SCG59-01 Room:106 Time:May 27 16:15-16:30

Slip processes of gels with multiple asperities

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Understanding how multiple asperities rupture is one of the most important questions in both earthquake source physics and tribology. Here we study the elementary slip processes of gels having multiple asperities with in-situ optical observations.

Keywords: asperity, elementary process, gel, fast rupture, slow slip, randomness

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SCG59-02 Room:106 Time:May 27 16:30-16:45

Grain size segregation in a fault gouge

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The structures and textures of fault gouge are believed to provide with rich information on the coseismic slip dynamics of faults. In Chelungpu fault gouge, where the coseismic slip was accommodated in 1999 Chichi earthquake, grain-size segregation is found [Boulier et al. Gˆ3 10, Q03016 (2009)]. This could be an evidence for gouge-fluidization, because grain-size segregation is believed to require sufficient porosity in granular matter. Grain-size segregation is also find grain-size segregation in a laboratory friction experiment with large displacement (˜12m) and under intermediate normal stress (˜2MPa)[Ujiie and Tsutsumi GRL 37, L24310 (2010)]. Here we wish to know whether grain-size segregation occurs as a result of gouge fluidization. To this end, we perform numerical simulation on a simple model of fault gouge, and show that grain size segregation occurs under a condition that may be relevant to faults gouge: the pressure of 1 MPa, the sliding velocity of 1 m/s, and the duration of 0.1 sec. Segregation occurs irrespective of gravitation and it is controlled by nonlinear velocity gradient. More importantly, we find that segregation occurs even if the granular matter possess yield stress, and therefore segregation itself does not imply gouge-fluidization.

Keywords: segregation, fault gouge, nonlinear velocity gradient

SCG59-03 Room:106 Time:May 27 16:45-17:00

Friction of granular layer at seismic slip rates - Effect of wall disturbances

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A natural fault has the cataclasite core zone, along which shear deformation concentrates. Rheology of these granular matters thus provides us an important insight in considering the nature of friction on faults from a microscopic point of view. In the past two decades, experiments conducted at sub-seismic to seismic slip rates (mm/s to m/s) revealed two remarkable phenomena of high-velocity rock friction; very long critical slip distance (Dc) of the order of 1-10m/s and the considerable weakening due to mechanochemical effects by frictional heating. Recently, Chambon et al.[2006, JGR] conducted friction experiment with very large shear displacement experiment on a thick granular layer, and reported significant slip-weakening behavior active over decimetric slip distances. However, the relation between long Dc observed in a thick granular layer and long Dc in the high-velocity friction is still not clear. We designed laboratory experiments to explore transient responses of a thick granular layer following a step change in slip velocity at seismic slip rates. We use simple particle and choose relatively low normal stress to exclude the possible mechanochemical effects caused by frictional heat. We find that friction coefficient and layer thickness show similar response that is symmetry with respect to velocity changes, and Dc is of the order of 10m. It appears that these responses are attributed to dynamics of granular matter. We report effect of wall boundary disturbance on the transient responses of granular layer.

SCG59-04 Room:106 Time:May 27 17:00-17:15

Non-equilibrium thermodynamical interpretation for rate- and state-dependent friction law

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The rate- and state-dependent friction law is based on the experimental results of rock sliding friction. This law unifies two types of rock experiment results; the first one is the time dependence of static coefficient of friction (Dieterich, 1972) and the second one is slip velocity dependence of the dynamic coefficient of friction (Dieterich, 1978). This law is reproduced by using two equations called as constitutive law and evolution law.

Several versions of evolution law have been proposed in order to reproduce the experimental data better. However, none of them are completely satisfied.

We analyze this rate- and state-dependent friction law for the velocity-step and the healing tests from a thermodynamic point of view. Assuming a logarithmic deviation from steady-state, both results are reproduced. The proposed system of equations is a unification of the classical models (Dieterich, 1979; Ruina, 1983).

Keywords: friction, constitutive law, non-equilibrium thermodynamics, evolution law

SCG59-05 Room:106 Time:May 27 17:15-17:30

Luminous phenomena due to impact shear fracture of various rocks

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Seismo-electromagnetic (s-EM)/luminous phenomena could be occurred due to dynamic shear deformations/fracture of rocks during not only a main shock but also the fore- and after-shock. In order to understand the source mechanism, the seismic luminous phenomena, a kind of s-EM, from impact shear fractured rocks were conducted using a Sharpy impact tester equipped with a CCD camera at room temperature in ambient atmosphere. In historical documents, luminous phenomona were often eye-witnessed during sector collapse associated with earthquakes, such as Gokken-zan (1701 Hoei EQ), Mayu-yama (1792 Shimabara, Unzen EQ),Ibuki-yama (1909 Kohno EQ). These mountains are consists of not only granite that has been often used in the laboratory tests, but also tuff, pyroclastic, limestone and etc.

The experimental conditions are: the impact speed was 4m/s. the impact energy was 25 J. The shutter of the CCD camera was opened for about 1 second between just before and after the impact at the ISO speed of 25,600. In addition to the impact tests, we also conducted both the thermally stimulated electron emission (TSEE) experiments and the thermal desorption mass spectrometry (TDMS) experiments.

As the results, intense luminosity was observed from fracturing rocks including biotite. Limestone and pyroclastic also showed luminous phenomena, but serpentine, ignimbrite and deposits of volcanic ash and sand did not. The mechanism of luminosity will be discussed in terms of ionization/discharge, thermo-luminescence and combustion of flammable gases contained in pyroclastic.

Keywords: luminous pehenomena, shear fracture of rocks, seismo-elecromagnetic, Sharpyi impact test

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SCG59-06 Room:106 Time:May 28 09:00-09:15

Unified understanding of frictional instability based on Rowe's theory on constant minimum energy ratio

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1. Introduction

With respect to frictional instability, many studies on rate and state dependent friction law and the microstructural observations of a gouge layer have been conducted (e.g., Dieterich, 1979; Byerlee et al., 1978). Moreover, Ikari et al. (2011) indicated that frictional parameter (a-b) transits with shear localization. However, the theoretical background for the relationship between frictional parameter and shear localization has not been clear yet. To understand it, we need to assess deformation process of gouges (e.g., shear localization) quantitatively. Here, we focus on Rowe's theory on constant minimum energy ratio (Rowe, 1962) because deformation process of particles is treated quantitatively in terms of energy. We also conduct friction experiments of simulated fault gouge to test the validity of the theory. So, based on the results, we aim to discuss frictional instability and particle deformation quantitatively in terms of analytical dynamics and thermodynamics.

2. Theoretical background

A stability of a system (e.g., a block slider model) depends on a non-linear effect of a damping (e.g., Thompson, 1982). Thus, stable slip is a result of a damping. In contrast, negative damping, or self-excited oscillation leads to unstable slip. The damping is decided by a damping constant; the system is stable when the damping constant is positive. Moreover, it is clear that displacement is controlled by the damping constant from the equation of motion. The damping constant derives from a friction force to a system. So, positive or negative of the damping constant means directions of friction force. Then, we consider that the frictional parameter deriving from coefficient of friction can be described as a ratio of tangential force (friction force) to vertical force. Therefore, frictional parameter has a close relationship with the damping force. Additionally, the relationship between stored energy in a system and energy ratio, or the ratio of input energy to output energy, is obtained from Niiseki and Satake (1981) and Landau and Lifshitz (1976). From these results, the range of energy ratio (K) is clear; in case of $K > 1$, system behave stable. On the contrary, system behaves unstable when $0 \leq K < 1$.

3. Friction experiments

12 friction experiments with simulated fault gouge (quartz) were conducted in a gas medium apparatus (Pc: 140-180 MPa). A geometry of gabbroic split cylinders sandwiching gouge were 20 mm in a diameter, 40 mm in a length and 50 degree precut from their cylindrical axis. The samples with gouge were loaded at a constant strain rate (10^{-3} /s). To obtain energy of gouge in directions of the maximum and minimum compressive stresses, strain gauges were placed. The loading and stop loading periods were repeated 4 times at differential stresses of about 190, 450, 640 and 800 MPa. After that, the sample was loaded again until strains exceeded the measurable range of strain gauges or unstable slip occurred.

4. Results and discussion

From our experiments, output energy can be expressed as a linear function of input energy. So, energy ratio of gouge is constant. Thus, gouge obeys Rowe's theory. However, in detail, the change in energy ratio was observed depending on each stress state. We consider that this change reflects the particle arrangement in each state, because energy ratio is a function of internal friction angle. Moreover, the change in energy ratio indicates the change in the damping constant. Additionally, frictional parameter is equivalent to the direction of friction force decided by a damping force. Thus, the change in the damping constant leads to the change in frictional parameter.

5. Summary

We investigated frictional instability of gouge by theoretical and experimental study. As a result, the physical and energetic background for the relationship between frictional parameter and shear localization become clear by using the damping constant based on Rowe's theory.

Keywords: frictional instability, simulated fault gouge, friction experiments, a gas-medium apparatus, Rowe's theory on constant minimum energy ratio

SCG59-07 Room:106 Time:May 28 09:15-09:30

Effect of liquid viscosity on the shaking condition required for the granular medium fluidization

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A liquid-immersed two-layered size-graded granular medium, where the upper layer forms a permeability barrier against the upward percolating liquid, is shaken vertically. A gravitational instability occurs above a critical acceleration (Γ_c) and its amplitude grows. We have previously reported the results of experiments for the water-immersed case (Yasuda & Sumita, 2014). Here we proceed to study the viscosity dependence by conducting experiments for the case in which the liquid is more viscous such that the Stokes velocity is smaller by a factor of 17, and shake it for a corresponding longer time span. We vary the acceleration and frequency of the shaking by 2 and 3 orders of magnitude, respectively, and find that fluidization occurs most efficiently at a frequency band centered around 100 Hz. Importantly, the high viscosity (HV) case has a smaller Γ_c. In addition the instability of the HV case has a shorter wavelength, and when scaled using the Stokes velocity, the growth rate is faster. The critical acceleration becoming minimum at 100 Hz can be interpreted as follows. For a flame structure to form, a sufficient amount of liquid should accumulate at the 2-layer boundary. A combined condition of energy and jerk of shaking exceeding their critical values, can explain this frequency dependence. A smaller critical acceleration for the HV case can be interpreted as a result of viscous lubrication. To confirm this, we conducted shear stress controlled fluidization experiments of the jammed particles using a rheometer. We indeed find that the fluidization occurs under a smaller shear stress for the HV case. Our experimental situation in which the gravitational instability occurs can be approximated as a thin low density, low viscosity layer underlying a thick high density, high viscosity (with a viscosity which is $\times\ \epsilon$ that of the low viscosity layer) layer. For this situation, linear stability analysis for viscous fluids indicate that the wavelength (λ) scales as $\lambda \propto \epsilon^{1/3}$. Our experimental results suggest that ϵ becomes smaller for HV case such that λ becomes shorter. A smaller ϵ value for HV case is consistent with our result indicating that fluidization occurs under a smaller acceleration.

Our experiments indicate that if shaken for a sufficiently long time, fluidization of the HV case occurs under a smaller acceleration because of viscous lubrication. This implies that fluidization of magma is more susceptible to fluidization than the water-saturated case. This may be relevant to liquefaction of magma and earthquake triggering of volcanic eruption.

Reference

Yasuda, N., Sumita, I. 2014, Shaking conditions required for flame structure formation in a water-immersed granular medium, Progress in Earth and Planetary Science, 1:13.

Keywords: earthquakes, liquefaction, fluidization, magma, triggered eruption, shaking experiments

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SCG59-08 Room:106 Time:May 28 09:30-09:45

Understanding characteristics of the granular compaction by analyzing visualized stress chain

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Granular material is defined by an ensemble of many solid grains. Although the grains composing granular material are solid, granular material sometimes behaves like fluid [1]. The rheological property of granular matter is very complex in general. Granular matter deeply relates to various phenomena occurring on the earth and planetary environments. For example, an avalanche or a liquefaction of ground caused by vibration such as earthquake relates to the complex nature of granular behavior. In this study, we focus on the granular compaction induced by vibration. Granular compaction is a peculiar phenomenon observed in various granular related behaviors, it is usually defined by the increase of the packing fraction of a granular bed.

To reveal the granular behavior, researchers have carried out various experiments. As a result, deeper understandings for the granular behaviors have been obtained. However, these understandings have not yet been perfect. In general, image analyses and data acquisition by sensors are used to investigate the granular behavior. For example, we can measure the packing fraction or the particle velocity in granular material from the former method [2]. In addition, the data such as pressure or acoustic wave on granular material can be obtained from the latter method [3]. However, we cannot completely understand the characteristics of individual particles from these macroscopic quantities. By using photoelastic discs, recent studies succeed in measuring the force applied to particle at each contact point and the stress distribution in a bulk granular material, so-called stress chain in the case of two dimension [4].

In this study, we carry out the experiment of tapping-induced granular compaction using photoelastic discs for granular material to understand granular compaction. In the experiment, we add vertical tapping to photoelastic discs piled layer in two-dimension (2D) experimental vessel. For this experiment, we use 2D experimental vessel made of acrylic plates and fill it with bidisperse photoelastic discs. To lead to the granular compaction, we tap the experimental vessel by using an electromagnetic vibrator. We systematically vary the tapping condition, the duration of tapping impulse and applied maximum acceleration. As a result, the degree of granular compaction varies depending on tapping condition. By taking and analyzing pictures of this 2D experimental vessel in the bright and dark fields at initial and tapped states, we obtain following results.

(1) Although both the packing fraction and total internal forces in the granular pile increase by the tapping, the latter saturates more quickly than the former.

(2) The applied forces on each particle become large, but the total length of the stress chain is almost constant during the granular compaction caused by tapping.

(3) The degree of granular compaction strongly depends on the applied maximum acceleration rather than the number of tapping or the duration of the tapping pulse.

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Keywords: granular matter, stress chain, granular compaction, photoelasticity

SCG59-09 Room:106 Time:May 28 09:45-10:00

Transition between frictional sliding and viscous flow in magmatic fractured zone

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Silicic magma intruded into shallow parts of volcanic conduits experiences shear localization and shear-induced brittle fracturing, resulting in the formation of a magmatic fault along conduit wall. Once the fault is formed, the frictional behavior of the fault controls the magma ascent process. The weak magmatic fault lubricates magma plug in the conduit, which results in rapid magma ascent and hence explosive volcanism. In contrast, if the fault heals during magma ascent, the ascent is controlled by viscous flow. In the viscous flow, magma is sheared, which causes efficient outgassing though shear-induced bubble coalescence and elongation. Thus, the healing of the fault may results in non-explosive volcanism. Here, we observed torsional deformations of a rhyolitic melt and a magmatic fault gouge in-situ at temperatures of 800-900 ℃ using synchrotron radiation X-ray radiography. The torsional deformation rate was set to be 0.1 to 10 rpm, corresponding to equivalent slip velocities of 2×10^{-5} to 2×10^{-3} m s^{-1} and shear strain rates <1 s^{-1}. The experimental temperature is greater than the glass transition temperature; hence, the experiments were conducted for supercooled rhyolitic melts. In experiments for rhyolitic melts, we observed brittle fracturing and formation of magmatic fault along a rotational piston. The fault did not heal under the constant deformation rate. In experiments for the magmatic fault gouge, the magmatic fault showed a frictional sliding as well as viscous flow; the deformation is controlled by the viscous flow under higher temperature, low deformation rate, and high normal stress. Based on the experimental results, we propose the ratio of timescales of fault healing and deformation as a criterion for transition between frictional sliding and viscous flow. The experimentally calibrated transition criterion infers that frictional sliding is predominant from several hundred meters in the conduit during explosive eruption on silicic volcanism; this may explain the rapid magma ascent without efficient outgassing. In contrast, once the fault heals, magma ascent may decelerate, resulting in effusive eruptions. In addition, the repeated magma fracturing, sliding, and healing would be a possible explanation for the cyclic behavior of magma ascent.

Keywords: Silicic magma, Viscous flow, Frictional sliding, X-ray radiography

SCG59-10 Room:106 Time:May 28 10:00-10:15

Shear-induced instability of an aging suspension

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In general, magma is one of typical examples of complex fluids. First of all it is a multi-phase mixture of contrasting physical properties. The volume fraction can easily change with the environmental conditions so that interactions between the constituent phases are highly variable. The characteristics make the magma complex. Rheology is an intrinsic property characterizing the complex fluid. Magma also exhibits non-Newtonian behaviors such as the existence of yield stress [M. Saar et al., 2001], shear-thinning [H. Sato, 2005], thixotropy, which is a kind of aging property [H. Ishibashi and H. Sato, 2007], and shear localization [S. Okumura et al., 2013, A. Hale and H. Muhlhans, 2007] under certain conditions. Consequently magma flow is expected to be unstable by control of complex rheology and it might be related volcanic oscillation phenomena such as volcanic tremor. However there are few studies, which focus on flow behaviors caused by the complex characteristics of magma rheology so far since it is difficult to control flow in magma and obtain reproducible results at high pressure and high temperature.

For this reason, instead of using real magma but by using analog material this study aims to reveal possible control of complex rheology in magma flow dynamics. We particularly focus on shear-induced instability of the suspension such as shear-banding phenomena to drive unstable and oscillatory flows. As an analog material we utilized an aging suspension of fine silica particles (Ludox TM-40, Aldrich) with salt water. The suspension is known to have yield stress, aging behavior and thixotropic natures [Moller et al., 2008], which can be an analog for the magma complexity. A series of rheological experiments with the use of a rheometer (AR1000, TA Instrument) and 1D and 2D ultrasonic speckle velocimetries (USV) [S. Manneville, 2004] have achieved to observe global rheology and local velocity profiles in the flow simultaneously. By results from the experiments under various conditions changing applied shear rate and aging time, we conclude that the flow behavior can be divided into three types; fluidization, unstable shear banding, and stable shear banding. In the cases of fluidization and unstable shear banding, shear stress fluctuates when the width of shear band and slip velocity show large shift. In this way, it was revealed that fluctuation of shear stress could occur in this kind of suspension and both shear-banding and wall-slip are responsible for driving the shear-induced global instability.

Keywords: aging, rheology, suspension, shear band

SCG59-11 Room:106 Time:May 28 10:15-10:30

Fundamental aspects of the thermo-elasticity in the columnar joint formation

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Columnar joints form as a result of unidirectional propagation of cooling and the consequent thermal contraction. So far in interpreting the columnar regular structures at nature, two hypotheses are assumed about the fracture threshold and propagation direction: 1) fractures take place at a certain temperature, that is, at the isothermal surface corresponding to the yield strength (fracture threshold hypothesis). 2) fractures propagate perpendicular to the isothermal surface (propagation direction hypothesis). However, those hypotheses have not been proved on the basis of the thermo-elastic theory. In this paper, we analytically show, using the thermo-elastic theory in 2D, that these two hypotheses are correct under the specific circumstances. Firstly we derive the relation between the stress field and temperature field in terms of principal stress difference, stress invariant and temperature. From the relation, we understand that the principal stress difference contributing to the crack initiation is exactly equivalent to a certain temperature when the minimum principal stress is small enough. The temperature corresponding to the crack initiation, which is determined by the yield strength, defines the fracture isotherm or crack front. Secondly we derive the direction of maximum extension on the fracture isotherm as function of azimuthal angle. If the stress is completely released in the region where fracturing already occurred and cracks are present, that is, where temperature is less than fracturing temperature, then the shear stress on the fracture isotherm must be zero, and one of principal stress is perpendicular to the fracture isotherm and another principal stress is along the fracture isotherm. These geometric relations naturally mean that the direction of maximum extension is perpendicular to the fracture isotherm. Numerical calculations well explain morphological features derived from our analog experiments, indicating that two hypotheses work correctly in real systems.

Keywords: columnar joint, thermo-elasticity, thermal stress

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SCG59-12 Room:106 Time:May 28 10:30-10:45

Analogue experiments of reproducing morphological features of entablature in columnar joints

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There are various types of morphological features in columnar joints, i.e. column width, column configurations (straight or curved) and the directions of developed columns. We have conducted analogue experiments by use of potato starch and water mixture to reproduce morphological characteristics of entablature and we have found the following two results: 1) when the desiccation rate increases instantaneously on the half way of columns development, the number of columns increases by column nucleation, 2) the direction of developing columns is perpendicular to the isopleth surface of the same water concentration with the exception under particular circumstances of stress field. In order to observe the time evolution of column development in the case of the spatially inhomogeneous desiccation rate, we used the X-ray CT (MCT 225 made by Nikon, owned by Fukuoka Industrial Technology Center) at a certain interval of time during the development of columns. We prepared potato starch and distilled water mixture with the same mass 150g each in a plastic cylindrical container. The light source (60 W lamp) is located at 3 cm above the surface of mixture thereby the thermal heterogeneity on the surface is made due to the highest desiccation rate just below the lamp and the lowest desiccation rate at the edge of circular sample surface. We took the X-ray CT images every 2 or 3 hours during the daytime to observe the change of water distribution by the gray scale intensity together with crack developments in the mixture with time. As a result, there is a higher brightness area like a crescentic shape at upper part of the mixture, which indicates lower concentration of water than at lower part, before the initial generation of cracks on the surface of the mixture. The area in which cracks develop coincidently take a similar crescentic shape. The lower area below the crack front indicates homogeneous brightness. The crack front advanced to the depth with keeping its crescentic shape and cracks developed not perpendicular to the crack front, indicating the discrepancy with the theoretical prediction for the crack direction under the simple condition. This discrepancy may be caused by the mechanical effect at the edge of the plastic container. In addition, we conducted the experiments in the case of drying from 3 non-parallel surfaces which provide spatially homogeneous desiccation rate each. We put the mixture into a triangular prism shaped metal frame. Two sides are dried through the membrane (surface B and C) and the other top side is dried directly on the air (surface A). We conducted experiments in the cases that the angle θ between surfaces B and C is 60 degree and 90 degree each. As a result, when θ is 90 degree, columnar joints developed from surface A, B and C simultaneously merge in the center of the mixture with curved structure which are fan-like structure at the edge of the triangle. From the comparison with the theoretical results, the characteristics of curved structure can be explained by the condition that a crack propagates perpendicular to the iso-concentration surface. We will investigate the interaction of columns developed from different directions in terms of angles between the desiccation surfaces as a parameter.

Keywords: columnar joints, analogue experiment, entablature, morphological features

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SCG59-13 Room:106 Time:May 28 11:00-11:15

Experimental study on the rheology of ice-rock mixtures: Implications for cosmoglaciology

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Icy bodies in the solar system have various shapes, bulk densities, and surface features. Icy satellites have a wide range of bulk density, 300 to 3000 kg/m^3, and those with small density have a residual porosity in their interiors while those with high density are composed of ice-rock mixtures. The shape of icy satellites is determined by the ratio of the stress by gravity and the material strength, that is, icy body has spherical shape when the internal stress is beyond the material strength. Furthermore, glacial features and large-scaled faults are observed on Mars polar regions and the surfaces of giant icy satellites such as Europa. Such the variations of shape and density and the tectonics of the surface features on Mars and icy satellites are controlled by the rheology and the failure stress of constituent.

Many researchers examined the rheology of H_2O ice. Particularly, they examined the effects of temperature and grain size on the flow law by laboratory experiments and field observations. However, icy bodies in the solar system are composed of ice-rock mixtures with various rock contents and small icy bodies are porous because of their small densities. Furthermore, the surface temperature can be estimated from the radiative equilibrium temperature while the internal temperature must be higher than the surface temperature. But it is very difficult to estimate the internal temperature distribution. Therefore, in order to clarify their evolutions and tectonics of Mars and icy satellites, we must examine the rheology of ice-rock mixtures in the wide range of rock content, porosity, and temperature. In this study, we did deformation experiments of ice-rock mixtures and examined these effects on the flow law systematically.

The samples were prepared by mixing ice particles with the diameter smaller than 710 μm and amorphous silica beads with the diameter of 1 μm. We prepared two kinds of samples. One is a frozen sample (f.s.) which is made by mixing ice particles, silica beads, and liquid water. The silica volume fraction of the f.s. was from 0 to 0.63 vol.%, and the porosity was 0%. The other is a pressure-sintering sample (p.s.s.) which is made by the compaction of ice particles and silica beads. The silica mass content of the p.s.s. was 0, 30, and 50 wt.%, and the porosity was changed from 0 to 25%. We did uniaxial compression tests under constant strain rate from 8.7×10^{-7} s^{-1} to 8.3×10^{-4} s^{-1} in the cold room at ILTS, Hokkaido University. The temperature was set from -10 to -25 ℃.

We examined the flow law expressed as $d\epsilon/dt = A_0 \exp(-Q/RT)\sigma_{max}{}^n$, which σ_{max} is the maximum stress on the stress-strain curve and $d\epsilon/dt$ is the strain rate. The dependence of the silica content was different between f.s. and p.s.s.. The σ_{max} increased with the increase of the silica content in the case of f.s. while it decreased in the case of p.s.s.. On the other hand, the σ_{max} decreased with the increase of the porosity or the temperature for both samples. From these results, we obtained the parameters, A_0, Q, n, on the flow law. The power n and the activation energy Q depended on only silica content, and the n at the silica volume fraction larger than 0.15 became twice larger than that of pure ice (n=3). The Q increased with the increase of the silica content. The A_0 depended on the silica content and the porosity, and the empirical equation, $A_0 = B\exp(\alpha\phi)$, which ϕ is the porosity, and B and α are constant depending on the silica content, could be obtained.

Next, we examined the deformation modes, ductile deformation or brittle failure. As a result, the f.s. at the silica volume fraction larger than 0.29 showed brittle failure at the temperature lower than -20 ℃. The temperature at the brittle-ductile boundary of the mixtures was 30-50 ℃ higher than that of pure ice at constant strain rate.

Keywords: Mars polar regions, icy satellites, ice-rock mixtures, porosity, flow law, brittle-ductile boundary

SCG59-14 Room:106 Time:May 28 11:15-11:30

Elasticity, anelasticity, and viscosity of a polycrystalline material at near-solidus temperatures

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For a quantitative interpretation of seismic structures in the earth's interior, understanding of rock anelasticity over a broad frequency range is needed. There are high-Q^{-1} and low-V regions in the upper mantle. To interpret them, it is important to understand effects of melt on anelasticity.

Anelasticity of mantle rock or rock analogue at seismic frequencies have been measured intensively. We use polycrystalline aggregates of organic "borneol" as rock analogue to accurately measure the anelastic properties over a broad frequency range. A sample made from borneol + diphenylamine binary system partially melts at T_m = 43 ℃ and its equilibrium microstructure is quite similar to that of olivine + basalt system.

Using these samples, forced oscillation tests have been performed to measure anelasticity as a function of frequency f, temperature T, grain size d, and melt fraction ϕ. McCarthy et al. (2011) showed that polycrystal anelasticity follows the Maxwell frequency (f_M) scaling, by demonstrating that all attenuation spectra Q^{-1}(f) obtained under various experimental conditions collapse onto a single master curve $Q^{-1}(f/f_M)$. However, this result was obtained from the data at $f/f_M < 10^5$, which is lower than the seismic frequencies normalized to f_M in the upper mantle ($10^6 \leq f/f_M \leq 10^9$). Recently, Takei et al. (2014) measured Q^{-1} of rock analogue up to $f/f_M \sim 10^8$ and showed that the Maxwell frequency scaling is not fully applicable to $f/f_M > 10^4$. They showed that the deviation from the master curve increases with increasing homologous temperature T/T_m (T_m: solidus temperature) and/or grain size. Based on their results, they speculated that at near-solidus temperatures high Q^{-1} and low V can occur even without melt. However, their data were limited to $T/T_m \leq 0.93$. Data at $T/T_m > 0.93$ are needed to examine the detailed behavior at the onset of melting.

In this study, we prepared 4 samples made from borneol + diphenylamine binary eutectic system with different grain sizes and melt fractions. Anelasticity of these samples was measured at near-solidus temperatures ($0.88 \leq T/T_m \leq 1.01$). In order to clarify the mechanism of anelasticity, mechanical data over a broad frequency range are needed. Therefore, in addition to forced oscillation tests, ultrasonic tests and creep tests were conducted to measure elasticity and viscosity at the same temperature conditions.

The samples were pre-annealed at supersolidus temperatures to prevent the rapid grain growth at the onset of melting. This improvement enabled us to measure elasticity, anelasticity, and viscosity at near-solidus temperatures and examine how these properties behave at the onset of melting. We found that although the ultrasonic velocities are discontinuously reduced by the poroelastic effect of melt, anelasticity and viscosity changed continuously with temperature even at the onset of melting. Based on these data, an empirical formula of the relaxation spectrum X was obtained as a function of nondimensional variables f/f_M and T/T_m. A preliminary appreciation of the formula to the upper mantle suggests that high Q^{-1} and low V can occur at near-solidus temperatures even without melt. It also suggests that seismic attenuation changes continuously even at the onset of melting, whereas seismic velocity changes discontinuously due to the poroelastic effect of melt.

In this study, the temperature dependence of anelasticity could be captured at near-solidus temperatures, but dependences on the grain size and melt fraction couldn't be captured. This is because the samples that experienced partial melting show various hysteresis effects, and the hysteresis effects masked these effects. Our next step is to investigate effects of grain size and melt fraction on anelasticity by using samples that do not experience partial melting and hence are free from the hysteresis effects.

Keywords: anelasticity, seismic attenuation, melt