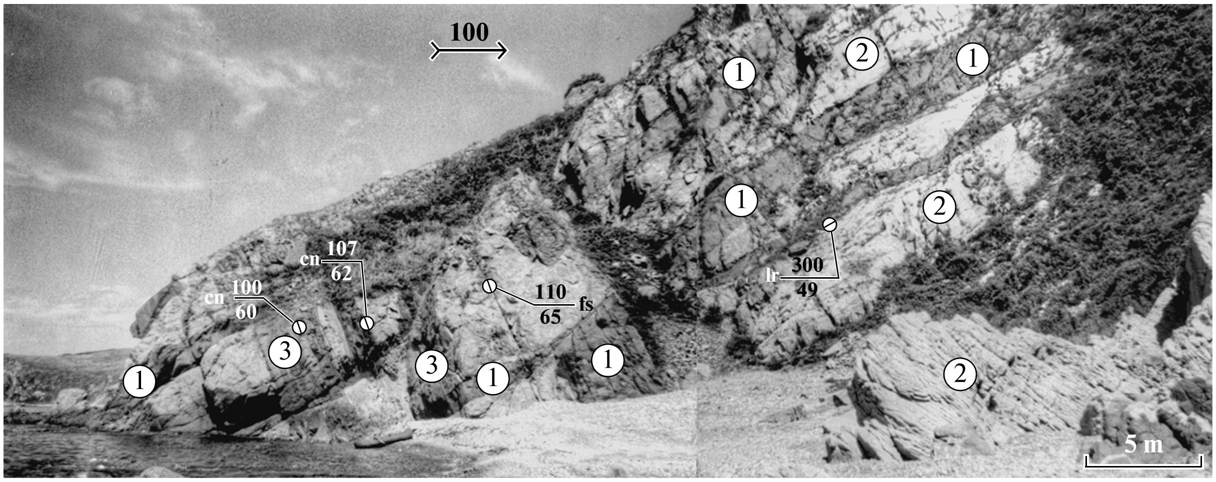


Fig. 8. A system of frequently alternating meridional acid and basic veins (3) developed among roughly "bedded" gabbro (1) and diorites (2).

movements also determined the formation of many small-scale en echelon quartz veinlets arranged in a stepwise manner at the fold limbs (Fig. 6d). It should be emphasized that all the above-mentioned folds are oriented orthogonally to the latitudinal lateral compression vector, which is exclusively characteristic of the Late Paleozoic structures in the western and southern Primorye regions.

Another important structural feature observable in the western part of the Dunai massif deserves attention (Fig. 6g). In this area, the gabbro are characterized by coarse-rhythmical heterogeneity probably related to layering with orientation corresponding to the kinematics of the Late Proterozoic–Early Paleozoic geodynamic period. This heterogeneity is expressed by the rhythmical "beds" of granodiorites 3–5 m thick among the gabbro and gabbrodiorites. The gabbro and gabbrodiorites are greenish gray to dark gray rocks, while the granodiorites are fine-grained pinkish light gray similar to other varieties of the massif, taxitic, and with distinct orientation of the amphibolites and secondary biotite. It is remarkable that the orientations of the taxitic textures and foliation coincide with each other: dip azimuths of 330°–350°; dip angles of 45°–70°. In other words, such orientation coincides roughly with the strike of the structures formed by the meridional compression during the Early Paleozoic geodynamic period. In our opinion, its deviation from the latitudinal direction is explained by the insignificant counterclockwise rotation consistent with left-lateral displacement along the nearby Dunai fault (Fig. 1).

The foliated and taxitic textures of the gabbrodiortes were superposed by a system of transverse closely spaced steep dikes dipping in the NNW and NS directions (Fig. 6g), The dikes 20–30 cm thick alternate in a fine rhythmic manner every 40–50 cm. They are probably the same veins or dikes observable in the vertical section in Fig. 8. Judging from their lithology, the dikes belong to two generations: the older dacitic and the younger andesitic crossing the former at very acute angles. Figure 6g shows that the dikes are displaced along the fractures developed subsequently parallel to the taxitic textures. Such a sublinear concentration of dikes (?) looks like coarsely rhythmical banding (probably resulting from tectonic pulses) extending along the coast for hundreds of meters. This coarsely rhythmical banding corresponds to cleavage oriented orthogonally to the dominant latitudinal compression vector characteristic of the Middle–Late Paleozoic geodynamic period.

Mesozoic sinistral strike-slip deformations. The dynamic consequences of this period are relatively well developed in the Dunai massif, probably even better than in other intrusions. It is sufficient to say that fragments emphasize the acute carinate folds with subhorizontal NE-trending hinges. In the diagram (Fig. 2c), the secondary maximums (VII and VIII) form peripheral shear belts 3, 4, and 5, which may be considered as resulting from the Mesozoic NW-oriented compression σ_3^1 with the steep positions of the axes of these belts and, correspondingly, an intermediate strain axis. Their spatial position and patterns are reflected in the diagram (Fig. 2c) by the maximums and equators of the banding belts, which also show the positions of the intermediate strain axes represented by fold hinges and belt axes. The intermediate strain axis s_2 is oriented in the NE direction. The banding bends that resulted in the formation of superposed belts are most likely related to the NE-trending strike-slip dislocations of the Mesozoic geodynamic period (Fig. 6f).

Tinkan Granite Massif

Its granites are involved into pseudofolds of the Anna gabbroid massif likely in response to extension, which probably explains also less developed taxitic textures and uniform crystallization of also rocks.

The Tinkan massif is located in the mouth part of the Rudnaya River and crops out at the Rudnev Bay coast. It is isometric in plan and has tectonic contacts with the Anna massif in the east and Paleozoic stratified sequences in the west. In its northern part, the massif is overlain by Jurassic sediments and intruded by Mesozoic granites (Fig. 1). The massif is two-phase in origin: the first phase is represented by yellowish light gray massive leucogranites with biotite, and the second one, by plagioclase–K-feldspar pinkish inequigranular granites and, less commonly, their gneissoze varieties. According to the legend to a series of geological maps, the massif is the Early Permian in age. The K–Ar geochronological dates are contradictive: 244, 230, 226, and 220 Ma (according to N.I. Polevaya); 555, 280, 265, 223, 211, 206, and 184–107 Ma (according to E.S. Ovcharek, Rudnaya Bay, K–Ar bulk analysis). It is considered that such different age estimates are explained by the superposition of Cretaceous magmatic phases.

Unfortunately, the Tinkan massif is structurally less investigated due to its heterogeneous lithology and poor exposition. Nevertheless, it exhibits single similarity with the Anna intrusion: it is characterized by vague gentle likely shear pseudofolds and by their shapes, sizes, and orientation resembling the Anna pseudofolds. Their difference consists only in the rock lithology. In the Tinkan massif, the host rocks are represented by leucogranites of the first phase, while bended pseudolayers are composed of pinksh K-feldspar granites of the second phase. The thickness of the pseudolayers varies from 10 to 30 cm. Hinges of such pseudofolds are usually gently dipping in the meridional direction. In their hinge areas, the pseudofolds exhibit vague linearity in the distribution of the acid plagioclase grains and K-feldspars in the surface fractures subparallel to the intermediate strain axis σ_2. Locally, there are closely spaced cleavage-type fissures produced likely by the sublatitudinal compression. In addition, granites of the Tinkan intrusion enclose sporadic small gently curved gabbroid bodies very similar to small pseudofolds with meridional bend lines, which also points to the probable influence of latitudinal compression.

DISCUSSION

The graphical and statistical methods used for the analyses of the structural patterns and parageneses including the structures of five orders characterizing the mesoscale geological space's organization in the basic intrusions of the southern Primorye region made it possible to obtain new factual data concerning this aspect.

The dominant structural patterns inherent in the different-order systems and interpreted on the different-scale maps, plans, and sections, as well as immediately in some outcrops, may be considered as geodynamically similar to each other, i.e., paragenetically or genetically interrelated. Moreover, this relationship is so close that supplementing each other they unambiguously point to the latitudinal lateral compression as a principal structure-forming factor [27, 30].

The same is true of the suppressed structural features observable in the examined intrusions. At the same time, each of them is controlled by the particular deformation style corresponding to one of three geodynamic periods: the Late Proterozoic–Early Paleozoic with the meridional direction of the principal lateral compression vector; the Middle–Late Paleozoic with the dominant latitudinal compression vector; the Mesozoic with the NNW-oriented compression [14]. If the orientation is ignored, the main structural features including the conjugate shears, cleavage, and primary (shadow) and secondary (pseudo) folds, which are defined for different geodynamic periods using some dominant property or certain set of elements, are principally similar to each other. The succession in the formation of the structural plans characteristic of these periods is also similar.

The data on the stable position of the relict primary host magmatites obtained for the Dunai massif point to the absence of a structure-forming force also in the basic magma, which was insufficient even for the disturbance of the past orientation of the protoinclusions. Such a phenomenon usually characteristic of granite massifs is likely widespread. It means that the magma passively filled free spaces in the primary framework, which appeared during the deformation under the influence of external forces. It should be emphasized that the structural patterns of the primary framework in the granites are expressed in the form of the initial (not reoriented) shadow textures.

Another important feature in the structure of the examined massifs is represented by the shear pseudofolds. These structures in the basic massifs are more distinct than in the granite intrusions. They are frequently composed of very contrasting late magmatic material. In the Anna and Gaidamak basic intrusions, such shear pseudofolds are marked by pinkish Tinkan granites. The observations in the southern and western Primorye region reveal an interesting phenomenon: the positions of the earlier structural elements remain unchanged during the formation of such structures (at least at the initial stages). At the same time, the secondary structures recognizable by analyzing the sections and natural pseudofolds [15] frequently form usual convergent (by an antiform) folds [30], which are frequently interpreted in metamorphic and igneous rocks as indicating a material flow. In our earlier work, we proposed the mechanism responsible for the formation of such folds in response to the development of conjugate shears initiated by a pure shear in systems of conjugate shears, which represent counter thrusts [15]. Such a model is also applicable for explaining the structure of basic massifs.

The pure shear mechanism is likely responsible also for the formation of the cleavage particularly well developed in the Anna intrusion. In this massif, pure shear acted in accordance with the low of plastic shearing [24] with obtuse angles between the intersecting cleavage systems represented mostly by shears of two directions. Moreover, the cleavage chords are subparallel to the axial surfaces of the primary and secondary folds in the section and to the hinges in plan. It should be noted that the secondary taxitic textures and banding in the basites are spatially subordinate to the position of the principal structural features.

It should again be emphasized that the available data point to the dominant external compression vector during each of the defined geodynamic periods.

The idea of the dominant external compression during the structure formation in intrusions was shared by the classics of structural geology such as, for example, Azhgirei [1] and Cloos [28]. When analyzing the types of the linear positions of the minerals in intrusive rocks, the first of them noted the coincidence of their orientation with the general strikes of the folded tectonic structures beyond the massifs. Based on these observations, he arrived at the conclusion that the orientation in the granite massif results from the influence of the regional tectonic forces on the host rocks and the partially solidified intrusion. Similar data provided grounds for Cloos to consider that the linear orientation of the crystals in massifs does not reflect the direction of the magma flow; it depends on the external compression, which is responsible for the flattening of the material and, correspondingly, the elongation of the formed massif.

This is likely the case: the examined intrusions are elongated precisely in such a manner, i.e., along the intermediate strain axis. It is remarkable that the positions of the strain field axes (the maximal, intermediate, and minimal) were established using the different-order features (from micro- to megascopic) by immediate observations, graphical constructions, and statistical analysis.

The elongations of all the massifs are sufficiently well correlated with the directions of the compression during the different geodynamic periods. The Tafuin massif is elongated in the ESE direction orthogonally relative to the Proterozoic–Paleozoic NNE compression, while the Anna, Gaidamak, Dunai, and Tinkan massifs are oriented in the meridional direction, i.e., orthogonally to the Middle–Late Paleozoic latitudinal compression vector (Fig. 1). Similarly, the Uspenka (K_1), Vodopadnoe (K_2), and Benevskoe (K_2) intrusions are elongated orthogonally relative to the Mesozoic NNW-directed compression [11].

All the important structural elements of all the massifs are regularly consistent with the axes of the strain fields. The same is true of the Late Cretaceous intrusions of the Petrovka depression (Fig. 1), which is also established by the natural observations. It is of interest that the dominant NE elongation of the Cretaceous massifs coincides with the orientation of the folded structures. The contacts between the dikes and host intrusions of the moderately acid and intermediate–basic compositions are frequently gradual. There is an impression that such relations between the granite intrusions and Mesozoic sedimentary rocks are widespread. It is conceivable that we are dealing with the initial stages of the process aimed at the replacement of the sedimentary rocks by the products of the tectono-magmatic transformations of the Sergeevka substrate. Following this impression, we may assume that the sharp contacts between the granites and host rocks are more frequent near the tectonic fractures. Precisely these areas are potential for the development of the effect of dynamic screening owing to the mobility of the shear limbs synchronous with the accumulation of the magmatic material. If the screen (for example, dikes) is mobile at least for some short period, this may lead to a gradual decrease in the grain-size composition of the igneous rocks up to the appearance of aphyric textures near the contact. Thus, this may result in developing the effect of the quenching zone. It is probably not incidental that any contact of the massif or dike coincides with the orientation of one or a group of shear fissures belonging to the dominant fracturing system.

Taking into consideration the available material, it should be noted that the geodynamic period comprises several pulses, since the organization of the structural forms exhibits discrete patterns. This is particularly well seen in the Tafuin massif with its two pulses in the reorientation of the compressive strains with the angular difference of 10°–15°. This and other massifs demonstrate a distinct succession of shear pseudofolds without the visible distortion of the earlier (including shadow) structures. These pulses should be considered as local derivatives of insignificant pulses in the principal compression, although more essential pulses in the geodynamic activity, which resulted, in combination with palingenic processes, in the transformation of the ancient substrate, cannot be ruled out. It is conceivable that these activity pulses are correlative with the available geochronological dates. At the same time, judging from rare publications, the dates corresponding to the recent level of the investigations are rare and cannot be used for such an analysis. The mass K–Ar age estimates are considered incorrect in many aspects, although, in some situations, they could be used for the correlation of the metamorphic and magmatic complexes constituting the examined massifs of the Sergeevka terrane with tectonic pulses. The structure of the Dunai massif implies repeated lithotectonic transformations within a relatively limited crustal space. This may serve as a basis for the "objectification" of the available different K–Ar dates for their testing by more reliable results obtained by advanced methods.

In this connection, we undertook an attempt to outline such stages based on the assumed "megalayering." Despite the apparent deficiency of data suitable for such an analysis, we defined four stages in the development history of the Sergeevka massif with each characterized by a pair of subsynchronous closely spaced contrasting granite and basite complexes [11]. In the situation under consideration, the basite Anna–Gaidamak and granite Tinkan complexes, which penetrate each other along a system of pseudofolds, may be considered as representing such a pair. The Tinkan granites are likely present as layering facies also among the basites of the Dunai intrusion.

This leads us to the important conclusion that the further development of criterions for the more reliable dating of geodynamic periods, combined with other factual data, may provide a tool for geochronological estimates and their testing.

CONCLUSIONS

The presented data on the structure of the Anna, Dunai, and Gaidamak gabbroid and Tinkan granite massifs point to their structurization under latitudinal compression during the Middle–Late Paleozoic geodynamic period, the middle one among three such periods established previously in the western Primorye region. Owing to such dynamics, the formed basite massifs were likely elongated in the submeridional direction. Under latitudinal compression, the rock complexes constituting these intrusions also acquired the dominant submeridional structural elements: layering, banding, taxitic textures, cleavage, and foliation. The intermediate strain axes outlined by the conjugation lines of the cleavage-forming shears and hinges of pseudofolds also occupied a gentle latitudinal position.

The investigation of the basite massifs confirmed the regularities of the structure of the intrusions previously observed in granite massifs. The main inference consists in the following: magma fills the free spaces, which appear in the geological medium under lateral compression, not breaks through the host substrate.

ACKNOWLEDGMENTS

We are grateful to V.G. Khomich, S.O. Maksimov, and A.V. Oleinikov for discussions and recommendations and to T.I. Karpenko and O.M. Molibog for their help in the preparation of the graphic illustrations. This work was supported by the Far East Branch of the Russian Academy of Sciences, project no. 09-03-A-08-405.

REFERENCES

1. G. D. Azhgirei, *Structural Geology* (MGU, Moscow, 1966) [in Russian].
2. V. D. Voznesenskii, "Structural Parageneses," in *Study of Tectonic Structures: Methodical Textbook on Geological Prospecting on a Scale 1 : 50000* (Nedra, Leningrad, 1984), No. 16, pp. 84–101 [in Russian].
3. *Geodynamics, Magmatism, and Metallogeny of East Russia*, Ed. by A. I. Khanchuk (Dal'nauka, Vladivostok, 2006), pp. 573–981 [in Russian].
4. *Geology of USSR. Vol. 32. Primorsky Krai. Part 1. Geological Description* (Nedra, Moscow, 1969), p. 696 [in Russian].
5. M. A. Goncharov, V. G. Talitskii, and N. S. Frolova, *Introduction in Tectonophysics*, Ed. by N. V. Koronovsky (KDU, Moscow, 2005) [in Russian].
6. S. V. Kovalenko and I. A. Davydov, "Sergeevsky Inlier—Ancient Structure of Southern Sikhote Alin," Dokl. Akad. Nauk SSSR **319** (5), 1173–1177 (1991).
7. Yu. S. Kutsev, *Schistosity, Its Formation, and Development* (Nedra, Moscow, 1988) [in Russian].
8. G. B. Levashov, *Geochemistry of Paragenic Magmatic Rocks of the Active Zones of Continental Margins (Sikhote Alin)* (DVO AN SSSR, Vladivostok, 1991) [in Russian].
9. A. V. Luk'yanov, *Plastic Deformations and Tectonic Flowage in the Lithosphere* (Nauka, Moscow, 1991).
10. L. F. Nazarenko and V. A. Bazhanov, *Geology of Primorsky Krai. Vol. 3. Tectonics* (DVO AN SSSR, Vladivostok, 1988) [in Russian].
11. P. L. Nevolin, V. V. Ivanov, S. V. Kovalenko, and A. N. Mitrokhin, "Geodynamics of the Structural Formation of the Sergeevka Crystalline Block and Control of Gold Mineralization, South Sikhote-Alin," in *Ore Deposits of Continental Margins* (Dal'nauka, Vladivostok, 2000), pp. 91–112 [in Russian].
12. P. L. Nevolin, V. P. Utkin, S. V. Kovalenko, et al., "Geodynamics of the Structural Formation of the Uspensky Granitoid Massif, Control of Dikes and Ore Manifestations," in *Ore Deposits of Continental Margins* (Dal'nauka, Vladivostok, 2001), No. 2, pp. 74–89 [in Russian].
13. P. L. Nevolin, V. P. Utkin, A. N. Mitrokhin, et al., "Cretaceous Intrusions of Southern Primorye: Tectonic Position, Structure, and Dynamics of Their Formation," Tikhookean. Geol. **22** (5), 73–86 (2003).
14. P. L. Nevolin, V. P. Utkin, T. K. Kutub-Zade, A. T. Kandaurov, A. A. Alenicheva, and A. N. Mitrokhin, "Western Primorye: Geology, Geodynamics of Structurization, and Metallogenic Aspects," in *Pacific Ore Belt: Materials of New Studies* (Dal'nauka, Vladivostok, 2008), pp. 278–299 [in Russian].
15. P. L. Nevolin, V. P. Utkin, and A. N. Mitrokhin, "The Tafuinsky Granite Massif, Southern Primorye Region: The Structures and Geodynamics of Longitudinal Compression," Russ. J. Pac. Geol. **4** (4), 331–346 (2010).
16. P. L. Nevolin, V. P. Utkin, and A. N. Mitrokhin, "Pseudofolded Control of Aplitic Dikes in the Paleozoic Intrusions of Southern Primorye," in *Tectonics and Geodynamics of the Phanerozoic Fold Belts and Plat-*

forms: Proceedings of 43th Tectonic Conference, Moscow, Russia, 2010 (GEOS, Moscow, 2010), Vol. 2, pp. 81–85 [in Russian].

17. L. M. Rastsvetaev, "Some General Models of Disjunctive Fracture Deformation," in *Experimental Tectonics in Theoretical and Applied Geology* (Nauka, Moscow, 1985), pp. 118–126 [in Russian].
18. E. W. Spenser, *Introduction to the Structure of the Earth* (McGraw-Hill, New York, 1977) [in Russian].
19. V. P. Utkin, *Shear Dislocations, Magmatism, and Ore Formation* (Nauka, Moscow, 1989) [in Russian].
20. V. P. Utkin, P. L. Nevolin, and A. N. Mitrokhin, "Two Deformation Patterns at the Eastern Flank of the Jilin–Laoelin Fold System," Dokl. Earth Sci. **389** (2), 171–174 (2003).
21. V. P. Utkin, P. L. Nevolin, and A. N. Mitrokhin, "Late Paleozoic and Mesozoic Deformations in the Southwestern Primorye Region," Russ. J. Pac. Geol. **1** (4), 307–323 (2007).
22. A. I. Khanchuk, Extended Abstract of Doctor Sci. (Geol.-Min.) Diss. (GIN RAN, Moscow, 1993).
23. A. I. Khanchuk, V. V. Ratkin, M. D. Ryazantseva, et al., *Geology and Minerals of Primorsky Krai: A Review* (Dal'nauka, Vladivostok, 1995) [in Russian].
24. G. Wilson, *Introduction to Small-Scale Geological Structures* (George Allen and Unwin, London, 1985) [in Russian].
25. S. I. Sherman, S. A. Bornyakov, and V. F. Buddo, *Areas of Dynamic Effect of Faults (Modeling Results)* (Nauka, Novosibirsk, 1983) [in Russian].
26. S. I. Sherman, and Yu. I. Dneprovskii, *Stress Fields of the Earth's Crust and Geological–Structural Methods of Their Study* (Nauka, Novosibirsk, 1989).
27. V. Yaroshevskii, *Tectonics of Ruptures and Folds* (Moscow, 1981) [in Russian].
28. E. Cloos, "Mother Lode and Sierra Nevada Batholith," J. Geol. **45**, 225–249 (1935).
29. S. M. Sinitsa, "The Cleavage Paradox," Geol. Pac. Ocean **15**, 116–121 (2000).
30. H. Ramberg, "Evolution of Drag Fold," Geol. Mag. **100** (2), 97–106 (1963).

Recommended for publishing by A.I. Khanchuk