RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 5, NO. 6, PAGES 439–454, DECEMBER 2003

A strong earthquake of 2003 in Gornyi Altai

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Abstract. The aim of this paper is to describe the macroseismic, geological, and seismological manifestations of the strong earthquake that occurred in the south of the Gornyi (Mountainous) Altai area on September 27, 2003. The earthquake caused damage to buildings and constructions in the area of the Chuya and Kurai depressions and was accompanied by the manifestation of the earthquake source on the ground surface with the formation of a system of WNW-oriented faults, which has been traced over a distance of 20 km in the region of the eastward plunge of the North Chuya Range. Secondary seismic dislocations manifested themselves in the form of rockfalls, landslides, and griffons in the area of the pleistoseist zone. The results of the preliminary study of the tectonic position of the earthquake source suggest that the Gornyi Altai is a direct continuation of the Mongolia and Gobi Altai areas, where earthquakes with magnitudes of more than 7.0 were recorded repeatedly, and allow us to combine all of the mountain systems of the Great Altai into one high-magnitude seismotectonic province.

Introduction

A large earthquake with a magnitude of 7.3, as recorded by the Geophysical Survey of Russian Academy of Sciences (GS RAS), occurred in the south of the Altai Republic on September 27, 2003, at 11 hours 33 minutes, Greenwich time. The focus of this earthquake was located in the area of the North Chuya Range, the Chuya and Kurai intermountain basins, and the Chagan-Uzun upthrown block between them. The earthquake was felt over an extensive territory of Russia (in the Altai, Khakassiya, and Tuva republics, in the Krasnoyarsk Region, and in the Novosibirsk and Kemerovo districts), North-west Mongolia, North-west China and in East Kazakhstan. According to the records of the GS RAS, it had a intensity of 8 in the Beltir area, 6–7 in Aktash, 6 in Tashtagol, 5-6 in Prokopievsk, 4 in Novosibirsk, Ust-Kamenogorsk, and Semipalatinsk, 3–4 in Abakan, 3 in Krasnoyarsk, Zaisan, and Kemerovo, and 2–3 in Barnaul, Alma-Ata, Taldy-Kurgan, and Astana. The effects recorded in the epicentral zone, comprising Bel'tir, Kurai, and Aktash settlements, included the destructions of stoves, the falls of chimneys, and the formation of typical fissures in the walls between the windows, and the occasional tumblings of the walls and corners of slag concrete buildings. Wood houses were more resistant and their damage consisted mainly in log displacements and partial roof destructions.

A network of five temporal seismic stations was installed by the Geophysical Survey of the Siberian Division of Russian Academy of Science to record any aftershocks. In addition, twelve digital seismic stations of this organization operate in the Altai region. The data recorded by the local seismological network located in the near zone of the earthquake and in the Altai region (Geophysical Survey of the Siberian Division of the Russian Academy of Sciences), and by the earthquake recording network of Russia and by the World Seismological Observation Network are processed in the mode close to the real time one.

The seismic event concerned was accompanied by numer-

Paper number TJE03141.
ISSN: 1681–1208 (online)

The online version of this paper was published 22 January 2004.
URL: http://rjes.wdcb.ru/v05/tje03141/tje03141.htm

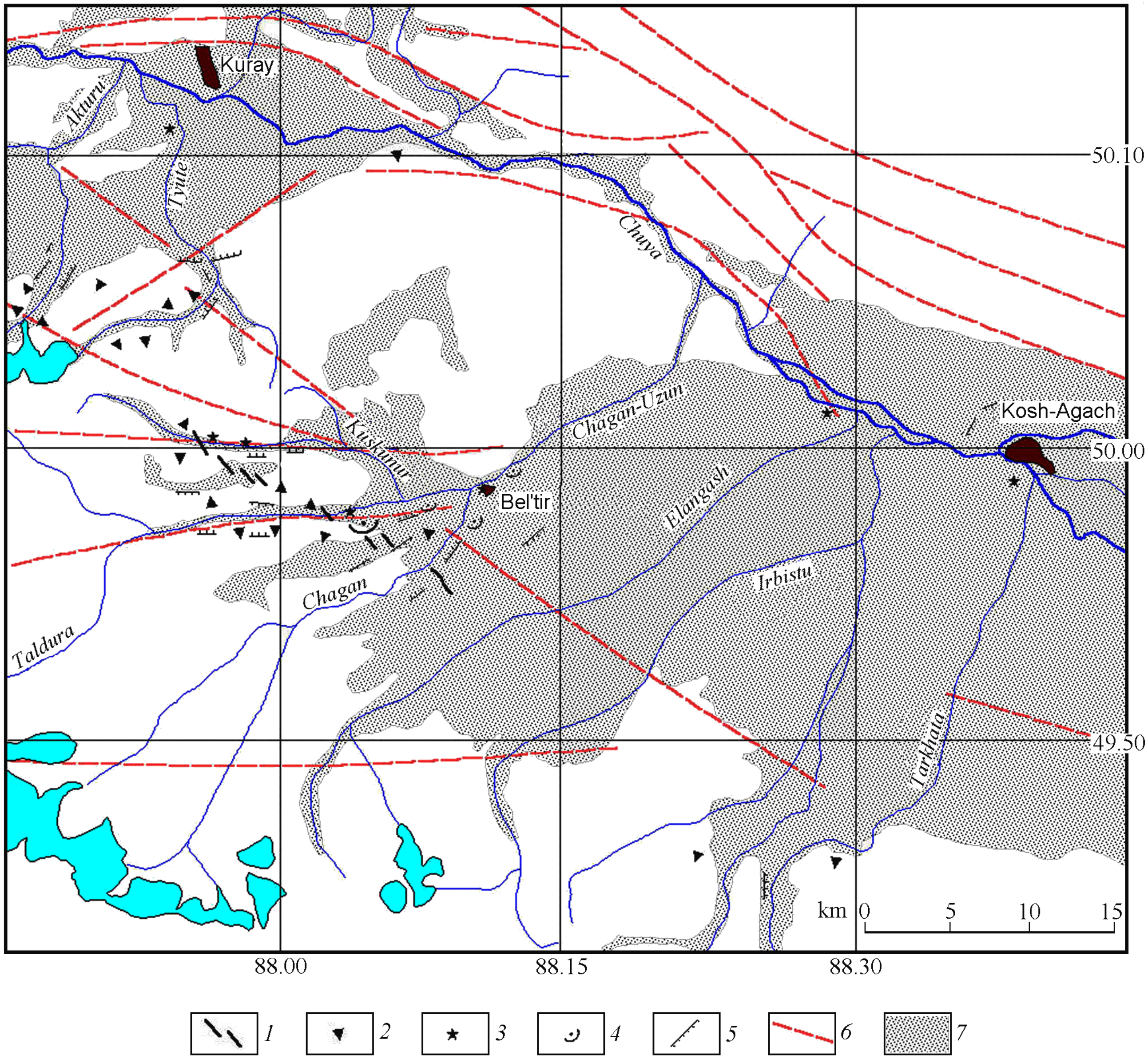

Figure 1. Map of seismic ruptures: (1) seismotectonic faults; (2) rockfalls; (3) ground dilution; (4) landslides; (5) seismogravitational breaks and downward movement of the slopes; (6) faults rejuvenated in Neogene-Quaternary time [*Devyatkin,* 2000]; (7) Quaternary alluvial, lacustrine, and glacial deposits.

ous aftershocks, two of which were especially high. The aftershock with M = 6.4, recorded at 18 h 52 min in September 27, 2003, was felt in Abakan and Biisk as an event of intensity 2–3 and in Novosibirsk as an event of intensity 2. The aftershock of October 1, 2003, was recorded at 1 h 03 min 28 sec Greenwich time as an event of magnitude 7.0 by the Geophysical Survey of the Russian Academy of Sciences. The aftershock of October 1 happened in the area of the Aktash settlement, where the damage of the buildings was estimated as equal to intensity of 7 and 8. The workers of the Geophysical Survey of the Siberian Division of the Academy recorded more than a hundred of repeated shocks with magnitudes of 2.2 to 7.0 on October 15, 2003. The epicenters of the aftershocks produced an elongated cloud, the long axis of which was oriented in the NW direction. The length of this oval was found to be about 90 km with a width of 20 km.

No earthquakes of this magnitude were observed during the entire period of observations performed in the south of Gornyi (Mountainous) Altai. However, the paleoseismological studies, carried out in 1996–1999, revealed that large earthquakes with magnitudes of 7.0–7.5 and recurrence interval of 1000 to 2000 years occurred in the Chuya and Kurai intermountain basins during the last 9 thousand years [*Rogozhin et al.,* 1998a, 1998b]. The southern areas of the

Gornyi Altai region are shown in the map of the general seismic zoning of the Russian Federation (GSZ-87) as belonging to a intensity-9 zone.

The earthquake of September 27, 2003, was accompanied by the formation of numerous earthquake-related ground-surface ruptures, including primary seismic fault systems and secondary seismic gravitational and seismic vibration ruptures. The subsurface shocks resulted in the violation of the natural topography mainly in the mountainous part of the pleistoseist area of an earthquake. The source region was exposed on the surface as a long (about 20 km) S-shaped system seismic faults.

Results of the Field Work in the Epicentral Zone

The residual ground surface ruptures (seismic dislocations) that had been produced by the earthquake were studied in the Kurai and Chuya intermontane basins and on the slopes of the South Chuya and North Chuya ranges. They are represented by primary dislocations, such as seismic faults, and by secondary deformations of seismic vibration nature. The secondary dislocations include earthquake-related landslides, avalanches, and rock falls, the gravitational falling off of the slopes, the discharge of liquefied sand and clay materials, and compensation related sagging of the ground surface (Figure 1).

In the course of the crust breaking the earthquake source was exposed on the surface in the form of the system of primary faults, which has been traced over a distance of 20 km in the Chagan-Uzun River basin in the area of the eastward lowering of the North Chuya Range.The nongravitational, that is, primary origin of these faults is indicated by their morphology and interrelations, and also by their arrangement into linear zones cutting across various topographic forms. In map view, this zone of the seismic faults has an S-shape form. Generally, this zone is an en-echelon system of compression and extension fissures arranged en-echelon into one NW–WNW striking line. This pattern of a seismotectonic fault supposes that the movement in the source was almost a pure strike-slip fault along the vertical plane.

The structure of the fault zone varies from site to site. At its southeast termination (flat uplifted area between the Chagan and Elangash rivers) the fault branches off into two main fissures of roughly N–S trend, at some 200 m distance from one to another. They are brought to contact each other 700 m farther, being replaced by NW-trending fissures (Figure 2). Both breaches are long and open or consist of short (<1 m) en-echelon fissures. The western branch shows a 0.5-meter right-lateral offset (Figure 3). The dextral displacement along the eastern branch is 0.2 m. The block between these fissures is 0.2–0.3 m subsided and cut by numerous diagonal (NW- and NE-trending) fissures which show occasional (less than 30-cm) vertical displacements. The transverse (sublatitudinal) breaches are the structures of compression and presented by the 0.3 to 0.7 m high pressure ridge and thrust scarps overlapping of the soil. This structural pattern extends as the en-echelon systems of detachment fissures showing a north-west orientation (NW 340°–350°). In the southeast the fractures cross the dry valley and attenuate at distances of about 400 m (Figure 4). The valley with relatively gentle (15°–20°) sides shows numerous open fractures and a few landslides of the loose sediments mainly from the southeastern side.

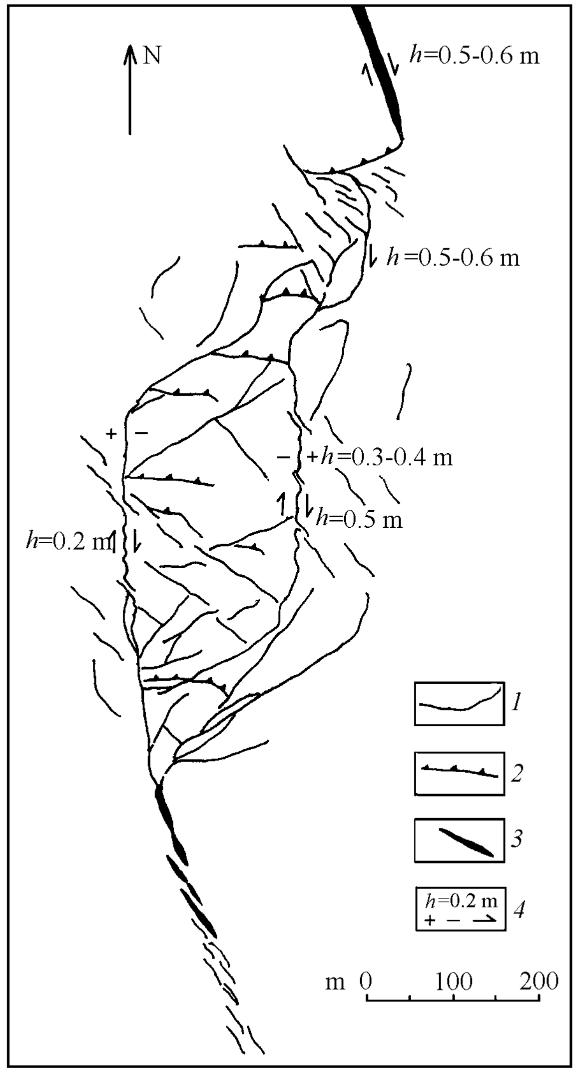

Figure 2. The structure of a seismic rupture in the area of the Chagan R. and Elangash R. watershed. (1) Closed fissures and cracks, (2) compression ridges, (3) seismic trenches, (4) amplitude and direction of offset.

The seismic fracture continues in the NW direction as an extensive trench with a maximum width of 1.5 m and descends into the valley of the Chagan River (Figure 5). Here, in addition to extension, the fault shows a right-lateral displacement of max. 0.5 m, which is recorded by the offset of individual small topographic forms. In the watershed of the Chagan and Taldura rivers the seismic source outcrops as a system of seismic trenches (detachment fissures) with openings of 1–3 m and a maximum length of 100 m

Figure 3. Right-lateral strike-slip fault.

(Figure 6). The trenches have orientations of about 320° and are arranged en echelon to form a zone striking 300°–310°. Throughout the segment described the faults cross the Middle-Lower Pleistocene glacial boulder-pebble deposits.

At the bottom of the Taldura R. valley the en-echelon system of seismic breaks has an orientation of 290°–300°. Here, the alluvial deposits are dissected by opened fissures, up to 2 m wide and up to 50 m long, and by closed fissures of the same strike (320°–330°) with a dextral offset of 0.1–0.2 m. The amplitude of the offset was estimated using the displacement of the road located there. The extension fissures are accompanied by linear zones of compression showing up-

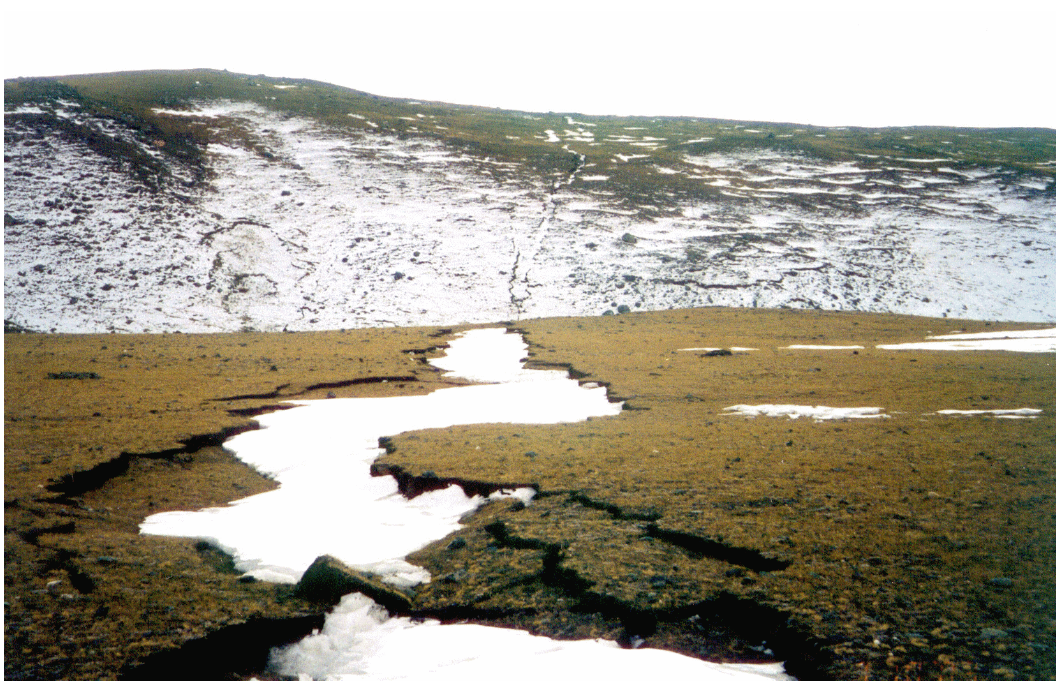

Figure 4. Seismic trench with seismogravitational slope collapse.

Figure 5. Seismic trench showing differences in the small topographic forms of the opposite sides of a fracture, which were used to estimate the amplitude of the right-lateral offset.

lifting of the soil to a height of 0.5 m. The orientation of compressive structures is of NE 40°–60°.

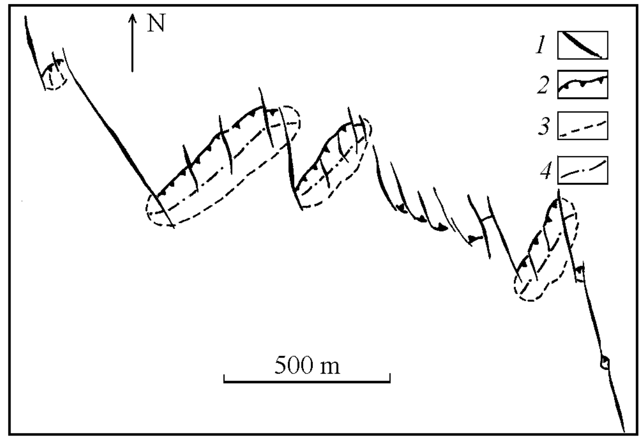

Figure 7. The structure of a seismic fault in the area of the watershed between the Taldura and Kuskunnur rivers. (1) seismic trench or open fracture; (2) dextral pressure ridges thrust scarp; (3) pressure ridge outline; (4) dextral pressure ridges axis.

The most significant seismotectonic faults deformed the ground surface in a broad saddle at the Taldura R.–Kuskunnur R. watershed (Uzyuk area). The saddle is about 4 km wide and is composed of Middle Pleistocene moraine deposits, whereas it is surrounded in the west and east by gentle hills composed of Devonian schist. This area is distinguished by dense meadow vegetation with scattered dwarf birch trees.

The fault zone has a sublatitudinal strike. The seismic faults are arranged into an en-echelon system of gaping trenches with linear compression zones between them (Figure 7). The seismic trenches are very large, up to 10 m

Figure 6. Seismic trench in the watershed between the Chagan and Taldura rivers.

Figure 8. Seismic fault of the earthquake and man's figure inside the fissure for the scale.

wide in width, up to 300 m long, and >30 m deep (Figures 8 and 9). Judging by some of the gaping fissures, the amplitude of the right-lateral displacement is as large as 0.5 m (Figure 10). The zones of compression are represented there by dextral pressure ridges, up to 2 m high and up to 50 m long, and by the overthrust scarps doubling the soil layer (Figure 11).

As the seismic faults extended into the slopes of the saddle, they were separated into two branches with the subsided blocks (micrograbens) compressed between them. In

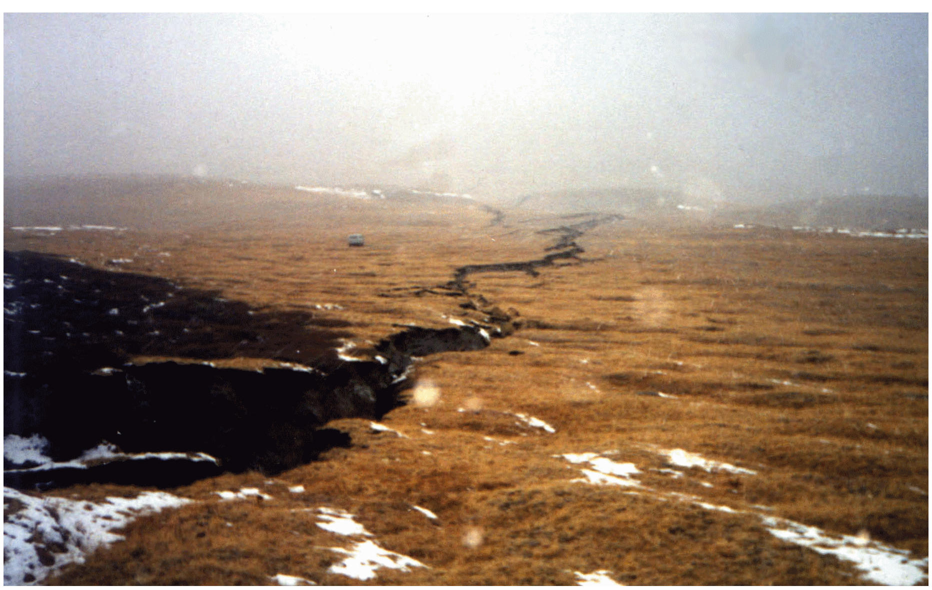

Figure 9. Seismic fault – the perspective view.

Figure 10. Right-lateral 0.5 m displacement.

the eastern side of the saddle this micrograben is not more than 50 m wide. The amplitude of its down warping is about 0.5 m (Figure 12). On the western slope the omitted block is up to 500 m wide, the maximum depth of its subsiding is 2.5 m (Figures 13 and 14). In both cases the micrograbens are restricted to small saddles. The faults are clearly expressed in the topography there as the benches separating the flat floors of the saddles composed of loose deposits from the relatively steep slopes where Devonian bedrock schists are exposed (Figure 15). The seismogenic displacements of September 27 merely rejuvenated these scarps.

The same area (the western slope) includes an old pressure ridge with a height of about 2 m, orienting perpendicular to the scarps, which was also rejuvenated during the

Figure 11. Compression ridges.

Figure 12. The breaking of the fault into two branches with a downthrown block between them.

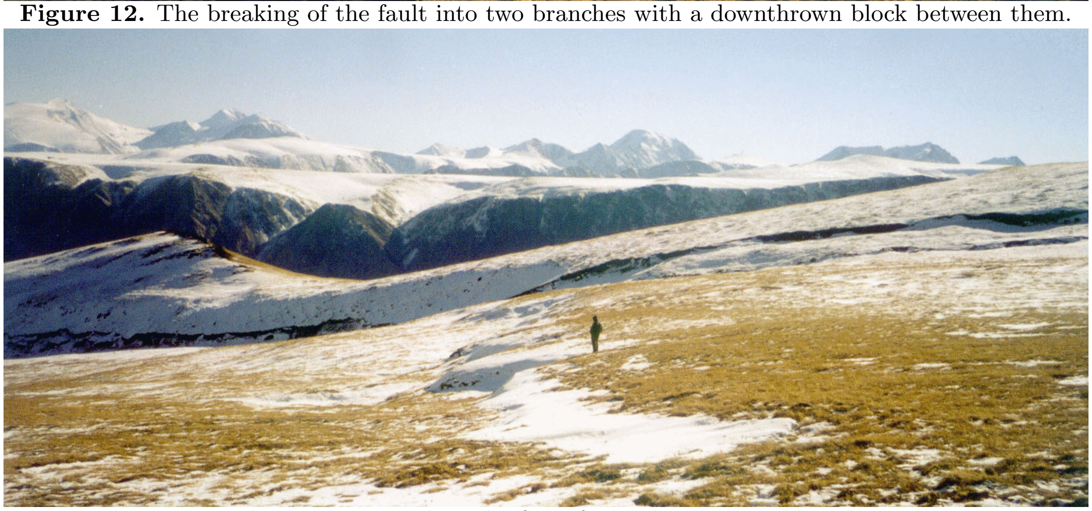

Figure 13. The southeastern branch of the fault, showing an old swelling rampart.

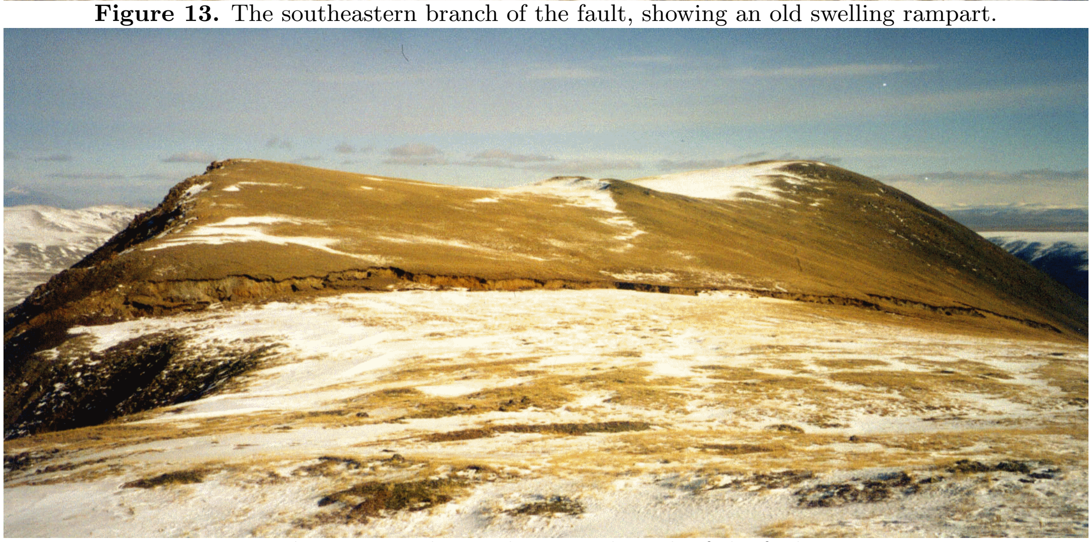

Figure 14. The northwestern branch of the fault.

Figure 15. The southeastern branch of the fault (a closer view). The amplitude of the micrograben descendence is about 2 m.

main shock of the last earthquake (Figure 14). The walls of the open fissures often show the traces of the crushing and ferrugination of the loose sediments, and also the wedges and lenses of ancient soil and peat, buried under the coarse clastic material (Figure 16). These facts prove the previous seismic events there, which might have been comparable with or, potentially, greater than the earthquake of September 27, 2003.

According to new results of radiocarbon dating of the paleosoil and peat samples these high magnitude seismic events could occur in 3340±30, 1780±30 and 1280±30 years b.p. (samples No. 2817, 2823 and 2818 IGAN). Thus, the observed recurrence interval might be of 500–1500 years.

Extending farther along the strike the northeastern branch of the fault is continued only. In the steep hard-rock slope of the Kuskunur River right-hand side it is accompanied by numerous debris produced by rock falls (Figure 17). Descending into the Kuskunur R. valley, the seismic breaks

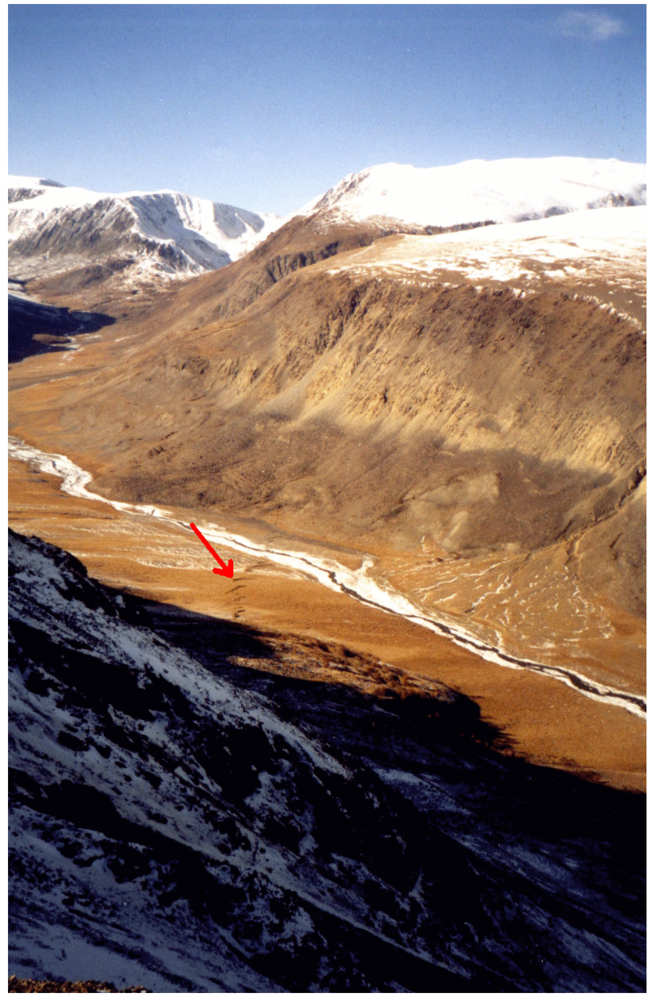

Figure 17. The seismic fracture in the Kuskunnur valley (view from above).

Figure 16. The buried paleosoil lenses in the wall of gaping fissure.

Figure 18. The close view of the seismic fracture in the Kuskunur valley, clearly showing a conjugated system of extension and compression breaches (gashes and moles).

are arranged into a zigzag-shaped system of moles and gashes and cross the alluvial pebble and gravel deposits (Figure 18). The system of seismic faults is marked there by the ridges of compression and overthrusting of the modern soil horizon (striking 40°–60°) and by trenches open to a width of 1 m and up to 3 m deep. The dextral offset of the road by extension fissures is of 0.3–0.4 m. The moles are as high as 0.5–1 m. The compression (moles) and extension (gashes) breaches have approximately equal lengths not exceeding 50 m. The faults cross the valley and extend to the op-

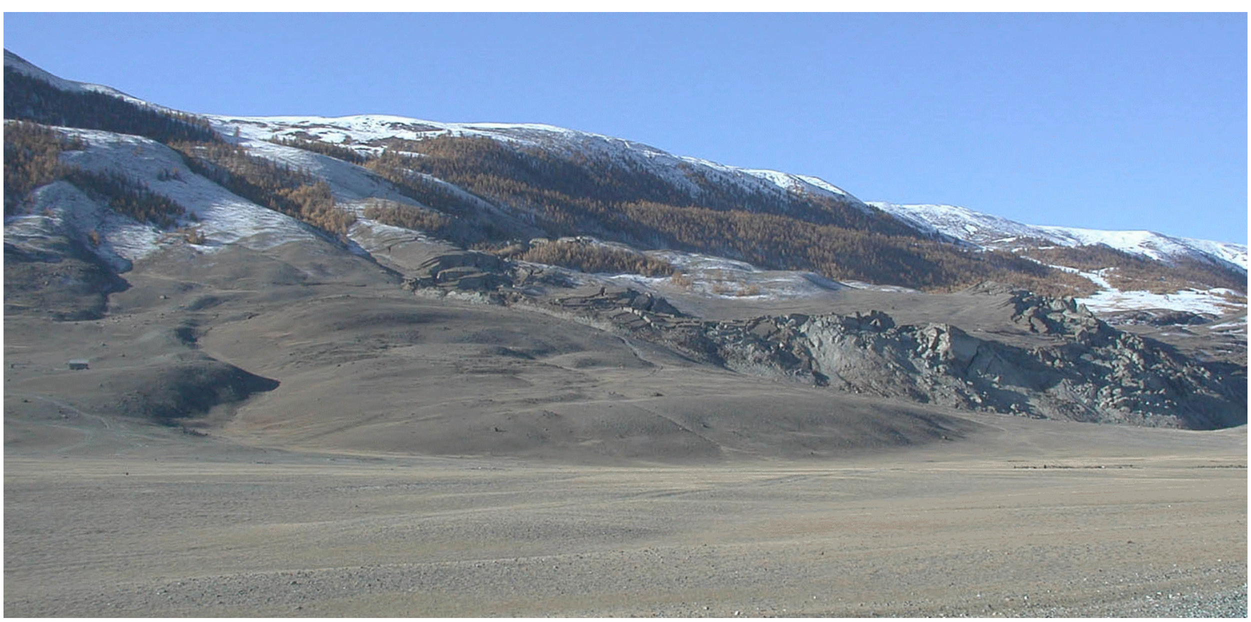

Figure 19. The general view of the landslide.

Figure 20. Fissures in the landslide body.

posite side, covered by numerous fresh debris and landslide rock masses, where they seem to attenuate. At any rate, their potential continuations have not been found along the trend of fault extending into the valleys of the Tyute and Akturu rivers.

Apart from the direct manifestation of the seismic source on the ground surface as a seismotectonic fault, there are ruptures of secondary origin in the pleistoseismic area, produced by the shaking of the day light surface due to the arrival of seismic waves to the latter. The secondary breaches of the topography, mapped during this study, are situated inside of the oval area, 70 km long and about 15 km wide. The long axis of this oval is oriented along the NW–SE strike of the fault and correlates well with the long axis of the oval cloud of the aftershock epicenters. The concentration of the secondary breaches varies in a normal way, attenuating away from the linearly elongated region where the source manifested on the ground surface.

The largest trace of the earthquake, a major landslide at the right-hand side of the Taldura River valley, is restricted to the area where the earthquake source had reached the ground surface. The wall from which the landslide masses had been collapsed is restricted exactly to the zone where the primary seismic breaks had developed. One of them had initiated the landslide motion. The landslide had been detached from the rupture wall at the height of about 150 m and had traveled into the valley over a distance of not less than 100 m. The volume of the landslide rock mass was calculated to be about 30 million cubic meters. The width of the landslide body is >500 m, its length being about 700 m (Figures 19 and 20). Similar landslides of smaller sizes had been formed at the slopes of the Chagan and Chagan-Uzun river valleys.

The main shock and the strongest aftershocks of the earthquake had been accompanied by extensive rock falls and debris flows. These breaches had embraced the areas of the steep rocky slopes of the river valleys. The main difference from aseismic rockfalls is the fresh appearance of the slope ruptures in the areas of their extensive development. Seismic origin also could be discriminated from some of their anomalous features, such as, the morphology of the rockfall and debris bodies, the sorting of the material, and the angle of the slope surface from which the rockfall bodies had been detached. In particular, the material of a small rockfall body was found at the rocky protrusions of the slope, dipping at an angle of 25° north to the central part of the Uzyuk saddle in the right-hand side of the Kuskunur R. valley. The landslide debris material deposited on the rocky slope protrusions in the Akturu R. valley show an abnormal distribution of the rock fragments of different sizes. The largest fragments are concentrated in the upper parts of the debris cones. This suggests the development of impulsive avalanches in the areas of debris development (Figure 21). Some individual blocks, up to 3 m in section, had travelled over significant distances along the floor of the river valley, namely, up to 200–300 m from the slope foot.

Figure 21. A rockfall in the valley of the Akturu River.

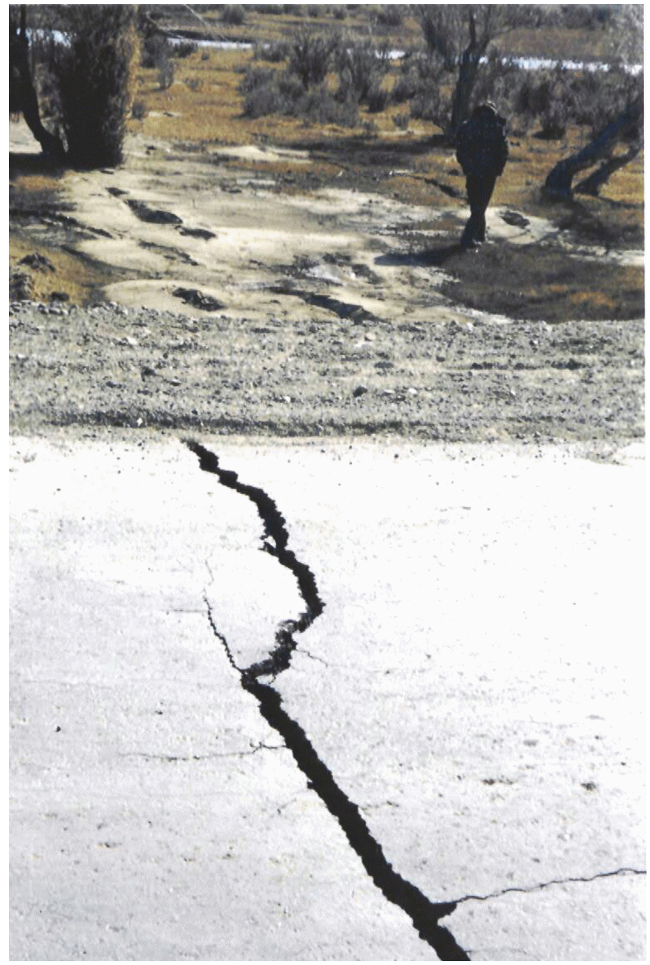

Figure 23. Gryphons on the extension of a seismic-vibration fissure in the Kosh-Agach-Beltir road.

Figure 22. Mud gryphons in the Chuya R. valley.

Figure 24. Areal spread of liquified sand from a fissure in the Taldura River flood plain.

Figure 25. Gryphons in the Beltir area. The thickness of the mud produced by them is about 1 m.

As follows from the observations of our colleagues from the Tomsk University, the earthquake shocks had caused substantial movements in the ice cover of the South Chuya Range. The previously existed cracks in the glacier bodies had grown larger. The nunataks had been exposed, and the glacier on the top of the Three Lake Dome had been detached from its source area.

Detachment cracks are abundant on the turf-covered, gentle slopes of the river terraces. Some of them had initiated microlandslides, where the rock material had moved over less than a few meters. Similar sodded loose landslides have been observed in the upper parts of the slopes from the upper-stage mountains. They were expressed by fissures in the sod cover produced by typical strike-slip and overthrust faults.

The areas of the man-made road beds had been broken by settling fissures and by the fractures that cross the road from one edge to the other. Some segments of the road bed had been displaced along these fractures.

A remarkable consequence of this earthquake was the formation of outbursts and flows of liquefied sand and mud in the forms of gryphons or small mud volcanoes. They are mainly restricted to low, sometimes bogged areas composed mainly of loose, fine-dispersed, water-saturated rocks, such as clay, loam, sand with gravel and dusty sand, capable of being liquefied and flowing to the ground surface in the form of small cone- or funnel-shaped mud volcanoes and compensation ground surface subsidence (Figure 22). This is usually a ground-surface process operating at a depth less than 20–30 m. In our case the lower boundary of the process was the permafrost top. In most cases gryphons are restricted to short open fissures of vibration or seismogravitational nature (Figures 23 and 24). The close vicinities of seismic fault zones showed the large flows of liquefied sand from open seismic-vibration fissures with a maximum length of 50 m. A striking example is the floodland of the Taldura River.

Voluminous mud flows and ejections were observed in the flood-plain areas of the Chuya and Chagan-Uzun rivers (Figure 25). The local manifestations of these activities are known in the Kurai Steppe, and also in the close vicinity of seismic cracks in the flood plain areas of the Taldura, Kuskunnur, and Chagan-Uzun rivers. It is remarkable that a less plastic material, namely, gravel and pebble material of the rivers, was found to have been ejected (Figure 26). Moreover, in some areas these phenomena had been accompanied by voluminous water flows and lake formation. Most

Figure 26. Gravel and sand material ejected from the open fissures.

of the lakes are restricted to preexisting drainless basins. A good example is a natural basin in the Beltir city, where a stadium has been built. Immediately after the main shock it had been flooded by water, 1.5 m deep, which had flowed from the open fissures of the gravitational origin on the basin slopes.

Discussion

It should be noted that the seismogravitational ruptures had been expressed less comparing to the seismotectonic ones. The largest avalanches have the form of cones up to 100 m wide and up to 300 m high, usually restricted to the steep, rocky slopes of the river valleys without covering them or reaching the opposite side. The large rock avalanches that dammed the rivers had been formed, for example, in Kirghizia during the 1992 Susamyr earthquake. This earthquake had a magnitude of 7.3 and the intensity of 9 in the epicenter. The movement in its source area was a strike-slip and thrust fault. The motion had a significant vertical component [*Bogachkin et al.,* 1997]. Similar mass phenomena accompanied the Racha earthquake of 1991 in Georgia. This earthquake had a somewhat lower magnitude (M = 7.0–7.2) with its intensity of 7–8 in the epicenter. The focal mechanism solution was interpreted as an almost pure overthrust [*Rogozhin and Bogachkin,* 1995]. The geomorphological conditions in the Gornyi Altai area, where an earthquake took place in September, 2003, do not preclude the formation of large stone avalanches. Phenomena of this kind are known to have happened in the past and are usually associated with the already occurred seismic events [*Rogozhin et al.,* 1998a, 1998b]. The absence of similar topographic disturbances during the earthquake of September 27, 2003, seems to have been associated with some peculiar type of oscillations. According to the eye-witnesses, the shaking during the main shock propagated in the horizontal plane. At the same time, it is known that high seismogravitational displacements arise during intensive vertical shaking and when seismic waves attain their critical acceleration, which diminish with the greater steepness of the slope and with the lower cohesion of the rock material [*Shteinberg et al.,* 1993]. Judging by the presence of old stone avalanches and rock falls, no conditions of this type had been manifested

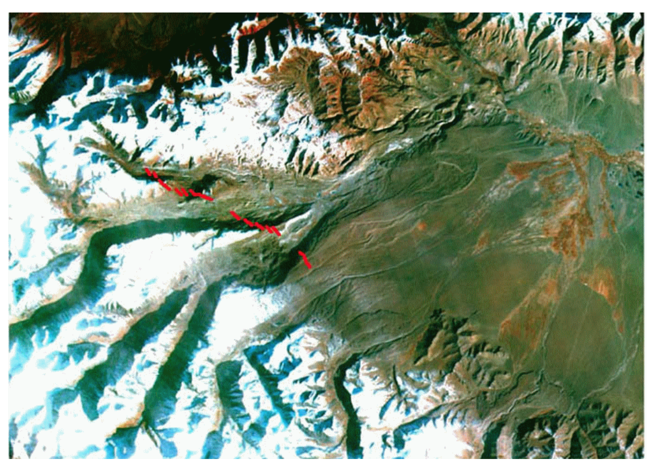

Figure 27. A picture sent back by the "Resurs" spacecraft on October 10, 2003. The red lines show the manifestation of the earthquake source at the ground surface.

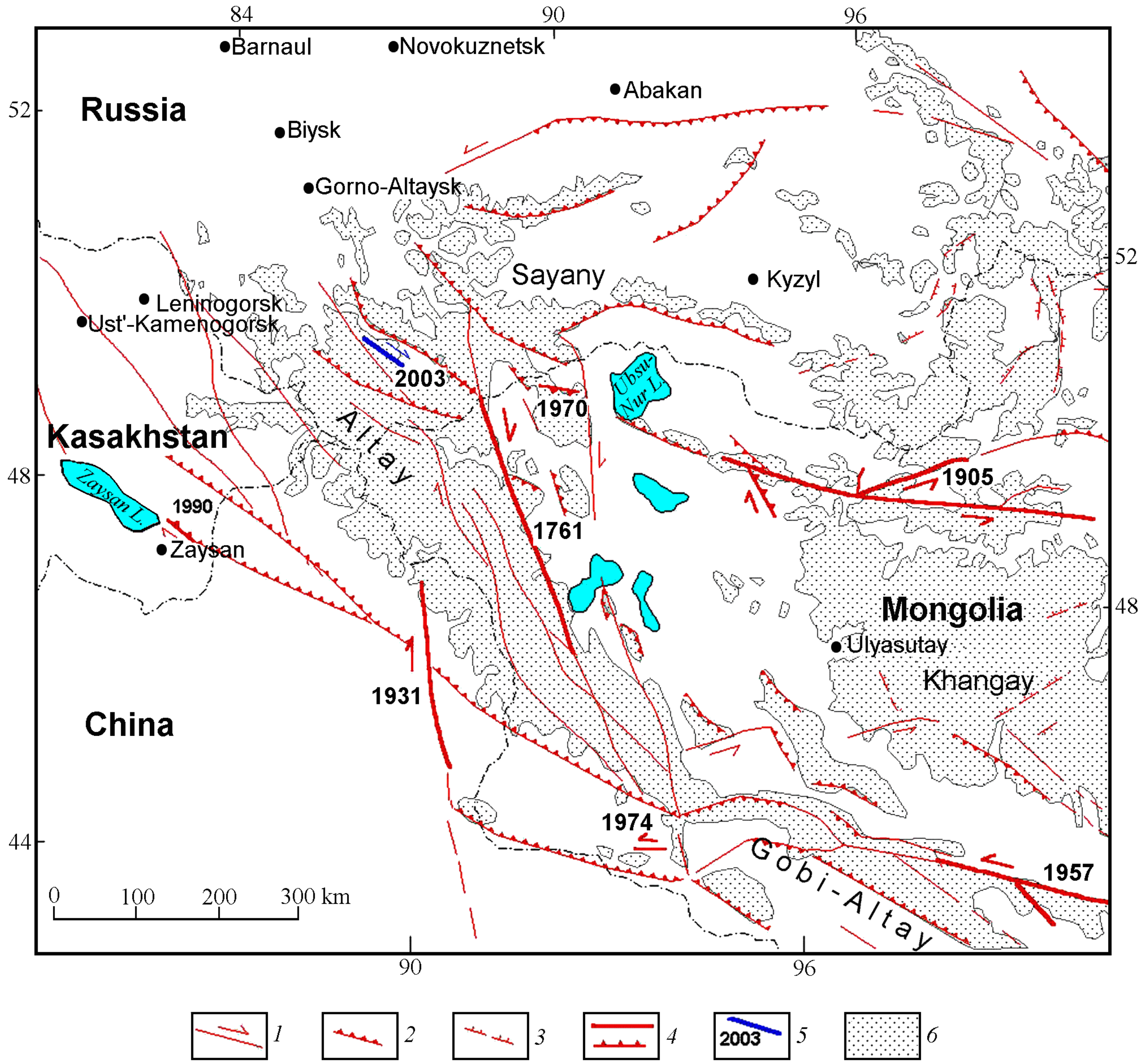

Figure 28. A seismotectonic map for the Mongolia and Siberia regions, compiled using the data reported in [*Earthquakes...,* 1985; *Molnar et al.,* 1995; *Rogozhin et al.,* 1995].
Legend: (1) strike-slip fault, (2) reverse fault, (3) normal fault, (4) area of earthquake activation, (5) the fracture that produced an earthquake on September 27, 2003, (6) elevations higher than 2000 m.

during the previous earthquakes. On the contrary, the earthquake of September 27, 2003, appears to be a weak event in terms of its effect on the natural and man-made objects. This is proved by the absence of any serious destructions in the settlements located in the pleistoseist region.

Figure 27 shows a seismic ruptures (with a space resolution of 40 m). The seismic fault has a good expression in the topography. There are the rectified segments of the river valleys, scarps, saddles, and distinct changes in the photographic tint. It should be noted that this structural feature is not shown in the maps of neotectonics [*Bogachkin,* 1981; *Devyatkin,* 2000]. This seems to be associated with the problems of tracing strike-slip faults by traditional geological and geomorphological methods used to map recent faults because of the absence of any significant vertical displacements of various geomorphologic levels (terraces and planation surfaces). At the same time it is evident that the earthquake-generating structure is able to demonstrate a high level of seismic activity. Figure 28 shows that the fault generated by the Gornyi Altai earthquake September 27, 2003 correlated well with the modern structural pattern of the Mongolia-Siberia region, being the continuation to north-west of the faults located in the West Mongolia territory, where catastrophic earthquakes with magnitude more than 7 are known to have occurred repeatedly. In the present-day stress field the NW-trending and submeridional faults manifested themselves as right-lateral strike-slip faults with a reverse fault component. On the other hand the NE-trending and sublatitudinal faults have manifested as left-lateral faults with remarkable normal fault component [*Earthquakes...,* 1985; *Molnar et al.,* 1995; *Rogozhin et al.,* 1995]. It follows that the kinematical characteristics of the fault that was regenerated during the earthquake of September 27, 2003, suggest there had been one stress field that had operated over the territory of the whole Great Altay area, including its Mongolia and Gobi segments.

Conclusion

The results of the preliminary study of the high-magnitude earthquake, which occurred on September 27, 2003, in the south of the Gornyi Altai region, allow us to derive a few conclusions on the specifics and results of seismic activity in this mountainous region. First, the Gornyi Altai region can be confidently interpreted as a direct northern continuation of the Mongolia and Gobi Altai, the regions where numerous earthquakes with magnitudes of >7.0 had occurred repeatedly, and combine all of the Greater Altai mountainous systems into one seismotectonic province with high magnitudes of expected earthquakes. Secondly, the sluggish character of the earthquake, responsible for the comparatively moderate macroseismic effect at the ground surface, in spite of its high magnitude and of its source located in upper crust, suggests the complex structure of the earthquake source, possibly, associated with the curvilinear form of the fault plane.

Acknowledgments. We are thankful to the administration of the Koshagach District of the Altai Republic for its help in our field operations. This work was partially supported by the Russian Foundation for Basic Research (projects nos. 02-05-64946 and 03-05-05-79080). The radiocarbon dating was fulfilled by team of Institute of Geography, Russian Academy of Sciences under management of Dr. O. A. Chichagova.

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(Received 15 January 2004)