Russian Geology and Geophysics
Vol. 39, No. 7, pp. 970-977, 1998

Geologiya i Geofizika
UDC 551.4+551.24(235.222)

NEOTECTONICS OF THE KURAI RIDGE
(Gorny Altai)

I. S. Novikov, A. R. Agatova, and D. Delvaux*

United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the RAS, prosp. Akad. Koptyuga, 3, Novosibirsk, 630090, Russia
**Royal Museum for Central Africa, I-3080, Tervuren, Belgium*

The idea of the neotectonic structure of the Kurai Ridge has been obtained on the basis of thorough geomorphological studies of its central part by large-scale SPOT imagery- and field-based mapping. The neotectonic framework is made up by a system of faults radiating in a fan-like manner in the vertical section and subparallel in plan. Motions on these faults have produced a "rose" structure expressed in a terraced topography. The ongoing tectonic activity in the territory is evident from seismically induced rockfalls and zones of minor faults displacing the steep sides of Late Pleistocene glacier valleys.
Geomorphology, paleostresses, seismic surface breaks, Gorny Altai

INTRODUCTION

First data on relations between the present-day topography and geology of Gorny Altai were published in 1845 in Paris in a report by Chikhachev [1] who was the first to explore the central part of the territory which was then poorly known. He interpreted the mountainous structures of Altai, in light of the geological ideas of his time, as a result of Paleozoic folding [1]. This concept had remained beyond question for 70 years and was referred to in various overviews, as no special geological studies were undertaken until V. Obruchev explored the southeastern part of Altai and inferred the origin of its mountainous relief from Cenozoic movements of tectonic blocks [2]. Grane [3] visited the northeastern part of Gorny Altai and described it as a margin of a large Cenozoic dome. Later the two extreme viewpoints were brought to a compromise by Nekhoroshev [4] who interpreted the Cenozoic history of Altai in terms of doming complicated later on by block movements. All concepts of the Cenozoic evolution of the Altai relief implied the existence of primary pre-Cenozoic peneplain disturbed by vertical movements, which acted as folding and faulting [5]. Although the first detailed geological survey in the area of the Aktash mercury deposit (Kurai Ridge) already revealed the reverse and thrust geometry of the main faults [7], prevalence of vertical motions in Gorny Altai was beyond doubt until the mid-1970s when the concept of a continental collision in Asia came into broad use [6]. Only in the early 1990s was the topography of the Central-Asian mountain belt including Altai interpreted in Russian geomorphological and neotectonic literature as resulting from regional-scale compression during a continental collision [8], and since then this idea has been actively developed [9, 10].

According to modern views, the main orographic features of southern Siberia are fault-bounded ranges produced by deformation of the primary peneplain. The border faults dip inward the ranges and have reverse or, less often, thrust geometries shown up on the surface. At greater depths they join and outline a sort of a risen prism first described in works on geomorphology of Inner Asia in the 1960s [11, 12]. This idea, however, did not fit the commonly accepted view of vertical motions as a dominant building mechanism for the relief and was rekindled only after publications on the role of plate tectonics for the mountainous framework of this territory of Asia [6].

A great part of information on the neotectonics of Southeastern Altai can be obtained from geomorphological analysis of the modern topography. Thus, motions on major border faults between uplifted blocks, topographically expressed as ranges, massifs, and plateaus, were inferred to involve a considerable strike-slip component [10]. Smaller faults inside the blocks are normal and reverse. The amount of vertical motion along them can be easily estimated from elevation contrasts relative to the preserved remnants of the primary peneplain, which is a sort of a marking geomorphic datum level.

STRUCTURAL POSITION AND GEOMORPHOLOGY OF THE KURAI RIDGE

The neotectonic framework of Southeastern Altai (Fig. 1) is made up by young surface breaks and partially by reactivated pre-Cenozoic faults, arcuate in plan and striking roughly west-east in the south and northwesterly in the north of the region. The Kurai Ridge forms a divide between the Chuya and Bashkaus river basins. Its neotectonic structure is not uniform. The central part is occupied by a lens-like northwesterly trending block (the Kurai block) bordered in the west and east by intricately built wrench fault zones. Along these zones, the block borders the Kubadru and Bashkaus massifs which are isometric neotectonically uplifted blocks. Boundaries between the ranges are expressed in the topography as deeply incised valleys within the wrench fault zones. In the northeast and southwest, the Kurai block is bordered by systems of thrust and reverse faults forming a typical "rose" structure.

The major geomorphic features of the ridge are its northern and southern slopes shaped-up by first deformations of the primary peneplain. Other landforms were produced later by dislocation of the slopes. Inasmuch as the neotectonics of the extremely rugged northern slope is obscure, our studies focused on the southern slope.

The southern slope of the Kurai Ridge has a clearly terraced structure (Fig. 2). The shelf surfaces are fragments of the pre-orogenic peneplain bordered by gentle slopes, and the escarpments are formed by steep

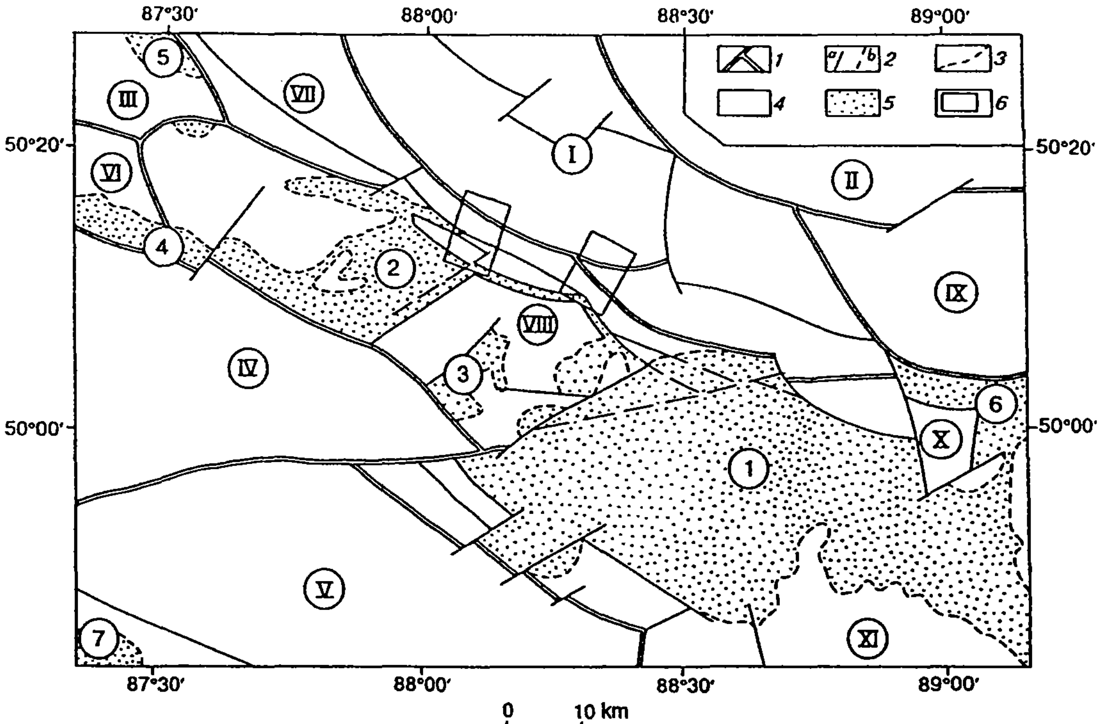


Fig. 1. Neotectonics of the Kurai-Chuya system of intermontane areas and their margins (structure names follow [9] with some supplements). *1* — major faults; *2* — minor faults: *a* — observed, *b* — hypothetical, possibly existing beneath the Late Cenozoic sediment cover; *3* — boundaries of Cenozoic sedimentary basins in place of pre-existing depressions; *4* — blocks of the Paleozoic basement topographically expressed as positive structures: I–V — ranges (elongate blocks): I — Kurai, II — Chulyshman, III — Aigulak, IV — North-Chuya, V — South-Chuya; VI–IX — mountains (small isometric blocks): VI — Estulin, VII — Chagan-Uzun, IX — Bashkaus, X —Kyzylchin, XI — plateaus (large isometric blocks): Sailyugem; *5* — blocks of the Paleozoic basement topographically expressed as negative structures: 1–7 — depressions (Cenozoic sedimentary basins): 1 — Chuya, 2 — Kurai, 3 — Ildyskel', 4 — Eshtykel', 5 — Sorlukel', 6 — Kokorya, 7 — Samakha; *6* — areas shown in Figs. 2 and 3.

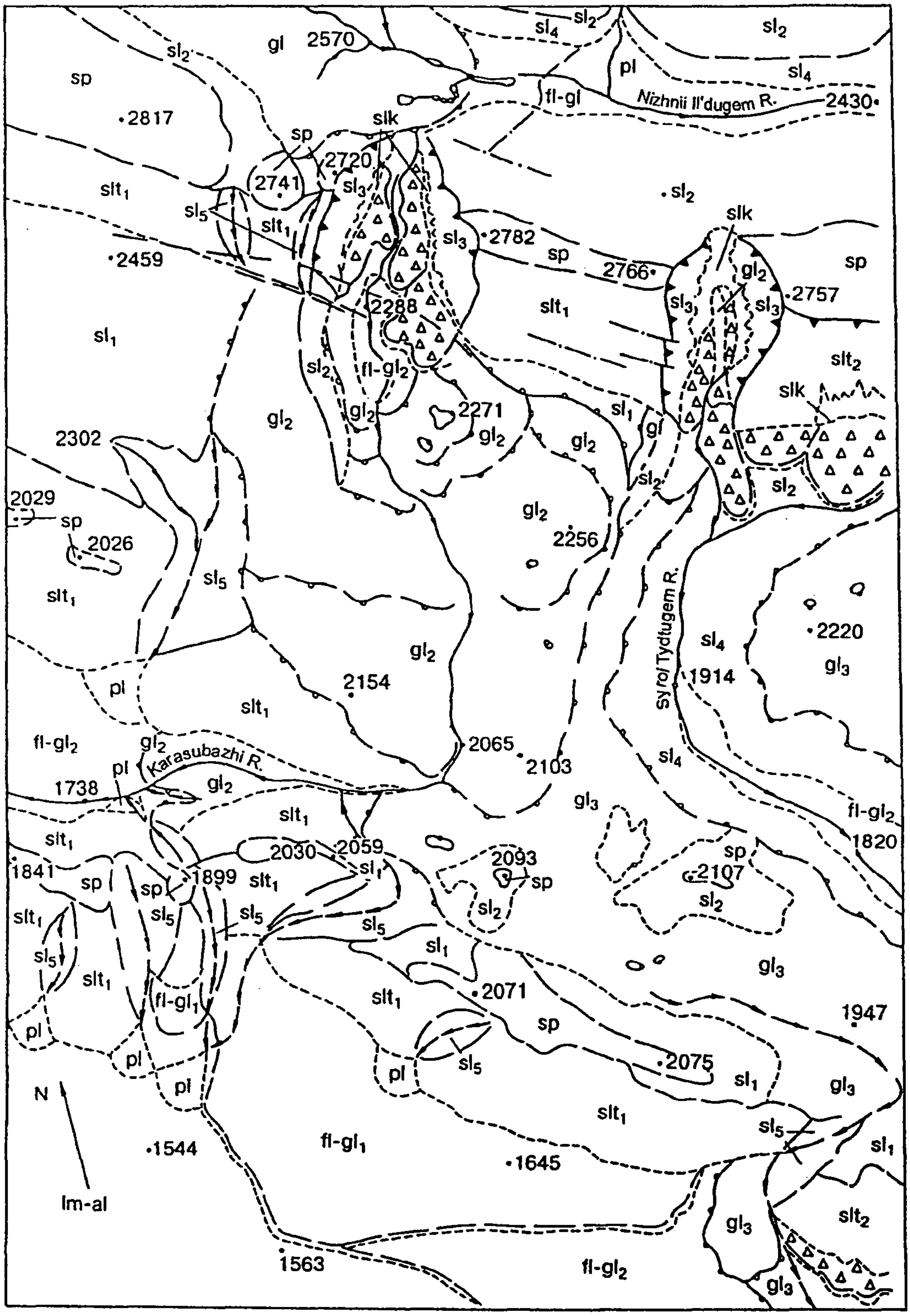
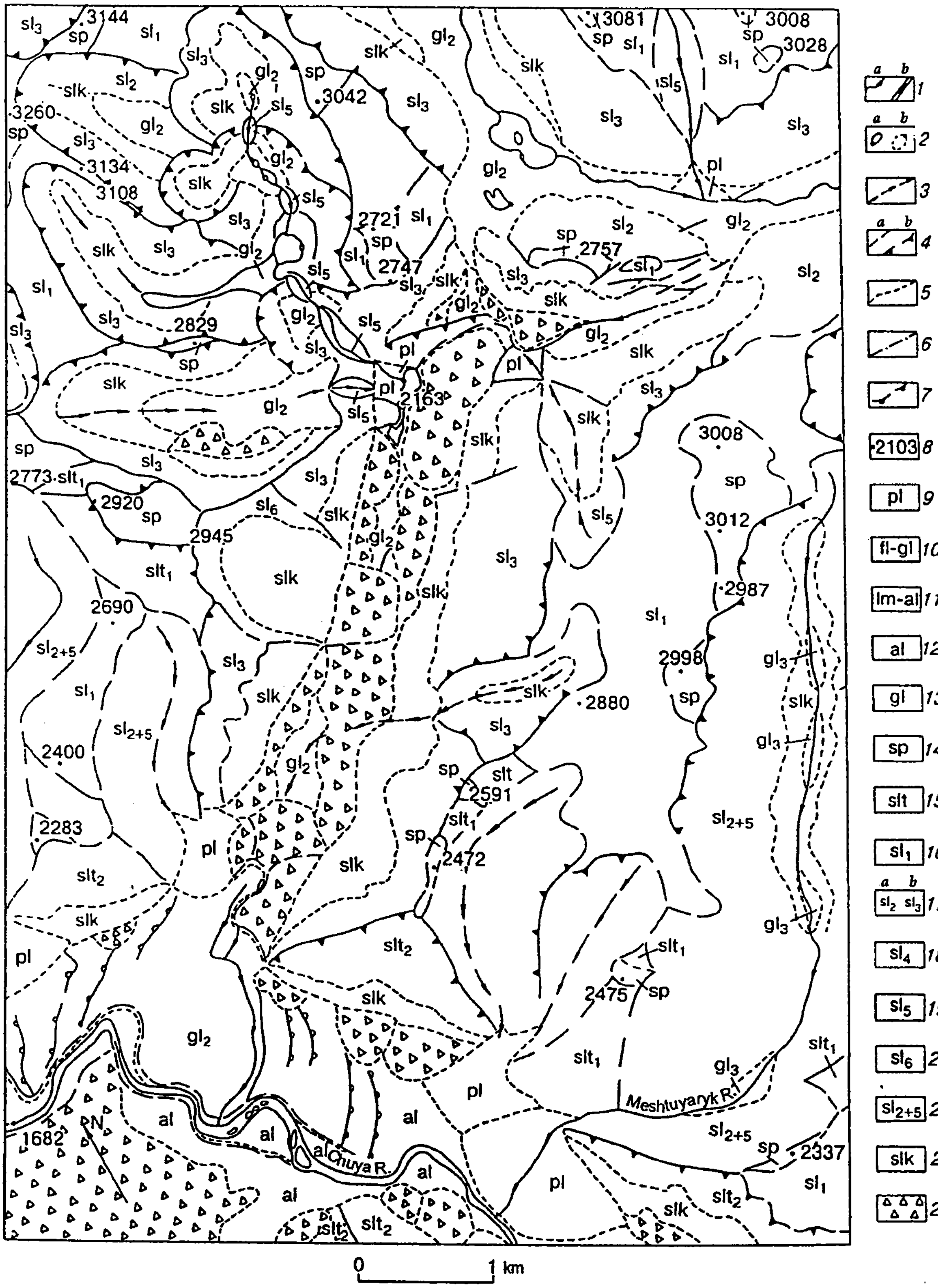


Fig. 2. Geomorphology of the western (A) and eastern (B) areas of detailed studies. 1, 2 elements of drainage network: 1 — rivers: *a* — small, *b* — large, 2 — lakes: *a* — permanent, *b* — ephemeral; 3–5 —geomorphologic boundaries: 3 — thalwegs, 4 — brows: *a* — smooth, *b* — bluffy, 5 — rear sutures; 6–8 — other symbols: 6 — young faults, 7 — boundaries of moraine deposits and recessional moraines, 8 — absolute altitudes, in m; 9–23 topographic features: 9 — talus cones, 10 — glaciofluvial trails: older with traces of abrasion terraces (1), younger (2), 11 — lake alluvial plains, 12 — alluvial terraces, 13 — moraine fields: of Little Ice Age (1), smoothed (2), strongly smoothed

B



(3), 14 — fragments of primary peneplain, 15 — steep fault slopes: moderately steep (1), steep, cut with rockfall scars (2), 16 — gentle-sloping near-top slopes, 17 — slopes of glacial valleys and outliers: (*a*) gentle-sloping, steep, (*b*) cut with rockfall scars, 18 — slopes of glaciofluvial incision, 19 — slopes of erosion valleys, 20 — rockfall scars, 21 — slopes of glacial valleys reworked by glaciofluvial erosion, 22 — talus slopes, 23 — fallen rock bodies.

fault planes. Although the primary relief was considerably reworked (chiefly by glaciers), its original structure is clearly evident in broad areas preserved between the valleys. Glacial valleys have young, nearly vertical rocky sides framed with talus cones below and often cut with rockfall scars. Fallen rocks make up 0.5 to 1.0 km wide isometric fields. All found rockfalls overlie the glacial till and thus are younger. Their great sizes and location far from the scars suggest origin by some additional forces, possibly by an earthquake, rather than by simple gravity downsliding. Clastic material brought from the glacial valleys is accumulated on the surfaces of lowest or, less often, moderately subsided blocks. Some subsided blocks are completely covered with till. Their central parts are usually occupied by lake alluvial plains, which give way outward to glaciofluvial trails and moraine fields.

Moraine deposits make spacious fields with a typical hummocky relief where recessional moraines mark the position of past glaciers. The fields fall into three main groups on the basis of the relief. The first group involves strongly hummocky fields of the Little Ice Age evident in the Kurai Ridge only in valleys on the northern slope. The second and the third groups include weakly or strongly smoothed younger fields related to early stages of the Late Pleistocene glaciation. The respective moraines, ubiquitous in the valleys, mark stages of degradation of the Late Pleistocene glaciation.

Postglacial erosion is rather poorly expressed in the region. Its typical form is an erosion pit with a talus fan in the outlet. Activity of meltwaters released by deglaciation is more pronounced and is evident in at least two generations of broad glaciofluvial trails (the older trails are cut by abrasion terraces of an ancient glacial damlake and the later ones formed after it had disappeared), as well as in deep valleys across moraine fields on flat areas of the southern slope of the Kurai Ridge.

Thus, the analysis of the primary tectonic relief and its later rework shows that all elements of block tectonics had formed by the latest Pleistocene, the time of the broadest spread of the last glaciation.

MORPHOLOGY AND NEOTECTONICS OF THE SOUTHERN SLOPE OF THE KURAI RIDGE

Geomorphology of the areas studied in more detail reflects main elements of the regional neotectonic structure represented by fault-bounded blocks. Although strongly weathered, they retain enough remnants of paleorelief to evaluate the amount of vertical displacement on major faults and the deformation style inside the blocks. Two reference areas were selected to characterize the western and eastern parts of the southern slope of the Kurai Ridge, the central segment of which coincides with the Kurai neotectonic block.

The western area (Fig. 3, *A*) has a regular terraced neotectonic structure and is a fragment of an enormous "staircase" originated from displacement of the ancient nearly flat peneplain by vertical motions on a set of northwesterly striking subparallel faults. The flat shelves are 1 to 5 km wide, and the escarpments are 100 to 400 m high. The absolute altitudes of the shelves increase inward the area from 1800 to 2850 m. The major fault planes are cut by minor younger faults. The major faults, thoroughly investigated during studies of the Aktash ore province, have reverse geometry with a strike-slip component [13]. Younger faults are of normal geometry.

The eastern area has more complex neotectonics as the major fault zone there splits into two branches (Fig. 3, *B*). Along with the terraced topography, its northern part involves triangular subsided blocks within highest elevated shelves. The shelves on the southern slope of the Kurai Ridge change progressively in absolute altitudes along the ridge and thus cannot have formed like pediments by slope retreat. Elevations of the shelves in the eastern area rise centerward from 2200 to 3200 m and the escarpment heights range from 100 to 200 m. A prominent feature of the paleorelief is nearly horizontal lower and upper shelves and outward sloping intermediate ones that is clearly reflected in their elevation contrasts (under 100 m for the horizontal shelves and 200 m or higher for the sloping ones). This fact proves valid the previously published hypothesis [10] that smooth swell-like uplifts used to exist in place of the present-day uplifted blocks at early stages of the recent orogeny in Southeastern Altai. The block structure was produced by later movements on faults during the formation of "rose" structures after the ductility limit of the lithosphere had been passed over by continuing regional compression.

The idea of the present stress field can be gained from the latest report on fault plane solutions by Zhalkovskii et al. [14]. The mechanisms of four of the six earthquakes yield stress tensors of strike-slip type with NNE principal stress axes and WNW-ESE S_{Hmin} (Fig. 4, *A*). A set of five stress tensors was obtained from slip lines in Late Pliocene-Pleistocene sediments along the eastern part of the southern slope of the Kurai Ridge, which reflect motions on northern boundary faults of the Chuya Depression (Fig. 4, *B*). As a result, NNE-trending horizontal compression was inferred, i.e. the same as the present direction of the principal compression axis. The stress field observed in Late Pleistocene-Holocene sediments in the western Chuya

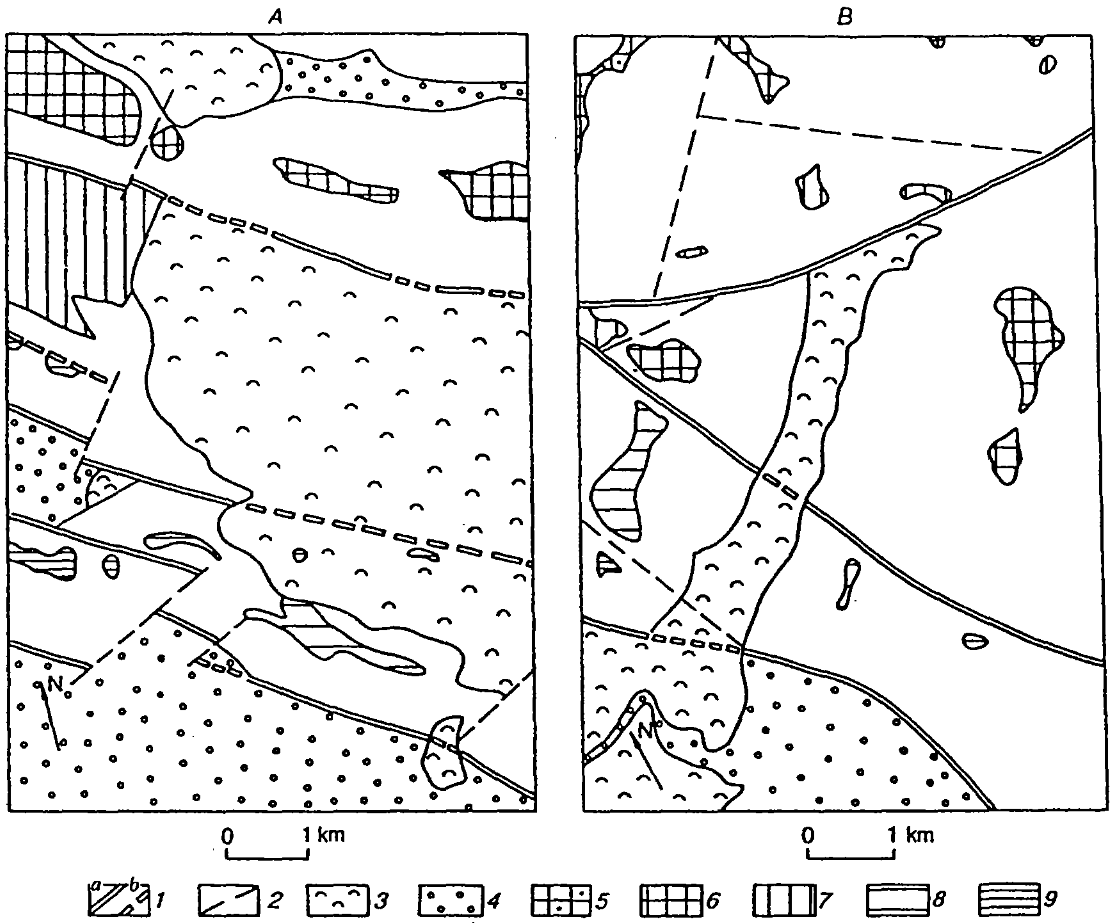


Fig. 3. Neotectonics of the western (*A*) and eastern (*B*) areas of detailed studies. *1* — major faults: topographically expressed as escarpments (*a*), overlain by unconsolidated deposits (*b*); *2* — minor faults; *3*, *4* — unconsolidated deposits in erosional and tectonic depressions: *3* — moraine and rockfall-related, *4* — wash and glacial-wash ; *5–9* — surfaces of tectonic shelves: *5* — first upper (3150–3200 m (*B*)), *6* — second upper (2750–2850 m(*A*), 3000–3050 m(*B*)), *7* — middle (2300–2450 m(*A*), 2750–2850 m(*B*)), *8* — first lower (2000–2100 m(*A*), 2400–2600 m(*B*)), *9* — second lower (1800–1900 m(*A*), 2200–2300(*B*)).

Depression along the boundary with the Kurai Block shows a greater extension. Thus, maximum stresses are concentrated along the Kurai Fault zone delimiting the stable Kurai Block, and this is reflected inside the depression itself. The average regional stress field must be thus intermediate between pure compression, as in the Kurai Ridge, and pure extension, as along the Chagan-Uzun Block. To sum up, the present stress field obtained from slip lines is in good regional-scale agreement with that inferred from earthquake focal mechanisms.

CONCLUSIONS

Geomorphic features and fault geometries indicate that neotectonic activity in the Kurai-Chuya zone of intermontane basins is controlled by NNE horizontal compression expressed in active faulting and block tilting. Motions on faults along the southern slope of the Kurai Ridge are of thrust or, more often, oblique (reverse to strike-slip) geometry, especially along the border fault. This setting is typical of positive terraced features structured under general compression accompanied by development of "rose" structures. Normal faulting is evident along NNE-striking faults nearly parallel to the principal compression axis. The western part of the Chuya Valley, adjacent to the Kurai Ridge is developing as a half-ramp basin with southward block tilting. The Chuya half-ramp basin is active along its northern shoulder whereas the southern one bordering the

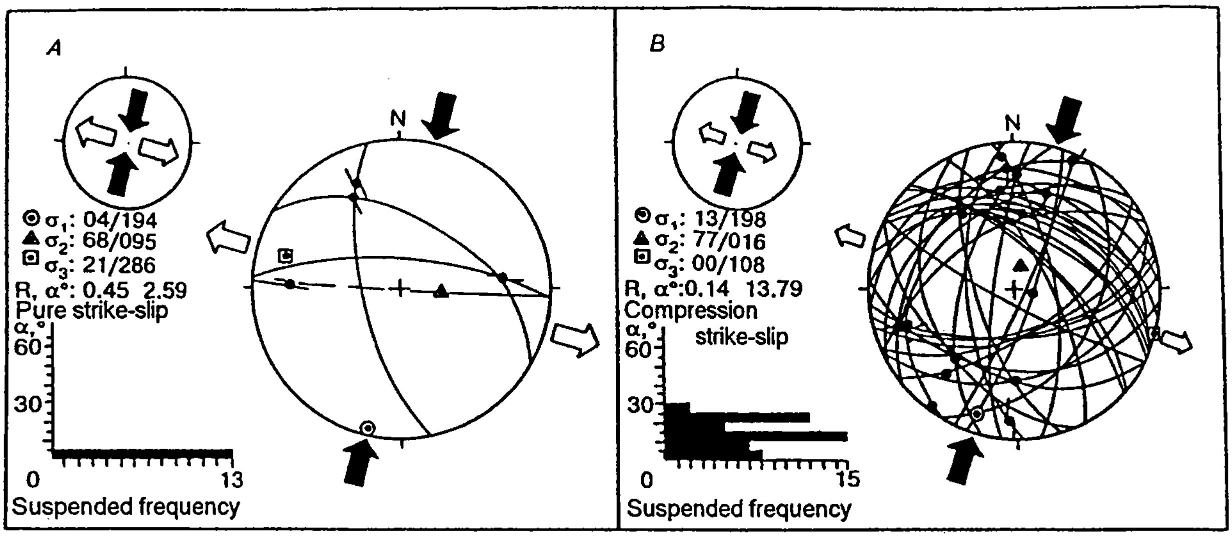


Fig. 4. Paleostress analysis. Fault plane stereograms. Stress tensors from (*A*) focal mechanisms, and (*B*) from slip line measurements in 35 faults, processed with TENSOR program. Stereograms (Schmidt net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses. Histograms show deviatons of the observed slip from the theoretical shear for each fault plane. Principal axes: 1 – maximum compression; 2 – intermediate; 3 – minimum compression. Arrows show orientations of principal horizontal axes, maximum stresses shown by filled and minimum ones by open arrows.

Sailyugem dome has no counter parts. Paleostresses, style of recent block faulting, and the related geomorphology of the Kurai Block show that it is a typical fragment of the zone of compressive lithospheric warping. Being lenticular in plan, the block is bordered in the west and east by wrench fault zones, along which the adjacent blocks move nearly horizontally. In the southwest the block is bordered by a system of reverse faults typical of the boundaries of "rose" structures. Similar terraced topography in the northeastern boundary of the block suggests the presence of an equivalent symmetrical feature there. It means that the Kurai Block is a typical neotectonic "rose" structure developing under regional-scale compression, similar to those west and east of Altai. Therefore, the neotectonic evolution of entire southern Siberia is controlled by the same mechanisms and motive forces.

The neotectonic studies of the Kurai Ridge were supported by grant 93-134 "Continental Rift Tectonics and Evolution of Sedimentary Basins" from INTAS.

REFERENCES

[1] *Gornyi Zhurnal*, vol. 1, no. 10, p. 221, 1845.
[2] V. A. Obruchev, *Zemlevedenie*, vol. 3, p. 1, 1915.
[3] I. G. Grane, *Izv. Zap.-Sib. Otd. Russkogo Geogr. Obshch.*, vol. 3, issue 1–2, p. 1, 1915.
[4] V .P. Nekhoroshev, in: *Oirotiya* [in Russian], Moscow, Leningrad, p. 27, 1937.
[5] E .V. Devyatkin, *Cenozoic deposits and neotectonics of Southeastern Altai* [in Russian], Moscow, 1965.
[6] P. Molnar, P. Tapponnier, *Science*, vol. 189, no. 4201, p. 419, 1975.
[7] A. S. Mukhin, V.A. Kuznetsov, *Vestn. Zap.-Sib. Geol. Upr.*, no. 1, p. 49, 1939.
[8] G. F. Ufimtsev, *Geomorfologiya*, no. 1, p. 5, 1989.
[9] I. S. Novikov, *Geomorphology and geology of southeastern Gorny Altai* [in Russian], available from VINITI, no. 102, 19.01.1993.
[10] 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.
[11] N. A. Florensov, *Geotektonika*, no. 4, p. 3, 1965.
[12] G. F. Ufimtsev, *Geotektonika*, no. 5, p. 115, 1969.

[13] P. M. Bondarenko, *Izv. Alt. Otd. Geogr. Obshch. SSSR*, no. 9, p. 130, 1969.

[14] N. D. Zhalkovskii, O.A. Kuchai, V.I. Muchnaya, *Seismicity and some characteristics of the stress state of the Earth's crust in the Altai-Sayan region*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 36, no. 10, p. 20(16), 1995.

Recommended by Ch.B. Borukaev

Received 24 September 1996