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EXPRESS LETTER

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Frictional properties of anorthite (feldspar): implications for the lower boundary of the seismogenic zone

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Abstract

Earthquake magnitude is closely related to the depth extent of the seismogenic zone, and higher magnitude earthquakes occur where the seismogenic zone is thicker. The frictional properties of the dominant mineral constituents of the crust, such as feldspar-group minerals, control the depth extent of the seismogenic zone. Here, the velocity dependence of the steady-state friction of anorthite, the calcic endmember of the feldspar mineral series, was measured at temperatures from 20 to 600 °C, pore pressures of 0 ("dry") and 50 MPa ("wet"), and an effective pressure of 150 MPa. The results support previous findings that the frictional properties of feldspar play a dominant role in limiting the depth extent of the seismogenic zone. This evidence suggests that brittle deformation of anorthite may be responsible for brittle fault movements in the brittle–plastic transition zone.

Keywords: Fault friction, Feldspar, Anorthite, Albite, Quartz

Introduction

The depth extent of the part of the crust in which earthquakes occur in a given region (the seismogenic zone) is closely related to the magnitude of the earthquakes that occur in that region. Areas with seismogenic zones with greater depth extents experience larger earthquakes. Knowing the depth extent of the seismogenic zone is therefore important for earthquake hazard planning to mitigate earthquake damage. The processes that cause earthquakes are controlled by the frictional properties of the subsurface rocks in which faults move (e.g., Scholz 1998, 2019). Many laboratory studies have analyzed the velocity dependence of the steady-state friction of gouge consisting, for example, of granite (Blanpied et al. 1991, 1995; Lockner et al. 1986), quartz (Chester and Higgs 1992), and feldspar (albite) (Masuda et al. 2019), at temperatures and pressures equivalent to those in the seismogenic zone. Blanpied et al. (1995) found that velocity weakening appeared in Westerly granite gouge between 100 and 300 °C under wet conditions. Velocity weakening has been observed in other materials as well in several experiments under wet conditions. To understand the physical mechanisms of deformation processes in the seismogenic zone, a simple deformation model that depends on the material properties of its component materials is useful for obtaining a first approximation of the large-scale seismic behavior of the zone. Chester and Higgs (1992) showed experimentally that the frictional behavior of ultrafine quartz gouge can be understood in terms of a change in the dominant mechanisms of slip. However, there is little published information on the frictional properties of the feldspar group of minerals, which are dominant minerals in the crust. As a result, neither the temperature (depth) dependence of frictional stability for feldspar minerals nor the lower limit of the seismogenic zone are well understood. Masuda et al. (2019) measured the frictional properties of two major mineral components of crustal rocks, quartz and albite (sodic

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feldspar), under pressure and temperature conditions characteristic of the depths at which earthquakes occur and showed that albite, rather than quartz, was dominant in limiting the depth extent or thickness of the seismogenic zone. Furthermore, seismological observations show a clear correspondence of the lower limit of the seismogenic zone with the 350 to 400 °C isotherm, and this temperature range corresponds better to the transition from brittle deformation to plastic behavior in feldspar than to that in quartz (Hasegawa and Yamamoto 1994).

Feldspars make up 50–60% of the total volume of the Earth's crust. The major feldspar-group minerals are albite ($NaAlSi_3O_8$), anorthite ($CaAl_2Si_2O_8$), and K-feldspar ($KAlSi_3O_8$), and anorthite–albite series (plagioclases) are the most abundant minerals in the Earth's crust. Masuda et al. (2019) measured the frictional properties of albite, but those of other plagioclase-series minerals have not yet been measured. In addition, recent investigations of the interface between seismic and aseismic zones have shown that lithological, mechanical, and frictional heterogeneities within the fault zone and the morphology and geometry of the interface significantly affect seismogenic processes (Barnes et al. 2020; Kirkpatrick et al. 2020). Thus, the material properties of the rocks distributed in the lower part of the seismogenic zone can be expected to critically affect seismogenic processes.

In this study, the frictional properties of anorthite, the calcic endmember of the anorthite–albite series, were examined under dry and wet conditions at temperatures from 20 to 600 °C. These results for the frictional behavior of anorthite support previous evidence that feldspar minerals largely determine the depth extent of the seismogenic zone. Moreover, they show that anorthite exhibits brittle behavior under the temperature and pressure conditions of the brittle–plastic transition zone.

Methods

Sliding experiments were conducted in a triaxial gas apparatus in which argon gas was used as the confining medium (Masuda et al. 2002, 2006). A layer of anorthite gouge about 1.0 mm thick was sandwiched between two saw-cut alumina cylinders (20 mm in diameter, 40 mm long) in the same configuration as that used by Takahashi et al. (2007, 2011) and Masuda et al. (2019). The anorthite gouge samples used in this study were collected from Miyakejima Island, Japan, and had an average grain size of 1 μm. To ensure that the same effective pressure was used under both dry and wet conditions, the frictional properties were measured under dry conditions at a confining pressure of 150 MPa, and under wet conditions at a confining pressure of 200 MPa and a pore-water pressure of 50 MPa. Temperature was controlled by the outputs from two thermocouples, one at the top and the other at the bottom of the sample (Table 1). The apparatus and experimental procedure are described in more detail in Masuda et al. (2019).

The dependence of friction on velocity was measured by changing the axial displacement rate of the loading piston from 0.5 to 5.0 μm/s after steady-state strengthening was reached. The displacement of the loading piston was measured by a linear variable differential transformer located outside the pressure vessel, and the force applied to the sample was measured by two load cells, one attached outside and the other inside the pressure vessel. To calculate the frictional properties of the samples, internal load cell data were used when they were available; in other cases, external load cell data were used after correction for the friction due to the O-ring used as the seal between the loading piston and the pressure vessel

Table 1 Experimental conditions and results of experiments on anorthite gouge (average grain size 1 μm)

Run ID	Dry/wet[a]	T (°C)	Coefficient of friction, μ	Error[b] μ	$a-b$	Error[b] $a-b$	Load cell[c] data used
FD020	Dry	20	0.6970	0.0034	0.00092	0.00012	I
FD200	Dry	200	0.6863	0.0011	0.00233	0.00006	O
FD375	Dry	375	0.6842	0.0004	0.00299	0.00003	I
FD500	Dry	500	0.6760	0.0021	− 0.00320	0.00009	O
FD600	Dry	600	0.6415	0.0115	− 0.00044	0.00066	I
FW200	Wet	200	0.7071	0.0012	− 0.00037	0.00016	O
FW400	Wet	400	0.7483	0.0019	− 0.01587	0.00022	O

[a] In the dry experiments, Ar gas was used to apply a confining pressure of 150 MPa; in the wet experiments, a confining pressure of 200 MPa was applied, and the pore-water pressure was 50 MPa

[b] Errors on μ before the step change in sliding velocity and on ($a-b$) are reported as the curve-fitting error

[c] Differential stress in the gouge layer was measured by the internal load cell (I), but if no internal load cell data were available, corrected external load cell data (O) were used. See Masuda et al. (2019) for details

(Noda and Takahashi 2016). The friction coefficient μ is defined as the ratio of shear stress τ to normal stress σ_n on the sliding surface (Eq. 1), and the velocity dependence of steady-state friction $(a-b)$ is defined as the ratio of the change in steady-state friction μ_{ss} to the change of slip velocity V (Eq. 2):

$$\mu = \frac{\tau}{\sigma_n} = \frac{\sigma_{\mathrm{diff}}\sin(2\theta)}{2\left(\sigma_{\mathrm{diff}}\sin^2(\theta) + P_c\right)}, \tag{1}$$

$$a - b = \frac{\partial \mu_{ss}}{\partial[\ln V]}, \tag{2}$$

where σ_{diff} is the differential stress in the loading direction, θ is the angle between the sliding surface and the loading direction (30° in this study), and P_c is the effective confining pressure (150 MPa). The velocity dependence of steady-state friction $(a-b)$ is thus estimated as the difference between the parallel trends of steady-state friction before and after the velocity changes. In those cases in which the samples showed stick–slip behavior, the trend of the frictional curve was determined as the slope estimated by using the lowest points in each stick–slip cycle. Laboratory studies have shown that the mechanism of earthquake nucleation is controlled by the frictional properties of materials (e.g., Scholz 1998; Marone 1998). Because the focus of this study was on the potential of crustal materials for earthquake nucleation at the very beginning of fault movement, whether the frictional properties of the materials were seismic or aseismic was evaluated based on whether the parameter $(a-b)$ was positive or negative. If $(a-b)>0$, the material is considered velocity strengthening and is stable, corresponding to aseismic conditions. If $(a-b)<0$, the material is considered velocity weakening and is unstable, corresponding to conditions in a seismogenic zone (Scholz 1998, 2019).

Results

Examination of the friction coefficient μ as a function of the displacement of the loading piston (Fig. 1) showed that with a displacement rate of 0.5 µm/s, steady-state strengthening occurred when displacement was around 2 mm and $\mu = 0.64$–0.75 (average 0.69; Table 1). To measure the velocity dependence of friction, when the displacement was around 2 mm, the displacement rate was abruptly increased from 0.5 to 5.0 µm/s (fast step) (Dieterich 1979, 1981, 2009; Scholz 1998), and in some runs, the sliding velocity was changed from 5.0 to 0.5 µm/s (slow step) after the fast step. $(a-b)$ was calculated from the portion of the curve before and after the fast step (Fig. 2 and Table 1). Under dry conditions at temperatures up to 400 °C, $(a-b)$ of anorthite was positive, whereas at 500 and 600 °C, $(a-b)$ was negative. Thus, in the dry state, anorthite was unstable at higher temperatures (Fig. 2a). Under wet conditions at 200 °C, $(a-b)$ was negative (Fig. 2b), and the friction versus displacement curve showed stick–slip behavior both before and after the velocity step. $(a-b)$ was also negative at 400 °C, but the curve showed stick–slip behavior only after the velocity step (Fig. 1c). In contrast, Masuda et al. (2019) did not observe stick–slip behavior in their experiments with albite samples.

Discussion

Masuda et al. (2019) conducted laboratory experiments with quartz and albite and reported that feldspar plays a more dominant role than quartz in limiting the depth extent (thickness) of the seismogenic zone, but the frictional behaviors of other minerals in the lower seismogenic zone still need to be characterized. Frictional behavior depends in part on environmental conditions, including temperature and the presence of water (Blanpied et al. 1995; Scholz 1998), and the heterogeneity of fault materials (Barnes et al. 2020) or surface morphology (Kirkpatrick et al. 2020) at the interface between seismic and aseismic zones also affects seismogenic processes. Therefore, it is important to know the physical properties, especially the frictional properties, of materials in the transition zone around this interface to better understand seismogenic mechanisms. Recent advances in seismological observation and analysis techniques have allowed seismic velocity and density distributions to be determined in detail, but information on the physical properties of materials in high-seismicity regions is still lacking. Only laboratory measurements can provide basic physical information about materials, such as their frictional stability.

Effect of water on the frictional characteristics of materials

The velocity dependence of friction $(a-b)$ of quartz and feldspar, the two main components of the Earth's crust, is mostly positive under dry conditions at temperatures corresponding to those in fault zones (Masuda et al. 2019; Fig. 2a). Under wet conditions, however, $(a-b)$ is negative at temperatures of 200–400 °C. These results are similar to those observed in experiments using granite gouge, a main component of crustal rocks (Lockner et al. 1986; Blanpied et al. 1995). These experimental findings suggest that seismic behavior is induced in the deep crust in the presence of water. Various studies have shown that the mechanism by which water affects frictional behavior in the deep crust is solution–precipitation-aided cataclastic flow (e.g., Blanpied et al. 1995; Masuda et al. 2019). Here, scanning electron microscope images of anorthite gouge samples after the experiments showed

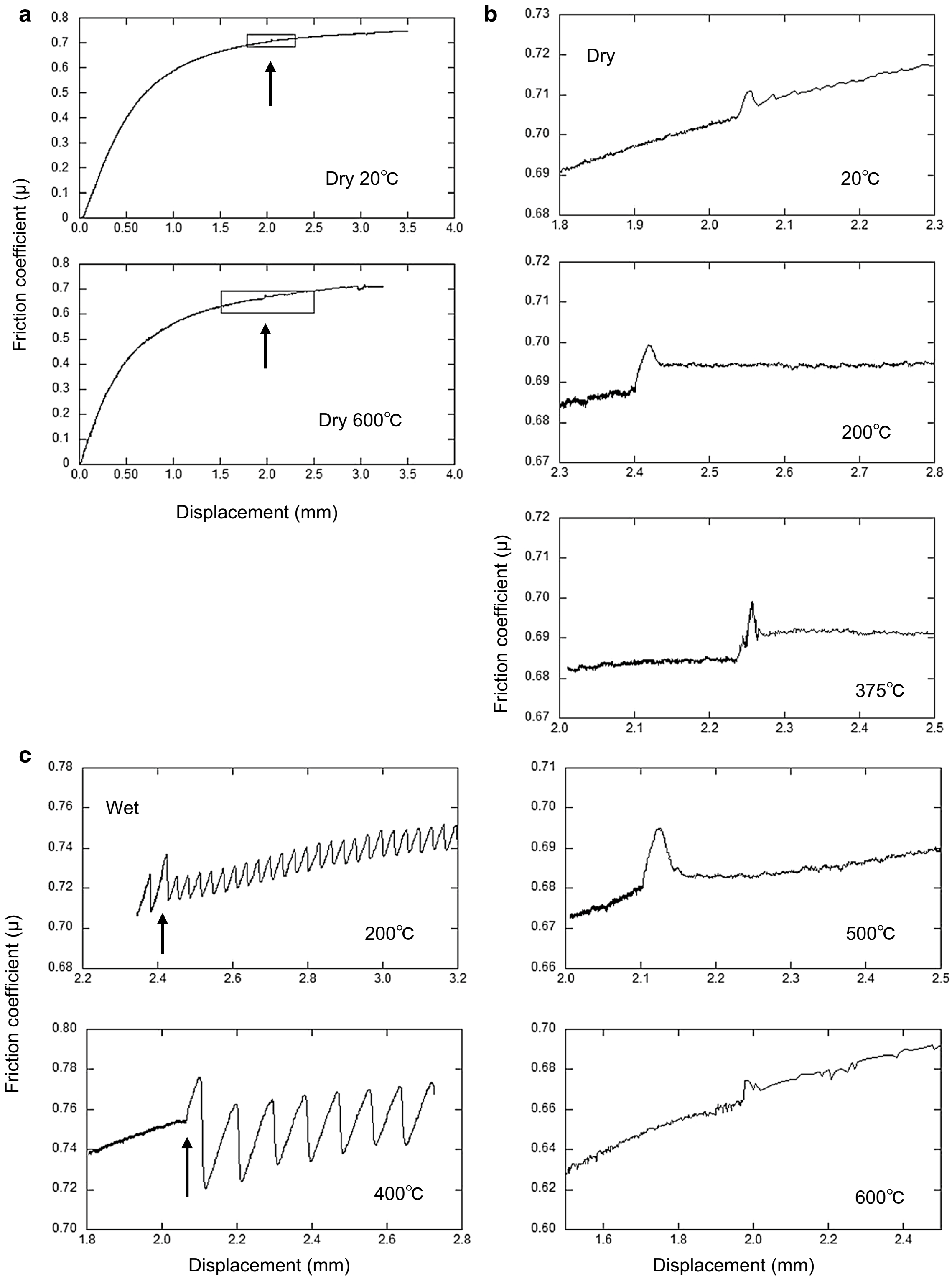

Fig. 1 Friction curves obtained in the experiments on anorthite. The friction coefficient μ, as defined in Eq. (1), is plotted as a function of the displacement of the loading piston. **a** Dry samples at 20 and 600 °C. The boxes show the portions of the curves enlarged in **b**. The part of the friction curve around the velocity steps: **b** dry samples at 20, 200, 375, 500, and 600 °C; **c** wet samples at 200 and 400 °C. The arrows in **a** and **c** indicate the timing of the fast step in sliding velocity

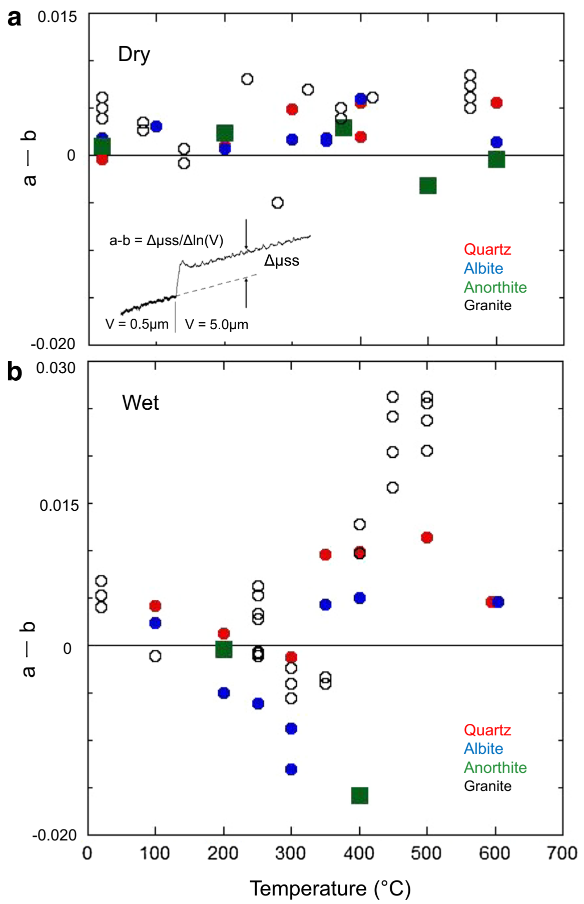

Fig. 2 Velocity dependence of steady-state friction ($a-b$) for anorthite, albite, and quartz, as determined by Eq. (2). **a** Dry conditions, $P_c = 150$ MPa (Ar gas); **b** wet conditions, $P_c = 200$ MPa (Ar gas), P_p (pore-water pressure) = 50 MPa (distilled water). The data for quartz and albite are from Masuda et al. (2019). The granite data for dry and wet conditions are from Lockner et al. (1986) and Blanpied et al. (1991), respectively. The velocity dependence of steady-state friction ($a-b$), as determined from Eq. (2), is represented by the difference between the parallel steady-state trend lines immediately before and after velocity step changes (inset diagram in **a**)

rounded grains only after the experiments conducted under wet conditions (Additional file 1). This result suggests that pressure solution occurred in the experiments under wet conditions.

Compared with quartz, plagioclase feldspars (albite and anorthite) have negative ($a-b$) values over a wider temperature range. This result suggests that under wet conditions, the frictional characteristics of feldspar minerals play an important role in limiting the depth extent of the seismogenic zone. The results of our anorthite experiments (Fig. 2) support the results of the albite experiments conducted by Masuda et al. (2019). Moreover, unlike albite, anorthite showed stick–slip behavior under wet conditions at temperatures of 200 and 400 °C. In geologic materials, stick–slip behavior is associated with brittle deformation such as slip on a fault (e.g., Brace and Byerlee 1966). This observed brittle behavior thus suggests that the frictional characteristics of anorthite can account for fault movements in the brittle–plastic transition region.

Lower boundary of the seismogenic zone

Mechanically weak heterogeneities at the base of the seismogenic zone would localize deformation in the brittle–plastic transition region and cause brittle faulting. The physical properties of anorthite support this concept. The stick–slip behavior observed in anorthite ($CaAl_2Si_2O_8$) was not observed in albite ($NaAlSi_3O_8$) (Masuda et al. 2019). Under ambient conditions, the feldspar mineral structure is based on TO_4 tetrahedra (where $T = Si^{4+}$ or Al^{3+}), within which low-charge cations (Na^+ or Ca^+) occupy large voids. Commonly, feldspars are thermodynamically stable at pressures up to 3 GPa. Because TO_4 tetrahedra show very little compression, they behave as a relatively rigid unit (e.g., Pakhomova et al. 2020). This rigidity may be one reason that feldspar is associated with brittle sliding even at high temperatures. In addition, because Ca^+ is heavier than Na^+, anorthite, the calcic endmember of the series, may be more rigid and therefore exhibit more brittle behavior (such as stick–slip behavior) than albite. In field observations of an exhumed fault zone exposed along the Hatagawa Fault Zone, northeast Japan, many localized brittle deformation zones, including highly fractured crush zones, are observed. In these zones, numerous fractures may have nucleated by fracturing of highly deformed fine-grained feldspar (Shigematsu et al. 2009).

In this study, we investigated anorthite, one mineral component of the Earth's crust. However, measurements of many component minerals and composite materials under a wide variety of possible conditions, as well as laboratory measurements of materials obtained by deep drilling projects (e.g., Kirkpatrick et al. 2020), are needed to construct a reliable conceptual model of seismic processes in the brittle–plastic transition zone at the depth limit of the seismogenic zone.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40623-020-01271-6.

Additional file 1. SEM images of anorthite samples. Images obtained after loading of 0.5 μm/s was stopped without a velocity step under **a** wet and **b** dry conditions at 600 °C. Under wet conditions, the rounded anorthite grains, the absence of internal fracturing of the grains and grain micronizing suggest that pressure solution occurred.

Additional file 2. Experimental data for friction curves. Each sheet corresponds to a friction ($\mu = \tau/\sigma_n$) vs displacement (Disp) curve in Fig. 1, where FD020 is dry, 20 °C; FD200, is dry, 200 °C; FW400 is wet, 400 °C; and so on. Friction was calculated by Eq. (1). Data from the internal load cell were used at temperatures of 20, 375, and 600 °C under dry conditions, as indicated in Table 1. Noise from the power supply for the internal heaters overlapped the data signal from the internal load cell at temperatures of 375 and 600 °C.

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Author's contributions

KM designed the study, conducted the experiments, analyzed the data, and prepared the manuscript. The author read and approved the final manuscript.

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Availability of data and materials

Tables of the data used to plot the friction curves in Fig. 1 are available as Additional file 2.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declares that he has no competing interests.

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