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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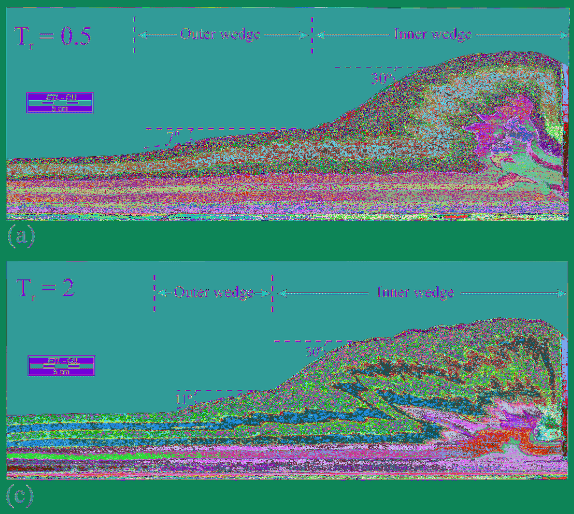
Thin-skinned tectonic models have been widely used to explain the process of sequential thrusting in convergent settings. These models generally treat the crustal horizon as a single mechanical layer on a weak basal detachment. However, many fold-and-thrust belts display multi-storied thrust sequences, 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



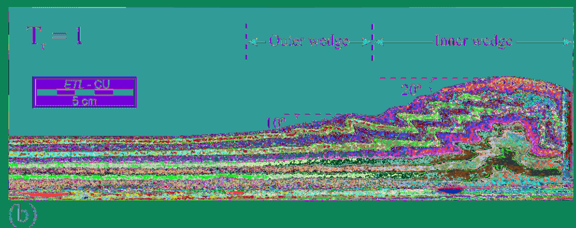


Figure 1. Development of inner and outer wedge in mechanically stratified models (μ_b= 0.36). Note that the lower strong layer remained completely undeformed below the outer wedge. Models show that the reactivation of earlier thrusts in the US separates the wedge into two segments: inner and outer wedge. 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.

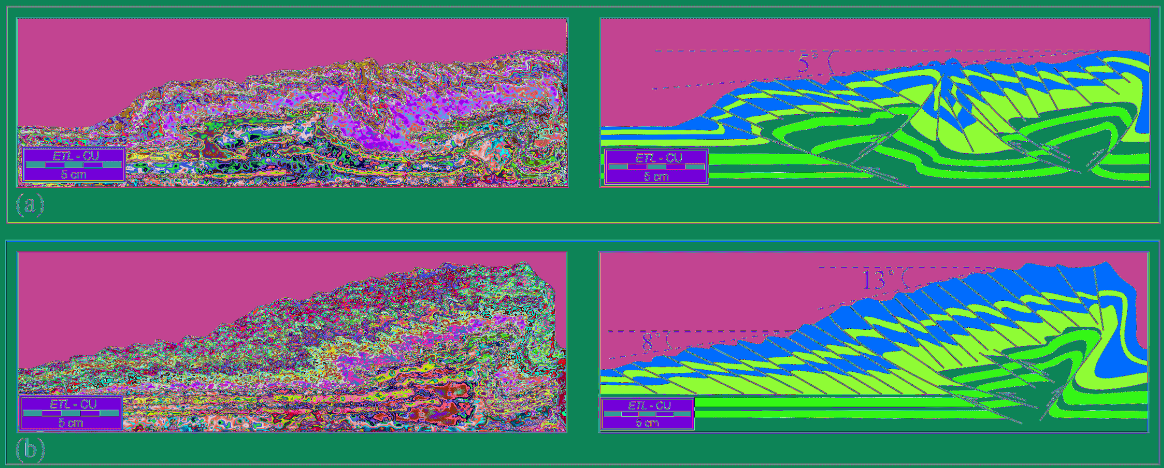


Figure 2. Multi-storied thrusting in sandbox models for varying basal friction (μ_b) and T_r=1. (a) μ_b= 0.36 and (b) μ_b= 0.46. Figures on the right side show corresponding sketches of the models. Note that the vergence of lower-order thrusts is sensitive to μb, where they form with both front and back 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

