In-situ stress-strain measurement of bridgmanite

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In order to understand mantle dynamics in the Earth’ s interior, it is important to know the viscosity of the Earth’ s lower mantle. One dimensional viscosity models of the Earth’ s mantle were proposed by geophysical observations while there are large inconsistencies of viscosity (2~3 order magnitude) in the lower mantle between suggested models. Therefore it is important to determine viscosity of lower mantle minerals by high pressure experiments in order to understand mantle dynamics. In this study, we conducted in-situ stress-strain measurements of bridgmanite aggregate using Deformation-DIA type apparatus as Kawai-type.

In-situ measurements were conducted using SPEED-Mk.II, which is D-DIA apparatus, as Kawai-type apparatus at SPring-8 BL04B1. Mg-pure bridgmanite aggregates were used as starting material. Experimental conditions are 1473-1673 K and 27-28 GPa. Pressures were estimated by equation of state on bridgmanite (Katsura et al., 2009). WC second cubic anvils with slit or cone (5°) to take tomography and 2D X-ray diffraction, was used along X-ray path. X-ray radiographies of the strain markers were taken using an imaging system composed of a YAG crystal and a CCD camera. Two-dimensional X-ray diffraction patterns were corrected for 180-300 s using CCD detector. To calculate pressure and the stress magnitude of bridgmanite, (111) (112) (200) X-ray diffraction peaks were used.

Measured uniaxial stress and strain of bridgmanite during deformation experiments were 0.3-1.3 GPa and < 6 %. Flow law in dislocation creep is described by,

$d\varepsilon/dt = A\sigma^3 \exp(-E^*/RT)$ (1)

where $d\varepsilon/dt$ is strain rate, A is pre-exponent, σ is stress, E^* is activation energy, R is gas constant and T is temperature. Least squares fit of Eq. (1) to these viscosity data yielded $A = 10^{7.6\pm1.5}$ and $E^* = 372 \pm 40$ kJ/mol. This activation energy of flow low is similar to that of atomic diffusion of bridgmanite by Xu et al. (2011). This fact supported deformation mechanism could be dislocation creep controlled by dislocation clime.

Keywords: bridgmanite, lower mantle, In-situ measurements, viscosity

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Diffusion creep and grain growth in forsterite + 15vol% enstatite aggregate

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In this study, we conducted grain growth and creep experiments on the same fine-grained forsterite + 15vol% enstatite aggregate under high temperature. We rapidly changed load applying to the sample for "stepped test", which was aimed to infer creep mechanisms at a wide range of stress. We gradually changed temperature under application of a constant load for "gradual temperature change test" to collect vast numbers of stress/strain rate/grain-size/temperature data which allow their statistical analyses to obtain precise flow parameters such as pre-exponential factors and activation energies for given flow laws. Grain growth experiment with a long duration (= 500 h) at different temperatures was aimed to obtain a precise temperature dependency of grain growth. Dependency of n on stress was investigated from the results of stepped tests conducted at temperatures from 1150°C to 1370°C at stress ranging from 5 MPa to 300 MPa. We found monotonic decrease of stress exponent from 2 to 1 with increasing stress and its rapid increase to > 3 at high stress regime. We inferred that interface-reaction control diffusional creep and grain boundary (GB) diffusion creep worked sequentially at low stress, while GB diffusion creep and dislocation creep worked parallel at high stress condition. Activation energy of 432 kJ/mol for GB creep and pre-exponential factor of 6.15×10^{11} $\mathrm{um}^3\mathrm{K/MPa/sec}$ were obtained from MCMC analyses mainly of the results of gradual temperature change tests. Grain growth experiment showed a monotonic increase in grains size of both forsterite and enstatite phases with increasing temperature at > 1300°C.

Diffusivities estimated from creep and grain growth rates using classic GB diffusion creep and grain growth laws well coincide at all experimental ranges indicating that governing diffusional processes for creep and grain growth are identical. We compare our obtained diffusivities with the results of previous direct measurements on grain boundary self-diffusivities of MgO (*Gardes and Heinrich*, 2011) and Si (*Fei et al.*, 2016) finding that MgO GB diffusion rather than Si explains our observations.

Keywords: upper mantle rheology, grain growth, diffusion creep, olivine, diffusivity, rate-controlling element

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Creep behavior and high-pressure faulting during the olivine-spinel transformation in fayalite

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Transformations from metastable olivine at large overpressures in cold subducting slabs may cause significant grain-size reduction and lead to the slab weakening and deep earthquakes. It is indispensable to investigate the coupling process between transformation and deformation under pressures of mantle transition zone. In the present study, we examined creep behaviors during the olivine-spinel transformation in fayalite (Fe_2SiO_4) up to ~14 GPa and observed some evidences for transformational faulting. Deformation experiments were conducted using a Deformation-DIA apparatus in the beamline of BL04B1 at SPring-8. After annealing polycrystalline fayalite at ~3.5 GPa and 900°C for 2 h, we observed the olivine-spinel transformation at ~6-14 GPa and 873-1173 K with and without deformation (in uniaxial compression with constant strain rate of 3-5 x 10^{-5} s^{-1}). Stress-strain and transformation-time (strain) curves were simultaneously obtained from time-resolved measurements of two-dimensional X-ray diffraction patterns and X-ray radiography images using monochromatic X-ray (energy 50-60 keV). Overpressures needed for initiating the transformation increased with decreasing temperature from 1.5 GPa and 1173 K to 3.8 GPa at 973 K in the case of no deformation. When the sample was deformed, the overpressures decreased by ~0.5-1 GPa, suggesting the enhancement of spinel nucleation by stress and/or deformation. Stresses in olivine, spinel, and the bulk sample (from stress marker arranged in tandem) were similar at the initial stage, and then spinel becomes dominant deformation phase at around 70% transformation. In these runs conducted at more than 973 K, transformation occurred at grain boundaries of parental phase, and the reaction rims were not formed. On the contrary, larger overpressures than ~5 GPa are needed to cause transformation at lower temperature of 873 K even with deformation, in which we observed faulting across the sample associated with lamellar intracrystalline transformations and micro fracture. The thin intracrysatlline lamellae in olivine crystal developed almost parallel to the main fault and consisted of sub-micron fine-grained materials. This may correspond to transformational faulting as previously observed in germanate olivine at lower pressure conditions of ~5 GPa (Schubnel+, SCI13), however further studies with AE measurements and TEM analysis are needed to understand the detailed process. We did not observe clear evidence for the weakening of bulk sample due to the grain-size reduction as proposed in previous studies.

Keywords: high pressure transformation, deformation experiment, D-DIA, in-situ X-ray observation, Deep Earthquakes

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On ductile-to-brittle transition of ice-silica mixtures under compressive loading

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On the bodies in the solar system such as Earth, Mars, and icy satellites, various landforms related to the flow and the fracture of ice-rock mixtures are found; for examples, glaciers on Earth, fretted terrains on Mars, relaxed craters and trough terrains on Europa and Ganymede. To clarify the formation processes and structures of these features, it is necessary to understand the rheological properties of ice-rock mixtures.

Ductile-to-brittle (D/B) transition is one of the most important rheological properties to determine the tectonic style on the bodies, flow features and fracture patterns. The D/B transition of water ice has been studied by some researchers and a theoretical model for the strain rate corresponding to the D/B transition was proposed [Schulson, 1990; Renshaw and Schulson, 2001]. This model indicates that the transitional strain rate depends on ice grain size, temperature, confining pressure, and degree of pre-cracks. However, the D/B transition of ice-rock mixtures has not been studied yet. In this study, we carried out compression experiments on ice-rock mixtures to examine the D/B transition. One of the parameters which is expected to affect the D/B transition of ice-rock mixture is a rock content. So we examined the effect of rock content on D/B transition and compared the experimentally observed transitional strain rates to predictions of the model proposed earlier.

The samples were prepared by mixing ice seeds (diameter < 850 μm) and amorphous silica beads with a diameter of 0.25 μm. To fill spaces and to reduce porosity of sample as soon as possible, the distilled water at 0° C was filled. The samples were frozen over a period of one day in a cold room set at -10° C. We made samples with silica volume fraction f of 0, 0.06, and 0.18. The sample has a cylindrical shape with a diameter of 30 mm and a height of 30 or 60 mm. We performed unconfined compression experiments under constant strain rate from 10^{-5} to 0.6 s^{-1} in a cold room at Ice Research Laboratory, Dartmouth College. The room temperature was set to be -10° C.

The deformation behavior, ductile or brittle, under compressive loading is characterized by the shape of stress-strain curve and by the relationship between peak stress on the stress-strain curve and strain rate. In the case of water ice, the peak stress increased exponentially with increasing strain rate in the ductile regime while it decreased with increasing strain rate in the brittle regime. In the case of ice-silica mixture with f=0.06, the peak stress change with strain rate was similar to that with pure ice (f=0), that is, the peak stress reached a maximum at the D/B transition. However, in the case of ice-silica mixture with f=0.18, the peak stress continued to increase with increasing strain rate. The stress-strain curves for f=0.18 remained ductile-like for all strain rates, so the D/B transition for f=0.18 was expected to be greater than the maximum strain rate (0.6 s^{-1}) explored in this study. Consequently, the transitional strain rates for pure ice and ice-silica mixtures were determined; 10^{-3}-10^{-2} s^{-1} for pure ice, 10^{-2}-10^{-1} s^{-1} for f=0.06 and > 0.6 s^{-1} for f=0.18. We found that the transitional strain rate increased with increasing silica volume fraction.

Finally, we compared the theoretical value predicted from the model by Schulson [1990] to the experimental value. In the case of pure ice, the theoretical transitional strain rate was in good agreement with the measured value. On the other hand, in the case of ice-silica mixtures the theoretical value was larger than the measured value. This might be caused by high sensitivity of the transitional strain rate to the stress exponent n, in the power law relationship between peak stress and strain rate ($d\varepsilon/dt=B\sigma_{peak}^{n}$).

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Keywords: ductile-to-brittle transition, ice-silica mixtures, silica volume fraction, stress-strain curve, compressive strength

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Effect of solid particles and grain boundary on deformation of fine-grained polycrystalline ice

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Behavior of Greenland ice sheet plays a fundamental role in global climate change. Understanding of ice sheet dynamics is important for high-accuracy prediction of sea level rise and ocean circulation variation. Although ice sheet behavior has large spatial-temporal scales, importance of microstructure of polycrystalline ice has been suggested from ice-core analysis (e.g., Faria et al., 2014). Flow law of large-grained polycrystalline ice has been studied by laboratory experiments. However, flow law of ice-sheet ice is complicated by various factors. Cloudy bands, which are localized in the ice sheet cores and contains highly-concentrated impurities, show finer ice grains. Although the interaction between solid particles and ice has been discussed by previous papers (e.g., Rempel and Worster, 1999, Durand et al., 2006), detailed effects in polycrystalline ice and ice core are still uncertain. We have performed mechanical tests and microstructure analysis using artificial ice to investigate the effect of solid particles on flow low of fine-grained polycrystalline ice.

We prepared artificial ice with and without silica-particles (particle size of 0.3 μm and dispersed-amount of 0.1wt%). Powder ice (made by spraying pure water and silica-dispersed water into liquid nitrogen) is compressed for an hour with 70 MPa pressure. Deformation experiments were conducted under constant temperature and pressure with various conditions. Our experimental results clarified the effect of solid particles as follows: 1) grain size of silica-dispersed ice is smaller than that of pure-water ice, 2) strain rate of silica-dispersed ice is larger than that of pure-water ice, 3) minimum strain rate (steady-state creep) was not achieved even with 10%-strain for both pure-water and silica-dispersed ice. Generally, a dislocation creep, which has no dependence on grain-size, dominates the ice deformation, however, our results (grain-size dependence and decreasing strain rate) suggest the possibility of grain boundary effect on the deformation mechanism.

In this presentation, we discuss the deformation mechanism of fine-grained polycrystalline ice from deformation test and microstructure analysis, and the flow of Greenland ice sheet.

Keywords: ice-sheet flow, solid particle

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Diffusion studies of water ice and its high-pressure phases: Implications for rheology

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Water ice is a primary constituent of the crusts and mantles of the large icy bodies such as Galilean satellites and Edgeworth-Kuiper belt objects. Understanding rheological properties of water ice including its high pressure phases are essential to understanding the dynamics of the large icy bodies. The real icy crusts and mantle include other constituents such as ammonia, Mg- and Na- sulfates, methane hydrate, and non-water ices. The influence of the sub-constituents on the dynamics is never negligible. The dynamics model based on the unary water system, however, will give some important implications, and be the useful approximation.

Our motivation for the rheological studies of water ice is the first step to understanding the dynamics of the real large icy bodies.The differential stress driving the convections of the icy crust and mantle is very low below 0.01 MPa. The deformation experiments at low-stress conditions are technically difficult. Thus the rheological properties of water ices must be examined by another approach. Newtonian-rheological model is most plausible under such low-stress condition. The Newtonian-rheological properties can be inferred from their diffusivities and the theories of diffusion creep. The ordinary isotope-diffusion method using the mass-spectrometer cannot be applied to the ice diffusion study. To defeat this problem, we have developed the isotope-diffusion method using micro-Raman spectroscopy. First, to conduct the diffusion experiments, the method for the quantitative analysis of isotope tracers using micro-Raman spectroscopy was constructed. The diffusion experiment of poly-crystalline ice I_h under confining pressure was carried out by using this technique, and the grain boundary diffusion coefficient was constrained. Further, we applied this method to the high pressure experiment using diamond anvil cell, and the diffusion coefficients of high-pressure phases were determined. In my presentation, I would like to talk about our efforts to determining the rheological properties of the ices and its high pressure phases through the diffusion studies following a short review for the previous studies. In addition, I will also discuss the condition requires to trigger convection in the large icy bodies based on the results of the diffusion experiments.

Keywords: ice, diffusion, rheology, high pressure, icy bodies

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Changes of viscosity and yield stress of montmorillonite-water system with reference to consistency limits

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Montmorillonite abundantly exists in the slip zones such as earthquake faults and landslides. Water contents are an important factor for controlling slip behavior, since montmorillonite contains a considerable amount of water molecules compared with other clay minerals. Clay-water system is known to act as a Bingham fluid and we estimated yield stress and Bigham viscosity at different water contents from 100 to 1000 % using a rheometer (Brookfield Rheometer). Starting material is montmorillonite (JCSS-3101; Na-montmorillonite from Tsukinuno, Yamagata Prefecture, NE Japan) provided by Japan Clay Science Society. Yield stress drastically decreases from ca. 20000 Pa (100% water content) to ca. 3000 Pa (600%), and it does not remarkable change at higher water content conditions. Bingham viscosity also large decrease from 1.6 Pa・s (100 % water content) to 0.4 Pa・s (600 %) and then it does not show remarkable change at higher water contents. Thus, there is an inflection point at 600%. The consistency limits of montmorillonite are accepted as ˜ 10 %, 54 ˜ 98 %, and 290 ˜ 710 % for the shrinkage, plastic, and liquid limits, respectively. The inflection point is well correlated to liquid limit of montmorillonite.

Keywords: Montmorillonite-water system, Slip zone, Fault gouge

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Effect of humidity and interlayer cation on frictional strength of montmorillonite

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Smectite has been ubiquitously seen in fault gouge [Ohtani et al., 2000; Schleicher et al., 2006; Kameda et al., 2015] and is characteristic by low frictional coefficient [Summers and Byerlee, 1977; Shimamoto and Logan, 1981]; consequently, it has a key role in fault dynamics [Ikari et al., 2007; Ujiie et al., 2013]. The water content of montmorillonite decreases with increasing depth corresponding to temperature and pressure [Bird, 1984]. And the interlayer cation species of montmorillonite change corresponding to depth [Kameda et al., 2016]. Thus, to more understand fault dynamics, it is necessary to study the effect of hydration on the frictional strength of montmorillonite, which have various interlayer cation spices. However, experimental study for frictional strengths of cation-exchanged montmorillonite under controlled hydration state has rarely reported. Because it is known that the water content of montmorillonite increases with relative humidity, we developed the humidity control system in biaxial friction testing machine and investigated the effect of relative humidity (hydration state) and interlayer cation on frictional strength of montmorillonite. The humidity control system consists of two units, the sample holder (pressure vessel) unit and the vapor generating unit. We controlled both the core holder temperature and the vapor temperature independently, thereby controlled relative humidity. The frictional experiments in this study were performed at five different relative humidity (RH) conditions (10, 30, 50, 70, and 90 %). Na-montmorillonite and Ca-montmorillonite (cation exchanged from Na-montmorillonite with $CaCl_2$ solution) were sheared in this study. In all experiments, the samples were applied normal stress during sliding was kept constant at 10 MPa and sheared at 3 μm/s, and the core holder temperature was kept constant at 95 °C. The results of frictional coefficients for both Na- and Ca-montmorillonite decrease with increasing RH. The frictional coefficient of Na-montmorillonite decrease from 0.33 at RH 10 % to 0.062 at RH 90 % and the frictional coefficient of Ca-montmorillonite decrease from 0.25 at RH 10 % to 0.037 at RH 90 %. The frictional coefficients of Na-montmorillonite are larger, compared to Ca-montmorillonite at same RH conditions, which is consistent with Behnsen and Faulkner [2013] using water saturated samples. This trend can be explained by difference of hydration energy, that is, the smaller hydration energy leads closer interlayer distance and stronger bonding between silicate layers [Behnsen and Faulkner, 2013]. There is a negative correlation between water content and frictional strength, which is consistent with previous research [Bird, 1984; Ikari et al., 2007]. For explain the decrease of frictional coefficient with increasing relative humidity, there are two main water weakening mechanisms; (1) the shear strength weakens due to hydration of interlayers and expands distance between layers in montmorillonite [Bird, 1984], (2) the shear strength decrease due to water-film on the particles become thick [Moore and Lockner, 2007]. The changes of interlayer distance with interlayer swelling corresponding to relative humidity are discontinuous at atmospheric pressure [Morodome and Kawamura, 2009], whereas water content of montmorillonite increases continuously with increasing relative humidity [Xu et al., 2000]. From our results that frictional strength decrease continuously with increasing relative humidity, the negative correlation between frictional strength and relative humidity can be explained by mainly interparticle swelling. Our results show hydration state and interlayer cation species are particularly germane to frictional strength. For considering frictional strength at deep underground, an important point to emphasize is that Na-montmorillonite is stronger than Ca-montmorillonite not only at saturated with water [Behnsen and Faulkner, 2013] but also dry state.

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Keywords: montmorillonite, hydration, humidity, interlayer cation, frictional strength

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Effect of preferred orientation on the frictional strength of montmorillonite gouge

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Clay minerals have been found in the sliding zones of natural faults and landslides. Most clay minerals are composed by the stacking of 1-nm thick structural layers, and shows large surface specific area. The surface of most clay minerals has high affinity with water and some clay minerals swell at highly humid conditions and in aqueous solutions. Since the presence of interlayer water alters the frictional properties of simulated gouges composed by swelling clay minerals, understanding of the swelling state at various environmental conditions is important for fault and landslides mechanics.

The morphology of clay minerals is plates with large aspect ratio. The preferred orientation of the particles along with the sliding plane can change the frictional properties of gouge [1]. Since the degree of preferred orientation depends on the environment of clay mineral formation [2], frictional properties of simulated gouge having clay minerals should be investigated for various degrees of preferred orientation. Here we measured the shear stress of montmorillonite gouges with two different degrees of preferred orientation under dry conditions.

The degree of the preferred orientation of montmorillonite gouge was evaluated by X-ray diffraction method. To prepare the dry montmorillonite particles without interlayer water, thermal analysis (TG-DTA) was conducted before the shear measurements. Highly oriented montmorillonite gouges shows long dehydration time relative to low orientated montmorillonite gouges. This can be interpreted by the difference of permeability of gouges.

Shear experiments were performed at the normal stress from 5 to 40 MPa. Highly orientated montmorillonite gouges shows high shear stress and strong normal stress dependence compared to the gouges of low orientation. This implies the cohesion force acting between montmorillonite basal planes at dry condition have a large effect on the frictional properties of highly orientated montmorillonite gouges.

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Keywords: Double shear test, Dependence of normal stress, Hydration, Swelling, Clay minerals

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Frictional characteristics of brucite (001) plane on the real contact area

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Sheet-structure minerals such as clay minerals are abundant in natural faults. As they are thought to be dominant elements of the slip of faults, it is important to investigate their frictional characteristics. While friction coefficients of general rocks are 0.6-1.0 (Byerlee 1978), sheet-structure minerals have smaller frictional coefficients of 0.2-0.4 (Behnsen and Faulkner 2012). Though this weak friction coefficient is considered to be caused by orientation of relatively weakly bonded (001) plane (Moore and Lockner 2004), no experimental evidence was provided. Recent experiments showed that friction coefficient of single crystal specimens of muscovite was about half of that of polycrystalline muscovite (Kawai et al. 2015), implying that the frictional mechanism of (001) planes is important to explain the low friction of clay gouges. The friction coefficients of sheet-structure minerals were thought to be proportional to the interlayer bonding energy (ILBE) of (001) planes (Moore and Lockner 2004), which is associated with mineral specific electrostatic forces between layers estimated by Giese (1978). However, recent experiments and theoretical calculations showed less relationship between ILBE and friction coefficient (Behnsen and Faulkner 2012; Sakuma and Suehara 2015; Kawai et al. 2015). Hence, it is required to understand a physical process that explains the frictional characteristics of sheet-structure minerals instead of ILBE. Here, we investigate frictional characteristics on real contact area of brucite (001) plane to develop the fundamental physics of the friction between (001) planes. Brucite ($Mg(OH)_2$) is a sheet-structure mineral richly contained in serpentinite often observed in natural faults. The crystal structure is simple and this mineral is suitable for the first principles calculations without high computational cost.

We calculate the potential energy surface under the friction of (001) planes of brucite by using the first principles calculation of electronic structure based on the density functional theory. The normal and friction forces were derived from the potential energy map as the method proposed by Zhong and Tomanek (1989).

Our preliminary results show internal friction coefficient = 0.048 and cohesion stress = 0.371GPa in the sliding direction of <010> on (001) plane.

We will estimate frictional characteristics in any sliding direction on (001) plane and discuss dependence of frictional characteristics on sliding directions. In addition, we will compare frictional characteristics of brucite with those of other sheet-structure minerals such as lizardite, talc, pyrophyllite, and muscovite, investigated by Sakuma et al. (2016) and Kawai et al. (2016) and discuss the difference of frictional characteristics on real contact area among sheet-structure minerals.

Keywords: Sheet-structure minerals, (001) plane, Frictional characteristics, Interlayer bonding energy, The first principles calculation of electronic structure

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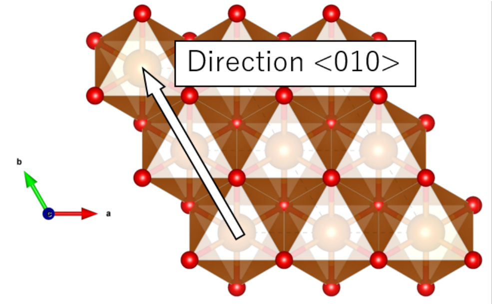
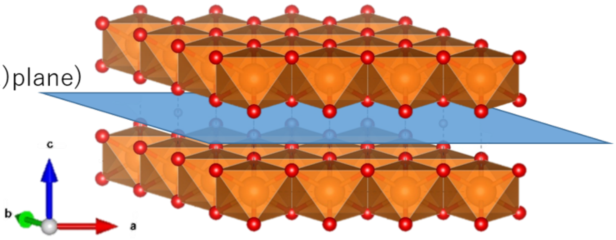


(001) plane



Sliding plane
(parallel to (001)plane)

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Evolution of the deformation band in the numerical sandbox experiment with 2.4 billion DEM particles

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We modeled a deformation mechanism of an accretionary prism using the numerical simulation of the sandbox experiment. We solved the motion of 2.4 billion solid particles with Discrete Element Method (DEM) on massively parallel supercomputer system. This huge number of particles enabled us to use the realistic parameters of the sand. Thus, we could successfully reproduce the prism evolution which was consistent with the lab sandbox experiment. One of the advantages of numerical simulation over the analog experiment is the ability to analyze the detailed deformation processes of the granular layer in 3D. We analyzed the mechanical state of particles inside the deformation band to reveal the relations between the growth mode and the wavelength of the deformation. From the results, we discuss the characteristic length to change the deformation mode between the discrete and continuous behaviors.

Keywords: accretionary prism, sandbox, DEM

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Scaling of convective velocity in intermittently vibrated granular packing

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When a granular packing is mechanically vibrated in a container, convective motion of constituent particles is often induced. This peculiar phenomenon is called ‘granular convection’. Recent studies have suggested that granular convection could occur on the surface of small asteroids such as Itokawa [1,2]. To quantitatively examine the feasibility of asteroidal granular convection, a scaling relation for granular convective velocity has been experimentally developed [3]. However, this scaling relation has been obtained under the steady vibration condition although the actual asteroidal vibration events should be induced by very intermittent meteorite impacts. The scaling relation for convective velocity in an intermittently vibrated granular packing has not been quantitatively obtained so far. Thus, it is necessary to study the granular convective velocity in an intermittently vibrated granular packing. Therefore, in this study, we experimentally measured the granular convective velocity in a two-dimensional granular packing under the successive intermittent vibrations, (tappings). And the obtained velocity scaling is compared with the scaling obtained with a steady vibration.

In the experiment, a two-dimensional chamber filled with bi-disperse disks (diameter: = 10 or 15 mm) is vertically mounted on an electromagnetic vibrator. Then the chamber is subject to 1,000 successive tappings (each tapping event consists of a single period of sinusoidal oscillation). The interval between these tappings is fixed at 2 s. We define the tapping strength Γ as $\Gamma = A(2\pi f)^2/g$, where A is vibration amplitude, f is its frequency, and g is gravitational acceleration (*i. e.* Γ means the ratio of maximum tapping acceleration and gravitational acceleration). Γ is systematically varied as $\Gamma = 2.5, 5, 10, 20$, and f is also varied in the range of $f = 50, 100, 200$ Hz.

In the analysis, we calculated particle velocities using by the particle tracking velocimetry method. In addition, we calculated vorticity field from each particle velocity so that we quantitatively evaluated the occurrence of convective motion in the intermittently tapped granular packing. When the particles form convective motion, we first normalize the mean particle’s velocity v as $v^* = v/(gd)^{1/2}$, where $(gd)^{1/2}$ is the characteristic velocity created by gravity and particle size. We then constructed the scaling relationship between v^* and the dimensionless parameter $S = (2\pi Af)^2/gd$ (Here, S denotes the balance between the squared tapping-velocity and the squared characteristic velocity created by gravity).

As a result, we found a scaling relationship between v^* and S for the intermittently tapped granular packing: $v^* \sim S^{0.56}$ (Fig.1). This result indicates that v is roughly scaled by $S^{1/2}$ which is almost identical to the scaling obtained with a steady vibration. Therefore, we conclude the intermittency of oscillation doesn’t affect the velocity of granular convection.

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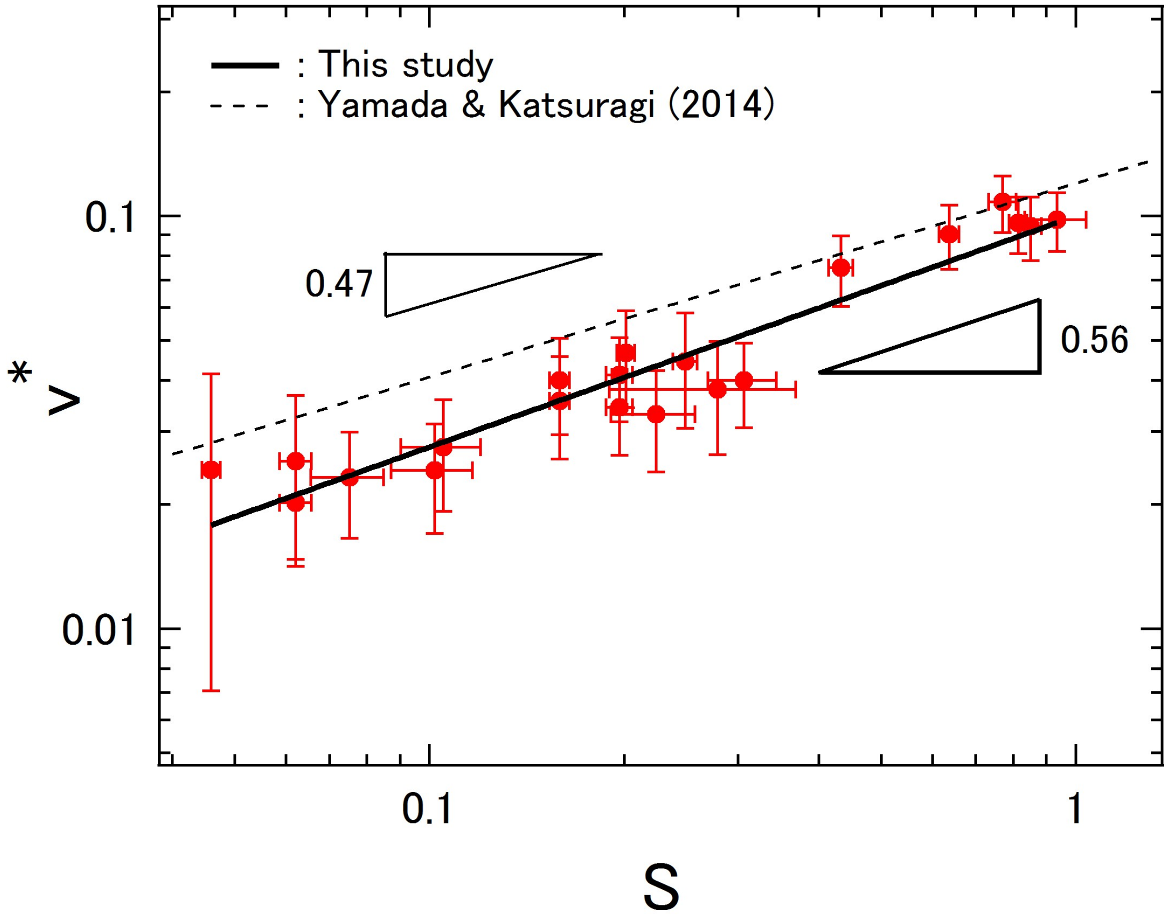
Keywords: granular convection, scaling, regolith



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Kinetics study on stress drop and recurrence interval during stick-slip with dehydration

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It has been found that the phase change of the material and the water generated by dehydration reaction influence the mechanical behavior of the rock. In particular, the frictional stability of the seismogenic zone is considered to change due to friction constant changed by phase-change. Many previous studies focus on instability of slip and localization of strain by the changes in mechanical properties (Proctor and Hirth, 2015). Because the volume of the water generated during the dehydration reaction is generally negligibly small, so that accurate measurement is difficult. For this reason, mechanical behavior is investigated by conducting experiments that controls pore-fluid pressure (Leclere et al., 2016). However, previous study that measures multiple slip events is few. The few studies have been conducted to combine the dehydration with recurrence interval of stick-slip events. In addition, there are few studies that discuss the dehydration not kinetic but mechanical point. In Sawai et al. (2013), kinetic models are applied to describe the dehydration reaction in experiments reproducing the seismogenic zone using serpentinite. Similarly, few studies applied over multiple slip events, and studies have not been conducted on the kinetics of the recurrence interval. When multiple slip events happen with the dehydration reaction, it is possible to describe the recurrence interval in terms of pore-pressure evolution kinetically.

In this study, we analyzed using the data of triaxial compression test made at Sasaki et al. (2016). In the experiment, simulated gouge sample of gypsum hemihydrate, bassanite, between precut gabbro pistons was deformed in high pressure gas medium apparatus at confining pressures of 10 - 200 MPa and temperatures up to 180 ℃. At 200 MPa, 70 ℃ corresponding to non-dehydration condition, samples exhibited stick-slip behavior and the strength of the samples became larger. On the other hand, at 200 MPa, 110 ℃ and higher, likely corresponding to condition for stable anhydrite phase, stick-slip behavior was found to be diminished with the reduction in mechanical strengths with strain.

In this study, we calculate recurrence interval and shear stress drop from data of deformation experiment. We found that recurrence interval and shear stress drop is proportional to confining pressure in experiments with non-dehydration reaction. On the other hand, both recurrence interval and shear stress drop decrease with time despite in an experiment with dehydration reaction. Because the experiment is conducted under constant confining pressure, we consider the decreases in the effective pressure by increasing pore-fluid pressure. From this knowledge, we estimated pore-fluid pressure at time with the effective pressure law. Also, we fit pore-fluid pressure data with Avrami equation. As a result, we found that the evolution of pore-fluid pressure can be described using Avrami equation. From this fact, we consider that by applying the same kinetic approach to different minerals as in this study, it is possible to evaluate the difference of the mechanical properties caused by the dehydration reaction

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Asperity contact and constitutive relations in gel friction

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It is believed that asperity contact plays an important role in fricton, in particular in onset of dynamic slip or stick-slip motions. However, there remain very few studies controling asperities and observing their effects on mascoscopic stick-slip behavior or frictional constitutive laws. Here we perform stick-slip friction experiments between compliant gels with well-controlled asperity shape/size/configurations by molding technique. We find that, as curvature radius of the asperity becomes larger and the normal stress becomes smaller, velocity dependence turns from rate-strengthening to rate-weakening and accordingly, frictional behavior transitions from steady sliding, slow slip to fast slip. In this talk, we discuss the asperity size effects based on microscopic/macroscopic observations as well as a theoretical argument.

Keywords: frictional constitutive relation, stick-slip, slow slip, asperity, laboratory experiment

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Rheological variety of mixtures of water and ash collected at Ontake and Sakurajima volcanoes

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Most volcanoes are covered with volcanic ash fallen after various types of ash-dominated eruptions. Once the ash combines with water, it is likely to run down slopes. The flow is referred to as lahar, which is widely observed all over the world. Lahar is one of the volcanic phenomena that cause severe damage to surrounding environment, since the speed is generally far faster than that of lava and the onset time is hard to predict [E. Bélizal et al., 2013; S. Jenkins et al., 2015]. Sometimes it occurs just after an eruption [Nakayama and Kuroda, 2003] whereas a large debris flow, which broke out about 30 years after the latest eruption due to heavy rainfall, was reported [Ogiso and Yomogida, 2015]. Moreover, lahar-flow is occasionally accompanied by seismic signals [Walsh et al., 2016; Ogiso and Yomogida, 2015], so that understanding flow characteristics of lahar is important to investigate the relation between lahar-flow and seismicity leading to early detection of the onset in addition to the purpose of simulating the flow.

Based on the background, we have performed rheological measurements of mixtures of volcanic ash and water, which are major compositions of lahar. The volcanic ash used in this study was collected at Sakurajima and Ontake volcanoes in Japan. The reason why the two volcanoes are focused is that lahar had flowed there after recent eruptions although the two types of volcanic ash are apparently different. In order to reveal key features in rheology and to compare rheological characteristics, the viscosity was measured changing the particle concentration and the shear rate. An important point of our findings is that the two types of mixtures show non-linear characteristics differently. For instance, Sakurajima samples show strong shear-thinning regardless of the particle concentration whereas the viscosity fluctuates in a longer time scale than rotational period of rheometer within a certain definite range of shear rate in the case of Ontake samples. Interestingly, the range of shear rate corresponds to that at which the relation between the viscosity and the shear rate shows positive slope or shear-thickening deviating from shear-thinning. Since these non-linear characteristics are considered to be induced by variations in particles such as size and shape [C. Chang and R. Powell, 1994; D. Genovese, 2012; S. Mueller et al., 2014], we mainly discuss the rheological changes of mixtures of volcanic ash and water with consideration for the particle size distribution.

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Rheological properties of Izu Oshima lava

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Apparent viscosities were estimated for 1950-1951 and 1986 lava flows effused from summit crater, based on the observed lava flow thickness, lava surface velocity and slope angle (Murauchi, 1950; Minakami, 1951; Shirao, 1986). They ranged 1.7×10^4 Pa s (1063 °C) - 3.3×10^6 Pa s (1048 °C) in 1950, 5.6×10^2 Pa s (1125 °C) - 2.3×10^4 Pa s (1038 °C) in 1951 and 1.7×10^4 Pa s - 1.2×10^7 Pa s for LA lava in 1986 (no temperature data). These values are curious in that the viscosity of 1950 lava changed over two orders within 15 °C, and 1950 lava at 1048 °C had over two orders higher viscosity than 1951 lava at 1938 °C. Minakami (1951) also pointed out that the apparent viscosities from observation were several tens times higher than the measured viscosity in laboratory. Systematic study has not been done for Izu Oshima lava rheology thus far. In the present study the viscosity of natural rock samples from Izu Oshima lava, mainly 1986 LC lava, was measured by uniaxial compression viscometry with temperature and stress range between 1000 °C and 1100 °C and 0.057 MPa and 10 MPa, respectively, at Earthquake Research Institute, University of Tokyo. Cylindrical cores with 15 mm diameter and 30 mm high were used for viscosity measurements. Viscosity was derived from deformation rate and sample dimension using Gent’s equation (Gent, 1960).

Contrary to the expectation before the experiment that the viscosity decreases continuously with increasing temperature, Izu Oshima lava becomes deformable drastically at around 1100 °C. Below this temperature viscosity changes continuously with temperature, although there are over one order scatters among used cores at the same temperature. Their minimum values are 2.1×10^{12} Pa s at 1059 °C and 1.7×10^{11} Pa s at 1082 °C. These values are almost at solid state and much higher than the observed viscosity. At the temperature that the sample becomes deformable, the main factor of the deformation was not viscous flow but brittle failure. Once the sample started to deform under constant stress, deformation rate increased with time. Or when the constant compression rate was applied, stress decreased drastically with time, which is in contrast with viscous flow that stress goes constant by balancing with applied strain rate. The drastic deformation tended to occur at lower temperature when the applied stress or strain rate was high. The samples after the drastic deformation had vertical cracks on its surface, and in case the compression stroke was large (a few mm) the middle of the cylindrical core was crushed and their surface skin pushed out brittly. Bistered surface gave us doubt that the oxidized strong surface layer sustained the applied stress before the drastic deformation, but the experimental result under reductive atmospheric condition (CO_2+5%H_2) was similar with those done under atmospheric air, indicating the influence of oxidation is minor on the rheological behavior of the used sample.

The present study indicates the Izu Oshima lava was almost at solid state below 1100 °C, and above this temperature the main factor of the deformation was not viscous flow but brittle failure. These imply the displacement of Izu Oshima lava was not by Newtonian flow, and these rheological properties may be the source of the above mentioned curious observed viscosity.

Acknowledgements

I am grateful to Prof. Hiraga and his students K. Sueyoshi and K. Yabe for their supports on viscosity measurements. This study is supported by grant in aid for cooperative work from Earthquake Research Institute, University of Tokyo.

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Keywords: Izu Oshima, viscosity, rheology

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Deformation experiments of foam during solidification -exploring the history of tube pumice-

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Tube pumice is a common product of explosive silicic eruptions forming calderas. It is characterized by bubbles which elongate in one direction. We expect that tube pumice records information about the process leading to a caldera eruption.

In the past, researchers focused on the capillary number (**$Ca=R\eta_0\varepsilon'/\Gamma$**), which represents the competition between the timescale of shear deformation due to external velocity field and that of shape relaxation due to surface tension. R is the bubble radius, η_0 is the viscosity of the liquid surrounding the bubbles, ε' is the shear rate, and Γ is the surface tension. The more elongated bubbles are observed with the larger Ca in steady states.

However, bubbles deformed by flow may be relaxed if they have enough time in the stress-free condition before solidification of the pumice. We define the pumice number (**$Pu=R\eta_0'/\Gamma$**) which represents the competition between the timescale of solidification and that of shape relaxation. η_0' is the rate of viscosity increase of the liquid. The elongated bubbles may be preserved in the pumice if the pumice number is high.

In order to determine the effect of the pumice number, we conduct deformation-solidification experiments on polyurethane foam using a rheometer (Ohashi et al., 2016, VSJ fall meeting). Shear strain is applied by rotating the inner rod at a constant speed when the viscosity reaches a specified value. After solidification, we observe the bubble structures of the samples with X-ray computed tomography (CT) and analyze the size and the deformation ratio of bubbles in the 3-D images.

We find a tube-like bubble structure in the sample which experienced large strain. Because it is difficult to quantify the structure due to the limited image analysis technique, experiments are conducted with smaller applied strain. The results clearly show that the deformation ratio cannot be explained by Ca alone. Within a single sample, estimated Ca and Pu vary depending on the sizes and locations of the individual bubbles, and the deformation ratios also vary. For the same Ca, the deformation ratio is smaller for the larger Pu.

To explain the results quantitatively, we apply the time-evolution deformation model with an additional effect of the exponential viscosity increase. The results of numerical calculation show that the amount of the relaxation after the elongation decreases as Pu increases as supposed. However, in the unsteady states, bubbles do not elongate during the shear deformation of the surrounding fluid. The detailed explanation of these behavior will be conducted in the presentation.

In conclusion pumice records bubble elongation at the end of the last shear deformation when Pu is large enough. Tube pumice indicates that the last shear deformation has occurred with sufficiently large Ca and sufficiently large strains.

Keywords: tube pumice, bubble deformation, rheology

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Numerical modeling of fracture of porous Maxwell fluid by phase-field method

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Brittle fragmentation of vesicular magma is a key process in explosive eruption. Recent estimation on the decompression time in real explosive events indicates that the style of fragmentation is to be “brittle-like fragmentation” (Kameda et al. JVGR 2013), which is defined as the solid-like fracture of the material whose bulk rheological properties is close to fluid state. We also found the fact that the spatial inhomogeneity of bubble distribution is a major source of crack development that may lead to brittle-like fragmentation (Kameda et al. in preparation).
In order to model our findings by numerical approach, we propose a continuum description of fracture in viscoelastic fluid using a phase-field method (Spatschek et al. Phil. Mag. 2011). The phase-field modes with sharp interfaces consist in incorporating a continuous field variable so-called “order parameter,” by which the magma and the bubbles (or the cracks) are distinguished. In this study, the evolution of the order parameter is described using the Allen-Cahn equation consisting of local elastic energy, surface energy and additional numerical parameters. Evolution of crack is driven by local elastic energy. A commercial multiphysics solver (COMSOL) is used as the platform of numerical simulation. The evolution of the order parameter is solved using PDE solver of COMSOL in which weak formulation of the governing equation is described by ourselves. The evolution of strain-stress field in the system is calculated using conventional finite element analysis (FEM) prepared in the solver, in which the rheology of unbroken magma is assumed to be a linear Maxwell fluid.
We consider a sphere consisting of Maxwell fluid and gas bubbles (Fig. 1). In order to reduce the computational cost, one-eighth portion of the sphere is used as the computational domain. A large bubble is placed at the center of the sphere. Another satellite bubble is placed beneath the large bubble. We tested two arrangements about the location of the satellite bubble. In one case, it is placed at the position equal distance away from three planes of symmetry. In another case, the position is biased toward one of the symmetry plane. Physical properties of the materials are determined according to our previous laboratory experiment (Kameda et al. 2013). Isotropic (spherical) negative pressure (gradually increases with time) is loaded outer surface of the computational domain as a decompression.
Time evolution of Maxwell fluid/gas interface is displayed in Fig. 2. Figure 2 indicates that the arrangement of the bubbles remarkably affects the evolution of the crack. The process is divided into four parts: First, a tip is formed on the satellite bubble toward the large bubble. Second, the tip reaches the surface of the large bubble. Third, only in the case where the position of the satellite bubble is biased, a plane crack beneath the large bubble is rapidly developed toward the plane of symmetry. Finally, the plane crack propagates toward outer boundary, then a sharp crack is opened.
We found that stress concentration due to mutual interaction of neighboring bubbles is a dominant factor to evolution of cracks in porous material. Differential stress around a solitary bubble by decompression is inversely proportional to the cube of relative distance in radial direction normalized by its radius (Zhang Nature 1999). In the field of multiple bubbles, the local differential stress is close to the sum of stresses induced by neighboring bubbles. This means that the maximum differential stress is found at the surface of small bubbles close to the large bubble. Evolution of the crack shown in Fig. 2 is explained well with distribution local stress concentration.
In conclusion, this simulation demonstrates that the evolution of crack is very sensitive to the arrangement

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of bubbles. Therefore, we should incorporate the effect of bubble arrangement into the criteria for the onset of fragmentation of vesicular magma.

Keywords: Explosive eruption, Fragmentation, Phase-field method

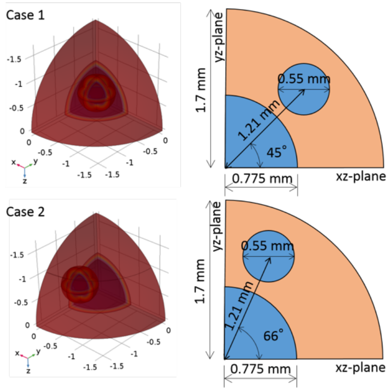
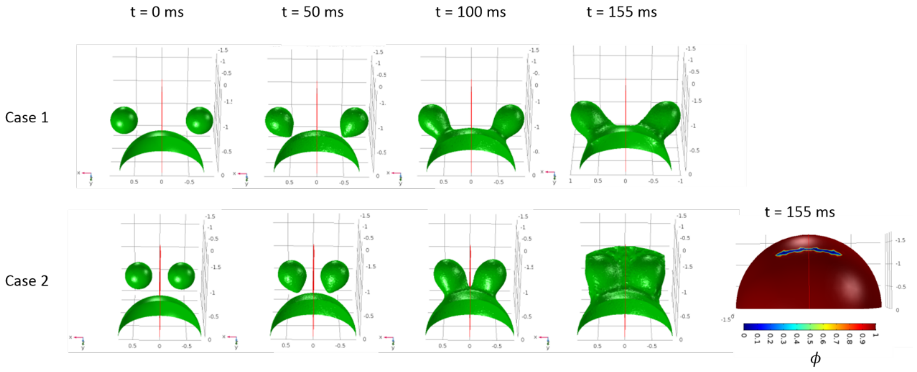


Fig. 1 Bubble arrangement in computational domain



Evolution of Maxwell fluid/gas interface

Outer surface

Fig. 2 Crack propagation in porous Maxwell fluid

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