Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SIT039-P01 Room:Convention Hall Time:May 24 14:00-16:30

Memory of clay paste and its visualization as desiccation crack pattern

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We find that clay paste remembers directions of vibration and flow due to its plastocity. We also find that these memories in pastes can be visualized as the morphology of desiccation crack patterns. When paste remembers the direction of vibration, the direction of crack propagation becomes perpendiculat to the direction of the vibration, while when paste remembers a flow direction, the direction of crack propagation becomes parallel to the direction of the flow [1-3]. This phenomenon is already applied to control crack patterns in the field of technology. Here, we want to discuss on possibility that clay pastes in nature remember earthquakes and diastrophisms which happend old days in the history of earth.

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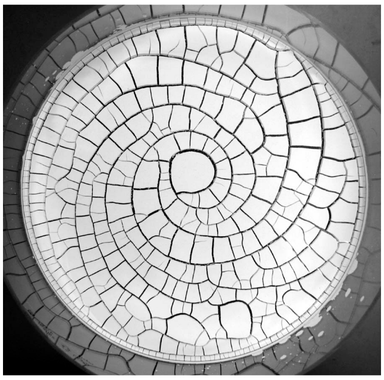

Keywords: memory, clay paste, rheology, desiccation crack pattern

Japan Geoscience Union Meeting 2011
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SIT039-P02 Room:Convention Hall Time:May 24 14:00-16:30

Composite elasticity of porous object investigated by a three-dimensional buffer-layer FEM modek

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A porous system has distinct macroscopic proprieties that are very different from those of a non-porous matrix. There has been much interest in clarifying such characteristics. In the present study, a three-dimensional buffer-layer finite element method (FEM) model was developed succeeding the two-dimensional buffer-layer FEM model. The comparison between the two and three dimensional models is discussed.

Keywords: FEM, porosity, composite elasticity

Japan Geoscience Union Meeting 2011
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SIT039-P03 Room:Convention Hall Time:May 24 14:00-16:30

Transition from velocity weakening friction to velocity strengthening friction

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Various mechanisms that weaken the fault strength at sub-seismic to seismic slip rate have been proposed: melting, silica-gel formation, thermal decomposition, moisture absorption/desorption , and flash heating (e.g., Shimamoto et al., 2003; Di Toro et al., 2004; Rice, 2006; Beeler et al.,2008). On the other hand, steady-state kinetic friction of dense granular matter such as fault gouge is revealed to be velocity strengthening in nature, and that is confirmed by numerical experiments (e.g., GDR MiDi, 2004; Hatano, 2007) . The velocity strengthening behavior has been also confirmed by laboratory experiments on glass beads at normal stress up to 0.05 MPa where frictional heating is negligible (Kuwano et al., 2009) . In this study, we conducted friction experiment on granite specimens at normal stress up to 0.9MPa where frictional heating plays an essential role. Experiments were performed with rotary shear apparatus at normal stress ranging from 0.01 to 0.9 MPa and slip rate ranging from 10ˆ-6 to 1m/s. Experiments were performed under both dry and ambient humidity condition. At lower slip rate, a typical friction coefficients of about 0.8 is observed. At slip rate of about 0.01 to about 0.1, decreases of friction coefficient occurred and minimal friction coefficient is about 0.2. This friction decrease is consistent with the results of the previous studies. At higher slip rate, however, friction increases linearly with slip rate. Scaling the slip rate by square root of normal stress, friction increasing parts of different normal stresses are well collapsed onto universal curve. Thus, it is inferred that the friction increase is due to energy dissipation by inelastic collision of granular matter.

Keywords: friction, constitutive law, rheology, granular matter, flash heating

Japan Geoscience Union Meeting 2011
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SIT039-P04 Room:Convention Hall Time:May 24 14:00-16:30

Anisotropy of bubble microstructure and gas permeability in sheared magma

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Permeable gas transport through connected gas bubbles (bubble network) in magma is a possible mechanism to induce magma degassing and reduce the explosivity of volcanic eruptions. The gas permeability of magma ascending in volcanic conduits has been investigated by performing decompression and shear deformation experiments for hydrous magma. The gas permeability of experimentally sheared magma shows the anisotropy (Okumura et al., 2009 EPSL). When large shear strain (>8) is applied to magma, the gas permeability parallel to shear direction starts to increase at a vesicularity of 30 vol% and reaches the order of 10^{-13} m^2 at a vesicularity of 50 vol%. On the other hand, the gas permeability perpendicular to shear direction is lower than the order of 10^{-16} m^2 at a vesicularity of <80 vol%. In this study, we investigated bubble microstructure of sheared magma to understand the origin of the anisotropy.

Three dimensional (3D) microstructure of bubbles in experimentally sheared rhyolite was observed using synchrotron radiation X-ray CT (BL20B2, SPring-8). The sheared rhyolites were prepared by performing the torsional deformation experiments at a temperature of 975oC and a rotational rate of 0.5 rpm. The outer parts of columnar run products were used for image analyses (256x256x256 voxels, corresponding to the actual size of 1.1x1.1x1.1 mm). In the 3D images, all bubbles in a sample were counted and their volumes were measured. In addition, electrical current simulation (ECS) was numerically done for networks formed by connected bubbles to investigate the controlling factors of the gas permeability.

With the increase in shear strain, the number of bubble networks which achieve from end to end along shear direction increases at a vesicularity of 9-41 vol%. The networks show tube shape rather than frothy shape. When we assume a tube model ($k = ad^2 / 32$, where k is the permeability;a, porosity ; d, tube diameter), the permeabilities calculated along the tube show similar values with measured permeabilities. On the other hand, no bubble network is percolated along the direction perpendicular to shear at <48 vol% vesicularity and 0-10 rotations. The ECS for the largest bubble network in a sample shows that there are some narrow bottle necks for the current flow perpendicular to shear direction. The bottle necks are located on the side of tube networks, resulting in the increase in the tortuosity for the flow. These results indicate that the anisotropic gas permeability is originated by the formation of tube bubbles which results in the enhancement of the gas permeability toward shear direction but decreases the gas permeability perpendicular to shear direction due to the formation of narrow bottle necks and the increase in the tortuosity.

Keywords: magma, shear deformation, anisotropy, bubble microstructure, gas permeability

Japan Geoscience Union Meeting 2011
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SIT039-P05 Room:Convention Hall Time:May 24 14:00-16:30

Estimates of elastic moduli and internal friction of Periclase(MgO) by Sompi analysis for resonant sphere spectroscopy

Megumi Yamamoto[1*], Akihiko Yamamoto[1], Ichiro Ohno[1]

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We applied the resonant sphere technique (RST) to measurements of elastic moduli and internal friction of small specimens of periclase(MgO). In RST, free oscillations of the sample are excited by impulsive input, and the output waveform data are acquired (FT method). The resonant spectra are obtained by spectral analysis. The elastic moduli C_{ij}'s are determined by inverting peak frequencies, and the internal friction ${Q^{-1}}_{ij}$'s are determined by using the half-width of the peaks. The Fast Fourier Transform(FFT) method has been used in the spectral analysis in RST, but the frequency resolution of the spectrum obtained by FFT is not sufficient, especially for the half-width measurements. In contrast, we used eigenfrequencies and eigendecayrates by Sompi analysis for inversion, which may yield better results. In this study both (1) FFT and (2) Sompi methods were applied in the analysis of RST data, and the results were compared. Although the results show that eigenfrequencies obtained by FFT and Sompi analyses are almost consistent, the internal friction analyses using the two techniques show different values. The internal friction obtained by Sompi analysis exhibits reasonable results ranging from 0.11x10^{-4} to 1.75x10^{-4}, whereas those by FFT technique range from -1.05x10^{-4} to 1.06x10^{-4} and show the negative minima for ${Q^{-1}}_{12}$ and ${Q^{-1}}_{k}$. The present study suggests that the Sompi analysis technique may be applicable even to anisotropic elasticity and internal friction.

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SIT039-P06 Room:Convention Hall Time:May 24 14:00-16:30

Strain Measurements of Rock samples using Neutron diffraction at J-PARC/TAKUMI

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A high-intensity proton accelerator facility named J-PARC (Japan Proton Accelerator Research Complex) has been constructed at Tokai in Japan. Various experiments are being performed using the globally highest intensity pulsed neutron beam at MLF (Material and Life Science Experimental Facility) in J-PARC. The Engineering Materials Diffractometer ”TAKUMI”, which was constructed at BL19 in MLF, was designed to research the stress of engineering materials. The first neutron beam was extracted in 2008, and user-operation commenced in 2009. Measurements of residual strain in superconductive materials, in situ neutron diffraction under tensile test and high-pressure neutron experiments have been performed at ”TAKUMI”.

Strain measurements using neutron diffraction are based on Bragg’s law. Tensile or compressive stress causes change in lattice spacing, which results in peak shift of Bragg peak. Strain value can be derived from this peak shift value. Since neutron penetrate materials more than X-rays, the strain inside the material could be obtained nondestructively using neutron diffraction technique. While the stress measurements using diffraction technique has been focused mostly on metals, the application to geological materials was examined. The aim of this study is to develop neutron diffraction technique applicable to the geological materials. High intensity neutron beam at J-PARC has potential to provide strain distribution of inner area of bulk rock specimen. In situ strain measurements on specimens under compression or heating condition will provide us a new insight into rock fracturing mechanism. In addition, the residual strain in rock samples, which is hard to measure by conventional methods, could be obtained using neutron diffraction technique.

Measurements of residual strain in a rock sample and in situ strain measurement on specimens under uniaxial compression have been performed at ”TAKUMI”. The residual strains in a quartz vein from the Sambagawa metamorphic terrain of the Nagatoro area in the Kanto Mountains, Japan, were measured. Various rock samples (e.g. Berea sandstone) were cored (14.6 mm diameter and ca. 40 mm length) and examined by neutron beam under uniaxial compression loading. These cored rock samples were compressed approximately by 80 MPa. The strain values were measured by both strain gauge and the change of the lattice parameter.

In spite of the long neutron path length (ca. 40 mm) and small gauge volume (2 x 2 x 2 mm), sufficient neutron diffraction patterns could be obtained. This indicates that the strain distribution in rocks is nondestructively measurable using ”TAKUMI”. Measurements of residual strain in a quartz vein revealed that the anisotropy of strain value in respect to the direction. In the in situ strain measurements experiment, discrepancy was found in values obtained by strain gauge and quartz lattice spacing. In this presentation, we will report the methods of strain measurements of rock samples at ”TAKUMI” and these results.

Keywords: Neutron diffraction, strain measurement, rock deformation

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SIT039-P07 Room:Convention Hall Time:May 24 14:00-16:30

Rapid pressure solution of point-loaded quartz in H2O fluid at a sub-critical condition

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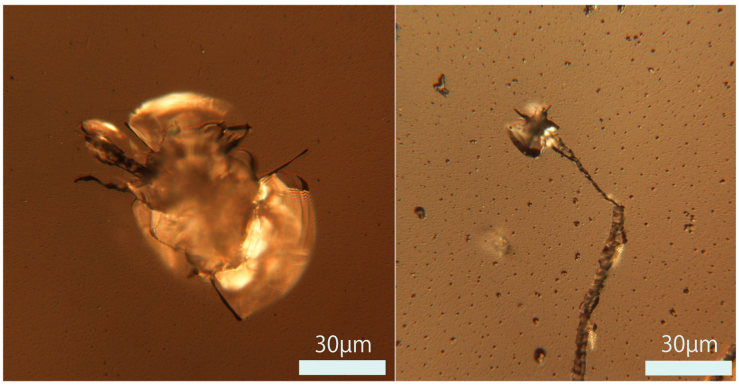
We performed a pressure-solution experiment of single crystal quartz perpendicular to the c axis loaded with a triangular pyramidal corundum indenter within H2O at 350 C and 25 MPa. The specimen was finally polished with abrasive aluminum gel of about 60nm diameter. The specimen was put on a corundum indenter. Then, water temperature and pressure was raised up to 350 C and 25MPa with a constant H2O flow of 5.0 g per minute. After keeping this condition for 215 minutes, temperature and pressure were released to room condition.

We observed the speciment with an optical microscope, a confocal laser scaning microscope, and an atomic force microscope. The point loaded part of quartz are widely dissolved as shown in Figure. At the poster, we explain precisely what we did.



Keywords: quartz, pressure-solution, point-contact, super-critical fluid

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SIT039-P08 Room:Convention Hall Time:May 24 14:00-16:30

Changes of flow strength during the albite decomposition

Naoko Doi[1*], Takumi Kato[1], Tomoaki Kubo[1], Masahiko Noda[1], Rei Shiraishi[2], Akio Suzuki[2], Eiji Ohtani[2], Akira Shimojuku[3], Takumi Kikegawa[4]

[1]Kyushu Univ., [2]Tohoku Univ., [3]ISEI, Okayama Univ., [4]IMSS, KEK

Phase transformations of minerals have an important role on the rheology of earth's crust and mantle. Flow properties and the dominant mechanism of deformation are possibly affected through changes of the crystal structure, grain size and polycrystalline texture during the transformation. In this study, we have carried out in-situ X-ray diffraction experiments on the high-pressure decomposition reaction from albite, one end member of plagioclase, into jadeite and quartz under uniaxial differential stress. Plagioclase is one of the principal materials that construct the oceanic and continental crust and it is important that consider effects of the decomposition reaction on the crustal rheology.

High-pressure deformation experiments of albite were conducted using multi-anvil type deformation apparatus D-CAP 700 installed at the NE-7 beamline of PF-AR, KEK. The plastic deformation and high-pressure transformation processes were simultaneously observed by time-resolved two-dimensional X-ray diffraction (2DXRD) measurements using monochromatic X-ray (energy 50 keV) and imaging plate (IP). 2DXRD patterns were used to obtain the transformed fraction and the differential stress of the sample that was estimated from the distortion of the Debye ring (azimuth angle-dependence of d-values) on IP. Plastic strain of the sample was measured from the X-ray radiography images. Synthesized polycrystalline albite with grain size of about 20 micron was uniaxialy deformed in the stability field of both albite and its high-pressure phases with the constant strain rates of $0.3\text{-}6.1*10^{-5}$/s at 1-4 GPa and 673-1073 K. The maximum axial strain of sample was reached to about 30%.

Deformation mechanism of albite was investigated from the stress exponent n in the flow law and microstructural observations of recovered sample. In the deformation experiments of albite, the flow strength was obtained after reaching the steady state at about 5 percent strain. The n-value was estimated to be 2.3 ± 1.5 from the relationships of the flow stress and strain rate at 873-1073K. The n-value and the elongated grain shape of albite suggest that the dominant deformation mechanism is dislocation creep.

The reaction started at the P-T conditions near the phase boundary at overpressures of 0.4-1.4 GPa and 873-1073K. Polycrystalline albite aggregates partially reacted during deformation. In contrast with the deformation of albite, differential stresses measured from each phase had not reached steady state and changed with the transformed volume fraction. The differential stresses measured from both parental albite and decomposed jadeite initially increased with the transformed fraction, suggesting the hardening due to the transformation. Microstructural observations revealed that nucleation of high-pressure phases occurred at grain boundaries of parental albite. The reaction products form growth domains which show the eutectoid structure with having very fine lamellar spacing of 0.1-1 micron. Those domains have not connected each other in this stage. Therefore albite possibly dominates the deformation of the sample. However in the later stage after the 80% transformation, the value of differential stress of jadeite rapidly dropped by one order of magnitude. We observed the formation of connection of the growth domains as the reaction proceeded, which may change the dominant deformation mechanism and cause the rapid decrease of differential stress of jadeite.

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Evolution of the uppermost mantle flow due to a back-arc spreading: evidence from Ichinomegata volcano peridotite xenoli

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To understand the uppermost mantle evolution, we studied microstructures and olivine crystallographic preferred orientations (CPOs) in naturally deformed peridotite xenoliths beneath the Ichinomegata volcano, in the back-arc region of northeast Japan arc, that were erupted after the opening of the Japan Sea during the Oligocene-Miocene. The peridotite xenoliths studied are mainly spinel lherzolites with a few harzburgites and have granular textures with sizes from 5 to 10 cm. Most of them have pervasive main foliations defined by compositional banding between pyroxene-rich and pyroxene poor layers and lineations defined by elongations of pyroxene and spinel grains. The olivine CPO data show dominantly (010)[100] and subsequently {0kl}[100] patterns, with [100] axes slightly oblique to the main foliations. We measured the angle between the orientation of the olivine [100] maximum and the lineation in each sample. As a result, the peridotite xenoliths having higher CPO intensities tend to show smaller angles between the olivine [100] maxima and the main foliations. We discuss that these various angles in the peridotite xenoliths could be indicative of the occurrence of a shear strain gradient in the uppermost mantle probably in relation to the back-arc spreading.

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Deformation experiments at the lower mantle condition using Kawai-type apparatus for triaxial deformation (KAT-D)

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Knowledge of rheological property of mantle constituent minerals is important for understanding of material behavior in the Earth's deep interior. The Earth's lower mantle consists of ˜77 vol% Mg-rich perovskite, ˜16 vol% ferropericlase and ˜8 vol% Ca-rich perovskite in pyrolite mantle (e.g. Irifune et al., 1994). In spite of its small proportion (˜16 vol%), there is a chance that ferropericlase dominates the lower mantle rheology because ferropericlase is significantly softer than Mg-perovskite (e.g. Yamazaki and Karato, 2001). The deformation induced microstructure is one of the most important factors which control viscosity of the rheologically heterogeneous aggregate. However, no experimental study has been conducted on the deformation microstructure of the lower mantle material due to difficulty in deformation experiments at high-pressure and high-temperature.

The Kawai-type apparatus for triaxial deformation (KATD) installed at Magma Factory, Tokyo Institute of Technology is a modification of cubic-type Kawai-type multi-anvil apparatus with top and bottom differential rams. In this study, we conducted deformation experiments of $(Mg,Fe)SiO_3$-perovskite at the lower mantle conditions (25 GPa, 1873 K) using KATD apparatus and WC second stage anvils with truncation edge length of 2 mm. Presintered of $(Mg,Fe)SiO_3$- orthopyroxene aggregates were used as starting material of deformation experiments. A strain of ˜30% was observed in the deformation experiments. Deformation experiments up to the top of lower mantle condition (25 GPa, 1873 K) using KATD became possible.

Keywords: Deformation experiments, Lower mantle, Perovskite, Kawai-type apparatus for triaxial deformation

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SIT039-P11 Room:Convention Hall Time:May 24 14:00-16:30

Deformation experiments of two-phase aggregates of H2O and CO2 ices

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We have conducted creep experiments on two-phase mixtures of dry ice (CO2) and H2O ices at CO2:H2O volume ratios of 4:96, 8:92, 21:79, 46:54, 75:25, under confining pressures of 20-100 MPa and temperatures of 170-190 K using a gas-medium triaxial deformation apparatus. Two-phase aggregates of CO2 and H2O ices were mixed as powders, hydrostatically compacted. Hydrostatic compression pressures to reach zero porosity were between 60 MPa and 140 MPa and were generally lower for samples with higher CO2 content. The compacted two-phase aggregates were then deformed at constant strain rates from 3e-7 to 1e-5/s. The measured flow stress is in the range of 2-25 MPa.

The creep experiments revealed that the flow strength of the two-phase aggregate decreases drastically with increasing CO2 content. The range of the stress exponents and the activation energies in the aggregate flow law are 3.6-7.0 and 51-41kJ/mol, respectively. These values gradually change from those of one end member to those of the other. The rheology of the two-phase aggregate roughly matches an average of isostress and isostrain models. The flow strength in the 4 vol.% CO2 aggregate is almost half of that in pure H2O ice at the strain rate of 1e-6/s. The presence of 4 vol.% CO2 ice in H2O ice decreases viscosity by more than one order of magnitude at a differential stress of 0.1 MPa. Microstructural observations of the deformed samples are important future studies.

CO2 ice has been observed on the surface of Mars's residual south polar ice cap and is likely to be present on most icy bodies in outer solar system. The present study clearly demonstrates that presence of small amounts of CO2 ice can drastically decrease the flow strength of the two-phase aggregate. It is important to consider the influence of the rheological behavior of two-phase aggregates of CO2 and H2O ices on tectonics and internal dynamics of icy bodies, as well as the stability of the Mars polar cap. Present results can be used to constrain allowable concentrations of CO2 ice to support the Martian south polar ice cap, and suggest that the presence of small amounts of weak non-water ices such as CH4, N2, and CO2 possibly has important roles on viscous relaxation of craters, surface tectonics, and internal convection of icy bodies of outer solar system.

Keywords: H2O ice, CO2 ice, two-phase aggregate, rheology, icy body

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SIT039-P12 Room:Convention Hall Time:May 24 14:00-16:30

Constitutive law of rock rheology with fractional order derivative

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Flow law of rocks, a constitutive law for anelastic behavior of rocks, has long been investigated and established based on the experimental and theoretical studies of microstructures in rocks and minerals and played significant roles in developing the framework of the plate tectonics or geodynamic simulations. However, the flow law cannot express the transient behaviors, i.e., the responses to the sudden change in stress or strain rate. Though some empirical laws have also been proposed for the transient behaviors such as Andrade creep law, there are few studies sufficient to explain the mathematical and thermodynamic background for the constitutive equation of transient behavior. Recently, Yajima and Nagahama (2010, J. Phys. A: Math. Theor.) derived a generalized constitutive equation for viscoelastic behavior from an general energy function in terms of differential geometry with fractional order derivative in which the order of derivative is extended from natural number to positive real number and intrinsically includes the effect of time delay. When the strain is differentiated by deformation time in the fractional order, the equation corresponds to the definitional equation of the Boltzmann superposition principle, the fundamental principle of viscoelastic behavior explaining the memory effect. Also the general constitutive law represents the behavior between Hookean elasticity and Newtonian viscosity and involves any type of viscoelastic models such as Maxwell, Kelvin-Voigt and Zener models. Using a reduced equation of the generalized constitutive law, we analyze the experimental data of high-temperature deformation of rocks such as marble, halite and lherzolite and decide the order of the fractional derivative. These rocks exhibit temporal power-law scalings in the relaxation modulus (the ratio of stress to strain, approximately), so the exponent corresponds to the order of the fractional derivative. The orders can be transformed into the exponent of stress in the flow law, and the constitutive law can express both transient and steady-state behaviors. The orders range from 0.04 to 0.13 (the stress exponent, from 7.5 to 25.0) for the transient behaviors and from 0.14 to 0.25 (the stress exponent, from 4.1 to 7.1) for the steady-state behaviors. The exponent of stress in the flow law depends on the deformation mechanisms such as diffusion and dislocation creeps, so we suggest that the order of the fractional derivative is an important parameter connecting the macroscopic time delay to microscopic deformation mechanisms.

Keywords: viscoelasticity, fractional order derivative, rheology, flow law, transient behavior, temporal fractal property

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SIT039-P13 Room:Convention Hall Time:May 24 14:00-16:30

Mechanism and kinetics of spinel-garnet lherzolite transformation: An experimental study

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The phase transformation from spinel lherzolite to garnet lherzolite occurs at around 2.0 GPa in the upper mantle, in which spinel reacts with pyroxenes to form garnet. Previous studies have reported the reaction textures of partially transformed natural peridotite rock samples (e.g., Obata and Morten, 1987), and the phase boundary of this transformation from high-pressure experiments (e.g., Walter *et al*., 2002). However, the kinetics of spinel-garnet lherzolite transformation has not been examined so far, which makes it difficult to discuss time-dependent processes of mantle flow across the phase boundary.

In order to study the kinetics of this reaction, high-pressure experiments were conducted in the garnet lherzoltite stability field (3.2 GPa and 1273-1473K for 0.6-30 hours) with a spinel single crystal embedded into powder mixture of orthopyroxene and clinopyroxene. We used crystals from San Carlos mantle xenolith as the starting material. In some experiments, spinel surface was deposited by platinum and half of the spinel was covered with olivine to know the direction of garnet growth.

Microstructural observations of recovered samples revealed that garnet reaction rim was formed between single crystalline spinel and polycrystalline pyroxenes. The width of garnet reaction rim (x)t linearly increase with the square root of time t. The growth of kinetics can be described by $[x(t)]^2 = 1.3*10^{-8} m^2 s^{-1} \exp(-188 kJmol^{-1}/RT)t$, based on the diffusion-controlled growth mechanism. This is much faster than lattice diffusion coefficients of divalent species in garnet which previous studies report. Because the platinum markers were at the spinel-garnet interface, it is thought that the garnet reaction rim grows toward the pyroxene region. This suggests that the rate-limiting process is the grain boundary diffusion of trivalent species in the garnet reaction rim.

Development of corona textures around spinel with garnet reaction rims from natural peridotite rocks has been reported in previous studies. We experimentally reproduced the formation of corona texture and clarified the kinetics of the diffusion-controlled garnet rim growth. Our results can be used to constrain their cooling rate or P-T-t paths, and to discuss mantle flow across the spinel-garnet lherzolite boundary.

SIT039-P14 Room:Convention Hall Time:May 24 14:00-16:30

High-pressure transformation with shear stress component and its application to the deep earthquake

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Observations of the depth distribution of seismicity suggest that the mechanism of deep earthquake is greatly influenced by property of the minerals of subducting slab. Especially, phase transformation, induces stress generation or strength of mineral, is considered to play an important role for the occurrence of deep earthquakes. Almost high-pressure transformational experiments have done under hydrostatic pressure condition. To study phase transformation in subducting oceanic plate with slightly stress condition, we used thin plates of single crystal of olivine (San Carlos) and pyrope garnet (Czech) as starting materials. Two single crystals were attached directly on one flat surface with pressure medium of sodium chloride in a Re gasket hole. The set of plates slightly tilt in the sample chamber, which generate small shear stress at the boundary of the sample surface. We performed high-pressure high-temperature experiment using laser heated DAC (LHDAC) up to 30GPa, and observed recovered samples using SEM (scanning electron microscope). Especially at boundary of samples, change of grain-size or deformation caused by phase transformation has been confirmed. These observations suggest that the phase boundary may be different under hydrostatic pressure condition or pressure gradient condition. We will report the detail of the experimental method and results of analysis including how to relate to deep earthquakes.

Keywords: deep earthquake, phase transformation, shear stress, LHDAC