

Stabilization of slip behavior of a clay-bearing fault

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Abstract: Tectonic fault cores are formed substantially of clay minerals. Even a slight change in mineral composition or in water saturation can result in a significant alteration of the sliding regime on the fault. We present results of laboratory experiments on a slider model set-up that was used to study the regularities of slip behavior in a model fault filled with gouge. The gouge consisted of quartz sand and clays of different types (bentonite, illite and kaolinite). The slip behavior essentially depended on gouge mineralogy. The accumulated stress could release via both fast and slow slips. The scaled kinetic energy for fast slips was 10^{-5} – 10^{-3} , while that for the slowest slips was 10^{-9} – 10^{-7} . Fast stick-slip is characteristic of model faults filled with quartz sand in dry and moistened conditions. A gradual transformation from stick-slip to stable sliding was observed for quartz sand/clay gouge as the clay content approached 20%. Under moistening clay, mineralogy played a key role. If the illite clay content was 5%, the moistening led to an increase in peak velocity by more than an order of magnitude; if the 5% bentonite clay was 5%, it led to stabilization of sliding. While alteration in friction coefficient after moistening remained relatively small, the scaled kinetic energy could vary by several orders of magnitude.

Keywords: sliding regime; clay gouge; radiation efficiency; fault rheology; slider-model

1 Introduction

Tectonic fault is the main structural peculiarity of the Earth's crust. In case a fault has formed in a rock mass, further cumulation and release of tectonic stresses will also be controlled by the structural properties of the fault. More powerful human-induced earthquakes are localized near tectonic faults, both in the vicinity of ongoing mining operations and at some distance from them. Human-induced earthquakes may be disproportionately serious because of the large loss of life and resources caused^[1-2].

Mature faults that had formed in transformation of the initial protolithic rock represent a collage of rocks and mineral compositions of different types^[3-6]. The long-term evolution of a fault is accompanied by metasomatic processes. An active fluid input occurs. Crustal and mantle fluids penetrate into faults facilitating chemical reactions, namely, the replacement of strong mineral phases with weak ones. So, there are clay minerals (illite, montmorillonite and other mineral types) that often concentrate in fault cores^[2, 7]. These clay minerals affect frictional properties of faults^[8-10]. Their properties essentially alter after moistening. Clay minerals in the principal slip zone can absorb interlayer water and noticeably change the strength and frictional properties of fault cores. Minerals such as chrysotile, montmorillonite and lizardite can lose up to 50% of their strength after water saturation^[11]. Under some conditions, clay-bearing layers show

noticeable dilation, which can lead to intensive crossflows, a decrease in pore pressure and stabilization of sliding^[12]. Slip behavior of faults rich in clay material at shallow depths can be determined by their viscoelastic properties. The latter are governed by differences in micro-mechanisms, such as thermally active processes at the micro level, which cannot be considered in detail based on macroscopic measurements.

Experimental works on the alteration of the friction coefficient, with varying proportions of clay minerals in the filler of the discontinuity have shown that the friction coefficient can change essentially. The work^[13] has shown that increasing the proportion of shale material in the calcite matrix from 0 to 50 % leads to a decrease in the friction coefficient from 0.71 to 0.37. According to experiments in article^[14], the friction coefficient decreased from 0.61 to 0.39 as the proportion of talc in quartz sand was raised to 25 %. Clay-bearing materials mainly show the property of velocity strengthening (an increase in shear resistance of the fault under growing slip velocity), unlike the quartz, feldspar and calcite fillers, which are drawn to velocity weakening^[7, 9].

Depending on the composition of minerals making up the fault core, different seismogenic or aseismic slip modes can realize on the fault loaded with tectonic or gravitation forces^[15-16]. Among other things, the advances in understanding the mechanism of fault behavior and alterations of shallow seismicity are promoted by laboratory experiments. This work presents laboratory

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experiments that study regularities of sliding regime of model faults filled with sand-clay filler under moistening. We investigate the transition from stick-slip to stable creep and demonstrate the change in rheological and energy characteristics of dynamic slips.

2 Material and methods

Laboratory studies of frictional sliding on model fault were held at a set-up presented in Fig.1. The model fault is a contact of two rough surfaces of plexiglass blocks. The roughness height of block surface was about 0.5 mm. The gap between blocks was filled with a layer of granular material – a mix of sand and clay (S). In the experiments, the moveable block B1, 8 cm×8 cm×3 cm in size, slid along the immovable block B2 under normal (σ_N) and shear (σ_s) stresses. The normal stress σ_N was determined by the weight of loads and was usually about 80 kPa. The shear stress was applied through a spring K with a stiffness of 60 kN/m. The end of the spring was pulled at a constant displacement rate (u_s) of about 20 $\mu\text{m/s}$. The relative displacements of blocks were measured with a laser sensor (D) ILD2300-100 (Micro-Epsilon, Germany) in the frequency range of 0-5 kHz with an accuracy of 1 μm . The shear force was controlled with a sensor (F) CFT/5 kN (HBM, Germany) with an accuracy of 1 N. A typical view of temporal variations of the mechanical parameters is presented in Fig. 2.

Two 1 mm-diameter holes were drilled in the immovable block 3 cm from each another. The holes were connected with an injection channel (W, Fig.1). They served for pumping water of room temperature and mineralization of 1g/L into the model fault. The water discharge was constant. Water pumping started after the sliding regime had become regular. Pumping was performed during 120–150 s and the overpressure did not exceed 0.5 kPa. It was terminated at the moment when the interblock contact was entirely watered. There was no noticeable alteration of pore pressure in such an experimental setting, so all the observed effects were caused by alteration of rheologic properties of the gouge layer after full watering.

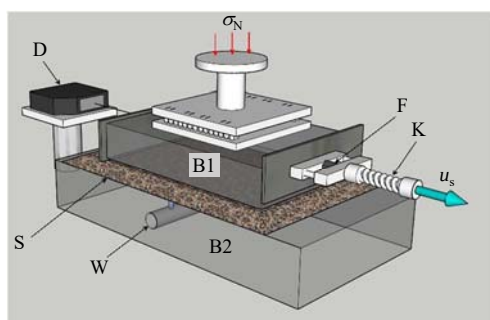
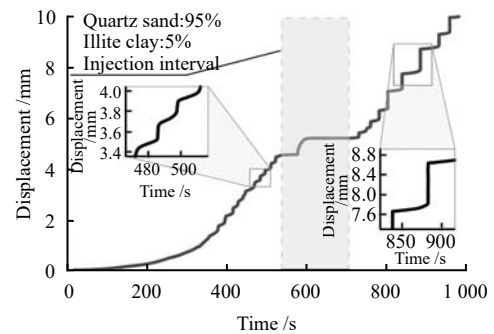
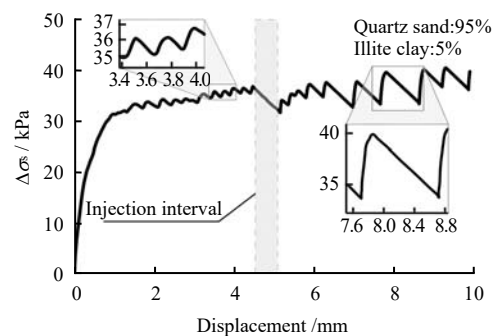


Fig. 1 Scheme of the experimental slider model set-up



(a) Time-displacement curve



(b) Displacement-stress drop curve

Fig. 2 Mechanical parameters (displacement and shear stress) recorded during the experiment

Mixes of quartz sand and different clays were used as fillers of the model fault. The quartz sand consisted of moderately rounded grains ranging in size from 0.160 to 0.315 mm. Clays of the main types (bentonite, illite and kaolinite) were used as the second component of the filler. Mineral compositions of the clays are given in Table 1. These clays were chosen because they are wide spread and they are often found in the gouge of tectonic fault cores^[17]. The clays were of fine grinding with occasional inclusions of siltstone material, which was removed at the stage of probe preparation. Contents of the main clay minerals vary in the presented set of clays (bentonite clay, illite clay and kaolinite clay). The proportion of clay-forming materials determines physical and chemical properties of clays. For example, as the content of montmorillonite decreases, the swelling ability of the clay decreases, as well as its sorption activity.

Table 1 Mineral content of the clays used in experiments

Clay type	Minerals content /%								
	Montmorillonite	Kaolinite	Illite	Chlorite	Quartz	Microcline	Plagioclase	Anatase	Siderite
1	74.7	—	—	—	15.6	—	7.5	0.7	1.5
2	—	6.3	50.4	6.3	15.2	7.0	6.9	—	—
3	—	84.0	7.0	—	8.0	1.0	—	—	—

Note: Type 1—bentonite clay (Taganskoye deposit); 2—illite clay (Nikolskoye deposit); 3—kaolinite clay (Eleninskoye deposit)

A wide spectrum of sliding regimes was realized in experiments – from regular stick-slip to stable creep. Acts of slip (dynamic slips) were determined as relative displacements of the sides of the model fault with a peak velocity exceeding the speed of loading u_s . Parameters of dynamic slips (amplitude of displacement $-\Delta x$, drop of shear stress $-\Delta\sigma_s$, duration of the slip $-\Delta T$, peak velocity $-V_{\text{peak}}$) were determined to describe the sliding regime.

3 Results

3.1 Variations of fault sliding regimes

Alteration in material composition of the filler of model fault led to a radical change in the parameters of dynamic slips. Under “room temperature and humidity”, the model fault filled with quartz sand demonstrated a regular stick-slip. Dynamic slips were characterized by peak velocities V_{peak} from 0.6 to 3.0 mm/s, and on average were about 1.5 mm/s. After moistening the characteristics of dynamic slips altered essentially: peak velocity increased 40 times, amplitude of stress drop and amplitude of displacement per slip increased 3 times, while duration of dynamic slips decreased 2.5 times. The friction coefficient after moistening increased from 0.45 to 0.50.

In dry conditions, a stabilization in sliding regime was observed when clay was added to the sand and the proportion of clay increased (Figure 3). This stabilization manifested in decreasing peak velocity, drop of shear stress, amplitude of displacement, and increasing duration of slips. An ultimate stabilization of sliding (transition to a stable creep) was observed when the clay content in the filler reached 20 %, this value being the same for all the three mineral types of clays under investigation. It should be noted that the friction coefficient of clay-bearing faults did not depend on clay type and increased from 0.46 (no clay) to 0.54-0.55 (20% of clay content).

The frictional strength of clay-bearing fault did not change after moistening (if compared to the strength in dry conditions), but the character of their deformation altered radically. The difference in values of peak velocities under the same content of clays of different types reached two orders of magnitude (Figure 3(c)). A tendency to a decrease in peak velocity as the clay content in the filler grew was observed for all the three types of clays. Dynamic slips on the fault with illite clay showed rather high peak velocities (if compared to the fault with bentonite and kaolinite clays) until the clay content reached 15%. For the model fault containing 5% of illite clay peak slip velocities decreased less than by an order of magnitude in relation to the fault filled with a pure quartz sand. For bentonite and kaolinite clays, a similar decrease was

by 2-3 orders of magnitude, the concentration of clay being the same (Figure 3(c)). For the 20% content of clay in the filler, the difference in fault behavior containing clays of different types was indistinguishable.

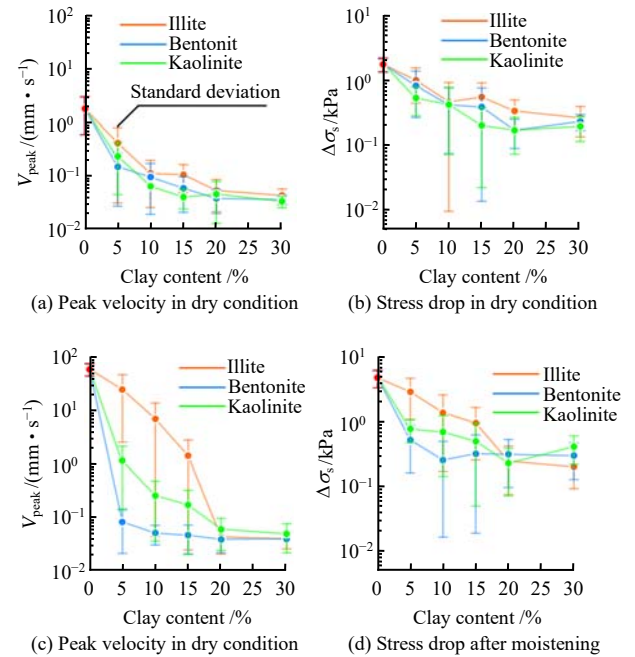


Fig. 3 Variations of peak velocity and stress drop versus clay content in dry conditions and after moistening

Curves of the shear stress drop per slip versus the content of clay in the filler demonstrate the same tendencies, though less pronounced (Figure 3(d)). Peculiarities of transformations in the sliding regime on the model fault after moistening can be expressed through variations of the Z-factor^[6], which characterizes the relative reduction in the average peak slip velocity after moistening of the fault zone compared to its initial state under dry conditions, is calculated as follows:

$$Z = \frac{\langle V_{\text{peak}}^0 \rangle - \langle V_{\text{peak}}^1 \rangle}{\langle V_{\text{peak}}^0 \rangle} \quad (1)$$

where $\langle V_{\text{peak}}^0 \rangle$ is the average peak velocity before moistening and $\langle V_{\text{peak}}^1 \rangle$ is the same value after moistening. So, if the Z-factor is negative, an increase in peak velocity after moistening is observed. If the parameter is close to zero, peak velocity before and after moistening are nearly the same. The dependencies of the Z-factor on content of clay in the filler (Fig.4) show that for a pure quartz sand, the peak velocity after moistening increased by about 30% ($Z \approx -30$). For a filler containing at least 5% of bentonite or kaolinite clay, the peak velocity after moistening remained nearly the same ($Z \approx 0$). However, for the filler containing 5%–10% of illite clay, the peak velocity after moistening increased dramatically compared to the dry condition. As the content of illite

clay in the filler grew, the peak velocity decreased, and the sliding regime gradually stabilized. The unique behavior of the Z-factor for illite clay can be explained by the significantly higher peak velocity after moistening compared to the velocity before moistening. From the graph, it is evident that the velocity after moistening $\langle V_{\text{peak}}^1 \rangle$ exceeds the velocity before moistening by almost 50 times.

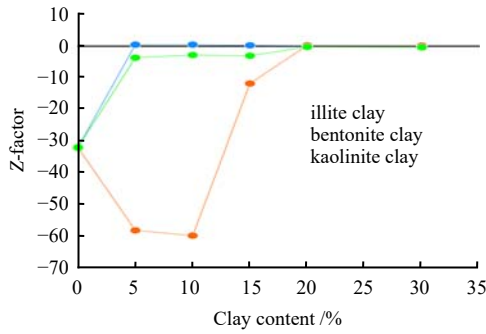


Fig. 4 Z-factor versus clay content in the model fault

3.2 Scaled kinetic energy of dynamic slips

Changing the clay content in the filler essentially affected the balance of energy during dynamic slips. The scaled kinetic energy was estimated for all the detected events as follows:

$$e_{\text{lab}} = \frac{E_k}{M_{\text{lab}}} \quad (2)$$

where e_{lab} is the scaled kinetic energy; E_k is the maximum value of kinetic energy of movable block B1 during a slip; and M_{lab} is the laboratory seismic moment, which can be assessed as follows^[18]:

$$M_{\text{lab}} = \Delta\sigma_s SL \quad (3)$$

where L is the length of block; and S is the area of the contact.

The parameter e_{lab} is an analogue of the energy/moment ratio $e = E_s / M_0$ (E_s – seismic energy, M_0 – scalar seismic moment)^[18], which is used in seismology to characterize the seismic efficiency of an earthquake. Small values of e_{lab} correspond to “slow slip events or slow earthquakes”, while high values are intrinsic to “laboratory earthquakes”.

The scaled kinetic energy can be easily expressed via parameters of dynamic slips:

$$e_{\text{lab}} = \frac{E_k}{M_{\text{lab}}} = \frac{mV_{\text{peak}}^2 / 2}{\Delta\sigma_s SL} = \frac{m}{2SL} \frac{V_{\text{peak}}^2}{\Delta\sigma_s} \quad (4)$$

Figure 5 presents variations of e_{lab} depending on the parameters of dynamic slip. In dry conditions, faults containing clay produced slow slips with scaled kinetic energy of 10^{-9} – 10^{-7} . The difference between

different mineral types of clay is unnoticeable, and e_{lab} in most of “dynamic” events does not exceed 10^{-5} . The number of dynamic slips with e_{lab} lying in the range of 10^{-7} – 10^{-5} essentially increased after model fault moistening. When the content of illite clay reached 5%–10%, peak velocity increased by two orders of magnitude and scaled kinetic energy reached the value of 10^{-3} .

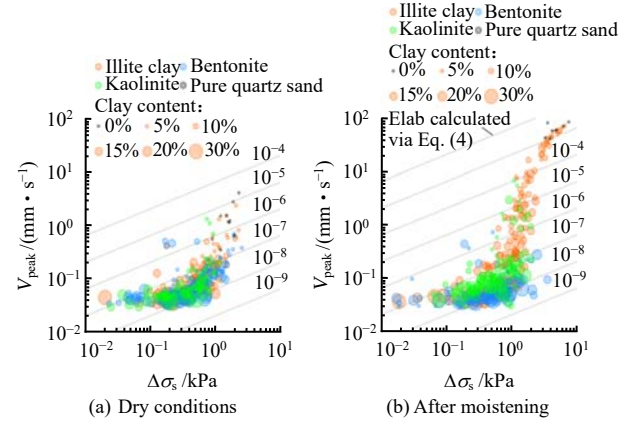


Fig. 5 Peak velocity versus shear stress drop

Variations in parameters of dynamic slips in the performed experiments demonstrate the evolution of sliding regime on the fault caused by increasing clay content and changing mineral composition of the filler. This evolution embraces a wide range of scaled kinetic energies (6 orders of magnitude).

3.3 Rheology of a model fault

Peculiarities of fault behavior are determined by rheological properties of fault gouge. The model of structural superplasticity, that is usually used to describe deformation of polycrystalline materials, can be employed to describe the fault rheology^[19]. The phenomenon of structural superplasticity determines mechanisms of intergrain slips and grain rotation that occur under high concentrations of stresses at their boundaries (under experimental conditions, grain destruction does not occur). The peculiarity of behavior of polycrystalline materials suggests that the classical dislocation creep is not limited by plastic deformation of each grain but is characteristic of a collective behavior of many grains. Therefore, the deformation of a granular material under some conditions can be described by relations specific for the phenomenon of intergrain sliding^[6, 20]:

$$\dot{W} = \frac{1}{\zeta} \sigma_s^{1/\alpha} \quad (5)$$

where $\dot{W}$ is the strain rate; ζ is a material constant; σ_s is the applied stress; and α is a material parameter characterizing stress sensitivity.

In the case when the main portion of shear deformation localizes in the fault core, displacement is

described as follows:

$$W(t) = \frac{\tau V_{\text{peak}}}{\alpha} \left\{ 1 - \left[1 + (1 - \alpha) \frac{t}{\tau} \right]^{\frac{\alpha}{\alpha-1}} \right\} \quad (6)$$

where $V_{\text{peak}} = \frac{dW}{dt}$ is the slip velocity at the moment when the postdynamic sliding starts; W is the displacement along the interface; t is the slip duration; $\tau = \frac{\alpha}{k_s V_{\text{peak}}} \sigma_{s0}$ is the characteristic time of the process; σ_{s0} is the tangential stress at the boundary of model fault at the moment when creep begins; and k_s is the shear stiffness of the fault.

The key parameters of Eq.(6), that allow estimating the rheological properties of fault gouge, are the exponent α , the characteristic time of the process τ and the shear stiffness k_s . The exponent α in Eq.(6) changes from 0 to 1. When $\alpha \rightarrow 1$, Eq.(6) tends to a corresponding rheological equation for the viscous fluid:

$$W(t) = \int_0^t V_{\text{peak}} e^{-\frac{t}{\tau}} dt = V_{\text{peak}} \tau \left(1 - e^{-\frac{t}{\tau}} \right) \quad (7)$$

When $\alpha \rightarrow 0$, Eq.(6) asymptotically tends to a logarithmic relation characteristic of Coulomb (dry) friction^[20]:

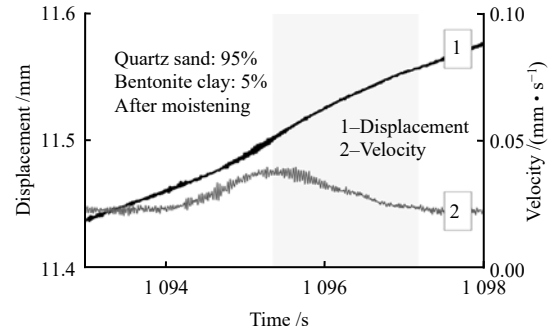
$$W(t) = \int_0^t \frac{V_{\text{peak}}}{1 + \frac{t}{\tau}} dt = V_{\text{peak}} \tau \ln \left(1 + \frac{t}{\tau} \right) \quad (8)$$

Figure 6 presents displacement records of dynamic slips with different rheologic parameters. An approximation of experimental records via Eq.(6) was used to describe the rheologic properties. The section of the curve, for which the approximation was applied, corresponds to the phase of postdynamic movement. The beginning of the section corresponds to the moment at which the sliding velocity is maximal, and the end corresponds to moment when creep begins. This moment comes when the velocity at the postdynamic phase becomes equal to the velocity at which the spring is being pulled. Parameters α and τ were determined via non-linear approximation using the method `nlinfit` in MATLAB.

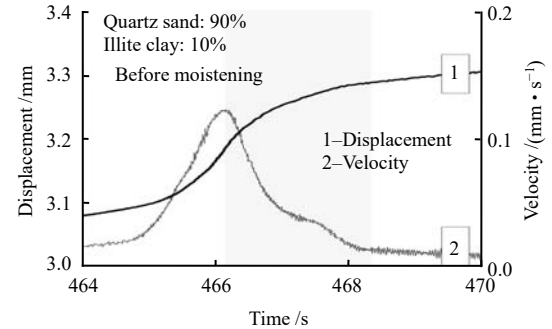
The parameter α allows to estimate the effect of moistening on the rheology of a clay-bearing fault. The parameter α is close to 0 for a fault filled with pure quartz sand, i.e., the rheology can be described by the relations of dry friction. Let's trace alteration of parameter α as the content of clays of different types changes. The results presented in Fig.7 testify that as the proportion of clay increases, the behavior of both

dry and watered fault gradually transits to the rheology of viscous fluid, but peculiarities of this transition depend on both mineral type of the clay and moistening. For example, the rheology of the model fault with the filler containing the kaolinite clay is nearly the same in dry and water-saturated cases (Fig. 7(b)), while for the filler containing the illite clay the transition to the rheology of "viscous fluid", as the proportion of clay increases, is much faster for the dry mix.

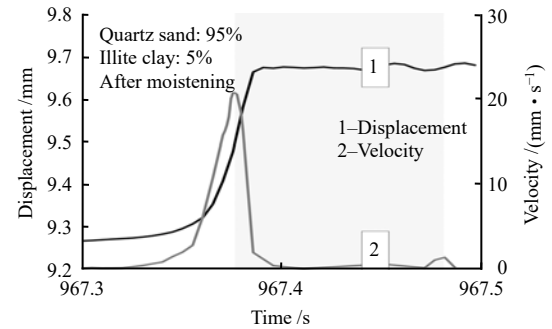
Characteristic time τ indicates the duration of postdynamic phase. It also alters in a wide range. As the clay content increases, τ increases by 1–2 orders of magnitude, but peculiarities of this increase strongly depend on the mineral type of clay in the filler (Fig. 8).



(a) Rheologic parameters: $\alpha = 0.99$, $\tau = 2.71$, $V_{\text{peak}} = 0.04$ mm/s.



(b) Rheologic parameters: $\alpha = 0.56$, $\tau = 0.66$, $V_{\text{peak}} = 0.125$ mm/s.



(c) Rheologic parameters: $\alpha = 0.01$, $\tau = 0.0065$, $V_{\text{peak}} = 21$ mm/s.

Fig.6 Examples of dynamic slips on model fault with different rheologic parameters The gray area marks the postdynamic phase

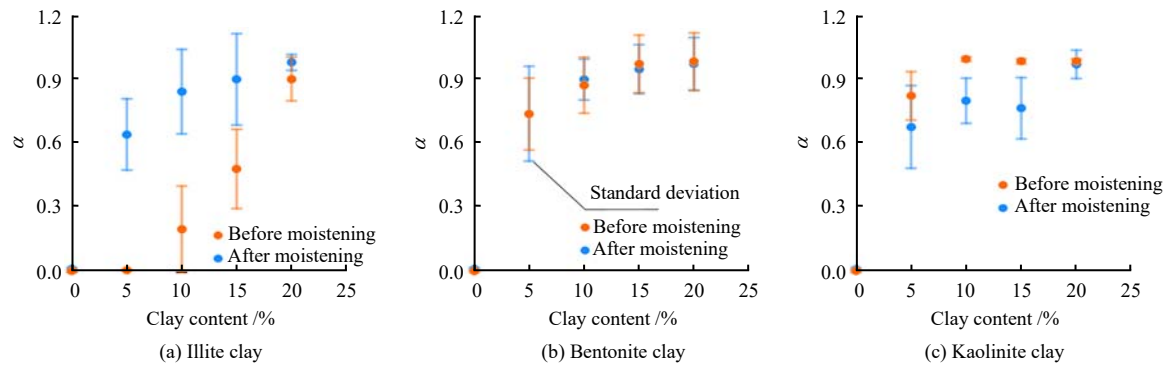


Fig. 7 Variations of exponent α versus clay content

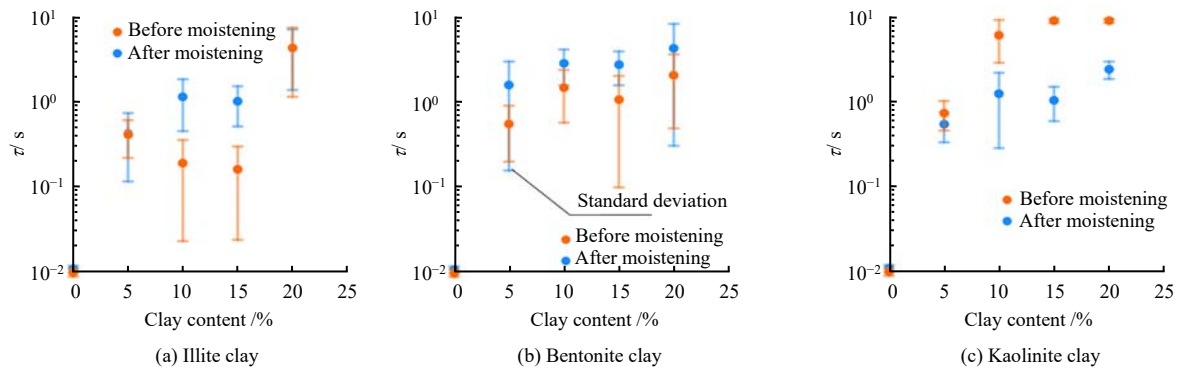


Fig. 8 Variations of characteristic time τ versus clay content

4 Discussion

Fluid saturation can radically change the sliding regime on a clay-bearing fault. Peculiarities of transformation of the sliding regime are essentially determined by the mineral content of the filler, as well as by the degree of moistening. The mechanism of seismogenic slip is usually considered in the context of the classical effect of rising pore pressure^[21-22], as well as lowering friction coefficient resulting from the inflow of fluid into the fault zone^[23]. At shallow depths, fluids can penetrate into the rock massif and trigger seismicity as a result of both anthropogenic processes (injection of water to the Earth interior or change of water level in a storage reservoir^[24]). It also can take place as a result of natural processes, for example, snow melting^[25] and after abundant rains^[26]. The endogenous sources of fluids can also play an important role, for example, magmatic and mantle fluids that can rise along faults or the intratelluric fluids that circulate in sediment and metamorphogenic interiors^[27]. Moreover, the water applies the stabilizing influence when it is either trapped within or between rocks of low permeability and can provide a high pore pressure when the rocks are deformed, or loosely bonded in a mineral structure, as in the hydrated clays, where it can produce a pseudo-pore pressure when the clay is compressed^[28].

Increasing humidity essentially affects the rheological

properties of clays. Friction coefficients of such materials as montmorillonite or lizardite decrease several times after saturation, as the strength of adsorbing materials after water-saturation decreases^[29]. However, a decrease in friction coefficient of itself does not necessarily result in a higher probability of triggering seismogenic slips. In fact, variations of frictional resistance to shear may play a more important role in the dynamics of sliding. It is known that a gouge rich in weak phyllosilicate minerals with a lamellate structure demonstrates a more stable sliding (continuous creep), than a mix of minerals with a grain structure, and the orientation direction of clay particles is an important indicator of fault activity^[34]. Such an effect was observed both on natural materials extracted from fault zones and on artificial compounds. The performed experiments have revealed essential differences in frictional behavior of clay-bearing model fault after moistening. For example, when the content of moistened illite clay in the filler is in the range of 5%-10%, fast dynamic slips occur, during which a large portion of the accumulated energy is released in the form of elastic vibrations.

These slips can be treated as “laboratory analogues of ordinary earthquakes” with high radiation efficiency^[29]. At the same time, the model fault demonstrates a stable creep when the filler contains 10% of moistened bentonite clay. However, it remains unclear what threshold content of phyllosilicate in the

gouge can provide stabilization of sliding at different P-T (Pressure-Temperature) conditions and shear rates. The performed experiments have shown that at low normal stresses the presence of 20% of any clay material is enough for full stabilization of fault sliding. Increasing the normal stress will apparently result in a higher threshold. For example, for a material consisting of calcite and shale, a stabilization of the dry contact occurs when the proportion of shale exceeds 30%-50%^[26].

The effect of gouge on the slip mode has already been observed in situ^[15, 30-31]. Essential differences in the parameters of micro-seismic events induced by ripple-fired explosions during mining were observed in two different rock massifs^[15, 30-31]. Compared were seismicities of an iron ore deposit “Korobkovskoe” (Belgorod district, Russia) and an apatite-nepheline deposit in the Khibiny (Murmansk district, Russia). At both deposits, large fault zones were detected. The enclosing massif of the “Korobkovskoe” deposit is a monolith composed of ferruginous quartzite. It actually has no signs of the process of differentiation of mineral aggregates. Principal slip zones (PSZ) in the core of the North-eastern fault are composed of gouge. The prevailing mineral is chlorite, which forms very thin aggregates (sizes of particles do not exceed 10 μm). Biotite is traced in the quantity up to one percent. It accretes with chlorite aggregates. The geomaterials that compose PSZs show velocity strengthening^[31]. The section under observation at the apatite-nepheline deposit in the Khibiny contains tectonic discontinuities in the form of egirin veins (a mineral showing high brittleness) and spreusteinization zones (zone of nepheline oxidation). The nepheline can be wrecked quite easily during weathering. It is substituted in fault zones by zeolites, water aluminosilicates of calcium and sodium, including formation of a noticeable amount of clayish minerals – beidellite, montmorillonite, bowlingite, smectite and potassium illites.

The seismicity under analysis was recorded just after ripple-fired explosions when mining activities were stopped. The obtained waveforms were used for location and estimation of source parameters. Seismic events at the “Korobkovskoe” deposit grouped mainly in the vicinity of the blasted chamber and along the fault zone. Magnitudes of detected events varied from -2.8 to -0.8 . Higher magnitudes of 0.74 – 2.50 were obtained at the apatite-nepheline deposit in the Khibiny massif. The reduced seismic energy, E_s / M_0 (E_s – seismic energy, M_0 – scalar seismic moment) and the average velocity of rupture propagation differ essentially for the seismic events registered at these two deposits. The calculated reduced energy for the Khibiny deposit varies from 5.4×10^{-7} J/(N·m) to 10^{-5}

J/(N·m), while the rupture velocity is $V_r = (0.36\text{--}0.80) C_\beta$ (the velocity of shear wave propagation in the massif), which corresponds to the range of “normal” earthquakes^[15]. Essentially lower reduced energies were obtained at the “Korobkovskoe” iron ore deposit: $E_s / M_0 = 5.3 \times 10^{-9}$ – 2.2×10^{-6} J/(N·m). The rupture velocity is $(0.008\text{--}0.500) C_\beta$. The mean value is $0.16 C_\beta$ for shear cracks and $0.09 C_\beta$ for tensile cracks. These values correspond to the so called “slow” earthquakes^[31].

Such a strong difference in reduced seismic energies and rupture velocities are caused by different material compositions of fracture fillers. As it has been already mentioned above, geomaterials that compose PSZs of “Korobkovskoe” deposit usually show velocity strengthening. But at the Khibiny deposit a number of identified seismic events (for which signs of coseismic ruptures were detected) happened along egirin veins, i.e., along discontinuities composed of a brittle material showing velocity weakening. It should be noted that the focus of one of the strongest earthquakes in the Khibiny massif (1989 year, magnitude 4.8 – 5) was a dynamic slip along a flat dipping egirin vein^[25].

According to the results of observations of many years, in the Khibiny massif, a seasonal growth in the number of earthquakes is observed during the snowmelt and precipitation (May – October) if compared to the period of low watering (November – April)^[25, 32–33]. Many authors ascribe this effect to a growing pore pressure, as meteor fluids penetrate inside the massif along highly permeable zones of nepheline oxidation^[32–33]. We believe that a more probable cause is that spreusteinization zones which contain a great amount of clayish minerals (smectite and bowlingite). Their friction coefficients decrease to anomalously low values under watering^[29].

Changing the mineralogy of clays composing the principal slip zone of a fault can lead to a transition from an aseismic deformation regime to a seismogenic one. It is assumed that the transformation of montmorillonite into illite under some specific conditions can promote emergence of areas of higher seismic activity^[35]. A calculated depth of such a transformation under the Barbados accretionary prism (7 – 18 km) coincides with the boundary between the seismic gap under the part of accretionary prism directed to the sea and the seismic zone under the trench in the front arc (10 – 12 km)^[35].

A majority of induced earthquakes occur in intraplate areas. Human-induced seismicity may occur, and even be large, in regions that have been historically aseismic^[1]. Fault reactivation can be initiated by fluid injection^[36], but slip behavior can be

aseismic^[37]. Seismic risk assessment is failed if there is no historical earthquake^[37]. For mining operation areas, the lack of seismic data can be filled with geological information, due to the linking between microseismicity, fault structure and rheological properties^[31].

The key mechanism that controls sliding of gouge-filled fault is the interaction of grains in the confined gouge layer^[39]–40]. The application of normal and shear stresses leads to the formation of force chains inside the filler. These chains are composed of grains that bear the main load while the surrounding grains remain rather unloaded. It is these force chains that determine frictional resistance of the model fault. This has been frequently observed, for example, in experiments with photo-elastic materials^[41]. When a fault is moistened, and its filler contains a clayish component, the sorption activity of the clay leads to an increase in the volume of the clayish viscoplastic component. As a result, the probability of emergence of strong intergrain contacts between hard quartz particles decreases, and thus the quantity and structuredness of force chains decrease too^[42]. Clay materials with the highest sorption activity and the highest ability to swell are the minerals of the smectite group – montmorillonite, beidellite and nontronite. Illite does not adsorb water and does not swell in it. Hence, stabilization in sliding of a fault composed of illite clays takes place when their proportion in the filler is higher, which fully agrees with the results obtained here (Fig.3). It is convenient to use the model of intergrain sliding to describe peculiarities in deformation of a fault containing clayish gouge. It allows to estimate the change in parameters that are varied in the model depending on the content of clay, its mineral type and moistening. After that, estimating the rheologic alterations under changing environmental factors is possible.

Peculiarities of mechanical processes that take place in a confined gouge layer can be described via the effective viscosity of the layer^[43]. As the content of clay in fault filler increases, a transition from the rheology of dry friction to the rheology of “viscous fluid” is observed. It seems reasonable to introduce an additional term to the canonic “rate and state” friction equation (the “viscous” resistance to shear) to better account for this transition in numerical simulations^[43]:

$$\tau_{\text{vis}} = \eta V_{\text{peak}} / \delta \quad (9)$$

where τ_{vis} is the shear resistance associated with dynamic viscosity; η is the effective viscosity; V_{peak} is the peak velocity in the dynamic slip; and δ is the thickness of the layer. It should be noted that the effective viscosity of a solid body is not a property of

its material, as, for example, in the case of a Newtonian fluid. This parameter is a characteristic of the rheology of the solid body that depends on the specific time of the deformation process, or to be more precise, on the deformation rate. Thus, seismic hazard assessment may be carried out using field observations enhanced by numerical simulation.

5 Conclusion

It is shown the transformation mechanism of sliding mode of clay-bearing faults with changes in the clay content and mineralogy, including in the dry and moistened state. Fast dynamic slip is typical for quartz sand and mixtures containing up to 10% illite, while the transition to stable creep occurs in gouge containing from 5% to 20% clay, and the transition threshold changes depending on the mineral composition. Despite minimal changes in the coefficient of friction during moistening the energy dissipated during slip varied significantly, reflecting fundamental changes in the rheological properties of gouge.

As the proportion of clay increased, the general rheological behavior of both dry and watering faults gradually changed from dry friction to a viscous one. The nature of this change strongly depended on mineralogy, that emphasize critical role of the mineral composition in determining fault stability and slip dynamics. Even with the same clay content, different clay minerals can either increase slip stability or contribute to dynamic weakening, which has significant implications for assessing seismic hazards. Understanding these rheological changes is important for improving predictive models of fault mechanics, especially in regions where watering variations affect fault behavior over time.

Declaration of competing interest

We, the collective of authors, declare that we have no known competing financial interests or personal connections that may affect the work presented in this article.

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