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GEOPHYSICS

Connection between Variations of the Stress–Strain State of the Earth's Crust and Seismic Activity: The Example of Southern California

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Abstract—A three-dimensional geomechanical model of Southern California, including mountain relief, fault tectonics, and characteristic internal borders, such as the roof of the consolidated crust and Moho surface, was created. The initial stress state of the model is determined by the gravitational force and horizontal tectonic movement, established on basis of GPS observations. Monitoring of variations in the stress state of the Earth's crust and lithosphere, which are generated by seismic processes, has shown that the model enables us to predict an increase of seismic activity in a region and to mark the places in which average earthquakes can occur in the following two weeks.

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In the present work we demonstrate the three-dimensional geomechanical model of Southern California, including the mountain relief, fault tectonics, and the main structural borders, such as the roof of the lower crust and the Moho surface. The initial stress state of the model is determined by the gravitational force and horizontal tectonic movement, established on the basis of GPS observations. Monitoring of variations in the stress state of the Earth's crust and lithosphere, which are generated by seismic processes, has shown that the model enables us to predict an increase in seismic activity in the region and to mark the places where average earthquakes with $M = 3–5$ can occur in the next two weeks.

Crustal earthquakes are the result of slow tectonic motions of the Earth's crust, which form geological structures and lead to accumulation of a substantial elastic energy, which is discharged to the outer environment resulting in the destruction of the Earth's crust material in the places where tectonic stresses reach the greatest strength. The stress–strain state of the Earth's crust emerges as a result of many factors. Among the main ones, we can mention horizontal and vertical tectonic movements, noncompensated weight of mountain relief, density variations, and uneven heat. The kinds of stresses mentioned interact with complicated geophysical media, whose main peculiarities are the fault-block structure, vertical geological layering, the presence of fluids, and the mountain relief. The fault-block structure should be specially noted as it is genetically related to plate tectonics and seismic processes. Fault zones disturb the stress–strain state of the Earth's crust and accumulate a substantial quantity of potential deformation energy. The last circumstance was used for selection of zones where strong earthquakes may occur [1]. The model of the Earth's crust for the area located in the western part of basins and ridges of Southern California has shown that seismic activity substantially depends on the tectonic motions along faults [2].

3D GEOMECHANICAL MODEL

We should observe variations in the stress-strain state of the Earth's crust of the study area to predict earthquakes. It is possible to implement this within the framework of a quantitative 3D geomechanical model. In the past, this approach enabled us to connect ionospheric variations with the weak influence of atmospheric pressure gradients before the December 26, 2004 Sumatra earthquake with $M = 9.2$ within the area of the Philippine and Sunda island arcs [3].

For the area within 31.0°–36.0° N and 121.2°–114.0° W, we made a 3D model of Southern California, which included the mountain relief and the main structure borders [4], such as the roof of the lower crust and the Moho surface (Fig. 1a). The dimensions of the studied volume are 645 × 560 × 35 km.

In the model, the distribution of faults is taken into account. In a tectonic sense, a fault is a zone with a complicated internal structure. It can be considered as a geological body with length, width, and depth. The width of large fault zones can reach tens of kilometers

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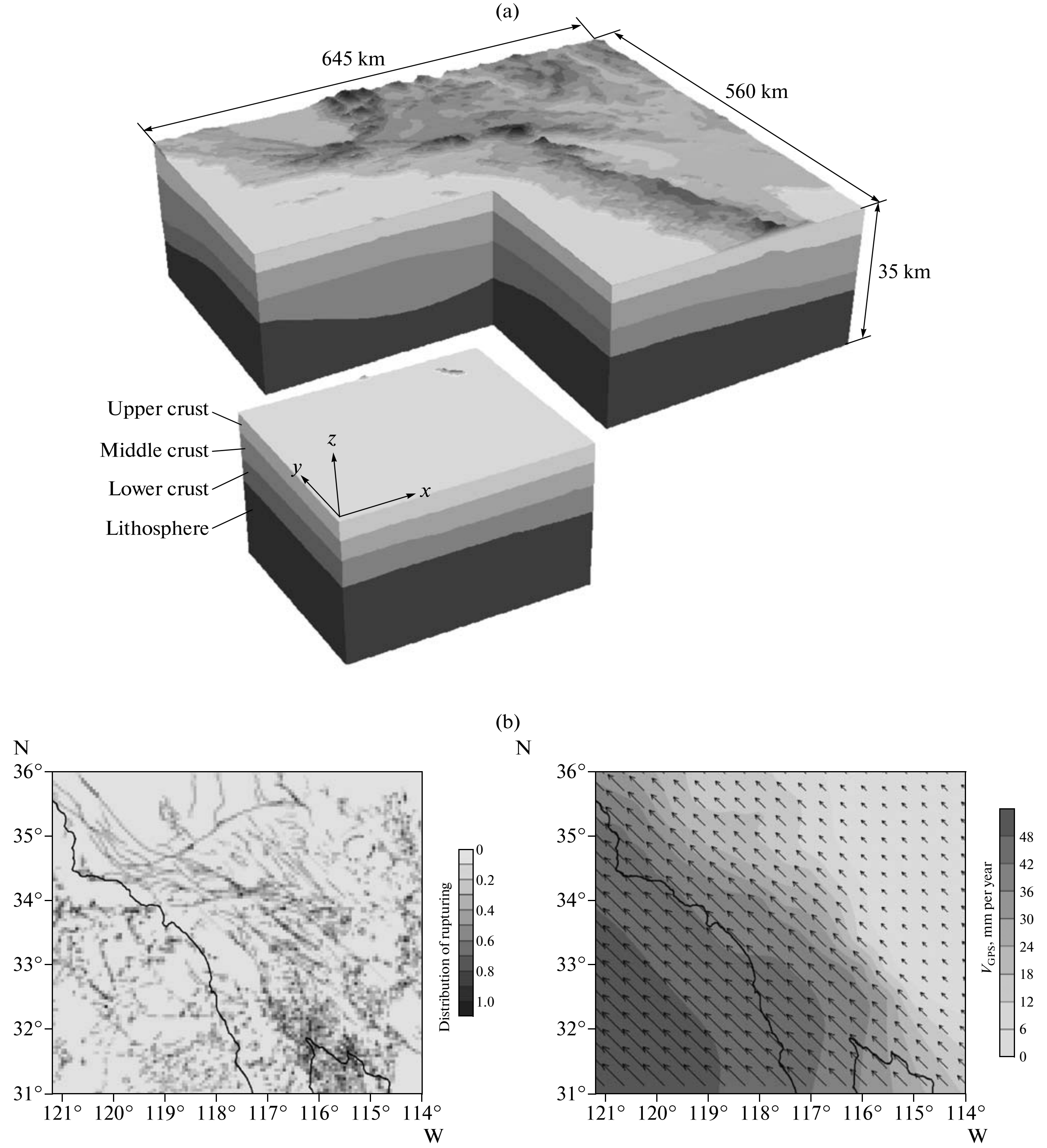

Fig. 1. Model of the Earth's crust in Southern California: (a) a general view, (b) normalized distribution of failure function $g(x_s)$ in the upper crust, and distribution of the Earth's crust motion velocities by the data of GPS measurements.

and includes faults of lower rank. Within the framework of the zone, rocks are fragmented and are characterized by higher fracturing. Resulting in a higher failure of media, their rigidity and strength in the fault zone are appreciably less than those for crustal blocks that are divided by such a zone. There is evidence on seismic wave velocities both in faults and out of them, and a higher seismic activity.

To obtain the quantitative characteristics of failure distribution in the Earth's crust, we used data of space picture processing. Failure of media is characterized

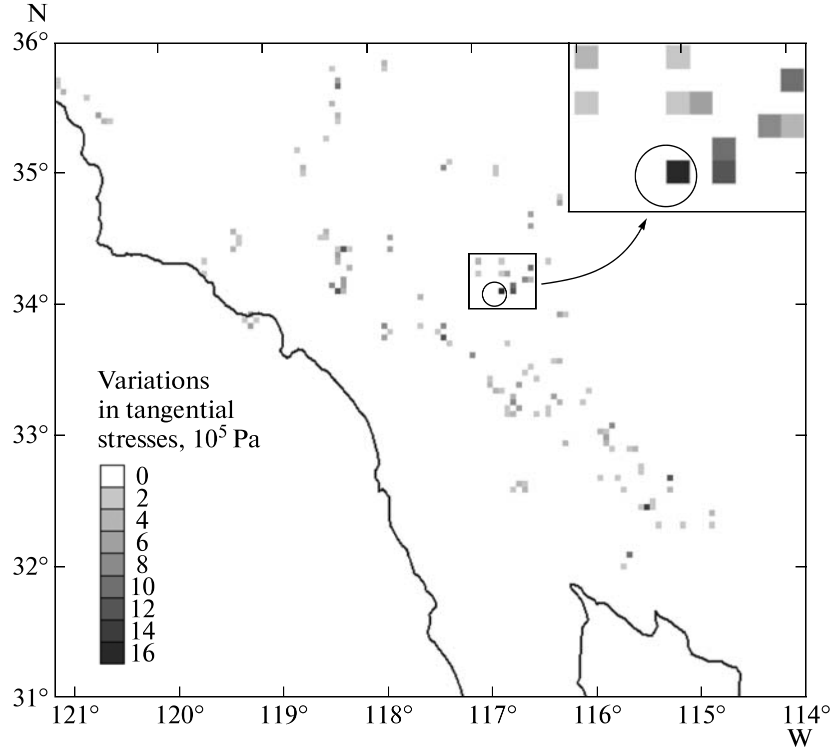

Fig. 2. Distribution of difference in variations of maximal shift stresses in the upper crust on Oct. 1, 2008.

by the heterogeneity function $g(x_s)$, which is 1 at the fault axis and 0 out of the zone of fault influence (Fig. 1b). Function $g(x_s)$ is approximated using spline functions. All mechanical parameters are set as

$$\Pi(x_s) = \Pi^0[1 - \kappa g(x_s)], \tag{1}$$

where Π^0 is the homogenous initial value of the parameter for the undisturbed plate and $\kappa \le 1$ is the smallness parameter.

Stressing of the Earth's crust in Southern California runs at the influence of its own gravitational force and the resulting horizontal motion of plates. The corresponding distribution of velocities by the data of GPS measurements is shown in Fig. 1b [5].

CALCULATION STAGES AND INITIAL DATA USED

Calculation of the stress state included two stages. First, we calculated the initial stress state of the model on the effect of its own gravitational forces. Then we set the velocity field (Fig. 1b) that led to the accumulation of stresses in the Earth's crust.

Next we calculated variations in stress states of the Earth's crust, related to development of seismic processes. When modeling the seismic process, we should act on the premise that motions along faults are controlled by forces of dry friction in accordance with Coulomb–Mohr strength condition. Thus, the system of blocks is strained elastically first, and, after reaching the strength condition, begins to move. As a result, the angle of friction decreases step-wise down to a minimal value and a new equilibrium at a lower stress level is formed. However, the effective mechanical properties of media in the neighborhood of a seismic event change and this leads to stress redistribution in the Earth's crust, and, finally, make ready for a new strong earthquake.

Every earthquake is an elementary failure, which could be included in the model of the Earth's crust, if we know the energy of an event and its mechanism. A collection of many seismic events could be interpreted as the seismic flow of rock masses. Methods of mechanics for bodies with numerous cracks enable us to set and solve the problem on changes of stresses and strains in the preliminarily stressed rupturing crust of the Earth. In order to do that, we should have a sufficiently detailed computer catalogue of earthquake mechanisms and know distribution of the initial stresses.

The initial data for calculations are distributions of discharged seismic energy for a three-month period, beginning from October 2007. The chosen time slot moves by 15 days every subsequent step. After the calculations of stresses for the previous and subsequent steps are finished, we find the difference between two states and estimate the changes occurring using this difference. Then we construct variations of the distributions for maximal tangential stresses, of the accu-

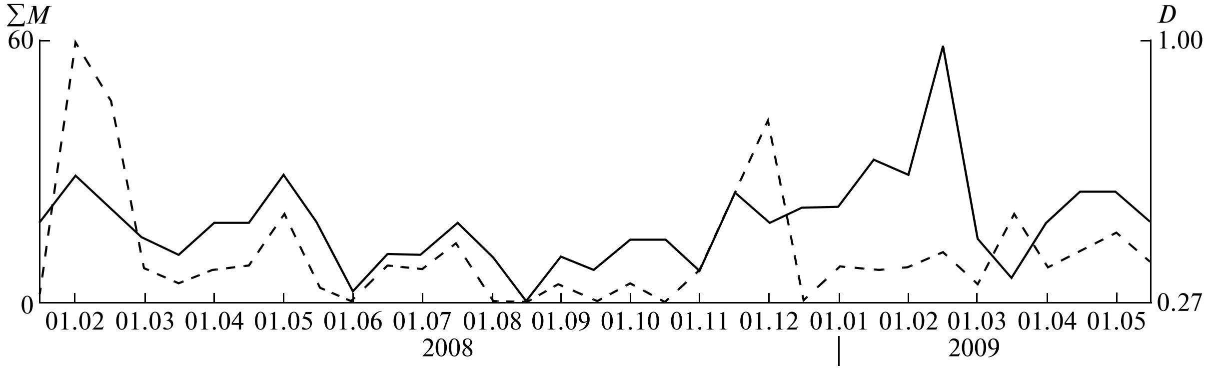

Fig. 3. Temporal changes in summarized magnitude of earthquakes $\sum M$ (dashed line) and the parameter of the stress state proximity to the ultimate strength in the upper crust D (solid line).

mulated elastic shift energy, and of the stress state proximity to the ultimate strength. However, we consider only parts of the Earth's crust where the parameter values are positive, i.e., larger than previous ones.

RESULTS

The calculated distribution of stresses enables us to learn how close the Earth's crust is to the ultimate strength. In the last case, the distribution of parameter D was studied, which characterizes the distance of the stress state from the strength surface. The smaller parameter D, the farther the stress state from the ultimate strength.

The example of maximal shift stress distribution for Oct. 1, 2008, is presented in Fig. 2. Analysis of this figure shows that there are spots within the study area where, since Sep. 15, 2008, the situation has become worse as a result of seismic processes; namely, tangential stresses have increased. The same is true for energy saturation in the Earth's crust.

It is supposed that, in the end, at this spot or in its surroundings, within a 15-day period earthquakes with $M > 3.5$ can occur. In the case considered, we marked an earthquake with $M = 4.1$ that occurred in the period from Oct. 1, 2008, to Oct. 15, 2008 (the circle in Fig. 2). One can see that this earthquake occurred within one of the spots marked after the calculation. Thus, the calculation can show places where earthquakes with an average magnitude can occur in the next two weeks.

It is interesting to find the relation between change in seismic activity and the approach or recession of the entire area from the ultimate strength. In Fig. 3 temporal graphs of change in parameter D and summarized amplitudes $\sum M$ are drawn. The values of the late ones are related to the beginning of the two-week period within which they occurred.

According to Fig. 3, changes in the parameter D predict well earthquakes with an average magnitude within a two-week period. Insufficient discrepancies of two graphs may be associated with the choice of the prognostic period.

Thus, the geomechanical model of Southern California enables us to conduct monitoring of changes in the stress state of the Earth's crust and lithosphere caused by seismic process in the region and to make a short-term prognosis of seismic danger.

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