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Special Issue on
Deep Slab and Mantle Dynamics

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Preface: Deep Slab and Mantle Dynamics

We are pleased to publish this special issue of the journal *Physics of the Earth and Planetary Interiors* entitled "Deep Slab and Mantle Dynamics". This issue is an outgrowth of the international symposium "Deep Slab and Mantle Dynamics", which was held on February 25–27, 2009, in Kyoto, Japan. This symposium was organized by the "Stagnant Slab Project" (SSP) research group to present the results of the 5-year project and to facilitate intensive discussion with well-known international researchers in related fields. The SSP and the symposium were supported by a Grant-in-Aid for Scientific Research (16075101) from the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government. In the symposium, key issues discussed by participants included: transportation of water into the deep mantle and its role in slab-related dynamics; observational and experimental constraints on deep slab properties and the slab environment; modeling of slab stagnation to constrain its mechanisms in comparison with observational and experimental data; observational, experimental and modeling constraints on the fate of stagnant slabs; eventual accumulation of stagnant slabs on the core-mantle boundary and its geodynamic implications. This special issue is a collection of papers presented in the symposium and other papers related to the subject of the symposium. The collected papers provide an overview of the wide range of multidisciplinary studies of mantle dynamics, particularly in the context of subduction, stagnation, and the fate of deep slabs.

Six papers in the first section, "Structure of subduction zones in the upper mantle", address seismological and electromagnetic structure in the northwestern Pacific subduction zone. In the SSP, ocean-bottom broadband seismic and electromagnetic stations were deployed in the Philippine Sea, and land-based broadband seismic stations were deployed in Far East Russia; the data from these sensors have been a key element in the success of the SSP. Yoshizawa et al. and Bourova et al. analyze land-based broadband seismograms recorded by the seismic network in Far East Russia, along with other permanent broadband stations, to determine 3D upper mantle shear velocity structure beneath the Japanese Islands and northeastern Eurasia, respectively. Both studies obtain fast and slow velocity anomalies associated with subducted slabs and the overlying mantle wedge, respectively, where the latter is suggestive of partial melting. Polarization anisotropy in the mantle wedge with SH-velocity greater than SV-velocity is observed by Yoshizawa et al., and azimuthal anisotropy with fast directions sub-parallel to the Kuril and Japan trenches is obtained by Bourova et al. Isse et al. analyze surface waves recorded by ocean-bottom broadband seismic stations to map shear-velocity and azimuthal anisotropy patterns in the Philippine Sea. They show that fast directions in the lithosphere are parallel to ancient seafloor spreading while those in the asthenosphere are parallel to the direction of present absolute plate motion. Baba et al. compare electrical conductivity structures beneath the Philippine Sea and the Pacific Ocean using data from ocean-bottom electro-magnetometers. Differences in conductivity at depths shallower than 200 km between the Philippine Sea and the Pacific Ocean are consistent with differences in lithospheric age. At depths greater than 400 km, the Philippine Sea mantle is more conductive than the Pacific mantle. Osada et al. perform a series of array analyses with seismograms recorded by Hi-net to determine the 3D geometry of the upper boundary of the subducted Pacific slab under Hokkaido, Japan. Syracuse et al. perform thermal modeling for 56 segments of subduction zones to obtain a comprehensive suite of thermal models for global subduction systems, providing insight into the dehydration and melting processes that occur in subduction zones. In spite of the wide range of slab geometries, ages and velocities, all models feature partial coupling between the slab and the overriding plate directly down-dip of the thrust zone, invoked to replicate the cold nose observed in measurements of heat flow and seismic attenuation.

The second section addresses lower mantle structure and the fate of subducted slabs. The subducted former oceanic crust is a key for understanding the origins of heterogeneities in the lower mantle and the D″ layer. Kaneshima and Helffrich employ an array processing technique to locate small-scale heterogeneities in the mid-lower mantle under circum-Pacific subduction zones. They find large-amplitude later phases after P, which they attribute to S–P converted waves from scatterers in a depth range of 1100–1800 km. They interpret these as arising from a post-stishovite phase transition of silica in remnants of subducted and folded former oceanic crust that preceded the current subduction of the Pacific plate. Nomura et al. determine the phase transition boundary of stishovite based on in situ X-ray diffraction measurements in a laser-heated diamond-anvil cell, placing the boundary at a depth of 1700 km along a typical mantle geotherm or somewhat shallower if it contains Al_2O_3 and H_2O, which is consistent with seismically detected scatterers. Bina interprets the scatterers as free silica in subducted oceanic crust, performing a simple numerical simulation to examine whether silica phases can persist in the lower mantle, particularly as polycrystalline silica within subducted crust. Tarits and Mandea determine a laterally heterogeneous conductivity model in the mid-lower mantle by inverting 32 years of global magnetic data. Their model shows a correlation with seismically imaged velocity maps, and some uncorrelated conductivity anomalies may be due to compositional effects. Seismic structure in the D″ layer is addressed by Takeuchi and Obara,

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Kawai and Geller, and Rost and Thomas. Takeuchi and Obara show that small-scale topography of the D″ discontinuity is correlated well with small-scale velocity anomalies beneath the southwestern Pacific: a deeper discontinuity yields lower shear velocity. The correlation is not linear, from which the authors suggest that thermo-chemical heterogeneities may be responsible for these observations. Kawai and Geller determine the 1D shear velocity model beneath Hawaii and find that velocities are reduced from 2700 km depth to the core–mantle boundary (CMB), suggesting a temperature increase. A comparison with other studies indicates that there is strong lateral heterogeneity in D″ beneath the Pacific. Rost and Thomas perform an array analysis of PcP waves to detect seismic discontinuities beneath the Alaska subduction zone. They fail to find the ultra-low velocity zone, which is often found in slow-velocity areas in tomographic images, but they detect a positive velocity jump 110 km above the CMB, which may be related to subducted and accumulated slab material.

The third section addresses rheology and mineralogy of mantle materials. It highlights the results of challenging experiments to provide basic data for understanding the deformation and stagnation of subducted slabs. Jackson and Faul perform torsional forced oscillation experiments for melt-free dry olivine to study grain-size sensitive viscoelastic relaxation. They obtain an extended Burgers model from the data and extrapolate it to mantle grain size and pressures, suggesting a significant contribution from grain-boundary relaxation under upper mantle conditions. Nishihara et al. perform stress relaxation experiments for olivine under high-pressure and high-temperature conditions using a Kawai-type multi-anvil and a 2D diffraction system with monochromatic synchrotron X-rays. They find that the deviatoric stress decreases with increasing temperature, and the final-state value of deviatoric stress increases with increasing pressure. The upper bound for the plastic strain rate in the final state was determined to be $10^{-7}\,s^{-1}$. Present results suggest a positive activation volume for the low-temperature rheology of olivine such as in a cold slab. Shimojuku et al. determine the temperature dependence of Si diffusion rates in polycrystalline Mg_2SiO_4 wadsleyite under nominally dry conditions (20–60 wt. ppm H_2O), obtaining Si diffusion rates that are about half an order of magnitude slower than those with 14–507 wt. ppm H_2O obtained previously. Enhancement of Si diffusivity through hydrogen incorporation possibly leads to water weakening in wadsleyite. Yamazaki et al. measure grain growth rates of majorite and stishovite, which are major components of subducted oceanic crust. For polycrystalline aggregates, the grain size of the constituent minerals is important to determine their rheological behavior. Grain sizes obtained by extrapolation to geological time scales are much smaller than those of olivine, wadsleyite, ringwoodite and (Mg,Fe)O but comparable to perovskite and periclase. Kawazoe et al. perform deformation experiments under high-pressure and high-temperature conditions of the mantle transition zone with a deformation-DIA apparatus, which will be useful in future rheological studies of the deep mantle. In addition to rheological studies, Kono et al. establish the first pressure-scale-independent P–V–T relation for MgO, which should provide an important pressure scale to accurately determine phase transition boundaries. Application of the present pressure scale to the post-spinel transition boundary yields a transition pressure of 23.0 GPa at 1873 K, which is only marginally lower than that of the 660 km discontinuity. Katsura et al. calculate the pressures of the olivine-wadsleyite phase transition and evaluate the temperature at the 410-km discontinuity using a newly determined equation-of-state (EOS) of MgO (Tange scale). Temperature is estimated to be 1830 K, which is lower than the authors' previous estimation by 70 K. The adiabatic temperature profile throughout the mantle is constructed by extrapolating the temperature at 410 km using thermal expansion coefficients obtained from EOSes of major mantle minerals based on the Tange scale.

The fourth section is a collection of papers on the transport of water into the mantle by subducting slabs. Water affects the physical properties of mantle minerals by decreasing viscosity and solidus temperature, as well as by perturbing seismic velocities and densities, with significant implications for the dynamics and evolution of the earth. Blueschists should play an important role in the initial water transportation process within subducting oceanic crust. Fujimoto et al. measure P-velocity and anisotropy of lawsonite and epidote blueschists up to 1 GPa and 400 °C. Comparison with seismic structures beneath NE and SW Japan suggests that subducted oceanic crust shallower than 50 km is composed of blueschists which is partially transformed to hydrous eclogite at 50 km. Osako et al. determine the thermal conductivity, diffusivity and heat capacity of serpentine (antigorite), which is formed in the mantle wedge by water dehydrated from subducted slabs. Both thermal conductivity and diffusivity are much lower than those of olivine, implying the existence of a thermal insulating layer in subduction zones. Jacobsen et al. show that a depth-variable (250–330 km) seismic discontinuity (X-discontinuity) can be attributed to a transition from orthoenstatite to high-pressure clinoenstatite in a depleted composition. The X-discontinuity depth could serve as an indicator of water content in the upper mantle, as transition pressures are sensitive to even minor amounts of water. The next four papers address water content in the mantle transition zone. Inoue et al. synthesize coexisting mineral assemblages of wadsleyite–ringwoodite and ringwoodite–perovskite and determine water partitioning with SIMS at temperatures in the mantle transition zone. The partitioning between olivine, wadsleyite, ringwoodite, and perovskite is estimated to be 6:30:15:1, respectively, suggesting that the mantle transition zone is a large water reservoir compared to the upper mantle and lower mantle. Shimizu et al. invert geomagnetic responses at observatories and submarine cables for 3D electrical conductivity structure beneath the northern Pacific and the Philippine Sea, finding a high conductivity in the mantle transition zone beneath Hawaii and the Philippine Sea. They attribute the former to high temperatures and the latter to high water content of 1 wt%. Suetsugu et al. analyze topography of the 660-km discontinuity and P-velocity tomographic images to estimate temperature anomalies and water content in the mantle transition zone beneath the Philippine Sea, where the Pacific slab is stagnant. They find that the bottom half of the stagnant slab is colder than average mantle by 500 K and the water content is 0.2 wt%, which is lower than the uncertainty level. The top half of the stagnant slab and the overlying mantle above it, on the other hand, may be hydrated. Richard and Iwamori hypothesize that a wet plume originating from the Pacific stagnant slab could be the origin of Cenozoic volcanism in East Asia. They perform a numerical experiment to show that the presence of water atop the stagnant slab could induce Rayleigh–Taylor type instabilities that can transport water up to the surface and produce melting at the base of the lithosphere.

Modeling and observational studies of slab subduction, stagnation, avalanche and whole-Earth scale convection are presented in the last section. Slab stagnation and avalanche into the lower mantle can be controlled by several parameters such as the sinking rate and dip of a slab, trench migration, phase transformations, and viscosity in the lower mantle. Gao et al. address phase transformations in the stagnant Pacific slab by applying a receiver function method to data from a Chinese broadband seismic network. The topography of the 410 km and 660 km discontinuities is consistent with thermal anomalies caused by the stagnant Pacific slab beneath China. A deeper discontinuity, at around 720 km, may represent the ilmenite–perovskite phase transition in the lower mantle part of the stagnant slab. The next four papers in the section discuss which parameters dominate slab behavior in the mantle transition zone. Billen compares observed subduction characteristics with analytical and numerical models of subduction dynamics and proposes two scenarios for formation of stagnant slabs: episodic trench retreat of young slabs with unstable overriding plates and slow lateral migration of older slabs with stable overriding plates. Nakakuki et al. examine slab rheology as a mechanism for producing different behavior of slabs in the mantle transition zone. Slab plasticity that memorizes the shape produced by past deformation can induce slab stagnation around at 660 km depth. Slab viscosity may contribute to the final state of slabs, as a low-viscosity slab can penetrate into the lower mantle. Yoshioka and Naganoda propose that supply of slab material from a trench provides an important control on slab behavior after stagnation. A shortage of material would produce extended slab stagnation around 660-km depth, and downward force due to continuous slab subduction would enhance its avalanche into the lower mantle. Bina and Kawakatsu construct thermal models of stagnant slabs and perform thermodynamic modeling of the consequent perturbation of high-pressure phase transformations. They find that buoyant bending moment gradients of petrological origin at the base of the mantle transition zone may contribute to slab stagnation. They compare their models with seismologically imaged features of stagnant slabs to show that slabs which bottom around 800 km and then bend upwards slightly can match the seismological image beneath Japan. Yanagisawa et al. reproduce seismologically determined behaviors of slabs using 3D spherical-shell mantle models of mantle convection which range up to Earth-like conditions in Rayleigh numbers. Calculations with phase transformations in the mantle transition zone and a viscosity increase at 660 km depth successfully exhibit a state of co-existing stagnant and penetrating slabs. Morishige et al., on the other hand, focus their study on the origin of low seismic velocity anomalies in the sub-slab (oceanward) mantle around 410 km depth. They propose that hot anomalies in the lower mantle – produced by internal, viscous and adiabatic heating – occasionally rise and are then entrained toward the 410-km phase boundary in the sub-slab mantle. Ogawa performs numerical modeling of thermo-chemical mantle convection with tectonic plates and mantle magmatism. He shows that subducted basaltic crust plays a key role in the generation of mantle plumes. The basaltic layer accumulates at the base of the mantle and forms into hot and chemically heterogeneous features similar to Earth's superplumes, which then produce hot plumes to cause hot-spot magmatism at the surface.

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