The mechanical property of a tunnel structure 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, 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)). The origin of this nonlinear response of wet granular matter to external loading has not yet been revealed sufficiently. Moreover, 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 deformed when it was uniformly loaded from the top of the layer with a very slow loading rate. By taking and analyzing the movies of deforming tunnel structures, we examined the temporal evolution of a projected cross section of the tunnel structure. Furthermore, based on the discussion of stability of tunnels in the soil (Knappett and Craig, *Craigs Soil Mechanics*, Spon Press (2012)), we estimated the maximum shear stress applied to the tunnel structure at each state. The experimental result showed that the mode of deformation depends on both liquid content and packing fraction. Particularly, the liquid-content dependence of the mechanical response is not monotonic. In addition, we defined two types of strengths characterizing a tunnel structure: yield and maximum stresses. As a result, we found that these strengths strongly depend on packing fraction. Besides, they show qualitatively different liquid-content dependence in relatively high liquid content regime. Finally, we briefly discussed a possible application of the experimental result for estimating the upper limit size of 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).

Feasibility Study of Morphological Characterization to Comminuted Particles by A Particle Characterization Approach (2)

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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 particle morphology and a style and a 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 10m.
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, Particle Shape, Commutation, Fractal Distributions

Large Scale High Precision Sand Box Experiments: Precise Measurements of Precursory Signal Preceding to Frontal Thrust Formation

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In order 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. In order to grab and understand the signal, we further improved the apparatus by installing the laser displacement sensor (resolution 0.1μm, span 800mm), a force sensor, and camera array for surface measurement. We will report the detailed information on the experimental apparatus our new findings.

Keywords: precursor, earthquake, sandbox experiment

Liquefaction experiments with a low permeability upper layer : dependence on layer thicknesses

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When a water-immersed granular layer is shaken strongly enough by an earthquake, liquefaction occurs. If this layer consists of a low permeability upper layer, flame structures form and sand boils are observed. Previous liquefaction experiments have shown that when such layers are shaken the number and the area of sand boils decrease as the ratio of the thicknesses of the upper to lower layer increases (Yamaguchi et al. 2008). However no physical interpretation of these results have been made, and the effect of each layer thickness has not been clarified. Here we conduct a series of experiments with a range of combinations of the two layer thicknesses to quantitatively study how liquefaction and related phenomena depend on the thickness of each layers.
We use a small case filled with a mixture of glass beads and water. The glass beads are size graded such that the upper layers consist of fine particles with a diameter of 0.05 mm and the lower layer consists of coarse particles with a diameter of 0.22 mm. As a result the upper layer is 32 times less permeable compared to the lower layer. We vary the thicknesses of each layer in the range of 0 to 40 mm. The cell is shaken vertically for 5 s at an acceleration of 30 m/s^2 and a frequency of 100 Hz. We use a high-speed camera and record the images which are then analyzed in detail.
From a series of experiments we recognize three phenomena, the compaction of the whole layer, formation of the flame structure, and eruption of water and glass beads. These phenomena are the consequence of gravitational (Rayleigh-Taylor) instability at the two-layer boundary (Yasuda & Sumita, 2014, 2016). Compaction occurred in all experiments whereas the formation of the flame structure or eruption water and glass beads occurred only when the upper layer is sufficiently thin. We studied the upper layer thickness dependence in detail for the case in which the lower layer thickness is in the range of 22-26 mm. We find that the wavelength of flame structure increases and the growth rate decreases as the upper layer becomes thicker. It appears that there is an upper limit wavelength. We also find that the peak amplitude becomes largest when the upper layer is at an intermediate thickness. We classified the results of all experiments using the values of the growth rate of the instability. We find that when the lower layer is thin, the growth rate depends on both the upper and lower layer thickness. However when the lower layer becomes thicker it depends on mainly on the upper layer thickness.
Our experimental results can be understood as follows. From Coulomb’s law of friction, the interparticle friction increases with depth z as $\sigma=\mu\Delta\rho\Phi gz$…(1), where μis the coefficient of friction, Δρis the particle-water density difference, Φis the packing fraction, g is the gravitational acceleration. As a result, we estimate that when the z is greater than a critical, friction exceeds inertia, and fluidization does not occur at the two-layer boundary. Linear stability analyses for viscous fluids (Whitehead & Luther, 1975) indicate that the wavelengthλand growth rate p of the instability can be expressed as $\lambda\propto\varepsilon^{13}h$…(2),$p\propto\varepsilon^{-23}h$…(3), where εis the upper to lower layer viscosity ratio and h is the thickness of the fluidized layer beneath the two-layer boundary. It follows that our result can be interpreted as a consequence of increasing εwith the thickness of the upper layer. Substituting the measuredλand p into Eq.(2),(3), we estimate that ε increased from 3 to 495 as the upper layer become thicker. This result is consistent with the increase of friction at the 2-layer boundary according to the Eq.(1). We consider that our results of upper layer thickness dependence can be interpreted as a result of the increase of effective viscosity of the upper layer.

Keywords: Liquefaction, earthquakes, low-permeability layer, gravitational instability, thickness dependence

Energetic Assessment of Frictional Instability and Quantitative Evaluation of Microstructural Development with Shear

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1. Introduction
Frictional instability has been evaluated empirically by using a frictional parameter (velocity dependence) on the basis of the rate and state dependent friction law (Dieterich, 1979; Ruina, 1983). In addition, shear development in a gouge layer influences frictional instability (e.g., Byerlee et al., 1978; Logan et al., 1979; Ikari et al., 2011; Onuma et al., 2011). Ikari et al. (2011) pointed out a possibility that velocity dependence of friction changes with shear. However, it is difficult to accurately observe shear structures developed in recovered gouge samples and deal with shear zone development in gouge statistically. Therefore, the underlying theoretical relation between frictional instability and shear development has not been clear yet. In the present study, we aim to clarify (1) relation between frictional instability and shear development by energetic analysis, and (2) process of shear development toward frictional instability of gouge through theoretical and experimental analysis.
2. The energetic criterion for frictional instability
Deformation of particles progresses in an energetically efficient way (Rowe, 1962). Thus, both energy ratio defined as a ratio of input mechanical energy to output energy, and hence dissipation energy of particles become minimum. Stability of a mechanical system is influenced by energy. If a frictional system represented by a spring-slider model experiences frictional damping, the stored energy in the system decreases leading to stable slip. In contrast, if the system experiences negative frictional damping, the stored energy increases leading to unstable slip. Negative frictional damping indicates that friction force works to the direction of motion and might be related to shear development. Because the stored energy coincides with the difference in energy during deformation, the stored energy can be represented by the energy ratio between input energy to output energy through deformation. Thus, the energetic criterion for frictional instability is obtained from the relation between the stored energy and mechanical behavior of the frictional system.
3. The friction experiments
We analyzed data of friction experiments using simulated fault gouge (Hirata et al., 2014) to obtain energy ratio of gouge during friction experiments in gas apparatus. The cylindrical samples with dry quartz powder as gouge were loaded under 140, 160, and 180 MPa of confining pressures. Data about stress and strain in major and minor principal axes were recorded through strain gauges placed onto samples. The values of energy ratios of gouge were obtained based on these values.
4. Results and discussion
We clarified that the output energy has a linear relationship with input mechanical energy, but energy ratios changed slightly with shear. Change in the energy ratio which is a function of internal friction angles implies shear development. R1-shear angles from major principal stress axis can be estimated using internal friction angles (Morgenstern and Tchalenko, 1967). Thus, the energy ratio controlled by the internal friction angle closely related to shear development.
R1-shear angles we estimated show that R1-shears becomes more parallel to a rock-gouge boundary before the occurrence of unstable slip. At 140 MPa of confining pressure, R1-shear was inferred to be developed almost parallel to the boundary (3 degrees to the boundary) at the top of a sample as deformation proceeds. The reduction of shear angles with respect to shear zone boundary with

progressive shear is consistent with previous works (e.g., Gu and Wong, 1994).

5. Summary

We investigated relation between frictional instability and shear development energetically. Our results revealed that (1) the energetic background for their relation; (2) the efficacy of the energetic criterion for frictional instability; and (3) shear development in gouge in situ.

Keywords: frictional instability, Rowe's theory, microstructural development, simulated fault gouge, friction experiments, energetic assessment

Distributions of physical property and anisotropy of unconsolidated sediments off Costa Rica under differential stress

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Static moduli of rock are used in borehole stability to evaluate elevated pore pressure and tectonic stress distribution. The static and dynamic moduli of the same rock may significantly differ from each other. The main reason is likely to be the difference in the size of strain between the dynamic and static tests. In the dynamic properties the strain is about 10^{-7}, while static strain may be about 10^{-2}.

The purpose of this study is to reveal the relationship between static and dynamic moduli of unconsolidated sediments obtained from off Costa Rica, and to evaluate anisotropy of static moduli using shear strain. To achieve this purpose, we obtained (1) static Vp/Vs using volumetric strain and shear strain from experiments in differential stress, and (2) dynamic Vp/Vs from dynamic wave propagation experiments. Then Poisson's ratio was calculated using Vp/Vs. Using Poisson's ratio, static and dynamic Young's moduli were transformed.

Used materials are unconsolidated sediments obtained by IODP expedition 344. We focused on reference site U1414, frontal prism U1412, mid-slope U1380. Materials were remodeled into cylinder shape for the experiments.

Equipment of laboratory experiment consists of pressure vessel, three syringe pumps, computer, transducer, oscilloscope, displacement gauge. In laboratory experiment, pore fluid pressure was kept 1MPa. Effective pressure was controlled by changing axial pressure and confining pressure. We calculated in-situ effective pressure using sample depth, bulk density and assumption of hydrostatic pressure of pore pressure. We conducted 4-5 steps of experiment with isotropic pressure up to in-situ effective pressure. Between each isotropic condition, differential stress experiments were conducted. In differential stress experiments, axial pressure was increased and radial pressure was kept in constant; increment of differential stress is three times as large as increment of effective pressure. Axial strain was calculated from a value of axial displacement gauge. Volumetric strain and porosity were calculated from remaining volume of pore fluid pressure in a pump. When strain reached at equilibrium condition, waveform, a value of axial displacement gauge and remaining volume of pore fluid pressure were recorded.

In the results, static Vp/Vs ranges 1.5-1.6, and dynamic Vp/Vs covers 2.0-2.1. Using each Vp/Vs, Poisson's ratio, static and dynamic Young's moduli were calculated. The ratio of dynamic to static Young's moduli (K) was about 0.6. Dynamic physical properties can transform into static physical properties using K value. Dynamic S-wave velocity was about 25% slower than static S-wave velocity systematically in all samples.

Shear strain of samples from U1414 was larger than that of samples from sites U1412 and U1380. Shear strain is described by the difference between axial strain and radial strain, suggesting anisotropy in reference site is larger than that in wedge.

Keywords: static moduli, Costa Rica, unconsolidated sediments

Plasticity index and mechanical bifurcation of soils and rocks

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In the field of soil mechanics, triaxial compression test is widely used to investigate mechanical properties of soils. Yielded specimens characterized by Mohr's stress circles have various deformation patterns depending on loading stages and stress ratios in spite of the same ground materials. Failure patterns of ground materials bifurcationally change to diamond, bulge and a pair of oblique shear patterns. The symmetry of deformation patterns (e.g. shear band patterns) has been illuminated by bifurcation analysis of governing equation of soil mechanics based on Cam-clay model. On the other hand, plasticity index, an empirical parameter to characterize the range of water contents where the soil exhibits plastic property, is known to describe mechanical characteristics (e.g. compressibility) of soils. However, it is an unknown theoretical relationship between mechanical bifurcation controlling the evolution of deformation patterns and plasticity index. Also the theoretical relationships between the empirical laws of soil strength and plasticity index have not been clear yet. Hence, we show that plasticity index theoretically determines deformation patterns of soils by Cam-clay model, and we prove that the index closely affects the bifurcation formulas on the basis of Shibi and Kamei (2002)’s bifurcation analysis. From the view point of the plasticity index, deformation facies representing various deformation patterns of rocks in geologic condition are controlled by mean ductility and ductility contrast, as quantitatively proposed by Uemura (1981).

Keywords: plasticity index, deformation patterns, bifurcation

Analogue experiments for understanding of factors controlling morphological transition in columnar joints

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Columnar joints in lava flows and welded tuffs have two different types of column structures adjacently within a single flow unit in terms of columns widths, column configurations and the directions of developed columns, which are called as Colonnade and Entablature. Colonnade consists of relatively large width, straight and ordered columns, while Entablature consists of relatively small width, curved and disordered columns. Columnar joint are formed due to volume contraction during cooling. The isotherms at a time are assumed to be perpendicular to the direction of columns if the directions of maximum tensile stresses are parallel to the isotherms. The assumption, which is based on thermal diffusion process during cooling, has been applied to the formation of simple cases in the curved structures. However, it still has not clearly solved how the complex structure in Entablature is related to the complex isotherms. In order to understand the formation process of Colonnade structure in columnar joints, analogue experiments using starch and water mixture as analogue materials have been conducted in terms of morphology, theory and crack formation. However, attempts to reproduce morphological transition from Colonnade to Entablature have not been conducted yet. This thesis aims at understanding the factors to control the transition between Colonnade and Entablature by means of drying experiments as well as reproducing curved structures which are seen in Entablature. I investigated the process of crack propagations and the relations between the water distribution and crack developments in mixture by observing X-ray CT images with changing time. Three sets of experiments conducted focus on: (1) Transfer processes in drying and cracking samples, (2) Water concentration and the direction of cracks with time and (3) Effects of sudden increase in desiccation rate on drying and cracking processes. The samples after all experiments are observed by using X-ray CT and compared with the models based a diffusion equation in Experiment 1 and 2. Further morphological analysis is developed for images taken in Experiment 3 for suggesting the possibility of column nucleation in nature. Results suggest: 1. Water transportation within the mixture can be explained by the diffusion process, 2. Crack development occurs perpendicular to the iso-water concentration surface in the mixture and 3. Instantaneous increase in desiccation rate causes columns nucleation.
I propose a scenario of morphological transition from Colonnade to Entablature at Shakushiiwa, which shows a threefold structure (Upper Colonnade –Entablature –Lower Colonnade) within Aso-4 welded tuffs in Oita prefecture, Japan, on the basis of above suggestions by introducing two heat transports: vertical heat transport within rocks by thermal diffusion to the uppermost of the rock, Q_1 and heat transport through the cracks, Q_2. Central Entablature has radial structures by originated from the tips of cracks in Upper Colonnade. These radial structures are horizontally aligned repeatedly. As the cooling process proceeds in Upper Colonnade by thermal diffusion Q_1 from hotter interior of the rock to the cooling surface at the top of the rock, cracks develop perpendicular to the isotherm of T_c, which is the temperature when cracks restart to propagate to form Upper Colonnade. When cracks developed from Upper Colonnade part to the boundary to Entablature, cracks themselves become the cooling surface and the heat transport Q_2 proceeds. This cooling process makes the configuration of the isotherm T_c to be convex downward around the tips of cracks. The heat transport transition from Q_1 to Q_1+Q_2 causes the abrupt increase in cooling rate and form smaller widths of columns than those in Upper Colonnade by column nucleation. Such

morphological change of columns is consistent with the field observation.

Keywords: Columnar jointing, Morphological transition, Analogue experiment

Rheological law and viscous-brittle transition of 3 phase magma; a case study for the 1946 andesitic lava from Sakurajima volcano, Japan

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Uniaxial compression deformation experiments were done for the 1946 andesitic lava from Sakurajima volcano, Japan, under conditions of temperatures from 1300 to1130 K, strain rates from $10^{-2.5}$ to $10^{-5.5}$ s^{-1}, and ambient pressure. The starting lava sample has ca. 20 vol. % of bubbles and the solid part consists of ca. 47 vol.% of rhyolitic glass, ca. 23 vol.% of microlites and ca. 30 vol.% of phenocrysts of plagioclase, pyroxenes, and Fe-Ti oxides. The experiments were done by using the uniaxial deformation apparatus at ERI, University of Tokyo. Deformation experiments were done after ca. 2h pre-heating at the experimental temperatures and the samples were quenched to 873 K with 15 min after the deformation was finished. During the experiments, stress and sample high were monitored under constant temperature. Deformation rate was changed stepwise due to examine non-Newtonian behaviors. Viscosity was calculated by the equation of Gent (1960) from the monitored stress-sample high dataset.
The lava behaves as a power law shear-thinning fluid at temperatures from 1300 to 1160 K under the experimental strain rate conditions. Viscosity increases from ca. $10^{7.3}$ to ca. $10^{11.3}$ Pa s with decreasing temperature and strain rate. An equation describing its dependence on temperature and strain rate was proposed. Relative viscosity, defined as the ratio of magma viscosity/melt viscosity, is almost constant around 100 (with assumption that melt water content is 0.2 wt. %) regardless of experimental temperature. At 1130K, fracturing occurs at strain rate of $10^{-3.5}$ s^{-1} whereas the lava behaves as viscous under strain rate of 10^{-4} s^{-1}. Crystallinity is almost constant around 0.53 regardless of temperature.
Deborah numbers are calculated to be lower than $10^{-2.65}$ for non-fractured samples and ca. $10^{-2.65}$ for the fractured sample. The relation between crystallinity and critical Deborah number for viscous-brittle transition is consistent with the criteria for crystal-bearing magmas proposed by Cordonnier et al. (2012). Present results indicate that the critical stress for viscous-brittle transition is ca. $10^{7.4}$ Pa. The present rheological law was used to calculate flow velocity of the 1946 andesitic lava flow; the result calculated at 1273 K well explains the field observation of Hagiwara et al. (1946). The temperature is consistent with petrological constraints. The calculated maximum shear stress in the lava flow is lower than $10^{6.5}$ Pa, indicating that any process concentrating stress on the lava surface is required to form the blocky structure.

Keywords: Rheological law, Lava flow, brittle-viscous transition, magma, Sakurajima volcano

Strain Behavior and Deformation Property of Aji Granite under Triaxial Compression Tests

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Fracture behavior of rock has been much researched because it is related to the mechanism of the earthquake and strength of the earth's crust. Recently, outcomes of these researches have been applied for hydraulic fracturing, which can create artificial geothermal fluid reservoir and such resources may have potential to solve Japan’s energy issues. However, this application (Hot Dry Rock power generation) has some problems and fundamental research is needed in order to understand deformational properties of crustal rocks. Therefore, we investigated the effects of confining pressure and pore pressure on the strain behavior and deformation properties of granite. We conducted strain measurements during triaxial compression tests of Aji granite at constant strain-rate (1.7×10^{-5} s^{-1}) under confining pressure ranging between 10 and 40 MPa, and pore pressure ranging between 10 and 30 MPa. The experimental results showed that the maximum stress and the onset of dilatancy increase with effective pressure but slightly decrease under wet condition. Young’s modulus increases slightly with effective pressure, whereas Poisson’s ratio is nearly constant in our experiments. Dilatancy that is related to the formation of micro-cracks during deformation is suppressed at high confining pressure, while dilatancy tends to be enhanced at low pore pressure, and hence high effective pressure, under wet condition. This indicates that the stress concentration related to the formation of micro-crack can be relaxed at high pore fluid pressure. Wet experiments have shown a rapid increase of water injection volume within the specimen at stress level of 96–97% maximum stress, which is probably attributed to the formation of micro-crack network. In addition, such increase of water injection volume became nearly constant at and after maximum stress, indicating that pore volume is may not be changed by localization of micro-cracking or macroscopic fracture. Based on these results, it is expected in hydraulic fracturing test that fracture under the ground can be efficiently created by lower injection rate and macroscopic fracture may occur soon after pore pressure decreases.

Keywords: Stress-strain relationship, Dilatancy, Pore pressure, Triaxial compression test, Granite, Hot Dry Rock power generation

Grain size distribution of quartz in the Sanbagawa metamorphic belt analyzed by the electron back-scattered diffraction (EBSD) method

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The size of dynamically recrystallized grains in naturally deformed rocks has been used for paleostress estimates. However, the meanings of the “average” grain size in previous piezometeric studies (e.g. Stipp and Tullis, 2003) often have two large problems. One is derived from difficulty in distinguishing grains and subgrains under an optical microscope, and the other is unclarity about what is the appropriate definition of the “average” grain size (e.g., the arithmetic mean, the root mean square). Different definitions could yield different stress estimates.
We measured grain size of quartz by optical microscopy and electron back-scattered diffraction (EBSD) mapping. In the optical method, grain boundaries were manually traced on photomicrographs according to the difference in extinction angles and analyzed by an image processing software. In the EBSD analyses, the grain boundaries with the misorientation angles exceeding 12° were automatically detected based on the Euler angles of the crystal lattice orientation. EBSD mapping was conducted with changing step size, 0.5, 1, 2, and 8 microns. The size of each grain was defined as the diameter of the equivalent circle.
We analyzed microstructures of a quartz schist in the garnet zone of the Sanbagawa metamorphic belt, which was taken from the Asemi-gawa area, Shikoku Island, Japan. Under an optical microscope, large quartz grains show oblique shape fabric and intracrystalline deformation features, and small quartz grains are formed at the margins of large quartz grains.
The grain size distributions quantified by the optical analysis and EBSD showed severely right skewed shapes. Hence, different definitions of representative grain size yielded quite different values. The distributions are far different from the bell-shape distribution known for static grain growth. Right skewed distributions can be produced by a simple nucleation-and-growth model (Shimizu, 1999, Phil. Mag.). The modes of the distributions vary with methods and step sizes, ranging from ~10 to ~50 μm. Because the mode was not well defined, we used, as the representative value, the class of grain size occupying the largest area in each mapped area, which can be related to the length scale in the nucleation-and-growth model of Shimizu (1999) and is robust because it reflects measurements of large grains. In the result, this value ranges from 110 to 120 microns. Using a revised theoretical grain size piezometer (Shimizu and Ueda, 2016, JpGU), which takes temperature dependence into account, and the temperature estimate of the sampling locality (516.4°C; Bayssac et al., 2002), the differential stress is 29 and 62 MPa, assuming intracrystalline recrystallization and marginal recrystallization, respectively. These stresses are higher than that given by the empirical piezometer of Holyoke and Kronenberg (2010) (17 MPa), which uses the root mean square as the representative grain size and does not take the temperature effect into account. We will show results from quartz schists of other zones of the Sanbagawa metamorphic belt.

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Keywords: quartz, recrystallized grain size piezometer, Sanbagawa metamorphic belt

Effect of water on rheology of plagioclase under high temperature and high pressure

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1. Introduction
Rheological behaviors of rocks depend on pressures, temperatures and chemical environment. Particularly, water is known to play an important role in rheology of rocks in terms of physical and chemical aspects by previous experiments. Here, two ways of water effects are considered. Pore fluid pressure reduces the effective stress of rocks supported by mineral frame. Water also reduces the strength of plastic deformation of minerals by increasing concentration of lattice defects. Moreover, tomographic observations have shown that there are fluid-rich zones beneath active fault zones and strain concentration zones in the middle-lower crust (e.g., Nakajima et al., 2010). It is proposed that water affects crustal deformation and earthquake occurrence (e.g., Iio et al., 2009). However, the effect of water on rheology has not yet been revealed quantitatively for lower crustal materials under pressure conditions equivalent to the lower crust. Moreover, in most of previous studies, experiments were performed under two end-member cases: water saturated or anhydrous conditions. Thus, it has not been understood in the environment that water is gradually introduced into samples similar to natural lower crustal condition.
2. Deformation experiment
In this study, we performed deformation experiments on synthetic anorthite (An) aggregates using the Griggs-type solid medium deformation apparatus. We added 0.5 wt% water to samples and infiltrated under high temperature and high pressure. Times for infiltration of water into samples were changed to investigate the variation of deformation behaviors associated with diffusion of water. Strain rate stepping test was performed at a temperature of 900 °C and a confining pressure of 1.0 GPa. Strain rates were 1st: 10^{-5}, 2nd: $10^{-4.5}$ and 3rd: 10^{-5} s^{-1}. Constant strain rate tests were also performed at a strain rate of 10^{-5} /s, temperature of 900 °C and confining pressures of 0.8 and 1.1 GPa. The experimental conditions in the present study were roughly equivalent to the environment of the middle-lower crustal fluid-rich zones. Thus, the present study is suitable for investigating the effect of water on plastic deformation in such zones.
3. Results
In all experiments, wet samples were weaker than an anhydrous sample. Strain weakening was observed in experiments at a strain rate of 10^{-5}/s at all confining pressure conditions. Strengths tended to decrease with infiltration time or strain magnitude. Photomicrographs after the experiments of wet An deformed under confining pressure of 1.0 GPa were taken. Almost no deformation was observed in the upper part of the sample, and deformation was concentrated in the lower part.
4. Discussion and implication
We compared the measured differential stresses with predicted values by the flow law for wet An obtained by low pressure experiments (~0.4 GPa, Rybacki et al., 2006). The estimated stress values were higher than the measured values in our experiments under similar conditions. Moreover, because recovered samples were deformed in their lower part intensively, actual strain rates might be higher and estimated stress values became higher for that part than those estimates. This implies that the chemical effect of water, such as fugacity, in higher pressure condition might be larger than those predicted by lower pressure experiments. Present study shows that measured differential stresses of hydrous samples tended to decrease with infiltration time or strain magnitude. It is assumed that plastic deformation is promoted by increase of water-related defects by water

diffusion into samples. The results of present study indicate that the strength of lower crust become lower than previous studies.

Keywords: plagioclase, deformation experiments, water fugacity, strength of the crust

Technical developments on acoustic emissions monitoring under the upper mantle conditions

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The subduction zone produces a major fraction of the Earth’s seismic activity. Intermediate-depth earthquakes within the subducting slab form a double seismic zone. The mechanisms of intermediate-depth (> 40 km depth) and deep-focus (> 300 km) earthquakes are fundamentally different from those of shallow (≤ 40 km) earthquakes. This is because the frictional strength of silicate rocks is proportional to the confining pressure and it exceeds the upper limit of the stress level in the upper mantle (< 600 MPa: Obata and Karato, 1995) at pressures higher than 1 GPa (~30 km depth). The causes of intermediate-depth and deep-focus earthquakes have been attributed to dehydration of hydrous minerals (e.g., Peacock, 2001) and anticrack faulting during the phase transformation of olivine (e.g., Green et al., 1992), respectively. To understand the mechanisms of failure of rocks under the upper mantle conditions, experimental techniques on acoustic emission (AE) monitoring have been adopted to multianvil apparatuses or Griggs apparatuses.
Green et al. (1992) conducted AE monitoring by using a Griggs apparatus combined with an AE sensor. Dobson et al. (2002, 2004) and Jung et al. (2006) adopted 2 or 4 AE sensors to a multianvil apparatus. However, the three-dimensional location of AE hypocentres have not been determined in the experiments because of not enough number of sensors used in the experiments, even though determination of the location of AE hypocenter is critical in the judgement of brittle failure of the sample surrounded by the solid pressure medium. De Ronde et al. (2007) adopted 8 AE sensors to a multianvil apparatus and they succeeded to determine the position of AE sources. Recently, Gasc et al. (2011) succeeded to develop an experimental setup that allows determining the position of AE source by using DIA-type multianvil apparatus combined with 6 AE sensors. Schubnel et al. (2013) adopted the experimental setup reported by Gasc et al. (2011) to a D-DIA apparatus installed at a synchrotron facility, and they succeeded to measure strain and stress of the sample and AE signals. We have developed an experimental setup that is optimized for the determination of the location of AE hypocentres in a synchrotron D-DIA apparatus.
Similar to Schubnel et al. (2013), we developed an AE monitoring system optimized for a D-DIA apparatus installed at BL04B1, SPring-8. One of big difference between previous systems and our system is the use of the MA 6-6 system (Nishiyama et al., 2008). In our system, the AE sensors were pasted to the backside of the second-stage anvils. Use of the second-stage anvil as a wave guide enables us to shorten the distance between the sample and the AE sensors, namely, attenuation of AE waveforms is reduced. Another advantage of our system is the large-volume cell assembly (sample diameter: 3mm; length: 4mm). Because the error on the hypocenter location is usually a couple of millimeter (e.g., Gasc et al., 2011), use of a sample having a large volume is critical when we judge whether a hypocenter locates inside of the sample or not. We succeeded to conduct experiments on AE monitoring during the deformation of olivine aggregates at pressures 1-3 GPa and temperatures 600-1100 degC. Pressure, stress, and strain were measured in situ by using x-ray diffraction patterns and radiographies. AEs were also recorded continuously on six sensors, and three-dimensional AE source location were determined. We will report some the details of experimental results, and we will consider further improvements on the system.

Keywords: acoustic emission, D-DIA, earthquake

Deformation experiments of ringwoodite at low temperature conditions

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Seismic tomography images that some subducting slabs horizontally stagnate near 660km discontinuity (e.g., Fukao and Obayashi, 2013). However, it has been difficult to explain the large deformation of deep slabs in mantle transition zone because the flow law of constituent minerals such as ringwoodite has not been determined yet. Low temperature plasticity (Peierls mechanism) could be a dominant deformation mechanism in cold subducting slab. In order to construct the flow law of ringwoodite in this deformation mechanism, we conducted deformation experiments of $(Mg_{0.9},Fe_{0.1})SiO_4$ ringwoodite at low temperature conditons. Here, we report its preliminary results.

High-pressure deformation experiments were conducted at 9-13 GPa and 500°C in constant-strain rate mode by Deformation-DIA apparatus installed at NE7 and BL04B1 beamlines in synchrotron facilities of PF-AR and SPring-8, respectively. We synthesized a polycrystalline ringwoodite with height of 1.2 mm and diameter of 0.9 mm at 22 GPa and 1400°C for 180 min from a single crystalline San Carlos olivine using a Kawai-type multi-anvil apparatus in Kyushu University. This was recovered and used as a starting material for the deformation experiment. Differential stress and axial strain of ringwoodite samples were estimated from the distortion of Debye ring and radiography image using 50 keV monochromatic X-ray.

Although deformation experiments were performed outside the ringwoodite stability field, we did not observe the back transformation up to at least 500°C. The sample stress almost reached steady state at the strain of about 3%, and then slightly increased under strain up to ~20%, suggesting the strain hardening. The effect of pressure was negligible in our experimental condition. The flow stresses of ringwoodite obtained at 500°C were 2.6-5.1 GPa at the constant strain rates of $1.2\text{-}5.9\times10^{-5}$ s^{-1}, which is smaller than those obtained at room temperature in the previous study (Nishiyama et al., 2005). Preliminary analysis of the creep data indicates that the stress exponent is about 6. The relatively large stress exponent may suggest that ringwoodite was deformed in low-temperature plasticity regime although further experiments are needed to construct the quantitative flow law.

