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Collision and Postcollision Structural Evolution of the Andrianovka Suture, Sredinny Range, Kamchatka

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Abstract—The structural evolution of the Andrianovka Suture exposed on the eastern slope of the Sredinny Range in Kamchatka is considered. The main structural suture divides the metapelitic rocks of the Kamchatka Group and the metavolcanics of the Andrianovka Formation. The early collisional deformational event related to the westward overthrusting of marginal-sea and island-arc complexes is established in the structural evolution of the allochthonous complex (Andrianovka and Irunei formations). The normal faulting at the postcollision stage is displayed in the structural assemblages of the autochthonous and allochthonous complexes. A zone of normal ductile fault in the upper portion of the autochthon (Kamchatka Group) is described. It is suggested that the exhumation of high-grade metamorphic rocks may correspond to the evolutionary scenario of the Cordilleran-type metamorphic core formation.

INTRODUCTION

The major structures of Kamchatka (Fig. 1) were formed in the Late Mesozoic and Cenozoic as a result of accretion and collision [1, 10, 13, 20, 21, 25, 27, 33, 50, 61]. The collision of the Ozernovskii–Valagin island arc with the continent, when the Cretaceous rocks of the marginal sea and island arc were thrust over the heterogeneous complexes of the Eurasian continental margin, was one of the major events in the regional geologic history. The northern segment of the arc overlapped the sediments of continental margin along the Lesnaya River thrust fault in the middle Eocene [27], while the southern segment contacts with metamorphic complexes of the Andrianovka suture zone [13, 23] on the eastern slope of the Sredinny Range.

The structural setting of the Andrianovka suture and the age of its formation remain a matter of debate. According to [13], the suture that divides the metamorphic rocks of the Malka Formation [21, 32] and unmetamorphosed marginal-sea sediments of the Irunei Formation was formed as a result of the early Eocene island-arc–continent collision. Other authors [23] regard the Andrianovka suture zone as a structure that divides the metapelitic rocks of the Kamchatka Group [8, 18], or Shikhta Formation [32], and metavolcanics of the Andrianovka Formation [8, 21, 32]. The suture was formed as a result of the island-arc complex thrusting over the Mesozoic continental margin in the Late Cretaceous [21, 23].

The origin and age of metamorphic rocks in the Sredinny Range of Kamchatka has remained a subject of discussion for the last 30 years. The protolith nature and age of metamorphism are the most dubious [1–3, 5, 6, 14, 15, 40, 47, 48]. Some researchers suppose that the protolith of the high-grade metamorphic rocks in the Sredinny Range is Precambrian in age [14, 15]. Recent data suggest the Cretaceous protolith for the Kolpakovo Group and the Paleocene protolith for the Kamchatka Group [47, 48]. The age of metamorphism was estimated in [5, 6] as Cretaceous [5, 6]; other authors distinguished the Campanian (~77 Ma) and Eocene (53–47 Ma) metamorphic stages [40]. According to a detailed geochronological study, the peak of metamorphism and migmatization was determined as the early Eocene (~52 ± 2 Ma) [48]. The neoautochthon (conglomerate of the Baraba Formation) that seals the collision structure was dated as 50 Ma [26]. This time probably marks the termination of collision stage and the onset of postcollision evolution. The succession of the structure development, characteristics of the main deformational events, and kinematic history of the Andrianovka suture are discussed in this paper on the basis of structural investigations carried out in the eastern framework of the Sredinny massif (Fig. 2).

GENERAL CHARACTERISTICS OF THE MAIN LITHOTECTONIC COMPLEXES

The metamorphic rocks of the Sredinny Range in Kamchatka are traditionally subdivided into three lithotectonic complexes [18, 32]: the high-grade rocks making up the core or basement of the Sredinny massif (Kolpakovo Group intruded by granites of the Kru-

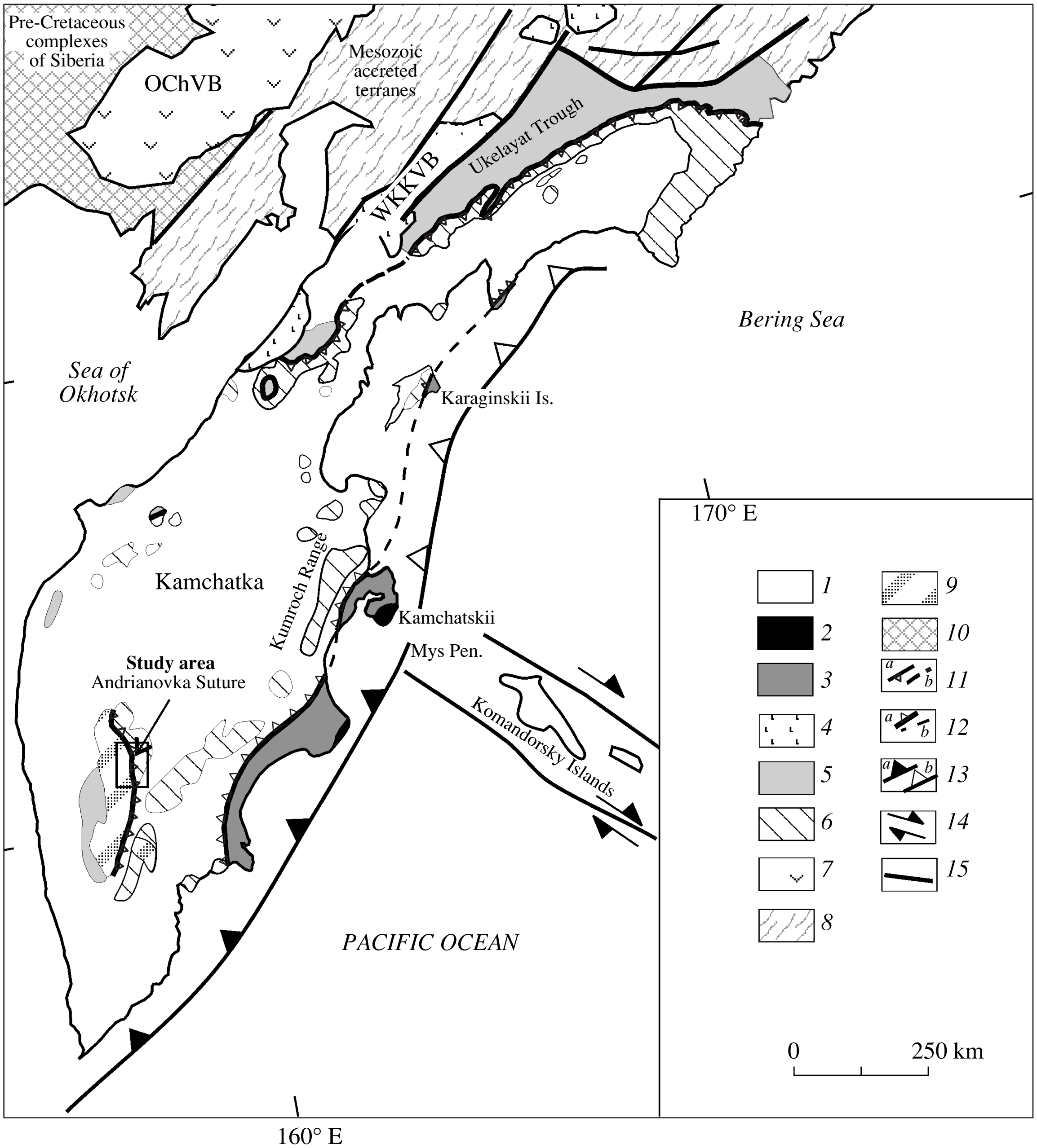


Fig. 1. Tectonic structure of Kamchatka and the southern Koryak region, modified after [20, 31, 33]. (*1*) Cenozoic cover; (*2*) Kronotskii island paleoarc (Late Cretaceous–Paleocene); (*3*) East Kamchatka accretionary zone; (*4*) West Kamchatka–Koryak volcanic belt (WKKVB) (middle Eocene–Oligocene); (*5*) Ukelayat–Lesnaya River trough (Late Cretaceous–middle Eocene); (*6*) Ozernovskii–Valagin island paleoarc (Late Cretaceous–Paleocene); (*7*) Okhotsk–Chukotka volcanic belt (OChVB) (Cretaceous); (*8*) Mesozoic accreted terranes; (*9*) metamorphic complexes of the Sredinny and Ganal ranges in Kamchatka; (*10*) pre-Cretaceous complexes of Siberia; (*11*) Vatyn–Lesnaya River–Andrianovka suture: (*a*) proved, (*b*) inferred; (*12*) Tyushevka–Goven suture (Grechishkin thrust fault): (*a*) proved, (b) inferred; (*13*) subduction zones: (*a*) modern, (*b*) ancient; (*14*) strike-slip fault zones; (*15*) faults.

togorov Complex); the metamorphic cover (Malka Complex including the Shikhta, Andrianovka, Alistor, Kheivan, and Khimka formations); and the slightly metamorphosed rocks of the Kvakhona terrane.

The relationships between these complexes are of principal importance. It was thought in the early works that the Malka Group (Shikhta, Andrianovka, Kheivan, Khimka, and Alistor formations) was a cover unconformably resting upon the Kolpakovo Group (regarded as a basement) with a conglomerate unit at the base of the Shikhta Formation. All of the contacts within the Malka Group were suggested to be stratigraphic, and the internal structure of these rocks was regarded as a nearly undisturbed sequence distorted only by discrete

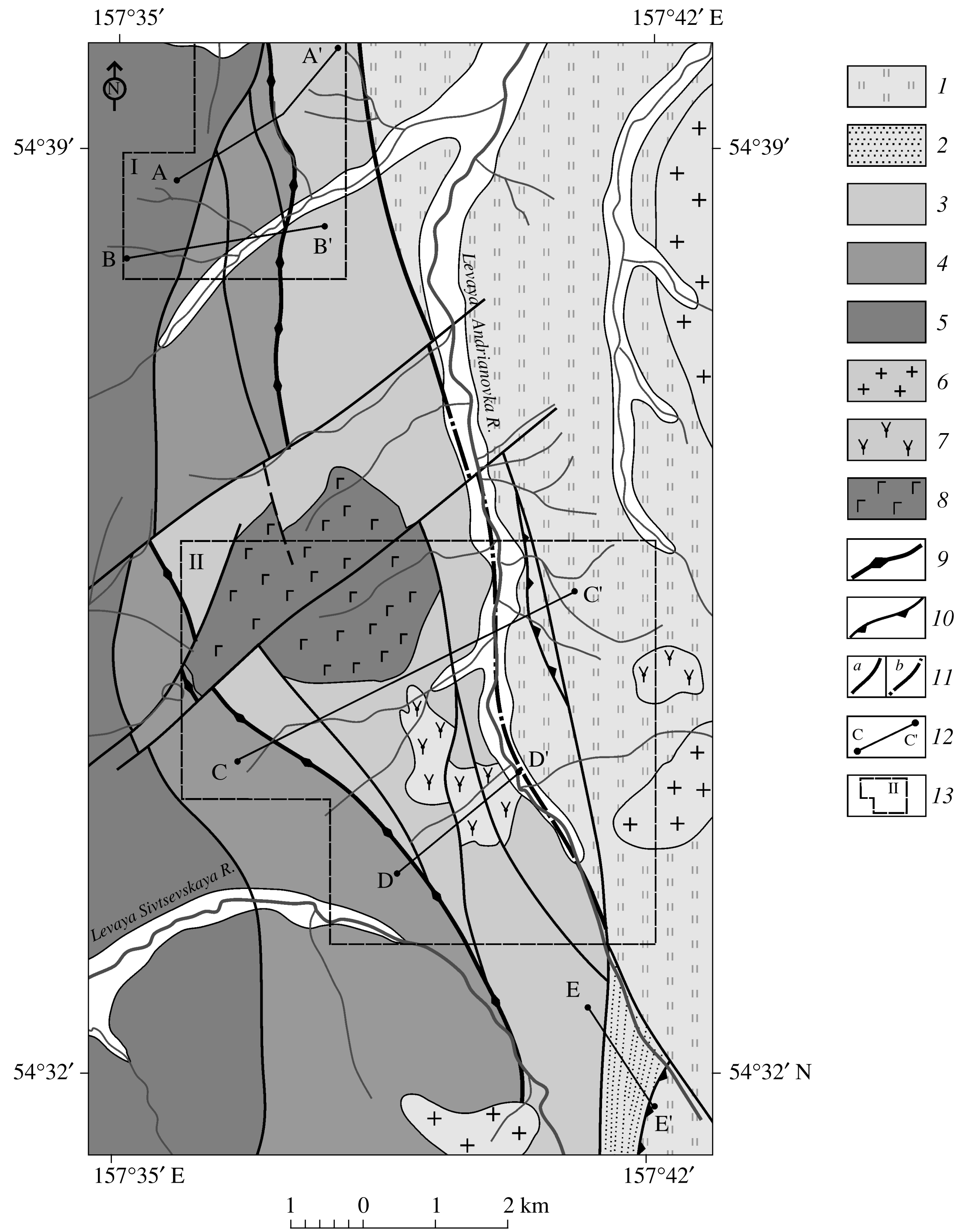


Fig. 2. Geological scheme of the eastern framework of the Sredinny massif at the headwaters of the Levaya Andrianovka River, modified after [8] and unpublished data of M.N. Shapiro. (*1*) Upper Cretaceous Irunei Formation; (*2*) Paleocene (?) Khozgon Formation; (*3*) metavolcanics of the Cretaceous Andrianovka Formation; (*4*) Kamchatka Group; (*5*) Kolpakovo Group; (*6*) Miocene granite; (*7*) Late Cretaceous syenite; (*8*) mafic and ultramafic intrusions; (*9*) Main Andrianovka fault; (*10*) thrust faults; (*11*) faults: (*a*) exposed and (*b*) buried beneath Quaternary sediments; (*12*) section lines (see Fig. 5); (*13*) areas of the detailed structural investigations: (I) northern area, see Fig. 3 and (II) southern area, see Fig. 4.

faults. The Sredinny massif was considered to be either a marginal part of the Sea of Okhotsk plate (platform) that underwent profound tectonomagmatic and metamorphic reworking [32, 50] or an inlier of the West Kamchatka platform basement [1]. The alternative view on the metamorphic complexes of the Sredinny massif assumes their formation as a result of the Cretaceous metamorphism superimposed on the Upper Mesozoic geosynclinal sequences [5, 16].

The ideas of the Sredinny massif as a deformed packet of tectonic sheets of various ages and origins were developed in recent years [2, 21, 23]. For example, the allochthonous sheet pertaining to the Andrianovka Formation with ophiolite fragments at the nappe base was mapped at the headwaters of the Krutogorov River [21], and similar observations were made in the eastern framework of the massif [23]. In terms of these ideas, the Kolpakovo Complex consisting of the highest-grade rocks is overlain by the Kamchatka Group (Shikhta Formation), and the latter is overthrust by the island-arc metavolcanics of the Andrianovka Formation.

The Kolpakovo Group consists of the kyanite, cordierite, cordierite–hypersthene, garnet–biotite gneisses, and plagiogneisses; garnet amphibolite and calciphyre are much less abundant [32]. The rocks of the Kolpakovo Group underwent a prograde metamorphism under the conditions of the kyanite–sillimanite facies (T = 560–800°C and P up to 7–8 kbar) and then experienced a retrograde metamorphism, resulting in the reverse or compound zoning of garnet, the partial or complete biotitization, and the replacement of kyanite with andalusite [32]. The rocks of the Kolpakovo Group are deformed into isoclinal folds; sporadic superimposed structures are developed in fault zones. The biotite granite of the Krutogorov Complex was emplaced into the gneisses. The granite locally becomes gneissic and was reworked by late tectonic processes with the formation of blastocataclastic structures and superimposed low-temperature mineral assemblages.

The age estimates for the Kolpakovo and Krutogorov complexes remain controversial [1–3, 5, 6, 14, 15, 40]. U/Pb SHRIMP timing has shown that the protolith of the Kolpakovo gneisses is Cretaceous (pre-Campanian) and that the Krutogorov gneissic granite crystallized 77 Ma ago. The peak of metamorphism is dated as ~ 52 ± 2 Ma.

The Kamchatka Group [8, 18], or the Shikhta Formation [32], is mainly composed of garnet-, staurolite-, and kyanite-bearing mica schists, staurolite–sillimanite and biotite–muscovite plagiogneisses, and migmatites. The grade of metamorphism varies from the schists of the garnet zone to the staurolite facies [21]. The metamorphism conditions correspond to P = 3–4 kbar and T < 630–640°C [32]. The rocks of the Kamchatka Group rest upon the metamorphic rocks of the Kolpakovo Group and Krutogorov Granite with unconformity and a basal conglomerate unit [21, 32]. The metamorphic rocks of the Kamchatka Group are overthrust by the Andrianovka Formation, and the latter is built on by the Kheivan and Khimka formations [21, 23]. The age of the Kamchatka Group protolith is estimated as Paleocene. The metamorphism and granite emplacement took place 52 ± 2 Ma ago [47, 48].

The Andrianovka Formation largely consists of amphibole, epidote–amphibolite, clinopyroxene–amphibole schists and amphibolites. The age of these rocks remains unknown. The syenite that intrudes into the metavolcanics in the eastern framework of the massif is dated as 70.4 ± 0.4 and 63.0 ± 0.6 Ma [25, 48]. ***The Kheivan Formation*** is composed of metasandstone, metasiltstone, and less abundant mudstone and gravelstone. ***The Khimka Formation*** comprises the albite–actinolite schists developed after the tuff, tuffite, metasandstone, and quartzite. The amphibole schists after the ultramafic rocks and mafic volcanics dominate in the ***Alistor Formation*** [2]. These rocks are regarded as a facies analog of the Khimka [2, 32] and Andrianovka [2] formations. A gradually declined metamorphic grade from the Andrianovka to the Khimka formations is interpreted in different ways [6, 16, 21, 32]. The lateral metamorphic zoning discordantly arranged relative to the group and formation boundaries is less distinct [16].

The slightly metamorphosed and unmetamorphosed rocks of the Sredinny Range pertain to the autochthonous or paraautochthonous units of the Upper Cretaceous–Paleocene Khozgon Formation [34, 48], allochthonous Upper Cretaceous units of the Irunei terrane (Irunei and Kirganik formations) [10, 13, 34], and neoautochthonous middle Eocene mollasoid sequence (Baraba Formation) [26].

Thus, complexes that underwent different degrees of metamorphic and structural reworking are juxtaposed in the eastern framework of the Sredinny massif along the Andrianovka suture. It has been suggested that these rock complexes are divided by the western-vergent thrust faults [10, 23]. In terms of the previously proposed models, the Kolpakovo and Kamchatka groups are referred to as an **autochthon**. The terrigenous rocks of the Khozgon Formation are regarded as an **paraautochthon**. The metavolcanics of the Andrianovka Formation and tuffaceous cherty rocks of the Irunei Formation are allochthonous. **The lower** (Andrianovka Formation) and the **upper** (Irunei Formation) **allochthonous complexes** are recognized.

RESEARCH METHODS

The structural paragenetic analysis [7] was the main research method; its mechanical principles are described in [11, 12, 28, 30]. *The structural parageneses (assemblages)* are defined as systematically repeated combinations of various elementary structures formed under specific mechanical conditions (compression, extension, shear, transpression, transtension, or flow) [11, 12, 28]. The mechanical, deformational–chemical [9], and deformational–metamorphic structural assemblages [7] are distinguished depending on the leading deformation mechanisms. The genetic interpretation of the particular structures and structural assemblages is based on a model of structural rearrangements. The principles of this model are set forth in [29, 30].

The morphological study of structures was accompanied by an analysis of the orientation of planar and linear structural elements [58]. The petrofabric (microtectonic) analysis provided insights into the fabric formation sequence and its relations to the metamorphism [55]. In the study of tectonites, primary consideration was given to the kinematic indicators [22, 35, 37, 39, 45, 52, 55].

The term *asymmetric fold* is widely used in the description of fold morphology. The study of fold asymmetry is applied to the reconstruction of large folds in the monotonous sequences [58]. The terms *S-*, *Z-*, and *M-folds*, resembling the respective letters in shape, characterize the fold morphology in section, e.g., S- and Z-folds occur on the opposite limbs of a large fold while a M-fold is formed at its hinge. In the case of gently plunging hinges, the type of fold symmetry (S or Z) was determined down the dip.

The term *vergence* is used in a kinematic sense to designate the direction of displacement and/or rotation during the deformation both on the fold limbs and in fault zones [53]. In other words, the vergence is a kinematic term rather than a term designating the direction of the fold axis plane or fault inclination (e.g., an eastward dipping normal fault is western-vergent). Characterizing the vergence, it is appropriate to use some attributes that specify the direction of both lateral (eastern, western, etc.) and vertical (reverse, normal) displacements.

STRUCTURAL INVESTIGATIONS

The general structure of the central segment of the Andrianovka suture zone is a monoclinal packet of tectonic sheets with east- and northeastward dipping of the fault planes and planar elements of the rock fabric (Figs. 2–5). The structural investigations were carried out along several transects within two areas (Figs. 3 and 4). Some additional observations were made to the south, in the tectonic wedge composed of the Khozgon Formation (section E–E' in Fig. 5).

The Northern Area

In the northern area, we studied the structure of the Kolpakovo and Kamchatka groups and a fault zone with eastward dipping planes that separates the rocks of the Kamchatka Group and the Andrianovka Formation (Figs. 3 and 5, sections A–A' and B–B'; Figs. 6–8). The western block comprises the biotite, kyanite, and sillimanite gneisses and migmatites of the Kolpakovo Group, as well as the garnet–biotite, biotite, quartz–feldspar–biotite–muscovite, and quartz–feldspar–muscovite–chlorite schists of the Kamchatka Group. The eastern block is composed of the amphibole, quartz–albite–actinolite–chlorite schists, and quartzite of the Andrianovka Formation. Tectonic lenses of amphibolite, up to 10–20 m thick, are noticed in the western block within the fault zone. In the northern part of the area, the rocks of the Kamchatka Group are severely silicified with the formation of discrete and thin units of secondary quartzite reaching a few tens of meters in thickness.

Allochthon. The schistosity in the rocks of the Andrianovka Formation gently dips to the east and northeast (Fig. 6). The schistosity intensity increases within the intraformational fault zones where quartz-vein banding, small faults, and kinkbands (kinkzones) are abundant. The normal-fault kinkzones and east-vergent folds are extensively developed together with the west-vergent folds (Fig. 7A). The younger normal-fault kinkzones superimposed on the schistosity within the intraformational fault zones can be observed in some cases (Fig. 7B). The orientation of fold hinges and kinkzones in the rocks of the Andrianovka Formation (Fig. 6) allows us to suggest a strike-slip component of displacement, sinistral in the reverse fault zones and dextral in the normal fault zones.

Autochthon. The rocks of the Kamchatka Group have an intricate internal structure (Figs. 7C–7F). The east-vergent folds, often with crenulation cleavage, are abundant in the fault zone with eastward dipping schistosity (Fig. 6). In this case, the cleavage zones are parallel to the gently dipping and horizontal fold axes (Fig. 7C). The hinges plunge at low angles both to the south and north. The incipient east-vergent sheath folds were observed in one of the section interval (Fig. 3, inset).

A lineation of large (up to 1–2 mm) biotite crystals and aggregates is developed fragmentarily. The lineation within the foliation planes steadily dips at angles of 30°–40° N (Fig. 7C). Direct observation has shown that the mineral lineation predated the folding. At the contact with the metavolcanics of the Andrianovka Formation (Fig. 5, section A–A'), the rocks of the Kamchatka Group host numerous quartz veins. The quartz veins are strongly deformed, parted into boudines, folded (Fig. 7D), broken, and in some cases reveal a mullion lineation (discrete fragments of the folded quartz veins stretched along the hinges, see Fig. 7E). Beyond the contact zone, the quartz-vein banding is predominant while the folded veins occur only sporadically. The axial surfaces of the older folds are deformed together with the metamorphic foliation and lineation into the younger east-vergent folds (Fig. 7D).

As follows from the petrofabric analysis, the early deformational–metamorphic structural assemblages (Fig. 8) comprise the pervasive schistosity and metamorphic banding with synkinematic [55, 57] garnet and biotite porphyroblasts. The direction of the porphyroblast rotation indicates displacement down the dip of schistosity (Figs. 8A and 8B). The pressure shadows of the porphyroblasts are filled with quartz and newly formed biotite (behind the biotite porphyroblasts). The biotite porphyroblasts underwent boudinage and breakup, with the subsequent rotation of fragments and the formation of asymmetric pressure shadows filled with quartz (Fig. 8D). The crenulation cleavage is

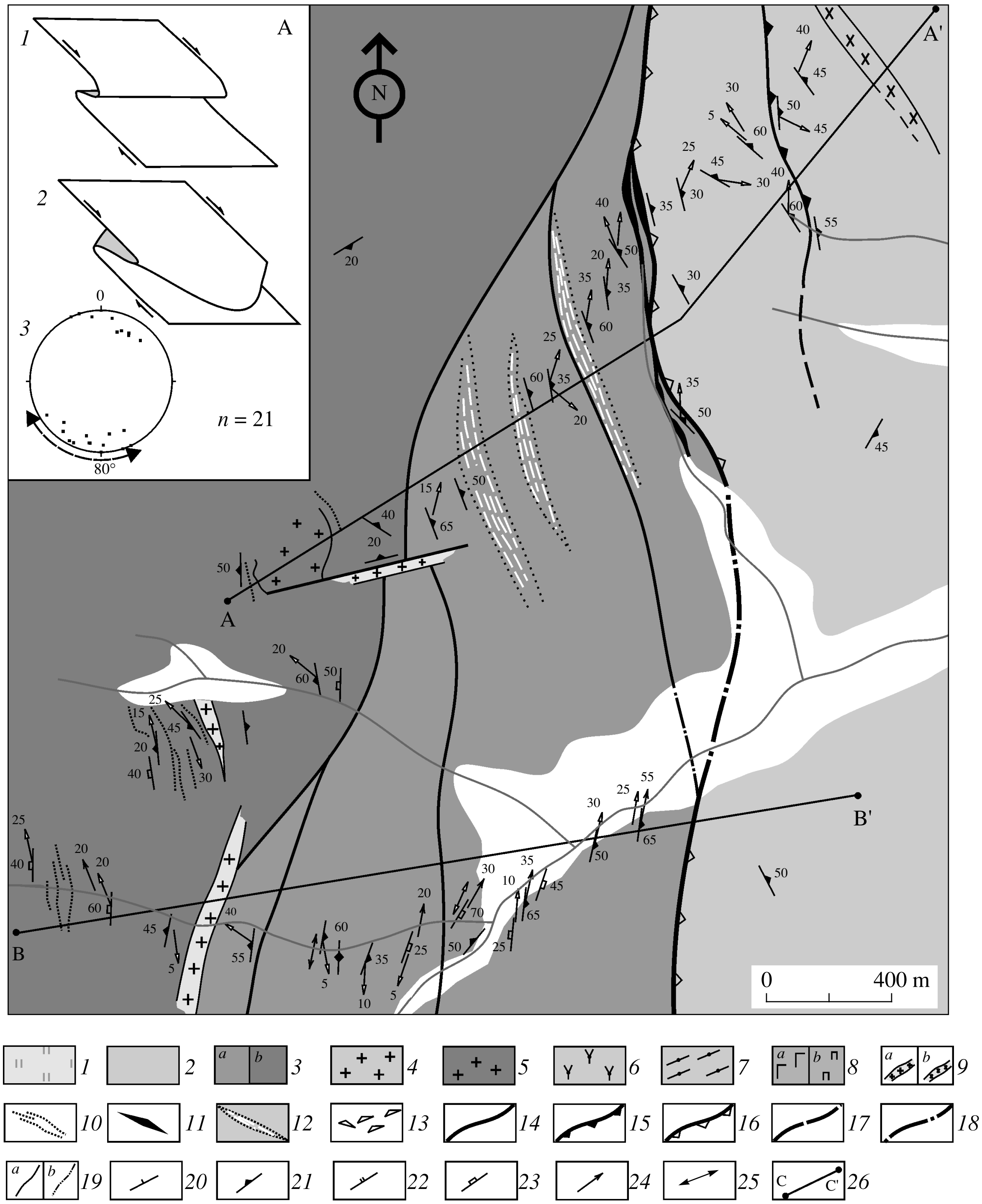


Fig. 3. Geological scheme of the northern area; see Fig. 2 for the area location. Allochton: (*1*) Upper Cretaceous Irunei Formation, (*2*) metavolcanics of the Andrianovka Formation; (*3*) autochthon: (*a*) Kamchatka and (*b*) Kolpakovo groups; intrusive rocks: (4) synmetamorphic (?) granite, (*5*) postcollision Miocene granite, (*6*) Late Cretaceous syenite, (*7*) mylonitized syenite, (*8*) composite mafic and ultramafic intrusions including (*a*) gabbro and (*b*) gabbropyroxenite, (*9*) dikes of (*a*) granite and (*b*) diorite, (*10*) aplite dikes and migmatized rocks; (*11*) amphibolite and pyroxenite; (*12*) silicified zones; (*13*) tectonic (?) breccia; (*14*) unspecified faults; (*15*) thrust faults; (*16*) normal faults; (*17*) inferred faults; (*18*) fault inferred beneath the cover of Quaternary sediments; (*19*) geological boundaries: (*a*) proved, (*b*) inferred beneath the cover of Quaternary sediments; strike and dip symbols: (*20*) bedding, (*21*) schistosity, (*22*) crenulation cleavage, (*23*) axial surface of folds, (*24*) mineral lineation, (*25*) fold hinges; (*26*) section line. Inset A: (*1*, *2*) basic scheme of the sheath fold formation by hinge line bending as an explanation of (*3*) variable hinge orientation along a segment of the Kamchatka Group fold section. The conformal projection, the lower hemisphere; (*n*) number of measurements; 80° hinge angle.

Fig. 4. Geological scheme of the southern area, modified after data of M.N. Shapiro. See Fig. 2 for the area location and Fig. 3 for legend.

abundant at the hinges of small folds (Fig. 8E). The quartz veins are severely deformed; they are flattened, folded, have undergone boudinage, and make up a newly formed lenticular banding (Figs. 8F and 8G). The mylonites occur as particular zones, commonly with subsequently superimposed crenulation cleavage, silicification, and diaphthoresis. The mylonitized rocks are characterized by a banding expressed in the alternation of quartz- and mica-rich bands. The orientation of biotite and muscovite flakes in the latter bands crosscuts the metamorphic banding and the main schistosity. Such fabric is very typical of mylonites (S–C tectonites in Fig. 8C) [52]. Their orientation indicates a strike-slip component of the deformation that corresponds to the direction of porphyroblast rotation in the rocks of the Kamchatka Group. The mylonitized zones are distributed nonuniformly and disappear in the rocks of the Kolpakovo Group.

The rocks of the Kamchatka Group were affected by the retrograde metamorphism, especially in the silicified zones where biotite is replaced by chlorite and garnet is transformed into the mica aggregate (Fig. 8B). The prekinematic (?) garnet porphyroblasts with abundant matrix inclusions do not bear indications of rotation. The synkinematic porphyroblasts are characterized by an S-shaped internal structure emphasized by the fine-grained matrix inclusions (Fig. 8A). The relationships between the internal (within porphyroblasts) and external bandings testify to shortening of up to 50%. The replacement of some porphyroblasts by the secondary minerals is confined to the small tensile cracks oriented at an angle to the schistosity (Fig. 8B). Together with the asymmetric pressure shadows, this shows that the shear rotation of porphyroblasts continued at the retrograde stage. In the rocks that experienced the strong diaphtoresis, the major mineral assem-

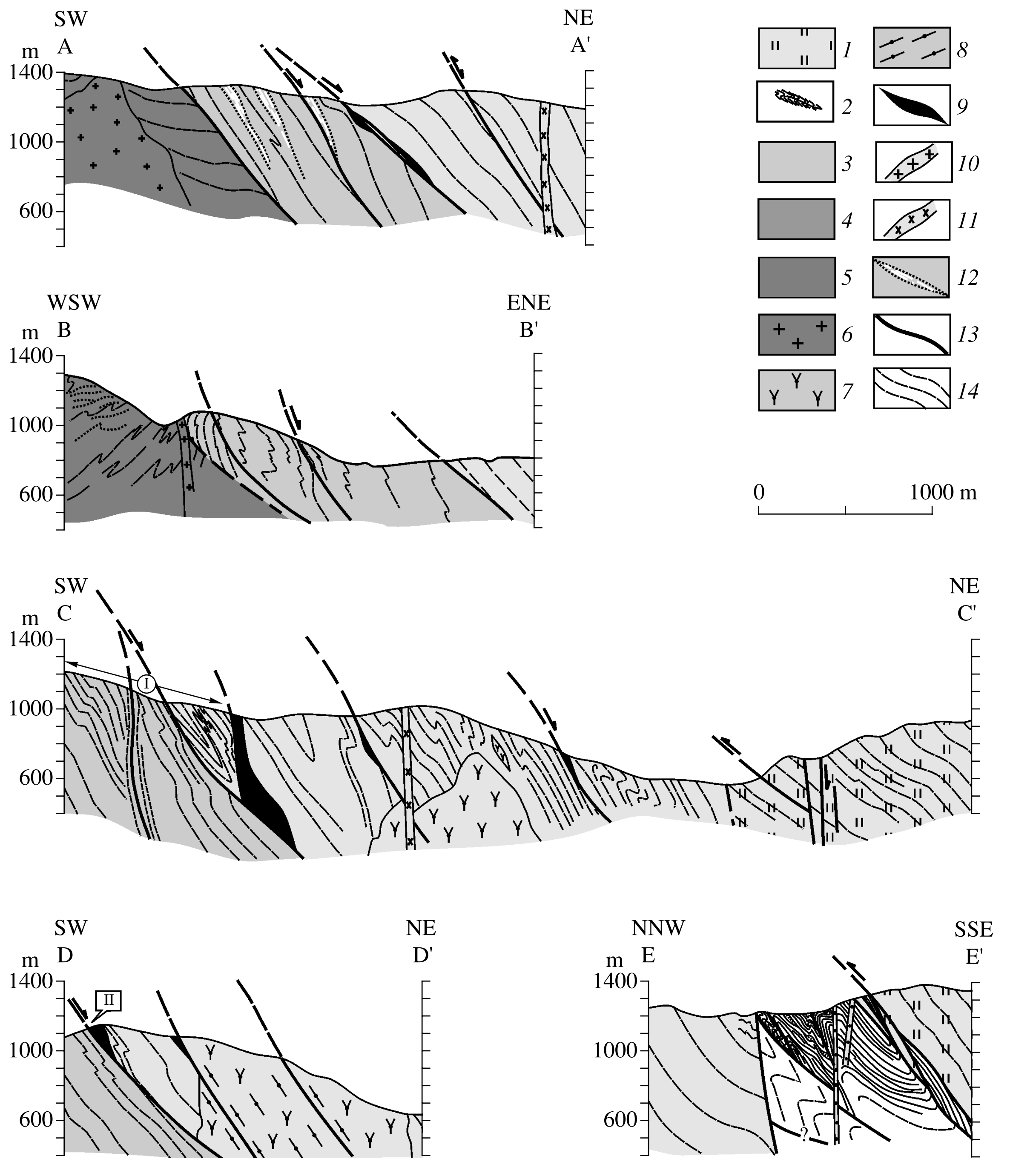


Fig. 5. Geological sections across the Andrianovka zone; see Fig. 2–4 for the section location. (*1*) Upper Cretaceous Irunei Formation, (*2*) Paleocene (?) Khozgon Formation; (*3*) metavolcanics of the Andrianovka Formation; (*4*) Kamchatka Group; (*5*) Kolpakovo Group; (*6*) synmetamorphic (?) collision granite; (*7*) Late Cretaceous syenite; (*8*) mylonitized syenite; (*9*) tectonic lenses of pyroxenite and amphibolite; dikes of (*10*) granite and (*11*) diorite; (*12*) silicified zone; (*13*) faults; (*14*) bedding or schistosity. See Fig. 10F for inset I on section C–C' and Fig. 10E for inset II on section D–D'.

blage consists of biotite, muscovite, chlorite, and sporadic tourmaline.

Thus, the general retrograde metamorphic trend is typical of the Kamchatka Group. The majority of structural elements bear a synkinematic character and make up a deformational–metamorphic structural assemblage formed under the shear environment in the normal ductile fault zone during progressive deformation at decreasing *P*–*T* parameters. The stylolites and corrosion sutures filled with a micaceous material developed at the final stage in the quartz rocks and, to a lesser extent, in quartz veins (Figs. 8H and 8I). They have a characteristic

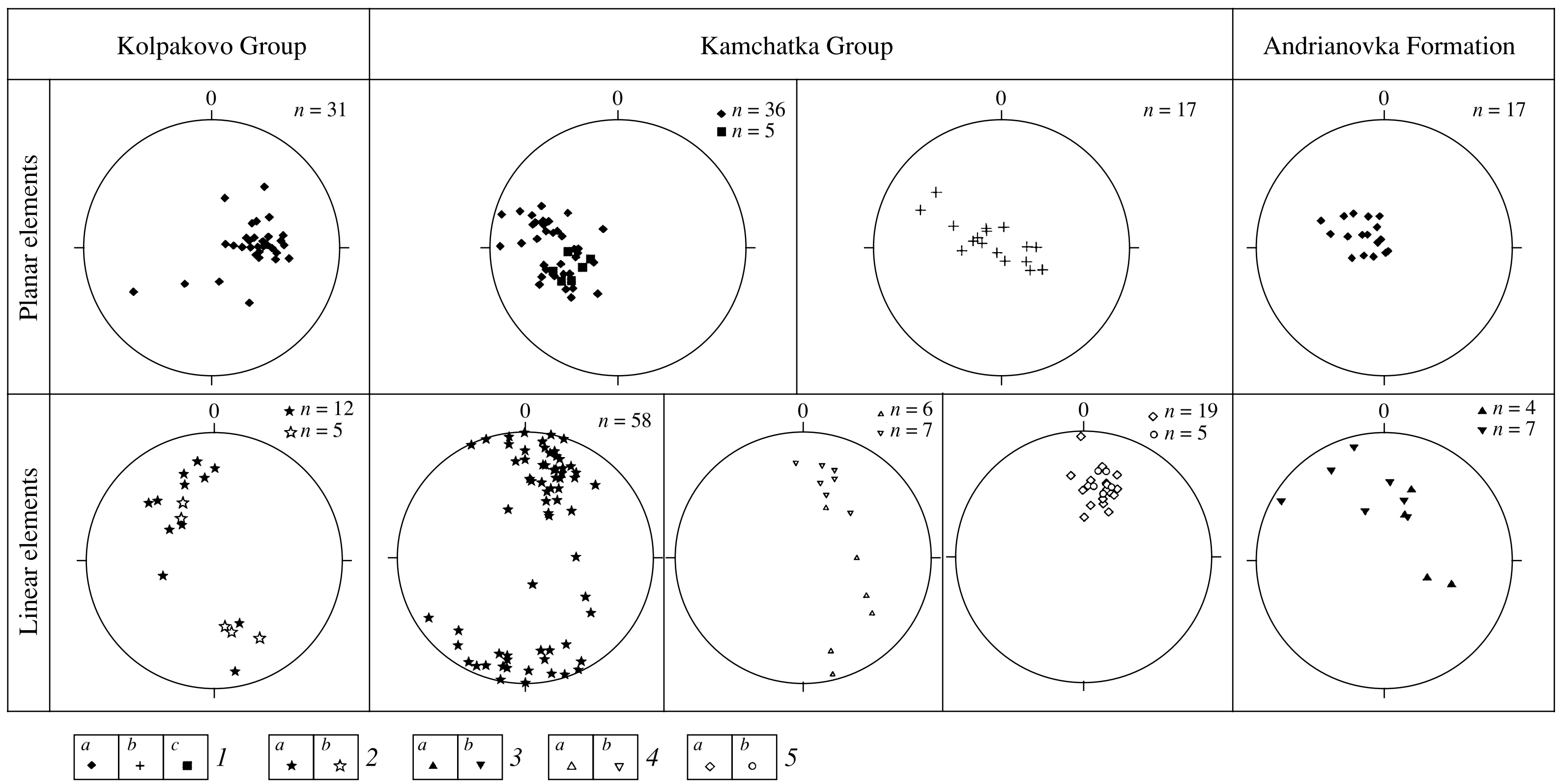


Fig. 6. Orientation of structural elements in the northern area (conformal projection, the lower hemisphere; *n* is number of measurements). (*1*) planar elements: (*a*) schistosity and metamorphic banding (*b*) axial surfaces of folds, (*c*) mylonite banding; (*2a*) fold hinge, (*2b*) ptygmatic fold hinges of deformed aplite veins; (*3*) hinges of (*a*) west- and (*b*) east-vergent folds and kinkzones in rocks of the Andrianovka Formation; (*4*) hinges of (*a*) west- and (*b*) east-vergent folds and kinkzones in mylonites of the Kamchatka and Kolpakovo groups; (*5*) lineation: (*a*) mineral and (*b*) aggregative (formed by quartz mullions).

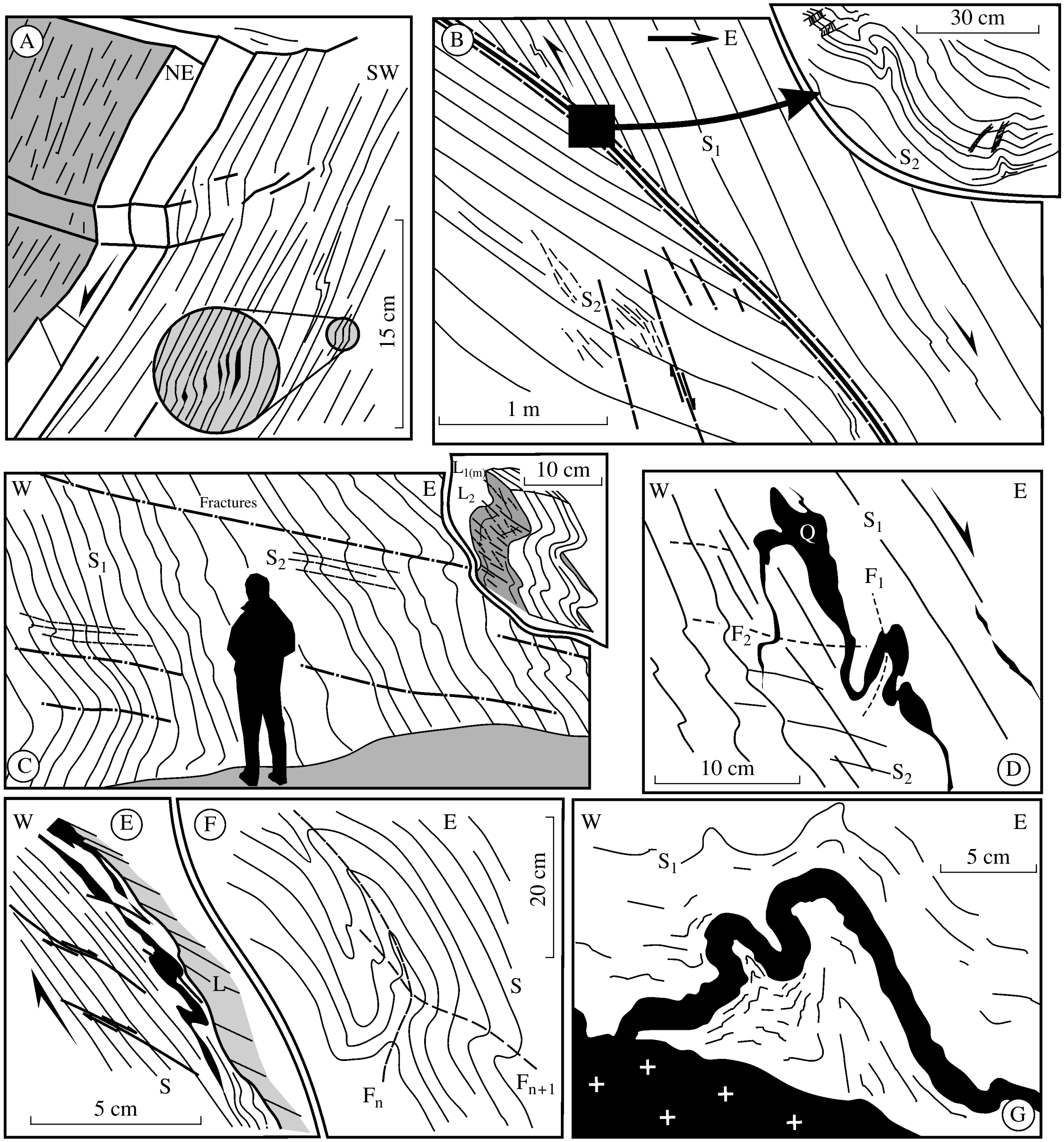


Fig. 7. Structures and structural assemblages in rocks of the Andrianovka Formation, Kamchatka and Kolpakovo groups and their kinematic interpretation. Northern area (panels A–E and G are drawn after photographs; panel F is a sketch of outcrop). Andrianovka Formation: (A) east-vergent folds and kinkzones; (B) east- and west-vergent folds of schistosity S_1 within a zone of the intraformational thrust fault superimposed on schistosity S_2 of the east-vergent kinkzone (see inset). Kamchatka Group: (C) east-vergent folds; schistosity and metamorphic banding S_1; crenulation cleavage S_2; inset: relationships of folds, mineral lineation, and intersection lineation (schistosity/crenulation cleavage); (D) younger east-vergent folds F_2 and crenulation cleavage S_2 superimposed on the quartz-vein banding (Q) involved into folding F_1. Mylonites in rocks of the Kamchatka Group: (E) quartz veins deformed into the east-vergent asymmetric folds; (F) younger normal-fault folds F_{n+1} superimposed on the older thrust-fault quiver-shaped folds F_n; mylonite banding S. Kolpakovo Group: (G) aplite veins deformed into the ptygmatic folds; schistosity S_1.

stepwise morphology and are oriented at an angle to the bedding, testifying to the shear conditions. The fibrous calcite veins are associated with stylolites.

The Kolpakovo Group is separated from the Kamchatka Formation by a fault sealed with minor granitoid bodies including the granitic dikes. In some cases, the

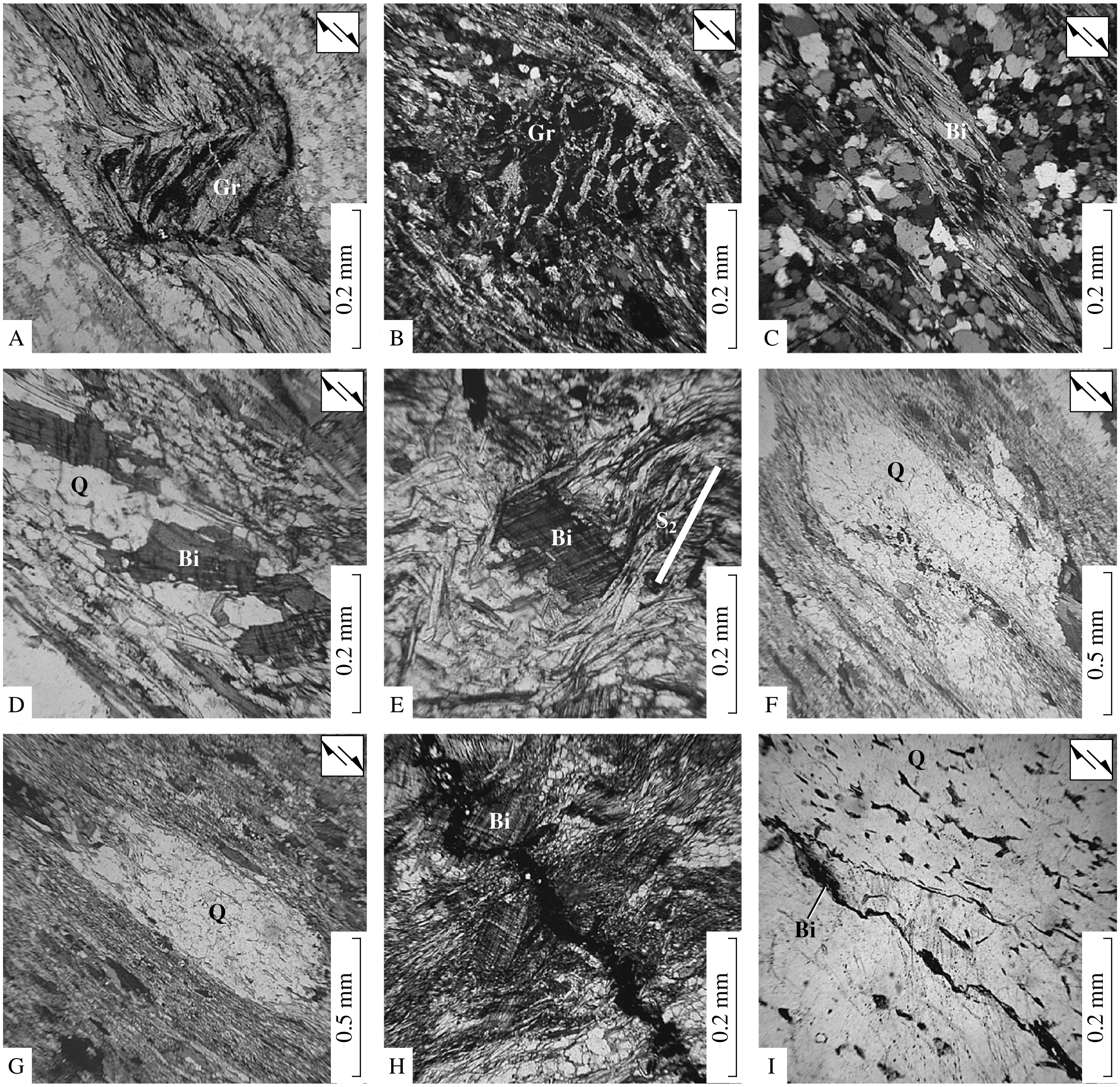


Fig. 8. Microfabric of rocks of the Kamchatka Group in the northern area on photomicrographs of thin sections made without analyzer or with crossed polars (+). (A) rotation of garnet porphyroblast, a quartz–feldspar–chlorite–muscovite schist (mylonite); (B) broken garnet porphyroblast with precipitation of carbonate material in fractures, a diaphtorized garnet–biotite schist (+); (C) cross-cutting relationships of schistosity in mica interlayers and metamorphic (mylonite) banding, a structure of S–C-tectonites in a quartz–feldspar–biotite schist (+); (D) deformation of the biotite porphyroblast with pressure shadows filled with quartz, a mylonite; (E) crenulation cleavage S_2 and biotite porphyroblast, pre-kinematic with respect to the crenulation cleavage, a quartz–feldspar–chlorite–muscovite schist (diaphtorite); morphological types of quartz veins deformed into microfolds: (F) asymmetric tight fold; (G) fusiform vein, a fragment of the flattened fold hinge; further evolution consists in the formation of a new lenticular quartz-vein banding; (H) stylolites (dissolution sutures) with ore fill in diaphtorite; (I) stylolites in the secondary quartzite with biotite fill. The stepwise structure of the suture typical of the shear fractures is clearly seen in the latter photomicrograph. Minerals: (Gr) garnet, (Str) staurolite, (Bi) biotite, (Amph) amphibole, (PFS) potassium feldsapr; (Q) quartz.

tectonites and mylonites after the rocks of the Kamchatka Group turn into the rocks of the Kolpakovo Group through a series of closely spaced faults. The internal structure of the Kolpakovo Group is sharply discordant relative to the structure of the Kamchatka Group: the shistosity and fold axes dip westward (Fig. 5, section B–B' and Fig. 6); the metamorphic grade increases; numerous aplite veins are often deformed into ptygmatic folds (Fig. 7G); and migmatites are noticed. The fold vergence allowed us to reconstruct

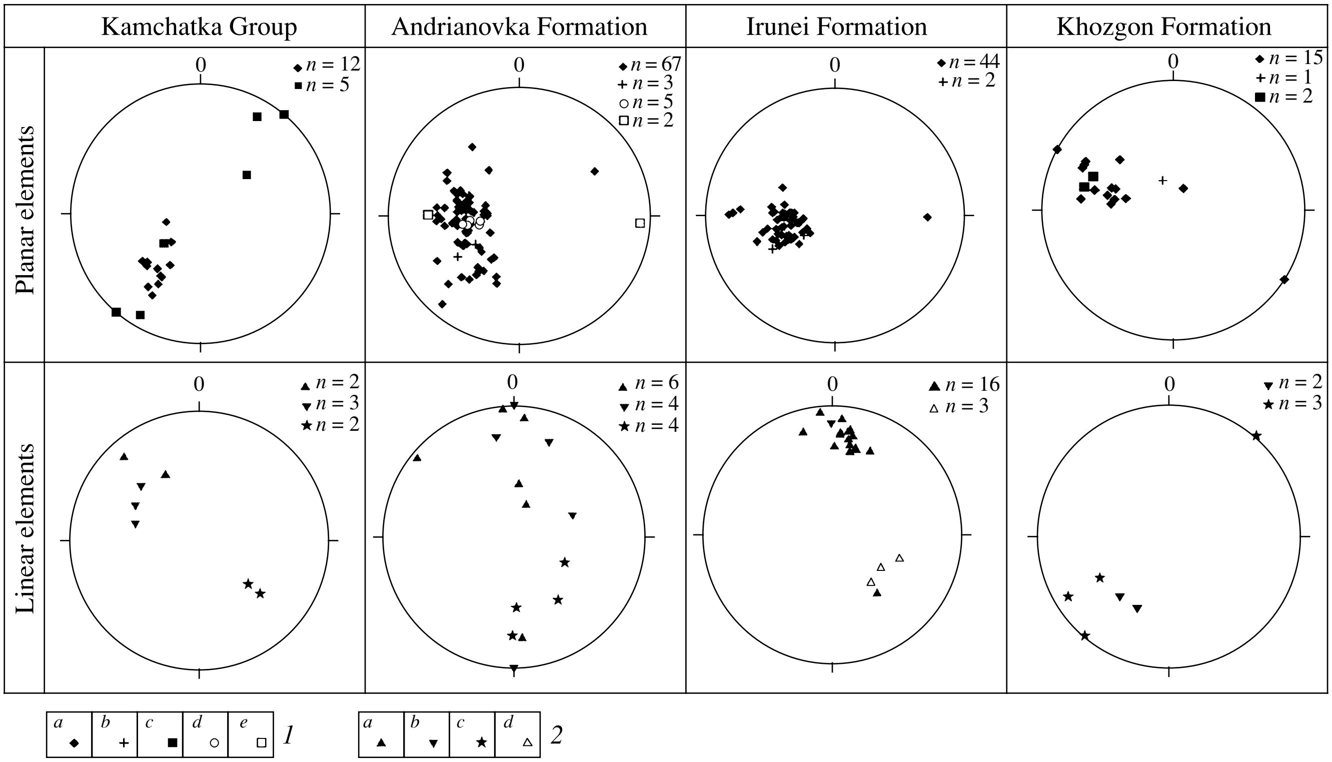


Fig. 9. Orientation of structural elements in the southern area (conformal projection, the lower hemisphere; *n* is number of measurements). (*1*) planar elements: (*a*) bedding in the Irunei Formation, bedding and cleavage in the Khozgon Formation, schistosity and metamorphic banding, (*b*) axial surfaces of folds, (*c*) mylonite banding, (*d*) cataclastic banding in syenite, and (*e*) crenulation cleavage; (*2*) fold hinges: (*a*) west- and (*b*) east-vergent folds, (*c*) M-folds, and (*d*) west-vergent folded quartz veins.

a fragment of the fold section (Fig. 5, section B–B') where the zone of intense deformation is related to the belt of aplite veins and migmatized rocks.

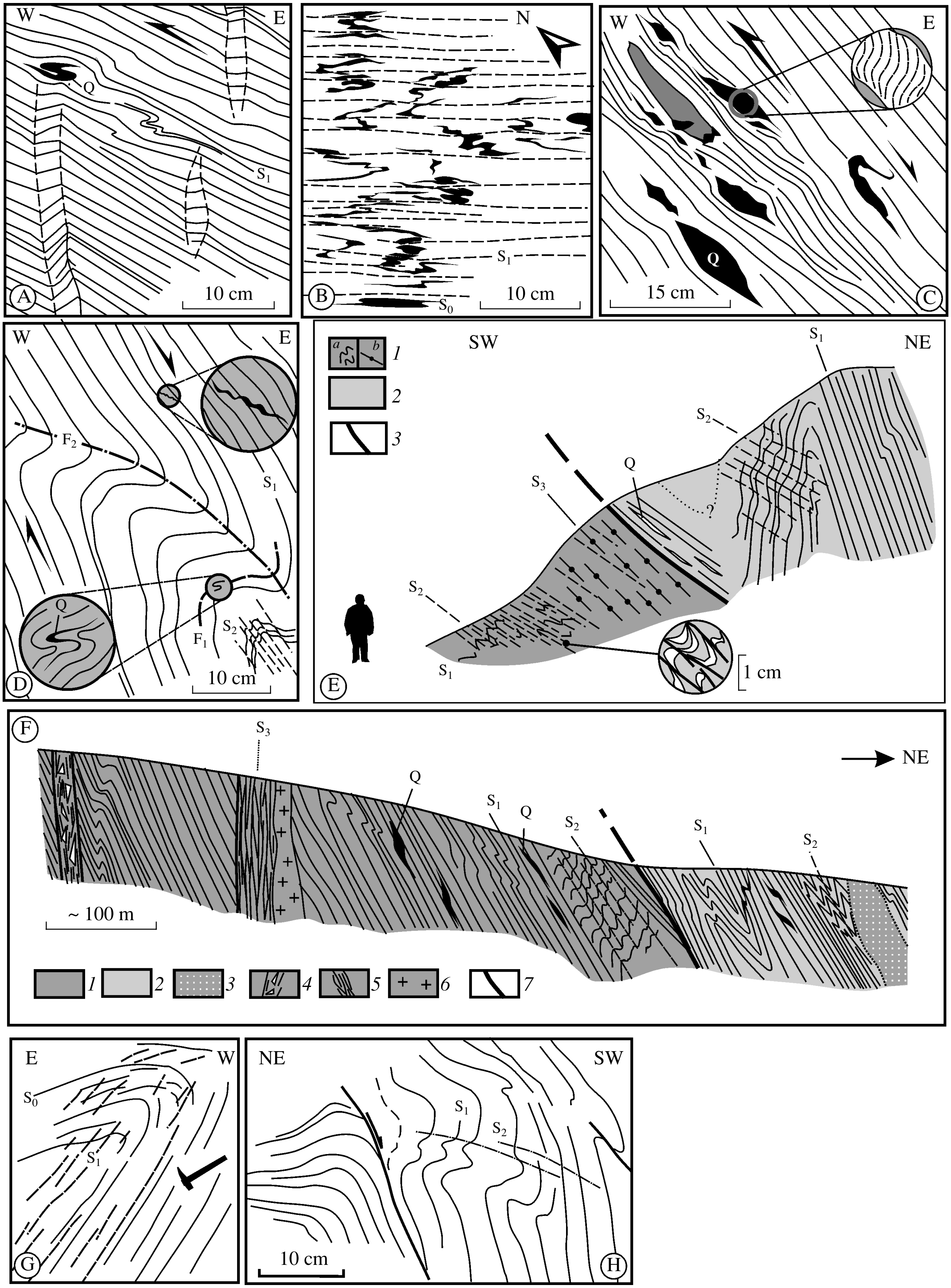
The Southern Area

In the southern area we studied the deformation of the rocks pertaining to the Irunei and Andrianovka formations, the structure of the mylonite zone after the rocks of the Kamchatka Formation (Figs. 4 and 5, sections C–C' and D–D'), as well as the internal structure of the Khozgon tectonic wedge (Fig. 5, section E–E').

The upper allochthonous complex. The Irunei Formation consists of the tuffaceous cherty rocks. The bedding steadily dips eastward (Fig. 9). In some zones, the rocks are severely foliated with the development of sericite–chlorite aggregates along the schistosity planes; cleavage is observed in the tuffaceous varieties. The kinkbands are superimposed on the older cleavage and schistosity (Fig. 10A); flat and folded quartz veins are pointed out. In the foliation zones, the bedding is deformed into isoclinal folds (Fig. 10B). The overwhelming majority of the west-vergent fold hinges and kinkzones plunge at angles of 20°–30° to the north (Fig. 9) indicating a short sinistral displacement along the thrust fault. The folds with southeast-plunging hinges (Fig. 9) are sporadic and commonly occur in quartz veins. The fusiform quartz veins oriented nearly parallel to the bedding concentrate in separate units. The vein morphology points to their formation by bed separation in zones of reverse-fault bends. This mechanical environment is often emphasized by en echelon arranged veins and bends of rough fibers within veins (Fig. 10C). In general, the Irunei Formation is characterized by a low grade of metamorphism and by the deformational–chemical [7] structural assemblages, e.g., the stylolite sutures + fibrous quartz veins in the cherty rocks as shown in Fig. 11A.

The contact between the Irunei and Andrianovka formations bears indications of a gradual transition, but is distinctly fixed by the microscopic examination of rocks owing to the appearance of amphibole. M.N. Shapiro (private communication) pointed out the younger, nearly vertical normal faults along with the thrust faults in the contact zone, and this was confirmed by our observations.

The lower allochthonous complex. The Andrianovka Formation consists of quartz–feldspar–amphibole and quartz–feldspar–chlorite–amphibole schists. The quartz beards typically overgrowing the pyrite grains in greenschists are notable (Fig. 11B). Large amphibole porphyroblasts partly replacing the fine crystalline matrix are observed at the base of the tectonic sheet composed of the Andrianovka Formation.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The amphibolite bodies are related to the intraformational faults.

The Andrianovka Formation is composed of monotonous rocks with sporadic fold fragments. The tightly compressed acute keel-shaped folds with southeast-plunging hinges occur at the contact with the rocks of the Kamchatka Group. As has been established in one such fragment, the east-vergent (normal-fault) folds with the megascopic crenulation cleavage at the hinges were superimposed on the older west-vergent structures (Fig. 10D). Most of the reverse-fault and normal-fault small folds and kinkzones plunge to the north (Fig. 9), and this indicates that they were localized close to the internal line of rotation during their formation. The west-vergent reverse-fault folds reveal a sinistral component while a small dextral component is related to the normal-fault faults.

The mafic–ultramafic igneous rocks and syenite were emplaced into the rocks of the Andrianovka Formation. The massive syenite grades into the foliated variety and then into fine-grained, thin-banded epidotized rock (Fig. 11I and 11J), which are indiscernible by the naked eye from the rocks of the Andrianovka Formation. Such rocks were identified as mylonites (varying from protomylonite with incipient crushing to the mylonite and blastomylonite [46]) related to the fault zones and accompanied by the advanced epidotization and sporadic sulfide mineralization without indications of the porphyroblast rotation.

Autochthon. The sharp contact between the rocks of the Andrianovka Formation and Kamchatka Group is distinctly developed (Fig. 10F). The garnet amphibolite bodies occur in the Andrianovka Formation near the contact. The crenulation cleavage and small folds were formed along the basal cleavage in the autochthon rocks. The orientation and vergence of asymmetric folds are similar to those in the rocks of the Andrianovka Formation (Fig. 9). The widespread fusiform quartz veins are elongated down the dip of schistosity; the nearly vertical zones of mylonites and brecciated rocks are notable (Fig. 10F). The steeply dipping lineation in the mylonites is displayed in the orientation of the oblong quartz mullions.

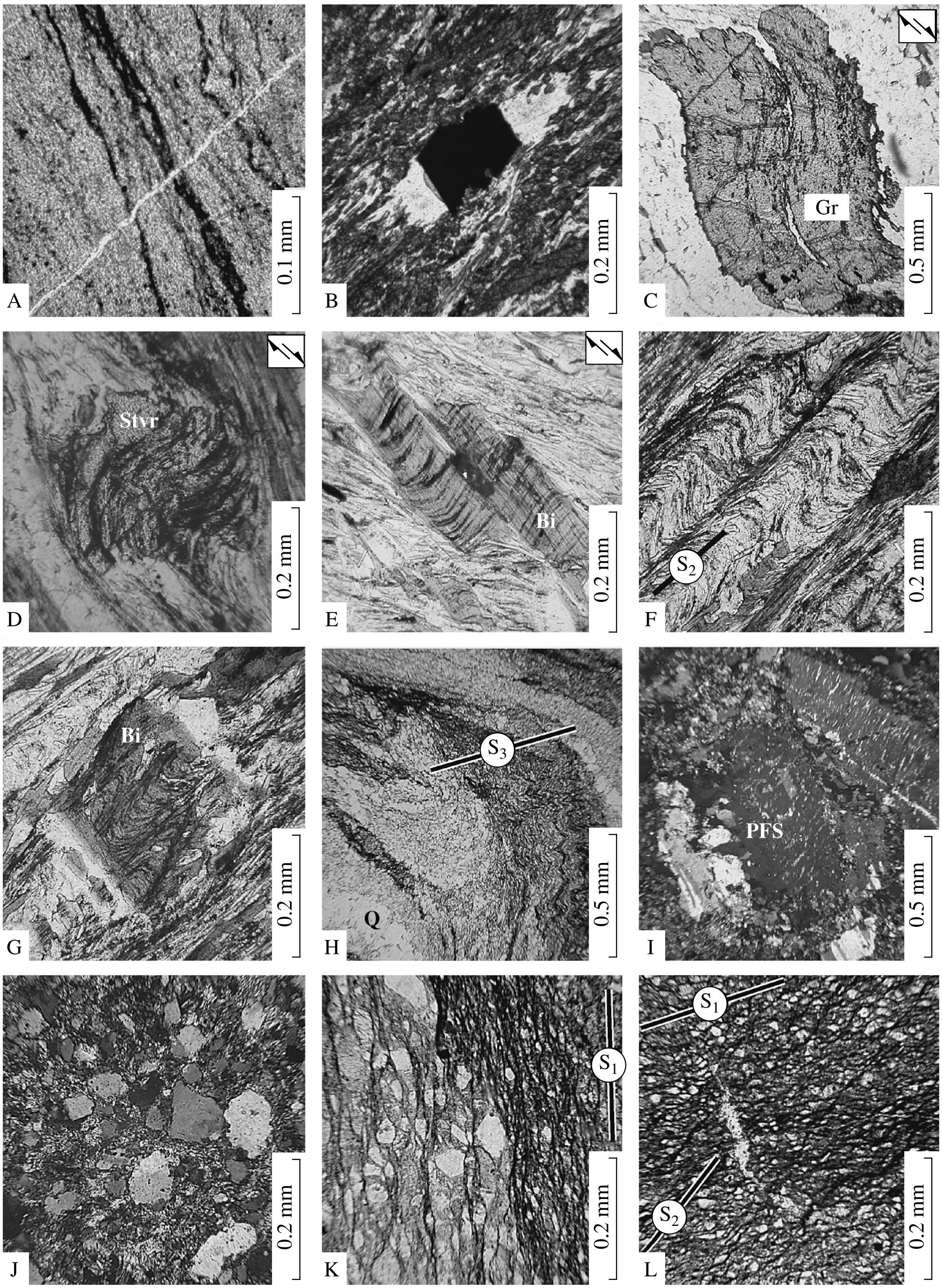
As in the northern area, a petrofabric analysis of the rocks from the Kamchatka Group confirmed the synkinematic character of the garnet, staurolite, and biotite porphyroblasts (Fig. 11C–11E). Their orientation indicates the normal-fault kinematics of tectonite zones, occasionally with a dextral strike-slip component. The crenulation cleavage develops somewhere along the basal schistosity and after S- and C-tectonites (Fig. 11F). The garnet porphyroblasts are prekinematic with respect to this cleavage. The biotite porphyroblasts, rotated during their growth, as a rule, were broken up at the subsequent stages. The individual fragments of crystals were turned relatively to one another along a system of antithetic shears (Fig. 11E) and often underwent boudinage with the redeposition of low-temperature and free of impurities biotite and quartz in cavities. Biotite porphyroblasts, post- and synkinematic relative to the crenulation cleavage (Fig. 11G), were also observed. The pressure shadows behind them were filled with quartz beards at the late stages. The rocks with numerous quartz veins are deformed to the greatest extent. Relics of the early fabric, including schistosity and crenulation cleavage, were detected in the shadow zones of deformation at the hinges of the folded quartz veins. The newly formed pervasive schistosity is a result of the complete reworking of the crenulation cleavage. The deformation proceeded against the background of the retrograde metamorphism with a prevalent development of the chlorite–muscovite assemblages and the silicification of rocks in the later stages.

At the southern flank of the study suture zone segment, the contact between the Kamchatka Group and Andrianovka Formation is composed of the mylonite that experienced the retrograde alteration (Fig. 5, section D–D'; Fig. 10E). The greenschists from the hanging wall were identified under a microscope as the gabbroids that underwent the strong mylonitization and diaphthoresis. The mylonites developed after the Kamchatka Group rocks are composed of the quartz–feldspar–chlorite–biotite–muscovite schists. The crenulation cleavage is superimposed on the mylonite banding deformed into isoclinal folds (Fig. 11H). The lineation in mylonites is made up of small fold hinges cut off by cleavage zones (Fig. 10E, inset). The further evolution

Fig. 10. Structures and structural assembalges in rocks of the Irunei, Andrianovka Formation, and Kamchatka Group (panels A–D, G, and H are drawn from photographs; panels E and F are the sections). The Irunei Formation: (A) conjugated kinkzones superimposed on schistosity S_1 within the zone of intraformational thrust fault; (B) schistosity S_1 cross-cutting bedding S_0 in the hinge of a small fold within the thrust-fault zone; (C) quartz veins arisen by separation along the schistosity planes. The Andrianovka Formation: (D) relationships between the early thrust-fault folds F_1 and the late normal-fault folds F_2; schistosity S_1; megascopic crenulation cleavage S_2; quartz veins Q. The Kamchatka Group: (E) relationships of planar structures in mylonites, an enlarged fragment II of section D–D', see Fig. 5: (*1*) mylonite (quartz–feldspar–biotite schist) including (*a*) crenulation cleavage S_2 (see inset) modifying the early mylonite banding S_1 and (*b*) newly formed mylonite banding S_3 formed by flattening of the plicated rocks; (*2*) diaphtorized mylonite (chlorite schist) after gabbroids (?) with plagioclase porphyroclasts; schistosity S_1, crenulation cleavage S_2, and quartz vein Q; (*3*) fault. (F) relationships of the planar structures in mylonite, an enlarged fragment I of section C–C', see Fig. 5: (*1*) metapelites of the Kamchatka Group, (*2*) amphibole schists of the Andrianovka Formation, (*3*) silicified zone, (*4*) zone of brecciated rocks, (*5*) mylonite, (*6*) aplite dike, (*7*) fault; schistosity, metamorphic banding, and the early mylonite structure S_1; crenulation cleavage S_2; late mylonite structure S_3; quartz vein Q. The Khozgon Formation: (G) overturned fold with axial-plane cleavage; (H) disharmonic folds at the base of the Khozgon wedge, a contact with rocks of the Andrianovka Formation (deformed cleavage S_1); crenulation cleavage S_2.

of the crenulation cleavage gave rise to the newly formed mylonite banding.

Paraautochthon (?). We carried out some observations in the tectonic wedge of the Khozgon Formation localized between the blocks composed of the Irunei and Andrianovka formations (Fig. 2; Fig. 5, section E–E'). The pervasive intergranular cleavage oriented parallel or at a very acute angle to the bedding is inherent in



sandstones and siltstones of the Khozgon Formation (Figs. 10G and 11K). Such relationships between the pervasive cleavage and bedding testify to the tight, up to isoclinal, folding of the Khozgon Formation. The cleavage is associated with the fibrous quartz veins partly dissolved in the cleavage zones. At the contact with the Andrianovka Formation, the rocks are transformed into a melange and deformed into numerous, often disharmonic, folds. The siltstone with an already developed cleavage and embedded quartz veins were involved in the folding (Fig. 10H).

At the upper tectonic contact, the tectonized cherty rocks of the Irunei Formation are transformed into the finely foliated material with lenticular inclusions, up to a few centimeters in size, incorporated into the matrix and elongated parallel to the schistosity. The dissolution under pressure actively proceeded within the melange zone under compression at the late stages of the fault evolution. The lower tectonic contact is poorly exposed. The isolated outcrops of the Andrianovka Formation exhibit the chlorite–sericite greenschists with a relict clastic fabric. The lower tectonic contact of the Khozgon wedge is probably cut off by a younger, steeply dipping normal fault. The west-vergent folds and crenulation cleavage that occur in the rocks of the Andrianovka Formation are strongly affected by the retrograde metamorphism.

Two types of planar structures are noticed in the rocks of the Khozgon Formation. The crenulation cleavage is widespread, often in association with fibrous quartz veins (Fig. 11L). The thick cleavage sutures dividing the megascopic lithons with the retained fragments of the older deformational–chemical assemblages are locally developed in the tectonic melange. The planar elements (bedding, intergranular cleavage, and mylonite banding) normally dip to the east-southeast (Fig. 9). It has been suggested that the rocks of the Khozgon Formation known from this area make up the limb of a large anticline cut off by faults and complicated by the east-vergent folds (Fig. 10G). Such fold vergence and the systematic development of the crenulation cleavage may testify to the two-stage formation of the Khozgon wedge. The fold structure with a series of overturned isoclinal (?) folds with the pervasive intergranular cleavage was formed at the early stage and followed by fold deformation at the second stage (Fig. 10H). The eastward vergence was likely related to the normal-fault kinematics of displacements along faults.

MECHANICAL INTERPRETATION OF THE STRUCTURAL ASSEMBLAGES. A STRUCTURAL EVOLUTION MODEL

The following model of the Andrianovka suture structure and evolution may be proposed (Fig. 12). The structural–metamorphic zoning is expressed in the increasing metamorphic grade from east to west. The gneisses of the Kolpakovo Group are virtually not affected by the retrograde metamorphism and characterized by the discordant internal structure relative to the rocks of the Kamchatka Group. The deformation in the rocks of the Kamchatka Group (Fig. 12A) is concentrated within the normal ductile fault zone characterized by the retrograde metamorphic trend from the earliest garnet–staurolite–biotite mineral assemblage to the low-temperature biotite–chlorite–muscovite assemblage. In some cases, the latest processes were associated with the acid leaching of rocks [4] and the strong hydrothermal alteration of the fault zone. The schistosity, S–C-tectonites, metamorphic and mylonite banding S_1, and synkinematic porphyroblasts were formed at the first stage D^1. The second stage D^2 is characterized by the formation of folds and flexures, folding of the older deformational structures, and development of the crenulation cleavage S_2. The quartz veins were formed on the fold limbs in the detachment zones. Subsequently, the veins were folded and flattened out with the appearance of the newly formed banding. The kinkzones, folds, and crenulation cleavage S_3 were formed at the third stage D^3. The final episodes of the structural evolution (D^4?) are displayed in the deformational–chemical structural assemblages recognized in the mylonites (stylolites S_4) and fibrous quartz veins. Thus, the Kamchatka Group may be regarded as a zone of tectonites consisting of the rocks that underwent a different degree of the tectonic reworking varying from the fragments with well-preserved early deformational–metamorphic structural assemblages to the tectonites (mylonites) with relics of the early garnet, staurolite, and biotite porphyroblasts. The most pronounced retrograde metamorphism accompanied by silicification developed at the northern

Fig. 11. Microfabric of rocks of the Kamchatka Group in the southern area on photomicrographs of thin sections made without analyzer or with crossed polars (+). See Fig. 8 for mineral abbreviations. The Irunei Formation: (A) deformational–chemical structural assemblage: stylolites (rough cleavage) + quartz veins. The Andrianovka Formation: (B) quartz beard overgrowing the pyrite grains. The Kamchatka Group: synkinematic S-shaped curved (C) garnet and (D) staurolite porphyroblasts with inclusions; the internal structure of the matrix inclusions captured during the porphyroblast growth is clearly seen; (E) breakup of synkinematic biotite porphyroblast with shearing; (F) crenulation cleavage S_2 in the quartz–feldspar–muscovite–biotite schist; (G) biotite porphyroblast with quartz beards in pressure shadows, postkinematic with respect to the crenulation cleavage; (H) double folding of the mylonite banding with formation of crenulation cleavage S_3 in the fold hinge. Tectonites superimposed on the intrusive rocks: (I) breakup of the large potassium feldspar crystal, a protomylomite in syenite (+); (J) epidotized mylonite in syenite (+). Khozgon Formation: (K) cross-cutting relationships of bedding and intergranular cleavage S_1 in the fine-grained sandstone and siltstone; (L) deformational–chemical structural assemblage: crenulation cleavage S_2 + quartz veins; crenulation cleavage is superimposed on the intergranular cleavage S_1.

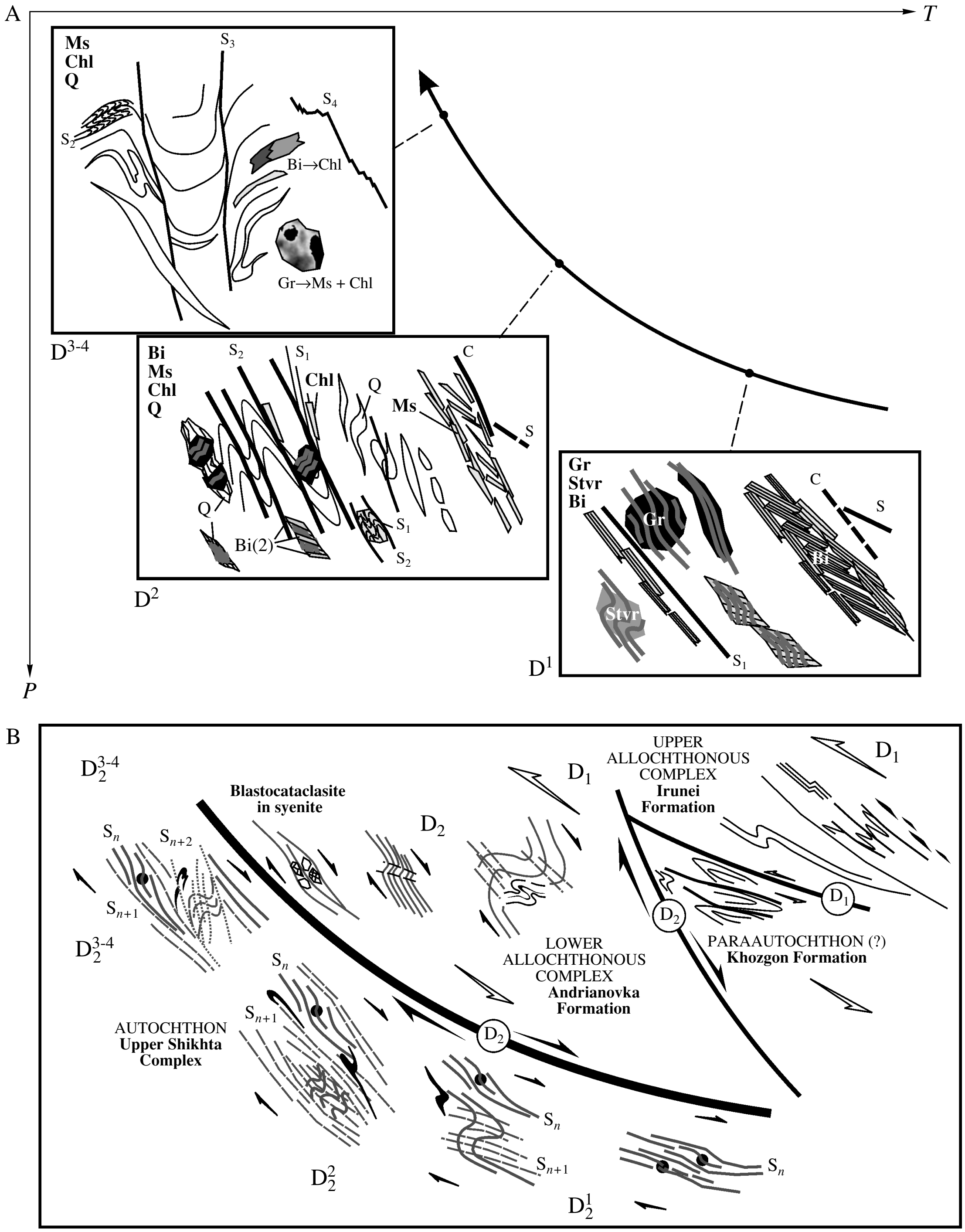


Fig. 12. (A) Stages of structure formation in rocks of the Andrianovka Formation and (B) structural evolution of the Andrianovka suture at the collision (D_1) and postcollision (D_2) stages—a basic model. See text for explanation. D_n—deformation stages and D^n—substages. Ms—muscovite, Chl—chlorite; see Fig. 8 for abbreviations of other minerals; S and C—directions of crystallization schistosity in S–C-tectonites; S_{1-4} are generations of planar structures: 1—early schistosity, 2—crenulation cleavage, 3—crenulation cleavage superimposed on the mylonite and quartz-vein banding, 4—stylolites.

flank of the fault. In general, the thickness of the normal ductile fault zone at the roof of the Kamchatka Group attains a few hundred meters.

Paraautochthon composed of the Khozgon Formation [34] is a tectonic wedge between the rocks of the Andrianovka and Irunei formations (Fig. 5, section E–E'). Two events are exhibited in the structure of the Khozgon wedge. A cleavage-related assemblage was formed at the early stage, and the superimposed east-vergent folds, probably resulting from the normal faulting along the early cleavage, are the structures of the second stage.

Kinematic analysis has shown that the structures of the **lower allochthonous complex** (Andrianovka Formation) were partially formed due to the updip westward tectonic transport (Fig. 12B). The structures and structural assemblages are less abundant as kinematic indicators of the normal faulting. Thus, two stages of structural evolution are suggested: the first, related to the thrusting and the second, proceeding under extension.

The joint kinematic analysis of the kinkzones and drag folds requires special comment. The kinkbands (kinzones) are the typical deformational structures of strongly delaminated rock bodies varying in scale from the intergranular space to the beds and their packets. As has been shown in [36, 56, 58], the asymmetric kinkzones are formed under compression at angles of 20°–30° relative to the schistosity (bedding or cleavage). Compression along the bedding results in the formation of conjugated kinkzones. Thus, these structures can be used as kinematic indicators. The metavolcanics of the Andrianovka Formation demonstrate the consistent hinge orientation in kinkzones of various vergences, thus providing general evidence for compression along the bedding. Such conjugated (?) kinkzones with different vergences could be formed as a result of the metamorphic schistosity bending provoked by the thrust, reverse, and normal faulting. Besides this, the conjugated kinkzones with a variable hinge orientation could form along the schistosity in ductile fault zones due to the triaxial flattening [49]. The accepted two-stage model is supported by structural observations testifying to the close orientation of the fold hinges and kinkzones of the respective vergence and by the direct evidence for the superposition of the younger east-vergent folds and kinkzones upon the older structural elements.

The protomylonite and mylonite formation in syenite intruding into the allochthon may be related to either of these stages. Taking into account that the planar structures are sensitive to the subsequent deformation resulting in the superimposed fabric formation, it is reasonable to refer the mylonitization of syenite to the late normal faulting.

The upper allochthonous complex is made up of the Irunei Formation with a predominance of the structures indicating a westward tectonic transport during the thrusting (Fig. 12B).

Summarizing the structural data, we propose the following model of structural evolution. The compressional environment of the early stage D_1 was related to the collisional thrusting that gave rise to the tectonic juxtaposition of rock complexes (Fig. 12B). The structures and structural assemblages in the rocks of the Andrianovka and Irunei tectonic sheets and the Khozgon tectonic wedge sandwiched between them pertain to different depth levels and *PT* conditions, respectively. The structures in the Kamchatka Group, formed during the early prograde metamorphic stage, were almost completely reworked by superimposed processes and retained only fragmentarily. The syncollision metamorphism at deep levels was accompanied by migmatization of rocks and granite formation, as is evidenced from the Kolpakovo Group exposed in the core of the Sredinny massif.

The normal ductile fault that corresponds to the main part of the Kamchatka Group in the study segment of the Andrianovka suture (Fig. 12B) was formed under extension during the postcollision stage. The deformation within the fault zone indicates normal-fault kinematics at decreasing *PT* parameters characterizing the multistage exhumation of the metamorphic rocks. The structures of the postcollision extension are less abundant in the Andrianovka sheet and inferred in the Khozgon Formation. The nearly vertical normal brittle faults are predominant in the upper portion of the tectonic packet (Irunei Formation).

A sinistral strike-slip component is fixed in the allochthonous structure related to the early thrust events, while the dextral component probably prevailed during the late stage of the normal faulting.

DISCUSSION

The collision and postcollision stages are recognized in the Andrianovka suture evolution from the results of structural investigations.

The collision stage. The formation of the west-vergent thrust fault in the Andrianovka suture zone was related to the compressional environment caused by the collision [13] of the Cretaceous island arc with the northeastern margin of Eurasia in the late Paleocene and early Eocene (Figs. 13A and 13B). The suture nature of the Andrianovka fault is emphasized by lenses of mafic and ultramafic rocks at the base of the island-arc sheet in the Krutogorov River valley [21]. The sinistral strike-slip component of the allochthonous structures at the collision stage is consistent with the previously obtained data on the strike-slip component of the Lesnaya River thrust fault [27]. The collision thrusting in the eastern framework of the Sredinny massif is confined to a rather narrow age interval between the ages of the Kamchatka Group protolith (lower limit) and the Baraba Formation (upper limit). The Baraba Formation was traditionally considered to be Upper Cretaceous [34] and referred to the neoautochthon sealing of the older structures of the Sredinny massif. However, this formation was recently dated as 50 Ma (lower Eocene) [26]. The age of the Kamchatka Group protolith is crucial for the timing of collision deformation. Because this age corresponds to the Paleocene [47, 48], the whole packet of tectonic sheets consisting of the rocks metamorphosed to various degrees may be regarded as a collision structure formed 55–50 Ma ago. The rocks of different metamorphic grades may be interpreted as collision structure fragments exhumed from various depths.

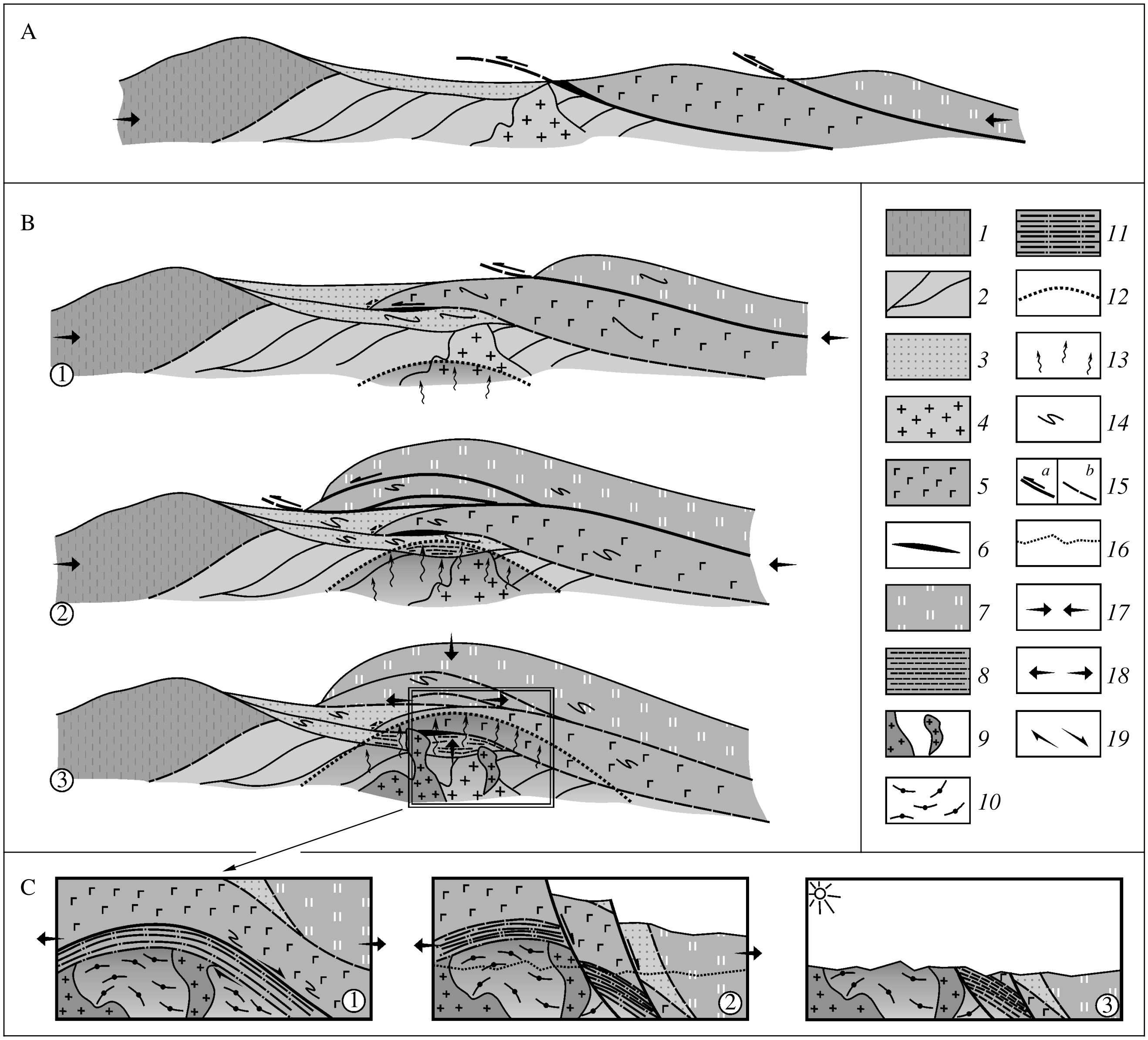


Fig. 13. Tectonic evolution of the Andrianovka suture (out of scale; age of events is given after [47, 48]; see text for explanation): (A) precollision stage (~60 Ma ago), (B) collision stage (55–52 Ma ago), (C) postcollision stage (<52 Ma ago). (*1*) Heterogeneous complexes at the northeastern margin of Eurasia; (*2*) terrigenous complexes of the accretionary wedge; (*3*) sedimentary cover of the accretionary wedge; (*4*) granite of the Krutogorov Complex; (*5*) rocks of the Andrianovka Formation; (*6*) mafic and ultramafic rocks; (*7*) rocks of the Irunei Formation; (*8*) schists of the Kamchatka Group; (*9*) synkinematic granite; (*10*) gneisses of the Kolpakovo Group; (*11*) mylonite in rocks of the Kamchatka Group within the normal ductile fault zone (only in panel B); (*12*) metamorphic front; (*13*) migmatization and granitization; (*14*) folds; (*15*) faults: (*a*) active and (*b*) inactive; (*16*) present-day erosion level (panel B, 2); geodynamic environments: (*17*) compression, (*18*) extension, (*19*) shear.

Postcollision stage was characterized by the extension and exhumation of the high-grade metamorphic complexes of the Sredinny Range and their juxtaposition with the lower-grade complexes (Fig. 13C). The zone of the ductile normal flow described above is the crucial evidence for the tectonic denudation resulted in the exposition of the high-grade rocks in the Andrianovka suture zone. The main structural suture at the contact of the Kamchatka Group and Andrianovka Formation is largely controlled by the concentration of deformations at the base of the Andrianovka sheet. The structures of the early (collision) stage are unknown in the Andrianovka Formation, and the porphyroblast rotation indicates normal faulting was already present at the early stage of metamorphism. The burial of the marginal continental terrigenous sequences beneath the island-arc sheet (Fig. 13B, 1, 2, and 3) and the following metamorphism of subsidence that resulted in the complete reworking of the older fold structure, probably with a rapid change of kinematic sense (Fig. 13B, 3), is a plausible explanation of this phenomenon.

The boundaries between the Kolpakovo and Kamchatka groups, as well as between the Andrianovka and Irunei formations, have the greatest contrast. At the same time, the discordant structural grains and the abrupt lateral change of the metamorphic grade are more likely determined by the juxtaposition of rock complexes as a result of displacement along the younger brittle faults (Fig. 13C, 2). The formation of nearly vertical normal brittle faults in the upper (Irunei) sheet is a structural manifestation of this process.

The formation of the normal ductile fault at a depth and the brittle faults near the surface is the typical feature of the Cordilleran-type metamorphic cores [24, 51, 54, 62]. The restored lateral series of the structural assemblages related to the Andrianovka suture is consistent with the vertical structural zoning and demonstrates a different reaction of rocks to the applied loads. The results obtained cannot be regarded as unequivocal evidence for this mechanism of metamorphic rock exhumation, but the model of metamorphic cores could be assumed as a starting point for further investigations.

The progressive deformation in the zone of normal ductile fault is supported by numerous examples [51, 54, 59, 60, 62]. A number of variants of the competing deformation mechanisms with strengthening and weakening in zones of mylonitization were discussed in [56, 57]. A model of structural rearrangements [29, 30] suggests that variation in the relaxation ability of the deformed body due to the change of its fabric is the main factor controlling the replacement of one deformation mechanism by another.

The zones of viscous faults are characterized by the multifold superposition of deformations along with the retention of the general structural evolution trend toward the flattening of rocks and the formation of planar fabric (schistosity or mylonite banding) with the complete reworking of the folds arising thereby. The folding of the schistosity and metamorphic banding and their further flattening at the grain-size level (granulation, recrystallization, etc.) in the course of increasing deformation give rise to the complete obliteration of the older folds by the newly formed schistosity, which turns out to be indiscernible in morphology from the older one.

The qualitative change occurs at a shallower level and at decreasing temperature and pressure. The folding results in the strengthening of rocks, and the flattening of the newly formed folds becomes impossible, because the intergranular deformation under these *PT* conditions does not work and cannot relax the applied load. The formation of mylonite zones with relict fragments of the older folds and crenulation cleavage is a more efficient and energetically favorable mechanism under these conditions. The active fluid migration promotes the formation of hydrothermal veins largely composed of quartz. The quartz-vein and mylonite banding becomes the major structural elements that control the newly formed layering. The evolution of planar structures proceeds in the course of multifold contortion and the subsequent flattening of the vein and mylonite banding until the deformed body reaches a depth where such cyclicity of the structure formation is not maintained by the external *PT* conditions. The dissolution under pressure results in the formation of the latest structures (rough cleavage sutures, stylolites, and planar fibrous veins). Further evolution results in brittle shearing with fault breccia formation. Thus, variation of the *PT* conditions is one of the leading factors of structural rearrangements that determines the progressive deformation in the normal ductile fault zone.

The following important comment should be made with respect to the proposed two-stage model of the Andrianovka suture formation. The interpretation of the west-vergent (reverse-fault) folds in the mylonite banding of the Kamchatka Group remains the most ambiguous. Two versions of a kinematic interpretation of these structures look possible. One of them regards the variably vergent folds with a cluster-type distribution of hinge orientation (Fig. 6) as fragments of the quiver-shaped folds (Fig. 7F) with the nearly horizontal or gently dipping axes formed by a slip along the fold strike. The orientation of the mineral lineation plunging northward at low angles (Fig. 6) is consistent with this interpretation, because it is commonly assumed that the lineation in strike-slip ductile fault zones is oriented in the direction of displacement. The large sheath folds were repeatedly described in metamorphic complexes in many regions, where they have been reconstructed from detailed mapping, observations of the fold hinge vergence, and an analysis of their orientation on spherical diagrams [38, 43, 44]. Small folds of this type often accompany the strike-slip ductile fault zones (in mechanical sense), where they are formed as a result of the fold axis bending [39, 55].

The alternative variant suggests the superimposed character of the west-vergent folds in the rocks of the Kamchatka Group. The deformation of the previously formed mylonite banding may be related to the latest thrusting along the tectonites of the Andrianovka fault. This event is correlated with the post-Eocene thrusting of the tectonic packet (Khosgon and Irunei formations) over the Baraba Formation [34]. Thus, the competitive interpretations suggest either a considerable lateral displacement along the fault or its late remobilization under compression. The available data do not permit us to give preference to one of these versions.

The inferred strike-slip component of the normal fault determines a probable peculiarity of high-grade rock exhumation in Kamchatka. The active role of strike-slip faulting at various stages of metamorphic core evolution has been established for many regions [41, 42, 60]. The elucidation of the role of shear deformation at various stages of tectonic evolution is important for structures with an alternating sense of displacement along the faults. Such a model was proposed in [19] for transpression zones.

A model of tectonic evolution of the Andrianovka suture. In the Late Cretaceous, the Kamchatka margin was an accretionary–collisional region with two types of the juxtaposed complexes: the allochthonous terranes (e.g., the Kvakhona terrane [2, 13, 32]) that were displaced for a long distance and the autochthonous terrigenous sequences formed at the northeastern margin of Eurasia (Fig. 13A). The pre-Campanian terrigenous rocks (lower units of the Khozgon Formation and their analogs) as probable elements of the accretionary wedge and the granites of the Krutogorov Complex emplaced 77 Ma ago served as a protolith of the Kolpakovo Group [48]. The Ozernovskii–Valagin ensimatic arc approached the Kamchatka margin of Eurasia at a distance of a few hundred kilometers about 60 Ma ago [13, 33]. The terrigenous sedimentation in the relict basin between the continental margin and arc lasted until ~55 Ma ago (the upper units of the Khozgon Formation) [48], and these rocks made up a protolith of the Kamchatka Group schists. After 55 Ma ago, the marginal-sea and island-arc sheets were rapidly thrust over the heterogeneous marginal complexes (Fig. 13B). The sheet, which was subsequently transformed into the rocks of the Andrianovka Formation, has been first thrust (Fig. 13B, 1) and then overthrust by the sheets of the Irunei allochthon. The marginal continental sequences were rapidly buried beneath a packet of tectonic sheets (Fig. 13B, 2). The marginal complex and the lower allochthonous sheet were affected by metamorphism. The peak of this process accompanied by anatexis fell 52 Ma [48]. Pegmatites and granites were emplaced at the same time (Fig. 13B, 3). The postcollision collapse of orogen with the exhumation of metamorphic rocks occurred soon after that or simultaneously with granite emplacement (Fig. 13C). The deposition of the lower units of the neoautochthonous Baraba Formation commenced about 50 Ma ago [26]. The metamorphic rocks of the Sredinny Range were involved into erosion somewhat later. The conglomerate of the Baraba Formation may probably be regarded as a fanglomerate formed in the hanging wall of normal faults during the exhumation of metamorphic complexes.

CONCLUSIONS

(1) The main structural suture of the study segment of the Andrianovka zone divides the metapelitic rocks of the Kamchatka Group and the metavolcanics of the Andrianovka Formation.

(2) The early collision deformational event related to the westward overthrusting of marginal-sea and island-arc complexes is recognized in the structural evolution of allochthonous complexes (Andrianovka and Irunei formations).

(3) The postcollision event is related to the opposite normal faulting along the Andrianovka fault zone. These displacements are established in the structure of both the autochthon (Kamchatka Group) and allochthon (Andrianovka Formation). The normal ductile fault zone was developed in rocks of the Kamchatka Group at the autochthon roof.

(4) Heterogeneous autochthonous complexes of the northeastern margin of Eurasia and allochthonous marginal-sea and island-arc complexes, metamorphosed to various degrees, are tectonically juxtaposed in the eastern framework of the Sredinny Massif.

(5) The exhumation of high-grade metamorphic rocks of the Sredinny Range of Kamchatka and the juxtaposition of variably metamorphosed complexes in the present-day structure may be compared with an evolutionary scenario of the Cordilleran-type metamorphic core formation.

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