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Introduction

# The mantle transition zone: composition, discontinuities, dynamics

The seismically defined 'mantle transition zone' is a physically anomalous region between approximately 410 and 660 km depth in the Earth in which density and seismic velocities appear to increase abruptly. A complete understanding of the dynamics of mantle convection, plate-scale flow and the distribution of geochemical reservoirs in the Earth is strongly dependent on our ability to characterize the composition, structure and physical properties of the transition zone.

On 7 April, 1993, a special interdisciplinary SEDI session entitled "The mantle transition zone: composition, discontinuities, dynamics" was convened by G.Y. Bussod, H. Paulssen and P. Machetel at the European Union of Geosciences (EUG VII) in Strasbourg, France. Twenty-six papers were presented and an enthusiastic discussion on the existing experimental constraints and the robustness of our models for the transition zone ensued. Based on the success of this symposium we invited interested participants and members of the community at large to submit manuscripts for a special issue of *Physics of the Earth and Planetary Interiors* on the same topical issue. The outcome of this effort is presented in this issue which contains 13 papers. The multidisciplinary format of the special issue is emphasized by presenting the contributions under three subheadings, "Experimental Constraints", "Seismic Constraints" and "Modelling."

Technological advances in multi-anvil and diamond-anvil apparatus permit the synthesis of high pressure mineral assemblages relevant to the transition zone, and the characterization of their stability fields, thermoelastic properties and reaction kinetics. Based on experiment and observation, the velocity and density increases within the transition region correlate with pressure-induced phase transformations of an isochemical mantle. The upper boundary of the transition zone at 410 km, is associated with a seismic discontinuity involving a velocity increase linked to an exothermic olivine to $\beta$-spinel phase transition, followed by an anomalously high velocity gradient at greater depth. Similarly, the base of this region is associated with a sharp velocity increase at 660 km depth, and linked to either an endothermic phase transition of $\gamma$-spinel to silicate perovskite and ferro-magnesiowüstite and to a possible increase of Fe or Si content of the mantle.

Various degrees of uncertainty weaken considerably the correlations presented above. While an isochemical model is compatible with existing data, the uncertainties are large enough to allow a wide variety of mantle compositions ranging from 'pyrolite' to 'piclogite'. Because of these uncertainties, no single line of evidence can help discriminate between a dynamically and/or compositionally stratified mantle and a non-layered isochemical mantle. Whereas the geophysical evidence appears to favor penetration of subducting slabs and plate-scale flow through the full depth of the mantle, some geochemical models suggest that only the upper mantle is depleted and many geochemists advocate layered convection. Early numerical models of mantle convection with en-


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dothermic phase changes suggest a 'leaky layered' structure is possible, however in view of recent computational developments and better experimental contraints, these conclusions must also be re-evaluated.

In the section on "Experimental Constraints," the late A.E. Ringwood presents his synthesis of experiment and observation, in which he contends that the 660 km discontinuity acts generally as a barrier to subducted slab penetration into the lower mantle. In his model, the upper and lower mantle are chemically similar, but the transition region is heterogeneous and comprised of components of ancient oceanic slabs. Ringwood's concept is based principally on three conditions: (i) a negative Clapeyron slope for the major mantle phase transitions, (ii) differentiation of oceanic slabs favoring buoyancy, and (iii) accumulation of oceanic crust as a garnetite layer in the transition zone.

Even in the simpler olivine-rich end member model 'pyrolite', the olivine component represents less than 60 modal % of the natural assemblage. The other major phases are pyroxenes which breakdown to majorite and perovskite components at transition zone conditions. Canil experimentally determined the stability field for $CaMgSi_2O_6$ diopside and found a negative Clapeyron slope ($-2$ MPa/°C) for the breakdown reaction. On the strength of these results, he suggests that formation of Ca-perovskite is responsible for the 520 km discontinuity. Rigden et al. present the first measurements on the pressure derivatives of the adiabatic bulk modulus and shear modulus of majorite-pyrope garnet solid solution. They suggest that the presence of garnet may best explain the shear wave velocity structure of the transition zone. In their paper, Brearley and Rubie predict substantial mechanical weakening of oceanic slabs at transition zone depths owing to a shear-like $\gamma$ to $\beta$ transformation mechanism. All of these experimental constraints are consistent with Ringwood's transition zone model of resistance to slab penetration, however, the rheological properties of the transition zone are unknown. Indeed, Sharp et al., in the first paper on the transmission electron microscope examination of experimentally deformed specimens of $\beta$-phase, suggest that this $(Mg, Fe)_2SiO_4$ high-pressure polymorph can deform by dislocation creep. Consequently, deformation of the transition zone may result in anisotropic structures and physical properties in at least some areas of this region.

Major advances have been made in the characterization of the fine structure of the seismic discontinuities encountered in this zone and some of these are exemplified in the section on "Seismic Constraints". Kennett et al. derive the P- and S-velocity structure for the Indonesia New Guinea earthquake belt of northern Australia. With these data, they are able to infer the upper mantle P to S velocity ratio from an internally consistent data set as is done only in very few other studies. Stutzmann and Montagner present the first global shear wave model based on phase-velocity measurements of fundamental and higher mode surface waves. The incorporation of higher mode data is particularly relevant because they are very sensitive to the structure of the mantle transition zone. Conversely, the question of the interrelationship between volumetric velocity anomalies in the transition zone and the topography of the discontinuities is addressed in the paper by Lavely et al. This contribution illustrates the possible bias introduced by boundary topography in mantle structures determined in tomographic studies, and the problems involved in reducing these uncertainties. In another approach van der Lee et al. show that the topography of the 660 km discontinuity may focus or defocus seismic phases that convert from P- to S-wave type. They use the variability in the observations of these phases to infer relatively small scale topography on this discontinuity beneath northwestern Europe.

The effects of depth-dependent properties on mantle convection are of particular interest as they generally serve to induce large-scale circulations as well as producing a focusing effect on plumes. In the section on "Modelling" geodynamic 2-D and 3-D numerical models are used to understand the physics involved in the interaction between the upper and lower mantle. Steinbach and Yuen focus on the controlling parameters involved in strong gravitational ('flush') instabilities, a phenomenon linked to catastrophic transitions from layered to whole mantle convection. They explore the effects of depth-dependent properties (thermal expansivity, viscosity and thermal conductivity) on a convective mantle and include the effects of the two major phase transitions. Their results indicate that the depth dependence generally promotes layering of the system. Yuen et al. present 3-D convection simulations with depth dependent properties and phase transitions. Their models strengthen the conclusions of Steinbach and Yuen and demonstrate that the addition of a third dimension serves to enhance layering. Numerical experiments on chemically stratified convective systems are presented by Hansen and Yuen who investigate the behaviour of plumes in a mantle with a depth dependent thermal expansivity. They show that thermal-chemical plumes can penetrate a compositional boundary and that a chemically stratified mantle does not necessarily require layered convection. All of these studies demonstrate that as the complexity of the dynamical models increases, a departure from the two end-members of layered versus whole mantle convection is indicated.

The models listed above focus principally on the communication between the upper and lower mantle by convection and mixing from below (rising plumes). The contribution by Rubie and Ross attempts to constrain the degree of slab penetration into the lower mantle through the transition zone using available kinetic data for the olivine to spinel transformation. Considering the effect of latent heat production on the transformation kinetics, their model predicts that a wedge of 'cold' metastable olivine from subducted oceanic slabs may persist to depths greater than 500 km but that the subsequent transformation to the spinel phase could drastically affect the rheological properties of the slab. This development could prevent penetration into the lower mantle, as proposed by Ringwood.

The principal goal of this special issue is to provide a multidisciplinary perspective on the problems relevant to the transition zone. The exchange of information in this issue between the different disciplines is in its infancy, but it is hoped that it will provide the impetus for further communication among theoreticians and experimentalists in geology and geophysics.

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