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## GEOLOGY

# Tectonic Deformation of Granites in the Tien Shan and Transbaikal Regions

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Study of manifestation modes of the 3D mobility of crystalline rocks of the basement is a crucial issue in geology. Interest in this issue arose as early as the 1960s (see works by G.D. Azhgirei, L. King, E.I. Patalakha, and H. Stille). However, investigations in this field virtually ceased in the 1970s–1980s. They were revived in the early 1990s in connection with the publication of new facts and theoretical approaches (see, for example, works by M.G. Leonov), as well as new achievements in mesomechanics (see, for example, [1]) and mechanics of granular media (e.g., [2]). Basement rocks, granites included, are undoubtedly subjected to significant structural transformations. Granites make up cold crystalline protrusions after evolution as magmatic bodies. These positive morphological structures are characterized by specific structural properties, which suggest that their exhumation can be attributed to 3D mobility and rheid (from Greek ρεο meaning "to flow") deformation (see works by L. King, M.G. Leonov, and E.V. Patalakha) and such structures can be considered as crystalline protrusions. Descriptions of granite protrusions are rare in the literature, and manifestation modes of 3D deformations are insufficiently studied, although elucidation of the 3D mobility of rocks has principal significance for understanding tectonics of the consolidated crust, for example, for elucidating mechanisms of the exhumation of abyssal masses. The problem is also of practical importance, since the tectonic structure of granite massifs determines their oil and gas potential [3, 4]. We studied 3D deformations in some granite massifs of the Transbaikal and Tien Shan regions.

*Tugnui horst.* The Tugnui horst is located in the Tungui depression (the western Transbaikal region), which is largely composed of Mesozoic volcanosedimentary sequences, and divides the depression into two basins. The horst is composed of granosyenites and granites of the late Dzheda Complex ($C_2$) with inclusions of gabbroids of the Monostoi Complex ($PZ_1$). The Dzheda Complex also encloses syenite and leucogranite bodies of the Sogotin Complex ($P_2$) and probably basaltic andesites of the Ichetui Formation ($J_{1-2}$). Granites are brecciated, crushed, and disintegrated up to the point of cataclasis of mineral grains (Fig. 1). The rock groundmass lacks internal coherency and is transformed into tectonic breccia (pseudodebris) or sand. The rock is largely transformed into structureless material that encloses oval, lenticular, or subrounded granite blocks with relict primary textures and structures (Figs. 1B, 1C). The blocks are chaotically scattered, but their long axes are similarly oriented (dip angle varies from 40° to 90°) and almost parallel to each other. Transitions from monolithic blocks and lenses to the cataclased matrix are sharp or vague with gradual decrease in the brecciation degree. At the same time, boundaries between the monolithic blocks and the crushed matrix are frequently marked by fractures. The general pattern of foliation and intense fracturing zones and the arrangement of monolithic blocks can be defined as chaotic, reticulate, and lenticular. The granite groundmass contains small chaotically scattered (milonitized, grinded, and chloritized) basic bodies that could represent initially the dike complex intruding the granites. There are also reversed relationships: rounded and spherical granite blocks are enveloped by the groundmass of foliated basic rocks (Fig. 1C). As a whole, the rocks of the Tugnui horst resemble a tectonic granite–basic rock melange. They represent either granitic and basic outliers in the cataclased granite matrix or granite blocks in the foliated and mylonitized basic rock groundmass. Such relationships between rocks are also observed in other areas of the Transbaikal region (Fig. 1E).

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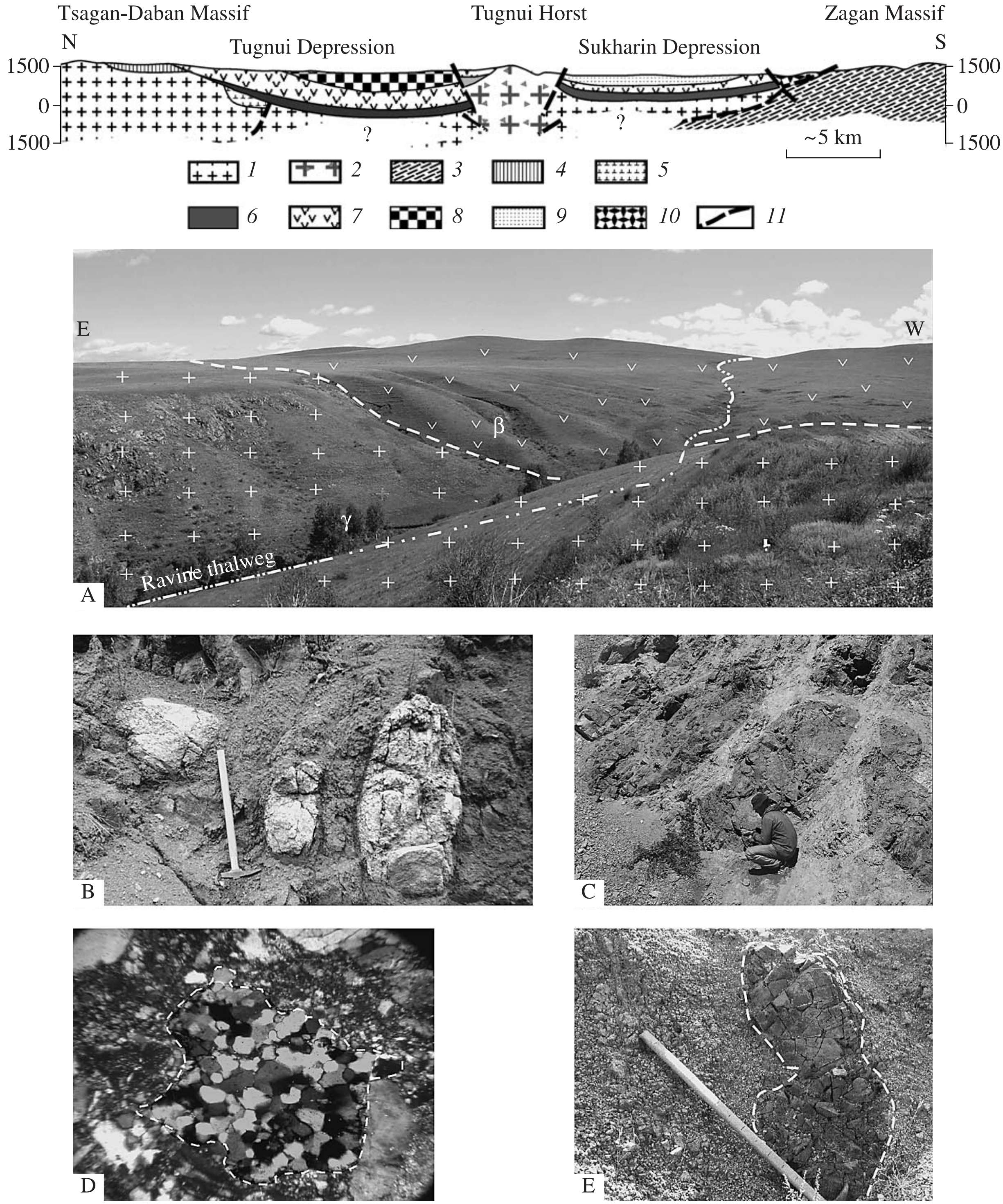

**Fig. 1.** Granites of the Tugnui Horst. The upper figure presents the schematic geological cross section of the Tugnui and Sukharin depressions (based on data by V.D. Ermikov). (*1*) Granites and volcanoplutonic complexes (Paleozoic) of the Tsagan-Daban Uplift; (*2*) cataclastic granites and granosyenites of the Dzhida Complex (probably $C_{2-3?}d$); (*3*) granite-gneisses of the Zagan metamorphic core; (*4*) andesites, basaltic andesites, dacites, trachyrhyolites, and their tuffs (Alentui Formation, $P_2$); (*5*) trachybasalts, trachyandesites, and tuffaceous sedimentary rocks of the Chernyi Yar Formation ($T_{2-3}$); (*6*) conglomerates, gravelstones, and sandstones of the Berezovsk Formation ($J_1$); (*7*) trachyandesites and trachybasalts of the Ichetui Formation ($J_{1-2}$); (*8*) coaliferous (Tugnui Formation, $J_2$) and terrigenous (Galgatai Formation, $J_3$) sediments; (*9*) terrigenous Murtoi and Ubukun formations ($K_1$); (*10*) metaconglomerates of the Kataev Formation (unknown age); (*11*) presumable faults and basement structure and composition. (A) Granite outcrop in the Tugnui horst near the Mukhorshibir Settlement (general view); (B, C) internal texture of granitoids; (D) cataclastic granite (thin section) with granular quartz; (E) cataclastic granite with crushed gabbro block (Tsagan-Khuntei Range).

Granites are more readily subjected to erosion as compared with basalts, which is evident from the sharp bend of the ravine thalweg in the transitional zone between basalts and granites. Nevertheless, both cataclased granites and the surrounding massive and hard basalts ($J_{1-2}$) are exhumed to the same hypsometric level. Moreover, the granites are even observed at a higher level in the apical part of the massif (Fig. 1A). Such a relationship can only be provided by a continuous delivery of granite material from below. This may be explained by the protrusive mechanism related to viscosity inversion. The decrease in viscosity is provided by the 3D cataclasis.

*Mt. Sherlovaya (Chita region).* Mt. Sherlovaya represents a rounded-elongated (diameter ~2.5–3.0 km) massif composed of pinkish gray coarse-grained leucocratic and biotitic granites of the Kukul'bei Complex ($J_3$) and whitish aplitic quartz porphyries ($K_1$) intensely altered by metasomatic processes (Fig. 2). The massif is located among Paleozoic terrigenous–volcanogenic rocks ($D_1$–$C_1$), which are partly overlain by Mesozoic and Cenozoic terrigenous sediments. Like counterparts in the Tugnui horst, granites in this area are disintegrated, brecciated, and cataclased into an incoherent material. The rocks are crushed up to the point of complete loss of coherency and the cataclasis of mineral grains. Quartz porphyries are deformed differently (Figs. 2B, 2C). We can define two types of their structural transformation.

The first type is represented by subparallel fissures developed throughout the entire rock volume (the dominant dip azimuth and angle are 220° and 60°–70°, respectively). These main fissures are crossed by other fissure systems (dip azimuth and angle: 90°, 50°; 270°, 60°; 60°, 30°). The fissures are either rectilinear or slightly undulating. In some places, they merge at acute angles and again diverge. The distance between fissures ranges from ~10–15 to ~30–50 cm. Convergence and intersection of different fissure systems result in the separation of subparallel bodies (elongated lenses, plates, slices,[1] rhombohedral blocks, and duplexes). The plates (slices) are crosscut by a system of transverse subparallel (usually open) fissures that are not filled by any material. The orientation of fissures, their interrelationship, separation of lenticular bodies, and formation of mesoscale duplexes indicate the relative displacement of material nearly parallel to fissures. The regular distribution of subparallel open fissures, which are orthogonal relative to the strike of slices, indicate subvertical extension, the relative value of which amounts to 1–5 cm per meter in some places.

The second type of structural transformation is related to the formation of tectonic breccias and cataclasis. The degree of disintegration is variable, although rocks are practically always brecciated, crushed, and cataclased. They are locally crossed by a system of fissures and characterized by a brecciated texture. Some rock fragments (clasts) are separated from each other, displaced, or rotated relative to their initial position. The brecciated rocks contain abundant hollows, suggesting decompression settings during their formation. Fragments constitute up to 90 vol %. Cement is lacking or some sectors are silicified. The fragments are 1–5 to 30–40 cm in size (rarely, 1 m or more).

Brecciation zones occupy different positions relative to slices. Locally, brecciation involves only separate slices or bodies of different shapes. In this case, the size of fissures, their density, and interrelations are determined by the thickness of slices. Brecciation within slices varies in intensity. Sometimes, large fragments of the slice are preserved, but brecciation can occupy large volumes of rocks. In this case, the slice is apparently dissolved in the general mass of clastic breccia. In some places, disintegration is so strong that a tectonic gouge is formed. The shape of rock fragments is determined by the type of structural transformation. They are isometric acute-angle or rhombohedral fragments. Long axes of rhombohedra are oriented parallel to the dip/rise of slices. The central part of the massif is exposed by a quarry (up to 200 m). Here, one can see that disintegration of rocks is not related to surficial weathering and is inherent to deep levels of the granite massifs as well.

In its apical part, the massif is overlain by a sequence (0–20 m) of coarse-detrital breccia with sandy cement (Fig. 3D). The rock fragments are represented by quartz porphyries similar to the underlying rocks. The fragments are angular, acute-angled, or with smoothed edges and shaped as flattened and elongated parallelepipeds. Their size ranges from 5–10 cm to 1 m (usually 15–30 cm long). The material is practically unsorted with a chaotic distribution or obscure orientation of rock fragments. Vague bedding surfaces are observed locally. Long axes of fragments are locally subhorizontal in apical parts of the dome to slightly inclined (up to 10°–20°) on the slope. The groundmass is represented by fine-grained quartz (presumably derived from the underlying disintegrated quartz porphyries). The fragments constitute up to 90 vol %. One can see rare fragments of gabbroids and fine-grained basalts. Breccias cover slopes over a distance of 100–800 m and then disappear, probably due to erosion and reworking. The fragments in breccias are similar in shape to clasts in the quartz porphyry sequence: small fragments are irregularly shaped and acute-angled, while larger ones represent parallelepipeds or irregular rhombohedrons. Taking into consideration the similarity in the composition and shape of fragments in breccias and outcropping quartz porphyries, as well as their localization in apical parts of the dome, the formation of clastic material is undoubtedly related to tectonic disintegration of quartz porphyries, and the breccias should be identified with tectonic mixtites (according to the classification by M.G. Leonov). Some breccias

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[1] We define such bodies as "slice structures" (hereafter, slices), although this term is applied rarely in the English geological literature).

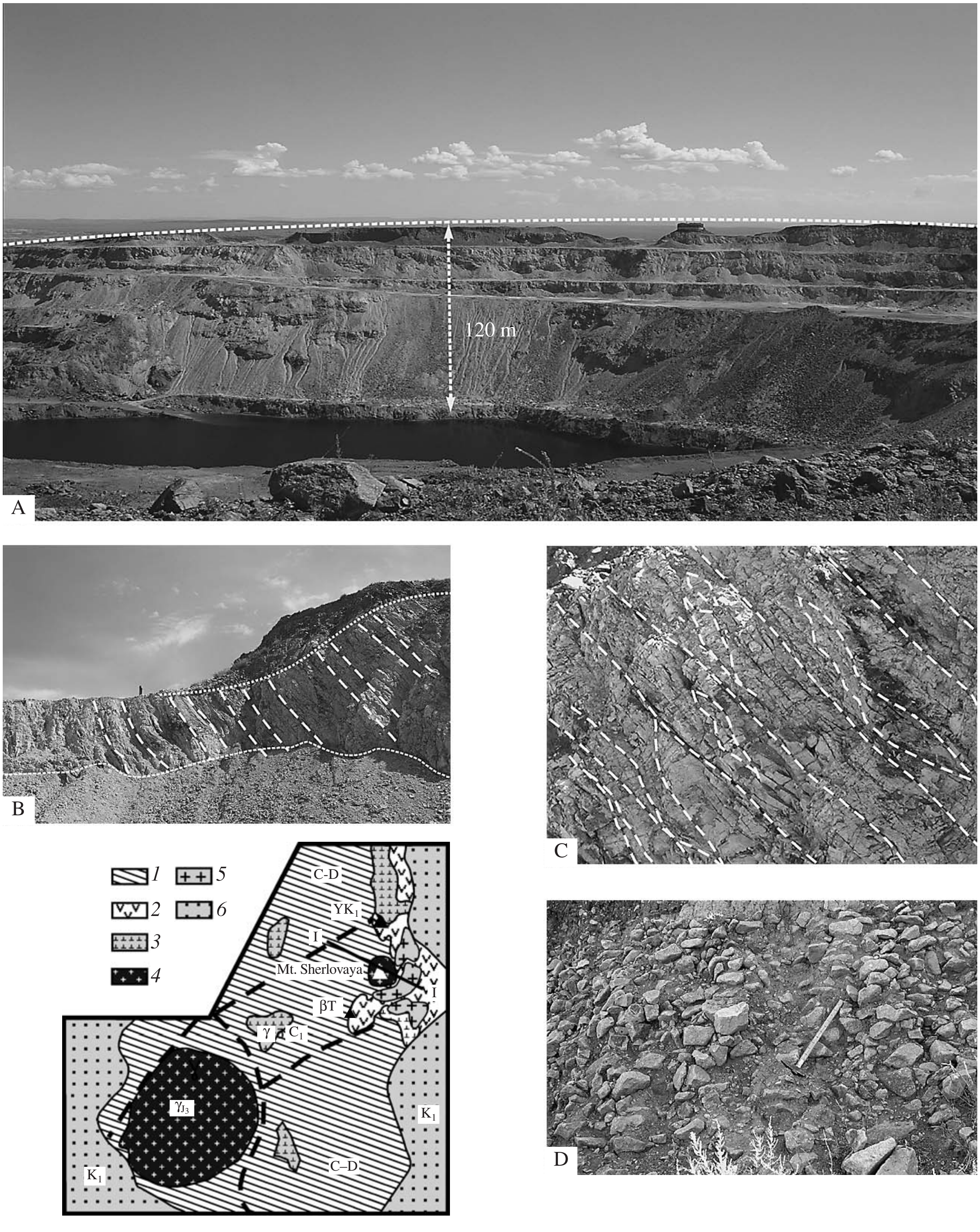

**Fig. 2.** Geological structure of the Mt. Sherlovaya area (Chita region) [5]. The map (below left) presents the schematic geological structure of the area. (*1*) Volcanosedimentary rocks (Middle Paleozoic), (*2*) basaltic andesites, dolerites, gabbrodiabases (Triassic), (*3*) granodiorite porphyries and granites (Lower Carboniferous), (*4*) leucocratic and biotitic granites (Upper Jurassic), (*5*) granite porphyries (Lower Cretaceous), (*6*) terrigenous and coaliferous sediments of intramontane depressions (Lower Cretaceous). (A) General view of Mt. Sherlovaya with distinct dome-shaped surface of the massif; (B, C) internal texture of quartz porphyries; (D) tectonogravitational mixtites constituting the “cap” of the granite massif.

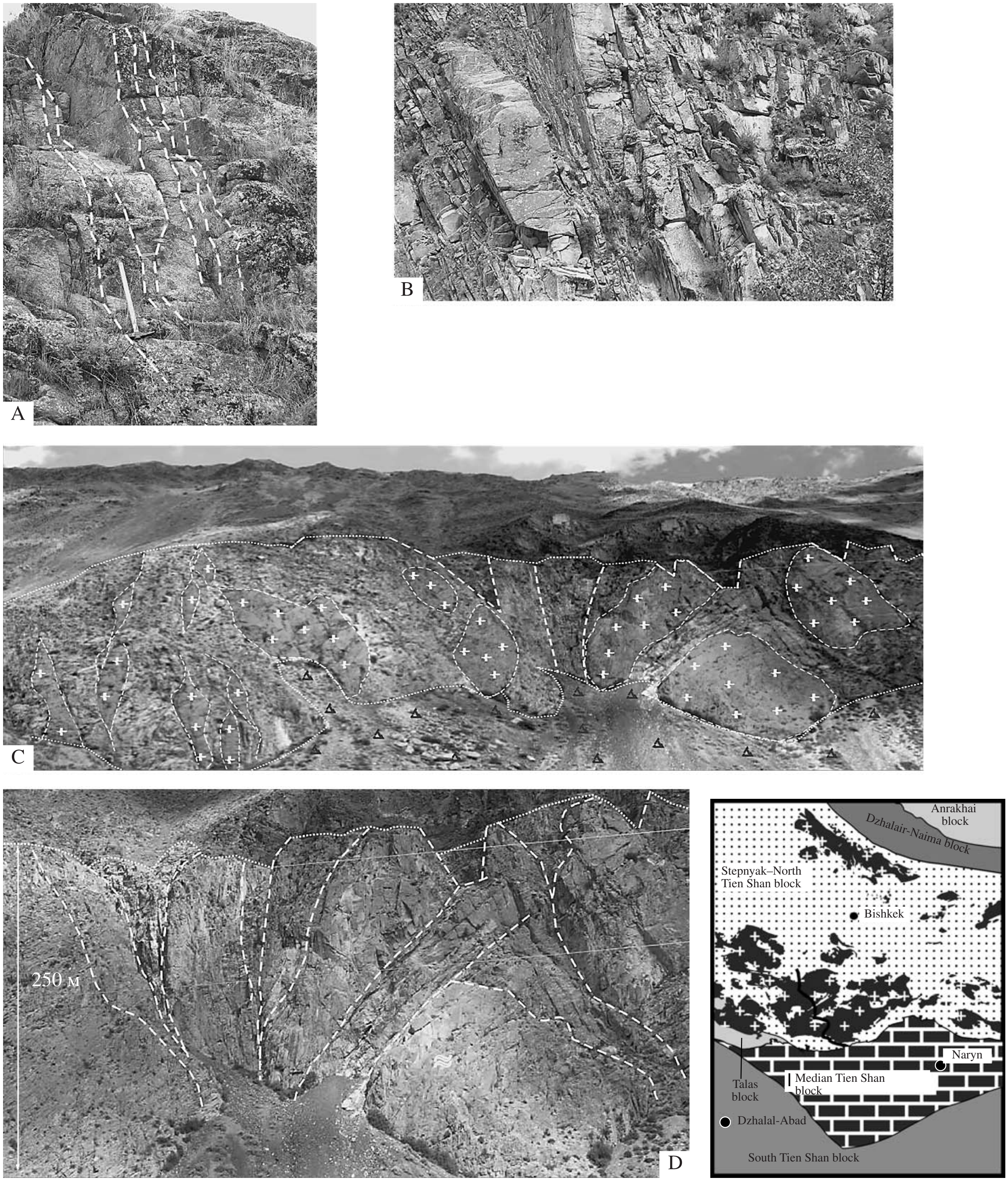

**Fig. 3.** Granitoids of Tien Shan. The map (below right) demonstrates the position of the Susamyr granite massif in the Tien Shan structure. (A, B) "slice" structure of Susamyr granites; (C) general tectonic structure of one of the domes in the Susamyr Massif; (D) fan structure in the central part of the granite dome.

were displaced downslope and subjected to diagenetic transformation typical of eluvium. Therefore, the conglobreccia sequence may partly refer to tectonogravitational mixtites, i.e., detrital rocks with material formed by tectonic processes and displaced by gravity processes.

The Mt. Sherlovaya Massif forms a dome towering above the general topography by 200–250 m. Its surface represents a low-angle convex arc with a dip angle of 5°–10° in its apical part (Fig. 2A). As in the previous situation, the question arises as to how incoherent disintegrated rocks make up distinct positive structures, while compact rocks constitute depressions. The massif is characterized by the following structural features: 3D tectonic disintegration of granites; tectonic structure (lenticular patterns, formation of slices and duplexes); orientation of structural elements; isometric shape and its higher hypsometric position as compared with surrounding stable rocks; tectonic and tectonogravitational mixtites. All these features indicate a loss of integrity and variation of viscosity properties (decrease of viscosity) of granites. Hence, the Mt. Sherlovaya Massif could be a secondary protrusion. Judging from its morphology and the occurrence of a "cap" of virtually incoherent tectonosedimentary conglobreccias, the protrusive mechanism has also been active during the recent stage. This is recorded, for example, in the neighboring Adun-Cholon Massif [5]. Similar relationships are relatively frequent in the Baikal region (see, for example, [6]).

*Susamyr Massif (Northern Tien Shan).* We studied structures in two areas of this granite massif (Pz) (Fig. 3). Granites are crosscut by a system of subparallel vertical or steep (dip angle 60°–80°) fissures (Fig. 3A). They divide the massif into separate extended slices from 10–15 to 30–50 cm thick (1 m or more in some places). The fissures are rectilinear or undulating. They merge at acute angles to diverge again and form reticulate-lenticular patterns. Granites are crosscut by numerous cleavage and foliation (microslide) zones, where the rocks are disintegrated up to the point of cataclasis of mineral grains. The orientation of meso- and microtextures is similar to that of fissures that border macroslices. They enclose lenses and blocks of slightly deformed granites (Fig. 3B). Within individual slices, the rocks are crosscut by transverse open fissures that indicate subvertical extension. Granites also experienced chaotic 3D brecciation and cataclasis over significant areas of the massif. The disintegrated groundmass encloses blocks and slices of less destructed granites (Fig. 3C). The cold rigid stage of the development of granite domes is characterized by the formation of fan-shaped structures. They represent a system of fracture, shear, and foliation zones, which are arranged as an upward widening fan. Downward, all the fractures and fissures merge into a single plane. Against the background of the general convex surface of the granite massif, they form a graben-shaped depression with rocks locally squeezed upward. The single dome-shaped surface of the massif is distorted, and some sectors are displaced vertically. The formation of such structures is related to tectonic subsidence, which compensates for the growth of the dome and elongation of its surface (extensions regime). Their shape resembles a typical flower or palm tree. Such structures are formed in transpression settings [7, 8]. In our case, the structure is related to extension; i.e., we are dealing with the phenomenon of convergence of features. We also discovered the fan-shaped structures in other granite massifs, e.g., in granosyenites of the Pavlovsk arch (Voronezh anticline), while 3D catalysis is widespread in granite massifs of different regions (see references above).

Thus, we can make the following inferences.

(1) Granite massifs underwent 3D transformation (macro-, meso-, and microscale disintegration, brecciation, and cataclasis of mineral grains) after their formation as intrusive bodies.

(2) In addition to well-known cleavage and brecciation, other types of tectonic reworking (slice and fan structures), which are less reported in the literature, have been established.

(3) The 3D disintegration represents relaxation of the stressed state in rocks, resulting in the loss of their coherency and development of the granular texture.

According to [9, 10], granular media are characterized by reduction of the effective viscosity of rocks; reduction of the effective friction angle, which is interpreted as superplasticity; dilatational rearrangement of rocks (expansion); ability for cataclastic 3D flow; and increase in the shear velocity depending on the friability degree of the material. These properties promote the development of a specific plastic state at discrete sliding surfaces that separate undeformed rocks, resulting in the development of numerous sliding surfaces (cleavage, foliation, and slices) and nearly layered heterogeneity of the tectonic flow. All these factors stimulate the 3D mobility of rock masses mainly related to the mechanism of cataclastic flow, which produce structures of the protrusion type. We believe that the granite massifs under consideration belong to this type. Thus, protrusion represents one of the mechanisms responsible for exhumation of rocks in the crystalline basement.

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