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GEOPHYSICS

Reconstruction of Tectonic Stresses and Seismotectonic Strains: Methodical Fundamentals, Current Stress Field of Southeastern Asia and Oceania

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In devising methods for the reconstruction of tectonic stresses and seismotectonic strains, it is proposed that such work be guided by the following principles, characterizing the process of quasi-plastic deformation of fractured mediums.

1. The geological medium has many defects of various scale and genesis, expressed as variously oriented surfaces of reduced strength. In the process of deformation, the transformation of a part of elastic strains into irreversible ones, which promotes dissipation of the elastic energy within a macrovolume of geological medium, is linked to several factors, including displacement along the surfaces of reduced strength (shear surfaces). Under certain means of averaging, the formation of new shear fissures and the activation of existing ones can be considered as a microact of a quasi-plastic strain.

2. Within each spatiotemporal scale level determined by fissure size and time span of averaging, the multitude of microacts of quasi-plastic strains in the form of displacements along the fissures causes formation of the average (for a given spatiotemporal macrovolume) macroplastic strain tensor similar to that of effective elastic strains (principal axes of tensors are coaxial, and coefficients of a strain type are equal).

3. In relation to the stress tensor averaged within the spatiotemporal boundaries of a macrovolume that is quasi-uniform in a stress-strained state, the displacements along the fractures occur arbitrarily, but in such a way that the value of elastic energy released by the microact of quasielastic strain is positive. The maximum of dissipation energy, calculated for a uniform sample of structural kinematic data on shear fractures and fissures (SKDF), is achieved in a true stress tensor.

The first of the aforementioned principles is used in methods for the kinematic analysis of shear fissures. The second is a result of the experimental observations [1], and the last follows from Drucker's postulate [2], which serves as a basis for the modern theory of plasticity. This postulate determines the nonnegativeness of work produced by an additional load in the deformation process during the complete cycle of loading and unloading. One of the consequences of Drucker's postulate is Mises' principle of maximum, according to which the true stressed state is that in which the dissipation velocity of mechanical work is maximum. Another consequence is the requirement of positiveness of the mechanical energy dissipation velocity in the true stress tensor

$$dE = \sigma_{ij} d\varepsilon_{ij} > 0. \quad (1)$$

In describing a quasi-plastic deformation proceeding in a fractured medium due to displacements along the surfaces of reduced strength, σ_{ij} and $d\varepsilon_{ij}$ ($i, j = 1, 2, 3$) are considered to mean the average (for spatiotemporal macrovolumes) components of the stress tensor and average increments (rates) of quasi-plastic strains.

Let us consider every displacement along the shear fissure as the result of a plastic strain. Then

$$d\varepsilon_{ij}^{\alpha} = K^{\alpha}(n_i^{\alpha} s_j^{\alpha} + n_j^{\alpha} s_i^{\alpha}), \quad K^{\alpha} = \frac{\Omega^{\alpha} D^{\alpha}}{2V^{\alpha}}, \quad (2)$$

defines the average (for all points of the elastic unloading region V^{α}) contribution of the displacement deformations along the crack α to the tensor of effective quasi-plastic strains. In (2), n_i^{α} and s_i^{α} are the components of the unit vector of a normal to the fissure plane and of the displacement vector, respectively, D^{α} is the average value of displacement along fracture plane, and Ω^{α} is the fracture area. Let us extend the requirement of positivity of the energy dissipation velocity for the required effective stress tensor to each of the fractures. Substitute $d\varepsilon_{ij}$ in (1) via (2) and rewrite it in the coordinate system related to the main axes of stress tensor:

$$dE^{\alpha} = K^{\alpha}[(1 - \mu_{\sigma}) n_1^{\alpha} s_1^{\alpha} - (1 + \mu_{\sigma}) n_3^{\alpha} s_3^{\alpha}]\tau > 0, \quad (3)$$

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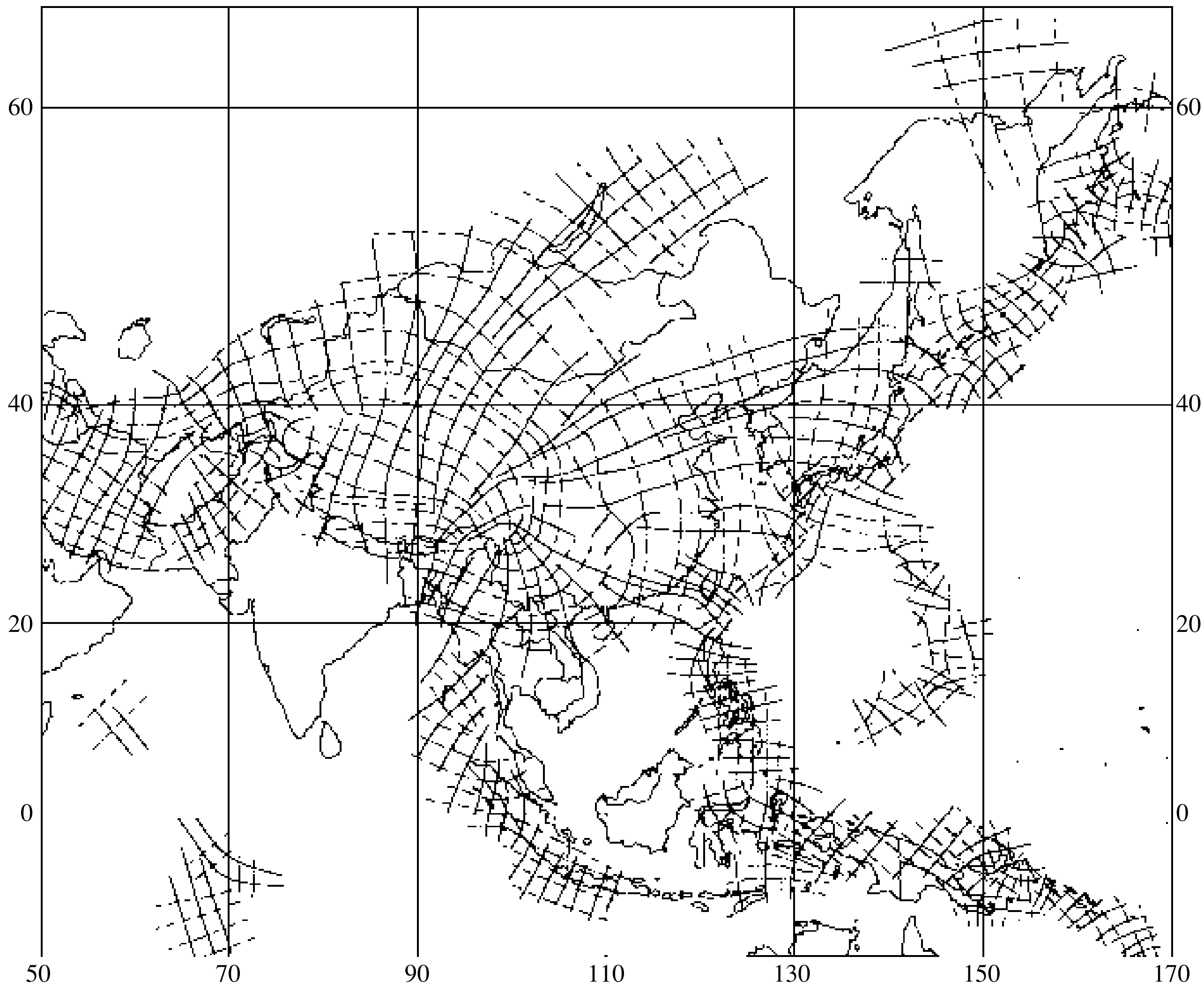

Fig. 1. Trajectories of minor (solid line) and major (dash-dot line) semiaxes of the ellipse on the horizontal section of the stress ellipsoid.

where

$$\mu_\sigma = \frac{\sigma_2 - \sigma_3}{\tau} - 1, \quad \tau = \frac{\sigma_1 - \sigma_3}{2}.$$

Here, σ_i are the principal normal macrostresses ($\sigma_1 > \sigma_2 > \sigma_3$), μ_σ is Lode-Nadai's coefficient, τ is the modulus of maximum tangential stress, dE^α is the average energy dissipation velocity in the unit volume for points within the elastic unloading region near the fissure α, and K^α is the positive coefficient. It follows from (3) that the direction of displacement along an arbitrarily oriented fissure plane with the normal $\mathbf{n}^\alpha$ cannot be arbitrary. To fulfil the condition of positiveness of the energy dissipation increment for $\mu_\sigma \to 1$, it is necessary that $n_3^\alpha s_3^\alpha < 0$, and for $\mu_\sigma \to -1$, that $n_1^\alpha s_1^\alpha > 0$. Thus,

$$n_1^\alpha s_1^\alpha > 0, \quad n_3^\alpha s_3^\alpha < 0 \tag{4}$$

defines the fulfillment of the requirement $dE^\alpha > 0$ for any possible value of μ_σ. Expressions (4) are similar to the known inequalities of the “right dihedra” method [4] and kinematic method [5]. In these methods, however, the inequalities were obtained from the condition of the coincidence of translation and tangential stress vectors on the fracture plane and showed the possible orientation of the principle strain axes with μ_σ changing from 1 to –1.

For calculation of the density of the elastic energy dissipation in every macroregion by the use of SKDF, it is necessary to sum the contributions of every shear fissure to the energy dissipation process. In doing so, it should be taken into account that each fracture has its own region V^α, within which the averaging (dE^α) of an individual event takes place:

$$dE = \sigma_{ij} S_{ij},$$

$$S_{ij} = \left\langle \sum_{\alpha=1}^{A} d\varepsilon_{ij}^\alpha \right\rangle_V = \left\langle \sum_{\alpha=1}^{A} K^\alpha (n_i^\alpha s_j^\alpha + n_j^\alpha s_i^\alpha) \right\rangle_V. \tag{5}$$

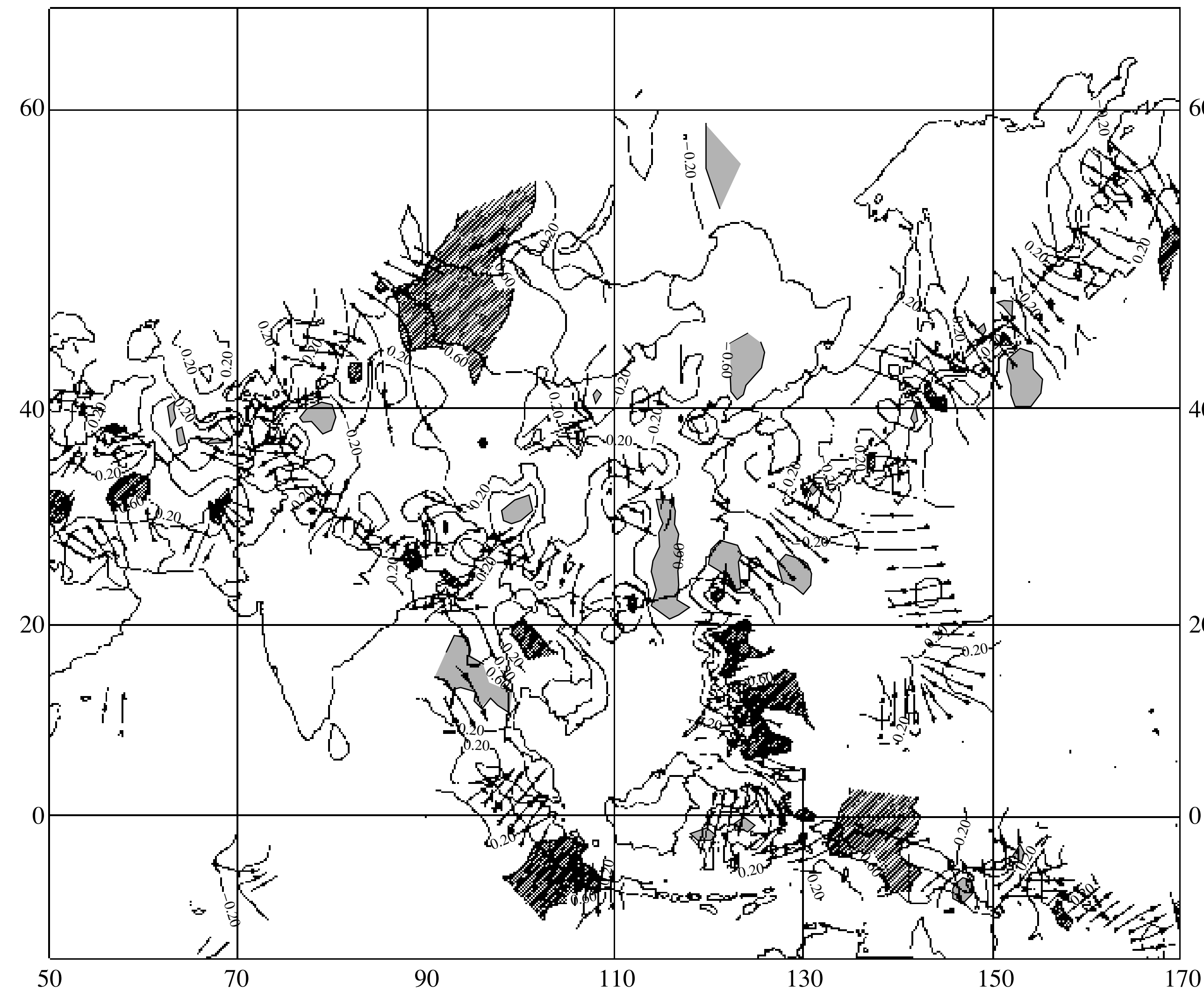

Fig. 2. Isolines of Lode-Nadai's coefficient (hatched zones correspond to values of >0.6; speckled zones indicate, values <–0.6) and trajectories of the vectors of tangential stresses on the horizontal planes (arrows).

In the last expression, index V on the angle brackets determines that summarization of individual contributions ($d\varepsilon_{ij}^{\alpha}$) in the seismotectonic strain tensor (**S**) has to include only those shear fissures whose elastic unloading zones contain a macropoint of the calculated energy dissipation density. The analysis carried out in [6] has shown that the value of K^{α} is close to a constant. Thus, in equation (5), it can be assumed that $K^{\alpha} = K$, and K can be factored out from the summation sign. In such a form, equation (5) is the tensor of the true seismotectonic strains for the points within a macrovolume of the intersection of elastic unloading zones of the SDF population.

Expression (5) is similar to that for the average mechanism of the earthquake population, suggested in [7]. However, in spite of their similarity, the principles of their calculation are different. The tensor of the average mechanism can be calculated for any SKDF population contained in an arbitrarily separated macrovolume, whereas the tensor of seismotectonic strains in form (5) requires that, first, the volumes V^{α} should have an intersecting zone, whose points are given a significance of a tensor (**S**) according to calculation, and, second, the earthquakes of the $\alpha = 1, \ldots, A$ population should enter a spatiotemporal macrovolume, which is uniform in terms of the strained state.

The above expressions allowed us to develop an algorithm of a reconstruction of the seismotectonic strain tensor and tectonic stress tensor in terms of SKDF. The algorithm is based on the following main procedures: specification of uniform (in space and time) macrovolumes within which the uniform SKDF populations are set up, using the application of inequalities (4); and calculation on the basis of expression (5) of a seismotectonic tensor in the center of population, i.e., in the macrovolume of intersection of the elastic unloading zones for the SKDF population.

The software, which was developed on the basis of the algorithm above to fit the seismologic data on the focus mechanism, was tested on the seismological database for more than 9000 focal mechanisms of crustal earthquakes with magnitudes $M_s > 4$, which occurred in southeastern Asia and Oceania in the period from 1924 to 1990. The analysis of the data obtained has shown that the principal features of the reconstructed field of the current tectonic stresses of southeastern Asia and Oceania are as follows:

1. The seismofocal areas adjacent to the oceanic troughs are characterized by normal (to their strike) orientations of projections of axes of the principal compressive and tensile deviator stresses, with the axes of the principal compressive stresses dipping under the oceanic lithosphere plates (Fig. 1) [8].

2. In the conjugate zone of the Indian and Eurasian plates, the axes of the principal compressive stresses are also directed along the normal to the strike line of the Pamir–Himalayan seismic region, with dipping under the Indian Plate. A set of directions of the principal stress axes forms a radial-concentric field, which becomes more sharply distinguished when constructing trajectories of the principal axes of the ellipse on the horizontal section of the ellipsoid of stresses (horizontal compressive and tensile stresses, Fig. 1) [8].

3. The known rift zones (Indian oceanic and Baikalian continental rifts) are characterized by normal (to their strikes) direction of the principal tensile stresses and by subvertical direction of the principal compressive stresses. These zones are characterized by Lode-Nadai's coefficient close to zero (pure shear displacement).

4. On the basis of data on the orientation of the principal strain axes and Lode-Nadai's coefficient values, the directions of tangential stresses on the horizontal planes have been calculated (Fig. 2). Figure 2 shows that at the bottom of oceanic lithosphere plates, the subduction forces are oriented from the ocean to the continent, which lends support to the validity of considering deformation processes over the oceanic trough zones in the context of the plate tectonics and explaining these processes by convection fluxes in the upper mantle. Within the narrow Pamir–Himalayan collision region, the orientation of these subductive forces also corresponds to the concept of the active subcrustal fluxes, which are sources of the submeridional movement of the Indian Plate.

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