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

SIT039-01 Room:301A Time:May 24 08:30-08:45

Deformation textures and mechanical behavior of hydrated amorphous silica

Akito Tsutsumi[1]*

[1]Kyoto University

Previous experiments have discussed the possibility that fault weakening at rapid slip velocities is caused by faulting processes such as frictional melting, thermal decomposition of the fault material, or silica-gel formation. Among these processes, silica-gel formation may be distinguished from the others because the weakening has occurred even at relatively low slip velocities ($V > 0.01$ mm/s) [Goldsby and Tullis, 2002; Di Toro et al., 2004], under which conditions transformation reactions (e.g., melting, decomposition, etc) are unable to proceed because of low temperatures. Goldsby and Tullis [2002] and Di Toro et al. [2004] have suggested that the weakening is caused by formation and thixotropic behavior of a silica gel (hydrated amorphous silica) layer within a siliceous rock sample. Despite the general acceptance that frictionally generated silica gel plays an important role in the weakening process of siliceous materials, there exists little information on the frictionally generated material (described as fine grained amorphous silica by Di Toro et al. [2004]) on a fault of quartz-rocks; consequently it remains unclear whether the material could behave as a fluid, and whether flow processes contribute to fault weakening. In this study, to better understand the mechanical properties of frictionally generated fault material within quartz-rock, we conducted a series of friction experiments on chert and a synthetic quartz crystal at intermediate to high slip velocities.

We conducted a series of friction experiments on chert at intermediate to high slip velocities (V = 0.87 - 104 mm/s) and at low normal stress of 1.5 MPa to better understand the process of fault weakening by silica-gel formation, as identified in previous friction experiments on quartz-rocks. Fault weakening in chert samples occurred in association with the formation of a 0.1-mm-thick fault gouge layer that contains a thin, foliated layer of fine-grained material and a cataclastically fragmented zone characterized by clast?matrix texture. MFT-IR and XRD analyses reveal that the fault gouge consists of a mixture of hydrated amorphous silica and quartz grains. The mechanical behavior of the fault gouge at a small magnitude of strain (shear strain = 0.008), as examined independently of the friction experiments using a rheometer, is characterized by a negative dependence of shear stress on strain rate with a notable hysteresis behavior.

Keywords: silica gel, amorphous silica, rock friction, chert

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Origin of velocity strengthening in granular friction

Takahiro Hatano[1*]

[1]ERI, University of Tokyo

A simple theory for a constitutive law of granular matter is presented. Starting from the energy balance equation together with the kinetics of grains, the energy dissipation rate in granular matter is estimated, which leads to a constitutive law for steady-state kinetic friction. Our theory indicates that a lower density system is stronger than a higher density system, albeit somewhat counterintuitive. This is a direct consequence from the fact that the grain rearrangement, which causes energy dissipation, is more frequent in a system of low density. Thus, the velocity-strengthening nature of granular friction is naturally explained by the negative shear rate dependence of the density. The present theory also qualitatively explains the experimental observation in which a system containing less gouge layer tends to be velocity-weakening.

Keywords: fault gouge, friction law, rheology, shear transformation zone

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SIT039-03 Room:301A Time:May 24 09:00-09:15

Temperature- and velocity-dependent deformation structures of antigorite gouges

Miki Takahashi[1*], Ichiko Shimizu[2]

[1]Geological Survey of Japan, AIST, [2]Graduate School of Science, Tokyo Univ.

On the shear deformation of granular materials, we should consider two types of the deformation mechanism; one is the friction that uses surface of the grains for sliding, the other is the creep, intra-crystal deformation. Which mechanism of them becomes to dominate the shear deformation will depend on the deformation conditions, temperature and sliding velocity. It was well known that serpentine, a type of phyllosilicate minerals, showed not only friction-type deformation style but also creep-type deformation style (Reinen et al., 1994). However, temperature-velocity dependence of their deformation mechanisms had not been enough clarified.

The deformation mechanisms of antigorite gouge (high-T type serpentine) were investigated by a velocity-step change technique, under various temperature-velocity conditions (refer to Takahashi et al., 2011, in S-SS29 at this year JpGU Meeting for details of the experimental procedure). One of the main results is a drastic change in the deformation style from the creep-type to the friction-type at around 450 deg.C, caused by partially dehydration reaction of the antigorite. This partial, small amount of forsterite (a product of dehydration reaction of the serpentine) had a possibility to control the strength and the behavior of the antigorite gouge sliding even though the dehydration was limited.

In this presentation, we will focus on the gouge structures relevant to the deformation styles. A preliminary SEM observation found streaky alignments of the sub-micron sized forsterite particles along the Riedel shears at the temperature higher than 450 deg.C. That revealed that the serpentine at the shear-localized zone were reacted preferentially. Using EDS analysis, here, we will report results of detail observations on the distributions of the forsterite particles in the antigorite gouge, supporting a possibility of the shear-induced dehydration during the deformation.

Reference: Reinen et al., 1994, Pure and Applied Geophysics, v. 143, p. 317-358.

Keywords: shear-induced dehydration, serpentine gouge, frictional deformation, creep type deformation

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SIT039-04 Room:301A Time:May 24 09:15-09:30

Experimental investigation on viscosity of crystal-bearing magma; a case study for the 1778 Izu-Oshima basalt

Hidemi Ishibashi[1*], Hiroaki Sato[2]

[1]Geochemical Research Center, Univ. Tokyo, [2]CIREN, Shizuoka Univ.

In this study, laboratory viscosity measurements combined with textural analyses were performed on the tholeiitic basalt erupted in A.D. 1778 from the Izu-Oshima volcano, Japan, to evaluate the effect of suspended crystals on viscosity of magma in relation to textural characteristics. We used the atmosphere-controlled high-T concentric cylinder rotational viscometer at Kobe University. Measurements were done at temperature from 1531K to 1395K under Ni-NiO oxgen buffered conditions and a part of melted sample was collected after each measurement, quenched and processed to thin section for textural analyses using an electron microprobe. During measurement, apparent viscosity at first decreased with increase of total strain and then achieved to steady state (thixotropy). Large amount of strain ($>$ 100) is required to achieve steady state of viscosity. The obtained viscometry datasets at steady state were analyzed based on Bingham fluid models to determine Bingham viscosity and yield stress.

Crystallization of plagioclase started at ca. 1446K followed by pigeonite at ca. 1413K, and trace amount of augite and magnetite crystallized at ca. 1395K. Crystallinity increased monotonously up to 0.29 as cooling. Plagioclase crystals are tabular; 50% of them have apparent width/length ratios lower than 0.25. Their crystal size distributions show similar pattern with those of natural lavas and

Bingham viscosity increased from 42 to 1765 Pas and relative viscosity (defined as the ratio of Bingham viscosity to melt viscosity) increased up to ca. 9. Shear thinning behavior was found at temperatures below 1413K (crystallinity above 0.13) and apparent yield stress monotonously increased up to 210 Pa with cooling.

When crystallinity is relatively lower, the effect of crystals on viscosity of magma is known to be well described by the Krieger-Dougherty (KD) equation,

ln relative viscosity = -vFm ln (1-F/Fm)

where F is crystallinity, Fm is maximum packing fraction, and v is an intrinsic viscosity. The Einstein-Roscoe (ER) equation, which is conventionally used to describe the effect of uniform equant crystals, is a specific case of the KD equation with vFm = 2.5 and Fm = 0.6. The Casta equation, which is proposed to describe relative viscosity in full range of crystallinity, can be simplified to the KD equation when F is well lower than Fm. The obtained relative viscosity increased sharply against crystallinity compared with both the ER equation and the Costa equation. The deviation of our data from these equations are chiefly attributable to difference in crystal shapes. The values of vFm and Fm were determined by least square fitting of the KD equation to be 2.3 and 0.47, respectively. Note that the obtained value of vFm is similar to that of the ER equation, indicating that the effect of crystal shape on relative viscosity can be evaluated only by adjusting the value of Fm. The obtained value of Fm is significantly lower than the numerical one calculated for randomly oriented, uniform oblate particles with the same mean width/length ratio. This may be due to the effect of crystal shape distribution; more anisotropic crystals effectively affect on relative viscosity of magma.

The critical crystallinity for onset of yield stress, Fc, is at least lower than 0.13 and yield stress increased with crystallinity. The value of Fc is lower than the numerical one calculated for randomly oriented, uniform oblate particles with the same mean aspect ratio. This discrepancy may be also explained by the effect of crystal shape distribution; only small amount of crystals with very low width/length ratios may contribute to yield stress generation and therefore the effective aspect ratio for onset of yield stress is lower than those expected for the mean value for this sample.

Keywords: viscosity, crystal, texture, non Newtonian fluid, Izu Oshima, basalt

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SIT039-05 Room:301A Time:May 24 09:30-09:45

Experiments on buoyancy-driven crack around the brittle-ductile transition

Ikuro Sumita[1*], Yukari Ota[1]

[1]Earth Sciences, Kanazawa University

We report the results of laboratory experiments exploring how a buoyancy-driven liquid-filled crack migrates within a viscoelastic medium whose rheology is around the brittle-ductile transition (Sumita and Ota, EPSL, in press). To model such medium, we use a low concentration agar, which has a small yield stress and a large yield strain (deformation) when it fractures. We find that around the transition, the fluid migrates as a hybrid of a diapir (head) and a dyke (tail). Here the diapir is a bulged crack in which fracturing occurs at its tip and closes at its tail to form a dyke. A small amount of fluid is left along its trail and the fluid decelerates with time. We study how the shape and velocity of a constant volume fluid changes as two control parameters are varied; the agar concentration (C) and the density difference Delta rho between the fluid and the agar. Under a fixed Delta rho, as C decreases the medium becomes ductile, and the trajectory and shape of the fluid changes from a linearly migrating dyke to a meandering or a bifurcating dyke, and finally to a diapir-dyke hybrid. In this transition, the shape of the crack tip viewed from above, changes from blade-like to a cusped-ellipse. A similar transition is also observed when Delta rho increases under a fixed C, which can be interpreted using a force balance between the buoyancy and the yield stress. Our experiments indicate that cracks around the brittle-ductile transition deviates from those in an elastic medium by several ways, such as the relaxation of the crack bulge, slower deceleration rate, and velocity becoming insensitive to medium rheology. Our experiments suggest that the fluid migrates as a diapir-dyke hybrid around the brittle-ductile transition and that fluid migration of various styles can coexist at the same depth, if they have different buoyancy.

Keywords: brittle ductile transition, crack, experiment, buoyancy

Japan Geoscience Union Meeting 2011
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SIT039-06 Room:301A Time:May 24 09:45-10:00

Superplastic rock deformation accompained with grain boudary sliding and dynamic grain growth

Takehiko Hiraga[1*], Tomonori Miyazaki[1], Miki Tasaka[1], Hidehiro Yoshida[2]

[1]University of Tokyo, [2]NIMS

Recently, we have succeeded in demonstrating superplasticity of forsterite system (Hiraga et al. 2010). Microstructure of the deformed samples exhibits the coalescence of secondary grains (periclase and pyroxene) perpendicular to the tensile direction, which is well explained by grain switching as a result of grain boundary sliding. Coalescence of the grains promotes reduction of the numbers of the secondary grains, which are the pinning phase for grain growth of the first phase, so that grain growth of the both phases occurs with this process. We quantify the growth and coalescence based on laws of Zener and dynamic grain growth. The results indicate that 80% of the first phase involved in a single grain switching event and the largest numbers of coalesced grains correspond to the numbers estimated from the numbers of switching events from total strain of the sample. This analytical method is applied to granite origin ultramylonite revealing rock strain of at least larger than 2.

Keywords: superplasticity, grain boundary sliding, dynamic grain growth, mylonite

Japan Geoscience Union Meeting 2011
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The effects of secondary mineral to grain-size sensitive creep

Miki Tasaka[1*], Takehiko Hiraga[1]

[1]Univ. of Tokyo, ERI

Natural rocks are generally multiphase, thus the effects of secondary minerals are important and not negligible. Some study suggests that with respect to the volume fraction of secondary minerals (f_2), grain size, viscosity and deformation mechanism could be changed. Especially grain size is one of the important parameters, which could change viscosity and deformation mechanism directory. Hiraga et al. (2010a) determined grain growth law using forsterite (Fo) ? enstatite (En) systems, and they showed the grain size ratio changes with respect to enstatite fruction (f_{en}) can explain Zener relations. They estimate the viscosity changes with respect to f_{en} using Zener relation and grain growth law.

Zener pinning is the effect that one phase blocks grain boundary movement of another phase. Zener pinning can be characterized following equation, $d_1/d_2=b/f_2^m$ (eq.1), where d_1 is grain size of first phase, d_2 is grain size of second phase, f_2 is volume fraction of second, b and m is parameter of Zener relation (Smith, 1948).

In this study, we determine grain growth law and conduct deformation experiments using Fo97En3 to Fo4En96 samples. According to the results of grain growth experiments, the grain growth can be characterized by $d^n-d_0^n=kt$ (eq.2), where d is grain size of after grain growth, d_0 is initial grain size, n is grain growth exponent, k is grain growth coefficient and t is time. The grain growth coefficient of k show the velocity of grain growth, and it becomes smaller with increasing f_2. It suggests that with increasing f_2, grain growth velocity become slower. This grain growth function of k changes with respect to f_2 can explain the model of grain growth function of K (Takayama et al. 1982; Hiraga et al. 2010a).

In addition, we conduct the deformation experiments and determine the effects of secondary minerals for deformation following, 1) viscosity changes during the deformation can explain grain growth during the deformation (eq.2) and strength difference between forsterite and enstatite. We make the model to consider the viscosity changes and it has good agreement comparing our experimental results. 2) Zener relation (eq.1) is effective not only in the initial samples but also the deformed samples. 3) With increasing f_{en} deformation mechanism also change grain boundary sliding (GBS) accommodated dislocation creep to GBS accommodated diffusion creep.

Consequently, Secondary mineral volume fractions have large effect to rheological changes during grain size sensitive creep.

Keywords: peridotite, forsterite, grain size, deformation mechanism, Zener relation

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SIT039-08 Room:301A Time:May 24 10:15-10:30

Superplasticity in Fine-grained Oxide Ceramics

Hidehiro Yoshida[1*]

[1]National Institute for Materials Science

Within the field of material science, superplasticity is defined as the ability of a polycrystalline material to exhibit a high tensile ductility, and provides an attractive route for net-shape forming and the joining of materials. Ceramic materials are generally very brittle in comparison with metals and alloys, but when their grain size is controlled to less than about 1 micrometer, they become highly deformable at high temperatures. Superplasticity in ceramics was first demonstrated by Wakai et al. in 1986, and this discovery was followed by developments of various superplastic ceramics. In ceramic materials in which the grains are rigid, the combination of grain boundary sliding and grain switching can be regarded as the main mechanism of superplastic deformation. In actual ceramic materials, however, experimental studies have shown that superplastic deformation is inherently accompanied by accelerated grain growth (dynamic grain growth) and intergranular cavitation. The former increases the level of flow stress for a given strain rate and enhances the latter. The purpose of this paper is to provide an overview of superplasticity in fine-grained oxide ceramics, placing emphasis on the microstructural conditions essential for the occurrence of superplasticity.

Keywords: superplasticity, oxide, grain boundary, ductility, grain growth, diffusion

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SIT039-09 Room:301A Time:May 24 10:45-11:00

The deformation mechanisms of ultramafic ultrafine fault rock ”mylonitic pseudotachylyte”

Tadamasa Ueda[1*], Masaaki Obata[1], Ichiko Shimizu[2], Shun-ichiro Karato[3], Kazuhito Ozawa[2]

[1]Earth&Planetary Science, Kyoto Univ., [2]Earth&Planetary Science, Univ. Tokyo, [3]Geology&Geophysics, Yale Univ.

Because grain size reduction can significantly contribute to rock weakening, fine grained shear zones may accommodate large portion of macroscopic deformation. Therefore, the rheology of fine grained material and the mechanisms of shear localization are important.

This presentation introduces pseudotachylytes having an ultramylonite-like texture (hereafter ”mylonitic pseudotachylytes (M-PsTs)”) cropping out in Balmuccia peridotite massif in northwestern Italy, and discusses the deformation style of the M-PsT as a natural example of a ultrafine grained shear zone. In this presentation, ”pseudotachylyte(PsT)” means PsT preserving melt-origin texture well, and ”M-PsT” means a fault rock superficially looking ultramylonite but having textures implying seismic melting origin. We use the word ”M-PsT” as a working category for such fault rock.

Balmuccia massif is mainly of spinel peridotite. In the study area, there is a network of pseudotachylytes (PsTs), M-PsTs and shear zones of non-molten (ordinary) mylonites. There is a tendency in the field such that the more melt-origin texture is obliterated by recrystallization, the less the fault has injection veins. However, there are some faults that contain both PsT melt-origin texture and M-PsT texture gradually changing from one to the other. Wall rocks of M-PsT often show mylonitic shear localization approaching the fault. This wall mylonitization forms neoblast of olivine, orthopyroxene, clinopyroxene, spinel, and hornblende.

M-PsT consists of porphyroclasts (olivine, spinel, pyroxenes) and ultrafine matrix of olivine, orthopyroxene, clinopyroxene, spinel, hornblende, dolomite, small amount of sulfide, and/or plagioclase. The grain size of the matrix is submicron ˜ a few microns. Grain boundaries of the matrix minerals often form triple junctions.

Both M-PsTs and partially recrystallized PsTs contain a characteristic texture called ”Opx fringe”, which is pairs of orthopyroxene rims developed in a particular orientation on olivine grains in the veins. The orthopyroxene rims are aggregates of fine grained orthopyroxenes bulging into the olivine grains. The orientation of this orthopyroxene rim development is roughly constant throughout each vein. The larger the olivine grains are, the thicker the Opx fringes are. In PsT that is not severely deformed, Opx fringe is found both on olivine clasts and on small (phenocrystic) olivine grains in the matrix, while in M-PsT, Opx fringe is only found on olivine porphyroclasts. In a M-PsT vein having both fault vein and injection vein, olivine-orthopyroxene alternation texture due to Opx fringe is observed in the less deformed injection vein matrix, whereas in the severely deformed fault vein matrix, matrix constituent minerals distribute randomly and the grain size is smaller than in injection vein. This implies Opx fringe structure is destroyed by deformation into more random and finer grained texture. The preferred orientation of Opx fringe development implies that stress is the critical factor for the formation of this texture.

Another feature of M-PsT is that matrix olivine has a lattice preferred orientation (LPO), which may be correlated to the deformation framework of the fault. M-PsT also has a collective optical anisotropy observable under polarization microscope, whose orientation of optical axes is consistent with the olivine LPO. In a complex M-PsT fault vein that records multiple seismic events, older M-PsT layer exhibits stronger optical anisotropy than younger M-PsT.

The condition and the process of formation and deformation of the M-PsT will be discussed in this presentation considering these textural features.

Keywords: pseudotachylyte, ultramylonite, peridotite, lattice preferred orientation, ultrafine polyphase aggregate, anisotropic texture

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SIT039-10 Room:301A Time:May 24 11:00-11:15

Deformation history of mantle peridotites decoded from chemical and textural patterns in pyroxenes

Kazuhito Ozawa[1*], Jean-Louis Bodinier[2], Carlos J. Garrido[3], Hiroko Nagahara[1]

[1]University of Tokyo, [2]Lab. Tec. Universite de Montpellier, [3]CSIC, University of Granada

Al and Ca contents in pyroxenes have been used as useful geothermobarometers for peridotites because of their different dependences on P and T, particularly in the garnet and plagioclase stability fields. The geothermobarometry is often problematic because of complicated kinetic processes in adjustment of the mineral composition in response to P-T changes and deformation (P-T-d history). However, the disturbance caused by kinetic processes provides rich information on the P-T-d history of mantle rocks. The modification of Al and Ca contents in pyroxenes during P-T changes occurs by two main mechanisms: (i) diffusive exchange of their components with or net mass transfer to/from the surrounding minerals and (ii) exsolution of other phases, such as pyroxenes and garnet, within crystals. Both mechanisms usually result in primarily concentric Al and Ca distribution patterns in crystal grains with some effects of crystallographic anisotropy. Deformation affects kinetic processes through the creation of fast diffusion paths inside the crystal such as localized high concentration of dislocations and tilt/twisted boundaries and even formation of new grain boundaries by recrystallization. It could result in non-concentric or striped Al and Ca distribution patterns, which potentially record coupling/decoupling of deformation with P-T changes. On these bases, the combined examination of the crystallographic orientation and the distributions of Al and Ca content in pyroxene crystals provides a powerful tool to unravel the P-T-d history of mantle rocks.

On the basis of this concept, orthopyroxene megacrysts as large as one to a few cm from Pyrenean peridotite massifs (Fabries et al., 1991) were examined with EPMA and FE-SEM attached with EBSD system to estimate their P-T-d history. The megacrysts are in a garnet websterite near the host peridotite from Bestiac, a thin websterite in spinel peridotite from Sem, and a spinel websterite in contact with spinel peridotite from Lherz massifs. Megacrysts were examined because they record the prolonged P-T-d history up to the higher temperature approaching the solidus and/or the higher pressure and temperature approaching the depth of derivation in the mantle.

The orthopyroxene megacrysts from the Pyrenean peridotites and pyroxenites have wide core region rich in exsolution lamellae of clinopyroxene, garnet, or spinel, which are absent in the marginal zone. The cores have high averaged Al and Ca content including lamellae than the outermost rim with or without a marginal high. These concentric features suggest overall cooling at various pressures depending on the mineral assemblage. Overlapping with such concentric variation, striped disturbances accompanied with distortion of lamellae and tilt boundaries are noticed particularly in the marginal zone of the megacrysts. Such stripes are nearly parallel to (001) and rich in Al with or without Ca enrichment as high concentration of clinopyroxene lamellae. In detail, the most of lamellae are asymmetric featuring gradual increase in Al from one side towards the high followed by rapid decrease on the other side. When the Ca enrichment overlaps with the Al high, clinopyroxene lamellae are mostly restricted on the Al-rich side. The location of tilt boundary almost coincides with the Al high, but is often shifted to the Al-poor side by a few to 10 microns. These features of striped zoning in the marginal zone indicate that the tilt boundaries were in motion during Al (and Ca) enrichment in orthopyroxene, probably corresponding to a short heating. Combined this with the overall Al and Ca zoning, it is inferred that deformation and P-T change were coupled in the latest stage of cooling of Pyrenean peridotite massifs.

Keywords: deformation history, mantle, pyroxene, chemical heterogeneity, subgrain/suboundary

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Are very-fine-grained polymineralic rocks extremely soft? Constraints from microstructures in naturally deformed rocks

Toru Takeshita[1*], Ayumi Okamoto[1]

[1]Hokkaido University

Although the strength profile of upper continental crust, where the upper part is deformed by frictional sliding and the lower part by dislocation creep of quartz, has been still applied to crustal dynamics, it is clear that there are two major problems in this profile. One is that although the differential stresses for frictional sliding determined by experiments are necessary to generate ruptures leading to earthquakes, which occur once per a few thousand years in fault zones to generate inland earthquakes, those in fault zones are far below the critical stresses during the inter-seismic period. The point of discussion is then how fast inelastic deformation occurs under such low differential stresses (i.e. do seismogenic faults creep during inter-seismic periods?). The answer is probably yes, because it is inferred that fairly high strain-rate deformation occurred in natural fault rocks by pressure solution creep under the conditions of brittle-ductile transition. Another problem of the existing strength profile is that although it is assumed that the upper part of continental crust consists of quartz alone, it in fact consists polymineralic rocks. Because of this reason, a variety of chemical reactions occurs in real crustal rocks aided by the diffusion of chemical elements via fluids. For example, if a large volume of phyllosilicates with low coefficients of internal friction forms during chemical reactions, the strength of rocks is greatly reduced (reaction softening).

We intend to constrain the strain rate by pressure solution in nature, based on microstructures in naturally deformed rocks. To do this, we first have to analyze strain caused by pressure solution creep, which is then divided by the time interval when it lasts. Strain fringes are one of the strain markers used for this purpose (Ring and Brandon, 1999), and the time interval of deformation can be constrained from cooling rate inferred from radiometric ages using the isotope systems with low closure temperatures such as fission tracks in zircon. Furthermore, it is often observed in nature that single phase quartz aggregates (e.g. quartz vein) are embedded and folded with fine-grained polymineralic aggregates. In such a case, the former and latter layers behave as competent and incompetent layers, respectively, and changes in orthogonal thickness of the latter layers can be used to infer the viscosity ratios between the two layers.

At the present, it is difficult to give a precise estimate for strain rate by pressure solution creep in naturally deformed rocks. In this presentation, we will introduce various microstructures perhaps indicating that pressure solution creep occurred at high strain rates, such as strain fringes with high aspect ratios, shear bands along which muscovite and chlorite were newly grown and quartz aggregates (precipitated grains) with random quartz c-axis fabrics. Furthermore, fault rocks consisting of very-fine-grained actinolite and those characterized by development of anastomosing chlorite seams, where a large amount of displacement perhaps occurred, will be introduced. It will be also emphasized that migration of chemical elements via fluids (i.e. metasomatism) is very important to form these kinds of fault rocks.

Keywords: pressure solution creep, strength profile of the continental crust, brittle-ductile transition, polymineralic rocks, reaction softening, metasomatism

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SIT039-12 Room:301A Time:May 24 11:30-11:45

Deformation of plagioclase accommodated by solution-precipitation process

Junichi Fukuda[1*], Takamoto Okudaira[2]

[1]Dept. Earth & Space Sci., Osaka Univ., [2]Dept. Geosci., Osaka City Univ.

Plagioclase is widely distributed in upper to lower crust. Its rheological behaviors have therefore been considered to be important to understand the crustal strength. Especially in high strain zones, deformation of plagioclase can be a load-bearing framework of rocks. Deformation of plagioclase has mainly been classified as two mechanisms; grain-size-insensitive creep (dislocation creep) and grain-size-sensitive creep (diffusion creep and/or grain boundary sliding) Grain-size-insensitive creep is characterized by formations of crystallographic preferred orientations (CPOs), which are indicatives of some slip systems (e.g., Kruse et al, 2001 for plagioclase). As experimentally investigated, the transition of these two deformation mechanisms of plagioclase are expected to occur within the grain size of 15-70 um under exposed P-T conditions as well as water contents, stress, strain conditions, etc. (Rybacki and Dresen, 2004).

In addition, several authors proposed that solution-precipitation creep can be important for mineral aggregates in the crust (e.g., Imon et al. 2002; Wintsch and Yi, 2002). Solution-precipitation creep has been argued mainly for quartz, which is widely yielded in middle-upper crustal rocks as well as plagioclase (e.g., Hippert, 1994; Vernooij et al., 2006). It is generalized that the solution-precipitation process occurs with dissolution of minerals under higher normal stress and precipitation under lower normal stress. CPO developments may be controlled by dissolution and growth rates, gradients of chemical potential, and diffusion rate of fluid with dissolved component to precipitation sites, as computationally simulated by Bons and den Brok (2000). In this point, the solution-precipitation process is partly similar to pressure solution. Also, observations for natural samples indicate that solution-precipitation creep can occur by reactions (Imon et al., 2002)

In solution-precipitation creep of feldspar group, the CPOs may be formed (Heidelbach et al., 2000; experiment for albite) or not (or not preserved) (Menegon et al., 2008; observation for natural K-feldspar). In spite of its universal presence in the crust, knowledge on solution-precipitation creep of feldspar group is thus limited, compared to the solution-precipitation creep of quartz and studies for grain-size-sensitive and -insensitive creeps of minerals including feldspar group.

In this study therefore, we focus on plagioclase which is included in granitoid mylonite within inner ductile shear zone in the Ryoke metamorphic belt, SW Japan. We obtain information of textural observations, compositions, and crystallographic orientations. The comparisons of their results with the large plagioclase grains which behaved as rigid body during deformation (porphyroclasts) are done, and the relations to the fabrics are discussed. We also compare our results for plagioclase with a lot of previous knowledge on the solution-precipitation process of quartz. Then, we shall try to figure out the solution-precipitation creep of plagioclase.

Keywords: solution-precipitation creep, compositional change, crystallographic orientation, green-schist facies condition

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Probing asthenospheric density, temperature and elastic moduli below western United States

Takeo Ito[1*], Mark Simons[2]

[1]Nagoya Univ., [2]Caltech

Ocean tides are a well-known phenomena resulting from periodic variations in the gravitational attraction of the Sun and the Moon. The Earth's response to ocean tidal loads (OTL) is controlled by internal variations of density and elastic parameters. In principle, observations of the Earth's OTL response can be used to constrain our models of Earth's internal structure. Tidally-related displacements on the surface of the Earth consist of two primary components, solid Earth body tides (SEBT) and the OTL response. SEBT are characterized by sub-meter amplitude and very long wavelength (tens of thousands kilometers and longer). SEBT are relatively insensitive to spatial variations in elastic structure, with less than one millimeter of variation. Hence, we consider SEBT as sufficiently known, and remove an a priori model of SEBT from our observations. In contrast, the OTL response has a richer spatial structure including power at regional length scales (a few hundred kilometers) with typical amplitudes on the centimeter scale. Although, the characteristic amplitude of the OTL response is smaller than SEBT, we show here that the sensitivity of the OTL response to reasonable variations in structure has amplitudes on the centimeter scale, an order of magnitude larger than for SEBT and within the range detectable using the global positioning system (GPS).

Large and dense GPS arrays have been deployed around the globe to improve the spatial-resolution of Earth's surface strain field. Measurement of the OTL response with GPS has dramatically improved in recent years, with an attainable measurement accuracy of better than 1 mm. OTL responses are reasonably well-predicted by global ocean tidal models, derived from assimilation of satellite altimetry and tide-gauge observations, and convolved with the elastic response of the Earth. In traditional GPS processing, these effects are modeled and removed from sub-daily GPS time series. Here, instead of modeling these offsets out, we estimate the OTL response directly from the data.

Using the OTL response as derived from GPS observations made throughout the western United States, we infer depth-dependent material property variations in the mantle down to about 350-km-depth. Seismologists are already adept at producing shear wave velocity (Vs) and compressional wave velocity (Vp) models. For the crust and uppermost mantle, these models are relatively insensitive to density. Typically, estimates of density and elastic moduli for Earth's interior are obtained by combining and/or scaling Vs and Vp models. This conversion step is fraught with uncertainty as to how to scale the inferred seismic velocities to account for both thermal and chemical effects. In contrast, by considering the spatial variation of the horizontal and vertical response (amplitude and phase) to OTL, we can independently constrain the depth-dependence of density and elastic moduli. Such an ability to constrain density variations in the Earth's interior is essential to our understanding of mantle convection and evolution of the overlying tectonic plates.

We present the first depth-dependent model for the crust and upper-most mantle that constrains independently density and elastic moduli below the western United States and nearby off shore regions. This model is unique since it is the first to be derived solely from geodetic observations of surface displacements induced by ocean tidal loads. Our observations require strong gradients in both density and elastic shear moduli at the top and bottom of the asthenosphere but no discrete structural discontinuity at 220 km depth. We find that at least regionally, there is a low-density anomaly in the asthenosphere of about 50 kg/m^3, corresponding to a temperature anomaly of about 300 C. Such a temperature anomaly can also explain differences in inferred elastic structure relative to globally averaged radial seismic models.

Keywords: ocean tidal loads, density, temperature, elastic moduli, asthenosphere, GPS

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

SIT039-14 Room:301A Time:May 24 12:00-12:15

Effect of water on the crystallographic preferred orientation of olivine under the asthenospheric mantle conditions

Tomohiro Ohuchi[1*], Takaaki Kawazoe[1], Yu Nishihara[2], Tetsuo Irifune[1]

[1]Geodynamics Research Center, Ehime Univ., [2]Senior Research Fellow Center,Ehime Univ

Crystallographic preferred orientation (CPO) of olivine, which is developed by dislocation creep, controls the seismic anisotropy in the upper mantle. One of the remarkable observations on the upper mantle near subduction zones is a striking rotation of fast direction of shear-wave splitting across an arc. Trench-normal fast directions are observed in the back-arc side, but trench-parallel ones are observed in the fore-arc side (e.g, Smith et al., 2001; Nakajima and Hasegawa, 2004). The rotation of fast direction of shear-wave splitting has been attributed to the transition of mantle-flow direction from trench-normal flow (in the back-arc side) to trench-parallel flow (in the fore-arc side) under the assumption that the A-type olivine fabric (developed by the (010)[100] slip system), which has a seismic fast-axis orientation subparallel to the shear direction, is assumed to be the unique cause of seismic anisotropy (e.g., Russo and Silver, 1994). However, this model is not fully supported by other observations such as geodetic observations.

Recent laboratory results have shown that the flow-parallel shear wave splitting is caused not only by A-type olivine fabric but also by C- (developed by the (100)[001] slip system) and E-type (by the (001)[100] slip system) olivine fabrics (Jung and Karato, 2001; Katayama et al., 2004). Moreover, flow-perpendicular shear wave splitting is also found to be caused by the B-type olivine fabric (developed by the (010)[001] slip system) (Jung and Karato, 2001). All of newly found olivine fabrics are developed under wet conditions. Based on the seismological properties of various olivine fabrics, it has been proposed that the trench-parallel shear wave splitting and trench-normal shear wave splitting are caused by trench-normal flow associated with B-type olivine fabric (in fore-arc side) and with C- (or E-) type olivine fabrics (in back-arc side), respectively (Karato, 2003; Kneller et al., 2005). However, it has recently been reported that the CPO patterns of anhydrous olivine depend on pressure (Jung et al., 2009; Ohuchi et al., 2011), suggesting the possibility that the fabric boundaries determined at low pressures (0.5?2 GPa: Jung and Karato, 2001; Katayama et al., 2004) cannot be applicable to the asthenospheric mantle wedges ($>$ 60 km depth).

In order to explore the effect of water on CPO of minerals at high pressures, we developed a new cell assembly for the multi-anvil assembly 6-6 (MA6-6) system combined with a deformation-DIA apparatus (Ohuchi et al. 2010). We have initiated a series of experimental studies on the effect of water on the CPO of olivine under the upper mantle conditions. We conducted the experiments of the simple-shear deformation of hydrous olivine at P = 2-7 GPa and T = 1400-1670 K for a range of shear strain rate 1E-5 to 1E-4 /s. Our experimental results showed that the A-type olivine fabric was the dominant under dry and moderately wet conditions. In contrast, B-type-like olivine fabrics were developed under wet conditions. These observations suggest that water content is one of the most important parameter controlling the fabric transition of olivine not only in the lithosphere but also in the asthenosphere. The water-induced fabric transition can be the cause of the rotation of fast direction of shear-wave splitting across an arc.

Keywords: olivine, crystallographic preferred orientation, water, seismic anistropy

Japan Geoscience Union Meeting 2011
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SIT039-15 Room:301A Time:May 24 12:15-12:30

Rheology of fine-grained forsterite aggregate under deep upper mantle conditions

Yu Nishihara[1*], Tomohiro Ohuchi[2], Takaaki Kawazoe[2], Dirk Spengler[1], Miki Tasaka[3], Takehiko Hiraga[3], Kikegawa Takumi[4], Akio Suzuki[5], Eiji Ohtani[5]

[1]SRF Center, Ehime University, [2]GRC, Ehime University, [3]ERI, University of Tokyo, [4]PF, KEK, [5]Tohoku University

Under the conditions of the Earth's mantle, both diffusion creep and dislocation creep can be the dominant deformation mechanism depending on physical and chemical environments. These two mechanisms are quite different in terms of stress dependence of viscosity and development of lattice-preferred orientation. Thus it is important to understand the dominant deformation mechanism in the mantle. Previous studies on rheology of olivine under high-pressure (>3 GPa) mostly focused on dislocation creep (e.g. Kawazoe et al., 2009; Durham et al., 2009). Knowledge of diffusion creep of olivine under deep upper mantle condition (>100 km) has been quite limited. In order to clarify the dominant deformation mechanism in the upper mantle, we have conducted deformation experiments at high-pressure and high-temperature using fine-grained forsterite aggregate.

Experiments were carried out using a D-DIA apparatus "D-CAP (deformation cubic-anvil press)" installed at NE7 beamline, PF-AR, High Energy Accelerator Research Institute, Tsukuba, Japan. The samples are sintered aggregate of 90%forsterite + 10%enstatite with average grain size of ~1.7 um. High-pressure was generated by MA6-6 assembly (e.g. Kawazoe et al., 2010) using cubic (Mg,Co)O pressure medium and WC and cBN anvils with 5 mm truncation edge length. High-temperature was generated using graphite furnace and was monitored by WRe thermocouple. Deformation experiments were conducted at pressure of 3-5.5 GPa, temperature of 1573 K, and uniaxial strain rate of 7 x 10^{-6}- 2 x 10^{-4} s^{-1}. Sample stress was measured by two-dimensional X-ray diffraction using monochromatized synchrotron X-ray (50 keV) and imaging plate detector (e.g. Nishihara et al., 2009). Sample strain was measured by X-ray radiography. The OH concentration in starting material and recovered samples was determined based on FTIR analyses (Paterson, 1982).

Steady state flow stress was determined at each deformation condition. The stress-strain rate data taken at "dry" conditions (<50 H/10^6Si) together with data at 0.1 MPa by Tasaka et al. (unpublished data) were analyzed using a flow law equation for diffusion creep (n = 1) and dislocation creep (n = 3.5) (e.g. Hirth and Kohlstedt, 2003). Based on the analysis, the activation volume ($V*_{dif}$) for diffusion creep of olivine was determined to be ~9 cm^3/mol. Karato and Wu (1993) discussed that diffusion creep is the dominant deformation mechanism below ~200 km depth using assumed value of $V*_{dif}$ = 6 cm^3/mol (estimated from dislocation recovery experiments). Present result ($V*_{dif}$ ~ 9 cm^3/mol) implies that diffusion creep is predominant only at deeper part of upper mantle.

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SIT039-16 Room:301A Time:May 24 12:30-12:45

Si-Al interdiffusion in majoritic garnet

Masayuki Nishi[1*], Tomoaki Kubo[2], Hiroaki Ohfuji[1], Takumi Kato[2], Yu Nishihara[1], Tetsuo Irifune[1]

[1]GRC, Ehime Univ., [2]Kyushu Univ.

It has been suggested that the mineral transformations in subducting plates are kinetically inhibited and therefore low-pressure phases could metastably survive without transforming to its high-pressure phases (e.g., Sung and Burns, 1976). Kinetic studies on the high-pressure transformations have suggested that olivine, pyroxene, and garnet metastably survive without transforming their high-pressure phases in cold subducting plates. Especially, the formation of majoritic garnet from pyropic garnet and pyroxene (the pyroxene-garnet trasnfomration) is very slow and phase relation of subducting plates is possibly different from the equilibrium phase relation. However, quantitative kinetic data for the pyroxene-garnet transformation have not been obtained yet. Here we report Si^{4+} + M^{2+} <=> $2Al^{3+}$ (M = Mg + Fe + Ca) interdiffusion rate in majoritic garnet, which controls kinetics of the pyroxene-garnet transformation. Based on the experimental results, we discuss the density of subducting plate.

We carried out four experiments at 17 GPa and temperatures of 1550-1700C (every 50C) for 5-50 hours using a multi-anvil apparatus. Pressure was generated by the double-stage system and the truncated edge length of the second-stage anvils was 8.0 mm. Garnet diffusion couples having different chemical compositions were used as starting material. One is natural single-crystalline pyropic garnet, and the other is polycrystalline majoritic garnet synthesized from pyrolite-minus olivine glass at 17 GPa and 1600C. The diffusion couples were contacted each other and surrounded by $MgSiO_3$ enstatite powder and Ni capsule. The sample assembly is composed of sintered (Mg,Co)O and ZrO_2 pressure mediums, a cylindrical $LaCrO_3$ heater, and a Mo electrode. Temperature was monitored with a W3%Re-W25%Re thermocouple. The diffusion profiles of run products were obtained using an analytical transmission electron microscope (ATEM, JEOL JEM-2010) with an EDS detector (Thermo-NORAN Vantage-ES). Thin foils perpendicular to the diffusion interface for ATEM analyses were prepared by a focused ion beam (FIB) apparatus (JEOL JEM-9310FIB). Water content of the majoritic garnet polycrystalline before and after diffusion experiments were determined by FT-IR spectroscopy on the basis of the Paterson calibration [1982], which yielded 20-40 wt.ppm H_2O.

The pyroxene-garnet transformation requires long-distance Si^{4+} + M^{2+} <=> $2Al^{3+}$ diffusion comparable to the grain size of original garnet. The results indicated that, if we consider the grain size of 1 mm for the original garnet, the transformation requires high temperatures of more than 1500C comparable to a normal mantle geotherm. This suggests that the pyroxene-garnet transformation would be kinetically inhibited in cold subducting plates and large amount of metastable regions exist in the subducting plate around the mantle transition zone.

Keywords: transformation kinetics, diffusion, subducting slab, majorite, pyroxene, garnet

Japan Geoscience Union Meeting 2011
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SIT039-P01 Room:Convention Hall Time:May 24 14:00-16:30

Memory of clay paste and its visualization as desiccation crack pattern

Akio Nakahara[1*], Hiroshi Nakayama[1], Yousuke Matsuo[1]

[1]Nihon Univ.

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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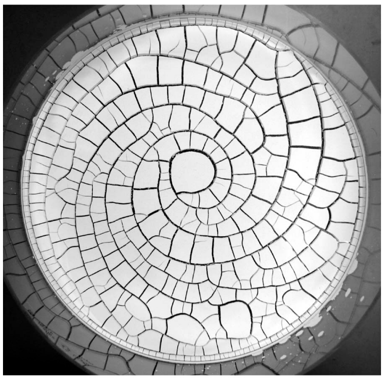

Keywords: memory, clay paste, rheology, desiccation crack pattern

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

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

Akira Yoneda[1]*

[1]ISEI, Okayama Univ.

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

Osamu Kuwano[1*], Takahiro Hatano[1]

[1]ERI, Univ. of Tokyo

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 10^-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

Satoshi Okumura[1*], Michihiko Nakamura[1], Tsukasa Nakano[2], Kentaro Uesugi[3]

[1]Dept. Earth Science, Tohoku Univ., [2]AIST/GSJ, [3]SPring-8/JASRI

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]

[1]Ehime University

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

Jun Abe[1*], Kotaro Sekine[2], Stefanus HARJO[1], Takayoshi ITO[1], Hiroshi Arima[1]

[1]Japan Atomic Energy Agency, [2]Institute of Fluid Science, Tohoku Univ.

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

Japan Geoscience Union Meeting 2011
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SIT039-P07 Room:Convention Hall Time:May 24 14:00-16:30

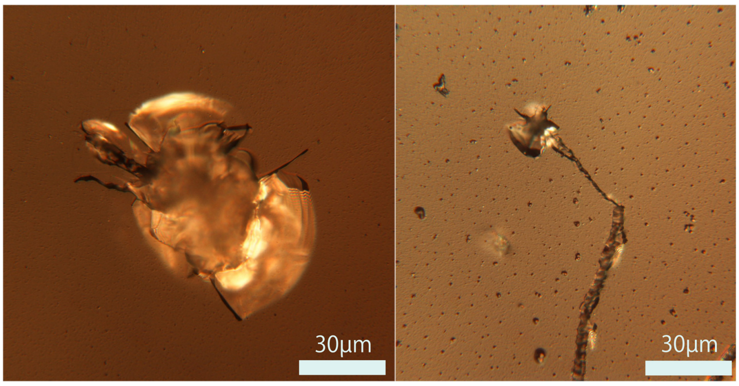
Rapid pressure solution of point-loaded quartz in H2O fluid at a sub-critical condition

Yusuke Moriya[1*], Yasutomo Omori[1], Toshiaki Masuda[1]

[1]Inst. Geosci., Shizuoka Univ.

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

Japan Geoscience Union Meeting 2011
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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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SIT039-P09 Room:Convention Hall Time:May 24 14:00-16:30

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

Takako Satsukawa[1*], Katsuyoshi Michibayashi[2]

[1]Geoscience, Shizuoka University, [2]Geoscience, Shizuoka Univesrity

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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SIT039-P10 Room:Convention Hall Time:May 24 14:00-16:30

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

Noriyoshi Tsujino[1*], Yu Nishihara[2]

[1]Tokyo Tech., [2]Ehime Univ.

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

Tomoaki Kubo[1*], William Durham[2]

[1]Kyushu Univ., [2]MIT

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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Constitutive law of rock rheology with fractional order derivative

Yusuke Kawada[1*], Takahiro Yajima[2], Hiroyuki Nagahama[3]

[1]ERI, Univ. Tokyo, [2]Dept. Physics, Tokyo Univ. Science, [3]Dept. Geoenviron. Sci., Tohoku Univ.

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

Maiko Nagayoshi[1*], Tomoaki Kubo[2], Takumi Kato[2]

[1]Kyushu univ., [2]Kyushu univ.

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.

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

Tanaka Kazunori[1*], Tadashi Kondo[1]

[1]Graduate School of Science, Osaka Univer

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