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RESEARCH ARTICLE

Possible locations of strong earthquakes in western Tan Shan

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Abstract

The occurrence of earthquakes depends on a variety of factors generating various anomalies that are used as earthquake precursors. Mathematical modeling of the stress-strain state of the Earth's crust, verified with available instrumental data, can be used to determine the possible locations of tectonic earthquakes. For this purpose, the stress-strain state of the earth's crust of the West Tien Shan microplate has been modeled. The modern movements of the Earth's crust are modeled using the hydromechanics equations of creep motion (Stokes equations). Known GPS data served as boundary conditions. For a number of reasons at this time it is difficult to solve three-dimensional continuum equations for the Earth's crust (not exact structure of crust layers, their physical properties, etc.). Since the strong earthquakes in the region under consideration occur at depths of 15-20 km, we decided to estimate the average stress state for these depths. The Stokes equations were averaged over depth. The averaged two-dimensional Stokes equations are solved by boundary element methods. Isolines of maximum tangential stresses are constructed. Together with the energy criterion of strength, they served to determine the locations of critical stresses in the Earth's crust, where earthquakes are possible. The main horizontal stress vectors σ_1, σ_2 are constructed from the averaged stresses σ_{xx}, σ_{xy}, σ_{yy}. With the addition of lithostatic pressure as the third component of the main vector $\sigma_3=\sigma_{ver}$, the geodynamic state of the Earth's crust was evaluated using Anderson's method.

Keywords: earthquake; earth crust; mathematical model; stress; geodynamics; Western Tien Shan

1. Introduction

The Western Tien Shan region, part of the Alpine-Himalayan seismic belt, experiences significant seismic activity due to the interaction of three major lithospheric plates: the Eurasian, Indian, and Arabian plates. The stress state of the Earth's crust in this area is influenced by these tectonic interactions. Numerous strong earthquakes with magnitude M≥6.5 have occurred within the Western Tien Shan microplate (1902, M=6.5; 1918, M=6.5; 1924, M=6.5; 1934, M=6.5; 1937, M=6.5; 1944, M=6.7; 1946, M=7.5; 1949, M=7.4; 1955, M=7.1; 1963, M=6.5; 1972, M=6.6; 1974, M=7.3; 1978, M=6.8; 1983, M=6.6; 1985, M=7;). By understanding the conditions under which these earthquakes occur, researchers can better predict potential

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future events. Morphometric indicators, which result from the deformation of the Earth's crust, are often used to signal potential earthquake activity. However, large deformations do not necessarily indicate an imminent rupture, akin to how rubber can undergo significant deformation without breaking. M.V. Gzovsky highlighted that the seismic process is primarily determined by the maximum tangential stress and the maximum velocity gradients[1]. He also noted that all-round compression can prevent the occurrence of earthquakes. Therefore, while morphological features indicate crustal involvement in deformation, they do not necessarily signify that the strength limit has been reached. The critical factor for predicting earthquakes is estimating the energy of an impending earthquake or assessing how close the stress is to the ultimate local strength of the crust. M.V. Gzovsky pointed out the partial inconsistency of using Quaternary geomorphologic features for pattern recognition in predicting strong earthquakes, as these features reflect average motion velocities over extended periods rather than the current dynamics of these motions. Since the stress states during current seismic processes and at the time of crustal fault formation can differ significantly, he proposed using fault activity as a criterion. Tectonic activity information can be obtained through seismotectonics, geodesy, and seismic methods. Y. Riznichenko emphasized the importance of evaluating earthquake potential by analyzing the seismotectonic flow of rock masses using mathematical modeling techniques [2]. Following this approach, we have decided to model the stress state of the Western Tien Shan crust, located in Uzbekistan, using the Stokes equations, which describe the slow motion of the medium.

2. Mathematical model of the stress state of the earth's crust of the west tan shan microplate

The mathematical modeling of the stress state of the Earth's crust is crucial for understanding and predicting tectonic activity, particularly in seismically active regions like the Western Tien Shan. The objective of this model is to assess the stress-strain state of the Earth's crust in the Western Tien Shan microplate using creeping motion hydromechanics. By applying different strength criteria, we aim to identify areas with concentrated stress where strong earthquakes are likely to occur. These equations describe the slow, viscous flow of the medium, which is appropriate for modeling the creeping motion of the Earth's crust over geological timescales. According to seismological databases, 9 earthquakes in the Western Tien Shan with M≥6.5 have occurred at the depths of 20 km. Since for a number of reasons at this time it is difficult to solve three-dimensional continuum equations for the Earth's crust (not exact structure of crust layers, their physical properties, etc.), we decided to estimate the average stress state for depths of 20 km. The Stokes equations in terms of creeping motion with respect to vertically averaged velocities of displacement and pressure have the following form[3,4]:

$$-grad\,\overline{p} + \mu\Delta\overline{v} = \overline{F} \tag{1}$$

$$F_1 = -\overline{\frac{\partial M_2}{\partial x_3}} - \frac{1}{(h-H)}\frac{\partial H}{\partial x_1}\overline{\sigma_{11}} - \frac{1}{(h-H)}\frac{\partial H}{\partial x_2}\overline{\sigma_{12}} - \frac{\mu}{(h-H)}\left(\frac{\partial H}{\partial x_1} + \frac{1}{2}\frac{\partial H}{\partial x_2}\right)\overline{v}_1 - \frac{\mu}{2(h-H)}\frac{\partial H}{\partial x_1}\overline{v}_2 - -\frac{k_a\rho g(h-H)}{2\mu/t_0} \tag{2}$$

$$F_2 = -\overline{\frac{\partial M_3}{\partial x_1}} + \overline{\frac{\partial M_1}{\partial x_3}} - \frac{1}{(h-H)}\frac{\partial H}{\partial x_1}\overline{\sigma_{12}} - \frac{1}{(h-H)}\frac{\partial H}{\partial x_2}\overline{\sigma_{22}} - \frac{\mu}{2(h-H)}\frac{\partial H}{\partial x_2}\overline{v}_1 - \frac{\mu}{(h-H)}\left(\frac{1}{2}\frac{\partial H}{\partial x_1} + \frac{\partial H}{\partial x_2}\right)\overline{v}_2 - \frac{k_a\rho g(h-H)}{2\mu/t_0} \tag{3}$$

In these formulas, $H(x_1,x_2)$ is the topography of the Earth's surface, $h(x_1,x_2)$ is the Moho depth, ρ is density and μ is the viscosity coefficient. In the calculations for different blocks, the shear modulus μ is chosen differently. $\overline{p}$ *is* avareged pressure, $\overline{v}$ is two-dimensional vector with components of averaged horizontal displacement velocities, *Δ*- two-dimensional Laplace operator, k_a is the coefficient of friction at the Moho boundary. The time scale t_0 is consistent with the fact that the maximum relaxation time of rock stresses is measured by a segment of no more than 10^4 years[5]. In the derivation of the equations, the relations resulting from the rule of the adopted averaging are also used:

$$\bar{\sigma}_{33} = \frac{1}{2}(\sigma_{33}|_h + \sigma_{33}|_H) = \frac{1}{2}\sigma_{33}|_h = \frac{1}{2}\frac{\rho g(h-H)}{\mu / t_0} \tag{4}$$

$$\bar{\sigma}_{i3} = \frac{1}{2}(\sigma_{i3}|_h + \sigma_{i3}|_H) = \frac{1}{2}k_a\frac{\rho g(h-H)}{\mu / t_0} \tag{5}$$

for i=1,2.

The averaged incompressibility equation assuming $v_3(x_1, x_2, h)=0$ takes the form:

$$v_3(x_1, x_2, H) = (h-H)\left(\frac{\partial \bar{v}_1}{\partial x_1} + \frac{\partial \bar{v}_2}{\partial x_2}\right) - \frac{\partial (h-H)}{\partial x_1}\bar{v}_1 - \frac{\partial (h-H)}{\partial x_2}\bar{v}_2 \tag{6}$$

The equations (1-3) are solved by the method of boundary integral equations[6]. For numerical solution the territory of the West Tien Shan microplate is taken as the area shown in **Figure 1**.

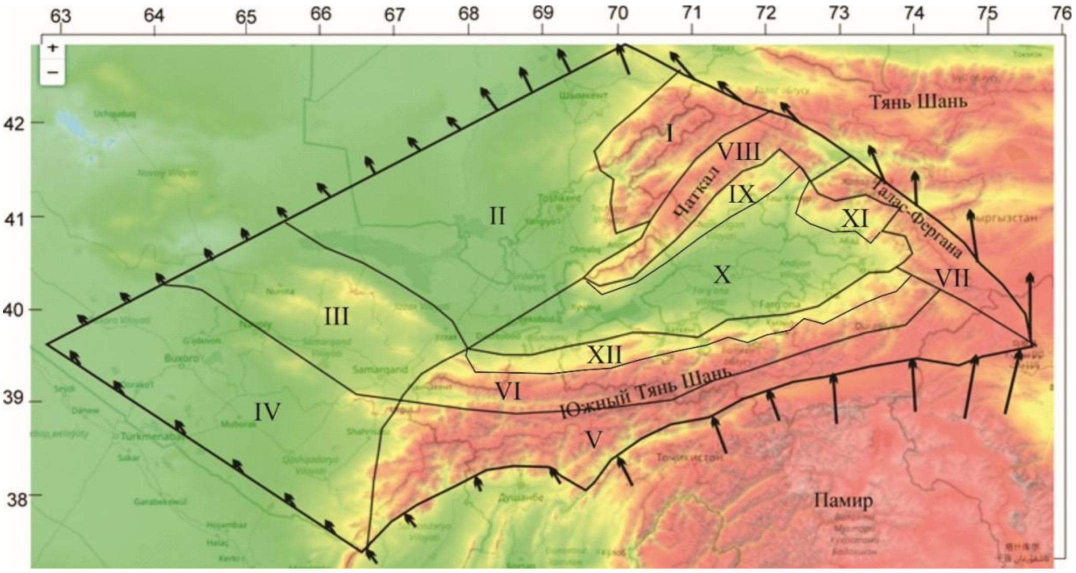

Figure 1. Definition area of the Stokes equation and boundary conditions.

This area is subject to various tectonic forces due to the interaction of the Eurasian, Indian, and Arabian lithospheric plates. The boundary conditions with respect to velocities are adopted according to GPS data[7] (Fig.2). Appropriate boundary conditions are specified along the edges of the domain to reflect the geological setting. These include velocities at the boundaries to simulate the tectonic movements. The figure includes significant geological features such as faults, lithospheric plate boundaries, and variations in crustal thickness. These features are crucial for accurately modeling the stress distribution so the area under consideration is divided into 12 subareas. The Stokes equations are applied within this defined area to compute the velocity field v_k and pressure p distribution, which are then used to determine the stress tensor components σ_{ij}.

3. Analysis of model solutions

As a result of solving the Stokes equation, displacement velocities (**Figure 4**), vertical velocities (**Figure 5**), stresses, and strain rates were obtained.

According to the results of the numerical solution, let us express the conditions of breaking the strength of the Earth's crust. To determine the conditions under which the strength of the Earth's crust is breached, we use several criteria from the theory of material strength [8]. One of the most widely used conditions is the strength limit determined by maximum tangential stresses, often represented by Mohr's circles. This criterion helps in understanding the stress state at which failure or rupture is likely to occur. The condition of failure based on maximum tangential stresses in our case can be expressed as follows:

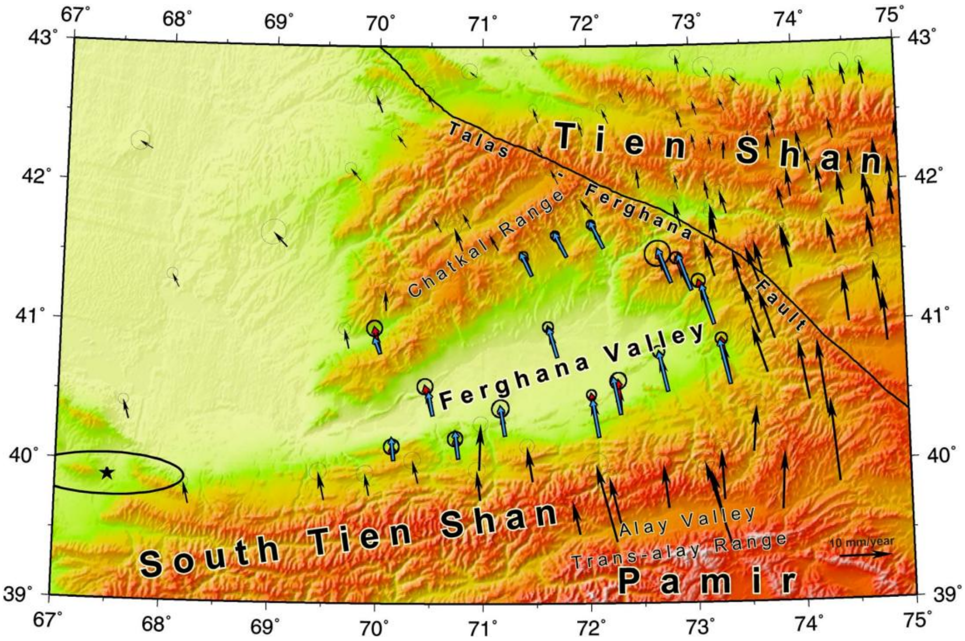

Figure 2. Vector field relative to the Euroasian plate according to GPS data [5] .

For numerical solution of equations (1-3) by the method of boundary integral equations, the considered area is divided into a grid of 1394 triangles (**Figure 3**)

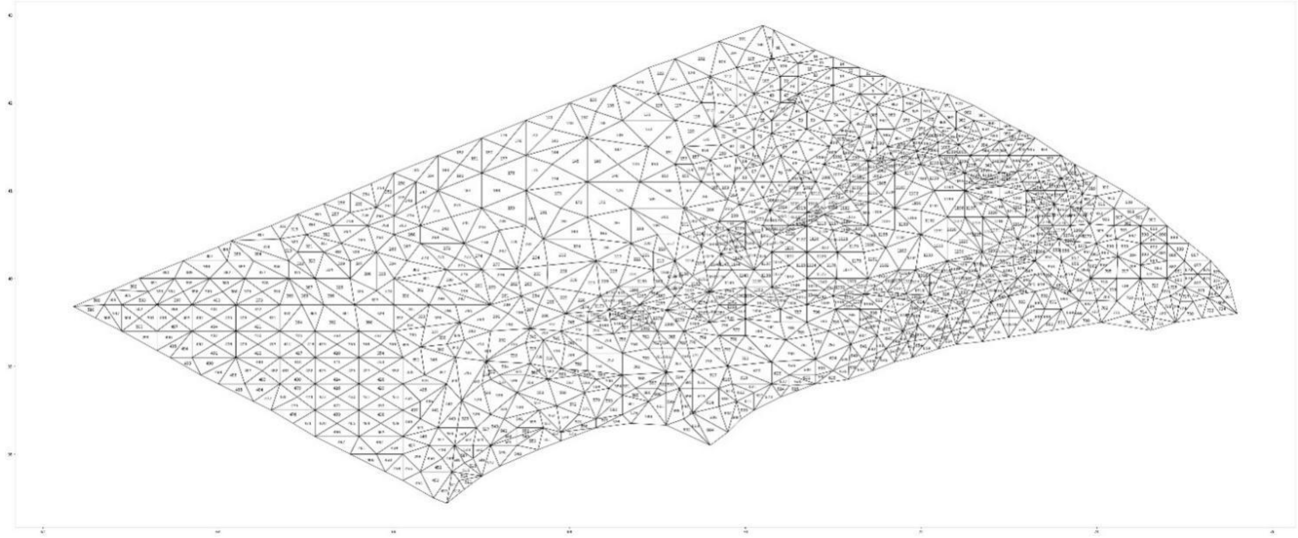

Figure 3. Mesh area for numerical solution of the Stokes equation.

The energy criterion is another widely used method for determining when a material loses strength. According to this criterion, the material's strength is compromised when specific energy-related conditions are violated. The context of the energy criterion, when the material is under tension, it loses strength when the stored energy exceeds a critical threshold specific to tensile conditions. These conditions vary depending on whether the material is under compression or tension[9]:

a) In compression (p<0)

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2 \le 2{\sigma_0}^2 \tag{9}$$

б) In tensile (p>0):

$$\sigma_1^{\,2}+\sigma_2^{\,2}+\sigma_3^{\,2}-2\nu(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_3\sigma_1) \le \sigma_0^{\,2} \tag{10}$$

$$\sigma_{1.2}=\frac{\sigma_{11}+\sigma_{22}}{2}\pm\sqrt{\frac{(\sigma_{11}-\sigma_{22})^2}{2}+\sigma_{12}^2} \tag{7}$$

$$\sigma_{\max}=\frac{\sigma_{11}-\sigma_{22}}{2} \tag{8}$$

In formulas (9-10) σ_1 and σ_2 are the principal stresses obtained from the solution of the averaged Stokes equations (1-3) for 15-20 kilometers. The lithostatic pressure corresponding to 20 kilometers of the Earth's crust is taken as σ_3. σ_0 is the strength limit of the Earth's crust, and ν is the Poisson's ratio which for a liquid is 0.5. The minimum stress at the points where the earthquakes occurred was taken as σ_0.

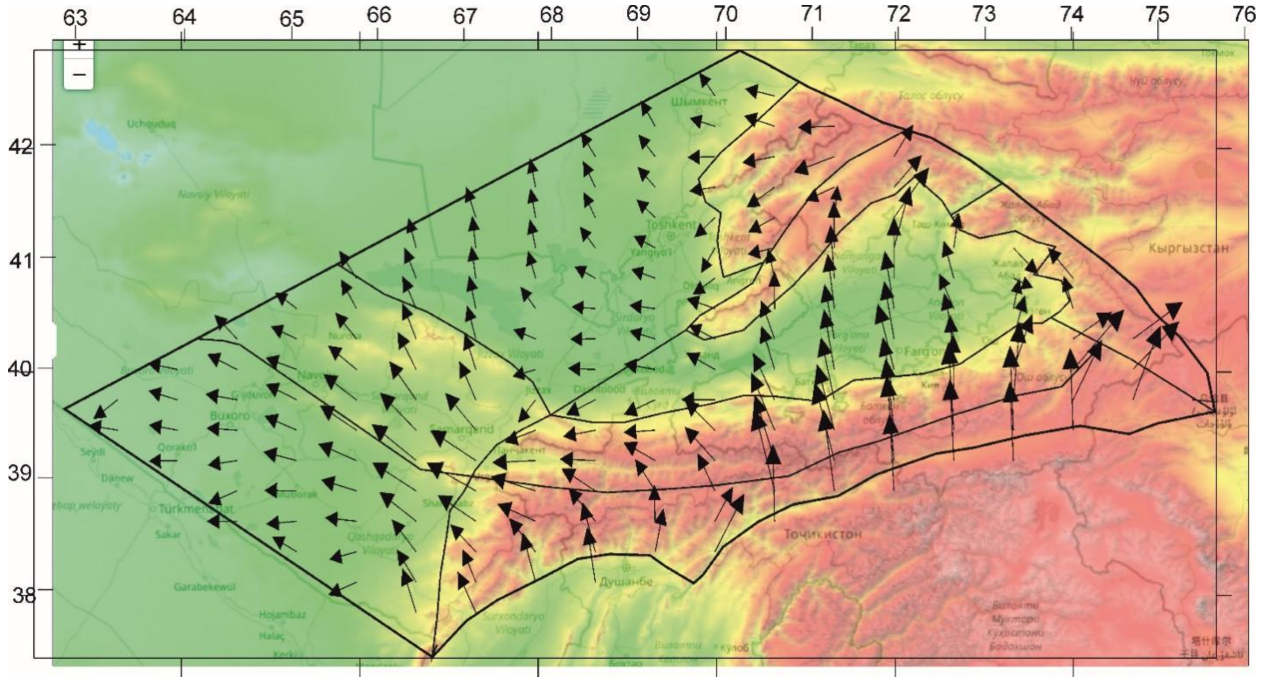

Figure 4. Displacement velocities of the Western Tien Shan microplate.

4. Analysis of stress conditions and geodynamic state

Figure 7 illustrates the zones of the Western Tien Shan region that meet the conditions (9-10) for material failure under compression and tension, as described by the energy criterion. These zones are marked with triangles. Additionally, earthquake epicenters with a magnitude of M≥5.5 that occurred for since historical times are indicated by circles. They approximately coincide with the earthquake centers indicated by circles. Blue squares are obtained at 0.95 σ_0 and correspond to locations where small stress increases can lead to earthquakes.

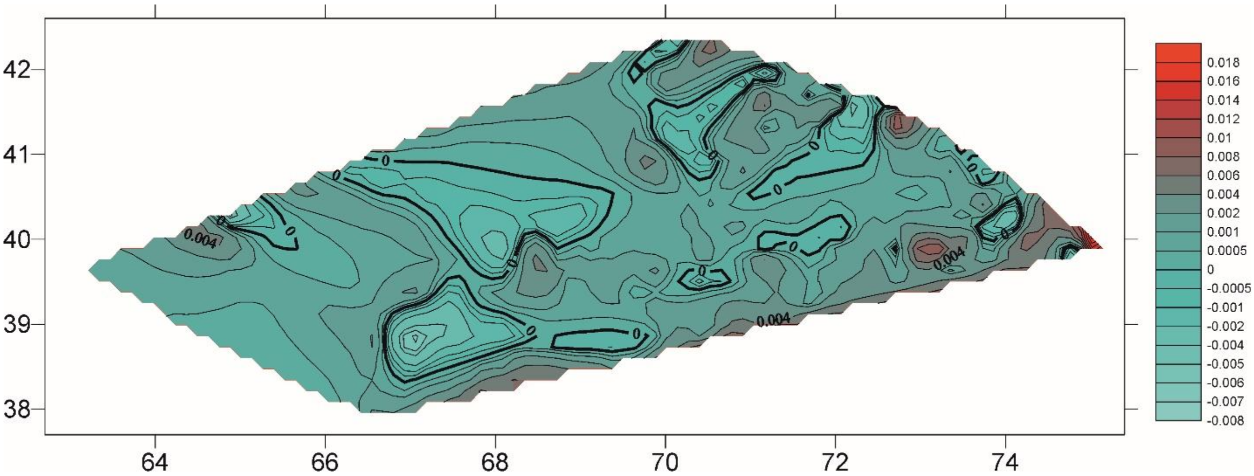

Figure 5. Isolines of vertical velocities on the ground surface of the West Tien Shan microplate.

Figure 6 shows the maximum tangent stress isolines at depths of 20 km.

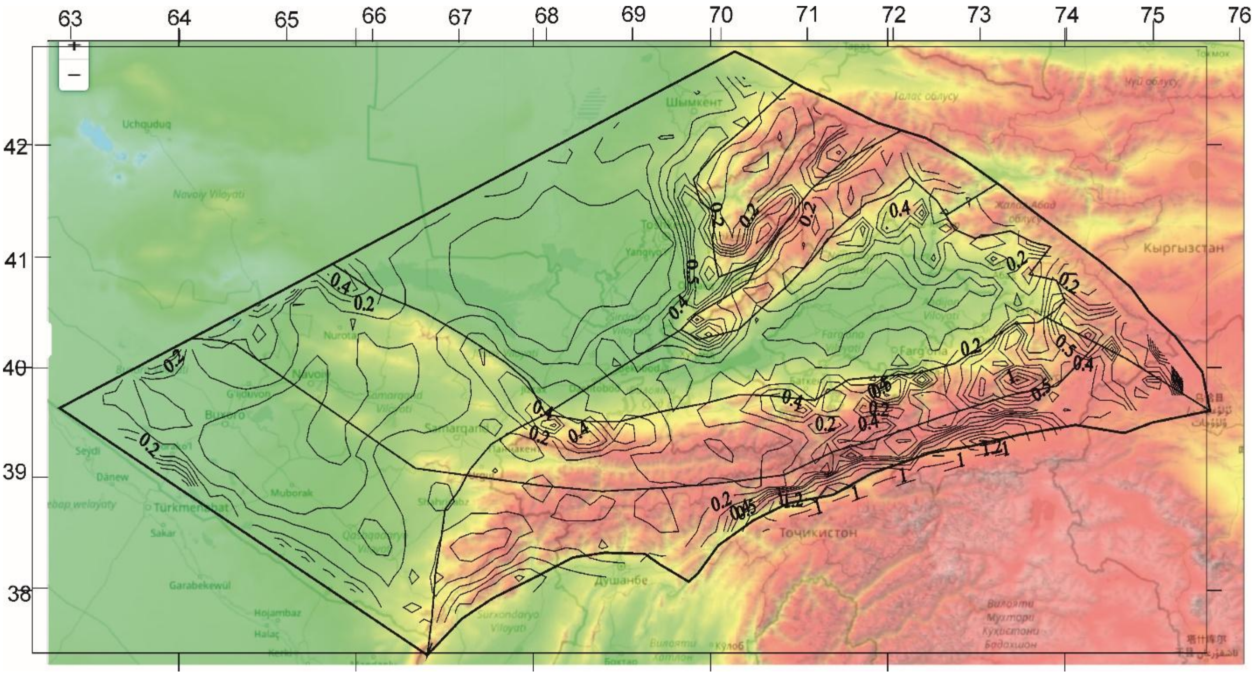

Figure 6. Isolines of maximum tangential stresses (in kbar) of the Earth's crust of the West Tien Shan microplate at depths of 20 km.

The obtained solutions were used to determine the geodynamic state (compression, tension, normal faulting, reverse faulting, strike-slip faulting) that may occur during earthquakes, following Anderson's theory of faulting[8]. According to this method, the relationship between the vertical stress σ_{ver} and the maximum σ_1 and minimum σ_2 horizontal stresses are compared. Three distinct cases are identified:

- Vertical stress dominates $\sigma_1=\sigma_{ver}$: Gravitational forces cause normal faults, resulting in horizontal extensional deformation.

- ○ Intermediate stress is vertical stress $\sigma_2=\sigma_{ver}$: The difference between the two horizontal stresses creates strike-slip deformation.
- ○ Horizontal stresses exceed vertical stress $\sigma_3=\sigma_{ver}$: Compressive deformation is balanced by reverse faulting.

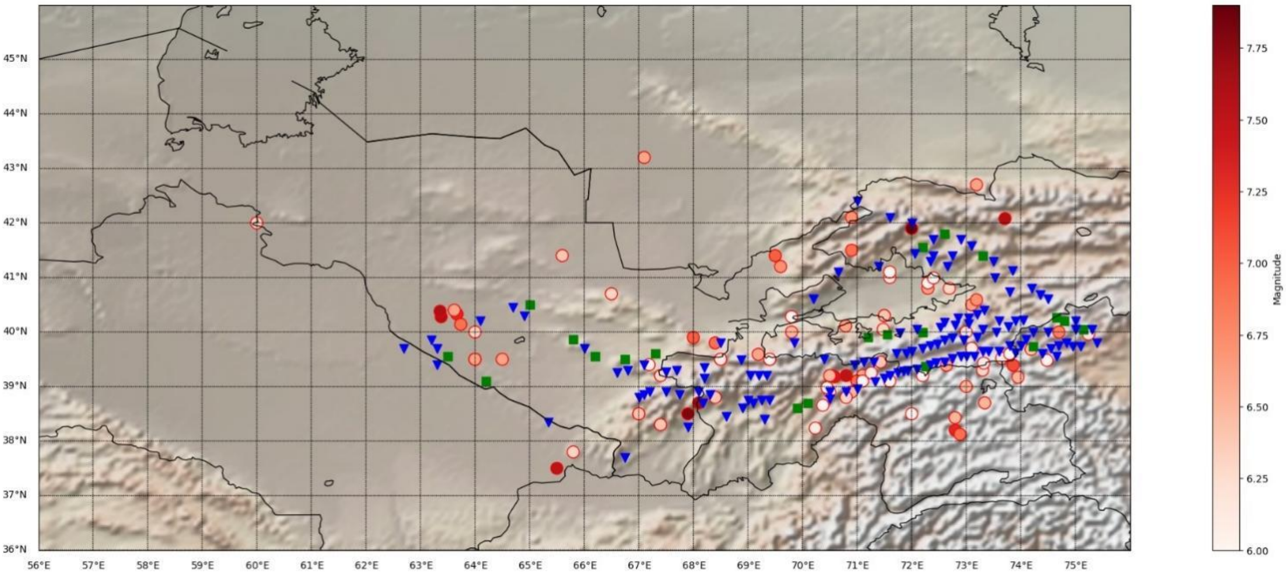

Figure 7. Locations where stresses exceed the crustal strength (triangles) and foci of earthquakes with magnitude M≥6 occurring since historical times (circles). Green squares correspond to a strength condition of 0.95 σ_0.

The values of maximum tangential stresses are found to be 6-7 times less than the maximum stress. The orientations of σ_1 are shown by directional segments, which satisfactorily align with the directions of the principal contemporary compressive stresses, constructed from records of strong earthquakes in the former USSR [1]. The possible earthquake mechanisms corresponding to the cases are normal faulting (B), strike-slip faulting (G), and reverse faulting (R). They are shown in **Figure 8**. The numerical model results indicate that the predominant geodynamic type of stress state for crustal depths of 15-20 km is a regime of horizontal bilateral compression. The direction of maximum stress slightly changes with depth. For depths below 40 km, the values of σ_1, σ_2, and σ_{ver} become nearly equal, making strike-slip faulting the likely earthquake mechanism, with minor deviations.

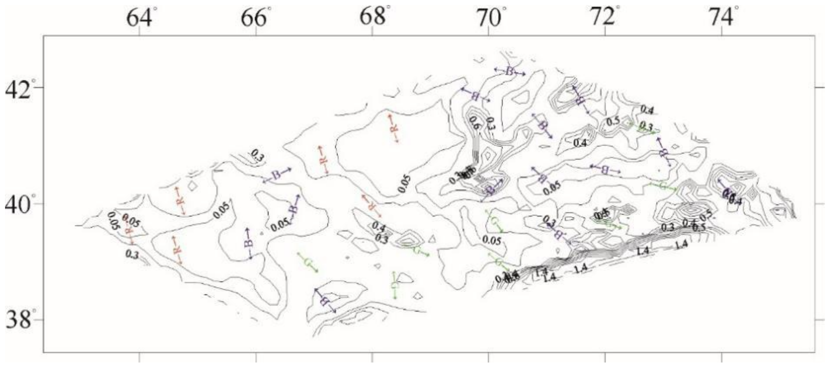

Figure 8. Geodynamic state of the Earth's crust for depths of 20 km and isolines of maximum tangential stresses in kbar. Horizontally is east longitude, vertically is north latitude. The orientation of the arrows indicates the σ_1 direction. The possibilities of thrust (R), normal faults (B), and strike-slip (G) earthquake are shown.

5. Conclusions

The stress state of the Earth's crust of the Western Tien Shan microplate is mathematically modeled.

According to the strength criteria, the places of the Earth's crust where earthquakes are possible were identified.

The geodynamic state of the region under consideration was evaluated by Anderson method.

Conflicts of interest

The authors declare no conflicts of interest in relation to this article.

Acknowledgments

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