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Active faults of the northern Tien Shan: tectonophysical zoning of seismic risk

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Abstract

This study continues the work by Mikhail Gzovsky on geological (tectonophysical) criteria for seismic risk. It is suggested to perform seismic-risk zoning according to parameters of normal and shear stresses on fault planes converted from results of tectonophysical stress reconstructions. The approach requires the knowledge of both dip and strike of the respective fault segments. Slip geometry is estimated from stress tensor, assuming that it is directed along shear stress. The suggested approach is applied to faults in the northern Tien Shan, and the current stress parameters are reconstructed using source mechanisms of catalogued earthquakes recorded by the KNET seismological network of the RAS Science Station in Bishkek. Stress modeling is performed by the method of cataclastic analysis providing constraints on stress ellipsoids, as well as on relations between the spherical and deviatoric components of the stress tensor. Plotted on the Mohr diagram, the fault stress points allow estimating whether the respective fault segments are close to the critical state (brittle failure). The suggested seismic-risk zoning of faults in the northern Tien Shan reveals up to 25 km long hazardous fault segments.

Keywords: current stress; seismic risk; tectonophysical zoning; active fault; hazardous fault; Coulomb stress

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Introduction

Detecting faults prone to generation of earthquakes is the key point in seismic risk assessment. Discrimination of fault segments in terms of potential hazardous slip or creep is important for safe and environment-friendly operation of transportation and pipeline systems. Currently seismotectonics and GPS measurements, as well as methods based on earthquake records, are most commonly used for these purposes. Hazardous faults are identified from signatures of present and past activity on the surface (rock falls, landslides, etc.) or in trenched faults. Seismotectonic analysis allows qualitative assessment of hazard in different fault segments while intensity of paleoearthquakes from trenching data provides quantitative support.

Land-base and remote GPS measurements likewise can reveal activity of faults but mostly within short observations periods restricted to ongoing faulting. Instrumental records of earthquakes highlight brittle failure processes deep in the crust, but seismic analysis applies to historic events which often have magnitudes much smaller than the maximum possible values. The latter are found from recurrence plots updated using information on historic and prehistoric events.

Tectonophysical zoning of active faults is an alternative approach, which was suggested by Gzovsky (1975) fifty or sixty years ago but has been almost forgotten. Gzovsky used the term *geological criteria of seismicity* referring to signatures of seismic hazard showing the most probable highest magnitude of shocks and their expected recurrence. In the present-day terminology, they are rather tectonophysical criteria, as we call them in the consideration below.

Tectonic and seismic activity occurs in areas of rugged terrain and structurally differentiated crust, with high-gradient slip rates, and also in fields of young volcanism (Gzovsky, 1975). The geological (tectonophysical) criteria of seismicity mafe basis for contouring areas of highest shear stress and high-gradient vertical motions within different periods: millions of years for neotectonic methods, thousands and tens of thousand years for geomorphology, and decades for GPS measurements. The results were used to predict stress and strain trends and to assess the energy of pending events and duration of critical stress periods (Gzovsky, 1975).

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By tectonic stress Gzovsky meant primarily the stress measured directly in rocks with implications for principal stress directions (the method of conjugate par faults), while estimation of total crustal stress was considered as a problem resolvable in the future.

We develop the approach by Gzovsky proceeding from today's advance in rock mechanic studies of critical preseismic stress.

Gzovsky's approaches to seismic zoning

In his synthesis of seismic risk data available at that time, Gzovsky (1975) noted that geological (tectonophysical) criteria of seismicity sometimes contradicted real observations. Specifically, they would indicate high activity in the Alps where actually the seismicity was low, but low activity in the Hungarian depression which was shocked by several earthquakes of shaking intensity 8. To explain the paradox, Gzovsky hypothesized deceleration of mountain growth in the Quaternary with decreasing deviatoric stress and proposed to study ongoing crustal movements using GPS.

Some other paradoxical examples are high seismicity in the Garm valley in spite of tectonic and geomorphic signatures of stability (Gzovsky, 1975) or low seismicity in the northwestern Greater Caucasus (zones of probable shaking intensity 6), though some parts of the shore between Sukhumi and Novorossiysk rather should belong to the intensity 8 zone according to geomorphology and tectonics. Gzovsky noted that the seismic process changed in time and crust movements had slower or faster rates, which tectonic and geomorphological data, averaged over long periods, failed to resolve.

Gamburtsev (1955) also mentioned that tectonic movements varied with time and earthquakes had greater intensity during reactivation of seismic sutures in the crust which would appear to be stable from parameters averaged over hundreds or thousands of years.

The earthquake magnitude was hypothesized (Gamburtsev and Belousov, 1960) to depend on the size of the high-stress zone and the magnitude of largest events to influence the frequency of earthquakes, as the duration of the pre-faulting maximum shear stress was related with the stress level. Therefore, the size of the zone of high potential energy of elastic strain was related to the length of seismogenic faults. Gzovsky (1975) noted in this respect that triaxial compression impeded earthquakes while faults could be healed.

He interpreted nucleation of large earthquakes in large faults as prolonged formation of small faults showing up as small earthquakes; in their turn, large earthquakes were understood as rapid motions along large faults as a result of pulse-like growth of originally isolated small faults (Gzovsky, 1975). The potential energy of elastic strain in the zone of high maximum shear stress drops dramatically as it becomes crosscut by a growing fault. Gzovsky (1975) considered a seismic source as an area where the potential elastic strain changed as a result of fault reactivation rather than as a tectonic suture (Dobrovolsky, 1991), an idea which agreed with the views by Benioff (1951), Bullen (1955) and Savarensky (1954). Gzovsky also mentioned the importance of faulting mechanisms in their relation to crustal stress.

The stress responsible for the ongoing seismic process can differ from that in which the respective faults were originally forming. Therefore, it is crucial to compare stress in active faults with the highest level and with stress estimates based on the amount of slip accumulated for hundreds of thousand or millions of years in the past.

Natural stress and strain: state of the art

Decades ago, when Gzovsky (1975) formulated the objectives of tectonophysics in seismic risk assessment, data of natural stress were collected by measurements of strain in crust and directly in mines during hydraulic fracture; by geomorphological and GPS measurements; and by methods of field tectonophysics and seismology. Geomorphological and GPS estimates gave rates of terrain changes and required the knowledge of relations between stress and gradients of motion. The measurements of joints in tectonophysics and fault plane solutions in seismology could show only principal directions but not the level of stress.

The situation has changed over the recent decades, both in methods and in amount of collected data. Remote sensing has allowed great progress in GPS measurements, with horizontal crust movements measured ten times more precisely than the vertical ones. Recent estimates of horizontal movements in Central Asian intracontinental orogens (Kuzikov and Mukhamediev, 2010; Sankov et al., 2011; Timofeev et al., 2009, 2013; Zubovich et al., 2007) were interpreted mostly in terms of regional evolution models, but they should be converted into gradients along some directions or rates of longitudinal strain. Strain can be also estimated by triangulation methods, which are quite well developed (Sankov et al., 2011; Tychkov et al., 2008). In continental active tectonic areas, lateral strain has annual rates of $n \times 10^{-8}$–$n \times 10^{-9}$ yr^{-1}; higher rates are obtained at shorter base lines and smaller scales of averaging (Karmaleeva, 2012; Kuzmin, 2004): three or four orders of magnitude higher at tens to hundreds of kilometer lines, while strain is localized in vicinities of large faults.

Stress patterns have been largely documented for the upper 3 km of crust (Brady and Bzown, 2004; Brown and Hoek, 1978; Herget, 1973; Potvin et al., 2007; Zubkov et al., 2010). Much evidence was obtained previously on horizontal compression shortening exceeding the standard lateral pressure (Dinnik, 1926) and vertical (overburden) pressure. Currently it is known that (i) vertical stress varies geographically but approaches the overburden pressure; (ii) most of measurements show horizontal compression exceeding the vertical stress in areas of long-lasting uplift; (iii) most of measurements show stress about the standard of Dinnik (1926) in areas of long-lasting subsidence and nearly vertical maximum compression; (iv) horizontal compression axis is especially variable near the surface (from 0.3 to many times as high as the overburden pressure) but the variations decrease with depth