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GEOPHYSICS

Tectonic Stress, Metamorphism, and Earthquake Source Model

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It is commonly assumed that the probability of brittle failure in rock massifs and seismic regime intensity directly correlate with tectonic stress. These ideas have fostered the development of a number of earthquake source models, e.g., the model of avalanche fracturing (hereafter, the IFZ model [named after the Russian acronym for our institute]) and the dilatancy–diffusion (DD) model, both of which suggest that the formation of an earthquake source (rupture) is caused by increase in deviator stress up to a certain critical level. Reconstruction of natural stress obtained from the cataclastic analysis of fractures [1, 2] shows that this statement is equivocal. Taking into account some additional hypotheses, the reconstruction ensures not only calculation of principal axes orientation and stress tensor mode, but also the estimation of tectonic stress values and parameters of the effective strength of rock massifs (adhesion and friction coefficient), which are derived from the data on earthquake focus mechanisms. In accordance with the experimental results [3], this method suggests that the Coulomb law governs the strength of rocks during the brittle failure of previously undisturbed rock domains as well as the limit resistance of dry friction during the reactivation of older fractures.

Principal trends revealed from calculation of natural stresses. The calculations carried out on active seismic zones in the Earth's crust of the South Kuril Islands and Japan, as well as on the aftershock region of the Northridge earthquake in 1994 [2] have shown that the effective adhesion τ_f for fractured rock massifs at an averaging scale of n–10 km does not exceed 50–100 bar (1 kbar in experiments on samples). The maximum tangential stress τ acting in the Earth's crust widely varies in the lateral direction and does not exceed 1.5 kbar in the South Kuril Islands and Japan (Fig. 1a) and 0.5 kbar in the aftershock region of the Northridge earthquake. These values are much lower than theoretical estimates (4–8 kbar at the Earth's crust base) obtained by Sibson [4], Ranalli and Murphy [5], and other researchers. Such a low level of stress is responsible for failures of strength in earthquake sources and is a result of the existence of older fractures, which diminish the effective strength of rocks, and of the elevated pore fluid pressure p_{fl}. The fluid pressure in deep zone is higher than the hydrostatic pressure and in some places approaches the lithostatic pressure. The calculations showed that the domains with elevated τ are characterized by decreased fluid pressure (Fig. 1b).

In materials, which obey the Coulomb law of strength, rock failure is controlled by the Coulomb stress, i.e., the difference between tangential stress at fault plane and stress of dry friction. Therefore, the critical state at fractures is determined by both the maximum tangential stress and the effective pressure p^* (tectonic stress minus fluid pressure). The relationship between τ and p^* depends on the stress tensor mode defined by the Lode–Nadai coefficient μ_σ. For the aftershock region of the Northridge earthquake, the average $\tau/p^* \approx 0.51$, 0.63, and 0.68 at $\mu_\sigma = -1$, 0, and 1, respectively. It is possible to detect crustal domains with different rates of *dilatancy* using estimated natural stress and the relationship $C_{Dl} = \sigma_1^*/\sigma_3^*$ (σ_1^* and σ_3^* are the algebraically maximum and minimum principal effective stresses; compression is negative) [2]. According to experiments [6], the C_{Dl} values of 0.2–0.4 correspond to the maximum dilatancy rate for rock samples. In the crustal domains with such C_{Dl}, the τ value can widely vary (Fig. 2b).

Results of the reconstruction show that the strongest earthquakes in the study regions (Fig. 2a) are confined to domains with the highest dilatancy rates, which are also characterized by *elevated, though not the highest levels of maximum tangential stress.* The fluid pressure in these domains ($C_{Dl} > 0.25$) varies widely (Fig. 2b); likewise the maximum tangential stress (τ/τ_f). The fluid pressure is characterized by minimal scatter and by maximal value in areas where the dilatancy rate is minimal ($C_{Dl} < 0$). The level of maximum tangential stress is very high here.

Parameters of natural stress and models of earthquake source preparation. Within the framework of results obtained, let us consider the processes

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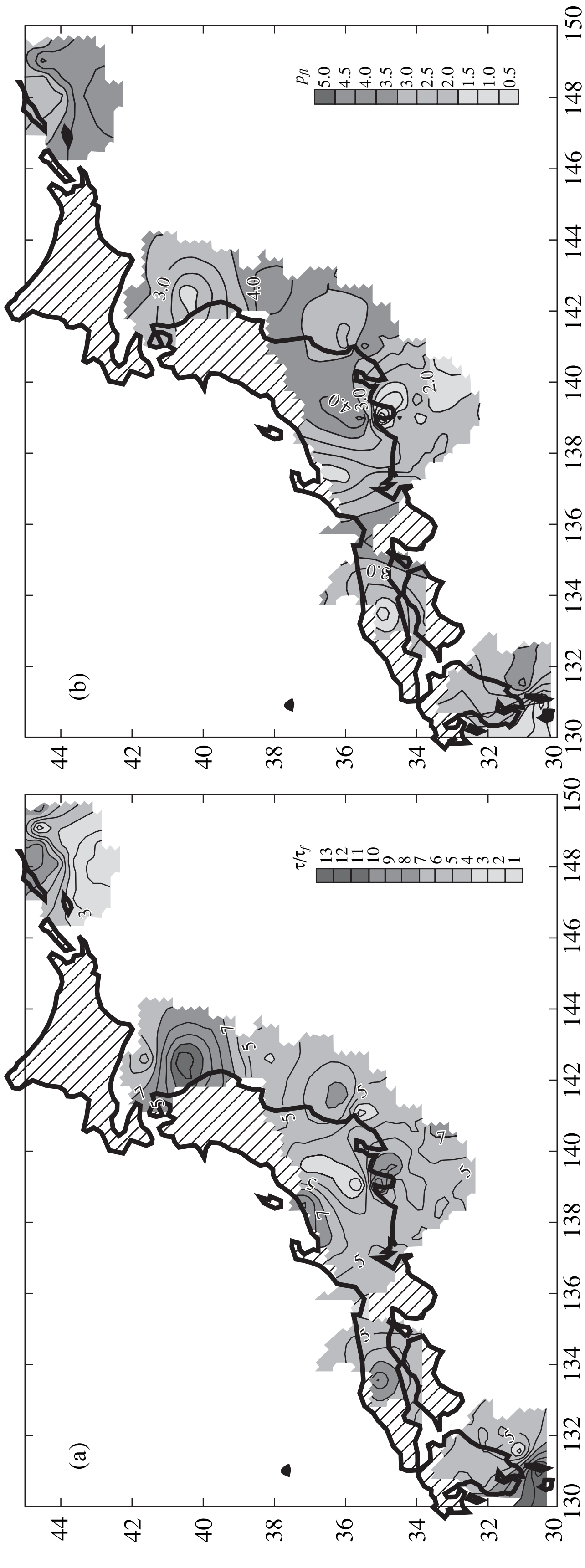

Fig. 1. Distribution of (a) relative values of the maximum tangential stress and (b) fluid pressure, kbar for the 20-km depth layer of the Earth's crust of the South Kuril Islands and Japan.

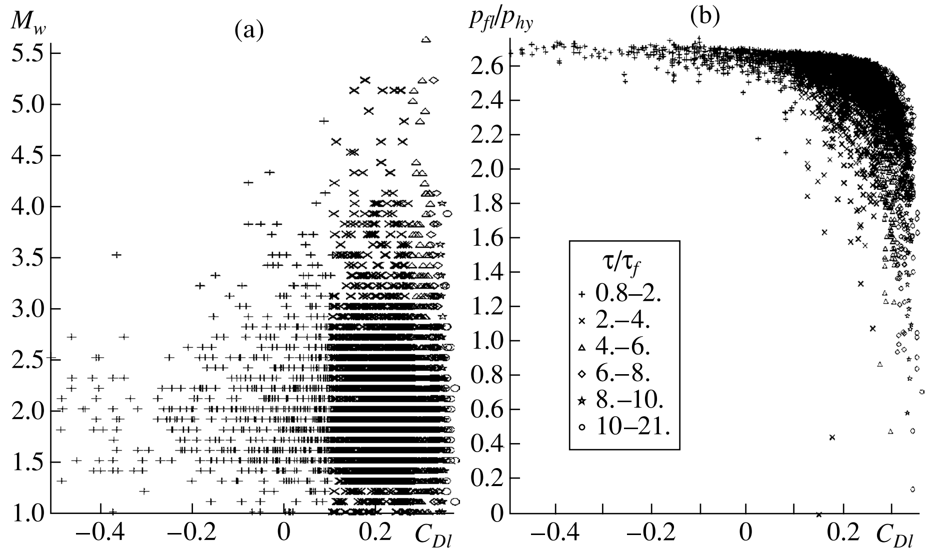

Fig. 2. Interrelations between parameters of the state of stress for the aftershock region of the Northridge earthquake: (a) magnitude of earthquake source M_w and (b) fluid pressure p_{fl}/p_{hy} versus coefficient C_{Dl} for various relative values of the maximum tangential stress τ/τ_f.

in a region of earthquake source preparation on the basis of the DD-model. In compliance with this model and according to the Coulomb theory of brittle failure, when Coulomb stress reaches 50–70% of the ultimate strength (due either to increasing deviator stress or decreasing effective pressure), brittle fractures are localized in rocks within relatively narrow shear bands, in which dilatancy abruptly accelerates owing to their structural inhomogeneity. The rapid expansion of the fracture–pore space results in fluid pressure drop. Consequently, effective pressure in the Coulomb medium increases and the Coulomb stress decreases, while the level of deviator stress is retained (the lower right sector in Fig. 2b). The effective strength τ_f somewhat decreases due to dilatancy. Owing to the growth of confining pressure, the given domain is strengthened and should be regarded as a more *rigid inclusion* [7] that intensely accumulates elastic strain. The increase in Coulomb stress here may be related both to the growth of deviator stress, due to the ongoing deformation of the Earth's crust, and to the increasing fluid pressure that decreases dry friction.

In terms of the DD-model, fluid transfer from neighboring domains accounts for the subsequent increase in fluid pressure. However, these domains have a substantially lower porosity. Therefore, the rate of pore liquid filtration is low and the process is inefficient. Moreover, such fluid transfer may result only in a leveling of fluid pressure in inclusion and country rocks (taking into account lithostatic pressure variation with depth), but this mechanism cannot explain the existence of the zone with *anomalously high fluid pressure* in the source region [8].

In terms of the fluid-metamorphic (FM) model of earthquake source preparation developed by Rodkin [9], an abruptly decreasing effective strength in the future source was first addressed to polymorphous transitions in rocks at the respective *PT* conditions [10]. Subsequently, fluid pressure growth as a result of metamorphic dehydration reactions was considered to be one of the crucial factors of rock failure. The FM-model introduces the notion of *soft and rigid inclusions* (mylonites and pseudotachylites) within the shear zone. These inclusions correspond both to regions where materials are transformed and to those where they are not [9].

It should be mentioned that the FM-model does not take the factor of time into account, although this factor is critical for the introduction of metamorphic effects into the source model. The dehydration that provides fluid inflow into pore space commonly proceeds slowly, because it requires the supply of additional heat due to the endothermic character of dehydration reactions. The reactivity of solids is controlled by the diffusion rate of reacting substances, as well as by rates of adsorption, desorption, and chemical reactions at grain surfaces. The rate of diffusion through the crystalline lattice is approximately 10^{-12}–10^{-14} m^2/s, which means that this process develops very slowly. Therefore, the FM-model version proposed in [9] may explain only the localization of strains in metamorphic zones (cataclastic metamorphism) and creep displacements along fractures [11].

Role of autodispersion of rocks in shear localization zones. The FM-model does not consider some factors that may accelerate metamorphic reactions in rocks up to the point of an impulse (explosive) process. One such factor pertains to the increasing dispersion of rocks within narrow zones of shear flow. The decrease in grain size and increase in the number of lattice defects within such zones are related to dilatancy, formation and increase of shear fractures, grinding of grains, and other mechanical processes. The dispersion of crystalline materials is possible not only by means of simple mechanical impacts upon fault zones, but also by the autochthonous disintegration of crystalline materials into finely dispersed crystalline and semicrystalline particles (spontaneous dispersion). The abovementioned processes abruptly accelerate in the presence of liquid phase. Beginning at a certain dimension (<1 mm), the dispersed particles acquire some properties of chemical components, and the diffusion rate in dispersed systems markedly increases [12]. The high dispersity of reagents and the presence of fluid promote faster supply of materials to the growing new phases. The energy that controls the kinetic barrier between metastable and activated states in such finely dispersed zones abruptly falls.

The process of reactions is accelerated not only by the degree of dispersion and the presence of liquid phase: deviator stress and strain rate also play a substantial role. The elevated values of these parameters may lead to an increase in the reaction rate by several orders of magnitude. Experiments show that at a sufficiently high level of shear stress in samples of the powderlike salts of metals [13], the dehydration reaction becomes explosive and is characterized by a diffusion rate that exceeds the respective value in liquid phase by several orders of magnitude. This endothermic reaction proceeds under isothermal conditions. The required heat is released at the moment of explosion and completely consumed in the course of chemical transformations. Like high confining pressure, the high level of deviator stress converts the crystalline lattice into an energetically excited state, promoting an immediate conversion of mechanical into chemical energy. This scenario of dehydration in shear zones ensures an almost instantaneous injection of a large body of fluid into the pore space. On the one hand, such processes may abruptly change the chemical composition of fluids and the resistivity of rocks and induce electromagnetic radiation. On the other hand, these processes strongly depend on electrical, electromagnetic, and radiation fields.

Petrofabric analysis of ductile strain zones in pyroxene samples conducted under laboratory high-pressure conditions [14] confirmed that the grain size diminishes, whereas the number and ordering of kink structures increase in approaching these zones. Such zones are marked by an appreciable transformation of minerals and the development of new phases of talc, carbonate, plagioclase and other high-pressure minerals. The newly formed structures are more ordered (e.g., the talc aggregate has a foliated and fibrous appearance). The autodispersion of materials in shear zones is accompanied by recrystallization, compaction, and sintering, resulting in the formation of coarse-grained polycrystalline aggregates. Autodispersion and compaction should be regarded as competing processes that are responsible for the intricate cellular structure of strain zones [14].

Model of brittle failure in the region of metastable state. As follows from the above discussion, structural–dynamic inhomogeneity related to the deformation of rocks may arise in suture zones. First of all, domains of the relict state of strain should be outlined (the upper left sector in Fig. 2b). Properties of this region depend on previous stages of fracture zone evolution characterized by a low degree of dilatancy. Narrow zones, which underwent shear strain and the consequent intense *dilatation*, are formed near and within these domains related to the stage of suture zone evolution, and they may be subdivided into three types. In domains of the first type, the degree of dispersion is insignificantly elevated. The grain size is smaller than the common one; therefore, dehydration is poorly developed. This type can be called a strengthened domain or *rigid inclusion*, since Coulomb stress is lowered here, while the stress level is rather high, and the fluid pressure is decreased (the lower right sector in Fig. 2b). The second type corresponds to domains with a high degree of dispersion, which provides active dehydration. The fluid pressure is high here. These domains are regarded as *soft inclusions*, with elevated Coulomb stress along with a medium intensity of stress (middle sector in Fig. 2b). Intense shearing (creep) may occur here. The third type comprises the compaction domains, which exhibit increase in grain size resulting from sintering and pressing.

The initial kinetic impulse induced in a particular rigid inclusion by ductile and quasiductile (microfracturing) strain in the course of ultrafast dehydration may give rise to brittle failure in the neighboring strengthened and energetically saturated domain. If the brittle fracture spreads over the neighboring rigid domains, an extended seismic fracture zone may arise. The formation mechanism of such an extended fracture zone, which crosses the domains with variable energy discharge efficiency, i.e., soft and rigid inclusions (Fig. 2b), is similar [9] in some sense to the stick-slip model. Another mode of ongoing failure in a rigid inclusion may be related to the termination of fracture propagation when it intrudes a strong, or conversely, a less rigid but more ductile domain (soft inclusion) of a larger dimension. The instability of rock failure evolution due to the spatial inhomogeneity of fracture zones makes it possible to identify them as zones of *metastable state* [15]. Note that many factors used to predict physical earthquakes (anomalies of electromagnetic fields, variations of electrical potential and conductivity) may develop similarly in both situations.

In order to explain earthquake source preparation, it is suggested to combine elements of the DD- and FM-models into a new dilatancy–fluid–metamorphic

(DFM) model including the following elements: (1) dilatancy and autodispersion of materials in the presence of fluid in narrow sliding zones; (2) ultrafast dehydration of severely dispersed segments of fracture zones and the generation of anomalous high fluid pressure; (3) nonuniform fluid pressure in fracture zones that makes up domains of variable effective strength in the Coulomb medium; (4) mosaic structure of fracture zone as a combination of soft and rigid inclusions that results in the random character of brittle failure and eventually in the metastability of source preparation domain.

Various stages of brittle failure preparation are controlled by physical parameters, which are related to the spherical (pressure) and deviator components of stress tensor, and by fluid pressure. The application of cataclastic analysis makes it possible to outline areas with different states and intensities of stress in the Earth's crust. These areas correspond to different scenarios of brittle failure. Thus, our method makes it possible to outline domains close to the metastable state.

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