Weakening mechanism and energy budget of laboratory earthquakes

*Alexandre Schubnel[1], François Passelègue[2], Nicolas Brantut[3], Soumaya Latour[6], Harsha Bhat[4], Stefan Nielsen[5], Raul Madariaga[1]

1.Laboratoire de géologie, Ecole Normale Supérieure, Paris, France, 2.University of Manchester, UK, 3.University College London, UK, 4.IPGP, France, 5.Durham University, France, 6.IRAP, Toulouse, France

The dynamics of earthquake ruptures in subduction zone are expected to be partially governed by the dehydra- tion of minerals during shear heating. In this study, we conducted and compared results coming from stick-slip experiments on Westerly granite, serpentinized peridotite, and serpentinite. Experiments were conducted under triaxial loading at confining pressures of 50 and 100 MPa. The angle between the fault plane and the maximum stress was imposed to be equal to 30 degrees. Usual a dual gain system, a high frequency acoustic monitoring array recorded particles acceleration during macroscopic stick-slip events and premonitory background microseismicity. In addition, we used an amplified strain gage located at 3 mm to fault plane to record the dynamic stress change during laboratory earthquakes. In all rocks, we show that increasing the stress acting on the fault leads to an increase of the seismic slip, which in turns leads to a decrease in the dynamic friction coefficient. However, for a same initial stress, displacements are larger in serpentinized peridotite and in serpentinite than in Westerly granite. While the partial melting of the fault surface is observed in each rock tested, the dynamic friction drop is larger in peridotite and serpentinite. This larger friction drop is explained by the dehydration of antigorite, which leaves a partially amorphised material and leads to the production of a low viscosity melt. Finally, using theroretical assumptions, we show that the radiation efficiency of laboratory earthquakes is larger in peridotite and serpentinite than in granite. This calculation is supported by larger elastic wave radiation, and by microstructural analysis.

Keywords: friction, dehydration, critical weakening distance

Revisiting the slip-weakening friction: probe into the true source properties from off-fault measurements

*Shiqing Xu[1], Eiichi Fukuyama[1], Futoshi Yamashita[1], Kazuo Mizoguchi[2], Shigeru Takizawa[1], Hironori Kawakata[3]

1.Nat'l Res. Inst. Earth Sci. Disas. Prev., 2.Centr. Res. Inst. Elect. Pow. Ind., 3.Ritsumeikan University

Slip-weakening friction, as evidenced by earlier pioneer rock fracture/friction experiments, has been widely used for numerically simulating earthquake ruptures, and for estimating earthquake source properties from seismological observations. Despite the great success, the accuracy of this constitutive relation is poorly known in the lab: measurements made close to the fault (yet still off the fault) were often assumed without validation to be the direct recordings of on-fault properties. Until recently, several works challenged this assumption, and showed that it may even lead to incorrect interpretation of rupture mode at speed close to the Rayleigh wave speed. This raises a concern on how to probe the true source properties on the fault using off-fault measurements, which was generally overlooked in the geophysical community.
To answer the question, we utilize a large-scale direct shear apparatus at NIED to monitor near-fault strain change during labquakes. By comparing our strain data with common slip-weakening model predications at various locations progressively away from the fault, we see systematically a decrease in apparent peak friction and an increase in apparent breakdown zone size. These features reflect the smearing out of the strain field away from the sharp rupture front. On the other hand, the initial strain before failure and the residual strain after the breakdown process are less sensitive to the sampling location, because the strain field is more homogeneous at those locations without sharp features. By fitting the strain data with templates created from a specific slip-weakening model, we are able to estimate the true source properties during labquakes within the framework of that model. If more data points were available, it would be even possible to probe the true “rupture distribution function” (Andrews, JGR 1976). In any case, our study suggests that care be taken when interpreting measurements during labquakes, especially when sharp features are involved during the rupture breakdown process (e.g. at a scale more than two times smaller than the source-recorder distance). Given the well-known Lorentz contraction effect, we may never be able to directly measure certain rupture properties at speed very close to the limit speed, which ultimately requires some indirect approaches.

Keywords: Slip-weakening friction, Dynamic rupture, Friction experiment

Understanding characteristics of granular convection by visualizing rotation of individual particles in tapped granular bed

*Noa Mitsui[1], Naoki Iikawa[1], Mahesh BANDI[2], Hiroaki Katsuragi[1]

1.Graduate School of Environmental Studies, Nagoya University, 2.OIST

Granular material is defined by a collection of athermal particles, and it sometimes behaves like fluid despite solid property of each particle [1]. One of the fluid-like behaviors is convection of granular bed induced by vertical vibration, and it can be observed in laboratory experiments with various types of particles and vibrations. Recent studies propose that granular convection relates to resurfacing process of small asteroids covered with regolith (e.g., [2]). Thus the mechanism of the granular convection is not only physical but also geophysical problem.

One of the ways to understand the mechanism of granular convection is to monitor all degrees of freedom (DOF) of individual particles as well as to monitor the collective motion such as convection. The considered DOF of individual particles are (1) translational and (2) rotational velocities of each particle and (3) contact forces applied between particles besides body forces. However, in most of laboratory experiments, only translational velocities have been monitored (e.g., [3]). Recent study has visualized contact forces by using photoelastic discs [4,5]. However, they have not monitored rotational motion of particles. Particularly, although the particle rotation has not been measured well so far, it could significantly relate to the mechanism of granular convection.

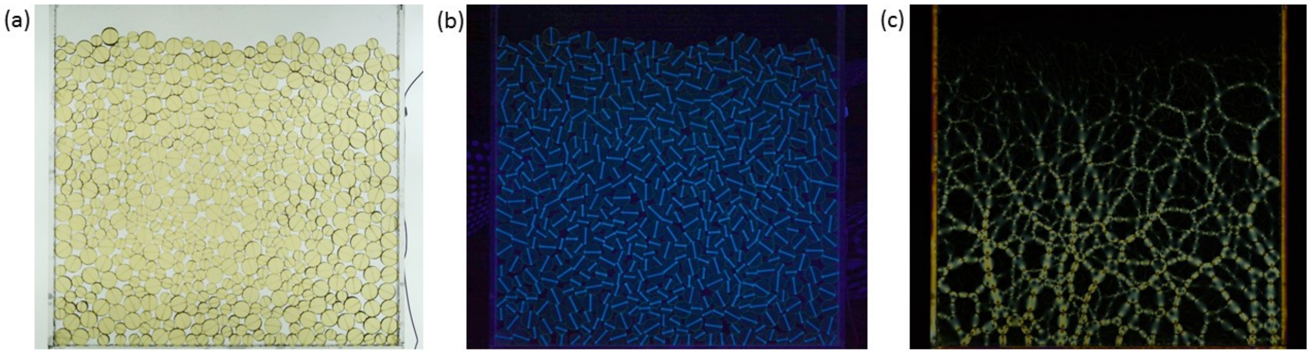
In this study, we are going to monitor all these DOF in granular convection by using photoelastic discs. We use bidisperse photoelastic discs to make two-dimensional granular layer. Then, vertical intermittent tapping is applied to the granular layer by using an electromagnetic vibrator. We conducted experiments with several tapping conditions (duration and the maximum acceleration of tapping impulse). The photoelastic discs are painted with a fluorescent paint along the diameter to visualize the rotation by using ultraviolet-light illumination [6].

All DOF of individual particles in each tapping can be obtained as follows. Figure shows three types of pictures taken in this experiment. They are taken by using (a) white light source, (b) ultraviolet-light illumination, and (c) white light source under cross-polarized mode, respectively. Translational velocity and associated vorticity of granular convection are obtained by analyzing (a). The rotational velocities of individual particles are obtained by analyzing (b). In addition, the contact forces can be computed by (c). As the first step, we will focus on the analysis of (a) and (b) in this study, and understand the relation between granular convection and rotational velocities of individual particles.

[1] Jaeger, H. M., S. R. Nagel, and R. P. Behringer (1996) Rev. Mod. Phys., 68, 1259-1273.
[2] Yamada, T., K. Ando, T. Morota, and H. Katsuragi (2015) arXiv: 1508.06485.
[3] Shukla, P., I.H. Ansari, R.M. van der Meer, D. Lohse, and M. Alam (2014) J. Fluid Mech., 761, 123-167.
[4] Iikawa, N., M. M. Bandi, and H. Katsuragi (2015) J. Phys. Soc. Jpn. 84, 094401.
[5] Bandi, M. M., M. K. Rivera, F. Krzakala, and R. E. Ecke (2013) Phys. Rev. E., 87, 042205.
[6] Pucktt, J. G., and K. E. Daniels (2013) Phys. Rev. Lett. 110, 058001.

Figure. Samples of photos taken by using (a) white light source, (b) ultraviolet-light illumination, and (c) white light source under cross-polarized mode, respectively.

Keywords: granular matter, granular convection, rotation


(a)
(b)
(c)

Granular friction: Triggering slip motion with small vibrations

*Valerie Vidal[1], Henri Lastakowski[1], Jean-Christophe Géminard[1]

1.Laboratoire de Physique, Ecole Normale Supérieure de Lyon - CNRS

We investigate experimentally the influence of mechanical vibrations on the characteristics of granular friction. The experimental system consists of a slider and a cantilever spring, pulled at constant velocity over a granular layer. The slider mass, spring stiffness and pulling velocity are chosen such that without mechanical perturbances, the slider exhibits a classical stick-slip motion. Horizontal vibrations are then applied to the whole system. When increasing either the amplitude or frequency of the vibrations, the amplitude of the stick-slip motion decreases, until the system exhibits a transition to a continuous slip motion. Previous numerical studies pointed out the acceleration of imposed vertical vibrations as the governing parameter for the transition, with a value of the order of the gravitational acceleration. In contrast to these results, we show that the quantity that controls the frictional properties is the characteristic velocity, and not the acceleration, of the imposed mechanical vibrations. The critical velocity at which the system undergoes the transition to a continuous slip motion is very small, of the order of 100 microns/s. Thus, when the system is statically loaded, the typical acceleration of the vibrations which trigger large slip events is much smaller than the gravitational acceleration. These results may be relevant to understand dynamic earthquake triggering by small ground perturbations.

Keywords: granular friction, stick-slip motion, vibrations, dynamic earthquake triggering

A new rheological model of magma for representing transigion from flow to fracture

*Mie Ichihara[1]

1.Earthquake Research Institute, University of Tokyo

Whether a flowing magma with increasing strain rate becomes brittle or ductile is an important but puzzling problem in considering eruption dynamics. The criterion of the brittle/ductile transition that is currently used in volcanology is thoroughly based on the linear viscoelastic model assuming small deformation. However, flow of magma to fracture is not in the linear regime, and the current model to describe the phenomenon reveals inconsistency. Here the problem is re-considered and a new constitutive equation for magma is proposed.
Magma rheology is frequently represented by the linear Maxwell model, which consists of a viscous element and an elastic element in line. It behaves elastically in a short time or in high-frequency oscillation, and viscously in a long time or in low-frequency oscillation. The dynamic viscosity is defined in oscillatory deformation as the amplitude ratio of the stress to the strain rate and is a function of frequency. For both of magma and the Maxwel model, the dynamic viscosity is constant in the low-frequency viscous regime, and decreases as frequency increases in the elastic regime. The frequency separating the viscous and elastic regimes is inversely proportional to the low-frequency limit of the dynamic viscosity.
There are two well-known rheological laws that generally hold for polymeric fluids including magma. The one is time-temperature superposition, which indicates that change of rheology with decreasing temperature is equivalent with increasing frequency. The other is what is called Cox and Merz rule: the steady-state viscosity as a function of strain rate under continuous flow is the same as the dynamic viscosity as a function of frequency and it decreases with increasing strain rate.
Combining the two laws has lead the idea that flowing magma may enter the glassy (elastic) regime either by cooling or increasing strain rate (Dingwell, 1996). This idea has significantly influenced modeling of volcanic phenomena. Although the viscosity increases with cooling, it decreases with increasing strain rate. It is not clear whether transition to the glassy state with decreasing viscosity by increasing strain rate is the same as that by cooling.
In the area of non-linear physics, on the other hand, the glassy state is regarded as the jammed state and the glassy to ductile transition is linked to yielding (Trappe et al., 2002). In this view, a material goes from a glassy state to flow with increasing strain rate, which is opposite to the concept in volcanology. Moreover, Miyazaki et al. (2006) shows that the dynamic viscosity in the oscillatory flow either decreases or increases as the strain rate amplitude increases depending on how it is increased, that is the product of the frequency and the strain amplitude is increased whether by increasing the frequency or by increasing the strain amplitude.
The linear Maxwell model does not represent the Cox and Merz rule or non-linear behavior in large deformation. Here a new phenomenological model is proposed, which consists of the Maxwell model with a viscous element having variable viscosity and an equation representing change of the viscosity by forcing and relaxation. It can represent the behavior similar to the Cox and Merz rule. Using the new model, it is shown that the not the strain rate but the strain acceleration is essential for bringing the flow to the brittle regime.

Keywords: magma, flow and fracture, rheology, Volcanic eruption

High precision prediction of dynamic instabilities

*Tetsuo Yamaguchi[1]

1.Graduate school of Engineering, Kyushu University

Prediction of dynamic instabilities in collapse of buildings, landslides and earthquakes is very important for preventing damages. Here we report our experiments on multiple degree-of-freedom snap-through buckling where we can predict the onset of dynamic instabilities with high precision. We also apply this idea to laboratory earthquake experiments and discuss how it works.

Keywords: buckling, earthquake, prediction, Critical slowing down

Earthquake model experiments in a viscoelastic fluid: A scaling of decreasing magnitudes of earthquakes with depth

*Atsuko Namiki[1], Tetsuo Yamaguchi[2], Ikuro Sumita[3], Takehito Suzuki[4], Satoshi Ide[5]

1.Graduate School of Integrated Arts and Sciences, Hiroshima University, 2.Department of Mechanical Engineering, School of Engineering, Kyushu University, 3.Graduate School of Natural Science and Technology, Kanazawa University, 4.Department of Physics and Mathematics, Aoyama Gakuin University, 5.Department of Earth and Planetary Science, University of Tokyo

We performed shear deformation experiments using quasi-Maxwell fluids. We found that, depending on the strain rates, the same material generates earthquakes associated with the elastic rebound and deforms viscously. Around the threshold, elastic rebound releases a certain fraction of the interseismic displacement, but the other fraction remains as a result of the viscous relaxation. We applied our experimental results to a subduction zone, in which the upper part of the hanging wall behaves as an elastic layer and generates seismicity, while the deeper part behaves as a viscous fluid and subducts with the slab. Our experimental results suggest that, around the boundary of the elastic and viscous layers, seismicity can occur, but only some part of the interseismic displacements is released. The experimentally obtained threshold of the seismic activity is determined by the combination of the subduction velocity *v*, the viscosity of the hanging wall *eta* , the fault length *W*, and the adhesive stress *sigma, v eta*/(*W sigma*)>1. This threshold suggests that if the viscosity of the hanging wall decreases with depth, the maximum size of the earthquakes also decreases with depth, and, finally, seismicity disappears. This hypothesis is consistent with the observed fact that slow earthquakes, characterized by their small magnitudes, are observed at the downdip limit of the seismogenic zone.

Reference: Namiki, A., T. Yamaguchi, I. Sumita, T. Suzuki, and S. Ide (2014), Earthquake model experiments in a viscoelastic fluid: A scaling of decreasing magnitudes of earthquakes with depth, J. Geophys. Res. Solid Earth, 119, 3169–3181, doi:10.1002/2014JB011135.

Keywords: Viscous relaxation, Shear deformation, Maxwell fluid

Striation process at subduction zones of terrestrial planets

*Takao Eguchi[1]

1.Dept. of Earth and Ocean Sciences, School of Applied Sciences, National Defense Academy

We consider the basic nature of dynamics at zonal convergence boundaries between separate lithospheres on the terrestrial planets.
In this study the surface of the terrestrial planet considered is covered with several spherical rigid lithospheres having non-negligible individual horizontal motions relative to the deeper planetary structure.
We can analyze the basic aspects of various features at lithosphere boundary zones using the classical concept of plate tectonics.
Smaller-scaled convex topography and/or irregular shallow structure of the underthrusting-side lithosphere at the contacting interface of the consuming boundaries would cause a sort of striation (or wear-related) process with the elastic and inelastic deformation.
The continuous striation process should record the direction of the relative lithosphere motions on the planer interface.
However, in the case of tightly coupled boundaries with the intermittent history of greater seismic events, the striation process may not be a steady state problem.
On the earth, a large number of marine surveys have been unveiling the detailed characteristics of both the topography and sub-surface structure of oceanic lithospheres around subduction zones.
Recent studies of sophisticated multichannel seismic prospecting identified fine-scaled non-uniform topography of the plate-interface just beneath the fore-arc overriding lithosphere at the Japan trench and Nankai trough subduction zones, etc.
Using engineering methods and survey results, we can decode the details of the strain-rate dependent (seismic/aseismic) striation process on the lithospheric-interface with the local convex topography etc. at the terrestrial subduction zones.
For the striation process, we should incorporate the effect of both the spherical bending and subsequent buckling of the downgoing-side lithosphere with the age-dependent EET (effective elastic thickness).
Although the spherical buckling at the consuming boundary requests a specific geometry of surface curvature mainly depending on the EET, the past tectonic history including the deeper material flow regime etc. would also influence the three dimensional morphology of the downgoing lithosphere.
Furthermore, the difference of the elastic constants between the overriding and underthrusting lithospheres may affect dynamically on the striation and on the other seismological phenomena.
We then discuss mathematically the strain-rate dependent striation process using a simplified mechanical model for the larger inter-lithosphere seismic events.

Keywords: striation process, wear, inelastic deformation, spherical buckling, subduction zone

Measurements of elastic wave velocity of Aji granite during triaxial compression tests under pore pressure

*Kanta Zaima[1], Ikuo Katayama[1]

1.Department of Earth and Planetary Systems Science, Hiroshima University

Elastic wave velocity is one of important physical properties to investigate structure in the Earth’s interior. Because of a markedly change in elastic wave velocity at the presence of fluid, the geothermal fluid reservoir is frequently detected through seismic tomography. Previous laboratory experiments have carried to investigate effect of confining pressure (e.g. Nur and Simmons, 1969), axial stress during deformation (e.g. Gupta, 1973; Bonner, 1974; Lockner et al, 1977; Yukutake,1989; Ayling et al. 1995), fluid saturation (e.g. Nur and Simmons, 1969). However, there are few studies examining elastic wave velocity change on fracture process under pore pressure. In this study, we examined change of elastic wave velocity, amplitude and wave period during triaxial compression tests under pore pressure as a fundamental research on estimating of artificial geothermal reservoir on hot dry rock system.

We used Aji granite with a cylindrical shape, 40 mm long and 20 mm in diameter. For triaxial compression tests, we used intra-vessel deformation and fluid flow apparatus at Hiroshima University and deformed sample at 0.01 mm/min displacement rate. On dry condition, confining pressure was 20 MPa, and on wet condition, we used water as a pore fluid and confining pressure was 20MPa and pore pressure was 10 MPa. We kept pore pressure constant using syringe pump and calculated approximate porosity from volume change of fluid at syringe pump. We adopted pulse transmission method using electric transducers directly attached on the sample, and elastic wave velocity (Vp, Vs), amplitude and wave period from waveforms were recorded by oscilloscope.

We observed a systematic change of elastic wave velocity possibly due to closure, growth and formation of cracks during triaxial deformation. While elastic wave velocity was increased due to closure of preexisting cracks at the primary stage of deformation, it decreased markedly at the late stage of deformation. Vp/Vs tends to increase in association with development of deformation on wet condition while it decreases on dry condition. These data are consistent with theoretical model by O’Connell and Budiansky (1974), in which fluid filled cracks increase Vp/Vs but open (dry) cracks have an opposite influence. Based on the model of O’Connell and Budiansky (1974), crack density is suppressed during deformation under wet experiments. During triaxial deformation amplitude was attenuated and wave period became long as a consequence of increasing cracks in the specimens. Attenuation of P wave is relatively small on wet condition because of less scattering of elastic wave at crack surfaces with water. On the other hand, amplitude of S wave vibrated perpendicular to compressional axis tends to increase at initial of deformation, because S wave is sensitive to closure of horizontal cracks. Our experimental results show a correlation between porosity and elastic wave velocity, and we could use this relation to infer extent of fluid reservoir through seismic wave velocity.

Keywords: elastic wave velocity, triaxial deformation, crack density, pore pressure

Role of super critical fluids in quasi-static fracture process of earthquake nucleation -case of 1965-1967 Matsushiro earthquake swarm-

*Yuji Enomoto[1], Tsuneaki Yamabe[2], Nobuo Okumura[3]

1.Shinshu Univeristy, Department of Texitile Engineering, Fii, 2.Shinshu University, Department of Texitile Engineering, 3.Genesis Research Institute, Inc.

None

Keywords: Fracture, Super critical fluids, Fractoemisson

Estimating stress fieldfrom seismic moment tensor data based on the flow rule in plasticity theory

*Satoshi Matsumoto[1]

1.Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University

Stress field is a key factor controlling earthquake occurrence and crustal evolution. A method that slip data on many pre-existing faults reveals relative stress tensor in a region have been applied many regions. On the other hand difficulty of the method arises due to non-linear relation of slip vector to traction on a fault.
Here, we show stress field in a region with seismic activity can be estimated from sum of seismic moment tensors in the region based on classical equation in plasticity theory. Seismic activity is a phenomenon relaxing crustal stress and creates inelastic deformation in a medium due to faulting, which suggests the medium could behave as plastic body. The simple mathematical manipulation make easy to estimate stress field in a region and to develop inversion method in further studies.

Keywords: seismic moment tensor, stress field

Stress states in the deep part of subduction megathrust estimated from dynamically recrystallized grain size and dislocation creep flow laws of quartz

*Ichiko Shimizu[1], Tadamasa Ueda[1]

1.Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo

Strength of the continental lithosphere has been extensively studied, but little is known about stress states in subduction zone megathrusts. In this paper, we estimate paleo-stress in a Cretaceous subduction zone of the Sanbagawa belt in southwest Japan, using grain size piezometers and dislocation creep flow laws of quartz.
Laboratory studies showed that recrystallized grain size in dislocation creep is primarily controlled by the applied stress but physical basis of the piezometric relations is still in debate. Theoretical models predict that the steady-state grain size in dynamic recrystallization (DRX) is not only dependent on stress, but also on temperature. The common idea among existing theories is that competition between grain-boundary formation, and grain growth determines the steady-state grain size. For grain growth, grain boundary migration driven by strain-energy (ρGBM), or that driven by surface-energy (γGBM), have been considered. Both processes result in overall coarsening, but in the case of ρGBM, strain-free small grains grow with the expense of larger deformed grains, while in γGBM, small grains shrink and larger grains grow. A simple nucleation-and-growth model with ρGBM produces a left-skewed distribution on a section that is approximated by a log-normal distribution with a single scaling parameter, *dc* (Shimizu, 1999). In addition to subgrain rotation (SGR) nucleation and grain growth by ρGBM, surface-energy drags were also taken into account in the revised theoretical piezometer (Shimizu, 2012).
We analyzed microstructures of quartz schists (meta-chert) taken from the Asemi-gawa root, central Shikoku. The grain size of quartz was measured by tracing grain boundaries on microphotographs and by mapping crystallographic orientations using the electron back-scattered diffraction (EBSD) method (Ueda & Shimizu, 2016, JpGU). Observed grain size distributions (GSDs), which were characterized by increasing numbers with decreasing grain size, were far different from bell-shaped distributions known for static grain growth driven by surface energy, and more like the theoretical distribution derived for the nucleation-and-ρGBM model.
To estimate differential stress, we applied the revised theoretical piezometer (Shimizu, 2012) assuming that the grain size at the largest volume fraction corresponds to *dc*. The paleo-stress estimates were also done by extrapolating dislocation flow law of wet quartz to the peak metamorphic temperatures. Preliminary results obtained for the sample in the garnet zone (ca. 500 $^{\circ}$C) were within reasonable agreement with the dislocation creep model, whereas direct application of the experimental piezometer proposed by Stipp and Tullis (2003), re-calibrated by Holyoke & Kronenberg (2010), gives considerably smaller estimates.

References

Holyoke, C.W. and Kronenberg, A.K. (2010). *Tectonophysics*, 494, 17–31.
Shimizu, I. (1999). *Philosophical Magazine A*, 79, 1217–1231.
Shimizu, I. (2012) In: "Recrystallization'', edited by Krzysztof Sztwiertnia, InTech, ISBN 978-953-51-0122-2, pp. 371–386.
Stipp, I. and Tullis, J. (2003). *Geophys. Res. Lett.*, 30, 2088–2092.

Keywords: differential stress, dynamic recrystallization, dislocation creep , grain size distribution, quartz, Sanbagawa metamorphic belt

Experimental evaluation of grain-size-sensitive creep and grain-size-insensitive creep of quartz

*Jun-ichi Fukuda[1], Caleb W. Holyoke[2], Andreas K. Kronenberg[1]

1.Department of Geology and Geophysics, Texas A&M University, 2.Department of Geosciences, University of Akron

Plastic deformation of polycrystalline materials is categorized into two main mechanisms; one controlled by grain boundary process which depends on grain size (grain-size-sensitive creep; GSS creep) and the other controlled by intragrain dislocation process which does not depend on grain size (grain-size-intensive creep; GSI creep). Studies of experimentally deformed and naturally deformed rocks suggest that in general, the transition between GSS and GSI creep can occur in the grain size of the micrometer order.
Quartz controls the ductile strength of continental rocks because of its abundant existence and weakness. Therefore, a lot of experimental studies have been done to construct the flow laws of quartz ductile deformation. Most experiments used large grain aggregates such as a few hundred μm of each grain, which promote GSI (dislocation) creep. The stress exponents were 3~4 and the microstructures exhibit elongated grains and/or recrystallized grains with host large grains. The host grains still constitute the large volume of the aggregates, leading to GSI creep. The mechanical properties of GSS creep are not well known. In this study, we use fine-grained quartz to experimentally demonstrate GSS creep and its transition to GSI creep.
We hot pressed fine-grained quartz powder of ~2 μm in a solid-pressure-medium deformation (Griggs-type) apparatus at 1.5 GPa and 900°C. We observed systematic grain growth from 2 μm to 25 μm with increasing annealing times from 1 hour to 240 hours. The hot-pressed samples show polygonal grain shapes, tight grain boundaries, and no lattice preferred crystallographic orientations (LPOs). Next, strain-rate stepping experiments were performed under 1.5 GPa, 900-600°C, and the strain rates of $10^{-3.5}$-$10^{-6.0}$/sec. At 900 and 800°C, the stress exponents determined were n=1.5~2.0 (av. 1.7) regardless of the different hot press durations. At temperatures down to 600°C, the stress exponents increased up to 5. The microstructure of the samples shows undulatory extinction and recrystallized fine grains of 1 μm. The crystallographic orientations have weak LPOs that reflect some crystal plasticity and recrystallization. The later stage of deformation appears to be controlled mostly by GSS creep of finely recrystallized grains, as indicated by low stress exponents. Temperature stepping experiments show corresponding two trends; one at 900-750°C and the other at 700-550°C. The activation energies for the high temperature data were 160-200 *kJ/mol* (av. 180 *kJ/mol*) with the stress exponents of 1.7. The strength changes by pressure stepping corresponded to the water fugacity changes. The obtained water exponent is r=1 with n=1.7.
We extrapolate our GSS creep data to natural conditions together with previous flow laws for quartz dislocation creep. Under mid-crustal conditions where the temperature and strain rate conditions are around 400°C and 10^{-14}/sec, respectively, the transition from dislocation creep to GSS creep is predicted at a grain size of ~10 μm. This result is consistent with observations for natural quartz deformed by GSS creep. Our data indicate that the transition from dislocation creep to GSS creep occurs at crustal conditions for fine-grained quartz-rich rocks.

Keywords: Quartz rheology, Flow law, Crustal strength, Griggs-type deformation apparatus

Rheological weakening due to phase mixing of olivine + orthopyroxene aggregates

*Miki Tasaka[1,2], Mark E Zimmerman[2], David L Kohlstedt[2]

1.Niigata University, 2.University of Minnesota

To understand the processes involved in rheological weakening due to phase mixing in olivine + orthopyroxene aggregates, we have conducted high-strain torsion experiments on samples of iron-rich olivine + orthopyroxene. Samples with volume fractions of pyroxene, f_{px} = 0.3, were deformed at a temperature of 1200°C and a confining pressure of 300 MPa using a gas-medium apparatus to total shear strains up to $\gamma \approx 26$.
Values for the stress exponent of $n \approx 3$ and grain size exponent of $p \approx 1$ at lower strain ($1.9 \leq \gamma \leq 4.2$) and $n \approx 2$ and $p \approx 3.5$ at higher strain ($\gamma \geq 24$) were determined from a linear least-squares fit to the strain rate, stress, and grain size data using a power-law creep equation. These values of *n* and *p* indicate that our samples deformed by dislocation-accommodated grain boundary sliding at lower strain, with an increased contribution of diffusion creep at higher strain.
The microstructures observed in samples deformed to lower strain are consistent with structures induced by a dislocation-accommodated creep mechanism, while the microstructures observed in samples deformed to higher strain are compatible with structures observed following diffusional creep. In samples deformed to lower strain, elongated olivine and pyroxene grains aligned sub-parallel to the shear direction, and dynamically recrystallized grains formed in both phases . In contrast, in samples deformed to higher strains, mixtures of small, rounded grains of olivine and pyroxene were developed. The mechanical and microstructural evolution observed in this study are an important step toward understanding dynamic processes of strain localization and rheological weakening during plastic deformation of the lithosphere necessary for the initiation and persistence of plate tectonics.

Keywords: phase mixing , olivine and orthopyroxene aggregates

Temperature dependence of polycrystal anelasticity at near-solidus temperatures: toward clarification of the underlying mechanism and applications to seismology

*Hatsuki Yamauchi[1], Yasuko Takei[1]

1.Earthquake Research Institute, The University of Tokyo

For a quantitative interpretation of seismic structures, it is needed to assess the effects of temperature, melt fraction, and grain size on the rock anelasticity. However, due to the limited understanding on the underlying mechanism, it is difficult to apply the experimental data to the condition of the mantle. To address this lack, we performed forced oscillation tests on the rock analogue (polycrystalline aggregates of organic “borneol”) and measured modulus and attenuation over a wide frequency range.

Attenuation spectra obtained from polycrystalline materials are generally represented by the superposition of a monotonic “background” and a broad “peak” which exists at relatively high frequencies. The background, which has been observed robustly in all experiments, follows the Maxwell frequency ($f_M = M_U/eta$, M_U = unrelaxed modulus, *eta* = diffusion creep viscosity) scaling. This shows that the mechanism of the background is “diffusionally accommodated grain boundary sliding,” which is rate-limited by matter diffusion in the same manner as the diffusion creep. Although we have a general consensus about the scaling law and mechanism of the background, those for the peak are still controversial. It is crucial to better understand the peak, because it dominates the background at seismic frequencies.

We focus on the relationship between peak and partial melting, such that a large peak is obtained for melt-bearing rocks. Recent data obtained from the analogue samples show that even at subsolidus temperatures the amplitude and width of the peak increase with increasing T/T_m (T_m: solidus temperature) [Takei et al., 2014]. This result suggests that, even without melt, low Q and low V can occur at near-solidus temperatures. However, their data are limited to T/T_m =< 0.93. In order to understand the effect of partial melting on the peak, it is important to investigate anelasticity at both subsolidus and supersolidus temperatures.

We measured anelasticity of the rock analogue at near-solidus temperatures ranging from subsoilidus to supersolidus temperatures (0.88 =< T/T_m =< 1.01). In addition to the forced oscillation tests at $2*10^{-4}$ Hz =< f =< 100 Hz, we performed the ultrasonic test to measure the unrelaxed modulus and the creep test to measure the diffusion creep viscosity to calculate f_M. Also, from the reduction of the ultrasonic velocity by partial melting, we estimated the total relaxation strength which exists at higher frequencies than the ultrasonic frequency (> 700 kHz). The results are as follows. (1) Although the total relaxation strength of the background is constant regardless of various experimental conditions, that of the peak increases with increasing T/T_m, showing the breakdown of the Maxwell frequency scaling in the peak. (2) The increase of the total relaxation strength of the peak starts at the subsolidus temperature (T/T_m = 0.93), indicating that the mechanism of the peak is some solid-state mechanism. This result is also supported by the ultrasonic data which show that the relaxation by the melt squirt flow mechanism occurs at much higher frequencies than the peak (> 700 kHz). (3) Samples which experienced partial melting sometimes show a hysteresis such that the large peak observed in the partially molten state remains even below the solidus temperature. This implies that even after the solidification a connected network of grain-edge tubules works as a fast diffusion path and enhances the peak. These results provide a key to clarify the mechanism of the peak. We further discuss the implications to seismology.

Keywords: anelasticity, seismic wave velocity and attenuation, partial melting

Effect of Dislocations on Rock Anelasticity: Experimental Approach by Using an Analogue Material

*Yuto Sasaki[1], Yasuko Takei[1], Christine McCarthy[2], Ayako Suzuki[1]

1.Earthquake Research Institute, University of Tokyo, 2.Lamont-Doherty Earth Observatory, Columbia University

Rock anelasticity causes seismic wave dispersion and attenuation. Therefore, it is important to understand the mechanism of anelasticity to know about the Earth's interiors from seismic tomographic images. Grain boundary sliding and dislocation motion have been two major mechanisms proposed for the rock anelasticity. Although extensive studies on the grain boundary sliding have been performed [1-4], few experimental studies have been performed on the effect of dislocations on the rock anelasticity [5, 6]. In this study, by using the organic polycrystalline material (borneol $C_{10}H_{18}O$, melting temperature Tm=204°C) as a rock analogue [3], the effect of dislocations on anelasticity was measured accurately over a broad frequency range (10^2-10^{-4} Hz).

-

First, in order to know the flow law of this analogue material, uniaxial creep tests were performed at T/Tm=0.66 (T=40°C) and 0.68 (T=50°C) and at various differential stresses from Δσ=0.27 to 2.3 MPa. To avoid the occurrence of cataclastic flow, confining pressure Pc=0.8 MPa was applied in a pressure vessel with a frictionless uniaxial piston designed by T. Sato in soil mechanics. As a result, we captured a transition from a linear (n~1) creep to a power law (n~5) creep: the transition occurs at Δσ≈1.4 MPa for T/Tm=0.68 (50°C) and at a higher Δσ for T/Tm=0.66 (40°C). In the deformed sample (Δε~0.5), grain boundaries became wavy and the grain size showed a larger variation than the undeformed samples, indicating the occurrence of grain boundary migration associated with dislocations. Therefore, we considered the power law creep as dislcoation creep which introduced dislocations into the samples.

-

Next, three creep tests with Δσ=0.27 (diffusion creep regime), 1.4 (transitional regime), 2.1 MPa (dislocation creep regime) were conducted on the same sample in the increasing order, and after each creep test anelasticity of this sample was measured repeatedly to detect the effect of predeformation and also to detect a temporal evolution during the anelasticity measurements. Each predeformation was performed in the pressure vessel at Pc=0.8 MPa and T/Tm=0.68, and the deformed sample was cooled down to room temperature under the differential stress. The predeformation took about 16-23 hours and the cool down took about 6 hours. The sample was then removed from the vessel and anelasticity was measured in the forced oscillation apparatus [3] at ambient pressure: Young's modulus E and attenuation Q^{-1} were measured over a broad range of frequencies f=10^2-10^{-4} Hz and at several temperatures from T/Tm=0.59 (10°C) to 0.66 (40°C). The results can be summarized as follows. (1) The anelasticity obtained after the test with Δσ=0.27 MPa and Δε=0.007 agreed well with the previous result measured under the offset stress Δσ=0.27 MPa [3]. (2) In contrast, after each of the latter two tests (Δσ=0.14 MPa and Δε=0.036, Δσ=2.1 MPa and Δε=0.12, respectively), Young's modulus E was lower and attenuation Q^{-1} was higher than the results in (1), and these changes were larger for the larger stress. (3) Over time, E and Q^{-1} gradually increased and decreased, respectively, finally converging into the property measured in (1). These results are considered to be attributable to the dislocations and their recovery.

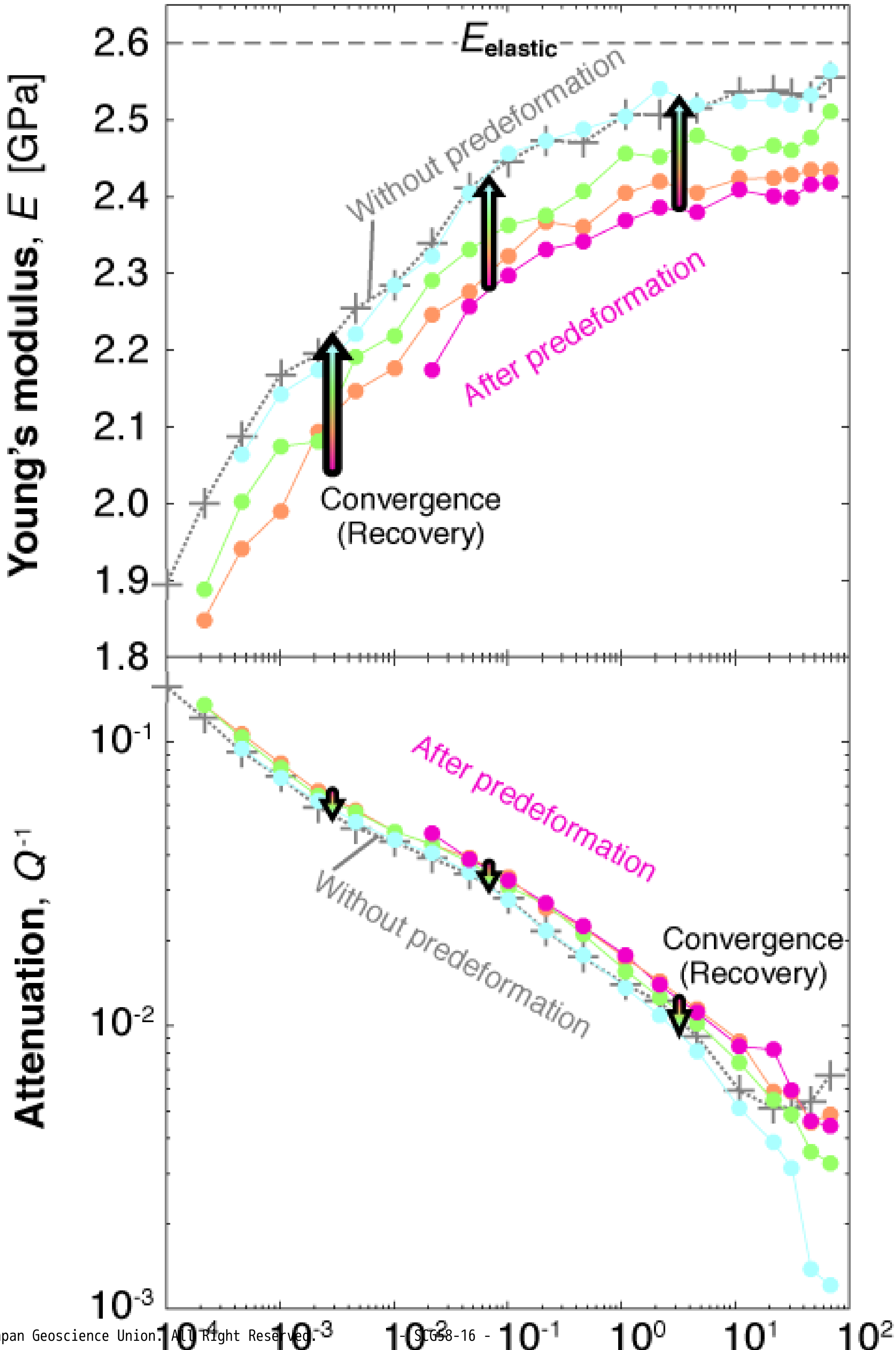
-

-

[1] Morris and Jackson, 2009, *J. Mech. Phys. Solids*

[2] Jackson *et al.*, 2014, *PEPI*
[3] Takei *et al.*, 2014, *JGR*
[4] Gribb and Cooper, 1998, *JGR*
[5] Guéguen *et al.*, 1989, *PEPI*
[6] Farla *et al.*, 2012, *Science*

Keywords: anelasticity, dislocation, seismic attenuation, analog experiment, polycrystal, defect



$E_{elastic}$
Without predeformation
After predeformation
Convergence
(Recovery)
Young's modulus, E [GPa]
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
After predeformation
Without predeformation
Convergence
(Recovery)
Attenuation, Q^{-1}
10^{-1}
10^{-2}
10^{-3}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}

Fabric transition in olivine due to temperature and stress at high pressures

*Ayako Suzuki[1,2], Shenghua Mei[1], David L Kohlstedt[1], William B Durham[3], Nathaniel A Dixon[3]

1.University of Minnesota, 2.Earthquake Research Institute, University of Tokyo, 3.Massachusetts Institute of Technology

The crystallographic fabric induced by deformation of mantle rocks reflects the dominant dislocation slip system and results in both rheological and seismic anisotropy in the upper mantle. The strength of the individual slip systems in olivine single crystals and the development of crystallographic fabric in olivine aggregates have been studied experimentally mainly in the high-temperature creep regime, with few measurements in the low-temperature plasticity regime. While a climb-controlled mechanism is important at higher temperatures and lower stresses, the dislocation slip mechanism in the low-temperature plasticity regime is considered to be glide-controlled. At low temperatures and high stresses, deformation of olivine aggregates follows an exponential flow law because dislocation motion requires a stress-dependent activation enthalpy for overcoming the Peierls barrier. In order to understand deformation mechanism and the dominant slip systems in the low-temperature plasticity regime, we investigated fabric evolution in olivine aggregates deformed experimentally at different temperatures changing from low to high at high pressures.

Samples were polycrystalline aggregates of San Carlos olivine with a grain size of 5-10 μm. Deformation experiments were carried out using the D-DIA apparatus at X-ray beamline X17B2 in the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory. Samples were deformed to strains of 20-30% at a constant displacement rate of 0.1-6.8 x 10^{-5} /s, temperatures of 673-1573 K, pressures of 4-9 GPa, and differential stresses of 0.6-3.8 GPa. Creep data at the highest temperature (T = 1573 K) and lowest stress indicated a dislocation, power-law creep mechanism, while creep results at lower temperatures (T < 1273 K) and higher stresses revealed an exponential flow mechanism (Mei et al., 2010).

After deformation experiments, we determined the crystallographic fabric (CPO, crystallographic preferred orientation) in the deformed samples using electron backscattered diffraction (EBSD). At the highest temperature (T = 1573K) and lower stresses (σ < 1 GPa), the poles of the (010) planes concentrated parallel to the maximum principal stress. This concentration of (010) planes is more dispersed at a temperature of 1473 K. In contrast, at lower temperatures (T < 1373 K) and higher stresses (σ > 2 GPa), the poles of the (100) planes concentrated parallel to the maximum principal stress. The change of crystallographic fabric in deformed samples is roughly consistent with the change of deformation mechanisms based on the analyses of mechanical data as stated above. This transition in slip plane associated with a change in temperature and stress is consistent with a difference in dominant slip systems of (010)[100] at higher temperatures and low stresses and (100)[001] at lower temperatures (Bai et al., 1991; Durham and Goetze, 1977; Tielke, 2016), indicating that the dominant slip system in the glide-controlled low-temperature plasticity regime differs from that in the high-temperature climb-controlled creep regime.

Keywords: low-temperature plasticity, slip system, olivine

Lattice-preferred-orientation of hcp metals studied by high-pressure deformation experiments

*Yu Nishihara[1], Tomohiro Ohuchi[1], Takaaki Kawazoe[2], Genta Maruyama[1], Yusuke Seto[4], Yuji Higo[5], Ken-ichi Funakoshi[3], Yoshinori Tange[5]

1.Geodynamics Research Center Ehime University, 2.Bayreuth Geoinsitut, 3.CROSS, 4.Kobe University, 5.JASRI

Many hypotheses have been proposed for origin of seismic anisotropy in the Earth's inner core which consists of solid metal (e.g. Sumita and Bergmann, 2009). Plastic deformation of constituent material (most probably hexagonal-close-packed (hcp) iron) is one of the candidate processes to form the inner core anisotropy. Thus knowledge of deformation-induced lattice preferred orientation (LPO) of hcp-iron is important for understanding of nature of the inner core. In this study, we have carried out shear deformation experiments on hcp-iron and its analogue materials, hcp-Co and hcp-Zn, and determined its deformation induced LPO.
Shear deformation experiments were carried out using a deformation-DIA apparatus at high-pressure and high-temperature. Experimental conditions were 14–18 GPa and 723 K for Fe, 3 GPa and 673 K for Co, and 2 GPa and 573 K for Zn. Development of LPO in the deforming sample was observed in-situ based on two-dimensional X-ray diffraction using an imaging plate or X-ray CCD detector and monochromatized synchrotron X-ray. In shear deformation of Fe, <0001> and <112(_)0> axes gradually aligned to be sub-parallel to shear plane normal and shear direction, respectively, from the initial random orientation. In final LPO of Fe, <0001> and <112(_)0> axes are back-rotated from shear direction by ~30o. On the other hand, in the deformation experiments of Co and Zn, the <0001> was aligned to parallel to shear plane normal. The above results suggest basal slip <112(_)0>{0001} is the dominant slip system in these hcp metals under the studied deformation conditions. The deviation of LPO of Fe from ideal orientation is presumably due to friction on the bottom plane of piston under higher pressure conditions.
It has been shown that Earth’s inner core has an axisymmetric anisotropy with P-wave traveling ~3% faster along polar paths than along equatorial directions. Although elastic anisotropy of hcp-iron at the inner core conditions is still controversial, recent theoretical studies consistently shows that P-wave velocity of hcp-iron is fastest along <0001> direction at least at low-temperatures. Our experimental results could be suggesting that most part of the inner core deforms with shear plane sub-parallel to equatorial plane.

Keywords: hexagonal-close-packed metal, lattice preferred orientation, inner core

