Chemically induced formation of pull-apart structure of Cr-spinel

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Cr-spinel is known as the most rigid mineral among constituents of mantle peridotite. However, it is often seen that it forms pull-apart structures in deformed peridotite as a result of brittle fracturing. Understanding of mechanical conditions for fracturing of Cr-spinel could give a clue for stress estimation. Therefore, comprehensive study on the cause of fractures in Cr-spinel is important. In this study, we performed petrological and microstructural analyses of Cr-spinel and host deformed dunite in Higashi-akaishi ultramafic body in Sanbagawa metamorphic belt. The occurrence can be related to physical and chemical conditions in subduction zones.

Characteristic microstructures of Cr-spinel are developed as a function of an increasing amount of antigorite in the host dunite in the following order: chemical modification from rim to core, pull-apart structures, polycrystalline textures and, finally, disseminated clusters of micro-grains. The microstructural evolution of Cr-spinel implies that there are some chemical effects on the fracturing. The chemical modification of Cr-spinel shows a systematic trend characterized by an increase of Cr# (atomic ratio of Cr / (Al + Cr)) and a subsequent increase of Fe towards end member of magnetite. Extents of chemical modification along cracks are lower than those along rims, indicating that tensile cracks are formed after commencement of chemical modification along rims. The critical mineral chemistry for fractures is defined as $Al / (Cr + Al + Fe^{3+}) < 0.15$. EBSD analyses revealed that sub-grains are dominantly formed in the altered rims and also that tensile cracks are propagated from sub-grain boundaries. Recrystallized micro-grains contain minor sub-grain boundaries and show random orientations, suggesting that they are neoblasts formed by nucleation and growth. The formation of neoblasts is concomitant with Fe-rich parts of Cr-spinel.

The above observations indicate that dislocation-controlled recrystallization depends on chemical compositions of Cr-spinel. Climb velocity of dislocation depends on a self-diffusion coefficient of the slowest diffusing species and self-diffusion coefficient of the slowest Cr in Cr-spinel increases with increasing Cr#. Therefore, it is interpreted that the chemical modification characterized by the increase of Cr# enhanced dislocation motions resulting in the localized sub-grain formation to the chemically modified domains.

We estimated fracture stress (i.e. fracture toughness) of Cr-spinel using a fracture model for a cylinder with a peripheral crack, assuming the widths of chemically modified domains as the potential depths of sub-grain boundaries that act as preexisting cracks. Strength of Cr-spinel is variable depending on mineral chemistry and width of crack and the estimated values for two samples are 84 and 243 MPa. On the other hand, differential stress estimated from dislocation density of olivine is lower than these values. The discrepancy can be explained by concentration of stress due to difference of elastic coefficients of Cr-spinel and surrounding olivine. To support this idea, the maximum intragranular tensile stress in Cr-spinel based on fiber-loading theory is higher than the fracture stress from a cylinder model.

The microstructural analyses reveal that compositional change of Cr-spinel under hydration reactions enhances its plastic deformation to develop weak planar defects such as sub-grain boundaries and grain

boundaries. Fracturing of Cr-spinel can be explained by the chemically induced defects and stress concentration due to the high elastic constant of spinel. It does not require an extremely large stress although the critical strength is variable depending on the Cr# of spinel.

In situ deformation experiments of coesite

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Since continental crust is chemically rich in SiO_2 and contains a large amount of radioisotope compared with bulk upper mantle, flux of subducting continental crust could affect terrestrial thermal history and chemical evolution. This flux is largely determined by viscosity of continental crust. Based on deformation experiments of quartz, Gleason and Tullis (1995) suggested that behavior of continental crust is controlled by frictional sliding and plastic deformation of quartz up to 90 km depth. Coesite is a stable SiO_2 mineral under P-T conditions from 90 to 270 km depth and expected to play a major role in the mechanical behavior of continental crust at this depth. However only one experimental study on viscosity of coesite has been reported (Renner et al., 2001), and pressure condition in the previous study is limited to 4 GPa (120 km depth) because of the limitation of the Griggs type apparatus.

To study rheology of coesite at higher pressures, in situ uni-axial deformation experiments of coesite was conducted using deformation-DIA apparatus "D-CAP" at the synchrotron beamline NE7A, Photon Factory Advanced Ring (PF-AR), National Laboratory for High Energy Accelerator Research Institute (KEK). Water content and microstructure of starting material and deformed sample were determined by Fourier-transform infrared spectrometer (FTIR) and field-emission scanning electron microscope (FE-SEM), respectively. Two types of starting materials were employed. One is polycrystalline quartz with 20 μm grain size and 460 wt ppm H_2O, the other is polycrystalline coesite 10 μm grain size and 10 wt ppm H_2O. A 7 mm cubic (Mg,-Co)O pressure medium was pressurized by WC and cBN anvils with truncated edge length (TEL) of 5 mm. High temperature was generated by a ϕ3.0/2.5 mm graphite heater and temperature was measured using a WRe thermocouples. To remove the initial stress, annealing was performed for an hour at high pressure (quartz was transformed to coesite at this stage) and then uni-axial deformation was done at constant strain rate. Monochromatic X-ray with 50 keV was used for the in situ observation of sample. Radiograph image was taken by YAG phosphor and CCD camera. Two-dimensional diffraction pattern by incident X-ray with dimension of 0.2 ×0.2 mm^2 was obtained using an imaging plate with exposure time of 3-6 min. Strain was determined from sample length on the radiographic image. Differential stress was calculated using equation by Singh et al. (1998) and shear modulus reported by Chen et al. (2015). Pressure was calculated from thermoelastic parameters reported by Angel et al. (2001) and; Galkin et al. (1987). Deformation conditions were temperature of 800 - 1100 ℃, pressure of 3 - 4 GPa, strain rate of 6.7×10^{-6} - 1.1×10^{-4} s^{-1}. Since, unfortunately, experiments at high pressures were unsuccessful, pressure condition was similar to that in Renner et al. (2001).

Steady state stress was determined for each deformation. Viscosity of coesite in this study shows good agreement with that reported by Renner et al. (2001) except for data at 800℃. The results fitted by constitutive equation, and stress exponent n and activation enthalpy H* were determined to be 2.9±0.5 and 99.5±27.7 kJ/mol, respectively. Renner et al. (2001) reported n and H* of 2.9±0.5 and 261±45 kJ/mol, respectively. The disagreement of these values may be partly due to large errors of the measured stress in both studies.
Ichikawa et al. (2013) reported that 2.2 km^3 /yr of continental crust material can be subducted to 270 km depth based on the numerical simulation using the flow law parameters of Renner et al. (2001). If flow law parameters determined in this study is used, the flux of continental materials would be less because the

smaller n value causes lower viscosity of coesite under natural strain rate of 10^{-12} - 10^{-15} s^{-1}.

Keywords: coesite, in situ, dislocation creep, continental crust

Mechanical properties of ice-silica mixtures: Fracture toughness and elastic moduli

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Ductile-to-brittle (D/B) transition is a key rheological property to determine the tectonic style (flow features and fracture patterns) on the surfaces of icy bodies in the solar system such as Earth, Mars and icy satellites and it has been studied by numerical models, laboratory experiments, and field observations. The theoretical model of D/B transition indicates that the transitional strain rate is controlled by some factors; for example, a power law relationship between stress and strain rate in a ductile behavior, $d\varepsilon/dt = B\sigma^n$ ($d\varepsilon/dt$ is the strain rate and σ is the stress), fracture toughness, and coefficient of friction [Schulson, 1990; Renshaw and Schulson, 2001]. Particularly, fracture toughness is one of the most important factor to determine the critical strain rate corresponding to the D/B transition. The fracture toughness of water ice has been studied by laboratory experiments and depends on temperature, porosity, ice grain size, etc. For example, the K_{Ic} of non-porous fresh water ice is about 100 kPa m$^{1/2}$ at -10° C [e.g., Nixon and Schulson, 1987]. The tectonic features found on Mars and icy satellites has a rocky component with various contents in water ice. Thus, the fracture toughness of ice-rock mixtures is important to determine the tectonic style on icy bodies but it remains unclear. In this study, we measured the fracture toughness of ice-rock mixtures and examined the effect of rock content on fracture toughness. Furthermore, we also measured elastic moduli, Young's modulus and Poisson's ratio, which are closely related to fracture toughness.

The samples were prepared by mixing ice seeds with a diameter smaller than 850 μm, amorphous silica beads with a diameter of 0.25 μm, and distilled water at 0° C to fill spaces among the ice seeds and/or silica beads. The samples which had a cylindrical shape with a diameter of 30 mm and a height of 60 mm were frozen in a cold room at -10° C for more than one day. The specimens for the measurements of fracture toughness were shaped by cutting original cylindrical sample to a rectangular parallelepiped shape and the notch was made by cutting at the center of basal surface. We made samples with silica volume fraction, f, of 0, 0.06, 0.12, 0.18 and 0.34. Fracture toughness was measured using the method of three-point bending in a cold room at -10° C at Ice Research Laboratory, Dartmouth College. The elastic moduli were determined by measuring the ultrasonic velocity of both longitudinal and shear waves. After the measurements, the microstructure of recovered specimens were observed using a cryo-SEM.

The fracture toughness, K_{Ic}, for pure ice was 99.8 ±18.5 kPa m$^{1/2}$, close to those of fresh-water ice obtained in previous studies at -10° C [e.g., Nixon & Schulson, 1987]. The values of K_{Ic} for each ice-silica mixture varied more than that of pure ice yet the fracture toughness increased with increasing silica volume fraction and scaled as the square root of silica volume fraction; i.e., $K_{Ic} \propto f^{0.5}$. Young's modulus, Y, increased linearly with increasing silica volume fraction over the range of silica volume fraction explored in this study. On the other hand, Poisson's ratio, ν, of pure ice and ice-silica mixtures were almost the same, irrespective of silica volume fraction. The average value was 0.33, consistent with that of polycrystalline granular ice at -5° C [Schulson and Duval, 2009]. Fracture toughness is related to Young's modulus and Poisson's ratio as $K_{Ic}=\sqrt{G_c(Y/1-\nu^2)}$, where G_c is the critical value of the crack-extension force. In our experiments, we found that the increase in fracture toughness with silica volume fraction primarily resulted from the linear increase in Young's modulus with silica volume fraction given assuming the crack-extension force G_c was independent of silica volume fraction over the range of silica volume

fraction explored in this study.

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Keywords: fracture toughness, Young's modulus, Poisson's ratio, ice-silica mixtures, silica volume fraction

Experimental study on the flow law of water ice with porosity higher than 50%

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Small to middle-sized icy satellites in the solar system (diameter < several hundreds of km) are mainly composed of water ice and rocky debris and they have porosity over a wide range. On these satellites, various landforms caused by tectonic activities are found; for example, impact craters on icy satellites has a shallow depth, compared with those on rocky bodies such as the Moon. The shallow depth is expected to be caused by the difference of viscosity and deformation strength, that is the strength of water ice is smaller than that of rock. Thus, to understand the tectonic activities on small to middle-sized ice satellites, it is necessary to understand the deformation strength of ice-rock mixtures over a wide range of porosity. Flow law is one of the most important rheological properties to understand the formation processes of flow features found on icy bodies. Furthermore. a deformation strength is characterized by a flow law. Yasui and Arakawa (2010) examined the flow law of ice-silica mixtures with silica mass content of 0-50 wt.% and porosity of 0-20% and they reconstructed the flow law by introducing the factors of silica mass content and porosity. In this study, we focused on the effect of porosity over a range of porosity higher than that explored by Yasui and Arakawa (2010). We carried out creep tests of water ice with a porosity higher than 50% and examined the effect of porosity on the flow law of water ice.
The samples were made of ice grains with an average diameter of 20 μm: they were put in a stainless mold of inside diameter 25 mm and then compressed by a piston to control the porosity of 50, 60, and 65%. We performed creep tests under constant stress from 6.6 to 59 kPa in a temperature-controlled box or a cold room at Kobe University. The temperature was set to be -20 or -10° C.
In the case of water ice without porosity, the constant strain rate showing beyond a strain of 2% on the creep curve (a relationship between strain and time) was applied to the flow law. However, in the case of our porous water ice, the strain rate continued to decrease with increasing the time even beyond a strain of 2%. This was caused by the compaction during creep test: for example, the porosity of our porous water ice measured before and after the test was changed from ~50 to ~45% at the temperature of -10° C. Therefore, we examined the strain rate in increments of a strain of 0.02 over a range of strain from 0.02 to 0.16 on the creep curve to examine the flow law. As a result, the slope of the fitting line on the relationship between strain rate and stress increased with the increase of strain. In this study, we applied the strain rate at a strain of 0.14 on the creep curve to the flow law to examine the effects of porosity and temperature.
The flow law could be expressed as $d\varepsilon/dt=B\sigma^n$, where $d\varepsilon/dt$ is strain rate, σ is stress and B and n are constants. At same temperature, the strain rate increased with the increase of porosity, that is, the constant B exponentially increased with an increase in porosity: for example, the B of the porosity of 50%, 5.3×10^{-11} $s^{-1}(Pa)^{-n}$, was two orders of magnitude smaller than that of 65%, 1.4×10^{-9} $s^{-1}(Pa)^{-n}$. However, the slope of the fitting line became almost constant, irrespective of porosity. This means that the stress exponent n became almost constant, ~0.9, and it was about 1/3 as small as that of water ice without porosity (n~3). In the case of same porosity, the strain rate increased as the temperature became higher while the stress exponent n became almost constant, irrespective of temperature. The B could be expressed by using the activation energy Q as $B=B_0\exp(-Q/RT)$, where T is temperature, R is gas constant and B_0 is constant. The activation energy Q of our porous water ice was about 60 kJ/mol, irrespective of porosity, and it was a little smaller than that of water ice without porosity, 80 kJ/mol (Barnes *et al.*, 1971).

Keywords: flow law, water ice, porosity, creep tests, activation energy, small to middle-sized icy satellites

Effect of pyroxene on the rheological weakening of olivine + orthopyroxene due to phase mixing

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To understand the processes involved in rheological weakening due to phase mixing, we conducted torsion experiments on samples composed of iron-rich olivine + and orthopyroxene. Samples with volume fractions of pyroxene of f_{px} = 0.1, 0.3, and 0.4 were deformed in torsion at a temperature of 1200°C and a confining pressure of 300 MPa using a gas-medium apparatus.
The value of the stress exponent, *n*, decreases with increasing strain, γ, with the rate of decrease depending on f_{px}. In samples with larger amounts of pyroxene, f_{px} = 0.3 and 0.4, *n* the stress exponent decreases from *n* = 3.5 at lower strains of $1 \leq \gamma \leq 3$ to *n* = 1.7 at higher strains of $24 \leq \gamma \leq 25$. In contrast, for the samples with f_{px} = 0.1, the stress exponent decreases from *n* = 3.5 at lower strain decreases only to only *n* = 3.0 at higher strains. In samples with larger f_{px}, the value of *p* grain size exponent changes from *p* = 1 at lower strains to *p* = 3 at higher strains. Furthermore, Hansen *et al*. (2012) observed that *n* = 4.l and *p* = 0.7 in samples without pyroxene (f_{px} = 0) regardless of strain. For samples with larger f_{px}, these values of *n* and *p* indicate that the deformation mechanism changes with strain, whereas for samples with smaller f_{px} no change in mechanism occurs.
The microstructures in our samples with larger amounts of pyroxene provide insight into the change in deformation mechanism identified from the experimental results. First, elongated olivine and pyroxene grains align sub-parallel to the shear direction with a strong crystallographic preferred orientation (CPO) in samples deformed to lower strains for which *n* = 3.5. Second, mixtures of small, rounded grains of both phases, with a nearly random CPO develop in samples deformed to higher strains that exhibited a smaller stress exponent and strain weakening. The microstructural development forming well-mixed, fine-grained olivine-pyroxene aggregates can be explained by the diffusivity difference between Si, Me (= Fe or Mg), and O, such that transport of MeO is significantly faster than that of SiO_2. These mechanical and associated microstructural properties provide important constraints for understanding rheological weakening and strain localization in upper mantle rocks.

Keywords: rheological weakening, phase mixing

Quartz microstructures and paleostress estimates in the Sanbagawa metamorphic belt, Central Shikoku, Japan

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The paleostress estimates for the ductile region of the Earth’ s crust largely depends on grain size piezometers of quartz. However, it has long been debated whether extrapolation of experimentally determined piezometric relationships to natural conditions is appropriate. Dynamic recrystallization theories predict temperature-dependent relationships between stress and grain size of quartz, but no systematic works have been made to apply the theories to naturally deformed rocks. We measured grain size of quartz in the Sanbagawa metamorphic belt, using electron back-scattered diffraction (EBSD) mapping, and applied a theory-based piezometric relationship. The samples were taken from the Asemi River route, Shikoku Island, Japan. The metamorphic grades increase northward from the chlorite zone through the garnet zone to the biotite zone and then decrease to the garnet zone. Sampling localities cover all these four zones. Except for the sample taken from the lowest metamorphic grade part of the chlorite zone, quartz shows undulatory extinction, subgrain boundaries, and crystallographic preferred orientations. Small quartz grains occur at the rims of coarse grains and sparsely inside the coarse grains. All the obtained grain size distributions were severely right skewed. The mean and the mode values were not well defined in both linear and logarithmic frequency diagrams because these values vary with the cutoff size. Instead, the grain sizes that occupy the largest area fractions were used for the ‘average’ grain size. The grain size of the largest area fraction ranged between ~20 and ~160 microns. Dynamic recrystallization of quartz is likely concurrent with the peak metamorphism, because grain size increases with increasing metamorphic grades. In addition, quartz fabrics show the top-to-west sense of shear in the south, whereas they indicate mainly top-to-east in the north. Previous geothermometric studies using Raman spectra of carbonaceous materials or the disappearance of pumpellyite yielded peak metamorphic temperatures ranging from ~330 to ~570 °C. The obtained stresses increase with decreasing metamorphic grades and reach ~100 or ~250 MPa at their maximum under the assumptions of intracrystalline or marginal nucleation models, respectively. The stress estimates with the marginal nucleation model are similar to or slightly lower than stress values calculated from a quartz flow law under assumptions of the possible plate convergence rate, temperature profile, and ranges of the crustal thicknesses of the subduction zone at the timing of the metamorphism.

Keywords: subduction zone, stress, quartz deformation

Monitoring of elastic wave velocity on the cracked granite during shear deformation

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[Introduction] Changes in elastic wave velocity have a possibility to illuminate physical processes during earthquake rock failure. As elastic wave velocity was affected by propagation and closing of cracks, laboratory study for triaxial compression tests showed increasing elastic wave velocities due to dilation and compaction with increasing confining pressure (Scholz et al. 1973). Seismic observation also showed variations in elastic wave velocity. Li et al. (1998) found that fault-zone p- and s- wave velocities increased with time after 1992 Landers earthquake. To find systematic variations in elastic wave velocity may approach a prediction of failure mode in seismic cycle. In this study, we focus on the detecting of systematic variation in elastic wave under friction experiments, and monitor the change in elastic wave velocity during shear deformation.

[Experimental methods] We conducted monitoring of elastic wave velocity during friction experiments using by biaxial friction machine. Two sliding surface were made by two side blocks placed together to produce a double-direct shear configuration. Normal stress was applied via a hydraulic ram on the side blocks with 5, 10, 20 MPa, and then shear stress was applied by advancing central block downward at constant velocity. Samples we used as simulated host rock were Aji granite. These were thermally cracked with baking at 600 C for 4 hours, because the host rocks along fault zone were expected to have amount of cracks produced by seismogenic faulting movement. In observation of elastic wave velocity, we adopted pulse transmission method using electric transducer directly attached on sample with a direction normal to simulated slide surface sandwiched between these. Elastic wave velocity, amplitude and wave period from waveforms were recorded by oscilloscope.

[Results&Discussion] Observed elastic wave velocity passing through Aji granite samples have a tendency to increase with increasing normal stress due to closure of pre-existing cracks with an orthogonal plane to normal stress. Response in elastic wave velocity given by shear stress showed systematic change similar to that of normal stress, increasing elastic wave velocity with increasing shear stress. This change in elastic wave velocity can be mainly explained by closure of pre-existing cracks with an orthogonal plane to shear stress. The change cannot be observed in phases that shear stress reached at steady-state friction. We also observed change in amplitude during experiments from waveform recorded by oscilloscope. Amplitude increases with increasing normal and shear stress, however amplitude showed almost constant value in phases that shear stress reached at steady-state friction, similar to that of elastic wave velocity. Our results showed that changes in elastic wave velocity and amplitude have a systematical dependence on stress state. As a stress is expected to accumulate in inter-seismic phase in seismic cycle, monitoring a temporal variation in elastic wave velocity and amplitude along fault zone has a one of possibility to understand process of earthquake failure.

Keywords: elastic wave velocity, friction experiment, cracked granite, earthquake hazard assessment

Fractal Size Reduction and Critical Slip Displacement during Fault Slip

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1. Introduction
To evaluate an occurrence of unstable slip, a systematic understanding of frictional instability is necessary. Critical slip displacement has been used to evaluate frictional instability of faults. The critical slip displacement is defined as the slip over which strength breaks down during fault slip or the slip distance, at a constant velocity, through which a population of contacts is destroyed and replaced by an uncorrelated set [Marone and Kilgore, 1994; Scholz, 2002]. Although previous studies have proposed various relationships between critical slip displacement and other factors [e.g., Sammis and Biegel, 1989; Marone and Cox, 1994], it is still open to debate that which factors dictate the critical slip displacement. In this study, we aim to theoretically clarify a factor that determines the critical slip displacement. Additionally, as fractured areas have a self-similar structure, we utilize fractal theory for understanding of the critical slip displacement. Through this study, it is clarified that comminution characterized by the fractal size reduction determines the critical slip displacement.

2. Fractal dimensions with comminution processes
A fractal dimension of surface roughness changes with comminution processes of materials: It takes on the values 3.0, 2.5, and 2.0 from high-velocity impact experiments, conventional milling, and finer grinding, respectively [Hukki, 1962; Rumpf, 1973; Nagahama, 1991, 1993; Muto et al., 2015]. Let us consider the underlying cause of changing in the fractal dimension of surface roughness. When rocks receive external force, a portion of work done externally is used for energy dissipation for fracturing. The energy per unit mass for fracturing is in proportion to the exponential function of a characteristic linear dimension with the fractal dimension of surface roughness as an exponent. Consequently, comminution processes influence the fractal dimension of surface roughness as well as dissipative energy for fracturing.

3. Relationship between critical slip displacement and shear strain
Shear strain for crushing gouge is defined as a ratio of a function related to particle size to shear stress [Draper, 1976]. The function can be approximately expressed as the maximum grain diameters after shearing with the fractal dimension as an exponent. The critical slip displacement is approximately proportional to the final maximum grain size [Dieterich, 1981]. Therefore, the relationship between the critical slip displacement and shear strain can be described as a linear function on a log-log plot. The slope of this function is related to the fractal dimension of the surface roughness. This relationship obtained from theoretical analysis is consistent with previous experimental datasets [Marone and Kilgore, 1993]. Thus, the fractal dimension of the surface roughness controlled determines the critical slip displacement.

4. Discussion –implication of dissipative energy
Fractal size reduction of materials also determined the surface roughness and particle size ranges. Through the theoretical analysis, it is clear that large dissipative energy means small critical slip displacement and/or high fractal dimension of surface roughness. The fractal dimension of the surface roughness ranges from two for smooth surfaces to almost three for rough surfaces [Avnir et al., 1983; Nagahama, 1993]. Thus, small fractal dimension of surface roughness, or small dissipative energy, indicates that gouge particles with various size ranges compose smooth surfaces with filled opening areas.

5. Summary
From this study, it is obvious that the critical slip displacement is originally determined by fractal size reduction of materials. Difference in comminution processes produces the differences in dissipative energy for fracturing, particle size ranges, the surface roughness, and the critical slip displacement.

Keywords: critical slip displacement, dissipative energy, frictional instability , fractal

Mode of tunnel deformations induced by loading in wet granular layer

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Stable burrows in wet sediments dug by tidal and shore animals play important roles not only in the ecological behaviors of the animals, but also in material circulation in the substrate and the sediment conditions. Thus, the burrow stability problem has been a challenging topic in the fields of sedimentology and biology. Modern ocypodid crabs are known to dig deep burrows in a sandy beach (Seike and Nara, *Palaeogeog., Palaeoclimat., Palaeoecol*, 252 (2007) 458). However, it has not been clarified that how stable these burrow structures are against the external loading.
For the quantitative understanding of strength of a burrow in sandy beach, we modeled it by a tunnel structure in wet granular layer, and focused on mechanical property of wet granular matter. According to the previous works, its mechanical property shows complex behaver. For example, tensile strength of wet granular column nonlinearly depends on liquid content (Scheel et al., *Journal of Physics: Condensed Matter*, 20 (2008) 494236, Herminghaus, *Wet Granular Matter: A Truly Complex Fluid, World Scientific* (2013)). However, little is known about the strength of a tunnel structure formed in wet granular layer.
In this study, we conducted a simple experiment to investigate the mechanical property of a tunnel structure in wet granular layer. In the experiment, we observed how the tunnel structure was deformed by slow uniaxial compression. During the compression, the projected cross section of the deformed tunnel was filmed by a CMOS camera. The compression force was also measured by a testing machine. In this experiment, we mainly varied following parameters: liquid content, packing fraction, initial diameter of the tunnel, and grain size. By analyzing the acquired movies, we examined the temporal evolution of a projected cross section of the tunnel structure. We found that the mode of tunnel deformations can be classified into three types: continuous shrink, shrink with collapse, and subsidence by collapse. The experimental result indicates that the mode of deformations is principally determined by the initial diameter of a tunnel and grain size.
Furthermore, based on a simple model of the force balance for tunnels in soil (Knappett and Craig, Craigs Soil Mechanics, Spon Press (2012)), we estimated the maximum shear stress applied to the tunnel structure. In addition, we defined two types of strengths characterizing a tunnel structure: yield and maximum stresses. As a result, we found that these strengths show qualitatively different dependences on experimental parameters.
Finally, we briefly discussed the condition to maintain a tunnel structure in a sandy beach environment by using the experimental result and information obtained in previous works (Seike, *Marine Biology*, 153, (2007) 1199-1206, Sassa and Watabe, *Report of the Port and Airport Research Institute*, 45, 4,(2006) 61-107).

Dependence of the Constitutive Parameters of RSF Law on Slip Velocity and Temperature at Subseismic Slip Velocities

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1. Introduction

The behavior of frictional resistance at intermediate ($10^{-3} < v < 10^{-1}$ ms^{-1}) to high slip velocities ($>10^{-1}$ ms^{-1}) are quite different from that at low slip velocities ($<10^{-3}$ ms^{-1}); at low slip velocities the value of steady-state friction coefficient tends to be between 0.6 and 0.85 [Byerlee, 1978], at intermediate slip velocities steady-state friction resistance exhibits velocity-weakening or velocity-strengthening, and at high slip velocities it shows dramatic velocity-weakening. The cause of this weakening/strengthening behavior is considered to be frictional heating (temperature) during the slip on a fault. For better earthquake prediction, it is required that earthquake simulations considering this behavior are performed. However, previous friction constitutive laws cannot explain the behavior efficiently.

One of the most useful friction constitutive law is rate- and state-dependent friction constitutive law (RSF law), developed by Dieterich [1979] and Ruina [1983]. RSF law was originally described to explain the behavior of frictional resistance at low slip velocities, and it has not been clarified whether this law can also explain the frictional behavior at intermediate to high slip velocities. In addition, the behavior of frictional resistance depends not only on slip velocity but also on temperature, so it is required to clarify the relationship between RSF law and temperature.

In this study, we carried out friction experiments at intermediate to high slip velocities, and estimated the constitutive parameters of RSF law from the experimental results considering the variation of temperature on the frictional surface.

2. Method

We conducted slip velocity step tests using a rotary-shear, intermediate- to high-velocity friction testing machine in Kyoto University at a normal stress of 1.5 MPa under room temperature and room humidity conditions. As a sample, we used a pair of hollow cylindrical Zimbabwe gabbro with an inner/outer diameter of 26/40 mm without sandwiching gouges. For the step, we defined two parameters, IRPM and ΔRPM; IRPM is the value of rotation rate of the servo-motor installed in the machine before stepping, and ΔRPM is one of slip velocity stepping. We selected all the combinations of IRPM and ΔRPM throughout the experiment: a value of IRPM of either 10, 20, 50 or 100 RPM, and a value of ΔRPM of either 80, 150, 200, 300 or 400 RPM. Note that we performed the next combination after the temperature on the frictional surface went down to the room temperature.

To estimate the values of constitutive parameters of RSF law and temperature on the frictional surface, we used the Levenberg-Marquardt method modified by Sakamoto et al. [2005] with a quasi-static spring-slider model and the FEM produced by Kuroda [2005], respectively.

3. Results

As a result of the experiments, the value of steady-state friction coefficient decreases with increasing slip velocity, which is consistent with Tsutsumi and Shimamoto [1997]. In the combination of (IRPM, ΔRPM) = (100, 400) frictional melting could be observed, and obvious slip-strengthening was observed until the molten layer was completely created. This result is also consistent with Hirose and Shimamoto [2005], which mentions that initial melting may act as a stopping mechanism for fault slip.

On constitutive parameters, the trends against slip velocity and temperature are similar; the value of each constitutive parameter linearly increases with increasing slip velocity/temperature. This trend is consistent with Nakatani [2001] and Nakatani and Scholz [2004]; they suggest that the constitutive parameters a and b have a linear dependence on the absolute temperature. However, our discussion on the relationship between the constitutive parameters and slip velocity/temperature is not enough because temperature on the frictional surface increases with increasing slip velocity. Therefore, it is needed to perform a further experiment in which the dependence of temperature on the constitutive parameters can be divided from that of slip velocity.

Keywords: friction, rate- and state-dependent friction constitutive law , intermediate to high slip velocity, temperature

The effect of decompression-induced crystallization on viscosity of basaltic magma: A case study of Fuji 1707 basaltic magma

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INTRODUCTION

Basaltic magma shows wide variety of explosive eruption style from mild strombolian to intense plinian. At Fuji volcano, mild strombolian eruption is the most common style of explosive eruption (e.g., 864-866 Jogan eruption). However, intense basaltic plinian eruption occurred at 1707 Hoei eruption. Mechanism of basaltic plinian eruption is not well understood. Plinian scoria of 1707 Hoei eruption is characterized by high abundance of plagioclase microlite (> 30 vol.%); the abundance is higher than that of strombolian scoria of 864-866 Jogan eruption. The fact cannot be explained by the difference of conduit ascent rate alone and suggests that difference of pre-eruptive temperature and/or melt water content may play an important role. In this study, we performed numerical simulation of decompression-induced crystallization to investigate the effect of pre-eruptive conditions on magma viscosity and eruption style of basaltic magma.

METHODS

We used the rhyolite-MELTS program (Gualda et al., 2012) for decompression-induced crystallization simulation. Composition of initial melt is the same as that of basaltic melt of the 1707 Hoei eruption. Plhase equilibrium calculations are repeated with 0.1 MPa step from 150 to 0.1 MPa. During decompression, we keep the conditions of temperature and oxygen fugacity (Ni-NiO buffer) constant, and crystallized phases and bubbles are immediately fractionated. Initial temperature and melt water content conditions vary in the ranges of 1184-1094 deg. C and 0.5-3 wt. %, respectively. At each pressure, melt viscosity is calculated from temperature and composition of melt by the model of Giordano et al. (2008) and relative viscosity is estimated from crystal content by Einstein-Roscoe equation, and magma viscosity is calculated from melt viscosity and relative viscosity.

RESULTS

Melt fraction at 1 atm (F_{1atm}) decreases and onset pressure of decompression-induced crystallization (P_s) increases as initial temperature decreases. F_{1atm} decreases from ca. 92 wt. % at 1189 deg. C to ca. 40 wt. % at 1094 deg. C. The relations between P_s-normalized pressure and F_{1atm}-normalized melt fraction are almost the same for runs of different initial conditions, indication that pressure-melt fraction path of decompression-induced crystallization is chiefly controlled by initial temperature condition. Increasing rates of magma viscosity during decompression strongly depend on initial temperature; magma viscosity is almost constant at 1184 deg. C whereas it increases by 6 orders of magnitude at 1094 deg. C during decompression.

DISCUSSION

Our results indicate that the effect of decompression-induced crystallization on magma viscosity strongly depends on pre-eruptive temperature condition. As initial temperature decreases, increasing rate of microlite increases, and as a result, both melt viscosity and relative viscosity increase. Therefore, magma viscosity significantly increases for initially H_2O-rich low-T basaltic melt. Increase of magma viscosity facilitates fragmentation. In addition, abundant microlites may suppress bubble coalescence and melt-bubble decupling. Consequently, magma degassing is inhibited and explosivity increases. In conclusion, eruption style of basaltic magma is strongly influenced by pre-eruptive temperature.

Keywords: decompression-induced crystallization, basaltic magma, viscosity, Fuji volcano, MELTS, eruption style

Viscoelasticity and Shear Deformation of Foam during Solidification

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Pumices produced by caldera-forming eruptions have a characteristic structure in which bubbles are elongated in one direction. They are called tube pumices. This study is a part of the research project to elucidate the origin of tube pumices to understand the behavior of magma in caldera-forming eruptions. The research uses rigid polyurethane foam (PUF) as a magma analogue. PUF is porous plastic material generated by mixing polyisocyanate liquid and polyol liquid with catalysts, blowing agents, and/or foam stabilizers. PUF during solidification is viscoelastic, which foams and solidifies like magma during an eruption. Magma is also viscoelastic and its behavior depends on viscosity, gas volume fraction, temperature, and time-scale like strain rate. Viscoelasticity of magma in a vent is crucial to determine the types of volcanic eruptions.
To use PUF as magma analogue, it is necessary to understand the mechanical property of PUF itself. This study is made to quantify the viscoelasticity of PUF during chemical reaction by applying shear deformation in various time-scales. This paper describes the results of comparison between oscillatory deformation behaviors and constant shear-rate behaviors.
The PUF is made of mixing polyisocyanate (Hycel 360P) and polyol (Hycel HW-408 without foam stabilizers), both of which are provided by Toho chemical Industry Co., Ltd.
Viscoelasticity measurements were made with a customized rotating cylinder rheometer (AR 2000ex, TA Instruments). The outer cylinder (polypropylene beaker, diameter: 11.5 mm) is held in place. The inner cylinder (aluminum rod, diameter: 7.5 mm) is controlled by the motor and rotates. The gap of the bottom of cylinders is 8 mm.
The PUF stock solution was poured between the cylinders. It expanded with heat generation to 60% porosity. We recorded temperature of the side of the cylinder by an infrared thermometer. The state of expansion was recorded by a video camera. The length of the specimen touching the inner cylinder was measured in the video images. In the oscillation tests, the complex viscosity was determined by comparing the length, the torque, and the angle of rotation. The apparent viscosity was determined by applying constant shear-rate deformation.
Two types of experiments were performed.
First, we measured the complex viscosity to clarify strain-amplitude dependence by oscillation with an angular frequency of 20 [rad/s]. It was found that the reproducibility of the viscoelasticity measurements was good when the strain amplitude was lower than 0.01.
Second, by giving oscillatory deformation and constant shear-rate deformation alternately to the specimen, the complex viscosity and the apparent viscosity were measured. Most polymers follow Cox-Mertz rule which states that the absolute complex viscosity is equivalent with the apparent viscosity when the angular frequency of the oscillation measurement and the strain rate during constant shear-rate deformation are equal (Marrucci, 1996). In a bubble flow, semi-empirical theory shows Cox-Mertz rule being true. According to Llewellin et al. (2002a), apparent viscosity and absolute complex viscosity depend on dimensionless numbers, which are capillary number Ca ($\propto$ shear rate) and dynamic capillary number Cd ($\propto$ angular frequency). The measurement revealed that, Cox-Mertz rule could not be applied to PUF when Ca is larger than 0.1. As Ca increased, the apparent viscosity became significantly smaller than the absolute complex viscosity.
Decreasing the apparent viscosity with increasing Ca has been understood as the effect of bubble

elongation by shear deformation. However, in this experiment, the apparent viscosity decreases more significantly than the semi-empirical estimate. Because the PUF used in this study has a very large porosity. We think that decreasing the viscosity is the result of larger elongation of bubbles which might be caused by bubbles interaction.

Keywords: foam, complex viscosity, apparent viscosity, capillary number

Large Scale High Precision Sandbox Experiments and Large Scale Numerical Sandbox Experiments - Precursory Signal Preceding to Frontal Thrust Formation

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To find out the mechanism of the three-dimensional complex shape formation in sequential thrust and uplift of an accretion prism, we have developed a large-scale high precision sandbox experimental apparatus since 2011. After a number of modifications in the experimental apparatus and experimental procedure, we developed a prototype of the apparatus in 2014. In specimen preparation, the thickness of a sand layer is controlled with the precision of less than single particle size. As a result, we obtained high reproducibility of the thrust formation including its position. With such a well-controlled experimental system, we found the precursory signal prior to thrust formation. To grab and understand the signal, we further improved the apparatus by installing the laser displacement sensor (resolution 0.1 μm, span 800mm), a force sensor, and camera array for surface measurement. In addition to the lab experiments, in which we can observe surface phenomena, we conducted the Discrete Element Method (DEM) simulations of the sandbox experiment. In the DEM simulation, we found similar preceding phenomena. We will discuss the mechanism of these preceding phenomena, comparing the lab experiment and the simulation.

Keywords: precursor, earthquake, sandbox experiment, DEM simulation

Feasibility Study of Morphological Characterization to Comminuted Particles by A Particle Characterization Approach (3)

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A faults zone contains fine rock powders called gouge that have been ground up by past fault motions. Particle size distribution and particle shape of gouge particles may affect the frictional properties of the fault and reflect the comminution process by the past fault motions. It is well known that particle size distribution (PSD) of fault gouge show power-law distributions. Exponent of this power law is considered to reflect the style and degree of deformation. In this report, we will discuss about the relationship between the PSD and the degree of comminution of model particles by automated particle image analysis and laser diffraction as a particle characterization method.
We did several shear experiments using a rotary shear apparatus with the shear displacement ranges between10mm to 1m. As an automated particle image analysis, Morphologi G3-SE (Malvern Instruments) was used for evaluation of particle size and shape. The observation mode was diascopic mode (Transmittance mode) and a magnification was choose to sufficient to cover 1 to 1,000um. The sample was dispersed with SDU (Sample Dispersion Unit) which attached Morphologi G3-SE. Number of measured particles was over than ten thousand and a parameter filter function on software was used based on shape and pixel number of particle image. We also used a laser diffraction instruments with dry dispersion methods, Mastersizer3000 with Aero unit (Malvern
Instruments) for evaluation of particle size in less than 1um as fine particles.

Keywords: Fault gouge, Particle size, Particls Shape, Comminution, Fractal Distributions

