

SIT039-01

Room:301A

Time:May 24 08:30-08:45

## Deformation textures and mechanical behavior of hydrated amorphous silica

Akito Tsutsumi<sup>1\*</sup>

<sup>1</sup>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

SIT039-02

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## Origin of velocity strengthening in granular friction

Takahiro Hatano<sup>1\*</sup>

<sup>1</sup>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

SIT039-03

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## Temperature- and velocity-dependent deformation structures of antigorite gouges

Miki Takahashi<sup>1\*</sup>, Ichiko Shimizu<sup>2</sup>

<sup>1</sup>Geological Survey of Japan, AIST, <sup>2</sup>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

SIT039-04

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

Hidemi Ishibashi<sup>1\*</sup>, Hiroaki Sato<sup>2</sup>

<sup>1</sup>Geochemical Research Center, Univ. Tokyo, <sup>2</sup>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 oxygen 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,

$$\ln \text{relative viscosity} = -vF_m \ln (1-F/F_m)$$

where  $F$  is crystallinity,  $F_m$  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  $vF_m = 2.5$  and  $F_m = 0.6$ . The Costa 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  $F_m$ . 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  $vF_m$  and  $F_m$  were determined by least square fitting of the KD equation to be 2.3 and 0.47, respectively. Note that the obtained value of  $vF_m$  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  $F_m$ . The obtained value of  $F_m$  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,  $F_c$ , is at least lower than 0.13 and yield stress increased with crystallinity. The value of  $F_c$  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

SIT039-05

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

Ikuro Sumita<sup>1\*</sup>, Yukari Ota<sup>1</sup>

<sup>1</sup>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

SIT039-06

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## Superplastic rock deformation accompanied with grain boundary sliding and dynamic grain growth

Takehiko Hiraga<sup>1\*</sup>, Tomonori Miyazaki<sup>1</sup>, Miki Tasaka<sup>1</sup>, Hidehiro Yoshida<sup>2</sup>

<sup>1</sup>University of Tokyo, <sup>2</sup>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

SIT039-07

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## The effects of secondary mineral to grain-size sensitive creep

Miki Tasaka<sup>1\*</sup>, Takehiko Hiraga<sup>1</sup>

<sup>1</sup>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 fraction ( $f_{en}$ ) 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

SIT039-08

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## Superplasticity in Fine-grained Oxide Ceramics

Hidehiro Yoshida<sup>1\*</sup>

<sup>1</sup>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



SIT039-09

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## The deformation mechanisms of ultramafic ultrafine fault rock "mylonitic pseudotachylyte"

Tadamasa Ueda<sup>1\*</sup>, Masaaki Obata<sup>1</sup>, Ichiko Shimizu<sup>2</sup>, Shun-ichiro Karato<sup>3</sup>, Kazuhito Ozawa<sup>2</sup>

<sup>1</sup>Earth&Planetary Science, Kyoto Univ., <sup>2</sup>Earth&Planetary Science, Univ. Tokyo, <sup>3</sup>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

SIT039-10

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

Kazuhito Ozawa<sup>1\*</sup>, Jean-Louis Bodinier<sup>2</sup>, Carlos J. Garrido<sup>3</sup>, Hiroko Nagahara<sup>1</sup>

<sup>1</sup>University of Tokyo, <sup>2</sup>Lab. Tec. Universite de Montpellier, <sup>3</sup>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/subboundary

SIT039-11

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

Toru Takeshita<sup>1\*</sup>, Ayumi Okamoto<sup>1</sup>

<sup>1</sup>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

SIT039-12

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## Deformation of plagioclase accommodated by solution-precipitation process

Junichi Fukuda<sup>1\*</sup>, Takamoto Okudaira<sup>2</sup>

<sup>1</sup>Dept. Earth & Space Sci., Osaka Univ., <sup>2</sup>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 indicative 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  $\mu\text{m}$  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

SIT039-13

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

Takeo Ito<sup>1\*</sup>, Mark Simons<sup>2</sup>

<sup>1</sup>Nagoya Univ., <sup>2</sup>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 ( $V_s$ ) and compressional wave velocity ( $V_p$ ) 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  $V_s$  and  $V_p$  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  $50 \text{ kg/m}^3$ , 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



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<sup>1\*</sup>, Takaaki Kawazoe<sup>1</sup>, Yu Nishihara<sup>2</sup>, Tetsuo Irifune<sup>1</sup>

<sup>1</sup>Geodynamics Research Center, Ehime Univ., <sup>2</sup>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 anisotropy

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

Yu Nishihara<sup>1\*</sup>, Tomohiro Ohuchi<sup>2</sup>, Takaaki Kawazoe<sup>2</sup>, Dirk Spengler<sup>1</sup>, Miki Tasaka<sup>3</sup>, Takehiko Hiraga<sup>3</sup>, Kikegawa Takumi<sup>4</sup>, Akio Suzuki<sup>5</sup>, Eiji Ohtani<sup>5</sup>

<sup>1</sup>SRF Center, Ehime University, <sup>2</sup>GRC, Ehime University, <sup>3</sup>ERI, University of Tokyo, <sup>4</sup>PF, KEK, <sup>5</sup>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  $\mu\text{m}$ . 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  $7 \times 10^{-6}$ - $2 \times 10^{-4} \text{ s}^{-1}$ . 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<sup>6</sup>Si) 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<sup>3</sup>/mol. Karato and Wu (1993) discussed that diffusion creep is the dominant deformation mechanism below ~200 km depth using assumed value of  $V^*_{dif} = 6 \text{ cm}^3/\text{mol}$  (estimated from dislocation recovery experiments). Present result ( $V^*_{dif} \sim 9 \text{ cm}^3/\text{mol}$ ) implies that diffusion creep is predominant only at deeper part of upper mantle.

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## Si-Al interdiffusion in majoritic garnet

Masayuki Nishi<sup>1\*</sup>, Tomoaki Kubo<sup>2</sup>, Hiroaki Ohfuji<sup>1</sup>, Takumi Kato<sup>2</sup>, Yu Nishihara<sup>1</sup>, Tetsuo Irifune<sup>1</sup>

<sup>1</sup>GRC, Ehime Univ., <sup>2</sup>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 pyrope garnet and pyroxene (the pyroxene-garnet transformation) 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  $\text{Si}^{4+} + \text{M}^{2+} \rightleftharpoons 2\text{Al}^{3+}$  ( $\text{M} = \text{Mg} + \text{Fe} + \text{Ca}$ ) 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 pyrope garnet, and the other is polycrystalline majoritic garnet synthesized from pyrope-minus olivine glass at 17 GPa and 1600C. The diffusion couples were contacted each other and surrounded by  $\text{MgSiO}_3$  enstatite powder and Ni capsule. The sample assembly is composed of sintered (Mg,Co)O and  $\text{ZrO}_2$  pressure mediums, a cylindrical  $\text{LaCrO}_3$  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  $\text{H}_2\text{O}$ .

The pyroxene-garnet transformation requires long-distance  $\text{Si}^{4+} + \text{M}^{2+} \rightleftharpoons 2\text{Al}^{3+}$  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