

## Tectonophysical Analysis of Fracture Deformation Zone of the Chuya Earthquake (September 27, 2003)

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The strong earthquake ( $M_s = 7.1-7.3$ ) on September 27, 2003 in the southern Gorny Altai is a unique seismic event. Therefore, this area has become a geodynamic test site for the study of seismotectonic deformations and verification of various geological–geophysical models simulating active faults. The first results of field inspection of the epicentral zone and seismological monitoring were published in [1–5]. The earthquake was accompanied by exposure of its source resulting in the formation of a WNW-oriented seismic fracture system that was first traced for 20 km at the eastern plunge of the North Chuya Range [2]. In 2004, we investigated this area and revealed that the seismic faults extend for more than 30 km. According to [3, 4], the focal mechanism for the major shock and main aftershocks was of the strike-slip type.

The objective of the present communication is to supplement the traditional seismogeological observations by tectonophysical analysis that provides insights into specific features of the internal structure of the newly formed seismotectonic fault zone from the point of view of the laws of deformation of real bodies and to reconstruct the stress field that initiated this seismic event. We carried out tectonophysical and geostructural investigations in the Chuya fault zone extending over 20 km from the Yelangash River to the Kuskunnur River. We examined seismic deformations of various ranks and tectonic fracturing in both loose sediments and bedrocks. Information gathering and processing were performed using the tectonophysical methods commonly applied to faults of various scales [6].

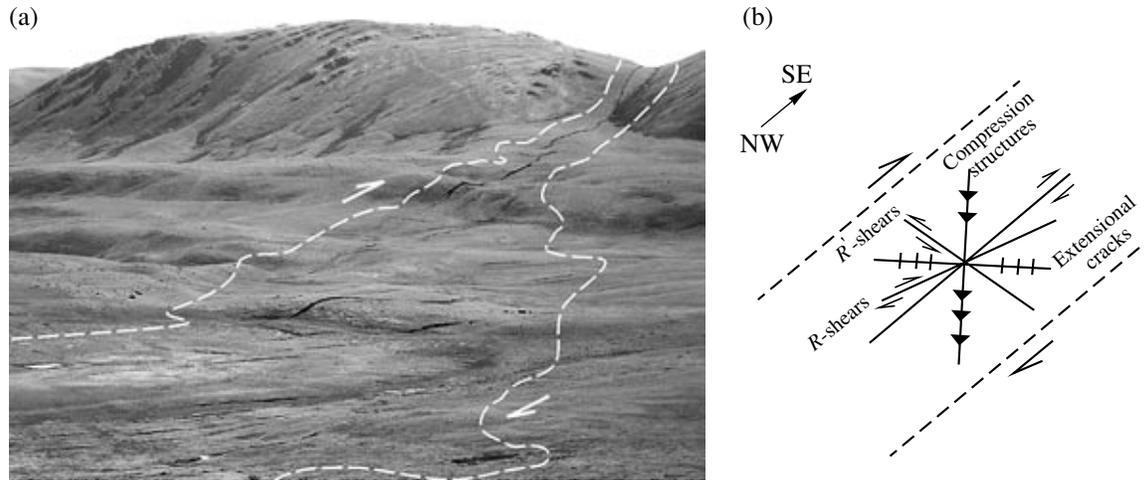
The results obtained show that the seismic fracture system produced by the Chuya earthquake is a typical fault zone with an internal structure typical of dextral

strike-slip faults governed by a set of systematically arranged structural elements (Fig. 1). The width of this zone between the extreme observation points that recorded the seismic fractures locally attains 4 km. In plan view, this zone reveals the following internal structure. Loose sediments are crosscut by a series of advanced strike-slip faults ( $R$ - and  $R'$ -shears) (often with gaps ranging from a few centimeters to several meters in width and maximal amplitude of dextral strike-slip equal to 2.5 m), extensional cracks represented by trenches 2–7 m wide, and compressive structures expressed as arches and folds. The considerable amplitudes of fault opening in loose sediments are most likely related to gravity effects. Analysis of seismogenic fracture directions indicated the prevalence of NW-trending ( $280^\circ-350^\circ$ ) dislocations with a distinct maximum at  $290^\circ-330^\circ$  corresponding to  $R$ -shears. The  $R'$ -shears ( $350^\circ-30^\circ$ ) are poorly expressed in rose diagram. Extensional and compressional structures are oriented perpendicular to each other ( $340^\circ-350^\circ$  and  $70^\circ-90^\circ$ , respectively). The distribution of advanced faults is highly differentiated (Fig. 1). In some cases, they occur as distinct (single or paired) nearly parallel faults and small fractures with a lesser density in comparison with other parts of the fault zone. Such segments are locally complicated by separate transverse cracks. The segments alternate with clusters of advanced fault systems (commonly, an echelon of cracks). The clearly expressed faults are found largely on slopes and summits of watersheds, whereas the dispersed deformations are confined to depressions with a thicker cover of sediments. At the junctions of large faults ( $R$ - and  $R'$ -shears), the fault zone has a more complex structure, and displacements along fractures of the same direction may be opposite.

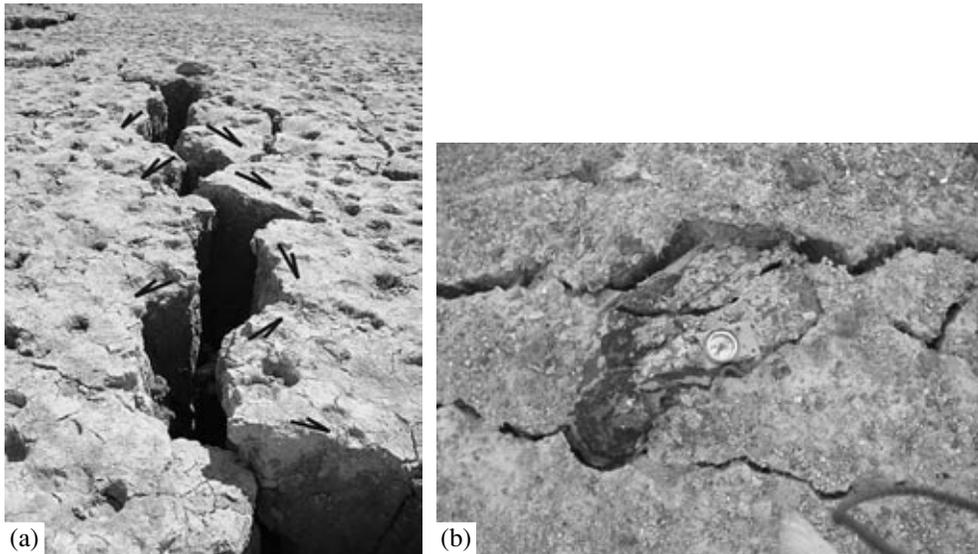
A detailed examination of advanced faults in loose sediments enabled us to understand their dynamics and propagation. First, they consist of fractures of a lower hierarchical level (no longer than 1 m) that make up a conjugated fracture system (Fig. 2a). The mutual opposite displacements along them produce rhomb-shaped blocks and pull-apart structures. Such displacements are responsible for the general sinusoidal morphology of advanced faults of variable extent. They reflect the

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**Fig. 1.** (a) A fragment of fault zone formed during the Chuya earthquake at the Taltura River/Kuskunnur River watershed and (b) idealized scheme of structural elements related to dextral strike-slip fault (after [6]). A zone of intense seismic fracturing is contoured in the photograph.



**Fig. 2.** Closeup fragments of seismic fractures in loose sediments. (a) A fault consisting of separate small fractures; arrows indicate motions along fracture walls; (b) fractures cutting pebble and soil in the same direction.

propagation mode of seismic oscillations (variations in the direction, amplitude, and wave propagation velocity) in elastic medium. Second, facts presented in Fig. 2 indicate that the medium responds to fast pulse motions during faulting as a homogeneous body despite the presence of numerous inclusions of hard rocks and vegetation (tree roots and stubs).

In bedrocks, the fracturing is largely expressed in opening of older shear zones and rejuvenation of some fractures with displacements reaching a few decimeters (Fig. 3). The degree of crystalline massif crushing directly correlates with the volume of body involved in deformations due to small-amplitude displacements

along short (up to 2 m long) fractures. In other words, the released seismic energy is dispersed along the existing fracture systems. The thick ancient sublatitudinal and NW-oriented fault zones are the most favorable structures for reactivation. Along healed shear zones in the less disturbed bedrocks, one can see seismic fractures (0.1–0.3 m wide) that are traceable as common sutures in both bedrocks and loose sediments (Fig. 3). In some places, indications of fast reactivation of older steep fractures are revealed. On the right wall of the Kuskunnur River, one can observe 0.2- to 3.0 m-thick crush zones dipping  $10^{\circ}$ – $30^{\circ}$  NE  $\angle 80^{\circ}$ – $85^{\circ}$  and  $110^{\circ}$  ESE  $\angle 75^{\circ}$ – $80^{\circ}$  in weakly fractured, almost solid crys-



Fig. 3. Seismic reactivation of an older shear zone dipping  $210^{\circ}(30^{\circ})\angle 85^{\circ}-88^{\circ}$  at a bedrock outcrop.

talline schists with subhorizontal tight foliation and rare subvertical cracks. The predominating strike of the recorded seismic faults in exposed bedrocks is  $300^{\circ}-320^{\circ}$ . One can also see large rejuvenated fractures extending along  $330^{\circ}-340^{\circ}$ ,  $20^{\circ}-30^{\circ}$ , and  $80^{\circ}-110^{\circ}$ .

Diagrams of fracture orientation show that systems corresponding to  $R$ - and  $R'$ -shears of dextral strike-slip faults are most clearly expressed in loose sediments in the overwhelming majority of cases. If the older NW-striking faults occur in bedrocks or a massif is only slightly fractured, a significant number of older fractures are reactivated and new fractures appear, resulting in a virtually complete coincidence of structural patterns in fracture diagrams for adjacent exposures of different rock types. In the fault zone dipping  $355^{\circ}-0^{\circ}$  N  $\angle 80^{\circ}-85^{\circ}$  that controls the Taltura River valley, such a scenario is realized rather infrequently because reactivation involves mainly sublatitudinal faults and new faults are rare. In general, fracture orientation diagrams show that the master seismic fault dips to NNE at an angle of  $80^{\circ}$ .

Specific features of the internal structure of the fault zone, displacements, fracturing, and slickensides allowed us to reconstruct the original stress field that produced the structural assemblage of seismic deformations during the Chuya earthquake. The solution obtained (compression axis  $347^{\circ}$  NW  $\angle 0^{\circ}$ , extension axis  $77^{\circ}$  ENE  $\angle 21^{\circ}$ , and intermediate axis  $256^{\circ}$  SW  $\angle 69^{\circ}$ ) corresponds to the strike-slip field and is close to the focal mechanism of the main shock reported by the USGS National Center for Information on Earthquakes [3].

Thus, it has been established that the system of seismic dislocations related to the Chuya earthquake is a fault zone more than 30 km long and no less than 4 km wide. Its internal structure is typical of dextral strike-

slip fault. In terms of tectonophysics [6], the systematic distribution of advanced faults corresponds to the late disjunctive stage of fracture zone evolution in the absence of a common main fault plane. Hence, the process of structure formation in very different rocks obeys general laws of solid-state deformation in the case of fast dislocations even under surface conditions.

#### ACKNOWLEDGMENTS

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