Field-based constraint on dehydration behavior of altered oceanic basalt at the seismogenic subduction boundary

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Recent progress on phase equilibria modelling in a complex chemical system allows us to model dehydration behavior of subducting crustal rocks along a given P-T path. However, there is limitation of such equilibrium approaches to model low temperature (<350 deg.C) domains of subduction zones (i.e., the seismogenic zone), because of the predominance of non-equilibrium features and the lack of reliable thermodynamic data and solid-solution models for low-T minerals. Nevertheless, phase equilibria modelling has shown that extremely high H_2O content is required for H_2O saturation in a basaltic system at low-T conditions, implying that the seismogenic depths of the subduction interface should be largely H_2O deficient or fluid absent due to the progress of basalt hydration reactions. However, detailed processes and extent of low-T equilibration of basaltic rocks are poorly known, and it remains unclear whether basaltic oceanic crust acts as a H_2O sink or a H_2O source at the seismogenic zone. Field-based studies are important to better understand the behaviour of subducting basaltic rocks into the seismogenic zone. The Northern Chichibu belt of SW Japan represents Jurassic accretionary complexes that formed around the brittle-ductile transition of quartz-rich rocks in a subduction zone setting. Widespread occurrence of lawsonite-rich veins in altered basalt is newly recognized from a non-metamorphic unit (230–240 deg.C) in the brittle part of this belt. Microstructural observations suggest that those lawsonite-rich veins formed by dehydration of pre-existed laumontite (zeolite) veins. The reaction laumontite -> lawsonite + quartz + H_2O took place during burial and compression to 0.35 GPa, which corresponds to ˜12 km depth. This lawsonite-forming reaction is a discontinuous reaction in the simple $CaO-Al_2O_3-SiO_2-H_2O$ (CASH) system, and thus reactive system of subducting basaltic rocks at the seismogenic zone is highly localized and deviated from basaltic bulk compositions. Zeolite dehydration may be an important source of water in deeper parts of the seismogenic plate boundary.

Keywords: subduction, altered basalt, dehydration

Metamorphic Olivine Formed after Orthopyroxene in Mantle Wedge during Serpentinization from the Khantaishir Ophiolite, Western Mongolia

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Dehydration of serpentine in subducting zone is thought to be associated with various subduction zone processes, including intermediate-depth earthquakes, slow earthquakes and arc magmatism.
Metamorphic olivine is direct evidence of dehydration of serpentine. In this study, we report a novel texture of metamorphic olivine found from the Khantaishir ophiolite in western Mongolia, and discuss its mechanism and tectonic implications.
The Khantaishir ophiolite is located in the western Mongolia, which belongs to the Central Asian Orogenic Belt. This ophiolite composed of ultramafic rocks, pyroxenites and gabbro, sheeted dikes, pillow lavas, and pelagic sediments is strongly sheared and thrusted, but well preserved ophiolitic sequence is partly preserved. Geochemical study of igneous rocks of the Khantaishir ophiolite in the Altai area suggested signatures of suprasubduction-zone origin such as boninite (Matsumoto and Tomurtogoo, 2003). In this study, we investigated the ultramafic body, the Naran massifs in the Altai region. Although a small ophiolite body in the Chandman area, occurred ca.180 km away from Altai, is cropped out close to eclogite bodies, relationship between metamorphism and ultramafic bodies is still unclear.
Most of the ultramafic rocks in the Naran massif are highly serpentinized. The most dominant one is antigorite in matrix, lizardite and brucite mixtures occurs as vein-filling of primary olivine, and chrysotile occurs as veins, cutting the all textures. About half of the samples within the Naran massif contained olivine as well as serpentines, spinel, magnetite, and brucite. Two types of olivine were found; primary and metamorphic origins, respectively. Metamorphic olivine is widely distributed in the Naran massif, and show higher Mg# (0.94-0.98) compared to the primary ones (Mg# = 0.92-0.93). A plot Mg# of primary olivine vs Cr# (0.70-0.82) of spinel suggests that the ophiolite was formed at fore-arc setting.
It is notable that metamorphic olivine commonly exists as fine-grained aggregates with aggregate size of ca.5mm, and showed aligned fractures filled with high Cr-richer antigorite, and a subtle amount of clinopyroxene was formed. These microstructural features indicate that such olivine was originated from orthopyroxene. Plümper et al., (2012) reported similar textures, and proposed two stages of bastite formation after orthopyroxene (hydroration) and then the olivine formation by dehydration reaction. In contrast, the samples with metamorphic olivine do not contain any evidence of talc formation; so, it is reasonable to consider that that metamorphic olivine was directly formed by silica-releasing reaction after orthopyroxene, which is coupled with the silica consuming reaction of primary olivine to produce antigorite. This indicates that metamorphic olivine was formed during serpentineization (hydration).
Petrological analyses implies that the breakdown of orthopyroxene to form olivine without talc formation could occur at high P- T condition (i.e., >1.5 GPa, ca 600˚C). Such conditions may be consistent with P-T condition (2-2.25 GPa, 590˚C-610˚C) of the eclogite body related to the Khantaishir ophiolite, ca.180 km away from the Altai area. At the margin of the Naran massif in the Altai area, we found amphibole-bearing metamorphic rocks, which contain albite, K-feldspar, with lessor amount of biotite, sphene, calcite, quart, chlorite and iron oxides. Amphibole shows a prominent compositional zoning; from actinolite at core to magneseoriebeckite at the rim, which is consistent with the wedge mantle condition at high P metamorphism. The metamorphic olivine after orthopyroxene in the Naran massif indicates the hydration of wedge mantle under unmature arc during the development of CAOB.

Keywords: Mantle wedge, Metamorphic olivine, Serpentinization

Evolution of redox state inferred from trivalent cations in antigorite from Higashi-akaishi peridotite body, SW Japan

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Antigorite is stable in a relativity wide range of temperature (200-600 ˚C) (Evans, 1977) and, therefore, it can be a witness of tectonic and geochemical histories in depths of subduction zones. Antigorite includes minor but various amounts of Al and Cr. Importance of these trivalent cations for antigorite formation in discussed from several points of view: stabilized condition (Bromiley and Pawley, 2003; Padron-Navarta et al, 2013) and reaction speed (Andreani et al., 2013). However, there are a few petrological works on natural antigorite to ensure these ideas. We focus on the trivalent cations in antigorite from Higashi-akaishi peridotite body, SW Japan, and interpret the compositional change in terms of hydration reactions and redox states in the system consisting of olivine, Cr-spinel and Fe-Ni sulfides.
Occurrence of antigorite is divided into two types: the discrete antigorite in weakly serpentinized dunite and the bundle antigorite in antigorite schist. The discrete antigorite shows conspicuous chemical zoning of Al and Cr, regardless of distance from chromite. The Al and Cr contents of discrete antigorite are evenly high implying these elements released from chromite were available for antigorite formation throughout the rock. The bundle antigorite has homogenous and relativity pure composition (poor in Al and Cr). Altered chromite shows wide range of chemical composition from Cr rich to Fe^{3+} rich, reflecting miscibility gap in Cr-spinel compositions and redox state of reaction. Pentlandite, Fe-Ni sulfide, occurs as inclusions in olivine and altered Cr rich chromite. In the matrix, the sulfide mineral assemblage coexisting with antigorite is mainly heazlewoodite + godlevskite + magnetite. Break down of pentlandite indicates that the redox state has changed from a reducing state to a relatively oxidizing state. This is consistent with the alteration trend in chromite compositions. Fe content of olivine (fayalite content) increases with increasing degrees of antigorite serpentinization. Magnetite formation, indicating oxidation of Fe in olivine, is inactive in the initial stage of antigorite serpentinization. At the later stage, its occurrence is dominant in antigorite schists although the cause of the oxidizing conditions is unclear.
This study correlates the compositional changes of antigorite with alteration of chromite. The difference in compositional trends is due to different oxidation states for two stages of antigorite serpentinization. Coexisting sulfide minerals give constrains on the redox states for these serpentinization stages consistently. The change of redox state took place during exhumation of the ultramafic unit implying more oxidizing conditions at the shallower depth along the subduction boundary.

Andreani, M. et al., 2013, Am. Min. 98, 1738-1744.
Bromiley, G.D. and Pawley, A.R., 2003. Am. Min. 88, 99–108.
Evans, B. W., 1977, Ann. Rev. Earth Planet. SCi. 5, 397-447.
Evans, B. W., 2010, Geology 38, 879-882.
Padron-Navarta, J. A. et al., 2013, Lithos 178, 186-196.

Keywords: antigorite, sulfide mineral, redox state

Petrological and structural analyses of ultrafine-grained ductile shear zone in hydrous peridotite: A case study of the Gongen outcrop in the Sanbagawa belt

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Shear zones are important to cause large tectonic displacement in the Earth’s crust and upper mantle. Weakening of mantle minerals is required for subduction boundaries with large displacements to be kept into depths. Grain size reduction of constituent minerals is generally observed in exposed shear zones and is considered as a major mechanism that reduces the rock strength. Therefore, it is important to understand recrystallization and weakening of olivine crystals in wet conditions from observations of natural peridotites.

A case study is carried out on an ultrafine-grained shear zone in the Higashi-akaishi ultramafic body in the Sanbagawa belt, SW Japan. Grain size, intracrystalline misorientation (MO) and crystallographic preferred orientation (CPO) are measured using EBSD maps. FE-SEM observations of dislocation microstructures are made on the samples after oxidation decoration at 900 degree C. Pressure and temperature conditions of the deformation can be constrained as about 3.5 GPa and 700 ℃ based on the syn-deformational mineral assemblage (chlorite is stable and antigorite and phlogopite are unstable) and the pressure-temperature evolution of the body. To evaluate the microstructural observations in terms of olivine rheology, a deformation mechanism map is calculated in the pressure-temperature conditions as a function of stress and grain size. Dislocation-accommodated grain boundary sliding (DisGBS), whose flow law is recently determined in water-saturated conditions, is taken into account for the map.

Olivine grains in samples can be separated into three groups: coarse grain (mm scale), fine grain (100 μm scale) and ultrafine grain (10 μm scale). Coarse grains are characterized by well-developed dislocation walls and large MO indicating dislocation gliding parallel to a– and c-axes. Fine grains have large MOs and high dislocation densities, and show a decrease in concentrations of CPO upon recrystallization (defined by proportion of ultrafine neoblasts). These features indicate a grain-size sensitive flow of DisGBS. Most of ultrafine grains show minor MOs and low dislocation density. The CPOs are weaker than those of fine grains and their concentrations are weaker in more recrystallized domains. Grain sizes and stress estimations for coarse, fine and ultrafine grains are plotted, respectively, within the regimes of dislocation creep, DisGBS creep and DiGBS-diffusion creep in the mechanism map. This is consistent with the above microstructural observations.

In fine grains, dense dislocation walls of various orientations form cellular structures that define sub-grains. They have locally developed to grain boundaries marking neoblasts with minor dislocations. The sizes of the sub-grains and the recrystallized neoblasts are about 2 μm. This value is consistent with an experimentally determined grain size piezometer. Difference in dislocation density between the old and new grains has caused grain boundary migration resulting in growth of ultrafine neoblasts. The typical grain size of about 20 μm is interpreted as a steady-state one determined under co-operation of dislocation and diffusion processes.

The microstructural analyses of this study indicate that grain size reduction in a DisGBS regime was controlled by formation and movement of dislocations. Initial stage of recrystallization possibly induced extensive weakening due to switch of deformation mechanism between two grain size sensitive creeps. However, a subsequent recovery of grain size has inhibited the effect to be moderate. Water-rich condition enhances both dislocation and diffusion processes and, therefore, contribute to the development of the ultrafine-grained shear zone.

Rheological transition during progressive antigorite serpentinization of peridotite

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Antigorite is inferred as a major hydrous phase in forearc mantle. A degree of serpentinization in mantle wedge differs depending on age, thermal state and location of the subduction zone. Under progressive serpentinization, antigorite-bearing peridotite consisting of olivine and antigorite is substantially important and is expected to have significant roles in the geodynamic processes. It is generally accepted that an increase of antigorite reduces strength of mantle above a plate interface resulting in slab-mantle decoupling. The idea of lubricant serpentinite is developed based on geological observations of serpentinite mélange that encloses high-P tectonic blocks. However, convincing evidence constraining rheological behaviours of antigorite is not found from structural and experimental works.

This study focuses on olivine and antigorite coexisting in partially serpentinized peridotite that is expected to have information of the relative strengths of these important minerals. Microstructural observations and crystallographic analyses of naturally deformed antigorite peridotite in the Higashi-akaishi ultramafic body revealed transitions of deformation mechanism of olivine during progressive antigorite serpentinization. Before serpentinization, in wet conditions, coarse olivine has deformed in dislocation creep regime and olivine neoblasts were dominated by dislocation-accommodated grain boundary sliding (DisGBS). In the early stage of serpentinization, fine grains of olivine deformed by both DisGBS creep and dissolution precipitation creep (i.e. grain boundary diffusion-controlled creep). Observations of higher dislocation densities in olivine grains adjacent to antigorite indicate that antigorite blades were rigid to keep higher local stress than those at olivine-olivine boundaries. With increasing degrees of serpentinization at lower temperature, proportion of smaller grains of olivine increases so that dissolution precipitation creep becomes dominant. The mechanism is supported by elongation to a-axis parallel to stretching direction and shortening parallel to b-axis. In the latest stage, crack-filling antigorite characteristically occurs in olivine grains, suggesting that olivine became rigid and antigorite has controlled the strain of rocks.

At the three stages of progressive serpentinization (associated with characteristic deformation) in the Higashi-akaishi body, dislocation microstructures, grain shape and CPO of olivine are consistent with deformation mechanism map based on experimentally determined flow laws for wet olivine. This indicates that these rheological equations determined at high temperature conditions (> 1000 ˚C) can be extrapolated to low temperature conditions of serpentine stability. Observations of the antigorite peridotite suggest that crystal plasticity of olivine exceeds that of antigorite. Antigorite-rich layers in highly serpentinized rocks acted as weak layers at deformation conditions of 500-600 ˚C although the deformation mechanism of antigorite is unclear. The strain rates of antigorite peridotite estimated for the early and later stages ($10^{-14\sim-16}$) are not sufficient to form a thin weak layer to cause slab-mantle decoupling. If rheological strength of antigorite schist is not largely reduced by intercrystalline displacement, alternative material should be considered as an explanation for a cause of ‘cold nose’ in mantle wedge such as talc and brucite.

Numerical model of reaction-advection system for serpentinization in permeable flow of silica-rich fluid: Examination of chemical behaviour

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Serpentinite is formed by hydration reaction of mantle peridotite. Its significant distribution in mantle wedge is inferred from geophysical observations. Alignment of serpentine crystals under anisotropic stress changes fluid pathways and, therefore, could have controls on direction and velocity of fluid migration. Understanding of such self-organizing processes of structural formation is very important to gain a dynamic image of fluid processes and hydration in mantle wedge. However, kinetic parameters for these processes in deep subduction zones are almost unknown.

Theoretical and numerical studies of non-equilibrium physics show that patterns of compositional structure can be variable depending on kinetic parameters in reaction-material transfer (e.g., diffusion and advection) systems. In this study, in order to extract direct information of the development processes from the serpentinite structures, we try to construct a non-equilibrium geochemical model of serpentinization including fluid advection. This will be a test whether the idea of non-equilibrium physics can be applicable to rock structures or not. If nature of mineral distributions in rocks is successfully reproduced, this gives constraints on kinetic information.

Our geochemical model is based on structural and petrological analyses of antigorite-olivine layering in the Higashi-akaishi ultramafic body: Infiltration of silica-rich fluid from the surrounding meta-sediments is critical for the heterogeneous hydration. We construct a numerical model adopting following chemical and physical descriptions: Main mineral-fluid reactions are dissolution of olivine and precipitation of serpentine; Aqueous species related to the reactions are Mg^{2+}, SiO_2 and H^+, and concentration of H^+ is buffered by dissociation of water; Extents of disequilibrium between aqueous fluid and minerals are calculated based on Deep Earth Water model (Sverjensky et al., 2013); Reaction rates follow a kinetic model of Lasaga (1995); Infiltration of fluid with a composition of talc-serpentine buffer is mainly driven by buoyant force and the permeable flow is described in Darcy’ s equation. Numerical calculations are made in a condition of 20 kbar and 550 degree C that are expected in mantle wedge along the Nankai subduction boundary.

We made short calculations for initial stage of serpentinization and checked chemical behaviors of the system upon reactions using a wide range of sets of reaction rate constants and permeability. There are three types of chemical shift in compositions of aqueous fluid under a constant flow rate. One is a smooth shift along or between equilibrium curves in advection-dominant conditions (lower reaction rate constants). In contrast, high reaction rate constants result in consumption of fluid species. Most interesting is that oscillating compositional shifts in fluid chemistry appear in intermediate conditions of reaction rate. Layered structures due to spatial variation of serpentine formation were observed in the oscillating conditions near the limit to the high reaction rate regime. Oscillations in concentrations of chemical species are known as one of the characteristic phenomena for non-equilibrium systems that result in formation of pattern structures. The results of this study implies that the conditions for layering in serpentinite are very limited in a simple reaction-advection system with a minor textural feedback for rate parameters.

Mis-indexing of antigorite crystallographic orientations in EBSD measurements

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Antigorite (Atg) is the dominant serpentine mineral in the hydrated mantle wedge above subducting slabs. Atg is a platy mineral and commonly shows strong crystallographic preferred orientation (CPO) either due to deformation or growth in a preferred orientation. The presence of an Atg CPO imparts a strong mechanical anisotropy to the host serpentinized peridotite. There have been many recent studies examining the elastic, permeability and frictional anisotropies of Atg and the consequences for shear wave splitting, fluid flow and seismicity in the shallow wedge mantle. To make a quantitative analysis of how Atg affects the anisotropic properties of hydrated wedge mantle it is essential to obtain reliable measurement of the pattern and the strength of Atg CPOs. Nearly all Atg CPOs are measured using an EBSD system and several distinct types have been reported. Most natural and experimental samples show point concentrations of the crystallographic axes with the *c*-axes perpendicular to the foliation and either the *a* - (A-type) or *b*-axes (B-type) parallel to the maximum finite extension direction. Others show general girdle distributions of *a*- and *b*-axes lying within the foliation. However, there are several potential difficulties in obtaining an accurate measurement of the crystal orientation of Atg by EBSD, in particular mis-indexing in the measurements and sample preparation affecting crystallographic orientation of the surface material. We use a combination of FIB-TEM and SEM-EBSD measurements in the same sample to examine the extent to which mis-indexing is an issue when Atg CPOs are determined using EBSD. We compare these results with Atg CPOs measured using synchrotron X-rays and U-stage techniques. In addition, we propose procedures for sample preparation and EBSD measurement that minimize the uncertainties in crystal orientation detection and are appropriate for automatic orientation mapping of samples.
Our conclusions concerning (1) mis-indexing and (2) sample preparation issues are as follows.
(1) The most likely mis-indexing results in an apparent rotation of the *a*- and *b*-axes around the *c*-axis. Similar problems may also affect the *c*-axes measurements but these are less significant than for the *a*- and *b*-axes when data are filtered using relatively low Mean Angular Deviation (MAD) values. Filtering using MAD values of less than 0.7° can significantly change the resulting CPO from A- to B-type. The EBSD results with low MAD values of less than 0.7° are in good agreement with the orientations determined by TEM observations. However, mis-indexing of the *a*- and *b*-axes rotated by 60° with respect to the *c*-axis occurs even for low MAD values.
(2) When thin sections prepared parallel to the foliation are used for EBSD measurements, the resulting Atg CPOs are independent of filtering using MAD values. This difference by the prepared sample plane is thought to be related to the weaker bonding in the *c*-axis direction of Atg than the *a*- and *b*-axes. We propose mis-indexing problems can be minimized by using thin sections cut parallel to the foliation or Atg orientations with MAD values of < 0.7°.
All of the previous limited reports of Atg CPOs in which MAD values have been described use a maximum value of 1.3°. In this study, all Atg CPOs obtained using thin sections parallel to the foliation or MAD value of < 0.7° show the strongest concentration of the *a*-axis parallel to the foliation and normal to the

lineation (B-type CPO). Mis-indexing by a rotation about the *c*-axis can in part help explain the variation in point clusters of the *a*- and *b*-axes commonly observed in reported Atg CPOs.

Keywords: Antigorite CPO, EBSD, MAD, FIB-TEM, Anisotropy

Effect of water on the rheology of cold mantle rocks: An experimental study

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Rheology of mantle rocks at low temperatures (< 800°C) is fundamental to comprehend the occurrence of earthquakes in the mantle lithosphere. Previous axial deformation experiments on natural dry peridotite revealed that glide-controlled crystal-plasticity is the dominant deformation mechanism at 600°C while brittle deformation also contributes increasingly at lower temperatures (Druiventak et al., 2011). Water infiltrating into oceanic and fore-arc mantle is expected to significantly affect the rheology of cold mantle rocks. A manner in which water influences the rock rheology varies depending on the mode of presence of water: (1) Aqueous fluid reduces the effective normal stress and promote brittle deformation. (2) Water incorporated into nominally anhydrous minerals reduces the strength of plastic deformation (Katayama and Karato 2008). (3) Hydrous minerals produced via hydration reaction can decrease the frictional and plastic strength of mantle rocks (Escartin et al., 2001). However, it is still unknown which effect becomes more dominant after aqueous fluid penetrates in to the dry cold mantle.
In order to evaluate the effect of water on the cold mantle rheology, we performed deformation experiments on natural dunite from the Horoman peridotite complex by using a Griggs-type apparatus at a temperature of 600°C, a confining pressure of 1.0 GPa, and a strain rate of $2.9 \cdot 10^{-6}$ s^{-1} in both dry and wet (1 wt% H_2O) conditions. Dunite was mostly composed of olivine (Ol) with minor amount of Al-bearing orthopyroxene (Opx; ~7 vol%) and serpentine veins (< ~5 vol%). Yield stress of dry dunite was 800 MPa, which is slightly lower than that obtained in the previous experiment (Druiventak et al., 2011; ~1000 MPa) while the strength of dunite in wet condition was reduced to 600 MPa and it gradually decreased down to ~500 MPa after reaching the peak strength. Textural observations indicated that pre-existing serpentine veins with an angle of ca. 45° to the shortening axis preferentially accommodated the deformation in dry condition. In wet condition, such a localized shear deformation in the pre-existing veins was not observed, and instead a large shear fault which divided the sample into two parts was formed with an angle of ca. 30° to the shortening axis. Along this fault, grain size of Ol and Opx (initially > ~100 μm) were significantly reduced down to several μm and talc along with Al-serpentine were formed in the matrix of the fine primary minerals through the preferential Opx reaction (Nakatani and Nakamura, 2016). On the basis of textural observations, it was suggested that high fluid pressure promoted cataclastic flow along the fault before reaching the peak strength and subsequent hydrothermal reaction in the fine grained region resulted in gradual decrease in the strength via the formation of weak phyllosilicates.
In both dry and wet experiments, clear shear faults were observed. Effective friction coefficients (μ_{eff}) at the peak and final strengths for wet experiment were calculated to be 0.23 and 0.19, respectively, which were lower than that calculated in dry condition (0.29). The reduction of μ_{eff} at the peak strength was attributed to the high fluid pressure while the formation of weak phyllosilicates might increasingly contribute after the peak strength. The hydrothermal shear experiment on Ol and Opx aggregate with weight proportion of Ol:Opx = 7:3 showed that μ_{eff} decreased down to 0.07-0.13 with increasing shear strain due to the formation of abundant talc along shear planes (Hirauchi et al., 2016). The relatively high μ_{eff} after the peak strength in this study could be explained by less effective talc formation due to the low strain during the experiment and small amount of Opx in the starting material. Our experimental results suggested that water infiltrated into the cold mantle leads to frictional deformation even at 600°C where

the ductile deformation is considered to be dominant in dry condition.

Keywords: mantle, water, rheology, earthquake, frictional deformation

Frictional properties of Akiyoshi greenstone: implications for the seamount subduction and earthquake generation

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Subducted seamounts may act as seismic asperities (e.g., Cloos, 1992), or as barriers (e.g., Kodaira et al., 2000). On the other hand, Mochizuki et al. (2008) assumed that interplate coupling is weak near subducted seamounts because the southern end of the Japan Trench near a seamount has been mostly aseismic over the past 80 years. Frictional properties of seamount materials have been poorly explored despite their possible importance on earthquake generation. We thus started (1) field work on faults associated with subducted and accreted seamount rocks, and (2) friction experiments on greenstones derived from seamounts. Akiyoshi terrane is a classical area with huge Carboniferous to Permian limestone accreted during the Permian time (e.g., Sano, 2006). Thin basaltic rocks are distributed over 10 km in length adjacent to a fault, and the rocks are likely to have derived from a seamount. Unfortunately, we could not find outcrops of the fault, and we used a hyaloclastite sample collected at Mitou, Yamaguchi in our friction experiments.

Experiments were performed at normal stresses of about 4.0 MPa under dry or wet (40 wt% H_2O) drained conditions, using a rotary-shear low to high-velocity frictional testing apparatus in Beijing. Crushed rock powders of about 1 mm in thickness were mounted between cylindrical pistons (Ti-Al-V alloy, 40 mm in diameter) with a Teflon sleeve outside. Two and three velocity-cycle tests were conducted for dry and wet gouges, respectively, by reducing slip rate V from 0.021 mm/s to 0.21 μm/s and by increasing V to 0.21 mm/s at each cycle. Friction experiments were done at V = 0.021 mm/s after each velocity cycle test by changing the normal stress from 3, 2, 1, 2 and to 3 MPa. This allows to determine the Teflon friction (its maximum) and friction coefficient from shear stress versus normal stress plots. Total slip was 0.91 and 1.37 m for dry and wet runs, respectively.

Experiments are still preliminary, but results show that friction coefficient (Teflon friction corrected) μ of dry gouge increases from around 0.3 to 0.7 from the first to the second V cycles. Whereas μ of wet gouges increases from about 0.25, 0.35 to ca. 0.5 from the first to the third V cycles; wet gouge is weaker than dry gouges by about 0.05 to 0.2. Such increases of μ with V cycles are likely to have been caused by shear-induced compaction. Those friction coefficients are consistent with those determined from tests at different normal stresses. The frictional strength of the wet Akiyoshi greenstone is notably greater than those of typical subduction zone materials with μ < 0.2 (cf. Sawai et al., 2014), and hence the seamounts might become seismic asperities due to their high frictional strengths. However, our current results exhibit slight velocity strengthening at both dry and wet conditions and a seamount may not be a site of earthquake nucleation. Those tentative conclusions will be tested by more detailed work in the future.

Keywords: seamount, subduction, friction, Akiyoshi

Detection of shear heating on an out-of-sequence thrust using Raman CM geothermometry and constraints on the fault strength and total displacement by thermal modeling

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Out-of-sequence thrusts (OST) in subduction zones contribute to the thickening of accretionary prisms and some parts of them are explained as splay faults branched from plate boundaries. Making reliable estimations of the fault properties and displacement histories is therefore an important part of developing better understanding of such as generation of large earthquakes and tectonic evolutions in subduction zones. Mechanical work during fault movement is largely converted into heat energy and therefore quantification of shear heating recorded in rocks around on-land exhumed OST has potential to help in understanding the above estimations. Here we show approaches to recognize shear heating and to constrain fault strengths and total displacements from rocks around on-land OST using the Raman carbonaceous material (CM) geothermometry and thermal modeling.
This study focused on the Aki Tectonic Like (ATL)—which is an OST bounded between the Cretaceous and Tertiary sedimentary rocks of the Shimanto accretionary complex—in the Umaji area of eastern Shikoku, SW Japan. Results of estimated temperatures using the geothermometer show a regional temperature of ~220–230 ºC. There is a significant rise in temperature to ~270–280 ºC near the ATL on both hanging wall to the north and footwall to the south. The spatial association of the thermal anomalies with the fault implies shear heating. In contrast, the width of the thermal anomaly on the hanging wall side is ~6 km while that on the footwall side is a few hundred meters, showing asymmetric distribution of the zones of shear heating between north and south of the ATL. One possible explanation for the asymmetric thermal structure is that the footwall part has been attenuated by post-heating faulting. To evaluate these results in terms of shear heating on the ATL, we compared the thermal structure of the hanging wall part—which is likely preserve original thermal anomaly—to the temperature distributions calculated using simple analytical solutions for one-dimensional conductive heat flow with a planer heat source. The results of the comparisons with a constraint on slip rate show that a coefficient of friction of greater than ~0.4 and a total displacement of ~25–50 km are required.

Keywords: shear heating, Raman carbonaceous material (CM) geothermometry, out-of-sequence thrust, thermal modeling, accretionary complex, Aki Tectonic Line

Strike-slip reactivation of regional scale thrust faults with moderate dips

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Moderately-dipping faults are considered to be unfavorably oriented for strike-slip motion. Nevertheless, strike-slip earthquakes on faults with dips of ~35-45° have caused fatalities and considerable property destruction in Japan and elsewhere. These include the 1923 Great Kanto earthquake (Mw 7.9, central Japan), the 2013 Balochistan earthquake (Mw7.7, south central Asia), and several paleoseismic events on the Median Tectonic Line (MTL) (estimated M > 6.8, southwest Japan). In each case, the source fault originated as a thrust fault in a convergent tectonic setting and was reactivated as a strike-slip fault in a succeeding intermediate-type setting. In the Great Kanto earthquake, the Sagami megathrust showed right-lateral-reverse slip in a ratio of strike-slip to dip-slip of approximately 2:1[1]. Geodetic models suggest that strike-slip movement may be the norm for this segment of the megathrust, where the plate boundary more or less aligns with the motion direction of the subducting plate[2]. In Balochistan, the 2013 earthquake propagated on the 45° NW-dipping Hoshab fault with nearly pure strike-slip motion[3]. The Hoshab fault originated in the thrust belt of the Makran accretionary wedge and is being repositioned into the strike-slip stress field caused by the Indian plate sliding past the Afghan block (Eurasia). In southwest Japan, the MTL may be a paleo-megathrust with a long history of oblique slip[4]. Now it accommodates right-lateral slip at the slip-partitioned Nankai subduction zone where paleoseismic evidence shows a recurrence interval of 1000-3000 yr for large earthquakes with 5-8 m of lateral slip[5]. While the likelihood of strike-slip reactivation of a moderately-dipping fault is expected to be small, the occurrence of large-magnitude earthquakes of this type suggests that we should reexamine this assumption. Even if uncommon, such faults may be more hazardous than anticipated if erroneous assumptions about fault geometry are used in hazard and strong ground motion estimates. Theoretical models have provided an initial insight into the factors that contribute to fault reactivation, but case studies show that the phenomenon is complex. For this study, we use an integrative approach to look at the much-investigated MTL in an attempt to understand the factors that contribute to its unusual behavior. We conclude with the suggestion that regions where thrust structures form in compressive regimes, now changed to strike-slip, be assessed to determine the orientations of known strike-slip faults, for example, the Tibetan plateau and the Indo-Burman wedge.

[1]Pollitz, F. F., Nyst, M., Nishimura, T., and Thatcher, W., 2005, Coseismic slip distribution of the 1923 Kanto earthquake, Japan: JGR, 110:B11408.
[2]Loveless, J.P. and Meade, B.J., 2010, Geodetic imaging of plate motions, slip rates, and partitioning deformation in Japan: JGR, 115: B02410.
[3]Avouac , J.-P., Ayoub, F., Wei, S., Ampuero, J.-P., Meng, L., LePrince, S., Jolivet, R., Duputel, Z., and Helmberger, D., 2014, The 2013, Mw 7.7 Balochistan earthquake, energetic strike-slip reactivation of a thrust fault: EPSL, 391:128-134.
[4]Sato, H., Kato, N., Abe, S., Van Horne, A., and Takeda, T., 2015, Reactivation of an old plate interface as a strike-slip fault in a slip-partitioned system: Median Tectonic Line, SW Japan: Tectonophysics, doi:10.1016/j.tecto.2014.12.020.
[5]Tsutsumi, H. and Okada, A., 1996, Segmentation and Holocene surface faulting on the Median Tectonic

Line, southwest Japan: JGR, 101:5855-5871.

Keywords: fault reactivation, Median Tectonic Line, microseismicity, earthquake tomography

