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CENOZOIC HISTORY OF THE CHUYA DEPRESSION (*Gorny Altai*): STRUCTURE AND GEODYNAMICS

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Detailed geological and geomorphological mapping of the transition zones from the Chuya depression to the surrounding mountains in the north (Kurai Range) and in the west (Chagan-Uzun block) allowed us to infer that both boundaries changed their evolution dynamics through time. The Chuya depression was initiated as a sedimentary basin bounded by uplifts in the Middle Miocene-Early Pleistocene and was then, apparently, a graben formed jointly with the neighboring Chagan-Uzun horst. The present-day structure of the depression has been produced by intense compression. In the latest Early Pliocene, the depression developed as a ramp basin, and in Late Pliocene and Quaternary time its northern boundary was rejuvenated by thrusting and transpression faulting. The Cenozoic history of the topography in southeastern Gorny Altai illustrates gradual progress of the deformation related to the India-Eurasia collision. As a result of this collision, since the Late Pliocene, the Altai orogen became separated from the Tuva-Mongolian microplate along a boundary following Late Paleozoic regional faults. The main regularities of the structure and evolution of the collisional boundary became evident owing to a special study, the results of which can be used in a description of similar neotectonic boundaries in Inner Asia.

Morphotectonics, neotectonic intracontinental deformation, orogeny, reverse faults, thrusts, Chuya depression, Gorny Altai

INTRODUCTION

The Chuya depression is part of the Kurai-Chuya system of Alpine intermontane structures formed in the second half of the Cenozoic in place of an Early Paleogene peneplain. The main recent structural features of the territory are fault boundaries between depressions and their mountainous borders to the northeast and southwest. In the northeast, a system of depressions is bounded by the Kurai Range broken by young NW-striking transpression thrusts into three blocks: Kubadra, Bashkaus, and Kurai [1]. In the south, the depressions are bordered by reverse fault scarps of the Shavly, North Chuya, and South Chuya Ranges separated from each other by strike-slip faults. The depressions are filled with a 1200 m thick complex sequence of Paleogene, Neogene, and Pleistocene continental deposits [2].

The Late Cenozoic tectonic activity resulted in the formation of the Kurai Range, folding and uplifting of Cenozoic deposits and their exhumation on the periphery of the Chuya depression. The Cenozoic history of the fill of the depression was studied by many authors [3–9], and the results were used for local and regional reconstructions.

During the work on the INTAS project 93-134 "Continetal Rift Tectonics and Evolution of Sedimentary Basins", the geodynamics and the evolution of the Chuya-Kurai depression were analyzed in the context of the structural position of Altai as part of the Central Asian mountain belt. As a result, it was concluded that Altai formed under compression related to the Eocene collision of India and Eurasia [10–13]. The evolution of the Chuya depression received a refined interpretation owing to new evidence, including data of medium-scale satellite imagery and large-scale aerial photographs, lithological and structural studies of Cenozoic deposition and faulting on the northern and western boundaries of the depression, and detailed geological and geomorphological investigation of several key sites in its western part.

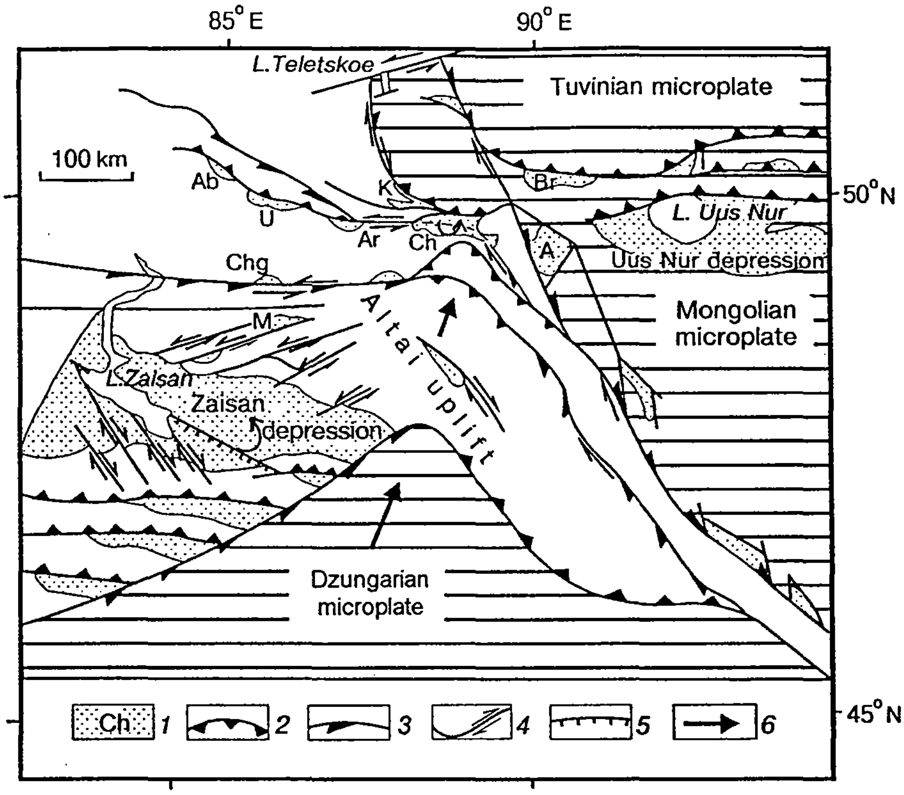

Fig. 1. Neotectonic framework of Altai. *1* **— Cenozoic deposits,** *2* **— thrusts,** *3* **— main strike-slip faults,** *4* **— boundaries of blocks and directions of relative displacement,** *5* **— normal faults,** *6* **— directions of principal compression. Depressions: Ab — Abai, U — Uimon, Ar — Argut, K — Kurai, Ch — Chuya, Br — Barlyk, I — Inital, A — Achitnur, Chg — Chingist, M — Markokol.**

In this paper we report new geological and geomorphological results, based on stratigraphy, paleomagnetism, structural position, and environments of Cenozoic deposits, as well as kinematics and dynamics of Cenozoic faulting. On the basis of these data we model the Cenozoic evolution of southeastern Gorny Altai in terms of progressive compression induced by India-Eurasia collision and SW-NE propagation of deformations that reactivated Late Paleozoic regional faults.

The neotectonics of southeastern Altai is related to the structure and geodynamic evolution of the junction zone between the Dzungarian and Tuva-Mongolia microplates [14] which repeatedly came into interaction and either thrust over one another or converged or rotated under regional compression. Mongolian Altai and Gobi Altai, which are the southeastern extremity of the Altai orogenic area at its boundary with the Dzungarian microplate, are typical examples of plate boundaries and resulting blocky structure of this kind [15–17]. This suggests a single mechanism for the formation of Altai by the Cenozoic tectonic activity in the context of collision of microplates and blocks (Fig. 1).

NEOTECTONICS OF THE NORTHERN AND WESTERN FLANKS OF THE CHUYA DEPRESSION

Geological and morphological studies of the transition zones from the Chuya depression to the Kurai Range (in the north) and the Chagaun-Uzun massif (in the west) showed that the two boundaries are markedly different. The northern boundary is delineated by a system of WE-striking oblique thrusts shown up as fault scarps in the modern topography (Fig. 2). The line of nearly parallel scarps is broken by S-N faults along river valleys. Most of the Cenozoic faults, easily interpreted as scarps in aerial photographs and satellite images (Fig. 3), are parallel to the range axis. There are also flat remnants of the pre-Cenozoic topography preserved at various altitudes on the main divide and on range spurs. These flat areas are often misinterpreted as a relict Late Cretaceous-Early Paleogene peneplain. However, the lower elevated flat surfaces belonged to the

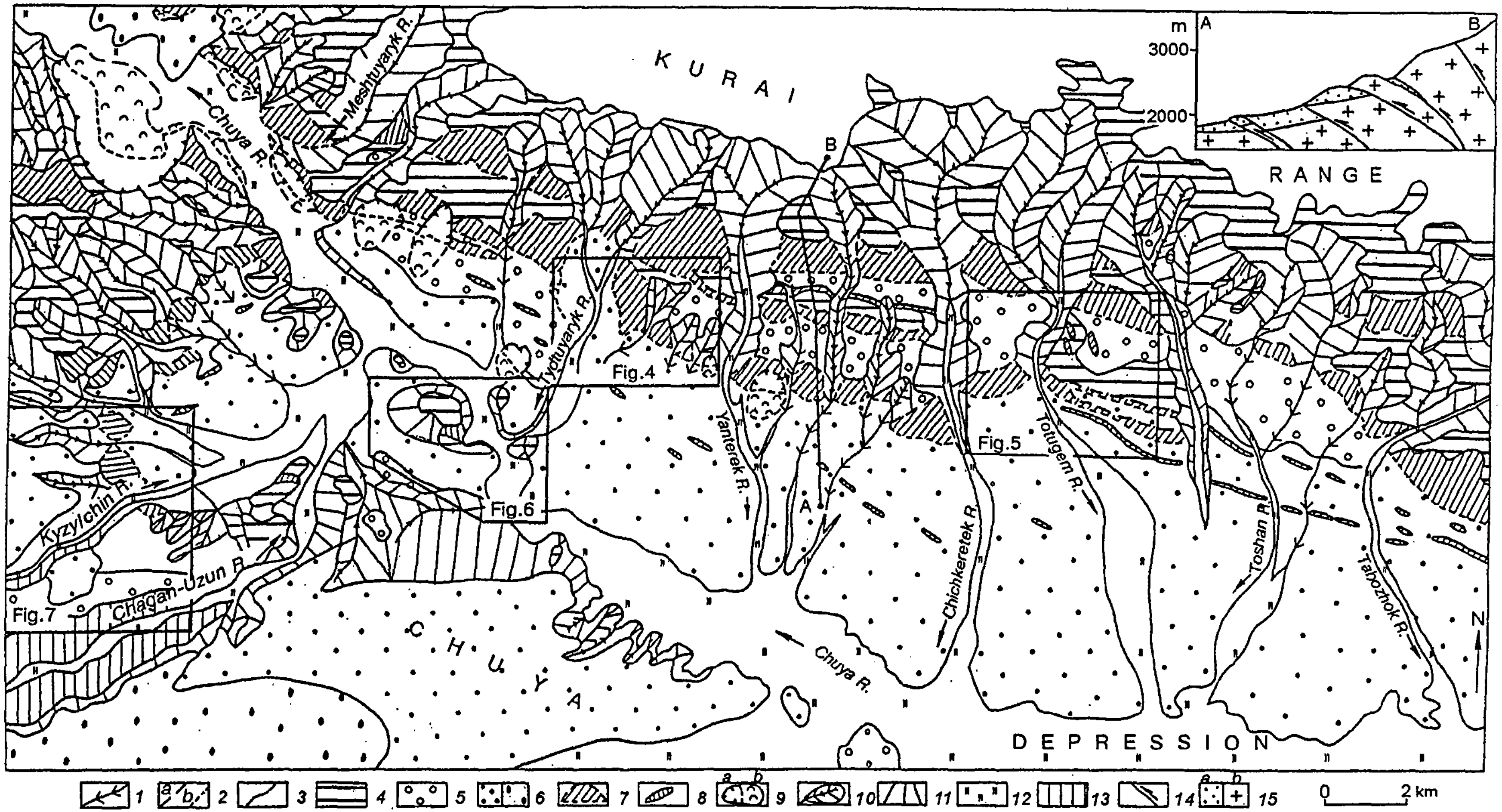

Fig. 2. Geomorphologic framework of the southern slope of the Kurai Range and northwestern Chuya depression (compiled by I. S. Novikov based on original geomorphological map, scale 1:50,000). *1–3* — geomorphic boundaries: *1* — thalweg, *2* — edges (*a*) and junction lines (*b*), *3* — edges, ranges, and junction lines of uncertain division; *4–13* — elementary geomorphic surfaces: *4* — fragments of flat pre-orogenic topography, *5* — fragments of pre-Quaternary piedmont debris mantles involved in uplift, *6* — Quaternary piedmont debris mantles (*a*) and moraine fields (*b*), *7* — fault scarps, *8* — out-of-scale small fault scarps within piedmont debris mantles, *9* — seismic rockfalls: detachment walls (*a*) and bodies (*b*). *10* — erosion land forms, *11* — erosion slopes, *12* — present flood plains and terraces, *13* — lake plain surface. Section A-B: *14* — faults, *15* — Cenozoic (*a*) and Paleozoic (*b*) rocks.

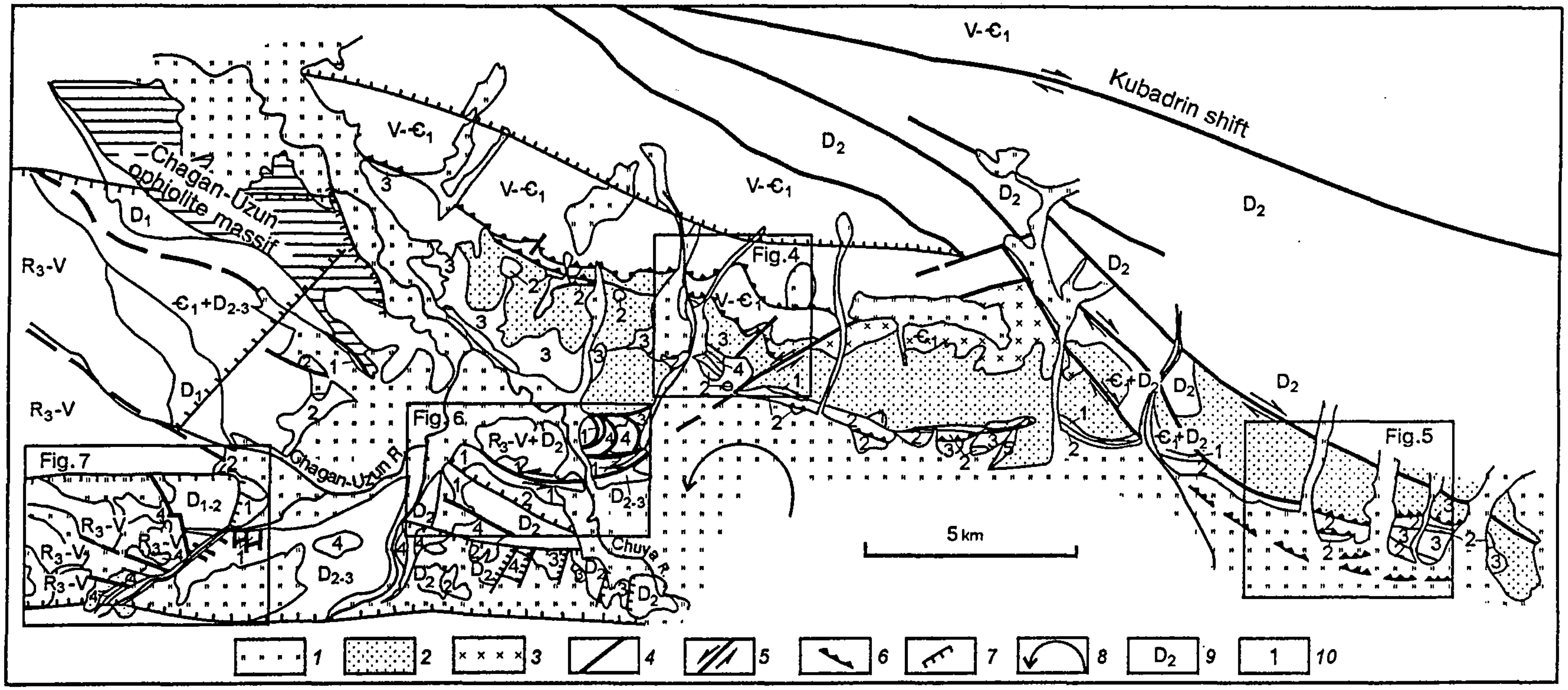

Fig. 3. Neotectonic framework of southeastern Gorny Altai. *1* — Quaternary deposits (Q_{2-3}), *2* — Terek-Bashkaus Formation (N_2^2-Q_1), *3* — Tadzhilin massif, *4* — faults (PZ), *5* — strike-slip faults (Q_1), *6* — thrusts (Q_1), *7* — reverse faults (Q_1), *8* — rotation of southern Chuya depression in the latest Miocene—earliest Pliocene, from paleomagnetic data, *9* — pre-Cenozoic rocks, *10* — localization of sites. Numerals stand for: 1 — Karachum Formation (P_3^{2-3}), 2 — Kosh-Agach Formation ($P_3N_1^{1-2}$), 3 — Tueryk Formation (N_1^{2-3}), 4 — Kyzyl-Gir Formation (N_1^3), 5 — Beken Formation (N_2^1).

depression periphery and were uplifted to the present level only at the final stage of orogeny, as indicated by the presence of overlapping Late Pliocene and Early Quaternary brown proluvial trains.

The transpressional geometry of movements along the southern fault borders of the Kurai Range is evident in exposures in river valleys that drain the range slope. There Paleozoic rocks are thrust over and strongly deform the Cenozoic fill of the depression [4–6, 18], and the thrust is expressed in the surface topography as a fault scarp [19]. The southern range slope now looks like an enormous staircase whose steps, bounded with active Cenozoic faults, are either relics of the former continuous planation surface or the depression's periphery, which were successively involved in uplifting.

In the west, the depression is bounded by the Chagan-Uzun horst. The flat top of the latter is covered with undeformed Cenozoic sediments (Tueryk Formation) [6]; therefore, in pre-Kyzyl-Gir time, it was hypsometrically equal to the basement of the Kurai-Chuya depression. Since the Late Neogene, the depression has been bordered by the Kurai Range on the north and by the North Chuya and South Chuya Ranges (which then made a single structure), and Sailyugem dome, on the south. Only later, during strike-slip faulting in the south, part of the depression bottom was uplifted to produce the Chagan-Uzun horst, which divided the depression into two structures.

Recent field studies showed good agreement of the geological and geomorphological results. Studies of all accessible exposures revealed young surface ruptures at the base of fault scarps (Fig. 1), which are either Cenozoic/Paleozoic tectonic boundaries or young faults within Paleozoic deposits associated with travertine lenses [20] and mylonitization.

STRATIGRAPHY AND DEPOSTIONAL FRAMEWORK

The existing ambiguity of division and correlation of the Cenozoic deposits of the region [4–9] made us revise their stratigraphy. In the 1960s, the structure, origin, stratigraphy, and paleontology of the Cenozoic fill of the Chuya depression and its evolution were studied by Lungersgauzen, Rakovets [4, 21, 22], and Devyatkin [6, 23]. The result was a detailed stratigraphic scheme, which was revised in the 1970s after more evidence had been obtained [7–9, 24–26], necessitating a new interpretation of the neotectonic history of Gorny Altai [9]. Recently, several key sections have been studied in more detail [27, 28] in order to trace the boundaries between various geological bodies, which will be used in further stratigraphic, paleontological, and paleomagnetic correlations.

The Cenozoic fill of the Chuya depression lies over the eroded surfaces of Paleozoic marine and continental deposits and the Paleogene weathering crust. *The Karachum Formation* at the base of the section consists of two facies. Subaerial brown-red kaolin clays, totaling a thickness of 40 m, mantle gently dipping slopes and include up to 1.5 m thick lenses and interbeds of poorly sorted clastics and subtropical paleosols [29]. In the lower part of the sequence, they grade into dark-gray montmorillonite clays deposited in a shallow-water limnic basin. The clays interlay with light-gray silts and fine-grained sands with siderite nodules. Some authors interpret them as a separate formation – *Taldydyurgun* [9, 24, 26]. The lower part of the Karachum Formation is in places nearly vertical, whereas its upper part is nearly horizontal. According to its structure, texture, color, lithology, bedding, and depositional environment, the formation is equivalent to the Early Oligocene Shand-Hol and Beger formations in Mongolia [30] and must be their stratigraphic analog.

The 200–250 m thick *Kosh-Agach Formation* transgressively, without notable gaps, overlies the subaerial and lacustrine slope deposits of the Karachum Formation and is found in the Chuya, Kurai, Dzhulukul, and Samakha depressions. It is mainly composed of brownish, greenish, and dark-gray clays, silts and fine-grained sands with numerous lignite interbeds and lenses, which tend to the periphery of the depression and are absent from its central part, and scarce siderite nodules. Kosh-Agach deposition apparently occurred in the Early-Middle Miocene (according to paleobotanical data), in a swampy limnic basin. The existence of shallow-water lakes and marshes surrounded by sedge and marsh cypress is attested by palynology [6].

The 138 m thick *Tueryk Formation* occurs within the Chuya and Kurai depressions and consists of dense greenish-bluish-gray and brownish-light-gray fine-grained carbonate silts and marls that include limestone lenses. The presence of dispersed lignite in the lower section indicates that Tueryk deposition inherited the Kosh-Agach one, which is supported by paleobotanical data showing the inheritance in vegetation [6]. Clastic material – sand, pebble, conglomerate – is found off the depression and at the base of the formation. Angular fragments of Paleozoic rocks are found in sections adjacent to the Kurai Range. Various organic remnants – imprints of leaves, fruits, seeds, spores, and pollen, mollusk and ostracod shells, fish skeletons, and rare bones of small mammals indicate a Middle-Late Miocene age of deposition. The mode of occurrence and the structure of the formation suggest its origin in a large limnic basin, and the presence of coarse-grained interbeds with angular fragments at the depression's periphery indicates the inception of the Kurai Range.

The 50 m thick *Kyzyl-Gir Formation* is composed of yellow-brown and gray coarse-grained sands, gravel, and rock debris with interbeds of light-gray and bluish thinly laminated clays and silts. Layers of stromatolite limestone found at various depths locally overlay Paleozoic rocks. The coarse-grained facies contain iron hydroxides. The deposits are abundant in remnants of ostracods, fishes, mammals, plants, and fresh-water mollusks. Fresh-water fauna is represented by more than 50 species. The mollusk fauna characteristically includes numerous series of parental endemic species. This made Devyatkin et al. [31] deduce that the formation was deposited in an enormous long-living deep lake. Similar assemblages of fresh-water mollusks were reported for Lake Baikal [32] and other long-living basins with advanced endemism of malacofauna, such as Ohrid, Tanganyika, Biwa, and Titicaca [33]. Proceeding from great diversity of thermophilic species of fresh-water fauna, we suggest a deposition in a low-elevated (up to 1000 m asl.) mountain lake. An age constraint – Late Miocene-Early Pliocene [27] – is inferred from remnants of hipparion reported in [6].

The relationships between the Tueryk and Kyzyl-Gir formations are disputable. Special attention in this study was focused on the Krasnaya Gorka site, where Erofeev [25] and, later, Bogachkin, Rosenberg, and Tsekhovsky [7–9] distinguished the Beken Formation and the Ortolyk Formation, consisting of deposits that were formerly assigned to the upper part of the Kyzyl-Gir Formation. As far as the Kyzyl-Gir Formation underlies the Tueryk Formation, this section was interpreted in [7–9, 25] as a facies variety of the lower part of the Tueryk Formation. Our field studies showed that the contact between the Kyzyl-Gir Formation and the clay sediments above, which were formerly assigned to the Tueryk Formation, is not stratigraphic but tectonic, made by a strike-slip fault. In this site, the Kyzyl-Gir Formation is overlain by green-gray argillaceous silt and fine-grained sand of the Beken Formation. The Ortolyk Formation was recognized on the Chuya left bank 3 km south of Krasnaya Gorka. Although according to [8, 9] the 12 m thick Kyzyl-Gir Formation is overlain by Tueryk sediments there, the green-gray silts can hardly be related to the Tueryk Formation because of the lack of carbonate sedimentation and the presence of stromatolites and fresh-water mollusks.

So, we assign the green-gray silt and fine-grained sand with lenses of poorly-sorted coarse material to the Beken Formation deposited during period of tectonic activity. The 100–200 m thick Beken Formation consists of Early Pliocene lacustrine and lacustrine-proluvial sediments [27], which give way to proluvial and slope coarse-clastic deposits close to the range [9, 23].

Subaerial coarse-clastic molasse fill of the Chuya depression was divided into two formations – red-brown *Terek* Formation and brown-yellow *Bashkaus* Formation deposited in different climates. The Bashkaus Formation, up to 200–250 m thick within the depression, is composed of brown pebbles, boulders, conglomerates, and rock debris with thin layers and lenses of sand, silt, and clay. Both formations contain a lot of coarse-clastic material of seasonal streams. The Terek-Bashkaus sequence accounts for the main stage of orogeny in southeastern Altai and formation of the present topography. Terek rocks appear to result from continental subaerial deposition which occurred in South Siberia 3–2.6 Ma ago, i.e., in the first half of the Late Pliocene [34]. This stage is recorded in red-brown subaerial deposits of the Vtorushkin Formation in Rudny Altai and the Chikoi Formation in West Transbaikalia and northern Mongolia. Bashkaus deposition probably started about 2.6 Ma ago.

Thus, the following formations were distinguished as a result of stratigraphic studies of the Cenozoic fill of the Chuya depression: Karachum (Lower Oligocene), Kosh-Agach (Lower-Middle Miocene), Tueryk (Middle-Upper Miocene), Kyzyl-Gir (Upper-Early Pliocene), Beken (Early Pliocene), Terek (Upper Pliocene), and Bashkaus (Upper Pliocene-Lower Pleistocene). Their depositional environments show that a stable plateau experienced an influence of orogenic movements.

GEOLOGY OF JUNCTION ZONES BETWEEN CHUYA DEPRESSION AND ITS MOUNTAIN BORDERS

Transitions from the depression to the bordering mountains are of two types: (1) a system of reverse faults, thrusts, and strike-slip faults on the boundary with the Kurai Range. These structures were studied along the transverse Tueryk and Totugem river valleys (Figs. 4, 5); (2) a complicated mosaic-block zone on the boundary with the Chagan-Uzun horst, which was studied in the Krasnaya Gorka site and in the Kyzylcha river valley (Figs 6, 7).

The Tueryk site occurs in the Tueryk river valley along the western slope of the Kurai Range and the adjacent part of the Chuya depression. The geological section was studied earlier [4, 6]. Neogene deposits form an antifold with its northern wall exposed on the left side of the Tueryk, where the Kurai Range meets

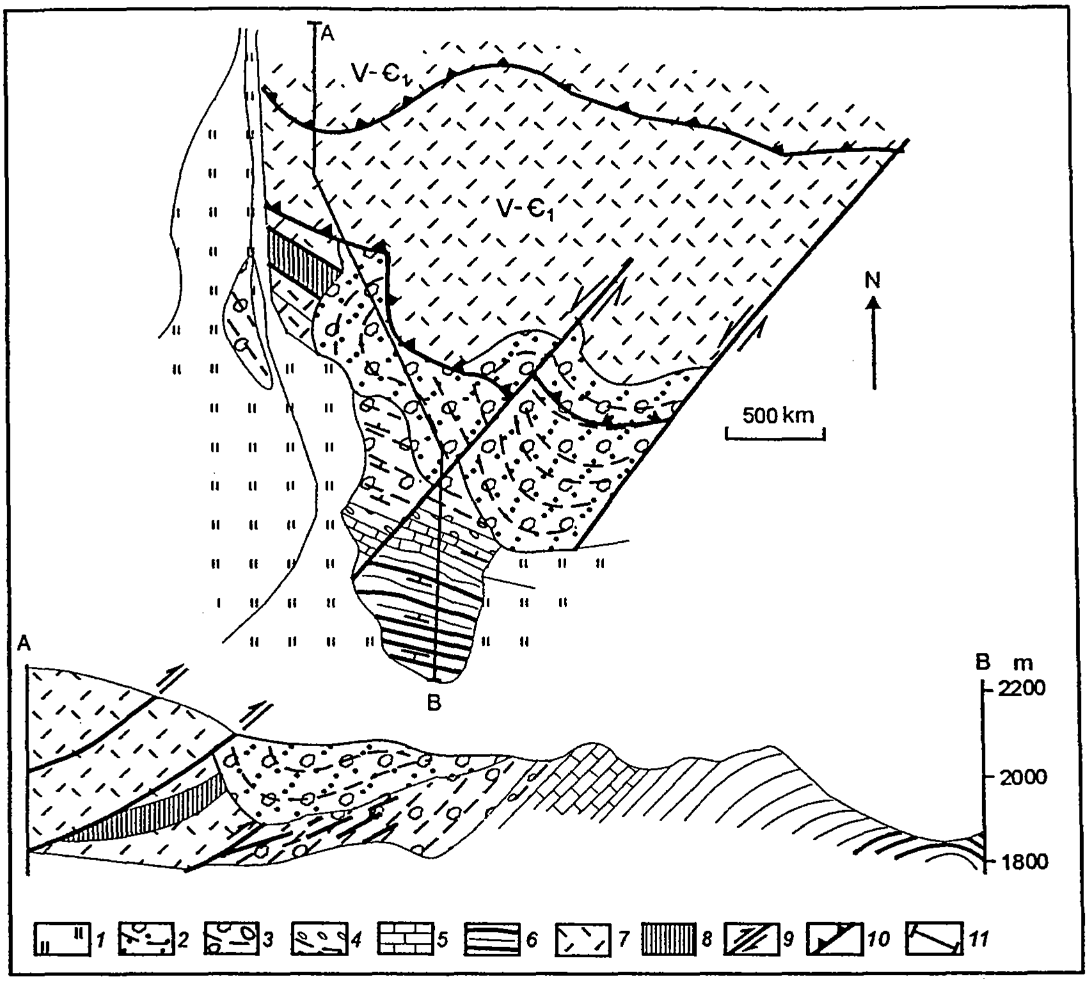

Fig. 4. Geological framework of the Tueryk site (for location see Figs. 2 and 3). *1* **— terraces of the Tueryk Riv. (Q_{2-4}). Formations:** *2* **— Terek and Bashkaus, undivided (N_2^2-Q_1),** *3* **— Beken (N_2^2),** *4* **— Kyzyl-Gir ($N_1^3N_2^1$),** *5* **— Tueryk (N_1^{2-3}),** *6* **— Kosh-Agach (N_1^{1-2}).** *7* **— V-Є$_1$ Vendian-Early Cambrian volcanosedimentary rocks,** *8* **— Paleozoic melange,** *9* **— strike-slip faults,** *10* **— thrusts,** *11* **— section line.**

the depression (Fig. 4). The core of the fold is composed of Kosh-Agach deposits, which are interbedding light-gray and gray-brown clays, sands, and siltstones. Interbeds and lenses of brown coal dipping at 0 to 30° are found in the lower part of the visible section. To the north, at the contact with the Tueryk Formation, the Kosh-Agach strata dip at 45–55°. The transition between the two formations is gradual. The Tueryk Formation consists of 70 m thick blue-gray carbonate clays and mudstones; it is overlain without any visible breaks and unconformities by brown-yellow pebbles of the Kyzyl-Gir Formation. Upsection the pebble beds are replaced by gravel and marl-bearing clay. The thickness of the Kyzyl-Gir Formation in this part of the depression is 10–12 m.

The Kyzyl-Gir clays are overlain by poorly sorted and poorly rounded sedimentary breccia of the Beken Formation, which is replaced up the section by rhythmically bedded molasse. The thickness of individual rhythms (cycles) ranges from 0.n m to several meters. Within each cycle, the basal boulder conglomerates give way up the section to pebble and then gravel beds. Each cycle is topped with sandstones with bedding-parallel plates of Paleozoic rocks or red fine-grained sandstones and clays. The long axes of pebbles and boulders are, as a rule, bedding-parallel as well. The clastic material corresponds to Vendian-Lower Cambrian volcanosedimentary and igneous rocks of the Balkhash Formation, Lower Cambrian terrigenous-carbonate rocks of the Kurai Formation, and Devonian gray and red-color sediments. The Paleozoic rocks are widely distributed

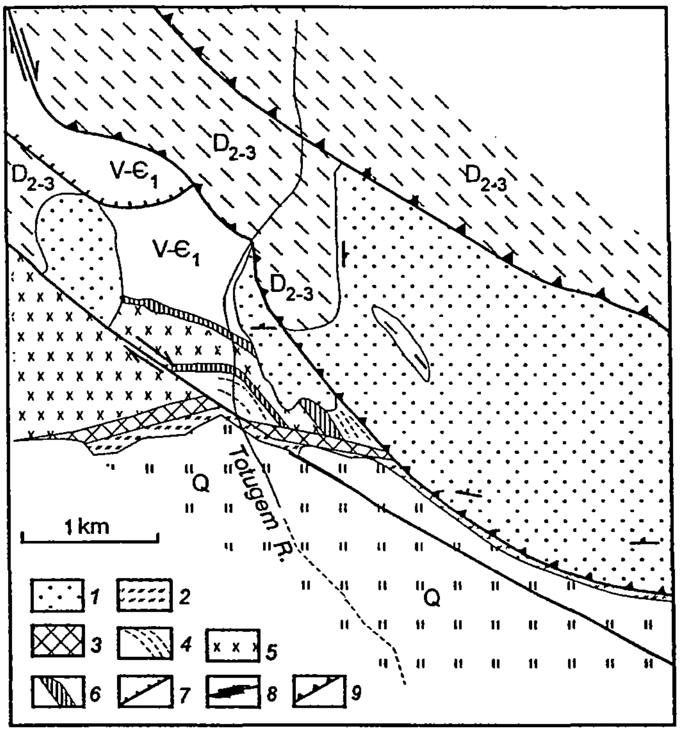

Fig. 5. Geological framework of the Totugem site (for location see Figs. 2 and 3). Formations: *1* — Terek and Bashkaus, undivided (N_2^2-Q_1), *2* — Kosh-Agach (N_1^{1-2}), *3* — Karachum (P_2^{2-3}), *4* — Middle-Late Devonian motley rocks (D_{2-3}), *5* — Early-Middle Cambrian gabbro-trondjemites of the Tadzhilin complex, *6* — melange, *7* — Late Paleozoic faults, *8* — strike-slip faults, *9* — thrusts.

only on the Kurai Range, and the parental Devonian red-color rocks are restricted to the northern slope. There the thickness of the Beken Formation is less than 120 m.

The beds of the Beken Formation dip toward the Paleozoic rocks of the Kurai Range at 40–60°. The bedding is broken by low-magnitude thrusts forming a system of planes which repeat every several tens of centimeters or 1–2 meters; dip azimuth and angle range from 20 to 340° and from 10 to 40°, respectively. Deformations are typical only of the Beken Formation. No signs of deformation have been found in the overlying Terek and Bashkaus Formations. The deformations predate the deposition of the Upper Pliocene sequence and record the initial stage of thrusting of the Kurai Paleozoic rocks over the Paleogene-Neogene fill of the Chuya depression. Older thrusts overlapped by the Terek-Bashkaus sediments are recorded in the Paleozoic rocks at the base of the Kurai Range. There a tectonic breccia is found within Balkhash volcanics. Angular volcanic fragments are cemented with fine-clastic matrix cut by veinlets of limonite and siderite. The Terek-Bashkaus sequence is composed of poorly sorted boulders, pebbles, and gravel with lenses and interbeds of brown sand, silt, and clay. No Devonian red-color rocks have been found among the clastics. The sediments form a downfold at the foothills of the Kurai Range. A boulder layer of variable thickness (up to 2–3 m) occurs at the bottom of the Bashkaus Formation. The contact between the basal boulder horizon and the underlying Beken Formation shows a clear angular unconformity in the vicinity of the range, which smoothes out southward, i.e., toward the Chuya depression.

Paleozoic rocks are overlain by the Bashkaus deposits in the northern wall of the downfold dipping southward at 60–70°. Up the slope this wall is overthrust by the Paleozoic rocks of the Kurai Range. The thrust is clearly shown up in the topography as a long fault scarp marking the boundary between the Kurai Range and the Chuya depression.

The Totugem site is located on the boundary between the Kurai and Chuya depressions (Fig. 5). The study of this site is especially important in terms of the evolution of sedimentation in the Chuya depression

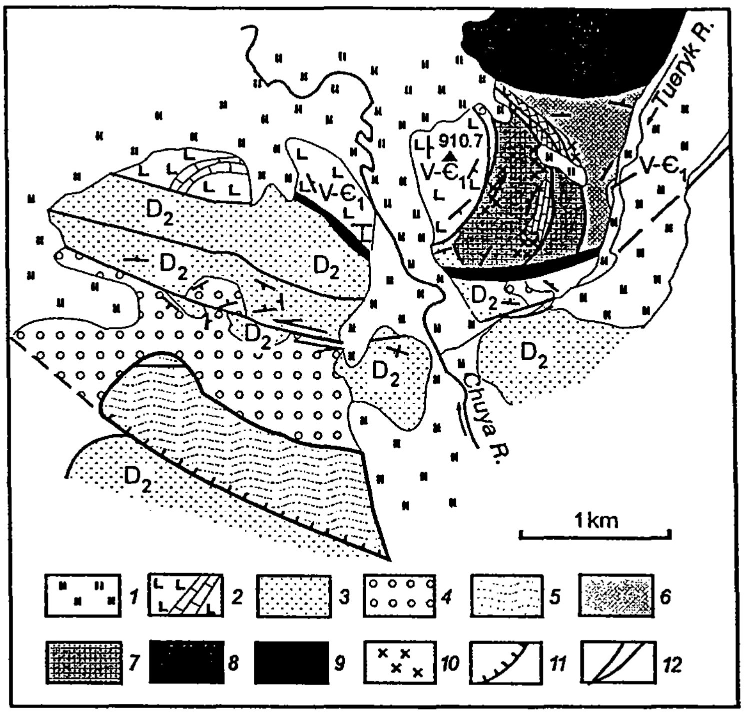

Fig. 6. Geological framework of the Krasnaya Gorka site (location see in Figs. 2 and 3). *1* **— terrace deposits (Q_{2-4}),** *2* **— Vendian-Early Cambrian lavas and limestones (V-Є$_1$),** *3* **— red-color rocks (D_2). Formations:** *4* **— Karachum (P_3^{2-3}),** *5* **— Kosh-Agach (N_1^{1-2}),** *6* **— Tueryk (N_1^{2-3}),** *7* **— Kyzyl-Gir ($N_1^3N_2^1$),** *8* **— Bashkaus (N_2^2-Q_1),** *9* **— serpentinite melange,** *10* **— stromatolites of the Kyzyl-Gir Formation,** *11* **— normal faults,** *12* **— strike-slip faults.**

and orogenic processes in the adjacent mountains. In the Totugem site, the Karachum slope deposits are transgressively overlain by the Kosh-Agach lacustrine deposits, both formations taking an overturned position.

Below is the succession of sediments on the left side of the Totugem valley (from south to north):

1. *The Kosh-Agach Formation* consisting of brown and gray coals up to several tens of centimeters thick, gray and greenish-gray clays, and sandstone with scarce fragments of poorly rounded Vendian-Cambrian and Devonian rocks. The beds dip northward at 70–90°; apparent thickness is 30–40 m. Erosion hollows denude a zone of strike-slip faults inside the sediments. Microstructural evidence indicates a dextral slip.

2. *Transitional member* consisting of interbedding brown coals, gray sandstone, red and yellow clays, sandstone, and gravel up to 3–5 m thick.

3. *The Karachum Formation* composed of interbedding kaolin clays (red, claret, gray, yellow), sandstone, and gravel. There are scarce angular fragments of Paleozoic rocks, such as Middle-Upper Devonian dark-gray limestone, sandstone, and siltstone and Early Paleozoic igneous rocks of the Tadzhilin complex and the Balkhash Formation. Large flat blocks of Paleozoic rocks up to 2–3 m thick and several tens of meters long, which obviously crept down the slope, are locally found in the sediments. Both Cenozoic sediments and Paleozoic blocks dip northward at 70–90°.

4. A *2–3 m thick layer* consisting of coarse-clastic breccia, gravelstone, and sandstone set in reddish-brown clay matrix. The composition of the fragments is the same as that of Paleozoic rocks up the slope. The uneven boundary between the sediments and Paleozoic rocks shows, in places, pockets of gravelstone and conglomerate. Within the horizon, the boulder conglomerate gives way to gravel and then to sandstone up the section. The beds dip northward at 80–90°.

5. Complexly structured *Paleozoic unit* in which tectonic sheets of Devonian gray rocks and Early-Middle Cambrian gabbro-trondhjemites of the Tadzhilin complex are separated by melange zones up to several tens of meters thick. The melange consists of large dense magmatic blocks cemented with crushed Devonian rocks. Devonian rocks in the sheets are folded. The fold axes and the melange zones strike northeastward.

6. The Paleozoic unit is overlapped by the *Terek-Bashkaus sequence*, which consists of brown clay and

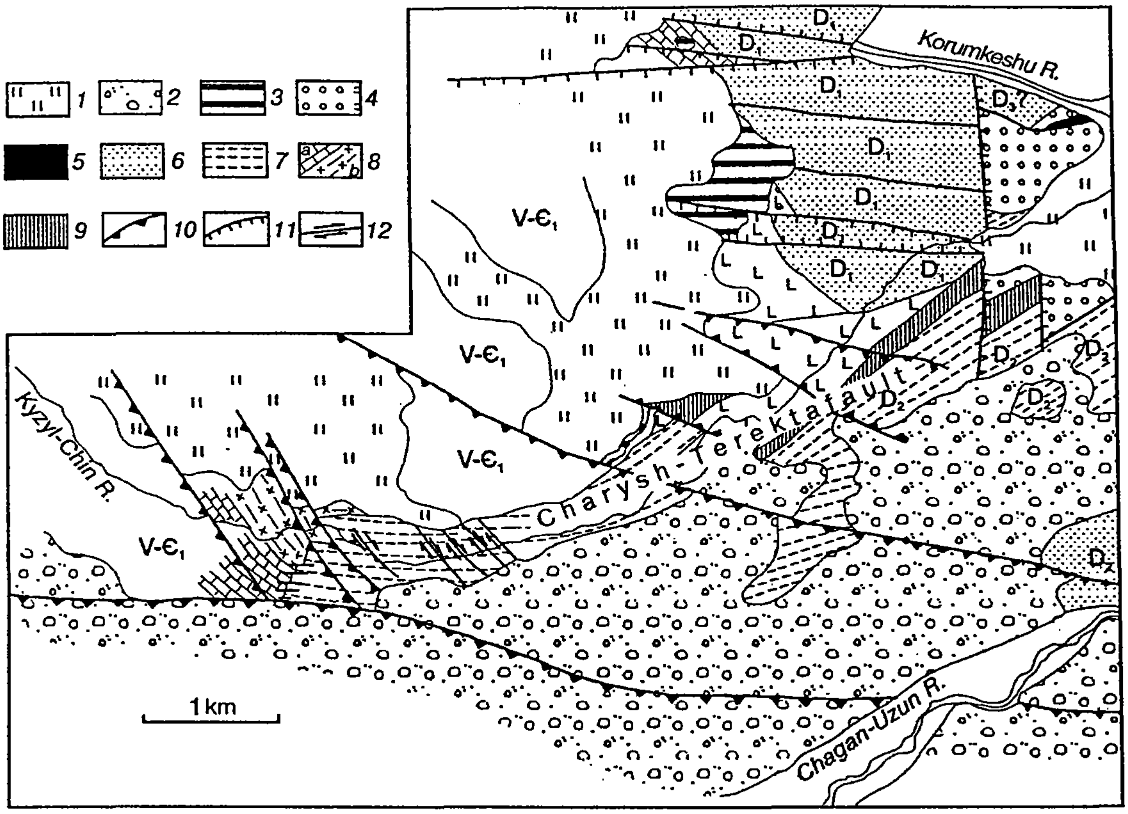

Fig. 7. Geological framework of the Kyzyl-Chin site (location see in Figs. 2 and 3). ***1*** **— Upper Pleistocene-Holocene,** ***2*** **— Upper Pleistocene moraine,** ***3*** **— Kyzyl-Gir Formation (Upper Miocene-Lower Pliocene),** ***4*** **— Karachum Formation (Oligocene),** ***5*** **— Upper Cretaceous,** ***6*** **— Devonian rocks of uncertain division,** ***7*** **— strained Devonian rocks,** ***8*** **— Late Vendian-Early Cambrian rocks:** ***a*** **— carbonate,** ***b*** **— siliceous,** ***9*** **— melange with blocks of Late Vendian-Early Cambrian rocks,** ***10*** **— reverse faults,** ***11*** **— normal faults,** ***12*** **— strike-slip faults.**

sandstone containing flat fragments of gray Devonian rocks. The thickness of the Bashkaus Formation is about 110–120 m; the beds dip northward at 40–60°.

7. The Bashkaus Formation is overlain, with tectonic contacts, by gray *Devonian rocks*. The contact surface dips northeastward at 40–60°. Close to the contact, the Bashkaus Formation is brecciated and densely cut by carbonate veinlets with slickensides that indicate a thrust nature of the contact. In turn, Devonian deposits are overlain by Bashkaus deposits, which dip northeastward at 40–60°. Large outcrops of Bashkaus deposits compose a plateau over the Devonian basement. In the north they are bounded by a scarp, which marks a strike-slip zone exposing Devonian rocks.

This succession of sediments, exposed on the Totugem left bank, and their contact with Paleozoic rocks indicate a stratigraphically overturned section. There, the basal layer of slope deposits — sedimentary breccia of member 4 — is overlain by red molasse of the Karachum Formation (member 3). Through the transition zone (member 2), the Karachum slope deposits are transgressively overlain by the Kosh-Agach Formation (member 1).

Structurally, the Totugem site consists of several blocks bounded by a dextral strike-slip fault. The fault, clearly marked in outcrops in the Totugem valley, displaces Cenozoic sediments by 300 m. Southeastward it grades on strike into a frontal thrust. Over the thrust 1.5 km southeast of the Totugem site there is an antifold filled with Kosh-Agach sediments. The southeastern strike of the fold axis conforms to the strike of the Cenozoic sediments in the site. The dip angle of the northeastern fold wall is 30–40°, whereas the southwestern wall is steeper (60–70°) and is complicated by a reverse fault. The anticline is overthrust by the Terek-Bashkaus sequence.

The Krasnaya Gorka site. Outcrops of Cenozoic rocks composing erosion outliers are located in the mouth of the Tueryk and on the opposite bank of the Chuya (Fig. 6). This site experienced repeated uplifting during the Cenozoic and counterclockwise rotation during the deposition of the Karachum, Tueryk, and Kyzyl-Gir Formations and in post-Kyzyl-Gir time, which resulted in its breakup into several blocks. This is indicated by arch-shaped outlines of the faults, deformation of Paleogene-Neogene deposits, and sedimentation gaps. Slickensides in the Cenozoic rocks found near the fault boundaries indicate strike-slip and transpression faulting. Structural unconformities are found west of Krasnaya Gorka, on the left bank of the Chuya, within the Karachum Formation [28]. To the east, other formations of the Chuya depression transgressively overlie fault-bounded blocks of Paleozoic rocks. Several stratigraphic contacts have been found there: Paleozoic-Karachum Formation, Paleozoic-Tueryk Formation, Paleozoic-Kyzyl-Gir Formation, and Kyzyl-Gir Formation-Beken Formation. These data are evidence for Cenozoic active tectonics in the Krasnaya Gorka site. The site is located in the area of the Charysh-Terekta active fault. The modes of occurrence of Cenozoic deposits on the Paleozoic basement characterize stages of its reactivation.

The Kyzyl-Chin site also occurs within the Charysh-Terekta fault, in the northwestern Chuya depression (Fig. 7), and is the peripheral part of the Chagan-Uzun block. The Cenozoic section in this site, described in detail in [6], characterizes the evolution of the latter. We studied active tectonics and block movements along Late Paleogene, Early Neogene, and Holocene faults of different geometry. Displacements of different ages in the Charysh-Terekta fault zone are marked by sedimentation breaks in Paleozoic rocks, on the one hand, and by contacts of the Karachum and Kyzyl-Gir Formations and Kyzyl-Gir and Bashkaus Formations, on the other hand. No deposits of the Kosh-Agach and Tueryk Formations have been found in the site. Cenozoic sediments are preserved only in the eastern, i.e., downthrown walls of blocks. The blocks are mainly bounded by reverse and normal faults, less often by strike-slip faults. Strike-slip faulting is indicated by the occurrence of numerous low-magnitude faults along the Kyzyl-Chin right-bank, at the contact of the Vendian-Early Cambrian carbonate-siliceous rocks of the Baratal Formation and the Middle Devonian red-color deposits. The contact is a Late Paleozoic NS-striking fault, which was broken by a series of younger WE-trending strike-slip faults. The fault age and the geometry of blocks show that the Chagan-Uzun block uplifted in post-Tueryk time. Its uplift was accompanied by active movements in the Charysh-Terekta fault zone in the Pliocene-Early Pleistocene. In the Late Quaternary, the eastern part of the block, including post-glacial deposits, was broken by WE-striking reverse faults into several stepped structures with uplifted southern steps. On the right bank of the Kyzyl-Chin, the bottom of the glacial section is 60 m higher or lower than that in the adjacent blocks. The movements of this kind possibly resulted from the growth of the Shavly, North Chuya, and South Chuya Ranges existing south of the Chuya depression.

CENOZOIC DEPOSITIONAL FRAMEWORK AND TECTONIC EVOLUTION OF THE CHUYA DEPRESSION

The detailed geological studies of the four sites allowed a more consistent idea of the depositional framework and tectonic evolution of the Chuya depression. The most complete Cenozoic section is found at the foothills of the Kurai Range, in the Tueryk and Totugem sites. Through the basal horizon of conglomerates and gravelstones, the Karachum Formation overlies the Paleozoic rocks of the Kurai Range. The presence of subaerial slope deposits indicates uplifted blocks. The Karachum deposits are continental molasse, as indicated by their coarse-clastic composition and motley color. The molasse marks the Early Oligocene stage of orogeny within the Chuya depression [6]. The deformed middle section of the Karachum Formation is evidence of active tectonics in middle Karachum time [28]. Up the section, the Karachum slope deposits are transgressively transient into the Kosh-Agach coal-bearing sediments. Lithologically similar fine-grained lacustrine-marsh facies of the Kosh-Agach Formation, up to 250 m in total thickness, are widespread within the Chuya, Kurai, Dzhulukul, and Samakha depressions. Therefore, the territory of southeastern Altai was a single extensive basin without large inflows. The absence of coarse-clastic deposits along the Kurai Range, which in Kosh-Agach time was a shallow-sided basement uplift within the basin, is evidence of its weak influence on the deposition [28]. Kosh-Agach deposition occurred in tectonically quiescent conditions of slow regional-scale subsidence of the territory. The Kosh-Agach shallow-water deposits grade into deeper-water lacustrine marl-carbonate sediments of the Tueryk Formation. In Tueryk time, the sides of the Chuya depression started to uplift, as indicated by the presence of coarse-clastic rounded sand, pebble, and conglomerate in the lower part of the Tueryk section, near the flanks of the present-day Chuya depression, and by the occurrence of angular fragments of Paleozoic rocks in sections adjacent to the Kurai Range. The occurrence of the Tueryk Formation in the Chagan-Uzun block and Kurai depression indicates that it deposited within the single Chuya-Kurai basin

[6]. The Kyzyl-Gir Formation deposited later within a long-living lake in a stable tectonic setting. The height of the surrounding mountains was under 1000 m [28].

The next stage of orogeny began in the latest Neogene and resulted in deposition of the Beken coarse-clastic fill in the lake and intense growth of the Kurai Range. The range thrust over the Chuya fill providing accumulation of poorly-sorted and poorly-rounded coarse-clastic rocks of the Terek and Bashkaus Formations in the Late Pliocene-Early Pleistocene, a time of culmination of the Kurai Range growth, accompanied by formation of three structural types: thrusts, domal uplifts, and transpression faults (Fig. 3). Thrusts are widespread in the basement of the Kurai Range, in the zone of its junction with the Chagan-Uzun block. The Tadzhilin domal uplift, with its core mainly composed of Cambrian igneous rocks of the Tadzhilin complex, is located on the Tueryk-Totugem watershed. It is bounded by strike-slip faults in the northwest and northeast, and in the south it overlies the Cenozoic fill of the Chuya depression along an overturned stratigraphic contact, locally broken by thrusts. Transpression faults are found in the Totugem basin. All these structures formed within the Kurai fault zone due to its reactivation by frontal compression.

A different depositional framework and a different neotectonic structure are observed on the western borders of the Chuya depression, at its boundary with the Chagan-Uzun block. Strike-slip, reverse and normal faulting of different ages deformed the Paleogene-Quaternary deposits and caused breaks in sedimentation. The deformations resulted from reactivation of the Charysh-Terekta fault.

Sedimentation breaks and block movements indicate intense tectonism in the western Chuya depression in Neogene-Quaternary time, which was related to reactivation of the Charysh-Terekta fault resulted from regional SW-NE compression. Younger Late Quaternary reverse faults have been mapped only in the southwestern Chuya depression. They characterize the next stage of activity, which caused overall uplift of southern Gorny Altai. The uplift was concurrent with the last stage of glaciation, and fault scarps dammed glacial valleys, as indicated by traces of abrasion.

STRUCTURE OF THE CHUYA DEPRESSION AND A MODEL FOR ITS FORMATION

Thrusts, strike-slip faults, transpression faults, reverse thrusts, reverse and normal faults of different ages within the Chuya depression illustrate its complex formation history. The orientation of the Tueryk thrusts indicates southwestern compression of younger sediments by the Paleozoic rocks of the Kurai Range. Paleogene-Neogene rocks form a wedge-like structure narrowing northwestward. The pressure of the Kurai Range on the Chagan-Uzun block was the strongest in the area of wedging-out and produced a thrust that involves deformed Paleogene-Neogene rocks and gauges.

The transpression thrusts in the Totugem site indicate a southeastern movement of the Devonian rocks of the Kurai Range along a reactivated Late Paleozoic fault, which marks the northeastern margin of the depression.

The contact of Paleogene-Neogene deposits and Paleozoic rocks of the South Chuya Range is covered with Late Quaternary sediments. A complex oblique thrust in that part of the depression appears to inherit the structure of the ancient basement that consists of Devonian and Cambrian blocks brought together within the Late Paleozoic Charysh-Terekta fault zone.

The Cenozoic tectonic evolution of the region is well expressed in the surface topography. As the pre-Cenozoic topography was quite flat, faults are marked by scarps whose heights show the amount of vertical offset of fault blocks. Active faults were localized on the basis of both geological and geomorphic evidence. The results of the two approaches coincided, and the geomorphic expression often provided more authentic evidence of the time of the latest motion.

The pre-Quaternary structure of the Chuya depression is complicated, as it inherits an older reactivated structure. It can be described as a half-ramp basin (Fig. 8), which formed within the junction of the Charysh-Terekta and Kurai faults. General NE compression [10, 11] reactivated the junction zone of older fault systems in the basement of the Chuya depression and the bordering mountains and produced variously oriented local extension and compression zones and turned different blocks whose rotation was inferred from geological and paleomagnetic data.

The regional stress tensor was determined by measuring fractures and slickensides in the Kurai and Charysh-Terekta fault zones [11]. Three tensors for the Kurai fault zone are relatively similar and show general NNE-SSW compression. Four tensors along the Charysh-Terekta fault zone are dissimilar, the dominating tensor showing a transtension regime with a strong strike-slip component: NW-SE horizontal extension and NE-SW compression.

The difference in stress fields of the Kurai and Charysh-Terekta fault zone can be explained by different

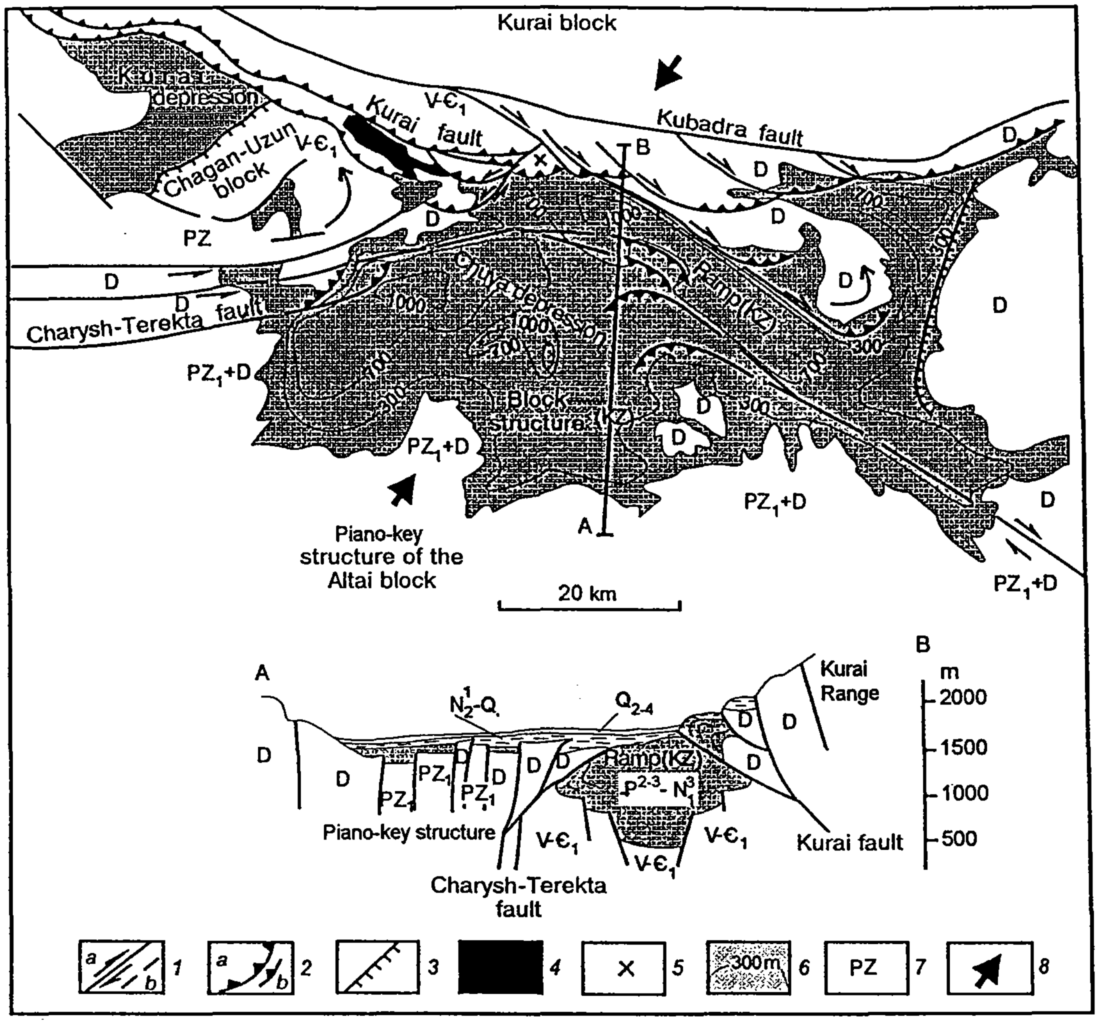

Fig. 8. Tectonic framework and a cross section of southeastern Gorny Altai. *1* — **strike-slip faults:** *a* — **observed,** *b* — **inferred,** *2* — **thrusts:** *a* — **observed,** *b* — **inferred,** *3* — **reverse faults,** *4* — **Chagan-Uzun ophiolites,** *5* — **Tadzhilin,** *6* — **contour lines of the thickness of Cenozoic deposits, from geophysical data,** *7* — **pre-Cenozoic rocks,** *8* — **direction of compression.**

orientations of fault systems with respect to the compression axes. During the NNE to NE compression, the Tuva-Mongolian block acted as a rigid block thrust over Cenozoic deposits. The stress was concentrated along the Kurai zone transverse to the direction of compression and induced the growth of the Kurai Range in the Upper Pliocene-Quaternary. The strike of the Charysh-Terekta fault zone is nearly parallel to the general direction of compression; therefore, blocks could move in different directions within this zone. Structural studies showed the presence of an extension zone within the fault, which correlates well with the maximum subsidence of the Chuya basin related to the reactivation of the Charysh-Terekta fault.

Paleomagnetic studies in the Chuya depression showed that tectonic movements were a combination of compression (crust thickening) and strike slip [35]. The multicomponent magnetization of Upper Oligocene red continental clays (Karachum Formation) makes it impossible to recognize a stable high-temperature magnetization. Stable magnetization (of pyrrhotite) was recognized in Middle-Late Miocene lacustrine clays of the Tueryk Formation as $D = 335°, I = 60°, \alpha95 = 6°$ (mean direction), $D = 337°, I = 68°, \alpha95 = 5°$ for Upper Miocene-Lower Pliocene sands of the Kyzyl-Gir Formation, and $D = 9.5°, I = 46°, \alpha95 = 7.5°$ for Lower Pliocene sands of the Beken Formation (on hematite). These results suggest that in the latest Miocene – earliest Pliocene the southern part of the Chuya depression, together with the Altai uplift, turned clockwise at 35±15° with respect to its stable northern part, the margin of the Tuva microplate.

The same tectonic pulse reactivated the Charysh-Terekta fault zone and initiated the Chagan-Uzun horst, as attested by geological evidence. The deformations, related to the NE migration of the Dzhungarian microplate in the latest Miocene–earliest Pliocene, split the Altai uplift into rotating blocks (Fig. 1). The compression resulted in the orogeny and formation of a high-mountain topography, and, as a result of rotation, a deep-water limnic basin formed on the margin of the uplift (Kyzyl-Gir Formation). As noted above, the Kurai Range grew later, in the Late Pliocene–Early Pleistocene, owing to the reactivation of the Kurai fault, marking the boundary between the Tuva-Mongolian and Altai microplates.

Figure 8 shows the neotectonic framework of southeastern Gorny Altai and thicknesses of Cenozoic sediments obtained from electromagnetic data by the Altai Geophysical Survey. The sediment thicknesses show abrupt changes along the northern and northwestern boundaries of the Chuya depression, which can be accounted for by the tectonic nature of these boundaries. The southern and eastern margins of the depression appear to undergo slow subsidence, as suggested by gradual change in sediment thicknesses and the absence of evident faults. A fault scarp was inferred in the central part of the depression, which possibly formed in the Late Miocene, simultaneously with the Chagan-Uzun and Kurai uplift; in the present structural framework it is covered with Pliocene-Pleistocene sediments.

CONCLUSIONS

The results of our study show that the dynamics of the formation of the Chuya basin and the bordering mountains changed through time. The Chuya depression formed in the Middle Miocene-Early Pleistocene as a sedimentary basin bounded by uplifts. It was probably then a graben conjugated with the growing Chagan-Uzun horst. The present structural pattern of the depression resulted from intense tectonic compression. In the latest Early Pliocene the depression developed into a ramp basin; in the Late Pliocene its northern boundary was reactivated by thrusting and oblique thrusting. The Cenozoic evolution of the topography of southeastern Gorny Altai illustrates gradual propagation of deformations induced by the Eocene India-Eurasia collision. The deformations separated the Altai orogen and the Tuva-Mongolian microplate in the Late Pliocene, reactivating mainly the Late Paleozoic regional faults.

The most prominent features of the structure and evolution of the Altai/Tuva-Mongolian boundary revealed by this study can be used for comparison in studies of similar neotectonic boundaries in Inner Asia.

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REFERENCES

[1] I. S. Novikov, *Geomorphological effects of intracontinental collision on the example of Gorny Altai*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 37, no. 11, p. 52(51), 1996.

[2] B. N. Luzgin, G. G. Rusanov, *Characteristics of formation of Neogeic deposits in the southeastern Gorny Altai*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 33, no. 4, p. 23(18), 1992.

[3] A. V. Aksarin, *Vestnik Zapadno-Sibirskogo Geol. Upravleniya*, no. 4, p. 41, 1938.

[4] G. F. Lungersgauzen and O. A. Rakovets, in: *Regional geology data. Geology and geomorphology of folded areas in Siberia and Central Asia* [in Russian], Moscow, p. 79, 1958.

[5] E. N. Shchukina, in: *Stratigraphy of Quaternary (Anthropogenic) deposits in the Asian part of the USSR and their comparison with European ones* [in Russian], Moscow, p. 127, 1960.

[6] E. V. Devyatkin, *Quaternary sediments and neotectonics in Southwestern Altai* [in Russian], Novosibirsk, 1965.

[7] L. I. Rozenberg, *Bull. MOIP, Otdel. Geol.*, vol. 48, issue 2, p. 45, 1973.

[8] B. M. Bogachkin, L. I. Rozenberg, Yu. G. Tsekhovsky, *Bull. MOIP, Otdel. Geol.*, vol. 49, issue 2, p. 5, 1974.

[9] B. M. Bogachkin, *The Cenozoic tectonic history of Gorny Altai* [in Russian], Moscow, 1981.

[10] N. L. Dobretsov, N. A. Berzin, M. M. Buslov, and V. D. Ermikov, *General aspects of the evolution of the Altai region and the interrelationships between its basement pattern and the neotectonic structural development*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 36, no. 10, p. 3(1), 1995.

[11] D. Delvaux, K. Theunissen, R. Van der Meer, and N. Berzin, *Dynamics and paleostress of the Cenozoic Kurai-Chuya depression of Gorny Altai (South Siberia): tectonic and climatic control*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 36, no. 10, p. 31(26), 1995.

[12] N. L. Dobretsov, M. M. Buslov, D. Delvaux et al., *Int. Geol. Rev.*, vol. 38, p. 430, 1996.

[13] M. M. Buslov, D. Delvaux, V. S. Zykin, and I. Yu. Safonova, in: *Continental rift tectonics and evolution of sedimentary basins* [in Russian], Novosibirsk, p. 43, 1996.

[14] L. P. Zonenshain and L. A. Savostin, *Introduction into geodynamics* [in Russian], Moscow, 1979.

[15] W. D. Cunningham, B. F. Windley, D. Dorjnamjaa et al., *Earth Planet Sci. Lett.*, vol. 140, no. 1–4, p. 67, 1996.

[16] W. D. Cunningham, B. F. Windley, D. Dorjnamjaa et al., *Tectonics*, vol. 15, no. 1, p. 142, 1996.

[17] W. D. Cunningham, B. F. Windley, L. A. Owen et al., *Tectonophysics*, vol. 277, no. 4, p. 285, 1997.

[18] A. S. Mukhin and V. A. Kuznetsov, *Vestnik Zapadno-Sibirskogo Geol. Upravleniya*, no. 1, p. 49, 1939.

[19] I. S. Novikov, A. A. Mistryukov, and Ph. Terfois, *Geomorphological structure of the Chuya intermontane depression (Gorny Altai)*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 36, no. 10, p. 64(57), 1995.

[20] V. V. Butvilovsky and L. A. Orlova, in: *Problems of Siberian geology* [in Russian], Tomsk, p. 224, 1994.

[21] G. F. Lungersgauzen and O. A. Rakovets, in: *Proceeding of the All-Union meeting on Quaternary* [in Russian], Moscow, vol. 3, p. 229, 1961.

[22] O. A. Rakovets, *Izv. Altaiskogo Otdela Geograph. Obshchestva SSSR*, issue 7, p. 3, 1966.

[23] E. V. Devyatkin, in: *Proceedings of the Committee for Quaternary studies, AN SSSR* [in Russian], vol. 2, Moscow, p. 32, 1963.

[24] V. S. Erofeev and L. N. Rzhannikova, *Izv. AN KazSSR, Ser. Geol.*, no. 5, p. 59, 1969.

[25] V. S. Erofeev, in: *Geology and metallogeny of Rudny Altai* [in Russian], Alma-Ata, p. 21, 1970.

[26] L. I. Rozenberg, *Izv. AN KazSSR, Ser. Geol.*, no. 10, p. 44, 1981.

[27] V. S. Zykin and A. Yu. Kazanskii, *Stratigrapy and paleomagnetism of Cenozoic (pre-Quaternary) deposits of the Chuya depression in Gorny Altai*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 36, no. 10, p. 67(75), 1995.

[28] V. S. Zykin and A. Yu. Kazansky, in: *Continental rift tectonics and evolution of sedimentary basins* [in Russian], Novosibirsk, p. 74, 1996.

[29] A. P. Feofilova, Yu. G. Tsekhovskii, and B. P. Gradusov, *Litologiya i Poleznye Iskopaemye*, no. 1, p. 18, 1981.

[30] E. V. Devyatkin, *The Cenozoic in Inner Asia: stratigraphy, geochronology, and correlations* [in Russian], Moscow, 1981.

[31] S. M. Popova, E. V. Devyatkin, and Ya. I. Starobogatov, *Mollusks of the Kyzyl-Gir Formation in Gorny Altai* [in Russian], Moscow, 1970.

[32] Ya. I. Starobogatov and T. Ya. Sitnikova, *Zhurnal Obshchei Biologii*, vol. 51, no. 4, p. 499, 1990.

[33] Ya. I. Starobogatov, *Mollusk fauna and zoogeographic zoning of continental water basins of the globe* [in Russian], Leningrad, 1970.

[34] V. S. Zykin, in: *Evolution of climate in the Late Miocene and Pliocene in the southern West Siberian Plain* [in Russian], Novosibirsk, p. 5, 1991.

[35] J. C. Thomas, A. Kazanskii, R. Lanza, and N. Semakov, in: *Continental rift tectonics and evolution of sedimentary basins* [in Russian], Novosibirsk, p. 70, 1996.

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