ISSN 1028-334X, Doklady Earth Sciences, 2008, Vol. 423A, No. 9, pp. 1448–1451. © Pleiades Publishing, Ltd., 2008.
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GEOPHYSICS

Possible Mechanism of Horizontal Compression Stress Generation in the Earth's Crust

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Presented by Academician Yu.G. Leonov April 14, 2008

Received May 22, 2008

DOI: 10.1134/S1028334X08090274

The problem of the generation mechanism of tectonic stresses in intraplate regions is a pressing one not only because of the importance of its solution within basic research but also owing to its wide application aspect. An increased level of horizontal compression compared with the prognostic ones frequently observed in the upper levels of the Earth's crust (hundreds of meters to a few kilometers) [1] leads to the necessity of individual calculation of the stability of mining works responsible for the specific conditions of tunnel driving. However, not in all cases at the stage of the project of mining operations is there a possibility to estimate the parameters of the stressed state using in situ methods. Therefore, the problem arises about development of a theory that can explain the mechanism of tectonic stress formation, which allows us to make the first preliminary estimates [2]. The author of [3] considered the mechanism of generation of increased horizontal compression stresses within the problem of the geodynamics of platform regions and intraplate orogens related to internal sources of mechanical energy, which include, first of all lithogenic and metamorphic processes. In this work, we give grounds for the possible mechanism of generation of stresses of high horizontal compression. The energy of residual stresses accumulated in the rock medium under the influence of gravity forces (the leading forces of lithogenesis) plays the main role in this mechanism.

GRAVITY STRESSES

In the case when rocks are in the elastic state, the stresses responsible for the action of their weight are determined by the following relation [1]:

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$$\sigma_{zz}^g = -\gamma H, \quad \sigma_{xx}^g = \sigma_{yy}^g = -\frac{\nu\gamma H}{1-\nu}, \qquad \sigma_{ij}^g = 0, \quad i, j = x, y, z, \quad i \neq j, \tag{1}$$

where ν is the Poisson coefficient, γ is the mean specific weight of the rock column with thickness H, and the z-axis is vertical. Vertical compression stresses are equal to the weight of the rock column at a given depth. They are the main compression stresses ($\sigma_{zz} = \sigma_3$). These stresses are active, while the horizontal stresses are reactionary caused by lateral constraint of the rocks determining the impossibility of their free deformation in the horizontal direction ($\varepsilon_{ii}^g = 0$, $i = x, y$). The value of horizontal stresses does not depend on the direction so that $\sigma_1 = \sigma_2$ (single-axis compression, Lode-Nadai coefficient $\mu_\sigma = +1$). At $\nu = 0.25$, vertical compression stresses are three times greater than horizontal compression stresses. Such a stressed state is called gravity stress in mining, while the regime (type) of the stressed state in geodynamics and tectonophysics is determined as horizontal tension.

The linear depth dependence of maximal shear stresses τ and isotropic pressure p follows from Eqs. (1):

$$\tau^g = \frac{\sigma_{xx}^g - \sigma_{zz}^g}{2} = \frac{1-2\nu}{2(1-\nu)}p_{lt}, \qquad p^g = -\frac{2\sigma_{xx}^g + \sigma_{zz}^g}{3} = \frac{1+\nu}{3(1-\nu)}p_{lt}, \quad p_{lt} = \gamma H. \tag{2}$$

The typical values for mountainous rocks are $\nu = 0.25$ $\tau^g = 0.33 p_{lt}$, and $p^g = 0.56 p_{lt}$.

The limit of the beginning of cataclastic flow

It is considered in geophysics and geodynamics that the stressed deformed state, corresponding to Eqs. (1) and (2), can exist only in the uppermost layers of the Earth's crust: the sedimentary cover. According to (2), the maximal shear stresses in the rocks, which are in the elastic state, linearly increase with depth. Such increase cannot be unlimited: beginning from specific depths, processes occur in the massif, which transform part of elastic deformations to residual ones. Cataclastic (faulting) flow in realistic rocks precedes the attainment of the plastic state [4]. The real plastic (dislocation law) flow at temperatures below 1000°C requires a high level of effective isotopic compression (3–4 kbar), which is almost impossible for a fluid saturated crust.

We use the Drucker–Prager criterion to determine the beginning of accumulation of residual deformations during cataclastic flow. This criterion relates deviator and isotropic stresses:

$$I_2 + k_c(I_1 + p_{fl}) \geq \tau_c \quad \text{at} \quad I_2 = \frac{2\tau}{\sqrt{3}}, \quad I_1 = -p. \qquad (3)$$

Here, I_1 and I_2 are the first and second invariants of the stress tensor, τ_c is internal cohesion, k_c is the coefficient of internal friction, and p_{fl} is fluid pressure in the faulting space of rocks. Fluid pressure decreases the pressing effect of tectonic isotropic pressure p decreasing the resistance of friction forces at the surfaces of the cracks.

We use Eqs. (2) and (3) to find depth H_p, beginning from which the rocks are subjected to cataclastic flow in the condition of only gravity stressed state

$$H_p = \frac{3(1-\nu)(\tau_c - k_c p_{fl})}{[(1-2\nu)\sqrt{3} - k_c(1+\nu)]\gamma}. \qquad (4)$$

We find that H_p = 1.8 km for the parameters of strength $k_c = 0.6$ (coefficient of internal friction for the majority of rocks in the condition of medium range pressure), τ_c = 25 kg/cm^2 (cohesion strength of solid samples of aleurites, argillites, and fissured rocks of the middle crust), specific weight $\gamma = 2.7$ g/cm^3, and Poisson coefficient $\nu = 0.25$ in the conditions of dry rocks ($p_{fl} = 0$). If the distribution of the fluid pressure at depth obeys the hydrostatic law $p_{fl} = p_{hy}$ ($p_{hy} = H\gamma_{fl}$, γ_{fl} = 1.0 g/cm^3), the transition to the cataclastic state occurs at $H_p \approx 0.38$ km, and if the fluid pressure variation with depth obeys a law close to lithostatic ($p_{fl} \approx p_{lt}$), $H_p \approx 0.18$ km.

GRAVITY STRESSED STATE IN THE CONDITIONS OF CATACLASTIC FLOW

The elastic cataclastic state considered in this paper, into which the rocks are transformed below depth H_p, is linearly nonuniform by depth and allows for very simple deduction of the parameters that determine it. They are based only on the lateral constraint condition $\varepsilon_{ii} = 0$ (i are lateral coordinate axes). The lateral constraint condition together with criterion (3) allows us to write the mathematical formulation of the problem to determine the stresses in the region of cataclastic flow. Accumulation of residual deformations at $H > H_p$ is performed to equalize the difference between stresses in the vertical and horizontal directions. Since the weight of the rock column fixes constant vertical compressing stresses ($\sigma_{zz} = \sigma^g_{zz}$), a decrease in the difference between this stress and stress of horizontal compression can be gained only owing to the appearance of additional horizontal compression

$$\sigma_{ii} = \sigma^g_{ii} + \Delta\sigma \quad \text{at} \quad \Delta\sigma < 0 \quad \text{and} \quad i = x, y. \qquad (5)$$

Using criterion (3) and relations for the first and second invariants, in which the appearance of additional horizontal stresses $\Delta\sigma$ (5) is taken into account, we find

$$\Delta\sigma = -\frac{[(1-2\nu)\sqrt{3} - k_c(1+\nu)]p_{lt} - 3(1-\nu)(\tau_c - k_c p_{fl})}{(\sqrt{3} + 2k_c)(1-\nu)} \quad \text{at} \quad H \geq H_p. \qquad (6)$$

When the fluid pressure is increased to lithostatic values, additional compression increases approaching the double maximum shear stresses at $\nu = 0.25$ in the elastic state (τ^g, see (2)).

Cataclastic flow of mountainous rocks leads to a decrease in the difference between the vertical and horizontal compressing stresses, but does not lead to a change in the index of the principal stresses in the vertical and horizontal directions. Thus, the geodynamic regime corresponding to this stage is also horizontal compression. The relations for the maximal shear stresses and isotropic pressure are written as

$$\tau = \tau^g + \frac{\Delta\sigma}{2}, \quad p = p^g - \frac{2\Delta\sigma}{3}. \qquad (7)$$

Figure 1 presents the depth dependences of these parameters of the stress state for different types of fluid pressure.

GRAVITY CONDENSATION

Additional horizontal stresses $\Delta\sigma$ appearing during cataclastic flow lead to the formation of additional elastic deformations in the horizontal and vertical directions:

$$\Delta\varepsilon^e_{zz} = -\frac{2\nu}{E}\Delta\sigma, \quad \Delta\varepsilon^e_{ii} = \frac{1-\nu}{E}\Delta\sigma \quad \text{at} \quad i = x, y. \qquad (8)$$

These residual deformations are determined from the condition of horizontal constraint ($\varepsilon^p_{ii} + \varepsilon^e_{ii} = 0$) and zero variation of volume during faulting flow:

$$\varepsilon^p_{ii} = -\Delta\varepsilon^e_{ii} = -\frac{1-\nu}{E}\Delta\sigma \quad \text{at} \quad i = x, y \quad \text{and} \quad \varepsilon^p_{zz} = -(\varepsilon^p_{xx} + \varepsilon^p_{yy}). \qquad (9)$$

It follows from Eqs. (8) and (9) that residual deformations $\varepsilon^p_{xx} = \varepsilon^p_{yy}$ are deformations of extension, while

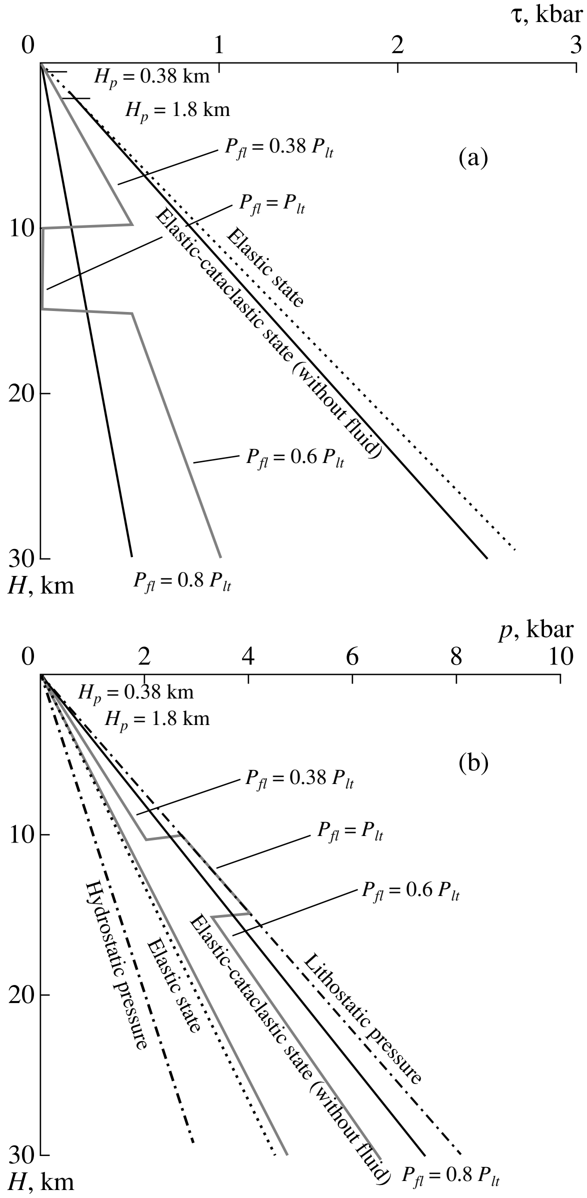

Fig. 1. Depth variation of (a) τ and (b) p for different regimes of fluid pressure (hydrostatic law with respect to depth $p_{fl} \approx 0.38 p_{lt}$; lithostatic law with respect to depth, $p_{fl} \approx p_{lt}$).

elastic deformations $\varepsilon_{xx}^e = \varepsilon_{yy}^e$ are deformations of contraction. Such interaction of elastic and residual deformations is characteristic of the flow in the conditions of lateral constraint.

In the conditions of the existing stressed state at the moment of cataclastic flow (sub-vertical axis of the maximum compression), the transition of part of the elastic deformations to residual deformations is determined by the appearance and activation of a large number of cracks and ruptures with the kinematics of the fault type (submersion angles are 20°–45°). Horsts and grabens should be observed in the rocks, which correspond in the standard geological and tectonophysical description to the mechanism of horizontal extension. However, in reality, lateral constraint hampers horizontal extension. According to Eqs. (8) and (9), the additional deformations in the vertical direction lead to elastic decrease in the thickness of the layer ($\Delta\varepsilon_{zz} = \varepsilon_{zz}^p + \Delta\varepsilon_{zz}^e < 0$) and total volume of the rocks ($\varepsilon_{zz}^e + \varepsilon_{xx}^e + \varepsilon_{yy}^e < 0$). Such deformation should be considered not as horizontal extension but as vertical condensation.

VARIATION IN THE STRESSED STATE DURING RAISING OF ROCKS

When local volumes of mountainous massifs of rocks, which accumulated additional compressing stresses in the depths, slowly raising in the vertical direction to smaller depths, they contact with the rocks with either smaller additional horizontal stresses or completely in the pure elastic state. Therefore, if the layer in which cataclastic flow occurred at depth $H^0 > H_p$ is transported vertically upwards along the transect to a new depth $H < H^0$ ($\Delta H = H^0 - H$) as a result of tectonic motions, it forms here the regions of increased horizontal compression compared to the surrounding rocks.

The possibility of conserving additional compressing stresses over a relatively long time is related to two factors. First, it is related to residual deformations accumulated as a result of cataclastic flow in the depths, which "seal" additional stresses in the rocks in the conditions of lateral constraint conserved during the ascent. Second, it is related to the low velocity of viscid flow of mountainous rocks determined mainly by diffuse viscosity in the internal parts of blocks in the upper part of the crust. When speaking about the mechanisms of conservation of stresses in the rocks, one should not forget the mechanism of "healing" the ruptures by means of mineralization. Newly formed nonisometric volumes of the medium tighten the rocks similarly to elastic reinforcement in preloaded constructions and "seal" the additional stresses appearing. After removing the lateral compression (constraint) from the drilled core of the rock massif subjected to gravity condensation, the stresses redistribute so that the self-equilibrium stressed state is established in the core with tension stresses in mineral formations filling the former fissures and ruptures. Such a state is not stable and usually leads either to instantaneous scattering of rocks or to its dynamic breaking after a specific period of time.

Thus, vertical ascent of rocks causes an increase in the stresses of horizontal compression, but the maximal compression in the vertical direction remains. The most important is the result of mountainous rock ascent when the rate of the surface erosion is comparable with the rate of ascent or when erosion completely leveled the topography after the stage of mountain formation. In this case, we can consider in a good approximation that vertical stresses are determined by the weight of the overlying column of the rocks while the horizontal stresses keep the record about additional compressing stresses obtained as a result of cataclastic flow at depth H^0. If complete erosion of the daytime surface topography occurs after the raise of rocks to a new depth H, the expressions for the vertical and horizontal stresses would be written as

$$\sigma_{zz}(H) = \sigma^g_{zz}(H), \quad \sigma_{ii}(H) = \sigma^g_{ii}(H) + \Delta\sigma(H^0) \quad \text{at} \quad i = x, y. \tag{10}$$

Erosion of the surface leads to the elastic relaxation of part of the horizontal stresses, during which the intensity of relaxation of horizontal stresses is three times less than relaxation of vertical stresses (see (1) and (2)). The existence of additional compressing stresses $\Delta\sigma(H^0)$ changes only slightly due to the low rate of relaxation and at specific relations between H^0 and H can lead to the fact that the stresses of horizontal compression become greater than the stresses of vertical compression. In this case, inversion of the axes of the principal stresses occurs so that the stresses of maximal compression would be directed horizontally $\sigma_{xx} = \sigma_{yy} = \sigma_2 = \sigma_3$. The stress tensor changes its type from single-axis compression ($\mu_\sigma = +1$) to single-axis extension ($\mu_\sigma = -1$). This can be observed during vertical displacements:

$$\Delta H > H^0\left[1 + \frac{1-\nu}{1-2\nu}\frac{\Delta\sigma(H^0)}{p_{lt}(H^0)}\right]. \tag{11}$$

Using Eq. (6) and simplifying it assuming that already at depths of 1 km the lithostatic pressure can exceed the cohesion of fissured rocks τ_c by more than one order of magnitude, we get the following approximate relation to determine the vertical displacements, after which horizontal compressing stresses in mountainous rocks can exceed the vertical stresses:

$$\Delta H > H^0\left[1 - \frac{[(1-2\nu)\sqrt{3} - k_c(1+\nu)] + 3(1-\nu)k_c\lambda}{(\sqrt{3}+2k_c)(1-2\nu)}\right] \quad \text{at} \quad \lambda = \frac{p_{fl}}{p_{lt}}. \tag{12}$$

This relation at the above-accepted values of the determining parameters of strength and elasticity ($k_c = 0.6$, $\nu = 0.25$) takes a convenient form for engineering calculations:

$$\Delta H > 0.921 H^0(1-\lambda). \tag{13}$$

According to (13) in the case of the hydrostatic law of fluid pressure variation with depth ($\lambda = 0.38$), the displacement of the volume of mountainous rocks from a depth of 2 km upwards over a distance of 1.2 km can cause reindexing of the main stresses and appearance of greater compression in the horizontal direction. If the fluid pressure at the depth where the cataclastic current occurred was equal to 60% of the lithostatic pressure, the raise by 750 m can cause reindexing of the main stresses. These values are quite standard for the regions subjected to vertical motions.

Thus, the mechanism of gravity condensing presented here, which is accompanied by the further raise of rocks closer to the day surface, explains the possibility of the appearance of horizontal compression stresses exceeding the vertical stresses. The geological data indicate that contrast of vertical motions is a distinguishing peculiarity of the orogen tectonics during the modern time. Neighboring regions are subjected to raise and sink. Such a tectonic regime facilitates formation of the stresses of maximal compression in the horizontal direction. At the same time, a regime of the stressed state of horizontal compression can be observed in the regions whose rocks were recently subjected to raise, while in the neighboring regions, which sink during the recent time, a regime of horizontal extension is observed.

The data of stratigraphic columns should be the initial material for the calculation of parameters of the stressed state in the regions of the upper crust intraplate orogens, which make it possible to determine quite exactly at which depths and at what time the rocks were located. The fluid pressure, which existed at the moment of gravity condensing of mountainous rocks, is a sufficient uncertainty in such calculations. We suggest performing calculations for the most probable range of fluid pressure, which can be in the interval determining the values of λ from the hydrostatic distribution of fluid pressure with depth (0.38) to anomalously high (0.6). According to our estimates, it is possible to suppose that over a few million years in time no significant viscous relaxation of stresses occurs in the upper layers of the crust in the rocks subjected to the vertical raising.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research (project no. 06-05-64410) and Program 6 of the Department of Earth Sciences of the Russian Academy of Sciences.

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