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On the Initiation of Dynamic Slips on Faults by Man-Made Impacts

G. G. Kocharyan[a], I. V. Batuhtin[a], A. M. Budkov[a], G. N. Ivanchenko[a], S. B. Kishkina[a, *], and D. V. Pavlov[a]

[a] *Institute of Geosphere Dynamics, Russian Academy of Sciences, Moscow, 119334 Russia*
**e-mail: SvetlanK@gmail.com*

Abstract—The subject of research is dynamic slips on large faults initiated by man-made impacts. In addition to recognized types of man-made impacts such as fluid injection or seismic vibrations, the possible trigger effect of rock extraction and displacement during mining operations is considered. It is shown that dynamic sliding can be initiated only on faults in which three geomechanical conditions for the occurrence of instability are fulfilled: closeness of the value of Coulomb stresses in the fault plane to the local ultimate tensile strength; the condition of weakening of frictional contact with an increasing sliding velocity and relative movement of fault sides; and the implementation of a certain ratio between the stiffness of the enclosing massif and the rate of reduction of resistance to friction. Features of formation of a dynamic slip on a fault are considered in the series of laboratory and numerical experiments. It is shown that the movement always begins in the segment with the property of velocity weakening, regardless of the location of such a segment relative to the load application. According to the calculations, the excavation of rock in a large mining quarry leads to a change of about 1 MPa in the Coulomb stresses in the fault plane in areas that significantly exceed the size of the nucleation zone of earthquakes with $M \leq 6$. This may turn out to be sufficient to initiate seismogenic slips on stressed faults.

Keywords: man-made earthquakes, trigger effect, active fault, Coulomb stress, open-pit mining

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INTRODUCTION

The occurrence of numerous weak seismic events as a result of engineering activity is common at many sites, and such "man-made" seismicity is usually not interesting until earthquakes of significant magnitude take place, such as M = 7.3 in Gazli (Uzbekistan, 1967) or a series of events with $M > 4$ in the mines of the Kola Peninsula (Lovchikov, 2013; Adushkin and Turuntaev, 2015; etc.).

The development of new mining technologies and the unprecedented increase in the volumes of works have led to a significant growth in the number and energy of rather large earthquakes related to man-made activity. The growth in seismicity in the Kuzbass, the sudden increase in the number of earthquakes with $M > 3$ in the central part of Northern America, and large incidents in the deposits of the Timan-Pechora region are just a few such events (Adushkin, 2016, 2018; Ellsworth, 2013).

It is well known that the large man-made earthquakes with $E_S > 10^9$ J ($M > 2.5$) are most often localized near the faults zones existing nearby a massif within the mining area and may occur with a delay, which is sometimes significant, with respect to the mining operations. They are characterized by a strike-slip focal mechanism. According to (Stec, 2007), e.g., a seismic moment tensor calculated for the mechanisms of seismic events, confined to the fault zones, contains more than 70% of a purely shear component. During weak events, a process of nucleation and propagation of fractures in geomaterial can be a source of seismic vibrations, while, at rather large earthquakes, the seismic vibrations can be caused by dynamic movement along the existing fault.

Considering the nature of large man-made earthquakes, we often say that such events occur in the massifs with a "high level of stresses," "a high tectonic component of the stress field," in "energy-saturated massifs," "in the presence of energy fluxes from external man-made sources," etc. (Adushkin, 2018). The inaccuracy and fuzziness of concepts such as "energy-saturation" is far from harmless. This makes it difficult to develop adequate ideas about initiation mechanics and does not allow creating obvious criteria for monitoring a rock massif during the engineering works. Meanwhile, it is especially important to determine the possible contribution of anthropogenic factors to the initiation of earthquakes. Since these events may take place in densely populated industrially developed regions and the source is located at a relatively shallow depth, the damage caused by earthquakes with magnitude of ≥4.5 is considerable.

This work considers the mechanics of initiation of dynamic movements along active faults by the basic types of man-induced impacts, such as fluid injection, the impact of seismic vibrations, rock excavation, and displacement in mining.

ACTIVE FAULTS AND CONDITIONS OF SLIDING INITIATION

Faults thread throughout all of the Earth's crust. Here and in what follows, we a priori assume that the source of intraplate crustal earthquake is a dynamic movement along an active tectonic fault. Active faults are elements of the Earth's crust structure that are main manifestations of neotectonic activity (Trifonov, 2017). The term "active fault" introduced in the 1970s (Bolt et al., 1978) implies that these are the faults along which the displacements were recorded in the past, are observed now, or may be expected in the near future. According to the standard definition, an active fault is a tectonic dislocation with features of constant or periodic displacements of its sides in the Late Pleistocene–Holocene (over the last 100000 years).

There is a lot of evidence of the fact that the brittle crust is critically stressed almost everywhere (Zoback, M.D. and Zoback, M.L., 2002); i.e., many faults are almost about to undergo frictional failure. The measurements of stresses under stratum conditions in the sedimentary basins all over the world confirm that the value of deviatoric stresses is often limited by frictional stresses on the optimally oriented preexisting faults consistent with the Byerlee law, i.e., the friction coefficient of 0.6–0.7 (Townend and Zoback, 2000). This assumption is supported by a wide distribution of induced seismicity, the observed phenomena of distant initiation of earthquakes by seismic waves, and the results of stress measuring in deep mines and boreholes (Townend and Zoback, 2000). Although these effects are most pronounced in seismoactive regions, they are also known to occur where background seismicity is extremely low or totally absent (Adushkin and Turuntaev, 2015; Fougler et al., 2018).

There are several global causes that influence the stress-state of intracontinental regions: the movement of tectonic plates, lithosphere bend, and density and thermal inhomogeneities of the lithosphere (Leonov, 1995; Zoback, M.D. and Zoback, M.L., 2002). The rates of variations in stresses determined by these global causes are extremely low far from the boundaries of the tectonic plates (~10^{-5} MPa per year or smaller) (Hill and Prejan, 2007); therefore, it is reasonable to assume that Coulomb stresses are close to friction ultimate tensile strength on any fault that underwent displacements recently, regardless of whether these displacements were seismogenic or aseismic. Certainly, when deformation activity is absent for a long time, the fault strength can noticeably increase due to effects of healing (Ruzhich et al., 1990). This unambiguous question (e.g., (Kocharyan, 2016)) requires separate consideration and goes beyond the scope of this work. The hypothesis that the stress state of active faults is close to limiting is also supported by studies of the parameters of unexpectedly high-amplitude current movements in the vicinity of the fault zones that are often more intense in aseismic, rather than in seismoactive, regions (Kuzmin, 1996, 2014; Kuzmin and Zhukov, 2014).

Despite the rather homogeneous stress field in many intracontinental regions (Leonov, 1995; Zoback, M.D. and Zoback, M.L., 2002), it is well known that not all faults are seismically active. We consider the conditions for one or another type of slip to occur on a fault. It was believed until recently that an earthquake and an aseismic slip are two opposite phenomena taking place under different conditions of loading the medium. The earthquakes were interpreted as quasi-brittle rock failure and a creep was considered a localized plastic flow (Rodionov et al., 1986).

As a result of an unprecedented increase in density and quality of instrumental observations over the last 25 years, the regimes of movements along the faults and fractures that are transitional from a stable slip (creep) to a dynamic rupture (an earthquake) were classified and studied. These regimes include seismogenic phenomena of slip along faults, fractures, interface boundaries with velocities lower by a factor of 1–3 than during "normal" earthquakes, and episodes of aseismic slip. The study of these phenomena considerably changes the understanding of how the energy accumulated in the process of the Earth's crust deformation is discharged: slow movements along the faults are no longer perceived as a special type of deformations but form a single row of slip regimes together with "normal earthquakes" (Peng and Gomberg, 2010; Kocharyan, 2016).

We formulate three main geomechanical criteria for the change in the regime of fault zone deformation.

One essential condition for slip to occur is the closeness of the value of effective stresses tangential to a fault plane, to a local or current ultimate tensile strength:

$$\tau \sim \tau_0. \tag{1}$$

We use the term "local ultimate tensile strength," since slip can occur at the level of shear stresses that are a priori smaller than the Coulomb ultimate tensile strength τ_p (Fig. 1).

Another condition for the appearance of slip is a decrease in frictional strength of contact at an increase in the velocity V of slip and/or displacement D, so-termed velocity weakening:

$$\frac{d\tau_{fr}}{dV} < 0 \text{ and } \frac{d\tau_{fr}}{dD} < 0. \tag{2}$$

It is clear that dynamics instability simply cannot otherwise occur. The possibility of implementing a regime of friction weakening is determined by *PT*-conditions, structural and physico-mechanical properties of geomaterial that composes a slip region (Scholz, 1998; Kocharyan et al., 2017b).

Another important parameter is the ratio between the stiffness of an enclosing massif K and stiffness of fault k_s on the branch of unloading. The slip regime and a share of deformation energy spent for seismic radiation are related by the ratio $\psi = |k_S|/K$. The stiffness of fault $|k_S| = |\partial\tau/\partial D|$ determines the rate of a decrease in slip resistance during a slip, and the stiffness of the massif $K = \eta G/\hat{L}$ is the rate of a decrease in elastic stresses in a massif due to shear along a fault. In these expressions, G is the shear modulus of an enclosing massif, $\eta \sim 1$ is the coefficient of a form, and $\hat{L}$ is the typical size associated with an earthquake magnitude (Kocharyan, 2016).

If the condition

$$|k_S| = \left|\frac{\partial\tau}{\partial D}\right| \geq K = \eta\frac{G}{\hat{L}} \quad (3)$$

is fulfilled, the energy is discharged from the system. Otherwise, a dynamic slip and consequently energy radiation are not possible. The ratio of $\psi = |k_S|/K$ determine not only the occurrence possibility, but also the character of the slip (Kocharyan et al., 2016). Figure 2 shows the dependence of the discharged energy on this parameter plotted based on the results of laboratory experiments (Kocharyan, 2017a). It is seen that a discontinuous slip occurs in a rather wide range of variations in ψ, while the slow regimes of slip take place in a narrow range of values $|k_S|/K \sim 1–2$. This means that, on brittle faults where stiffness (velocity of a decrease in slip resistance) is rather high, the deformation energy is discharged only in the form of dynamic slips, “normal” earthquakes. On faults with low stiffness, the slow slip events may take place. Since the massif stiffness in the crust varies weakly for the different regions and depths, the stiffness of the fault k_S should be accepted as the governing parameter.

This parameter, the typical values of which for the faults of different hierarchical levels can be found, e.g., in (Kocharyan, 2016), depends on substance composition of a slip zone, water content and chemical composition of a fluid, and PT conditions. The stiffness is the most sensitive to substance composition of the main fault plane zone. For example, the presence of water-bearing clays (or a certain amount of talc, which often replaces minerals from a serpentine group along the fracture walls as a result of chemical reaction between serpentinite and silicon dioxide in thermal fluids) sharply decreases the shear stiffness of a fault; as a result, this value may amount to less than 10% of the normal value.

The change in the level of effective normal stresses exerts a much milder influence on fault stiffness. In certain segments of the fault zone, there is a considerable decrease in stiffness seismogenic depths due to the sublithostatical level of a fluid pore pressure (Kis-

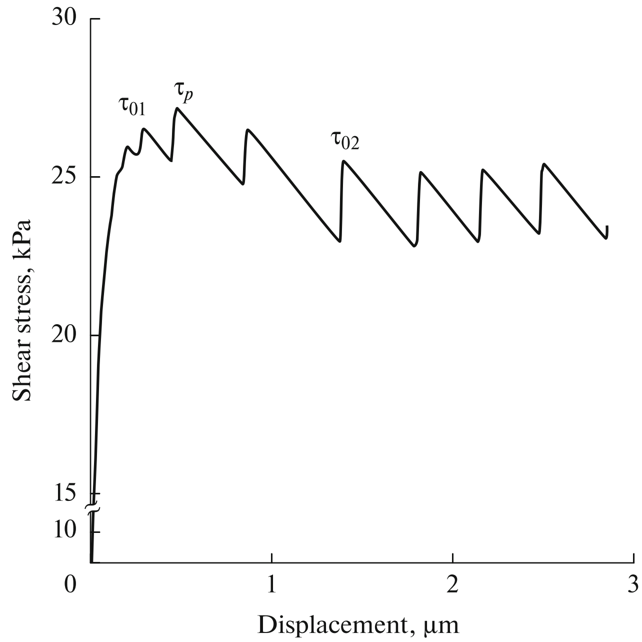

Fig. 1. Example of a shear stress–displacement dependence when a granite block slips along a thin layer of quartz sand τ_p is ultimate tensile strength of contact; τ_{01} and τ_{02} are examples of local ultimate tensile strength values.

sin, 2015), which, according to (Rice, 1992), occurs in the isolated layers in the central part of the fault confined by low-permeable formations.

Thus, a dynamic slip can be initiated only on those faults which fulfill all three geomechanical criteria of instability occurrence. Sometimes, when conditions (2) or (3) are not fulfilled, slow regimes of slip may act (Peng and Gomberg, 2010; Kocharyan, 2016).

FEATURES OF DYNAMIC SLIP FORMATION

A slip surface inside most fault zones is heterogenous in the sense that the mechanical properties and mineralogical composition of the geomaterial that forms a slip zone are inhomogeneous, varying within a rather wide range. In our work, it is important that there are regions formed by geomaterials with different dynamics of friction characteristics during a slip: segments of weakening, of strengthening, and almost neutral segments with respect to the velocity and displacement.

The general patterns of the start of dynamic movement along the fault were considered in a series of laboratory and numerical experiments.

In laboratory experiments, the process of start and propagation of rupture along the contact of the stressed elastic block of vacuum rubber and a rough dural plate was controlled. The experimental scheme is presented in Fig. 3. The contact between the surfaces was filled with a thin layer of loose material. The experimental

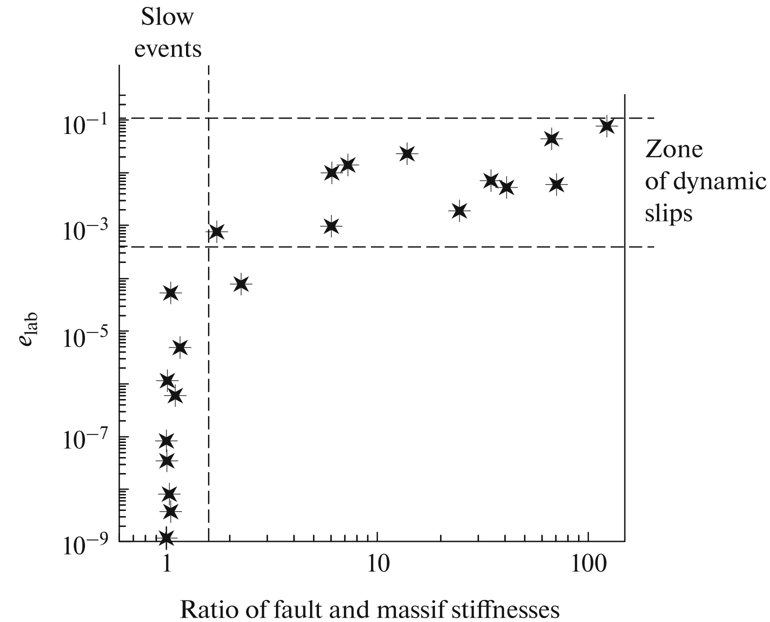

Fig. 2. Dependence of the value of discharged energy on the ratio of fault and massif stiffnesses.Symbols designate the results of laboratory experiments.

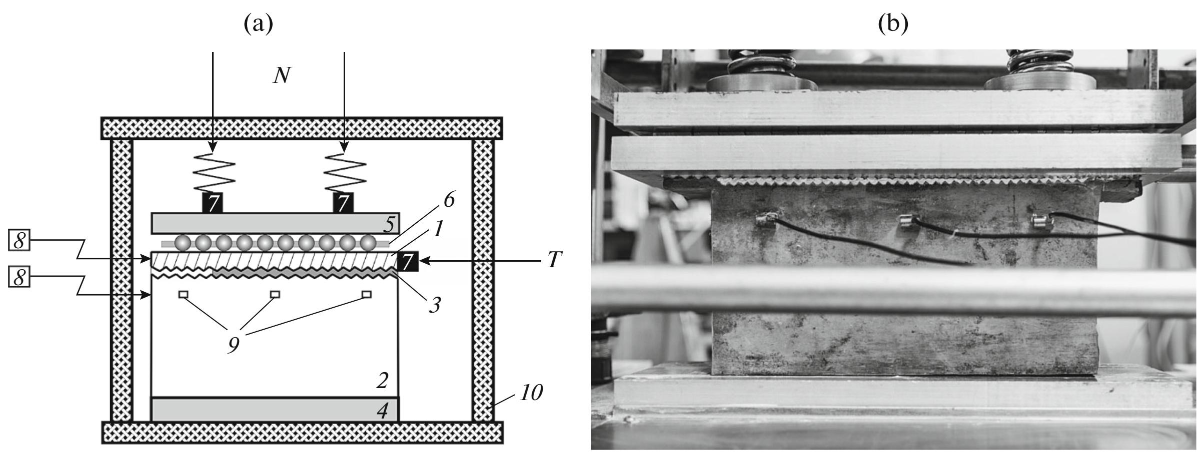

Fig. 3. (a) Scheme and (b) external view of experimental facility for studying a dynamic movement along a fault. (*1*) Upper moving dural block, (*2*) lower stationary rubber block sized 20 × 10 × 5 cm, (*3*) contact between the blocks filled with starch and clay, (*4*) lower fixing plate, (*5*) upper thrust plate, (*6*) thrust bearing, (*7*) force sensors, (*8*) laser displacement sensors, (*9*) accelerometers, and (*10*) steel frame. (*N*) Normal load and (*T*) shear load.

setup, procedure, and parameters of loading were described in detail in (Batukhtin et al., 2018).

The process of nucleation and propagation of rupture was controlled by Bruel&Kjaer miniature accelerometers, located on the block, as well as by ILD2220-10 laser displacement sensors with a measurement accuracy of 0.2 μm in a frequency range of 0–5 kHz.

The filler was starch, a material with the pronounced property of velocity weakening, and clay, which provides a stable slip. The value of Coulomb limit strength for the both fillers was approximately equal: $\mu = \sigma_n/\tau_n = 0.74$. In the described series of experiments, the materials were not mixed, but formed separate regions of the slip surface.

The measurement results showed that movement always starts at the segment that has a property of velocity weakening, regardless of the position of such a segment relative to the direction of load application. The examples of initial segments of accelerograms for the two variants of the filler position are presented in Fig. 4. This character of rupture "start" is also preserved when the configurations of the clay and starch patches are more complex.

In the numerical calculations, the process of relative displacement of two elastic blocks separated by the

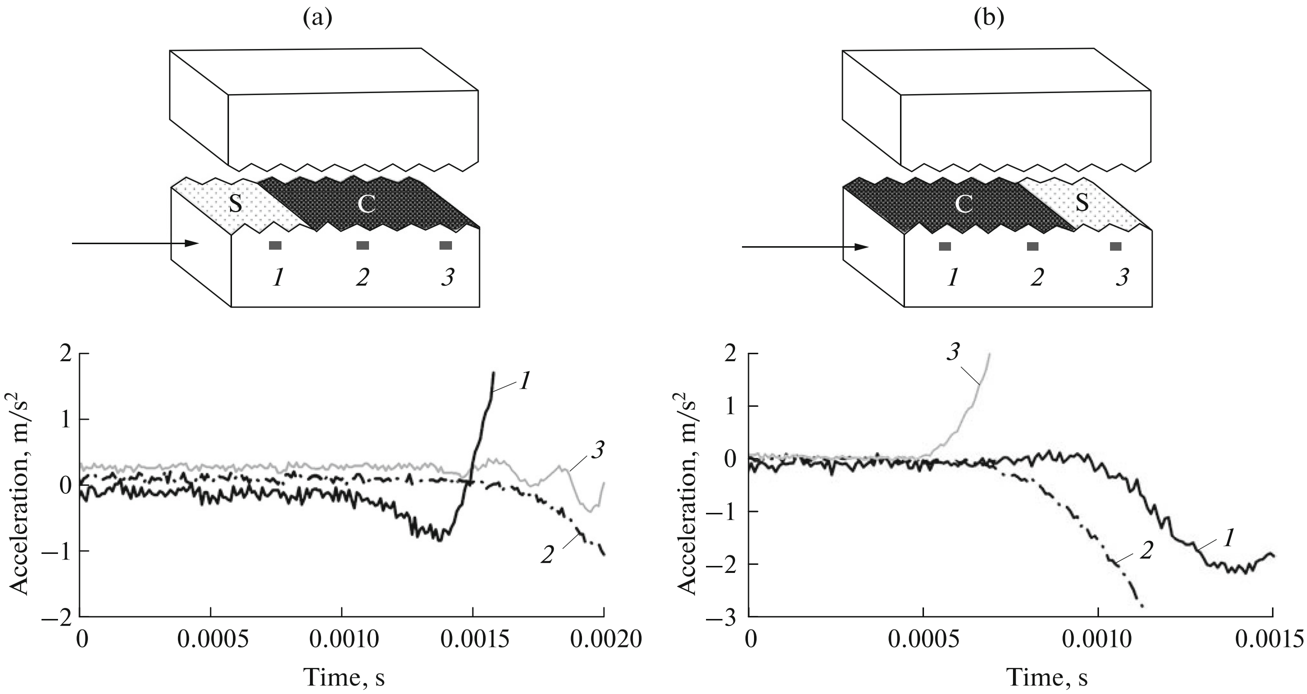

Fig. 4. Experimental setup and initial segments of wave forms of accelerations at different positions of clay and starch segments relative to the direction of load apllication: (a) load is applied to a contact segment filled with starch (S); (b) load is applied to a contact segment filled with clay (C). (*1–3*) Numbers of accelerometers.

slip surface was simulated. For these purposes, a 2D software complex (Arkhipov et al., 2003) developed on the basis of the Tensor Lagrange numerical method was used. The calculations were performed in a plane statement. In assigning a boundary condition on a slip plane, one or several patches were identified in which the friction was described by a rate and state law. According to the ratios of this known empirical model (Dieterich, 1979), the friction coefficient μ depends on instantaneous slip velocity V, time, and movement:

$$\mu = \mu_0 - a\ln\left(\frac{V_0}{V}+1\right) + b\ln\left(\frac{V_0\theta}{D_c}+1\right). \quad (4)$$

Here, μ_0 is the constant corresponding to a stable slip; V is the current velocity of displacement; θ is the variable of state; and a, b, and D_c are empirical constants.

At $(a - b) > 0$, a regime of velocity strengthening occurs; i.e., the slip remains stable. Condition $(a - b) < 0$ leads to velocity weakening and provides conditions for the appearance of a discontinuous slip.

The model coefficients, used in the main series of calculations, corresponded to the regime of velocity weakening: $\mu = 0.3$; $a = 0.0002$; $b = 0.0882$; $D_c = 1$ μm; $V_0 = 0.1$ mm/s. On the rest of the slip surface, the friction force was calculated by the Coulomb law using the same friction coefficient. The kinematic parameters of motion and stress tensor components were controlled in the calculations. For visualization of the region of elastic energy discharge, the spatial distribution of a change in energy density of shear block deformation at the different moments of time relative to the onset of slip was calculated.

The scheme and the results of one of the calculation variants are presented in Fig. 5. The calculation results show that the rupture starts at one of the segments with the property of velocity weakening and propagates in the both directions from the patch. In this case, outside the segment of weakening, the slip velocity decreases quickly and increases again on the neighboring patches. The higher the total share of segments with weakening is, the higher the share of deformation energy spent for elastic wave radiation in a high-frequency part of the spectrum is.

Although the maximum slip velocity outside the weakening zone decreases approximately proportionally to the distance, an integral value of a relative displacement of the sides of the faults remains almost unchanged in this statement. The rupture propagates along the stressed tectonic fault to the zone, inside of which the slip surface has a property of velocity strengthening and the displacement velocity decreases fast. If the sizes of the strengthening zone are rather large, the rupture fully stops. A rupture “jumps” a small zone, then “speeds up” again on the weakening patches. If there is no large strengthening segment on the fault surface, the rupture propagates through the entire length of the block.

INITIATION OF DYNAMIC MOVEMENT

The main man-made factors that can initiate a movement along the prepared fault are variations of

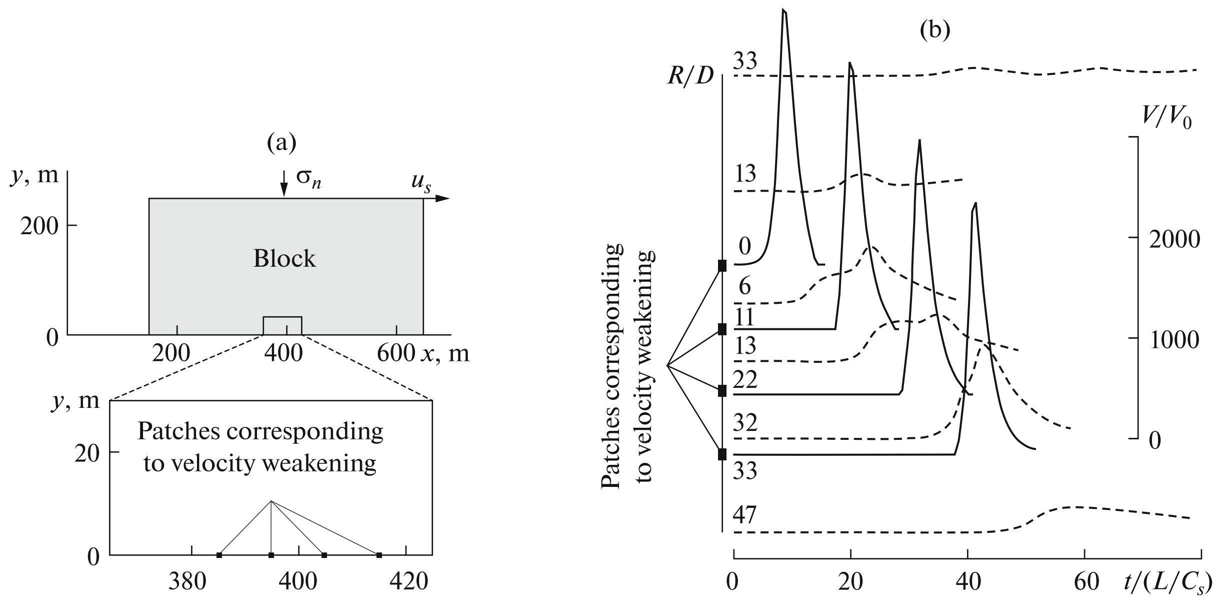

Fig. 5. Simulation of a relative shear process for two elastic blocks separated by a slip surface: (a) calculation scheme; (b) velocity profiles for the displacement of material in the direction parallel to the slip surface (in one calculation variant with four identical segments of velocity weakening). (b) Solid lines are profiles corresponding to points within the patches, dashed lines designate the profiles outside the patches, and numbers near curves mean the distance from the point of rupture onset normalized to the patch diameter. Amplitude of mass velocity is normalized to a displacement velocity value of the upper edge in the block. The first phases of movement are shown.

the fluid-dynamic regime in the fault zone, the impact of seismic vibrations, excavation, and displacement of large volumes of rock in mining. Despite what factor is meant, the above geomechanical criteria should be fulfilled at a certain segment of a fault zone and in the enclosing massif: (1) reaching local contact strength, (2) fulfillment of condition of velocity weakening, and (3) the ratio between the stiffness of the massif and the fault. It is logical to assume that the typical segment size required to do this is a fortiori larger than the size of the so-termed zone of earthquake nucleation, the area on which the rupture velocity increases to the dynamic value (Scholz, 1998). Currently, this value can be estimated very approximately. According to the seismological data (Papageorgiou and Aki, 1983; Ellsworth and Beroza, 1995; Ide and Takeo, 1997), the size of the nucleation zone L_n can reach a value of about 10% of the length of the rupture of the future earthquake; i.e., for $M = 6$ the size L_n is smaller than ~1000 m (in detail (Kocharyan, 2016)). Consider the possibilities of implementing formulated criteria under the impact of man-made factors.

Change in Fluid Dynamic Regime

The influence of injection or pumping out the fluid in rock massifs has been studied by many researchers. References to published works can be found, e.g., in the monographs and reviews (Adushkin and Turuntaev, 2015; Foulger et al., 2018; etc.). An increase in the intrapore or formation pressure and consequently, a decrease in the effective Coulomb strength of faults and fractures as a result of a man-made interference (a direct influence on the fulfillment of criterion (1)), is usually considered the main physical mechanism.

However, there is a whole set of evidence (Djadkov, 1997; Foulger et al., 2018; etc.) about the influence of weak variations in hydrostatic pressure (of a millibar order) on seismicity that the Coulomb model becomes hardly probable. A natural experiment established that the size of the region of the change in the parameters of the regime of slip along the fault can exceed the radius of the zone of the pore pressure change by several times (Guglielmi et al., 2015). This means that the injection or pumping out of the fluid can change the geomaterial characteristics.

A friction parameter of the material, the difference (a–b) from ratio (4) sharply decreases; i.e., velocity weakening becomes more pronounced even when a very small amount of fluid is added. In laboratory experiments, the addition of fluid amounting to 0.1% of the mass of the filler material for the laboratory fault turns out to be sufficient for the radical change in the character of a slip from a creep to a pronounced stick slip (Kocharyan, 2016).

The fluid injection is perhaps one of few possibilities of a man-made change in a friction parameter under natural conditions. This effect was observed during laboratory experiments described in (Kocharyan and Ostapchuk, 2015; Kocharyan et al., 2017a), where the process of a stick slip of a granite block along a thin layer of grained material was studied.

In the first series of experiments, a filler material was moistened in advance with a fluid of certain viscosity and was thoroughly mixed. The contact filled with dry quartz sand demonstrated a stable slip in the whole range of normal loads after the shear stresses had reached a Coulomb ultimate tensile strength. The increase in the content of fluid at volume content $\psi \approx 0.1\%$ leads to a rather sharp transition from a stable slip to a stick slip. When glycerin is used, the maximum slip velocity increases by more than a factor of 300. At a further increase in moisture, the regime is stabilized, and, up to $\psi \approx 10\%$, a change in the characteristics of the deformation regime almost does not depend on the content of fluid in a filler (Kocharyan and Ostapchuk, 2015). We associated this phenomenon with a character of interaction between the particles of the fracture filler. When a small amount of fluid is added, a thin submicron film of fluid is formed on the particle surface, which smoothens roughness and contributes to the formation of a contact between single grains. In this case, the regime of fracture deformation significantly depends on a value of fluid effective viscosity. The estimates show that, in the nature, colloidal films that envelop the fracture, filling particles, may form as a result of the aggregation processes, the formation of large structural elements as a result of adhesion of single particles. According to the results of the experiments, the viscosity of these films (and consequently the chemical clay composition) may affect the regime of fault deformation.

In the second series of the experiments, during loading, fluids with different properties were quickly injected into the contact zone, which led to the change in parameters of slip such as movement velocity, value of a downfaulted stress, and radiated energy (Kocharyan et al., 2017a). Note that the change in the pore pressure was insignificant compared to the level of normal stress on the fault; i.e., the slip regime varied due to the difference in the friction properties of the contact. Emphasize that, in this case, the effect was observed during the injection of a rather significant amount of fluid (~20% of the fracture volume at a filler porosity of about 35%); therefore, the fluid spread at ~80% of the contact area.

The injection of a significantly smaller amount of water in the experiments with loading of a monolithic heterogenous sample (Sobolev et al., 2010; Sobolev and Ponomarev, 2011) caused significant variations in the regime of acoustic emission and kinetics of the macrofailure process. These processes, which were probably determined by the physicochemical interactions in the cracktips of the Rebinder effect type, were not related to the effect of a change in the characteristics of the velocity weakening of the contact during a slip.

Thus, despite the fact that a man-made change in the fluid-dynamic regime may theoretically lead to the initiation of dynamic movement, recall that this change should occur at a rather large fault area.

Impact of Seismic Vibrations

The initiation of seismic events by earthquake vibrations at hundreds and thousands of kilometers is a recognized and quite ordinary example of a trigger effect (Hill and Prejean, 2007; et al.). According to the data of numerous studies of so-called dynamic initiation, note that, in most cases, we use a level of deformations $\sim 5 \times 10^{-7}$–10^{-6} as a minimum level required for initiation; although some authors indicate lower values (Sobolev et al., 2016). In most cases, the appearance of dynamically induced seismicity is associated with the impact of low-frequency surface waves with periods of 20–40 s. In this case, it is noted that initiation by high-frequency body waves is less likely. A detailed review of this information is presented in the monograph (Kocharyan, 2016).

The mechanics of earthquake initiation by seismic waves is not yet clear. With respect to the background regime of deformation, vibrations may both initiate large events and, on the contrary, create conditions for the redistribution of accumulated deformation energy in favor of relatively minor events (Kocharyan et al., 2013).

We turn now to a phenomenological model for the initiation of movements along the faults, which is based on the effect of accumulation of small strains (Kocharyan, 2016). The model that is proposed takes into account two effects of interaction between seismic vibrations. Firstly, due to nonlinearity of the "stress–strain" relations, the interaction of seismic waves with a quasi-statically loaded fault leads to the appearance of residual displacements of the fault sides. Secondly, the impact of low-frequency seismic vibrations can be an effective "destruction" mechanism for weak colloidal films that significantly reduce the fracture permeability of the massif and, as a rule, can be a mechanism for the local redistribution of pore pressure. In the both cases, the interaction efficiency is proportional to the amplitude of dynamic pulse and duration of a wave packet and is inversely proportional to fault stiffness. To estimate the cumulative value of displacement Δ, we use the relation (Kocharyan, 2016):

$$\Delta \approx A\alpha t \frac{V_m}{k_S}, \tag{5}$$

where A is the size parameter determined by physicomechanical properties of a massif and a fluid, V_m is the maximum velocity of displacement in a wave, t is the duration of a wave train, and k_S is the value of stiffness of a fracture or contact between colloidal particles.

Coefficient $\alpha < 1$ depends on the stress state of the contact and considers partial compensation of differently oriented shifts of residual displacements. In the model experiments, parameter α varied from 0.04 at

τ_S/τ_P ~ 0.5 to 0.8 at τ_S/τ_P ~ 0.99. As the contact approaches ultimate tensile strength, the value of residual displacement initiated by the same pulse increases. For the reliable estimation of the value of α, the data are not sufficient for natural objects, but, according to the results of measurements at large underground explosions, this factor turns out to be smaller by a factor of 1–2, $\alpha \sim 10^{-3}$–10^{-2}. The value of "critical displacement," interblock movement at which a dynamic slip occurs, does not depend on impact amplitude, but is determined by only the contact surfaces and its stress–strain state (Kocharyan et al., 2005). Under a periodic impact, the velocity of relative movement of the fault sides usually gradually decreases due to the "adjustment" of the medium to a dynamic load level. In this regard, according to the model, the threshold of an effective seismic impact is an amplitude exceeding the level of microseismic background in the corresponding frequency range (Adushkin et al., 2009).

The accumulation of inelastic strains and local variations in pore pressure due to fluid crossflows can change the value of the current strength of the contact and its stiffness. Thus, the impact of seismic vibrations on the stressed fault can affect the fulfillment of all geomechanical criteria we formulated.

The technical explosions turn out to be less effective in terms of initiating dynamic movements than large distant earthquakes. The results of measurements of parameters in seismic vibrations from mass explosions (see, e.g., (Goncharov et al., 2002, 2006; Kishkina, 2004)) allow estimating the maximum soil displacement velocity in a wave at different distances. For the total charge weight of 2–2.5 t in the group of deceleration, the maximum velocity of soil displacement does not exceed V_m ~ 0.3–0.6 mm/s at a distance R ~ 3–5 km. In this case, the typical frequency of vibrations f ~ 0.1–0.5 Hz and the wave train duration may reach 100 s. We emphasize that the increase in the total explosion energy leads only to the growth of signal duration at a distance of several kilometers, but almost does not affect the values of maximum mass velocity. Thus, at a depth of 3–5 km, the dynamic stresses in a seismic wave can reach just a few kilopascals and the dynamic stresses can amount to $\sim 10^{-7}$ relative units.

The results of estimations based on relation (5) and the data of precision measurements of residual displacements under the impact of seismic vibrations from the explosions on the fault zones (Adushkin et al., 2009; Kocharyan, 2016) show that the expected value of the residual displacement along the fault under the impacts of such level amounts to from less than 1 μ to tens of microns and may reach a value of about 1 mm only in extreme cases. At these values of displacements, it is difficult to expect that seismic explosion waves directly initiate an earthquake of significant magnitude, since, according to seismological data, the value of critical displacement for the moderate earthquake (M ~ 6) is about 10 cm (Elthworth and Beroza, 1995; Scholz, 2002).

A special case is the dynamic impact on the fault, which is in a state of ultimate stress. The possibility of transforming the vibratory movement of rock masses to translational movement was considered theoretically (Melosh, 1979), as well as was demonstrated in laboratory experiments (Kocharyan and Rodionov, 1988; Sobolev et al., 1991) and numerical calculations (Kocharyan and Fedorov, 1990).

Excavation and Displacement of Rock During Mining Operations

The subject of this work is dynamic movements along the large faults initiated by man-made activity, man-made tectonic earthquakes. Unlike rock bursts, the sources of these events are located, as a rule, at a distance from the front of mining operations and are often at a depth to several kilometers. Both the above-considered change in the fluid-dynamic regime and the impact of seismic explosion waves, as well as rock excavation and displacement, act as factors initiating large dynamic movements during mining operations.

Rock excavation and displacement in open-pit mining exert an influence only on the field stress parameters, i.e., on the fulfillment of the criterion of reaching local ultimate tensile strength (1). To approximately estimate the change in the stress–strain state of the massif as a result of rock excavation in open-pit mining, we use a solution of the Love problem (Love, 1935), which considers a stress field in applying a load to a rectangle segment on the elastic half-space surface. In this statement, the excavation at a depth h can be replaced by uniform unloading $\zeta_z = \rho g h$.

The analytical solution of the Love problem, describing the change in the values of stresses and displacements with respect to coordinates in the form of relations presented in (Korotkin, 1938), were used for calculating the parameters of the stress field in the vicinity of an excavation 10 × 2 × 0.3 km in size, which is typical for large quarries of mining enterprises. The calculation results demonstrate that, at a depth of 4–10 km, the change in principal stresses caused by uniform unloading at a working segment does not exceed 1 MPa, which at first glance indicates the insignificant influence of rock excavation on the stress–strain state of the rock massif at a probable location depth of the foci of seismic events.

To evaluate the importance of such changes, we apply the approach used in analyzing the location of aftershocks in the vicinity of the focus of the main rupture, according to which one of the probable causes of aftershocks is the change due to the movement of relationship in the focus between the normal and shear stresses on the plane of some faults located in the vicinity of the main rupture. Depending on geometry of the main earthquake focus and the location and orientation of neighboring faults relative to it, the change in the stress field (as a result of movement) either "pushes" the neighboring faults slightly closer to a failure threshold or, on the contrary, makes them more stable (Das and Scholz, 1981; King et al., 1994; etc.).

This effect is often described by estimating the variation of the Coulomb function at a site oriented in a certain way:

$$\sigma_c = \tau - \mu(\sigma_n - p), \tag{6}$$

where σ_n and τ are normal stress and shear stress to the fault plane, p is pore pressure, and μ is the friction coefficient.

At the stage of preparation of the dynamic slip, $\sigma_c < 0$. In the case of an increase in shear stress τ or the reduction of effective normal stress $(\sigma_n - p)$, the fault approaches a critical state, $\sigma_c = 0$. We emphasize that, even without knowing the absolute values of stresses, we can calculate the change in the Coulomb function using an incremental equation:

$$\Delta\sigma_c = \Delta\tau - \mu(\Delta\sigma_n - \Delta p), \tag{7}$$

which implies whether the fault "approached" a critical state (the positive increment $\sigma_c > 0$) or, on the contrary, "moved" to a more stable state ($\sigma_c < 0$).

A comparison of the results of calculating the changes in static stress fields with occurring aftershocks shows that a change in stresses $\Delta\sigma_c$ of about 0.1–0.3 MPa is often sufficient for initiating seismicity, while the decrease by the same value restrains it (King et al. 1994; etc.).

According to the calculation results exemplified in Fig. 6, such changes occur in the vicinity of a large quarry at a large site that exceeds the diameter of the nucleation zone of a rather large earthquake (M ~ 6) a priori.

If, for the fault located in the vicinity of the zone of mining operations, the conditions of reaching (1) ultimate tensile strength and (2) velocity weakening are fulfilled, but the condition imposed on the ratio of fault and massif stiffnesses is not fulfilled, dynamic slips do not occur along the fault and the whole accumulated energy of deformation is discharged by the way of creep or slow slip events without the radiation of seismic waves. When mining the deposits underground, a quite different effect can be observed: the initiation of a dynamic movement along a formerly aseismic fault. This is related to a noticeable influence of the branched network of workings in the vicinity of the tectonic fault on the effective stiffness of the massif and, consequently, on the possible dynamic movements.

To estimate this effect, we carried out numerical simulation of the strike-slip deformation of a rock block with the workings. The calculations were performed using a 2D software complex developed on the base of a Tensor Lagrangian numerical method (Arkhipov et al., 2003). The problem was solved in a plane statement. We considered an elastic block (the density

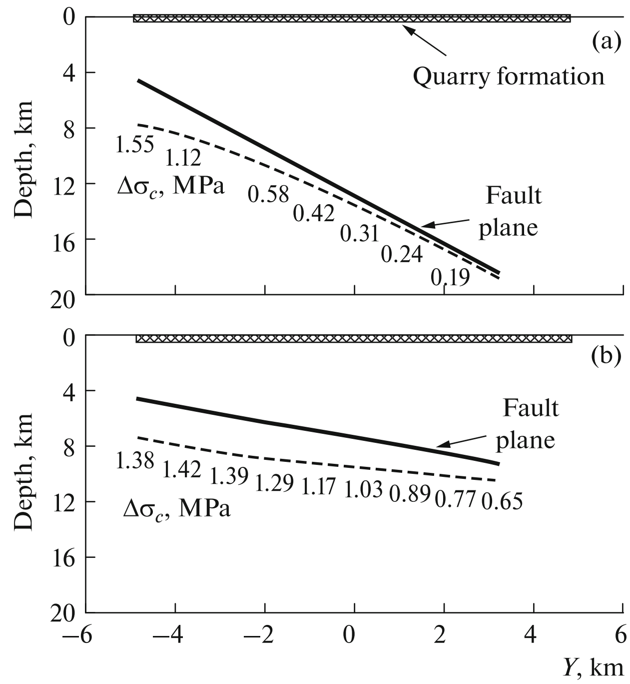

Fig. 6. (a, b) Variation in Coulomb stress in the fault plane with different angles of inclination as a result of formation of a quarry with a linear size of 10 km. Numbers mean the results of calculating the Coulomb function variation.

$\rho = 2.7$ g/cm^3; the volume compression modulus K = 28 GPa; shear modulus G = 11.435 GPa; and velocity of p waves a_0 = 4000 m/s). The inset in Fig. 7 presents the calculation scheme. The right side of the block is fixed tightly, and shear stress increasing linearly with time is assigned on the left side. The velocity of shear-stress increase was selected so that the block deformation regime was close to quasi-static.

The series of calculations carried out for the solid block showed that the estimate of the effective shear modulus calculated using the linear approximation of the relation

$$G_{\text{eff}} = \tau_S/\varepsilon, \tag{8}$$

yields the value G_{eff} = 8.84 GPa (linear regression with correlation coefficient R = 0.996), i.e., ~ 20% less than the shear modulus of the material.

The relative deformation was determined as the ratio of displacement of the upper left angle of the block to the width of the block $\varepsilon = W_r/H$. This discrepancy is a result of nonfulfillment of an assumption on a uniform distribution of shear stresses for the block of finite sizes. We may talk only about a certain effective shear modulus of massif G_{eff}: the coefficient of proportionality between the stresses and the strains.

To estimate the influence of the workings driven on the value of the effective modulus of the massif and, consequently, on the massif stiffness used in criterion of instability appearance (3), we performed calcula-

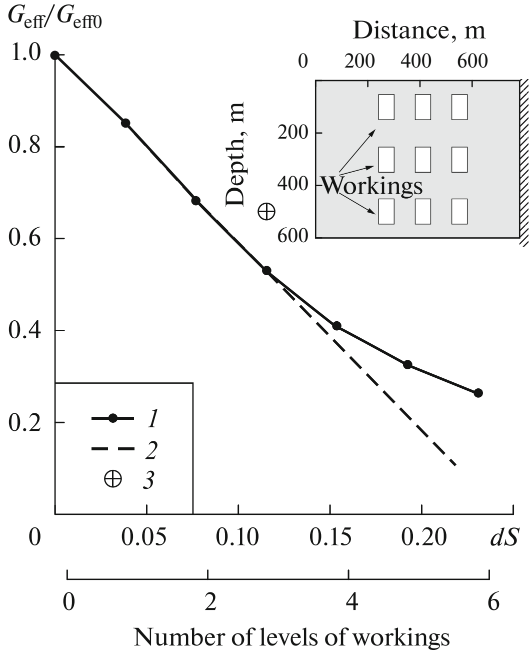

Fig. 7. Dependence of a relative effective shear modulus of a massif segment with workings on the segment of the area occupied by unfilled space (the scheme of a model massif segment with workings is shown in the inset). (*1*) Calculation results, (*2*) estimation by relation (9), and (*3*) calculation of the variant for workings filled with disintegrated rock. Value of effective shear modulus G_{eff} is normalized to a corresponding value for solid massif $G_{eff\,0}$.

tions with filled and unfilled spaces in the elastic block. The length and the height of one cavity were approximately 100 and 60 m, respectively. The distance between the workings was taken equal to 100 m. In the main series, the calculations were performed with one, two, and three levels of workings. The distance between the levels was 80 m. As we might expect, the value of the effective shear modulus is smaller the greater the degree of massif dislocation is. For one level of the workings, the value of G_{eff} decreases by approximately 20% and, for two levels, by a factor of 1.5. For three levels, the effective modulus of the massif decreases by almost two times. Based on relation (3), this decrease may turn out to be critical in terms of initiating a dynamic movement along the fault.

Despite the fact that the geometry of the massif with mine workings is far from a porous medium model, the results of numerical calculation coincide with good accuracy in a certain range of parameters with the result of estimating the effective modulus of the medium with respect to the relationships of the so-called Nur critical porosity model (Nur et al., 1998), according to which the shear modulus of dry porous medium G_{eff} is determined by the following way:

$$\frac{G_{eff}}{G_S} = \left(1 - \frac{\phi}{\phi_{cr}}\right)^b, \ \phi < \phi_{cr}, \qquad (9)$$

where G_S is the shear modulus of the solid massif, ϕ is effective porosity of the medium, ϕ_{cr} is the critical value of porosity (a relative void volume at which material loses connectivity), and b is the parameter determined empirically.

Dependence (9) at $b = 1$ and $\phi_{cr} = 0.244$ is presented in Fig. 7. Figure 7 also shows the results of numerical calculations. The values of the effective shear modulus are normalized to the value for the solid massif in each variant of calculation. In addition to it, the results of calculating additional variants with four, five, and six levels of workings are presented. It was noted that, at large relative values of the working areas, the dependence deviates from the relationship (9).

If the cavities were filled with disintegrated rock with elasticity modulus $E = 5$ GPa and Poisson coefficient $\nu = 0.32$, the reduction in the modulus is noticeably lower and, even at three levels of workings, it is only 34%, which significantly decreases the probability of instability when compared with the massif containing unfilled workings.

The calculations show that the rock excavation and displacement in both open-pit and underground mining can change the stress state of the massif so that the movement along the near tectonic fault is initiated. Given the large areas of modern quarries, open-pit mining is a potential trigger of rather large earthquakes.

CONCLUSIONS

Having selected the change in a fluid-dynamic regime, impact of seismic vibrations, and excavation and displacement of large volumes of rock in open-pit mining as the main man-made impacts on the rock massif, we considered the possible contribution of these factors to the process of initiation of dynamic movements along the fault. For this purpose, we provided geomechanical criteria which, when fulfilled, lead to a change in the regime of fault-zone deformation: the closeness of the Coulomb stress value in the fault plane to the local ultimate tensile strength, the fulfillment of the condition of friction contact weakening upon an increase in the slip velocity and relative displacement of the fault sides, and the fulfillment of a certain ratio between stiffness of the enclosing massif and the rate of decrease in friction resistance. The rate of decrease in slip resistance along the fault during slipping should be greater than the rate of elastic stress relaxation in the massif enclosing the fault. A dynamic slip can be initiated only on those faults for which all three geomechanical conditions of instability appearance are fulfilled. Sometimes, if conditions (2) or (3) are not fulfilled, the slow regimes of slipping can be implemented.

An analysis of existing ideas suggests that the Coulomb stresses in many faults that underwent displacements in modern times are rather similar to friction ultimate tensile strength, regardless of whether these displacements were seismogenic or aseismic.

One of the most important conditions of initiation is the circumstance that the change in the conditions of slip should occur in a rather large area which is a priori larger than the size of the earthquake nucleation zone: the segment at which the velocity of rupture increases to the dynamic value. The typical size of such segment for an earthquake with magnitude $M \sim 6$ can amount to 1000 m.

In addition to the common mechanism of initiation of seismic events as a result of a change in pore or formation pressure, injecting or pumping out a fluid are among a few possibilities for a man-made change in friction properties of the slip surface under in situ conditions.

The direct initiation of large earthquakes by seismic vibrations from mass explosions seems to be hardly likely due to the small amplitudes of impacts at a focal depth. An exception is the case when a significant fault area is in a state of ultimate stress, e.g., as a result of long-term rock excavation. One good example is the earthquake with $M = 4.8–5$ on April 16, 1989, in Khibiny (*Seismichnost'*..., 2002).

Rock movement is perhaps the strongest man-made initiating factor in mining. The excavation of material in a large operating quarry with typical sizes of kilometers in plan and hundreds of meters deep leads to a change in Coulomb stresses in the fault planes to several megapascals. Here, the biggest changes are observed on low angle overthrusts. This value, which is insignificant for the level of lithostatic stresses, can be sufficient for initiating seismogenerating movements along the stressed faults. This is indicated particularly by the known calculations of the change in the field of static stresses in the vicinity of aftershock hypocenters of large earthquakes. It is important to stress that, for large quarries, the size of the zone where the change in the Coulomb stresses in the fault plane exceeds a few tens of megapascals significantly exceeds the size of the nucleation zone of earthquakes with $M \leq 6$.

In conclusion, we emphasize that if open-pit mining only approaches an earthquake moment in most cases, the underground mining of deposits changes the effective elastic properties of a rock massif in the vicinity of an active fault. Therefore, it is quite probable that, in the absence of anthropogenic interference, the accumulated energy of deformation would release in a different way than by dynamic movement (an earthquake), e.g., by slow creep or the occurrence of slow slip events.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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