Heterogeneous rheological structures of the northeastern Japan illuminated by post-seismic deformation of the 2011 Tohoku-oki earthquake

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Viscoelastic properties of rocks play an important role in the long-term evolution of convergent margins. Especially, Billen and Gurnis (2001) proposed the presence of low viscosity mantle wedge to explain observable signals in topography and gravity for the Tonga-Kermadec trench. Furthermore, recent geodetic observations after the 2011 Tohoku-Oki earthquake also show transient viscoelastic flow plays dominant role even in the very early stage of the post-seismic deformation (e.g., Sun et al., 2014). Therefore, the nation-wide network of geodetic observations for the post-seismic deformation of the Tohoku-Oki earthquake can illuminate rheological properties and their heterogeneity in the northeastern (NE) Japan. In order to evaluate rheological heterogeneity reflecting thermal and petrological structures of the NE Japan, a model of two-dimensional viscosity structures of the NE Japan island arc-trench system were proposed (Muto et al., 2013). The model covers the source area of the 2011 Tohoku-Oki earthquake and can be applied to the analysis of the post-seismic deformation. From seismologically determined structures of the lithosphere, experimentally derived constitutive laws of various minerals, and densely measured geothermal gradient data for the NE Japan, we have proposed a model of steady state viscosity structures across the island arc. The profile shows strong lateral viscosity gradients both parallel and normal to the trench axis. Especially, the variation in viscosity structures across the arc is characterized by strong forearc and weak volcanic front. Using two-dimensional finite element modeling taking into account of the viscosity heterogeneity, we reproduced the observed post-seismic deformation of the 2011 Tohoku-Oki earthquake (Muto et al., 2016). We used terrestrial and seafloor geodetic data compiled by Iinuma et al. (2015) and modeled both horizontal and vertical displacement fields in two different time periods (1 and 5 years after the earthquake). From the analysis, we have succeeded in reproducing the local subsidence around Quaternary volcano (Mt. Naruko) by introducing the narrow low viscosity body beneath the volcano. The inferred low viscosity body is consistent with the low velocity anomaly in seismic tomography (Okada et al., 2015) and low resistivity anomaly in magnetotelluric observations (Ogawa et al., 2015). The presence of very localized rheological heterogeneity (low viscosity body) is inconsistent with Billen and Gurnis (2001)'s model of the wide low viscosity wedge in Tonga-Kermadec trench. However, the similar localized low viscosity zones are also predicted in the thermal-flow model of the NE Japan subduction zone (Horiuchi and Iwamori, 2016) which takes into account of temperature- and water-dependent flow properties of mantle wedge. The localized weakening by water infiltration, partial melting and serpentinization cause such localized low viscosity region in the mantle wedge. Combination of numerical modeling with rheological heterogeneity and detailed geodetic observation can contribute to illuminate small-scale (<20 km) heterogeneities and their rheological properties of NE Japan.

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Keywords: Rheology, Post-sesimic deformaiton, Tohoku-Oki Earthquake, Viscoelastic relaxation

Scaled laboratory experiments on sequential thrusting in a mechanically two-layered system and its implications in fold-and-thrust belts

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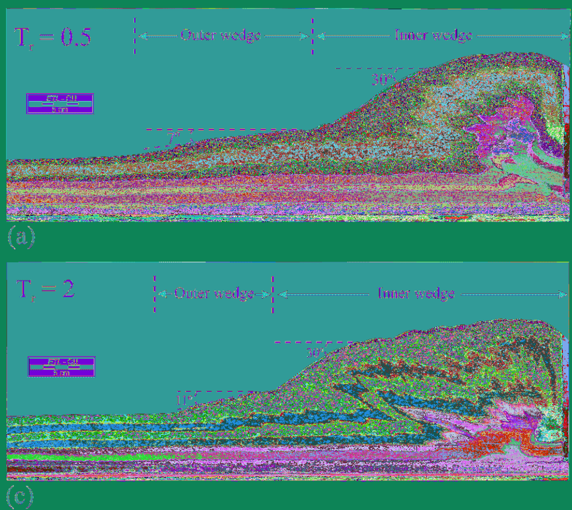
Thin-skinned tectonic models have been widely used to explain the process of sequential thrusting in convergent settings. These models generally treat the crustal horizon as a single mechanical layer on a weak basal detachment. However, many fold-and-thrust belts display multi-storied thrust sequences, characterizing a composite architecture of the thrust wedges. For example, the Himalayan wedge has produced a set of continental scale (first order) thrusts, namely Main Crystalline Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT), covering the entire strike length of the mountain belt. Taking a close-view to different sectors in this belt, one can find numerous closely spaced (higher order) thrusts in between any two first order thrusts.Despite dramatic progress in sandbox modelling over the last three decades, our understanding of such composite thrust-wedge mechanics is limited and demands a re-visit to the problem of sequential thrusting in mechanically layered systems. This study offers a new approach to sandbox experiments, designed with a two-layered sandpack simulating a mechanically weak Coulomb layer, resting coherently upon a stronger Coulomb layer. Experimental runs reproduce strikingly similar styles of the multi-storied frontal thrust sequences observed in natural fold-and- thrust belts. Our results show that the upper weak horizon undergoes sequential thrusting at a high spatial frequency, forming numerous, closely spaced thrusts, in contrast to widely spaced thrusts produced preferentially in the lower strong horizon. We investigated the development of such composite thrust styles by varying frictional strength (μ_b) at the basal detachment and thickness ratio (T_r) between the weak and strong layers. For any given values of T_r and μ_b, the two thrust sequences progress at different rates; the closely-spaced upper thrust sequence advances forelandward at a faster rate than the widely-spaced, lower thrust sequence. The stable elevation of a thrust wedge in a mechanically layered setup depends on the thickness ratio (T_r) between the weak and strong layers. The wedge can attain a stable hinterland elevation only when T_r 1 (Fig. 1). Basal friction (μ_b) has little effects on the thrust vergence in the upper weak layer and they always verge towards foreland, irrespective of *Tr* values. But, back-vergent thrusts develop in the lower strong layer when μ_b is low (˜ 0.36) (Fig. 2). In our experiments, closely spaced thrusts in the upper sequence (US) experience intense reactivation due to their interaction with widely spaced thrusts in the lower sequence (LS). This interaction eventually affects the wedge topography, leading to two distinct parts: *inner* and *outer* wedges, characterized by steep and gentle surface slopes, respectively.

Keywords: Mechanical layers, Multi-storied thrust sequences, Topographic slopes, Thrust wedge



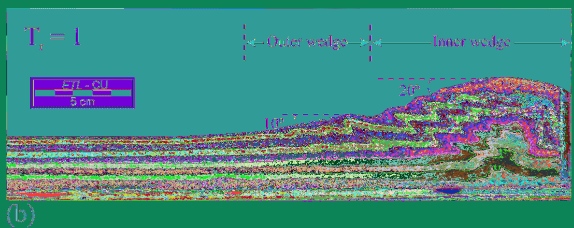


Figure 1. Development of inner and outer wedge in mechanically stratified models (μ_b= 0.36). Note that the lower strong layer remained completely undeformed below the outer wedge. Models show that the reactivation of earlier thrusts in the US separates the wedge into two segments: inner and outer wedge. Thickness ratios (T_r) between US and LS are 1:2 (a), 1:1 (b) and 2:1 (c); and the amount of shortening are 25 cm, 15cm and 28cm respectively. Note that the inner wedge has a flat topography near the hinterland buttress in (b) and (c), whereas (a) did not produce such a flat region in the inner wedge.

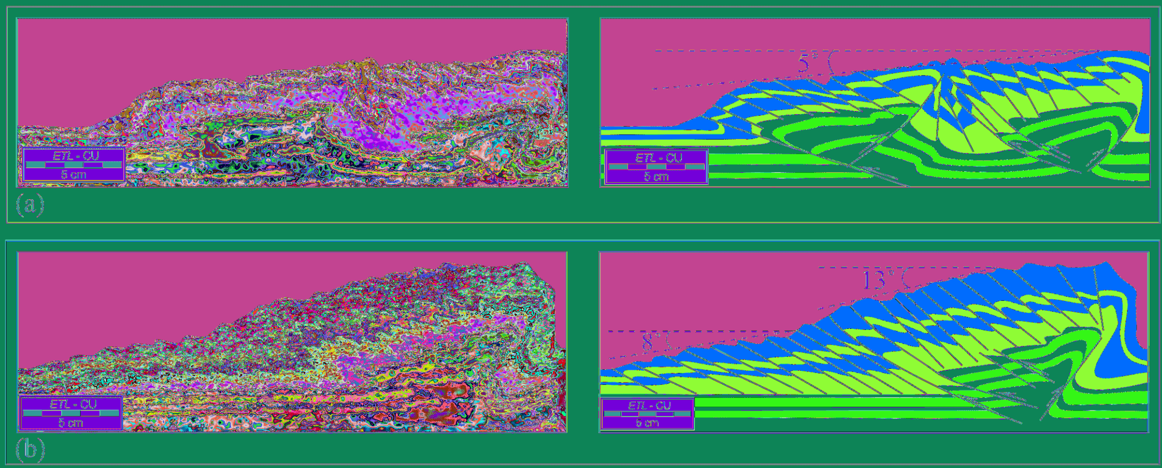


Figure 2. Multi-storied thrusting in sandbox models for varying basal friction (μ_b) and T_r=1. (a) μ_b= 0.36 and (b) μ_b= 0.46. Figures on the right side show corresponding sketches of the models. Note that the vergence of lower-order thrusts is sensitive to μb, where they form with both front and back vergence for low μ_b. In contrast, higher order thrusts in the upper sequence verge always in the frontal direction, irrespective of μ_b. The amount of finite shortening in (a) and (b) are 30 cm and 35 cm respectively. Note that the thrust ramp in the US has caused deformation localisation at their toes, resulting in their downward propagation into the lower strong layer.

Asymmetric convergent margins: What controls the hinge motion in subduction zones?

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Looking at subduction zones worldwide, a striking asymmetry can be identified: W- to SW-directed subduction zones (e.g., Marianas, Tonga, Sandwiches) present the lowest topography in the world, while on the E- to NE-directed subduction (e.g., Andes) and collision zones (e.g., Alps, Himalaya) are characterized by the highest mountains worldwide. This asymmetry appears primarily controlled by the slab polarity with respect to the westward drift of the lithosphere due to a global-scale eastward mantle flow (Doglioni *et al.*, 2007). However, the potential influence of a polarized mantle flow on the hinge motion in subduction zones has never been tested quantitatively, thus leaving significant gap in understanding of this key plate tectonic phenomenon. Here, we explore the effects of a priori defined mantle flow on the slab dynamics and response at the surface by means of self-consistent two-dimensional thermomechanical numerical experiments in which an oceanic plate sinks beneath a continental plate under the control of realistic visco-plastic rock rheologies.
Results show that the motion of the subduction hinge toward or away relative to the upper plate is the simple kinematic control for the occurrence of two different subduction styles: (1) When the subduction hinge converges toward the upper plate, the upper plate is shortened and a double vergent belt, such as the Alps, forms. On the contrary, (2) when the slab and the related hinge retreat relative to the upper plate, the upper plate is stretched (a backarc basin opens) and a single vergent belt develops, such as along the western Pacific margin. The two settings also show different type of rocks involved in the mountain building process. In the first setting, in fact, the orogen is principally composed by sedimentary cover, i.e., young and shallow rocks coming from superficial erosion of the plates involved in the subduction process. This occurs because the basal decollement of the subducting plate is never connected to the surface but is rather folded and swallowed down inside the subduction zone, being thus unable to feed the accretionary prism with rocks coming from high depths. On the other hand, the second subduction setting show orogens involving older and deeper rocks because of the deeper décollement planes, being thus able to involve the basement of the subducted plate. These findings are supported by a quantitative agreement with observations derived from the global-scale models, which indicate that mantle flow would be the leading feature influencing slab-dip, subduction rate and motion of the slab hinge: E- or NE-directed subductions have shallower slabs, with low dip angles (24° on average), while W- or SE-directed slabs are deeper and steeper (61° on average, Ficini *et al.*, 2017). These results, thus, mimic the asymmetry that can be recognized along the subduction zones worldwide. These models, combined with the observations, support the hypothesis of an asymmetric pattern of the mantle convection strongly driven by the easterly-polarized mantle flow.

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Keywords: subduction hinge, topography, orogens

An integrated study of the UAE-Oman mountain belt: Implications for collision tectonics and ophiolite emplacement

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The United Arab Emirates (UAE)-Oman mountains constitute a 700 km long, 50-150 km wide orogenic belt composed of a series of Tethyan thrust sheets overlying a passive continental margin. It contains the world’s largest and best-exposed thrust sheet of oceanic crust and upper mantle (Semail Ophiolite), which was obducted onto the Arabian rifted continental margin during the Late Cretaceous. Although the shallow structure of the UAE-Oman mountain belt is reasonably well known, the deeper structures remain poorly constrained. The mechanisms by which dense oceanic crustal and mantle rocks are emplaced onto less dense and more buoyant continental crust are still controversial and remain poorly understood. In this study, we have carried out the first integrated geological mapping, seismic reflection, refraction, passive seismic and potential field experiments in the UAE, from the Arabian Gulf to the Gulf of Oman, to provide new constraints on the nature of continental and oceanic crust beneath both the Semail Ophiolite and the offshore UAE-Oman margin. Reflection data were acquired along 925 km line in the Arabian Gulf and Gulf of Oman using a large-volume airgun source (7060 cubic inches) and up to 5 km long streamer. Refraction data were acquired along selected reflection lines using 25 land recording stations in the UAE. In addition, gravity and magnetic anomaly data were acquired along all the seismic lines as well as two onshore profiles. The results obtained provide constraints on crustal structure, hydrocarbon potential and seismic hazard of the northern UAE. Geological mapping combined with seismic constraints have revealed the geometry of the ophiolite thrust sheet and sub-ophiolite structure at depth. Seismic reflection data in the Gulf of Oman show clearly the contact between the ophiolite and overlying sediments and evidence for thick Cenozoic sediments, tilted fault blocks and re-activated faults that appear to have offset the seafloor. The seismic refraction data suggest ophiolite seismic velocities of about 5.5 km/s, which is underlain by a thick layer of faster material, where velocities vary between 6.0 and 6.4 km/s. The velocity and gravity models reveal a Moho depth that rises from c.a. 40 km in the west to ca. 20 km in the east towards the Gulf of Oman. We interpret the NE margin of the ophiolite to be a low-angle normal fault with up to 8 km of Cenozoic sediments in localized depocentres. In addition, passive seismic data, recorded on a temporary deployment as part of the project and UAE seismic network, has been used to calculate receiver functions across the mountain range and foreland basin to constrain the deeper crustal structure.

Keywords: Ophiolite, Oman Mountains, United Arab Emirates

Thermokinematic Model of Cenozoic Uplift of Danba Anticline, Northeastern Tibet: Implication of Mid-crustal Channel Flow

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We employed finite difference method to simulate the thermokinematic evolution of the Danba anticline, northeastern Tibet near the Sichuan Basin since 25 Ma. The major paradox of the Danba anticline is that its fold axis is subparallel rather than perpendicular to the crustal velocity field based on GPS observations. Recent studies suggested the uprising Tibet may drive the middle and lower crust to flow around the rigid Sichuan Basin. We solved the deflected mid-crustal flow beneath the Danba anticline by employing the corner flow theory and found that the flow is roughly perpendicular to the fold axis. This finding suggested the Danba anticline is formed by injection of mid-crustal material rather than buckling of its upper crust. By introducing a detachment folding theory, we calculated the crustal movement and the corresponding temperature of the Danba anticline since last 25 Ma. With that we computed the theoretical apatite and zircon fission track ages across the Danba anticline and compared them with the observed ones. Our optimal model suggested that since 25 Ma, the mid-crustal flow has accelerated as an exponential function. The optimal fold width is about 140 km with the mid-crust channel thickness of 14 km, which is consistent with a magnetotelluric observation. The amount of exhumation in the hinge of the Danba Anticline we estimate is about 19 km, which agrees well with the amount of exhumation (17~26 km) derived from geobarometry upon the Triassic decollement exposed in the core of the anticline.

Keywords: Danba anticline, Fission track age, Thermokinematic evolution, Tibet

Rheology and stress in subduction zones around the aseismic/seismic transition

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Subduction channels are commonly occupied by deformed and metamorphosed basaltic rocks, pelagic and clastic sediments, which form a zone up to several km thick to depths of at least 40 km. At temperatures above ~ 350°C (corresponding to depths of >25-35 km) the subduction zone is aseismic, and much of the relative motion is accommodated by ductile deformation in the subduction channel. Microstructures in metagreywacke suggest deformation occurs mainly by solution-redeposition creep in quartz. Interlayered metachert shows evidence for dislocation creep at relatively low stresses (6-13 MPa shear stress). Lack of evidence for significant strength contrast with metagreywacke suggests that this is a reasonable estimate for the shear stress in the channel as a whole. Metabasaltic rocks deform mainly by transformation-assisted diffusional creep during blueschist facies metamorphism, which may require somewhat higher stresses. Quartz flow laws for dislocation and solution-redeposition creep suggest strain rates of ~ 10^{-13} sec^{-1} at 500°C and 10 MPa shear stress: this is sufficient to accommodate 30% of a 50km/m.y. convergence rate within a 5 km wide subduction channel.
The up-dip transition into the seismic zone occurs through a region where deformation is still distributed over a thickness of several km, but occurs by a combination of microcracking and solution-redeposition. This process requires a high fluid flux, released by dehydration reactions down-dip, and produces a highly differentiated deformational fabric with alternating mm-scale quartz and phyllosilicate-rich bands, and very abundant quartz veins. Bursts of dilational microcracking in zones 100-200 m thick may cause cyclic fluctuations in fluid pressure, and may be associated with episodic tremor and slow slip events. Shear stress estimates from dislocation creep microstructures in dynamically recrystallized metachert are ~12 MPa.

Keywords: Subduction zone interface, paleopiezometry, pressure solution, dislocation creep, tremor, slow slip

Quartz and K-Feldspar Microboudins in Felsic Granulites: Evidence of Rheological Turnover and Implications to Weak Lower Continental Crust

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Quartz and feldspar are the major mineral constituents in quartzofeldspathic rocks abundant in the lower continental crust. Rheology of the lower continental crust is a vital aspect in Earth's dynamics. Deformation experiments and microstructural observations on naturally deformed rocks are the major ways to study the rheology of those mineral constituents to illuminate the rheology of the lower crust. We carried out microstructural observations of quartz and K-feldspar in quartzofeldspathic gneiss (QFG) samples from the Highland Complex of Sri Lanka. The Sri Lankan terrain is a lower crustal exposure of East Gondwana and it has undergone granulite facies metamorphism with multiphase ductile deformation. The QFG samples contain two sets of deformation microstructures (Athurupana et al., 2014). The first set is quartz ribbons, K-feldspar boudins in quartz ribbons, and dynamically recrystallized K-feldspar in the matrix. The second set is quartz boudins in K-feldspar matrix and exsolution microstructures of K-feldspar. The observed microstructures represent two high temperature (>450˚C) deformation events occurred at different times in the metamorphic history. The first set of microstructures belongs to a deformation event occurred on the prograde path before peak metamorphism. The second set of microstructures belongs to a deformation event occurred during the retrograde decompression cooling path.
Both quartz and K-feldspar domains show the formation of microboudins in QFG samples. Microboudins shapes represent viscosity contrast, large viscosity contrast causes rigid separation by fracture while low contrast cause for the formation of pinch and swell structures. Regarding crystal plasticity, quartz is weaker than feldspar in a wide range of crustal conditions (>400˚C). The K-feldspar microboudins in quartz manifest such general rheological behavior, which is visible in experimental studies and naturally deformed samples. Conversely, the formation of quartz microboudins in K-feldspar matrix indicates rheological turnover during the second deformation event. Both K-feldspar and quartz microboudins show necking related separation and it indicates moderate to low viscosity contrast. Especially, the K-feldspar boudins show much lower viscosity contrast to quartz ribbons. It would be a result of the weakening of K-feldspar by thermally activated creep processes related with the K-feldspar phase mixing on the prograde path. The rheological turnover during the second deformation is a result of the significant weakening of matrix K-feldspar. Exsolution microstructures indicate a ductility enhancement of K-feldspar due to the cryptoperthite formation (coherent spinodal decomposition) on the retrograde cooling path (Athurupana et al., 2016). The coherent spinodal decomposition enhances the rate of dislocation climb in K-feldspar. In addition, primarily coarsened (coarsening during spinodal decomposition) cryptoperthite lamellae form subgrain walls within K-feldspar grains. Such dynamic processes can cause a significant weakening in K-feldspar during fast syntectonic cooling. This microscopic weakening of K-feldspar allows QFG to maintain low bulk strength and accommodate large strains in ductile manner. Finally, the rheological turnover in QFG samples provides some implications to the weak lower continental crust where QFG are the dominant suits of rocks.

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Keywords: Quartz , K-feldspar, Quartz boudins, Rheological turnover, Exsolution, Weak lower continental crust

The Early-Cretaceous Sambagawa metamorphism and a cross-sectional view of the Late-Cretaceous Sambagawa subduction zone

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Recent petrological studies on the Sambagawa high-P/T metamorphic belt in Shikoku island, SW Japan, have recognized that the coarse-grained eclogite-bearing lithologies (so-called 'tectonic blocks' in earlier studies) in the Besshi area exclusively preserve evidence for the 'early' Sambagawa metamorphism, which can be related to onset of the Sambagawa subduction system during Early Cretaceous (c.116Ma). Geological mapping and associated multidisciplinary studies on the regional (spatially widespread) Sambagawa metamorphism (both the eclogite-facies and main metamorphic stages) have revealed the tectonic framework of the Late-Cretaceous Sambagawa subduction zone, which was located on the east Eurasian margin, as follows: (i) a spreading ridge was approaching to the margin and lay close to the trench; (ii) the subducting slab was coupled with the convective mantle at depths of >65 km; (iii) thickness of the hanging-wall continental crust was 30-35 km; and (iv) the forearc mantle wedge (30-65 km depth) was largely serpentinized. These features allow us to draw a semi-quantitative cross-section of the Sambagawa subduction zone at around 89-85Ma, implying that boundary conditions for thermo-mechanical modeling aiming to simulate exhumation of high-*P/T* metamorphic rocks are now well constrained. It has also become clear that ultramafic blocks having sizes of several-10s cm to several-km and dispersed in the higher-grade part of the Sambagawa belt were derived from the mantle wedge, i.e. the corresponding part of the belt has been re-evaluated as a 'fossil subduction boundary zone' of a relatively warm subduction zone. Field-based structural and petrological studies in the Sambagawa belt, therefore, have potential to provide invaluable information on material behavior at the slab-mantle wedge interface including domains of episodic tremor and slip (ETS) in present-day warm subduction zones.

Keywords: Sambagawa metamorphic belt, onset of subduction, ridge subduction, thickness of forearc continental crust, coupling of slab with convective mantle, serpentinized mantle wedge

Evidence for localized high fluid pressure along the paleo subduction boundary exposed in the Sanbagawa belt, SW Japan

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Petrological and thermal modelling has shown that the Sanbagawa metamorphic belt formed in a warm subduction zone setting. The metamorphic rocks mainly consist of pelitic, quartz and mafic schists derived from the subducted slab. However, ultramafic units locally reaching kilometers in scale are also found widely distributed throughout the belt. The distribution of these mantle derived units is restricted to the higher metamorphic grade zones. This observation shows that the mantle units of the Sanbagawa belt were derived from the wedge mantle and the boundary with the surrounding schists is a paleo subduction boundary. In present day convergent margins the subduction boundary between shallow mantle wedge and subducting slab is commonly the site of episodic tremor and slow slip. This relationship is particularly clear in warm subduction zones such as SW Japan. Slow slip is associated with very low stress drops and can be induced by small changes in the regional stress field of the order of 10s kPa. These observations require the subduction boundary to be very weak in the domain of ETS. Localized high fluid pressure is likely to play a role in forming weak boundaries and this is supported by seismic studies that reveal high Vp/Vs and Poisson ratios. However, the wedge mantle in this region is likely to be highly serpentinized and consist in part of minerals such as brucite and talc, which have low coefficients of friction. These minerals may also play a role in weakening the boundary. Structural-petrological studies of serpentinized mantle wedge adjacent to a paleo subduction boundary in the Sanbagawa belt reveal the presence of a strongly deformed zone of antigorite rock up to 100 m thick. This shear zone is overlain by a domain of metamorphosed serpentinite that originally contained 10-20 % brucite. The presence of significant amounts of brucite should cause the rock to be much weaker than the antigorite-dominant zone. However, the brucite-domain is largely undeformed. The only reasonable explanation of this observation is to invoke a high fluid pressure localized to the antigorite shear zone. The localization of the fluid can be explained by anisotropic fluid flow caused by the presence of the strong foliation.

Keywords: serpentinite, fluid pressure, subduction zone, Sanbagawa metamorphism

Numerical Experimentation to Study the Role of Serpentinization and Deserpentinization In Bending and Unbending A Subducting Slab

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There is increasing consensus that the mantle of the downgoing oceanic plate at a subduction zone may be extensively serpentinized, and that the deserpentinization of the downgoing slab is related to both intermediate depth earthquakes (cf. Seno and Yamamaka, AGU Mon. 96, 1996; Peacock, Geology, 2001) and arc magmatism. Here we investigate the hypothesis that the serpentinization and deserpentinization of the downgoing slab may play a significant role in plate subduction itself, as a driving force for the bending and unbending of a subducting slab, in addition to its previously suggested role as a ‘lubricant’ along the plate interface and weak zones for enhanced normal faulting within the bending slab.

Mantle serpentinization involves an increase of >20% in volume from pure harzburgite to pure serpentinite. We assume that deep lithospheric faulting at the outer rise often provides pathways for seawater to hydrate the uppermost 30-50 km beneath the Moho, consistent with current seismic observations on the depths of outer rise seismicity, and estimates of the slab-temperature-dependent width of the double-Wadati-Benioff zone within subducting slabs. If serpentinization occurs to a significant degree, then it can provide both weak planes for shear slip (across deeply-penetrating faults) and a significant volume increase within the upper sections of the lithosphere mantle (around these faults). The volume increase from the serpentinization of the lithosphere would strongly promote plate bending in the region undergoing serpentinization. Likewise, deeper deserpentinization of the subducting slab and eclogitization of the subducting oceanic crust (suggested earlier by Steve Kirby) would act to unbend it deeper within the subduction zone.

We have developed a new 2-D compressible viscoelastoplastic code to study the mechanics of this process. The goal of our initial numerical experiments is to compare the deformation, stress patterns, and energetics of incompressible plate bending and unbending control experiments with experiments that include a waxing volume within the outer-rise plate-bending region, and a waning volume in the depth-interval of slab dehydration and eclogitization.

Serpentinization-linked slab-bending can significantly ease the mechanical work needed to subduct a plate, which would provide a possible resolution to the enduring paradox (Conrad and Hager, JGR, 1999) that the bending and unbending of the downgoing plate could consume even more energy than that available from the negative buoyancy of subducting lithosphere.

Keywords: subduction, bend-fault serpentinization, mantle dynamics

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.

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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 $\mu < 0.2$ (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.

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