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A. G. Aronov, Sh. A. Mukhamediyev & T. I. Aronova

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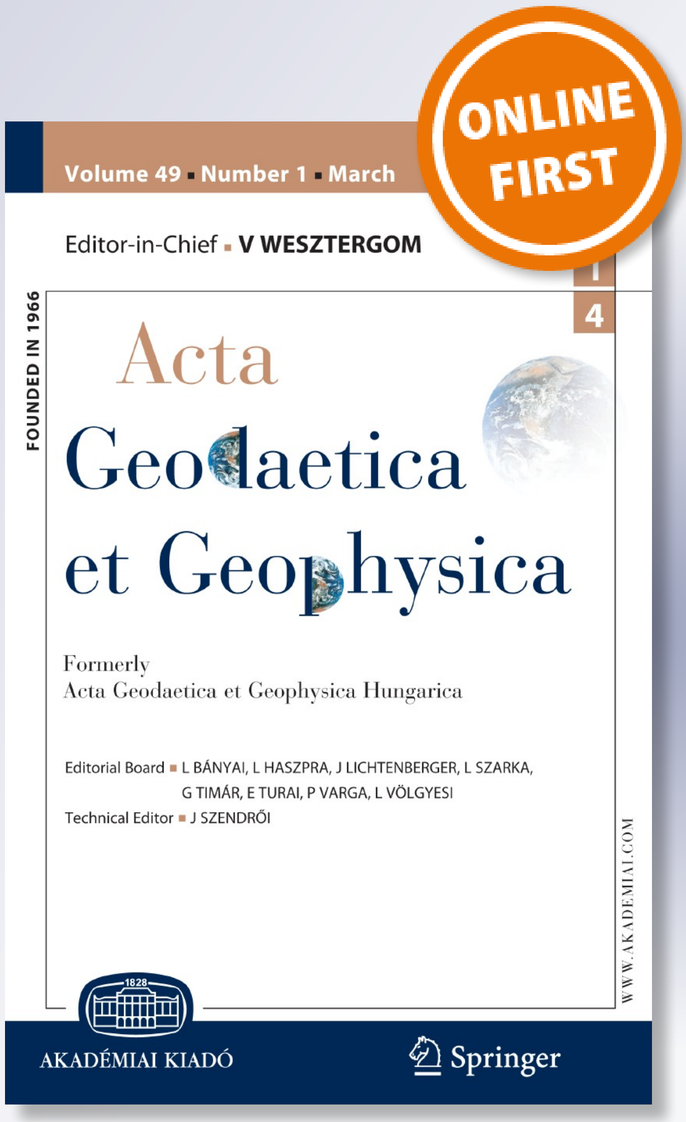

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Abstract On the basis of the experience of development of the Starobin potassium salt deposit (Belarus) the authors suggest a quantitative model of a relationship between the seismicity and stress state (SS) of the crust in the areas of mining activities. Within the Starobin deposit mining region, earthquakes arise outside the mine fields and are confined to the regional faults occurring there. The axis of the maximum horizontal compression $S_{H,max}$ shows a NNW orientation. Within the framework of a two-dimensional elastic model the authors consider mining induced disturbances of the initial homogeneous stresses. For simplicity, the mine field is simulated as a circle within which the elastic moduli are decreased as compared to those of the environment. The rock excavation results in considerable heterogeneity of the SS outside the mine field. Horizontal compressive stresses are concentrated in areas that extend across the $S_{H,max}$ axis giving rise to potential seismic slips of the thrust type. Conversely, the tension regime is realized in areas adjacent to the mine field along the $S_{H,max}$ axis, which can result in the re-activation of normal faults. Strike-slip faults can be activated in directions diagonal to the principal axis of the regional stress. With an increase of the excavated rock volume the area of seismic activity can be increased.

Keywords Seismicity · Earthquake mechanism · Tectonics · Hazard

1 Introduction

Among hazards appeared when underground mining works are carried out rock bursts, roof caving, face wall collapses, and earth's surface subsiding should be mentioned. A number of

A. G. Aronov (✉) · T. I. Aronova
Centre of Geophysical Monitoring, National Academy of Sciences of Belarus, 7, Academician Kuprevich str, Minsk 220141, Belarus
e-mail: aronov@cgm.org.by

Sh. A. Mukhamediyev
Institute of Physics of the Earth of the Russian Academy of Sciences, 10, Bolshaya Gruzinskaya str, Moscow 123995, Russia
e-mail: shamil@ifz.ru

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papers were devoted to studying these phenomena and finding the ways of their prevention (Gibowicz 2009; Brown 2012; Donnelly 2009). The mentioned hazards are local in the scale of their manifestation, as the area of their manifestation is restricted within the mine field area. For forecasting the above hazards it is necessary to carry out a continuous monitoring of the acoustic emission and seismic activity in operating mines, to know the geometry of mine workings and its changes with time, to apply correctly the failure and instability criteria.

The present paper deals with the other type of geoecological risks not directly related to specific mining conditions, but resulting from the proper fact that underground rock excavation is going on. These risks are caused by the fault activation in the mining region in consequence of stress changes in horizons subjected to the action of tectonic forces. The spatial distribution of the mentioned risks manifested as an increased seismic activity goes beyond the limits of the mine fields involving the territories adjacent to the region of mining activities. The averaged characteristics of the seismicity increase slightly depend on the rock excavation features, but are firstly determined by the geometry of faults in the region and the regional tectonic stress pattern. If not specific mining conditions, but their common features are considered it is possible to reveal the universal relationships between seismicity and stresses in mineral mining regions. This is especially important for forecasting geoecological risks in regions where underground mining activities are envisaged to be realized.

So, the problem is stated to reveal some general regular relationships between stresses, tectonic structure and seismicity, that will permit an integral assessment of the character of human impact upon the environment during underground mineral mining and a priori (before the beginning of mining) forecast of undesirable consequences. For best results it is necessary to take into account the previous similar investigations and to develop an adequate quantitative model of a phenomenon. In the present paper the relationship between seismicity and tectonic stresses working in the Starobin potassium salt deposit of Belarus is analyzed, and a model of such a relationship based on the calculation of concentration of stresses around an inhomogeneity in the elastic medium is suggested.

2 Seismicity in the region of the Starobin deposit

The Starobin deposit is the largest potassium salt occurrence in Europe. It was discovered in 1949, and its development started in the early sixties of the past century. The deposit covers an area of 325 km^2. The total ore reserves are 7.8 billion tonnes. The salt is extracted by underground mining method. The deposit formed about 300 million years ago at the end of the Devonian period of the geological evolution history (Garetsky et al. 2001) when a shallow sea with vast lagoons occurred in the place of the present-day Polessie region. Sodium and potassium salt deposits alternated with clayey–carbonate layers had been deposited as a result of active evaporation and downwarping of the basin floor caused by vertical oscillatory movements.

Potassium salt occurs inside rock salt beds. Several tens of potassim-bearing horizons were revealed in all within the deposit. Four horizons mostly uniform in area and thickness are of commercial interest. The tectonic conditions within the deposit are responsible for different depths of occurrence of potassium-bearing horizons. Commercial horizons occur in a depth range from 400 to 1,200 m and deeper. Their thickness varies between 4 and 20 m.

The Pripyat Trough, which the Starobin potassium salt deposit is confined to, is composed of the Pripyat Graben (palaeorift) and North-Pripyat Shoulder. The fault tectonics of the region have been studied in detail (Garetsky et al. 2001; Aizberg et al. 2007). In the south the

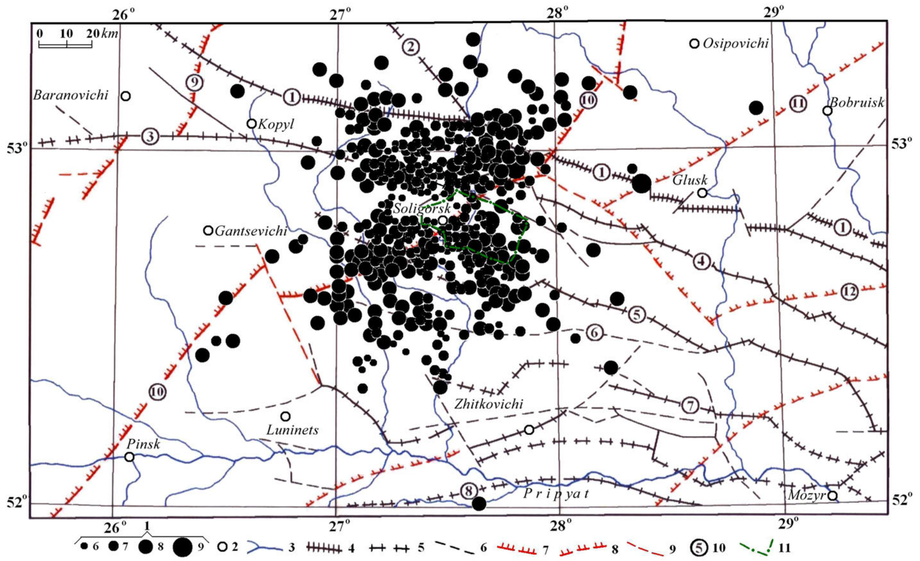

Fig. 1 Map showing seismotectonic processes manifested in the northwestern part of the Pripyat Trough within the period 1983–2012. *1* Energy class (K); *2* settlements; *3* rivers; *4–6* faults penetrating into the mantle (*4* superregional faults bounding the largest superorder structures; *5* regional faults bounding large structures of the I and II orders; *6* local faults); *7–9* faults not penetrating into the mantle (*7* superregional faults separating largest areas of different reworking age; *8* regional faults separating large areas of different reworking age; *9* local faults) *10* faults (*encircled figures 1* North-Pripyat, *2* Naliboki, *3* Ljakhovichi, *4* Rechitsa, *5* Chervonaya Sloboda-Malodusha, *6* Kopatkevichi, *7* Shestovichi, *8* Skolodin, *9* Vyzhevsk-Minsk, *10* Stokhodsk-Mogilev, *11* Krichev, *12* Chechersk); *11* boundaries of mine fields of the Soligorsk mining region

Pripyat Graben is separated from the Ukrainian Shield by the South-Pripyat marginal fault, in the north—from the Belarusian Anteclise and North-Pripyat Shoulder, Zhlobin Saddle and Gremjachin buried uplift by the North-Pripyat marginal fault. The Pripyat Trough is dissected by a system of mantle and crustal faults into several steps mainly of sublatitudinal trend. Marginal faults (the North-Pripyat and South-Pripyat ones) bounding the trough are listric mantle faults. The Chervonaya Sloboda-Malodusha and Rechitsa faults are also listric mantle ruptures. The other shallower faults are shown in Fig. 1.

Continuous seismological observations started in the region of the Starobin potassium salt deposit in 1983 (Paskaleva et al. 2006; Aronov et al. 2010). The first event which attracted attention to the regional seismicity was the earthquake of May 10, 1978, which was recorded by the seismic stations Minsk (epicentral distance is 170 km) and Obninsk (600 km). In all more than 1,200 seismic events were recorded and processed within the studied territory since 1983 till the present time. About 30–50 seismic events of the energy class K = 4–9 are recorded annually. The distribution of epicentres of the recorded earthquakes (Fig. 1) shows that many faults are still active. Epicentres of most of minor seismic shocks are concentrated along differently oriented faults and their members, i.e. minor earthquakes are generally tracing faults. Earthquakes are confined to the Beshenkovichi and Korelichi faults striking submeridionally, northeastwards striking Stokhodsk-Mogilev, Krichev, Vyzhevsk-Minsk faults, Polotsk, North-Pripyat, Lyakhovichi, Rechitsa, Chervonaya Sloboda-Malodusha, Kopatkevichi, Shestovichi, Skolodin faults of sublatitudinal strike. Some events are found in fault junction zones (Paskaleva et al. 2006; Aronov et al. 2010).

An analysis of the available seismological data makes possible a conclusion that earthquakes are tending to occur beyond mine fields, and that their epicentres are confined to faults found in the region. A high seismic activity in the deposit mining region is recorded against the background of negligibly small activity in the adjacent regions. It can be supposed that the main causes of the seismic activity in the region are (i) the proper fact that an area weakened by underground mine workings is found there, and (ii) action of tectonic forces.

3 Modeling of stresses in the environment caused by underground mining activities

The direction of the maximum horizontal compression $S_{H,max}$ in the region was assessed using various data and approaches. During the field tectonophysical investigations carried out within the western part of East European Platform we collected data on jointing of Mesozoic–Cenozoic sedimentary rocks (Belousov et al. 2006a). The earlier developed technique (Belousov et al. 1997) was applied to interpret the measurement data in terms of palaeostress axes. It was revealed that by the Late Pleistocene and Holocene the axis of the maximum horizontal compressive stress $T_2^0 = S_{H,max}$ became NW-NNW oriented (Belousov et al. 2006b). This orientation is similar to the present-day position of the stress axis $S_{H,max}$, which is determined from a summary diagram of earthquake focal mechanisms and shows a submeridional strike with a small deflation to NNW (Aronova 2006, 2007).

The mathematical problem is posed as follows. Assume that the lithostatic stress state (SS) described by the symmetric stress tensor T^0 had existed in the region before the deposit development started,

$$T^0 = I \int_0^z \rho\, g dz + T_1^0 e_1 \otimes e_1 + T_2^0 e_2 \otimes e_2, \quad (z > 0)\,, \tag{1}$$

where I is the unit tensor of the 2nd order, ρ—rock density, g—gravitational acceleration, z-axis is oriented vertically downwards from the free surface $z = 0$, $T_i^0, i = 1, 2$, are the principal horizontal stresses (positive under compression) directed along the Cartesian axes x_1, x_2 with unit vectors e_1, e_2 (Fig. 2). The stress field represented by the formula (1) is a superposition of hydrostatic stresses changing with depth z and horizontal tectonic regional stresses.

Assuming the elastic response of the medium, we conclude that disturbances of lithostatic stresses (1) beyond the mine field caused by the deposit development depend upon two most important factors:

(I) changes in the effective elastic properties of the developed massif as a result of creation of extended and voluminous underground mine workings;
(II) local (within the area of mining activities) redistribution of rock masses.

Let us assume that the geometry of mine workings does not cause essential anisotropy of effective properties of the massif. Then to make an account for the factor (I) the volume of a massif where underground mining is carried out should be represented as an inhomogeneity, in which the effective elastic moduli G (shear modulus) and K (bulk modulus) differ from the corresponding moduli G_0 and K_0 of the surrounding medium. In general, if there is no elastic interaction between workings, the coefficients G and K are less than G_0 and K_0. The factor (II) means that waste rocks (in this case, potash processing wastes) are usually stored on the surface in the mining area. Rock dumps and sludge-catchment basins create a load over the surface, which can be simulated as a normal stress applied to the surface $z = 0$.

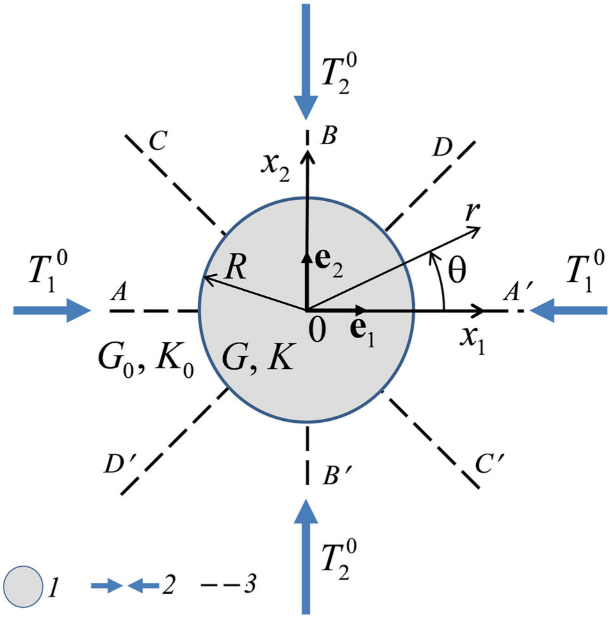

Fig. 2 Model geometry. Plane with elastic moduli G_0, K_0 involving a circular weakened inhomogeneity (1) with elastic moduli G, K is subjected at infinity to the action of the principal compressive stresses (2). *Dashed lines* (3) simulate faults, orthogonal (AA') and parallel axes of the maximum horizontal compression (BB'), as well as axes oriented diagonally to them (CC' and DD')

In the present paper we have studied the quantitative influence of the factor (I) for a two-dimensional model, the body forces being neglected. For simplicity sake assume that the mine field is a circle of radius R. Such a geometrical approximation seems to be fully satisfactory for the Starobin deposit, as mine fields of four mining groups of the JSC "Belaruskalij" form all together a single mine field rather isometric in plan. The basic idea of the problem statement and solution remain the same for the more general case when the mine field has an elliptical boundary. In this case the famous solution by Eshelby (1957) is true suggesting that the homogenous SS exists within an ellipsoidal inclusion, which elastic moduli are changed as compared to those of the surrounding medium.

Statement of the 2D problem is as follows (Fig. 2). In an infinite elastic plane with the moduli G_0, K_0 and the initial stress $T^0 = T_1^0 e_1 \otimes e_1 + T_2^0 e_2 \otimes e_2$ it is necessary to determine a plane field of symmetric stress tensor $T(x_1, x_2)$ which is caused by origination of a circular (with radius R) soft inhomogeneity with moduli G, K $(G \leq G_0,\ K \leq K_0)$. The compressive stresses are accepted as positive. At infinity the sought for field $T(x_1, x_2)$ approaches the tensor T^0, at the boundary of the inhomogeneity $(r = R)$ the stress and displacement vectors are continuous. To determine the stress field beyond the inhomogeneity it is convenient to use the complex elastic potentials of Kolosov-Muskhelishvili (Muskhelishvili 1966).

The solution of the above problem is described (with various details), e.g., in monographs (Muskhelishvili 1966; Jaeger et al. 2007). For $r < R$ SS remains homogeneous, the principal axes of the initial T^0 and disturbed T stress tensors being coincident. The principal stresses T_1, T_2 inside of the inhomogeneity are expressed in terms of the principal initial stresses as follow

$$\begin{aligned} T_1 &= D\left[(\beta\,(\kappa_0+2)+\kappa)\,T_1^0+(\beta\,(\kappa_0-2)-(\kappa-2))\,T_2^0\right] \\ T_2 &= D\left[(\beta\,(\kappa_0+2)+\kappa)\,T_2^0+(\beta\,(\kappa_0-2)-(\kappa-2))\,T_1^0\right], \end{aligned} \tag{2}$$

where

$$D=\frac{\beta\,(\kappa_0+1)}{2\,(2\,\beta+\kappa-1)\,(\beta\,\kappa_0+1)}, \tag{3}$$

and the following symbols are introduced: $\kappa = 3-4\,\nu$, $\kappa_0 = 3-4\,\nu_0$ for a case of the plane deformation; $\kappa = (3-\nu)/(1+\nu)$, $\kappa_0 = (3-\nu_0)/(1+\nu_0)$ for plane SS. Here ν_0 is the Poisson's ratio of the surrounding medium, ν—the corresponding effective coefficient for the inhomogeneity. The coefficients ν and ν_0 are connected with moduli G, K and G_0, K_0 by the relationships $\nu = (3K-2G)/(6K+2G)$, $\nu_0 = (3K_0-2G_0)/(6K_0+2G_0)$. In the formulae (2), (3) and below, the parameter β means the ratio of the effective shear modulus of the inhomogeneity to the corresponding modulus of the medium

$$\beta = G/G_0 \quad (0 \le \beta \le 1). \tag{4}$$

At $r > R$ for components T_{rr}, $T_{\theta\theta}$, $T_{r\theta}$ of the disturbed stress tensor T in polar coordinates r, θ (Fig. 2) we have

$$\begin{aligned} T_{rr}\,(r,\theta) &= T_{rr}^0+\left(\frac{R}{r}\right)^2\left(\tau^0 2A\cos 2\,\theta-P^0 B\right)+\left(\frac{R}{r}\right)^4\tau^0 3C\cos 2\,\theta \\ T_{\theta\theta}\,(r,\theta) &= T_{\theta\theta}^0+\left(\frac{R}{r}\right)^2 P^0 B-\left(\frac{R}{r}\right)^4\tau^0 3C\cos 2\,\theta \\ T_{r\theta}\,(r,\theta) &= T_{r\theta}^0+\left[\left(\frac{R}{r}\right)^2 A+\left(\frac{R}{r}\right)^4 3C\right]\tau^0\sin 2\,\theta \end{aligned} \tag{5}$$

Here

$$T_{rr}^0 = P^0-\tau^0\cos 2\,\theta,\quad T_{\theta\theta}^0 = P^0+\tau^0\cos 2\,\theta,\quad T_{r\theta}^0 = \tau^0\sin 2\,\theta \tag{6}$$

are the components of the initial stress field T^0,

$$P^0 = \frac{1}{2}\left(T_1^0+T_2^0\right),\quad \tau^0 = \frac{1}{2}\left(T_2^0-T_1^0\right), \tag{7}$$

are the plane average stress and intensity of shear stresses,

$$A=\frac{2(1-\beta)}{2\,\beta+\kappa_0-1},\quad B=\frac{\kappa-1-\beta\,(\kappa_0-1)}{2\,\beta+\kappa-1},\quad C=\frac{\beta-1}{\beta\,\kappa_0+1}. \tag{8}$$

The Figures below present characteristics of the disturbed stress field. Calculations were made for a case of plane deformation at $\nu_0 = \nu = 0.3$ which corresponds to the relationships between elastic moduli $K_0 = 2.17G_0$, $K = 2.17G$. The parameters that determine the solution in coordinates related with the orientation of the principal axes of the initial stress are as follow:

– decrease of the effective shear modulus in the inhomogeneity which is caused by the formation of underground cavities and is expressed by the β value (4); and
– degree of biaxiality of the regional SS which can be characterized by the coefficient α,

$$\alpha = T_1^0/T_2^0 \quad (0 \le \alpha \le 1). \tag{9}$$

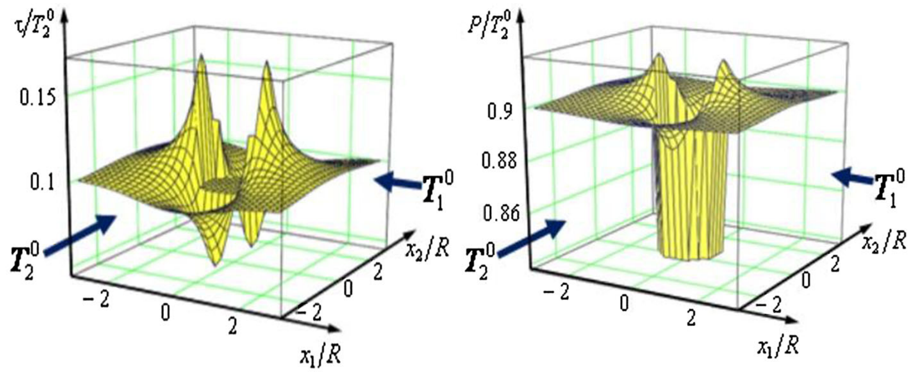

Fig. 3 Spatial distribution of the shear stress intensity $\tau(x_1, x_2)$ (*left*) and average stress $P(x_1, x_2)$ (*right*) near the weakened inhomogeneity at $\alpha = \beta = 0.8$

Figure 3 presents the spatial distribution of the shear stress intensity τ and average stress P (normalized to the maximum compression T_2^0)

$$\tau = \sqrt{\frac{1}{4}\left(T_{rr} - T_{\theta\theta}\right)^2 + T_{r\theta}^2}, \quad P = \frac{1}{2}\left(T_{rr} + T_{\theta\theta}\right), \tag{10}$$

for 20 % decrease of shear modulus ($\beta = 0.8$) and the degree of biaxiality of SS $\alpha = 0.8$. At the chosen values of the parameters α and β, the normalized values of τ and P inside of the inhomogeneity decrease from the initial values of 0.1 and 0.9 to 0.092 and 0.84, respectively. When the parameters α and β decrease, the τ and P values decrease more considerably. In the surrounding medium, the τ and P fields are characterized by the higher values in the areas adjacent to the inhomogeneity along the direction of action of the minimum horizontal stress T_1^0. This is the most characteristic feature of the solution which is due to the concentration of the circular tangential stress $T_{\theta\theta}$ at the inhomogeneity boundary at $\theta = 0$ and $\theta = \pi$. The concentration of the compressive stresses $T_{\theta\theta}$ at $\theta = 0$ and $\theta = \pi$ increases with increasing:

- degree of biaxiality of the initial SS (i.e. with decreasing α) and
- degree of the inhomogeneity attenuation (i.e. with decreasing β).

The coefficient of the concentration of the tangential stress $T_{\theta\theta}$ reaches its maximum (which equals 3) at $\alpha = \beta = 0$.

On the contrary, along the direction of the maximum compression ($\theta = \pm\pi/2$) the areas with the lower τ and P values adjoin the inhomogeneity from outside. This is explained by the fact that at $r = R$ and $\theta = \pm\pi/2$ the tangential stress $T_{\theta\theta}$ reaches its minimum value. The value $T_{\theta\theta}(R, \pm\pi/2)$ decreases with decreasing the parameters α and β. At the minimum α and β values ($\alpha = \beta = 0$), which corresponds to the uniaxial compression of a plate with circular hole, $T_{\theta\theta}(R, \pm\pi/2) = -T_2^0$.

To illustrate the behavior of a stress normal to the fault strike, Fig. 4 shows the plots of functions $\Delta T_{\theta\theta} = T_{\theta\theta}(r, 0) - T_2^0$ and $\Delta T_{\theta\theta} = T_{\theta\theta}(r, \pi/2) - T_1^0$ for a case of the uniaxial compression ($\alpha = 0$). These functions reflect a disturbance of the stress $T_{\theta\theta}$ along the AA' and BB' lines in Fig. 2 due to formation of a weakened inhomogeneity. For the Starobin deposit these lines AA' and BB' can be interpreted as the strikes of sublatitundal and sublongitudinal faults, respectively. On the line AA' which is orthogonal to the compression axis, the maximum $\Delta T_{\theta\theta}$ value as stated above is reached at the inhomogeneity boundary ($r/R = 1$). When the distance from the inhomogeneity increases, the stress

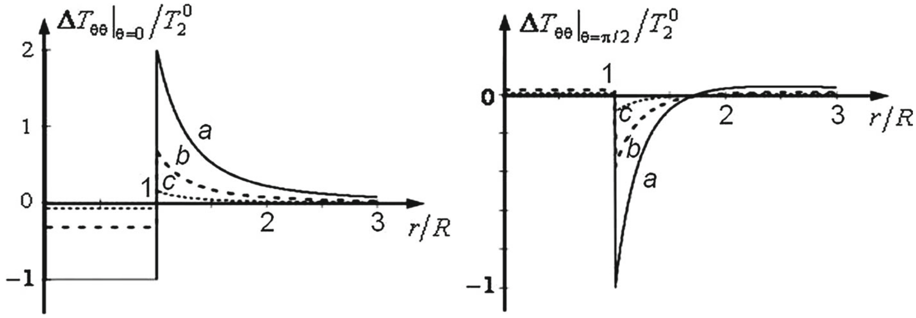

Fig. 4 Change of the normal compressive stress disturbance with increasing distance from the centre of the weakened inhomogeneity across the fault strike at $\alpha = 0$ and $\beta = 0\,(a)$, $\beta = 0.4\,(b)$, $\beta = 0.8\,(c)$. At the *left* fault orthogonal to the maximum stress axis (AA' line in Fig. 2); at the *right* fault parallel to the maximum stress axis (BB' line in Fig. 2)

disturbance decreases and asymptotically approaches zero. The stress disturbance increases with increasing the parameter β. On the line BB' which is parallel to the compressional axis, at $\alpha = 0$ and any value of β the disturbance $\Delta T_{\theta\theta}$ is negative at the immediate vicinity of the inhomogeneity. This cause the formation of normal tension stresses on BB'. The tension stresses decay rapidly when the distance from the inhomogeneity increases, and at $r/R \approx 1.7$ are changed by small compressive stresses. It should be noted, that when α increases, the minimum initial stress T_1^0 begins to prevent the formation of the tension stresses on BB'. In this case the effect of the inhomogeneity appearance is reduced to decreasing the initial normal compression across BB' at rather small distances from the inhomogeneity boundary.

Let's consider the disturbance of the tangential stresses $\Delta T_{r\theta}$ which is formed at $\alpha = 0$ on the regional main stresses diagonally oriented relative to the axes (line CC' and DD' in Fig. 2). Figure 5 presents the plots of the function $\Delta T_{r\theta} = T_{\theta\theta}(r, \pi/4) - \tau^0$ normalized to T_2^0 (τ^0 is the initial tangential stress $T_{r\theta}^0$ on the CC' and DD' lines). Inside of the inhomogeneity, $\Delta T_{r\theta}$ is negative and it is smaller, as the β is smaller. Outside the

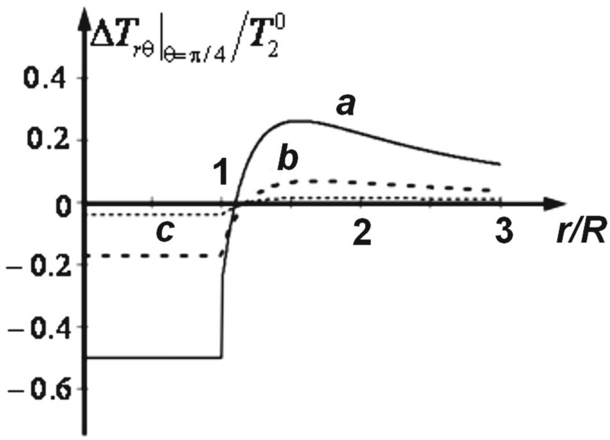

Fig. 5 Change of the tangential stress disturbance with increasing distance from the centre of the weakened inhomogeneity along the diagonal fault strike (DD' line in Fig. 2) at $\alpha = 0$ and $\beta = 0\,(a)$, $\beta = 0.4\,(b)$, $\beta = 0.8\,(c)$

inhomogeneity, the disturbance of the tangential stress $\Delta T_{r\theta}$ changes its sign to positive almost immediately and reaches its maximum at $r/R \approx 1.6$–1.8. The $\Delta T_{r\theta}$ value at $\beta = 0$ is about a quarter of the applied compressive stress, but it appreciably decreases with increasing β.

4 Conclusions

The suggested two-dimensional model and calculations give a possibility to make some general conclusions about the impact of the underground mining activities on the environment and, in particular, on the fault activation outside of the mine field. The rock excavation, which is followed by the formation of cavities in the worked massif, enables its consideration as a weakened inhomogeneity in the surrounding elastic medium exposed to the initial (regional) homogeneous tectonic stresses. Mining activities disturb the initial stresses transforming them into considerably inhomogeneous stresses outside the mine field. The horizontal compressive stresses are accumulated in the areas extended across the line of action of the maximum regional compression $S_{\mathrm{H,max}}$. If in these areas there are faults with their fracture plane declined to the horizon and having dip azimuth similar to the direction of the $S_{\mathrm{H,max}}$ axis, then the seismic movements of thrusting types can occur along these faults. On the contrary, the tension conditions are created in the areas adjacent to the mine field along the axis $S_{\mathrm{H,max}}$. The normal faults may be activated there along the inclined planes parallel to the $S_{\mathrm{H,max}}$ axis, and, in particular, grabens may be formed. The area of prevalent tension stress conditions is rather limited, its linear dimensions along the $S_{\mathrm{H,max}}$ axis do not exceed a radius of the mine field. Strike-slip faults can be activated along directions which are diagonal to the main axes of regional stresses. When the volume of excavated rocks is increased, and the effective elastic moduli of the weakened inhomogeneity are respectively decreased, the seismically active area may be also increased. However, at any volume of excavated rocks the radius of the fault activation area cannot probably exceed six radii of the mine field, which agrees with an estimate cited in the monograph (Brady and Brown 2004). The conclusions presented provide a new look at the seismicity manifestations caused by the Earth's crust stress changes when the underground deposit mining is carried out.

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