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DYNAMICS AND PALEOSTRESS OF THE CENOZOIC KURAI-CHUYA DEPRESSION OF GORNY ALTAI (SOUTH SIBERIA): TECTONIC AND CLIMATIC CONTROL

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Tectonic and geomorphologic investigation of the Cenozoic Kurai and Chuya Depressions of Gorny Altai (South Siberia), combined with the examination of the existing geological literature and interpretation of SPOT satellite images, show that these depressions developed under the complex interaction of tectonic, sedimentary and climatic processes. The structure of this system of depressions is controlled by the reactivation of the pre-existing Late Paleozoic fault systems. The pre-Paleogene weathering surface and the Pleistocene glacial deposits strongly record the evolution of the climatic input. The timing of tectonic movements and the orientation of the recent stress field are controlled to a large extent by external tectonics, probably in relation to the India–Eurasia convergence.
Depression, dynamics, kinematics, stress tensor, active tectonics

INTRODUCTION

The Altai region (Fig. 1) belongs to the Central-Asian transcontinental dislocation zone that traverses Central Asia from SW to NE and separates the stable Eurasian plate (including the Siberian and Kazakhstan platforms) from the mosaic of microplates of Southeastern Asia (Junggar (Dzungarian), Tarim, and Mongol-China plates). It comprises the Pamir and Tien Shan regions of dominantly reverse faulting, the Altai and Sayan regions of dominantly strike-slip faulting, the Baikal Rift Zone and the Stanovoy transpressional fault zone [1, 2]. It is thought that the convergence of India and Eurasia is the major mechanism which could explain the Cenozoic tectonics of this large area during the last 50 Ma [1–4]. However, the tectonics of the Baikal and West Mongolian region is also strongly influenced by the development of an asthenospheric diapir [5, 6]. The combined action of these two processes in this area is suggested by I. Baljinnyam et al. [7] and D. Delvaux et al. [8].

The Central Asian dislocation zone is of high seismic activity. Some of the world's strongest earthquakes occurred in the Mongol-Altai massif (western Mongolia), adjacent to the Gorny Altai region in Siberia, with a magnitude greater than or equal to $M = 7$.

It was recently shown that north of the Pamir-Tarim line, the continental lithosphere is affected by large-scale folding [9] and that a series of sedimentary basins of ramp or half-ramp type developed there [10]. However, little is known about the Siberian section of the Altai Massif (Gorny Altai) and the Sayan Mountains which lie between the Junggar-Zaisan basins and the Baikal Rift Zone.

The Gorny Altai region in South Siberia is situated near the cross boundaries of Russia, Mongolia, China and Kazakhstan. The territory of Gorny Altai corresponds to the western part of the Altai-Sayan fold belt, formed during Paleozoic accretion-collisional tectonics. Currently, it is a complex surelevated zone, in which thrusts and high-angle reverse faults are present, as well as normal faults. On the basis of fault geometry and earthquake focal mechanisms, P. Molnar and P. Tapponnier [1], P. R. Cobbold and P. H. Davy [2] and

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10

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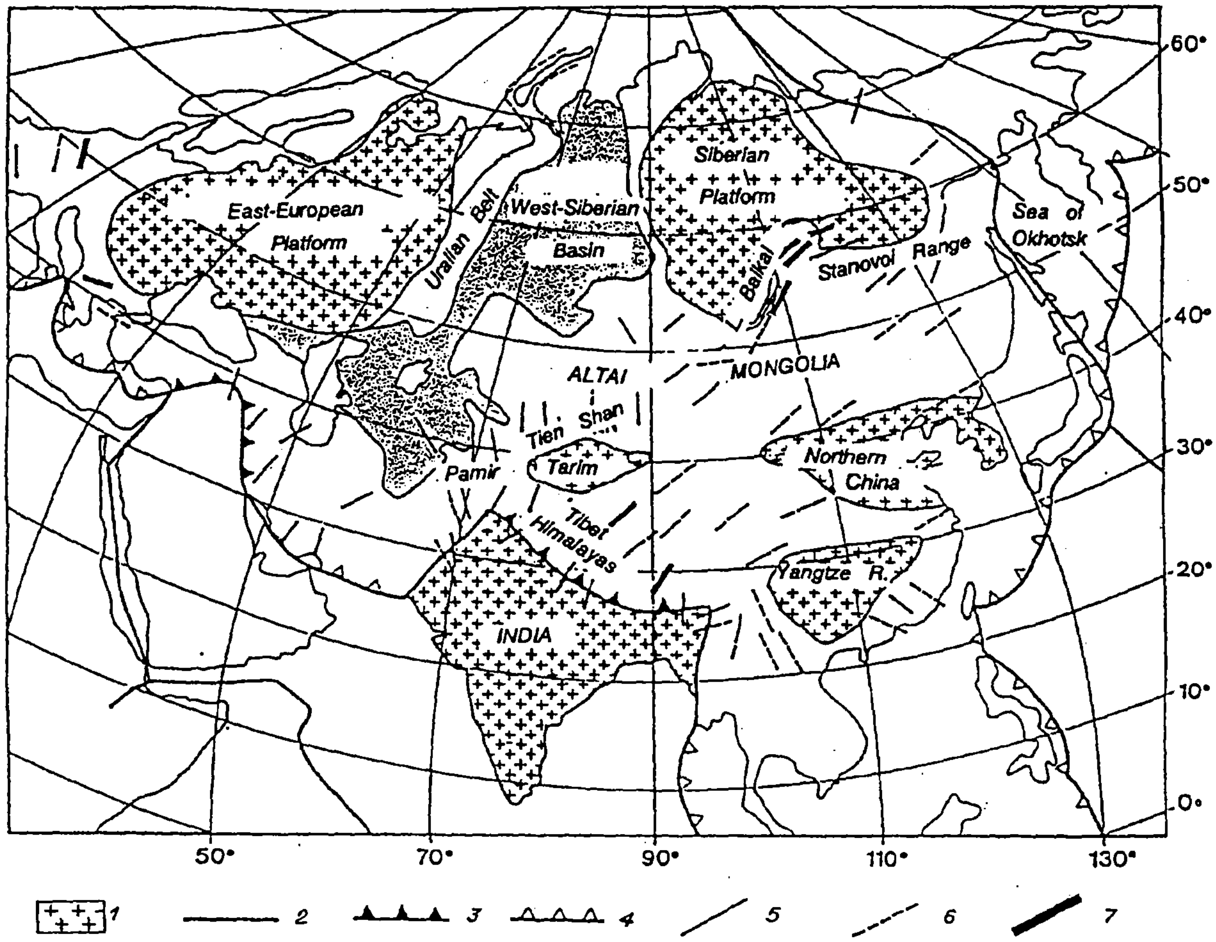


Fig. 1. Tectonic map of Eurasia, with trajectories of horizontal maximum principal stress (S_{Hmax}), compiled from the World Stress Map [12]. ***1*** **— cratons;** ***2*** **— plate margins;** ***3*** **— continental collision zones;** ***4*** **— deep-water trenches;** ***5–7*** **— average orientation (S_{Hmax}):** ***5*** **— compression regime,** ***6*** **— shear regime,** ***7*** **— extension regime.**

P. Tapponnier and P. Molnar [11] inferred a roughly N-S horizontal maximum compressive stress for the Altai region with a general strike-slip stress regime (both maximum and minimum principal stress axes being horizontal). This is consistent with the general stress trajectories of Eurasia (Fig. 1) deduced from the World Stress Map [12].

In this geodynamic context, dominated by horizontal N-S compressive forces and the activity of large wrench fault zones, a series of Cenozoic depressions developed in different tectonic settings. The Kurai and Chuya Depressions developed at a high angle to the direction of horizontal principal compression (NNE-SSW in this area), probably as a single "pull-apart" basin during the Tertiary, and as separated ramp-type basins in the Quaternary. The submeridional Lake Teletskoe — 40 km long, 4–5 km wide and up to 320 m deep — developed only during the Quaternary and opens as a giant tension gash, parallel to the local direction of horizontal principal compression (i.e. perpendicular to the principal tension) [13].

The objective of this work is to investigate the Cenozoic paleostress and kinematic evolution of the Kurai-Chuya sedimentary basin.

The work is based on regional as well as detailed field structural investigations, interpretation of SPOT imagery processed by Ph. Trefois et al. and stress tensor determination from minor faults with slip lines, measured in Cenozoic sediments. Preliminary results were already reported by D. Delvaux et al. [14] and R. Moeys and G. Stapel [15].

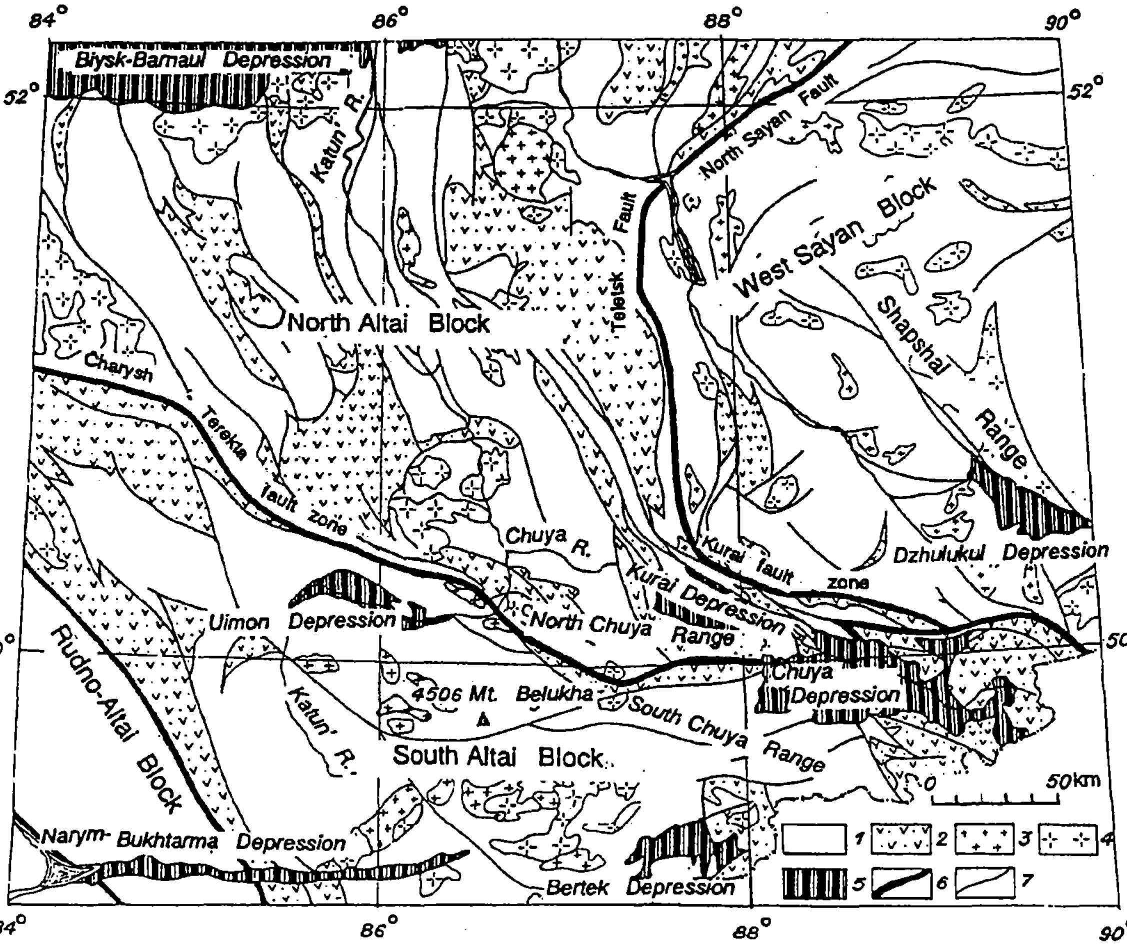


Fig. 2. Geological setting of Cenozoic depressions in Gorny Altai. *1* — **complexes of active margin of Paleoasian Ocean (V—Є), shelves and continental slopes (O—S);** *2* — **Devonian sedimental-volcanogenic complexes of various geodynamic settings;** *3* — **Lower Paleozoic granitoids;** *4* — **Middle-Late Paleozoic granites;** *5* — **largest Cenozoic depressions;** *6* — **major Middle-Late Paleozoic shear zones;** *7* — **other pre-Cenozoic faults.**

GEOLOGY AND TECTONICS OF GORNY ALTAI

The major features of the pre-Cenozoic geology of Gorny Altai were acquired during the Paleozoic (Fig. 2). Reconstruction of the Paleozoic history of Gorny Altai was the aim of the Fourth International Symposium of the IGCP Project 283 "Geodynamic Evolution of Paleoasian Ocean" held in Novosibirsk in 1993. The main stages of this evolution are summarized here, based on the results of M. B. Allen et al. [16], V. G. Belichenko et al. [17], M. M. Buslov et al. [18], A. M. C. Sengör et al. [19], N. A. Berzin and N. L. Dobretsov [20], N. Gusev [21], and D. Delvaux et al. [22].

In the **Vendian—Middle Cambrian**, Gorny Altai developed in the condition of active oceanic margin with subduction zone under the Siberian continent. The Gorny Altai accretionary prism was formed by successive accretion of island arcs of different ages. Four geodynamic units are distinguished from west to east: (1) Vendian-Early Cambrian primitive island-arc (ophiolites, tholeiite-boninite basalts), (2) Early Cambrian accretionary wedge, including basalts, olistostromes with fragments of oceanic crust and paleoseamounts (e.g. Baratal series) and ophiolite complexes (e.g. Chagan-Uzun metaperidotite, gabbro and serpentinite melange), (3) Early-Middle Cambrian volcanic series of normal island-arc (Gorny Altai complex), (4) Middle-Late Cambrian flysch, olistostromes and breccias (Anui-Chuya complex).

In the **Ordovician—Silurian**, the Altai-Mongolian microcontinent converged and collided with the

Siberian plate. The Gorny Altai block and the Cambrian island-arc were accreted to the West Sayan block. This caused the cessation of volcanism within the island arcs, intrusion of collisional-type granitoids, formation of local molasses and accumulation of flysch-type sediments in residual troughs and shelf deposits on stable blocks.

In the **Early Devonian**, the boundary between the West Sayan block and the Gorny Altai accretionary wedge was affected by considerable strike-slip movements mainly along the Kuznetsk-Altai lineament. Westward, a Devonian active continental margin with oblique subduction zone developed between the Gorny Altai and Kazakhstan blocks, in the Irtysh-Zaisan zone. It is marked by Early-Middle Devonian back-rift volcano-sedimentary complexes and intense magmatism (e.g. Chiquetaman granite pluton).

In the **Middle-Late Carboniferous**, translational movement of the Tarim and North China blocks relative to the Siberian plate and rotation of the Siberian plate itself caused the progressive closure of the Irtysh-Zaisan ocean between Kazakhstan and Siberia. This initiated giant strike-slip faults that were active through the Permian. The largest of them in southwestern Altai are the Kurai and Charysh-Terekta fault zones. The collision of Kazakhstan with Siberia occurred in the **Late Carboniferous—Early Permian**, marked by post-collisional magmatism and volcanism, reactivation of granite-gneiss domes and coal deposition in continental basins. Important left-lateral translational movement of the Altai block relative to the West Sayan block along the Kurai and Charysh-Terekta fault zones truncated the Gorny Altai accretionary wedge in the zone of the future Kurai-Chuya Depression (Fig. 2).

Tectonic movements were significantly reduced during the **Mesozoic**. Starting in the Early Jurassic, the West-Siberian basin developed north of the Altai region. In the Mongolo-Altai area, Mesozoic activity is represented by rare Triassic magmatism with associated mineralization and by large fault-bounded Jurassic-Early Cretaceous coal-bearing basins around the Hangay Uplift.

In the Late Cretaceous-Paleocene, tectonic stability under subtropical wet climate caused important denudation with intense chemical weathering and formation of kaolin-montmorillonite weathering crust [23].

The neotectonic structure of Gorny Altai is characterized by a system of WNW-ESE to NW-SE trending ridges 2,500-4,500 m high, separated by depressions lying at altitudes between 1,000 m and 2,000 m (Fig. 3). This general structure is partly controlled by Cenozoic reactivation of major fault zones which often correspond to Paleozoic suture lines and major strike-slip faults. These were reactivated several times, as confirmed by the frequent occurrence of Cambrian peridotite-serpentinite ophiolite fragments and Middle-Late Devonian, Late Carboniferous and Jurassic sedimentary lenses along them.

The pattern of neotectonic faults is shown in the map of active faults of the USSR and adjoining regions [24] and described by N. V. Lukina [25].

The formation of chains of Cenozoic depressions and mountain ranges is often controlled by the reactivation of ancient basement faults, but this relationship is not evident in every case (Fig. 3). The Saigonysh and Dzhulukul Depressions with adjacent mountain ranges are controlled by the reactivation of the Shapshal fault; the Kurai-Chuya Depression and Kurai Range, by reactivation of the Kurai fault zone; and the Surukul, Chuya and Samakha Depressions, by the Charysh-Terekta fault zone. The northern extremity of Lake Teletskoe is controlled by strike-slip movements along the North Sayan fault, but the long N-S segment of the lake is more loosely controlled by a belt of mylonitic schists. In the southern and southwestern Gorny Altai, the Cenozoic depressions are only partly controlled by active faults. As a rule, they cross ancient faults and folded basement structures, which is well expressed in the Markakol Depression and in the Narym-Bukhtarma group of depressions.

MORPHOLOGY AND STRUCTURE OF THE KURAI-CHUYA DEPRESSION

The Kurai and Chuya Depressions lie between the West Sayan and the Altai blocks, at the southeastern extremity of the Gorny Altai accretion wedge. Their basement consists dominantly of Vendian-Cambrian (Baratal, Balkhash and Gorny Altai series) and Devonian volcano-sedimentary sequences. It corresponds to the southeastern extremity of the Gorny Altai accretion wedge, squeezed between the Kurai fault zone to the north, and the Charysh-Terekta fault zone to the south, during the left-lateral translational movement of the Altai block relative to the East Sayan block (already incorporated into the Siberian platform), in the Late Carboniferous—Permian (Fig. 2). The geology of this area is largely described by P. M. Bondarenko [26], M. M. Buslov et al. [18] and N. A. Berzin and N. L. Dobretsov [20], for the Paleozoic basement, and by E. V. Devyatkin [23, 27], B. M. Bogachkin and L. I. Rozenberg [28–30], as well as B. M. Luzgin and G. G. Ruzanov [31], for the Cenozoic period.

Basement structure. Structural analysis reveals that post-Devonian structuring of the basement occurred

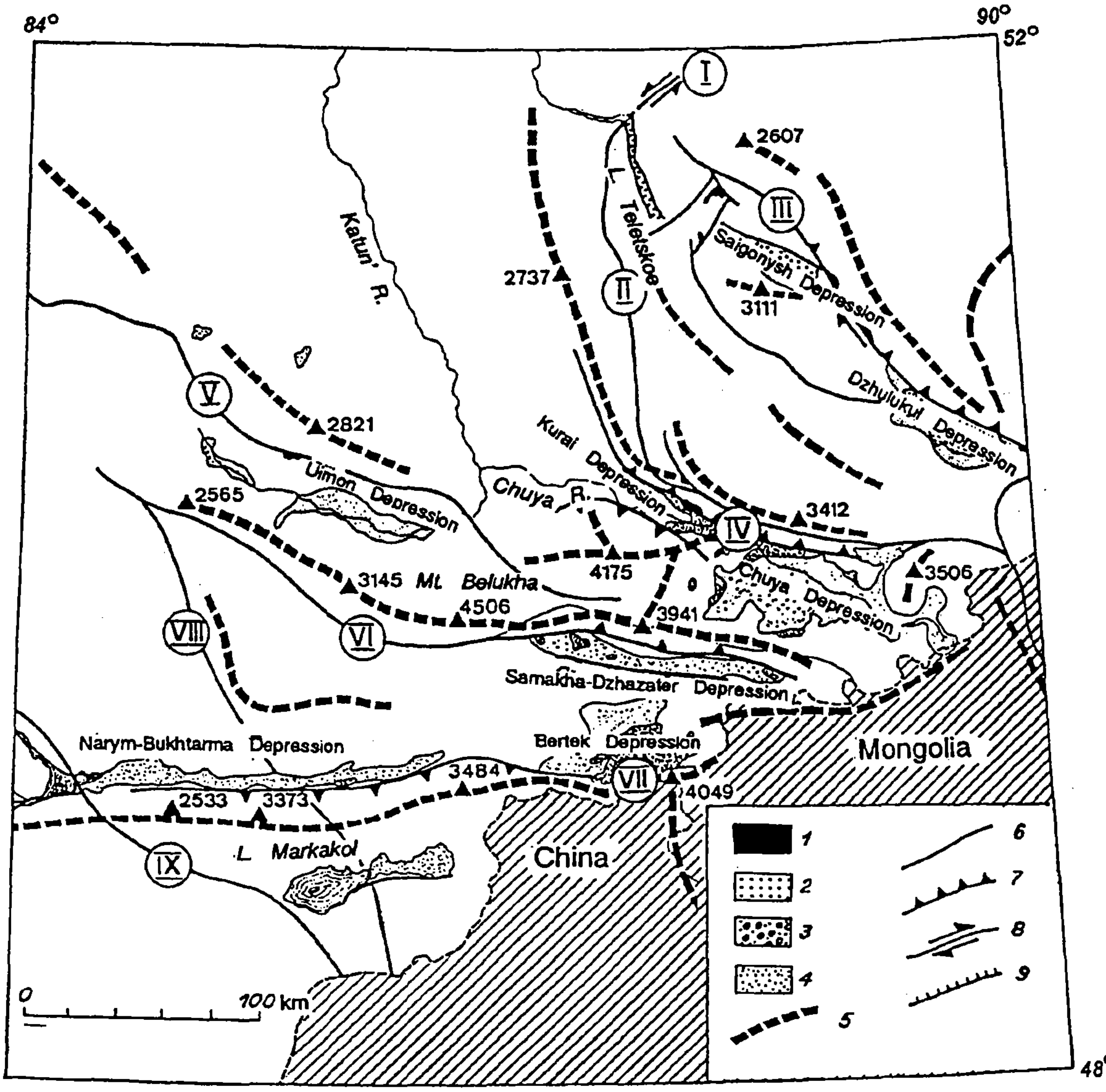


Fig. 3. Large-scale neotectonic structure of Gorny Altai, in relation to major Late Paleozoic basement faults: (I) North-Sayan, (II) Kurai-Teletsk, (III) Shapshal, (IV) Kurai, (V) Charysh-Terekta fault zone, (VI) – South-Katun', (VII) South-Altai, (VIII) Markakol, (IX) Irtysh. *1* – Carboniferous lenses along the major faults, *2* – Jurassic, *3* – Tertiary, and *4* – Quaternary deposits, *5* – mountain ranges with height marks, *6* – major faults with possible Quaternary movements, *7* – reverse faults, *8* – strike-slip faults, *9* – normal faults.

under the Chuya and Kurai Depressions in response to two successive compressive tectonic stages. The first stage caused general folding of the Devonian along a broad E-W axial trend, and reverse to thrust faulting in the pre-Devonian basement. The second stage corresponds to large-scale left-lateral strike-slip movements, reactivating the previous thrust faults and affecting the folded Devonian.

The Kurai and Chuya Depressions developed in the zone of more intense dislocation between the Kurai and the Charysh-Terekta fault zones. These faults separate the nonmetamorphic Early Cambrian and Devonian basement from Late Precambrian metamorphic gneisses to the north and large lenses of metamorphosed Cambrian (Gorny Altai series) to the south.

The Quaternary structural map (Fig. 4) shows that the major Late Paleozoic faults controlled basin structure and deposition of the Paleogene-Neogene sediments. The same fault zones were again reactivated

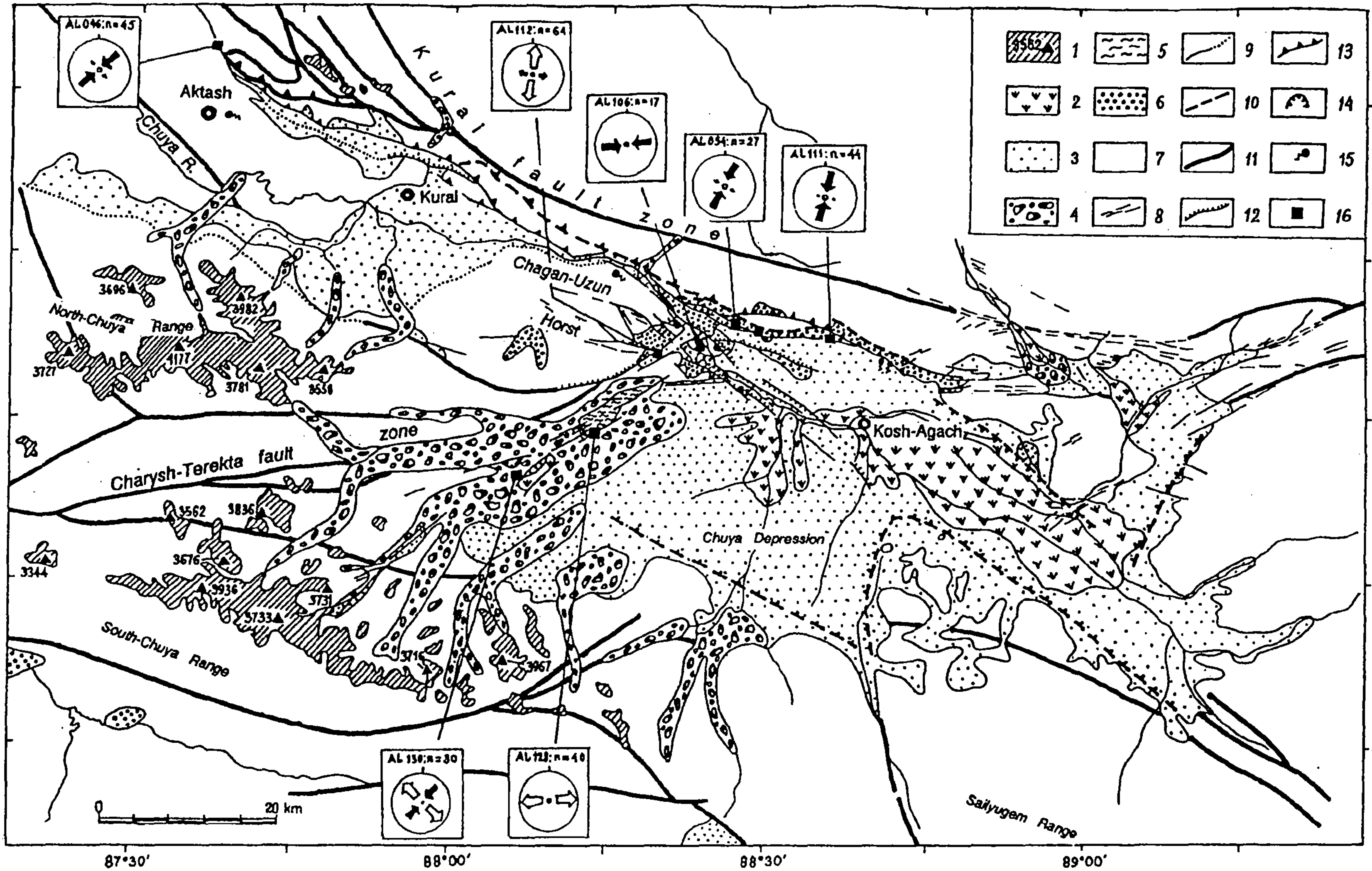


Fig. 4. Quaternary structural map of the Kurai-Chuya Depression with stereograms of secondary faults, fractures and their paleostress tensors. Geology is given according to E. V. Devyatkin [27], N. Gusev [21], and Geological Map of Gorny Altai on a scale of 1:500,000. The Quaternary structure is corrected in agreement with field observation and interpretation of satellite images. *1, 2* — Holocene: *1* — glaciers with altitude marks, *2* — swamps; 3–5 — Late Pleistocene: *3* — lacustrine-fluvioglacial, *4* — glacial moraines, *5* — varved clays; *6* — Tertiary deposits; *7* — whole basement; *8* — structural lines and lineaments recognized on satellite images; *9* — faults with Quaternary movements; *10* — Tertiary faults; *11* — major basement faults; *12* — strike-slip faults; *13* — reverse faults and overthrusts; *14* — landslides; *15* — sources; *16* — outcrops (stress symbols as in Fig. 9).

during the Quaternary, as indicated by the presence of neotectonic structures in Quaternary glacial deposits of Middle-Late Pleistocene age.

Morphology. The present floor of the 20 × 30 km Kurai Depression lies at an altitude of 1,550 m, and that of the 60 × 90 km Chuya Depression, between 1,800 and 2,100 m. They are entirely surrounded by mountain ranges and are drained by the Chuya River (Fig. 5). The Kurai Range borders on the north both the Kurai and Chuya Depressions, with a maximum altitude of 3,400 m. The North Chuya Range (max. alt. is 4,176 m) limits the Kurai Depression in the south. The northeastern extremity of this range forms the Chagan-Uzun horst (max. alt. is 2,900 m) which separates the Kurai Depression from the Chuya Depression. The Chuya Depression is bordered in the south by the South Chuya Range on its western half (max. alt. is 3,936 m) and by the Salyugem plateau on its eastern half (max. alt. is 3,500 m). The Chuya Depression contains up to 1,200 m of Cenozoic sediments (drilled to a maximum of 671 m) and has a general WNW-ESE orientation. In the Kurai Depression, the deepest section of the basement was reached at 525 m. Several boreholes in both basins allowed their structure and stratigraphy to be recognized in detail [27, 31].

The recent geometry of the Kurai and Chuya Depressions resembles that of a lozenge-shaped half-graben, but their Quaternary structure is closer to that of a full ramp basin for the Kurai Depression, and of a half-ramp basin for the western part of the Chuya Depression (Fig. 4). The lozenge-shaped geometry is mainly inherited from the Tertiary structure, which in turn was controlled by the pre-Cenozoic fault pattern.

Tertiary structure. Because of the intense tectonic activity in the Quaternary, the present structure and kinematics of the Kurai-Chuya Depression are different from the Tertiary ones. The structure of the Tertiary depression can be inferred from the isolines of the Cenozoic sediments shown by E.V. Devyatkin [27] for the eastern side of the Chuya Depression. They indicate the presence of a relatively narrow graben of Tertiary sediments in the axial part of the depression, bounded on the northern and southern sides by normal faults presently buried under the Quaternary deposits (B-B′ and C-C′ sections in Fig. 6).

On its southern side, the sedimentary basin is limited by alignments of smooth isolated hills (inselbergs) of Devonian rocks, surrounded by Quaternary sediments. These hills correspond to the highly degraded hanging wall of inactive Tertiary normal faults buried under the Quaternary cover (Fig. 4). These paleo-fault lines have a broken trace in map view, with the western segment lying about 16 km south of the eastern segment. The link between the two inferred Tertiary fault lines corresponds to a similar hanging paleo-wall of N-S trend, in the continuation of a basement fault known in the Salyugem plateau.

The Chagan-Uzun Massif forms a tilted, lozenge-shaped horst between the Kurai and Chuya Depressions, ranging from 2,600 to 2,900 m in height. It contains remnants of Tertiary sediments elevated relative to the present-day floor of the depressions (sections A-A′, B-B′, C-C′ in Fig. 6). This suggests that in the Tertiary, the Kurai and Chuya Depressions formed a single basin.

Quaternary structure. The western half of the Chuya Depression displays most clearly the structure of a half-ramp (Figs. 4, 6). The northern boundary of the West Chuya Depression corresponds to a complex thrust fault system that caused the successive tectonic superposition of Cambrian series, Ordovician granodiorite, Devonian and Carboniferous sediments over Oligocene-Miocene coal-bearing silt and clay deposits. It lies on the prolongation of the Aktash thrust system, which forms the northern tectonic boundary of the Kurai Depression 50 km westward.

In the Kurai region, the Aktash thrust system is well described by P. M. Bondarenko [26] who demonstrated its multistage origin. Detailed mapping and borehole information shows the tectonic superposition of Carboniferous deposits over Middle Pleistocene glacial deposits (Fig. 6, section A-A′). Overlying glacial deposits of Late Pleistocene age seem to be undisturbed. P. M. Bondarenko concluded that reactivation of the Aktash fault zone occurred until the Quaternary period, with the last movements in the Middle Pleistocene.

To the southwest, the floor of the Chuya Depression is progressively elevated from 1,800 m at its center, to the shoulders of the South Chuya Range (Fig. 5). The difference in altitudes between the center of the depression and the top of the South Chuya Range within a horizontal distance of 60–80 km is 2,100 m. This elevation is not accommodated by any significant Quaternary fault step, but by a long continuous gentle slope. Toward the summit the relief becomes more and more alpine, deeply incised by glacial valleys, but the tangent surface to the remaining mountain shoulders forms a continuous gentle slope, without significant breaks (Fig. 6, section B-B′). The Tertiary fault buried under the Quaternary deposits delimits the zone of basement outcrop from the zone of basin fill, but it does not appear to be significantly reactivated in the Quaternary.

The smaller Kurai Depression is also bordered to the south by a high mountain range (North Chuya Range, up to 4,176 m). The transition from center of the basin (1,550 m) to summit of the range occurs over

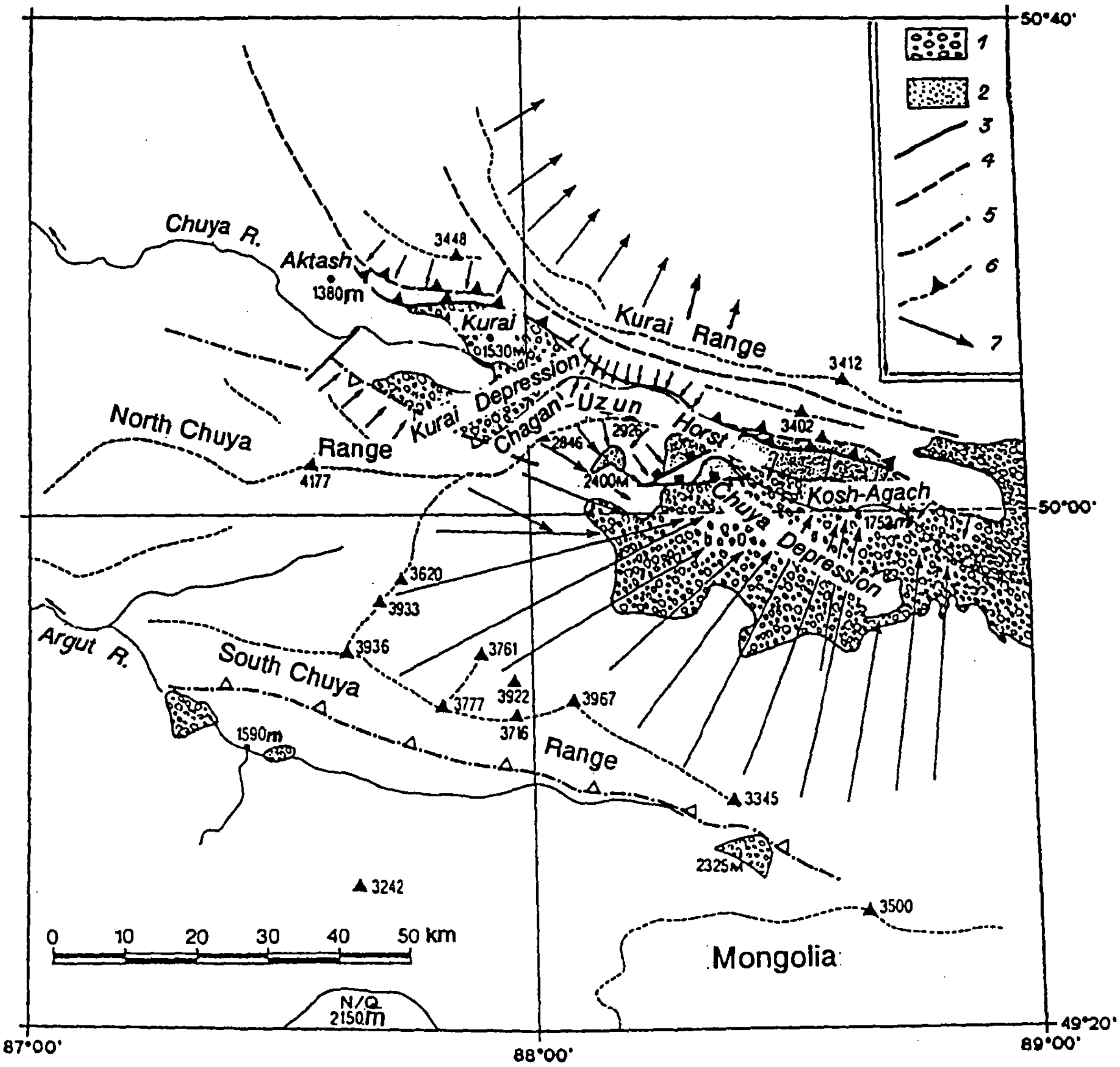


Fig. 5. Structural and morphological map of the Kurai-Chuya Depression. *1* — Quaternary and *2* —Neogene sediments, *3* — faults active during the Quaternary; *4* —faults possibly active during the Tertiary; *5* — supposed Tertiary faults, *6* — mountain ranges with altitude marks, *7* — general dipping direction of the morphological surface.

a short distance (20 km), possibly due to the action of a border fault, but the important glacial activity in this area masks the tectonic structure.

The Chagan-Uzun horst forms the western shoulder of the Chuya Depression, sloping progressively centerward, but separated from the Kurai Depression by a steep scarp (Fig. 6, section D-D′).

At the foot of the Chagan-Uzun tilted block, the Neogene Taldy-Dyurgun brown-coal deposits amount to 100 m in thickness and are overlapped by more than 125-m thick Quaternary deposits. These Neogene deposits are actually separated from the rest of the Chuya Depression by normal movements along a large NE-trending fault in the Kyzyl-Chin valley (Fig. 6: section E-E′). These movements occurred mostly in the Quaternary. The evidence is a 200-m high escarpment, the internal structure of the coal field [31] and the presence of minor faults affecting simultaneously the Neogene and Quaternary deposits.

STRATIGRAPHY AND BASIN EVOLUTION

The stratigraphic evolution of the Kurai-Chuya Depression is clearly controlled by tectonic pulses which

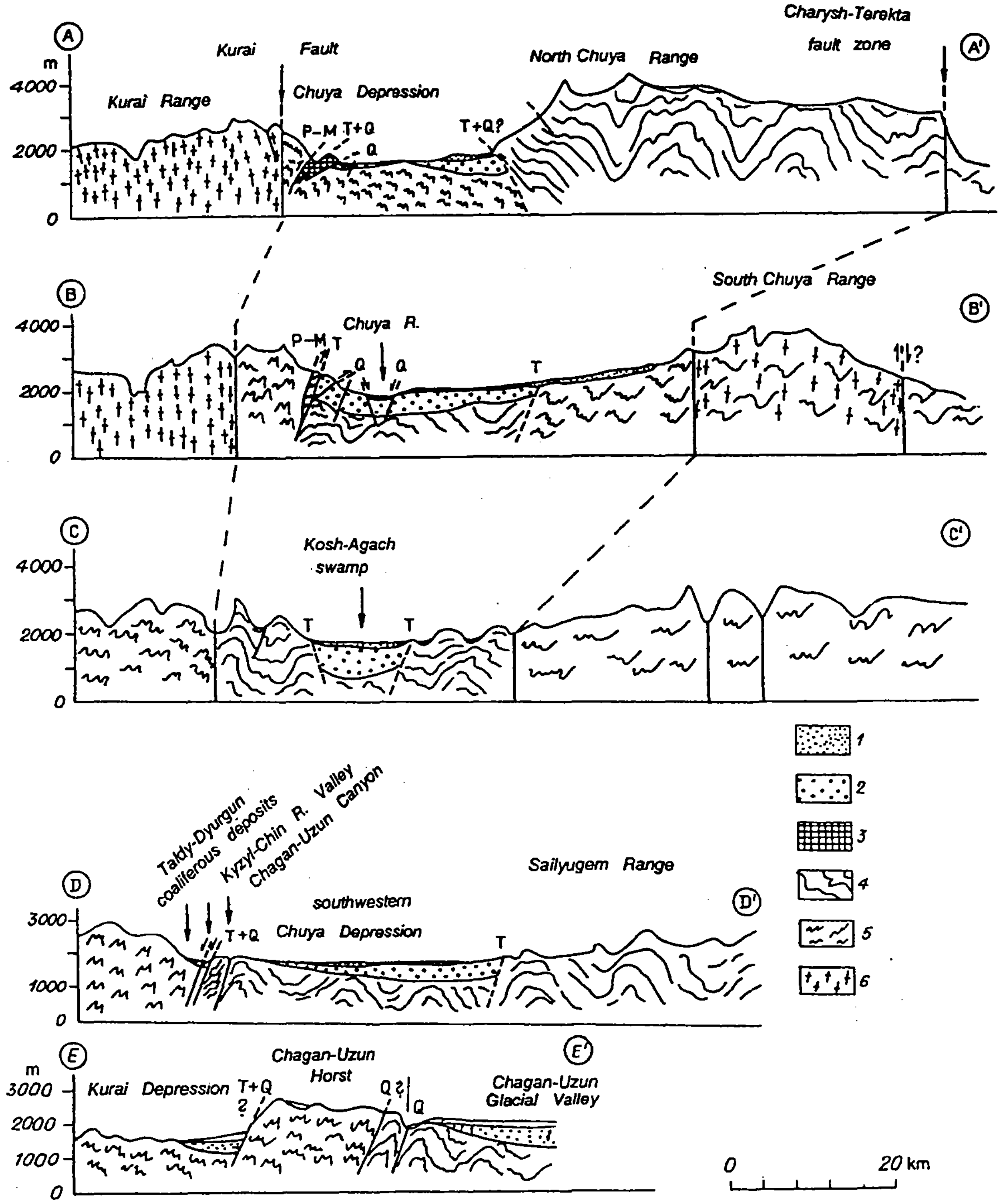


Fig. 6. Geological cross sections of the Kurai-Chuya Depression. Vertical magnification: × 4. Location of sections in Fig. 7. Period of fault activity indicated as P–M (Paleozoic-Mesozoic), T (Tertiary) or Q (Quaternary). *1* — Quaternary and *2* — Tertiary sediments, *3* — Carboniferous, *4* — Devonian, *5* — Vendian-Cambrian, *6* — gneisses and schists.

modified periodically the tectono-sedimentary environment. The following description is based on synthesis of descriptions given elsewhere [23, 27–31]. The Chuya Depression presents the best sections of Cenozoic deposits for the entire Gorny Altai, and the composition of sediments reflects the modification of the tectonic and climatic environment. However, it appears that the formations are dated by different authors in different ways [31], so the ages given here are just the most frequently cited and are to be interpreted with care.

Early Paleogene prelacustrine stage. In the Late Mesozoic-Early Paleocene (up to Middle Oligocene according to Devyatkin), stable tectonic conditions under humid subtropical climate caused intense denudation and chemical weathering of the basement, with formation of a well-developed peneplain with kaolin soil (**weathering crust** in the Russian literature). Tertiary sedimentation started with redeposition of the reworked material of the weathering crust in the Paleocene-Early Eocene Karachum Formation (Oligocene, according to E. V. Devyatkin [27]): subaerial sand-clay, reddish rose to white, deposits with subtropical fossil trees.

Remnants of the Late Cretaceous-Early Paleocene peneplain can still be seen at the top of the mountain relief as horizontal or gently inclined flat surfaces. The recognition of this reference surface gives us some idea of the amplitudes of vertical movements in the area surrounding the Chuya Depression.

The unconformity between the Devonian basement and the Tertiary sediments is very well exposed along the western border of the Chuya Depression, along the Kyzyl-Chin and Chagan-Uzun valleys. There, a 200 m high section exposes folded Middle Devonian shales, sandstones and volcanics, the top of which was completely weathered into clays (kaolin and others). The *in situ* weathered horizon is covered by a thin layer of limestone pebbles, then by well-stratified yellowish-reddish-whitish clay deposits. According to the local stratigraphy, the weathered horizon corresponds to the Late Cretaceous-Paleocene peneplain. The above pebble layer and clay deposit mark the onset of vertical tectonic movements, in the Karachum time, causing renewal of erosion and wearing of the weathering crust.

The relief of the basement/Tertiary unconformity also indicates that Early Paleogene tectonic movements took place prior to the deposition of the Kosh-Agach Formation. This suite, which marks the beginning of the lacustrine environment, rests (1) on *in situ* weathering crust formation, (2) on the redeposited products of the weathering crust (Karachum Formation), or (3) directly on fresh basement rocks [31]. E.V. Devyatkin [27, p. 204] showed that the relative differentiation of the pre-Oligocene relief in Southern Altai reached 300–350 m and even locally 700 m. On the basis of drilling data, this was confirmed by B. M. Luzgin and G. G. Rusanov [31] for the Kurai and Chuya Depressions.

Late Paleogene—Neogene lacustrine stage. The Chuya Depression is bordered by steep slopes since the Late Eocene or Early Oligocene and subsidence continued until Middle Pliocene, with relatively fixed contours. At that time, the Kurai and Chuya Depressions probably formed a unique basin, and a large, long-lived lake existed during all this period, allowing speciation of endemic fauna [28].

The lacustrine sedimentation started with the deposition of the **coal-bearing Kosh-Agach Formation** in a shallow water basin, and consists of lacustrine limy and silty clays with lenses of marls and brown coal and sand in the offshore regions. The Kosh-Agach Formation is believed to be of Early-Middle Miocene [27], Eocene-Oligocene [28, 30] or Oligocene to Miocene [31] age.

The **Tueryk Formation** was then deposited in a large lake basin, consisting of carbonate clays and mudstones with lenses of limestones and marls of Early Miocene age (or Middle Miocene-Early Pliocene [27]). In the Middle Pliocene, the Neogene lake presents an advanced stage of endemism, with the Kyzylgir Formation containing abundant freshwater mollusks, ostracodes, fish, mammals and plants [32]. Such an advanced stage of endemism is similar to the Baikalian stage at that time.

Late Pliocene tectonic pulse. It is agreed by most authors that in the **Late Pliocene** a rapid acceleration of tectonic movements initiated the third phase of basin development [27]. Sedimentation became coarser, with sands and gravels (**Beken Formation**). The former unique Neogene depression was split into two subsiding blocks (Kurai and Chuya), separated by a rising block (Chagan-Uzun tilted horst). In the meantime, reverse movements occurred along the common northern border fault. The two isolated depressions evolved differently. The Kurai Depression became a full ramp basin with reverse faulting along the southern boundary, while the Chuya Depression became a half-ramp basin, with block tilting and gradual uplift of the southern margin to an altitude of 4,000 m.

The combination of reverse movements along the northern border fault and tilting of the Chuya block in Late Pliocene-Pleistocene caused denudation and dislocation of the Tertiary sediments along the margins of the Chuya Depression. These were redeposited in the central part of the basin, which remained in a fluvio-lacustrine environment until at least the end of the Early Pleistocene (lacustrine silts, clays, stromatolites and limestones). The Neogene-Paleogene sediments of the uplifted Chagan-Uzun block were almost completely washed away. In Middle-Late Pleistocene, sedimentation is characterized by fluvio-glacial to glacial-lacustrine environment, with a dramatic influence of the Riss and Würm glaciations, combined with high rate of tectonic activity.

Late Pleistocene glacial period. The present-day surface geology is mostly inherited from the **Late Pleistocene glaciations.** Glacial moraines cover most of the western side of the Chuya Depression, owing to the coalescence of several important glaciers in the Chagan-Uzun valley. More limited moraines are also present along the Tarkhata River, on the southern border and along the Kakaria River, on the northern border. The rest of the depression is covered by fluvio-glacial deposits composed mostly of poorly sorted and poorly rounded pebbles of metamorphic basement. Glacial-lacustrine varved clays lie on the bottom of the U-shaped Chagan-Uzun valley, directly on the Devonian basement.

The presence of a Late Pleistocene glacial lake is indicated by a series of lacustrine terraces well preserved all around the Chuya Depression at altitudes ranging between 2,000 m and 2,100 m, while the present-day outlet of the Chuya River is at 1,720 m only. These are both sedimentary terraces at the mouth of the lateral rivers and abrasive terraces along the flanks of the tectonic scarps. The regular succession of terraces of decreasing altitude all around the Chuya Depression indicates a step-like lake level drop. The terraces are present also against the glacial moraines. Similar terraces were recognized in the Kurai Depression by E.V. Devyatkin [27]. Numerous traces of primitive human occupation were found all around the Chuya Depression at an altitude of 2,000-2,100 m, close to the highest terraces of the Late Pleistocene lake.

These terraces indicate the presence of a glacial lake during the last glacial period (Würm), owing to the ice damming of the Chuya River at the outlet of the Kurai Depression near Aktash, and in the canyon between the Kurai and Chuya Depressions [27]. A. N. Rudoy and V. R. Baker [10] explain the disappearance of these lakes by catastrophic flow outburst, following the rupturing of the ice dams during a warming period. However, the sudden disappearance of the glacial lake contradicts the presence of successive terraces of decreasing altitude. As an alternative explanation, it can be proposed that, initially, the lake level dropped progressively because of the increasing erosion of the outlet, then it dropped abruptly because of the rupturing of the ice dam. This is suggested by the geomorphological characteristics of the outlet of the Kurai Depression. In this area, the Chuya River is deeply incised into flat uplifted block, surelevated relative to the floor of the Kurai Depression. The altitude of this block ranges between 2,000 and 2,100 m. The uppermost lacustrine terraces lie precisely at the same altitude. A glacier flowing down from the North Chuya Range in the Mashei valley blocked the Chuya River which deviated to the north. It then eroded progressively to form a new valley, contouring the ice dam. During the warming period at the beginning of the Holocene, rupturing of the ice dams at the outlet of both the Kurai and Chuya Depressions may have caused the catastrophic flow outburst described by A. N. Rudoy and V. R. Baker [10] in the lower Chuya and downstream of the Katun River.

Holocene. The Holocene deposits correspond to alluvial wearing, kaolin redeposition on flat bottoms, swampy areas and periglacial structures. Neotectonic movements along the northwestern flank of the Chuya Depression uplifted the Paleogene-Neogene clays. These were remobilized, mostly along the active northern boundary faults, and flowed down to the center of the present depression by creeping and giant landslides. Finally, relatively pure white clay was redeposited on flat bottoms.

MICROTECTONICS AND PALEOSTRESS

Joints and minor faults with slip lines were measured along the Kurai fault zone which forms the northern boundary between the Kurai and Chuya Depressions, and along the Kyzyl-Chin and Chagan-Uzun (KC-CU) fault zone at the western side of the Chuya Depression. Measurements were made in Devonian-Carboniferous rocks (Kurai fault zone near Aktash: outcrop AL 046), in the Neogene or at the contact between basement and Neogene (Kurai fault zone at the northern border of the Chuya Depression: outcrops AL 054, 055, 106, and 111) and in the Neogene and Upper Pleistocene glacial deposits of the KC-CU valleys (outcrops AL 112, 128, and 130).

For each site, determinations of paleostress tensor and separation of fault population were made using the TENSOR program and according to the standard procedures of paleostress analysis. Fault plane and slip line orientations, including slip senses, are used to compute four parameters of the reduced stress tensor, as defined by J. Angelier [33]: the principal stress axes σ_1 (maximum compression), σ_2 (intermediate compression) and σ_3 (minimum compression) and the ratio of principal stress differences $R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. Two additional parameters of the full stress tensor are the ratio of extreme principal stress magnitudes (σ_3 / σ_1) and the lithostatic load, but these cannot be determined from fault data only. The first four parameters are determined using successively an improved version of the Right Dihedron method of J. Angelier and P. Mechler [34], and a rotational optimization method, using the TENSOR computer program developed by D. Delvaux [35].

The fault populations isolated for stress tensor determination were also used to obtain the mean movement planes and slip directions for each site. In some cases, the major fault system is accompanied by a conjugated system of less importance. In other cases, two or more independent systems are present. The paleostress results

Table 1

Outcrop List and Parameters of Reconstructed Stress Tensors

Outcrop	Region, age, and texture	n (nT)	% nT	σ_1	σ_2	σ_3	R	α	Tensor type
AL 046	Krasnye Vorota, Aktash Fault Zone	21 (170) 45 (170)	12 26	11/234 12/320	60,342 05/139	28/137 77/024	0.45 0.64	11.4 11.0	Pure strike-slip, *D* Pure compression, *A*
AL 054	Neogene, Northern boundary fault	27 (35)	77	04/029	08/299	81/145	0.65	15.9	Pure compression, *A*
AL 055	Neogene – Cambrian, Northern boundary fault	18 (40)	45	03/029	61/293	29/121	0.08	9.4	Compression strike-slip, *B*
AL 106	Chagan-Uzun R., Neogene base	17 (26)	65	13/083	05/174	76/286	0.50	11.1	Pure compression, *A*
AL 109	Yanterek R., Neogene	10 (12)	83	25/125	50/000	29/229	0.24	10.4	Weakly expressed
AL 111	Tydtugem R., Neogene – Devonian	45 (69)	65	00/198	03/108	87/293	0.38	18.5	Pure compression, *AA*
AL 112	Kyzyz-Chin R., Neogene	63 (79)	80	86/257	03/100	02/010	0.32	7.6	Pure extension, *AA*
AL 128	Beltir Village, Quaternary varved clays	40 (046)	87	64/037	19/171	17/266	0.49	σT_{max}	Pure extension, *A*
AL 130	Chagan R., Valley, Quaternary varved clays	30 (38)	79	05/043	81/162	08/313	0.70	8.7	Pure strike-slip, *AA*

Note. n — Number of data used; nT — total number of undifferentiated data in database; $\%nT$ — percentage of data used for computation; ($\sigma_1 - \sigma_3$) — principal stress directions in dip/azimuth format; R — shape ratio of stress ellipsoid $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; α — mean deviation angle between observed and computed slip directions. Tensor quality: AA = very good, A = good, B = medium, C = poor, D = bad. Tensor type: function of inclination of stress axes and R ratio.

are reported in Table 1, with tensor type and quality, and in Table 2, with the mean and auxilliary movement planes. The stress map symbols with the orientation of both horizontal principal stress (S_{Hmax}) and horizontal minimum stress axes (S_{Hmin}) are displayed in Fig. 4. Figure 6 shows the interpreted structure in cross sections, Fig. 7 synthesizes the Quaternary kinematics along the observed faults, and the complete stereograms are presented in Fig. 8.

The Kurai fault zone in Aktash. The Kurai fault zone is the active northern margin of both Kurai and Chuya Depressions. It has been investigated in detail by P. M. Bondarenko [26] in the area of Aktash because of mercury present in the fault gauge. The Kurai fault zone is particularly complex in the Aktash area, with three separated north-dipping thrusts causing the superposition of Early-Middle Cambrian, Late Cambrian-Ordovician, Devonian-Carboniferous and Tertiary-Quaternary: the Aktash, Meridional and Quaternary faults are recognized from north to south (Fig. 6, section A-A′). Their development is related to Late Caledonian, Hercynian, Mesozoic and Cenozoic periods of activity.

Drilling for Carboniferous coal and Neogene brown coal exploration in the northern border of the Kurai Depression revealed tectonic superposition of Paleozoic basement over Quaternary and Neogene. For example, BH-328 [27, Fig. 10] penetrated first Early Paleozoic limestone, then Lower Givetian porphyrite at 42 m (reverse fault), a melange of Devonian and Carboniferous coal at 74 m (reverse fault), Pleistocene moraine at 102 m (reverse fault), Tertiary brown clays at 220 m (normal stratigraphic contact) and finished in the Baratal series of Vendian-Early Cambrian age at 300 m (basement unconformity). The Givetian porphyrite and Devonian-Carboniferous deposits are tectonic lenses in the main zone of movement. In front of the Quaternary thrust fault, drilling also indicates the presence of a small Quaternary graben, parallel to the trend of the Quaternary fault, and limited in the south by a north-dipping normal fault (the Aktash graben).

Our measurement site AL 046 is situated in the western extension of this fault zone, in a deep gorge (Krasnaya Gorka) in a melange of Devonian and Carboniferous rocks. In total, four different tensors were determined, and their succession was established using crosscut relationships. At least the last two stages of faulting deformation affect simultaneously the Devonian and Carboniferous sediments. The youngest stage is attributed to the Quaternary, knowing that this fault was active during this period. In default of relevant data,

Table 2

Classification of Stress Tensors, with Principal Movement Planes

Outcrop	Description	$n(Q)$	σ_1	σ_2	σ_3	R	P. m. p.	A. m. p.
			Kurai Fault Zone, Tertiary (?)					
AL 046	Aktash Fault, Devonian–Carboniferous	21(*D*)	11/234	60/342	28/137	0.45	9 × 54/029 24/100 RS	7 × 87/055 08/095 RS
AL 055	Northern Chuya Depression, basement-Neogene	18(*B*)	03/029	61/293	29/121	0.08	7 × 86/257 0/167 RD	4 × 40/061 31/017 RD
Weighted mean: 2 tensors		39	04/221	61/318	29/129	0.28	Shear	
			Kurai Fault Zone, Quaternary (?)					
AL 046	Aktash Fault, the latest movement	45(*A*)	12/230	05/139	77/024	0.64	22 × 54/049 54/004 RD	10 × 89/337 52/248 NS
AL 054	Northern Chuya Depression, active escarpment	27(*A*)	04/029	08/299	81/145	0.65	21 × 48/022 47/037 RS	6 × 48/241 43/208 RD
AL 111	Northern Chuya Depression, active escarpment	45(*AA*)	00/198	03/108	87/293	0.38	26 × 45/009 45/018 RS	9 × 52/167 44/209 RS
Weighted mean: 2 tensors		117	04/213	02/123	86/005	0.54	Pure shear	
			Chuya Depression, western margin, Quaternary					
AL 106	Chagan-Uzun R., Neogene	17(*A*)	13/083	05/174	76/286	0.50	8 × 52/085 52/077 RD	5 × 70/270 58/216 RD
AL 112	Kyzyl-Chin R., Neogene-Quaternary	63(*AA*)	86/257	03/100	02/010	0.32	20 × 57/01 57/005 NS	20 × 86/137 24/225 ND
AL 128	Late Pleistocene, varved clays	40(*A*)	64/037	19/171	17/266	0.49	13 × 76/25 44/331 ND	10 × 50/047 39/094 ND
AL 130	Late Pleistocene, varved clays	30(*AA*)	05/043	81/162	08/313	0.70	13 × 82/153 00/243 RS	10 × 87/093 08/003 RD
Weighted mean, 4 tensors		150	86/003	03/234	03/144	0.81	Shear-extension	
			Kurai-Chuya Depression, Quaternary (bulk data)					
		267	04/224	85/007	03/133	0.43	Pure shear	

Note. ***n*** **— Number of data used; (*Q*): Tensor quality (see legend of Table 1); σ_1 — σ_3 — principal stress directions in dip/azimuth in format; *R* — shape ratio of stress ellipsoid $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; P. m. p. — principal movement plane with slip line and slip sense; A. m. p. — auxiliary movement plane with slip sense (number of faults, dip/dip direction of plane, plunge/azimuth of slip line). Movements: N — normal fault, R — reverse fault, D — dextral shear, S — sinistral shear.**

the previous stage is attributed tentatively to the Tertiary period. The stress tensors are of good quality, due to the large amount of data and a large variety of fault orientations (Table 1, Fig. 8, *A*). For the earlier movement, the stress tensor is of strike-slip type (σ_1 and σ_3 horizontal) with NE-SE S_{Hmax}. The dominant movement is oblique, reverse-sinistral along WNW-trending 54° N-dipping faults. For the last movement, the regime is strongly compressive (σ_1 horizontal and σ_3 vertical), with the same S_{Hmax} orientation and dominant reverse dip-slip movements along NW-trending 54° N-dipping faults. There are also conjugated faults in the form of NE-trending subvertical strike-slip faults.

The Kurai fault zone in the Chuya Depression. At the northern margin of the Chuya Depression, the structure of the Kurai fault zone is more simple. The major fault trace passes in the Kurai Range, 5–6 km to the north, separating the Late Proterozoic basement of the West Sayan block from lenses of Cambrian and Devonian rocks. Several closely spaced faults then caused the Cambrian and Devonian rocks to thrust over Tertiary and Quaternary rocks.

On the western half of the depression, along the first fault line, the basement is upthrown on the Tertiary rocks and corresponds to a relatively degraded morphological scarp which does not seem to be active in the Quaternary. Quaternary movements occurred along a new fault, 1–2 km toward the center of the basin, and

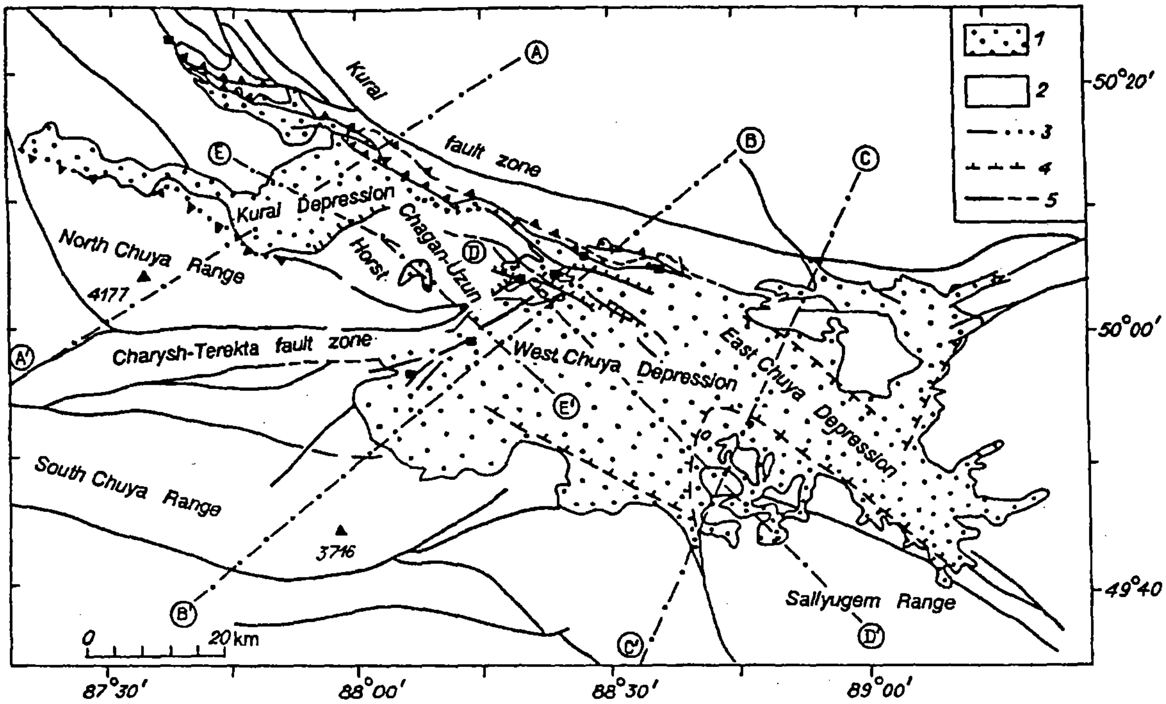


Fig. 7. Tectonic sketch of the Kurai-Chuya Depression with location of the geological sections of Fig. 6. ***1*** **— Cenozoic,** ***2*** **— basement,** ***3*** **— faults,** ***4*** **— Tertiary faults,** ***5*** **— major basement faults.**

affected directly the Neogene sediments. It corresponds to a fresh morphological scarp 200–300 m high, along which several large landslides occurred after the disappearance of the Late Pleistocene glacial lake. Toward the center of the depression, several minor normal faults disturb the Quaternary sediments and control the location of the Chuya River and the associated swampy plain. They caused the development of a small graben in the footwall of the main thrust zone (the Ortolyk graben), as in the Aktash region (Fig. 6, section B-B').

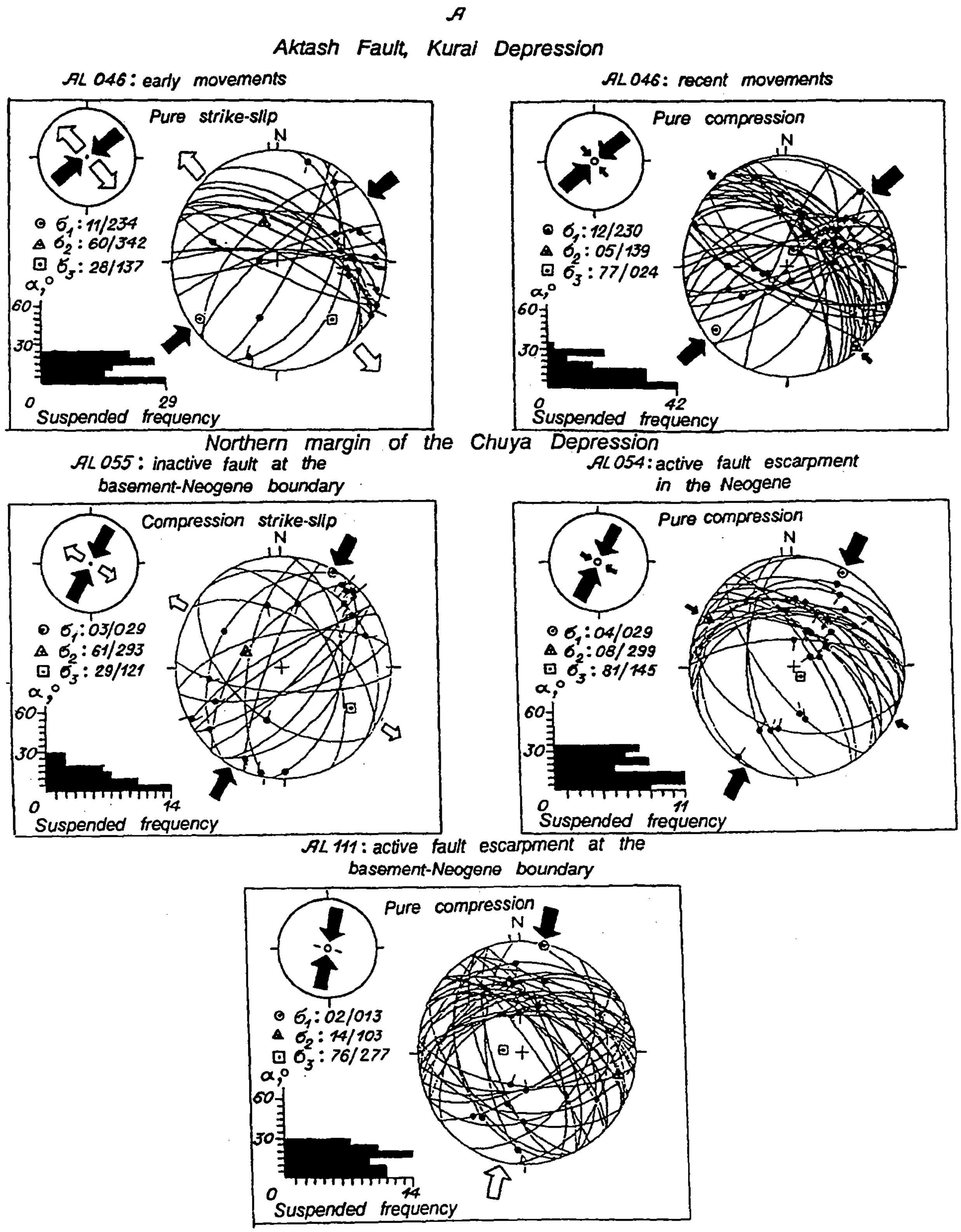
Outcrop AL 055 corresponds to the Tertiary inactive fault at the contact between Devonian and Neogene. The stress tensor is of strike-slip type with NNE S_{Hmax} direction and the dominant movement is dextral strike-slip along E-W trending subvertical planes and minor movement is reverse oblique-dextral slip along 40° NE-dipping, NW-trending planes. The Quaternary fault was studied in outcrop AL 054. The stress tensor is of compressive type with the same NNE S_{Hmax} direction, but the dominant movement is reverse dip-slip along 54° NE-dipping, NW-trending fault plane.

Eastward along the trend, the Tertiary and Quaternary border faults merge to a single fault zone (outcrop AL 111), superposing granodiorite, highly sheared Givetian and Neogene deposits with thin brown-coal seams. A melange zone of blocks of sheared Devonian in a matrix of Neogene clays marks the major fault trace. Minor faults with slip lines, conjugated joints and shear joints were collected in the granodiorite, Devonian and Neogene (stereogram, Fig. 8, *A*). The computed stress tensor is of compressive type, with a NNE S_{Hmax} orientation. The main microtectonic movement plane trends eastward at 95° and dips northward at 45°, while the conjugated plane dips southward at 44°.

The Kyzyl-Chin and Chagan-Uzun fault zone. The KC-CU fault zone trends northeastward, approximately parallel to the S_{Hmax} orientation determined for the Kurai fault zone. It separates the Chagan-Uzun tilted block from the Chuya Depression, and Quaternary normal movement along this NW-dipping fault zone is confirmed by field data. The four sites where microfaults were observed in the Neogene or Quaternary sediments give highly variable stress tensors (Fig. 8, *B*).

Site AL 106 near the Chuya River displays recent surface breaks with many reverse slip planes and slip lines in the Neogene clays. The compressive tensor with E-W S_{Hmax} probably corresponds to a local perturbation at the intersection of faults of different trends.

Site AL 112 along the Kyzyl-Chin River corresponds to the fault that limits the Taldy-Dyurgun brown coal deposit from the rest of the Chuya Depression. Minor faults were observed in both Neogene and


Д
Aktash Fault, Kurai Depression
ДL 046: early movements
Pure strike-slip
N
σ1: 11/234
σ2: 60/342
σ3: 28/137
α,°
60
30
0
29
Suspended frequency
ДL 046: recent movements
Pure compression
N
σ1: 12/230
σ2: 05/139
σ3: 77/024
α,°
60
30
0
42
Suspended frequency
Northern margin of the Chuya Depression
ДL 055: inactive fault at the basement-Neogene boundary
Compression strike-slip
N
σ1: 03/029
σ2: 61/293
σ3: 29/121
α,°
60
30
0
14
Suspended frequency
ДL 054: active fault escarpment in the Neogene
Pure compression
N
σ1: 04/029
σ2: 08/299
σ3: 81/145
α,°
60
30
0
11
Suspended frequency
ДL 111: active fault escarpment at the basement-Neogene boundary
Pure compression
N
σ1: 02/013
σ2: 14/103
σ3: 76/277
α,°
60
30
0
14
Suspended frequency

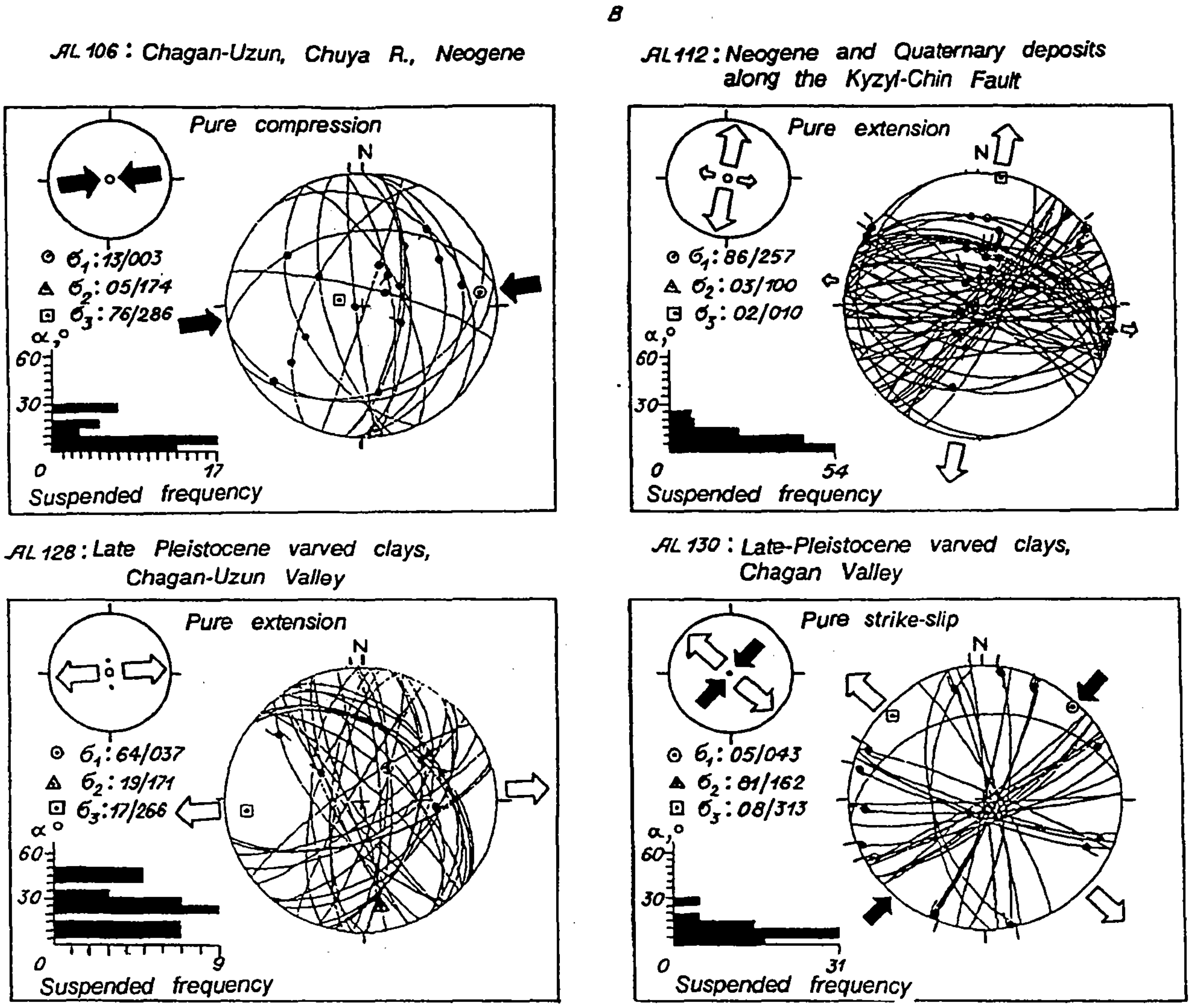


Fig. 8. Paleostress reconstructions for the Kurai (*A*), Chagan-Uzun and Kyzyl-Chin (*B*) fault zones. Stereograms (Schmidt net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses, histogram of deviation of the observed slip from the theoretical shear for each fault plane; $\sigma_1 - \sigma_3$ are stress types. Stress symbols as in Fig. 9.

Quaternary sediments: E-W trending normal faults and NNE-trending steeply inclined strike-slip faults and joints. These two trends correspond to the trends of two mapped faults which intersect each other in this area. The resulting tensor shows N-S horizontal principal extension (σ_3 axis). The E-S trending normal faults correspond to the southern flank of the small Ortolyk graben developed at the foot of the Kurai reverse fault.

Sites AL 128 and AL 130 were measured in lacustrine varved clays of the late Pleistocene glacial period along the Chagan-Uzun valley. The tensors show respectively E-W extension in an extensive regime and NW-SW extension in a strike-slip regime.

DYNAMICS AND KINEMATICS

Quaternary regional stress field. Seven Quaternary stress tensors determined for the Kurai-Chuya Depression can be used to estimate the regional stress tensor for this period (Fig. 9). Three tensors from the Kurai fault zone are relatively similar and indicate a general compressive stress regime with NNE-SSW S_{Hmax}. Four tensors along the KC-CU fault zone are highly variable in their type, but the weighed mean tensor corresponds to the extensional regime with a strong strike-slip component. The principal extension (σ_3 axis)

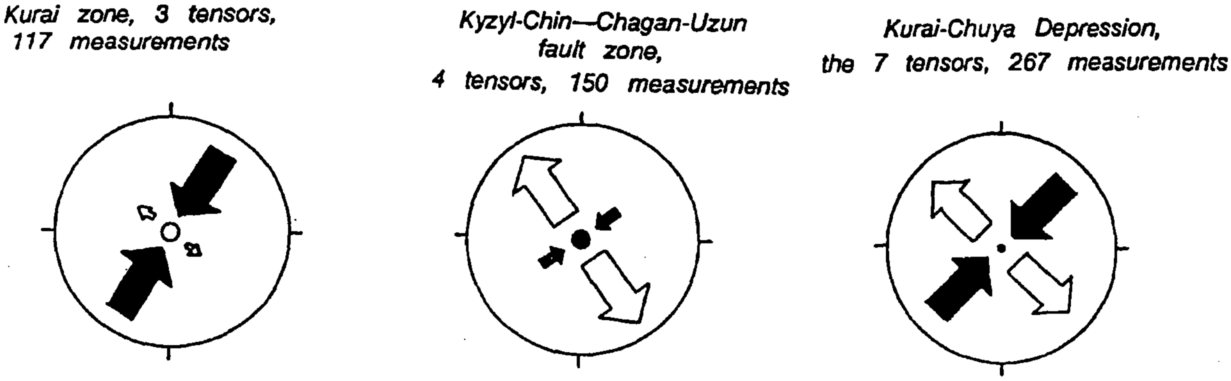


Fig. 9. Mean Quaternary paleostress tensors for the Kurai-Chuya Depression. Symbols displaying horizontal stress axes, with length proportional to their magnitude are as follows. Black inward arrows stand for compressive deviatoric stress and white outward arrows for extensive deviatoric stress. Central symbol is: open circle for compressive regimes, point for strike-slip regimes, black circle for extensive regimes.

is horizontal, trending NW-SE, while S_{Hmax} corresponds to the σ_2 stress axis and is directed from NE to SW. The similar S_{Hmax} directions for both groups of tensors allow reconstruction of a general strike-slip type of tensor with NE-SW S_{Hmax}, representing the seven measured tensors.

The differences in stress field along the Kurai fault zone and along the transversal KC-CU fault zone can be explained by the fault system geometry due to the movement relative to the West Sayan Massif, north of the Kurai-Chuya Depression. During NNE- to NE-directed compression, the West Sayan Massif acts as a rigid block and is thrusted over the Cenozoic sediments. The stress is concentrated along the leading Kurai fault zone and the S_{Hmax} magnitude increases to overcome the magnitude of the vertical stress. The KC-CU fault zone trends in parallel with the orientation of the S_{Hmax} and thus the local strain is very unstable and can change easily from place to place. The shear regime along this line is also favored by the convex arc-shape feature of the Kurai fault zone. The KC-CU fault zone thus acts as a decoupling structure between the Chuya Depression and the Chagan-Uzun block, in front of the major Kurai reverse fault.

An interesting Quaternary feature is the presence of the Aktash and Ortolyk small grabens limited by normal faults at the foot of the Kurai thrust fault. They can be explained by a roll-over mechanism due to the overloading imposed by the thrusting of the Kurai Massif over the Quaternary sediments of the Kurai and Chuya Depressions. They represent only a local perturbation in general compressive kinematics.

Tertiary to Quaternary stress evolution along the Kurai fault zone. The stress tensor evolution from Tertiary to Quaternary can only be estimated along the Kurai fault zone, which shows evidence for Early Cenozoic movement, older than the present one (Fig. 8, *A*, sites AL 046 and AL 055). Site AL 055 is situated along the basement-Neogene fault contact, which is apparently inactive in the Late Quaternary. These two tensors are of strike-slip type, with S_{Hmax} (σ_1 axis) oriented NE-SW. Compared with the local tensor for the Quaternary period, they have the same direction of principal compression, but the regime is strike-slip (σ_2 vertical), instead of being compressive (σ_3 vertical).

The supposed Tertiary strike-slip stress regime is in agreement with the idea that the initial Kurai-Chuya Depression was developed as a strike-slip basin between the northern (Kurai) and the southern border faults. The change from strike-slip to compressive stress regime along the Kurai fault may correspond to the initiation of the Late Pliocene tectonic pulse. This caused the reactivation of these former strike-slip border faults as thrust faults and the transformation of the basins into ramp-type.

Kinematic model. The available scientific information and the results of microtectonic and paleostress investigation give new guidelines in the interpretation of the mechanism of formation of the Kurai-Chuya Depression. A pure strike-slip ("pull-apart") model, with basin development between two major WNW-trending strike-slip faults, seems to be unlikely because of the absence of active faults along the southern border of the Chuya Depression. The lozenge-shaped geometry is mainly the result of structural control by pre-Cenozoic fault pattern. A pure extension ("rift") model is also improbable because of the dominantly reverse character of the northern boundary fault. A compressive model of formation with ramp-type development is more attractive.

Our results indicate that the dynamics of the basin formation changed with time. It seems therefore more appropriate to propose a model in which the Kurai-Chuya Depression developed initially as a single strike-slip basin, which was later disrupted into independent ramp-type basins. The present-day structure clearly results from compressive tectonics with a complex interaction between a full ramp (the Kurai Depression) and a half-ramp (the western side of the Chuya Depression). The eastern part of the Chuya Depression presently seems to be a simple downwarping, since no clear active border faults were observed around it.

GENERALIZATION AND CONCLUSIONS

The Cenozoic Kurai-Chuya Depression of Gorny Altai in Southern Siberia developed under the effect of four successive tectonic stages in a general compressive setting, with a strong climatic influence. Erosion, subsidence and sedimentation were governed by stepwise intensification of tectonic activity, in conjunction with a climatic evolution from subtropical to glacial and interglacial.

In the Late Cretaceous-Early Paleogene, stable tectonic conditions under humid tropical climate caused the development of an extensive peneplain with a highly weathered horizon (weathering crust). In the first half of the Paleogene, moderate tectonic movements caused local erosion and redeposition of the products of the weathering crust. Basin subsidence and sedimentation started in the Late Eocene-Oligocene, owing to intensification of tectonic movements. Up to the Middle Pliocene, the Kurai and Chuya Depressions formed probably a single strike-slip basin, and a large, long-lived lake existed during all this period, allowing the speciation of endemic fauna. In the Late Pliocene, a strong tectonic pulse caused important vertical differential movements, renewal of erosion, coarsening of sedimentation, disappearance of the Neogene lake and splitting of the former unique depression into two subsiding blocks (Kurai and Chuya), separated by a rising block (Chagan-Uzun). The Kurai Depression evolved as a full ramp basin, and the Chuya Depression as a half-ramp, owing to thrust reactivation of the border faults. The Late Pleistocene glacial period had a strong effect on present-day surface geology. Glacial moraines cover an important part of the depressions and important glaciers even caused the damming of the Chuya River at the outlet of the Kurai Depression and the creation of a giant Late Pleistocene lake in both Kurai and Chuya Depressions. A new outlet was then created north of the former course of the Chuya River. The presence of a series of abrasive terraces at decreasing altitude on the margins of the Kurai and Chuya Depressions suggests a progressive erosion of this new outlet, causing stepwise lowering of the lake level from a maximum altitude of 2,100 m. Rupturing of the ice dam during a warming period caused the final disappearance of the lake by catastrophic flow outburst.

Microtectonic analysis along the major Kurai fault zone and paleostress tensor reconstruction shows that the principal compression axis (σ_1) was horizontal and NE-SW trending during the basin development, with the strike-slip regime in the Neogene (σ_2 axis vertical), and the marked compressive regime in the Quaternary (σ_3 axis vertical). However, stress concentration probably occurs along the Kurai fault zone, due to the influence of the strong East-Sayan block north of it. Taking into account microstructures developed along the transversal Kyzyl-Chin – Chagan-Uzun fault zone, the regional strike-slip stress regime with NE-SW S_{Hmax} can be reconstructed for the Quaternary period.

Compared with the evolution of the Baikal rift zone 2,000 km eastward [5, 8], there is remarkable parallelism in the timing of tectonically induced and climatically influenced geological events: Late Mesozoic-Paleocene peneplanation and weathering, Paleocene-Eocene reworking of weathering crust with redeposition in shallow and localized depressions, initiation of significant vertical movements and creation of lacustrine depressions in the Oligocene and their gradual extension until the Middle Pliocene (slow rifting stage according to N. A. Logatchev [5]), significant reorganization due to rapid acceleration of tectonic processes in the Late Pliocene and continuous intense vertical tectonic movements since Early Pleistocene, leading to the present-day integrally deep Baikal depression (fast rifting stage according to N. A. Logatchev [5]).

This preliminary investigation, combined with the examination of existing geological literature, shows that the Kurai-Chuya Depressions of Gorny Altai developed under the complex interaction of tectonic, sedimentary and climatic processes. The structure of the depressions is controlled by the reactivation of pre-existing Late Paleozoic fault systems. The pre-Paleogene weathering surface, and the Pleistocene glacial deposits well documented the climatic factor evolution. The timing of tectonic movements and the orientation of recent stress field is controlled to a large extent by external tectonics, probably in relation to the India–Eurasia convergence.

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REFERENCES

[1] P. Molnar and P. Tapponnier, *Science*, vol. 189, no. 4201, p. 419, 1975.

[2] P. R. Cobbold and P H. Davy, *Indentation tectonics in nature and experiment. 2. Central Asia. Bulletin of the Geological Institutions of Uppsala, N.S.*, vol. 14, p. 143, 1988.

[3] P. Molnar, B. C. Burchfiel, L. K'uangyi, and Z. Ziyun, *Geology*, vol. 15, p. 249, 1987.

[4] L. P. Zonenshain and L. A. Savostin, *Tectonophysics*, vol. 76, p. 1, 1981.

[5] N. A. Logatchev, N.A., *Bull. Centre Rech. Explor.-Prod. Elf-Aquitaine*, vol. 17, no. 2, p. 353, 1993.

[6] F. F. Windley and M. B. Allen, *Geology*, vol. 21, p. 295, 1993.

[7] I. Baljinnyam, A. Bayasgalan, B. A. Borisov, et al., *Geol. Soc. Am.*, Mem. 181, 1993.

[8] D. Delvaux, R. Moeys, G. Stapel, et al., Paleostress reconstructions and geodynamics of the Baikal region, Central Asia. Part II: Cenozoic rifting, *Tectonophysics*, 1995, in press.

[9] A. M. Nikishin, S. Cloetingh, L. I. Lobkovsky, et al., Continental lithosphere folding in Central Asia (Part I): constraints from geological observations, *Tectonophysics*, vol. 226, p. 59, 1993.

[10] A. N. Rudoy and V. R. Baker, *Sedimentary Geology*, vol. 85, p. 53, 1993.

[11] P. Tapponnier and P. Molnar, *J. Geophysical Research*, vol. 84, no. 7, p. 3425, 1979.

[12] M. L. Zoback, *J. Geophysical Research*, vol. 97, no. 8, p. 11703, 1992.

[13] A. B. Dergunov, *Geotektonika*, no. 3, p. 99, 1972.

[14] D. Delvaux, P. Trefois, R. Van Der Meer, and N. Berzin, in: *Les Bassins d'avant-chaine. Societe Geologique de France, Grenoble, 21-22 Novembre 1994. Geologie Alpine, Serie speciale "Colloques et excursions,"* no. 4, p. 32, 1994.

[15] R. P. Moeys and G. Stapel, *Paleostress evolution in the Altay and Baikal regions, South Siberia. Free University of Amsterdam, Report*, 1994.

[16] M. B. Allen, B. F. Windley, and Zang Chi, *Tectonophysics*, vol. 220, p. 89, 1992.

[17] V. G. Belichenko, E. V. Sklyarov, N. L. Dobretsov, and O. Tomurtogoo, *Geodynamic map of the Paleoasian Ocean: Eastern segment*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 35, nos. 7-8, p. 29(36), 1994.

[18] M. M. Buslov, N. A. Berzin, N. L. Dobretsov, and V. A. Simonov, *Geology and Tectonics of Gorny Altai. Guide-book, 4th Int. Symp. IGCP 283 Geodynamic Evolution of the Paleoasian Ocean*, Novosibirsk, 1993.

[19] A. M. C. Sengör, B. A. Natal'in, and V. S. Burtman, *Nature*, vol. 364, p. 299, 1993.

[20] N. A. Berzin and N. L. Dobretsov, in: *Reconstruction of the Paleo-Asian ocean. VSP Intern. Sci Publishers*, R.G. Coleman (Ed.), Netherlands, p. 45, 1994.

[21] N. Gusev, *Terrain structure of Kurai zone in Gorny Altai. Report the IGCP 283 4th Int. Symp: Geodynamic Evolution of the Paleoasian Ocean.*, Novosibirsk, p. 78, 1993.

[22] D. Delvaux, A. Melnikov, R. Moeys, et al., Paleostress reconstruction and geodynamics of the Baikal region, Central Asia. Part I: Paleozoic and Mesozoic pre-rift evolution, *Tectonophysics*, 1995, in press.

[23] E. V. Devyatkin, *The Cenozoic of Inner Asia* [in Russian], Moscow, 1981.

[24] V. G. Trifonov (Ed.), *Map of active faults of the USSR and the adjoining areas. Scale 1:8,000,000*, Moskow-Irkutsk, 1986.

[25] N. V. Lukina, *Recent movements on microplate boundaries in southern Siberia and Mongolia, Ser. Geol.* [in Russian], Moscow, no. 3, p. 127, 1992.

[26] P. M. Bondarenko, *Modelling of overthrust dislocations in the folded areas. (On the example of Aktash structures in Gorny Altai)* [in Russian], Novosibirsk, 1976.

[27] E. V. Devyatkin, *Cenozoic sediments and neotectonics of Southeastern Altai* [in Russian], Moscow, 1965.

[28] B. M. Bogachkin and L. I. Rozenberg, *Bull. Sciences Naturelles, Sect. Geol.*, vol. 49, no 2, p. 5, 1974.

[29] B. M. Bogachkin, *Tectonic history of Gorny Altai in the Cenozoic* [in Russian], Moscow, 1981.

[30] L. I. Rozenberg, *Bull. Sciences Naturelles, Sect. Geol.*, vol. 51, no 3, p. 64, 1976.

[31] B. M. Luzgin and G. G. Ruzanov, *Characteristics of formation of Neogenic deposits in the Southeastern Gorny Altai*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 33, no 4, p. 23(18), 1992.

[32] V. S. Zykin and A. Y. Kazanskii, *Main problems of stratigraphy and paleomagnetism of Cenozoic (Pre-Quaternary) deposits of the Chuya Depression in Gorny Altai*, Geologiya i Geofizika (Russian Geology and Geophysics), v. 36, no. 10, p. 75(67), 1995.

[33] J. Angelier, *J. Structural Geology*, vol. 11, p. 37, 1989.

[34] J. Angelier and P. Mechler, *Bull. Soc. Geol. France*, vol. 7, no. 19, p. 1309, 1977.

[35] D. Delvaux, in: *Terra Abstracts. Abstract supplement No. 1 to Terra Nova*, no. 5, p. 216, 1993.

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