An Introduction to Post-Perovskite: The Last Mantle Phase Transition

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Discovery of the perovskite to post-perovskite phase transition in MgSiO₃, expected to occur for deep mantle conditions, was first announced in April 2004. This immediately stimulated numerous studies in experimental and theoretical mineral physics, seismology, and geodynamics evaluating the implications of a major lower mantle phase change. A resulting revolution in our understanding of the D″ region in the lowermost mantle is well underway. This monograph presents the multidisciplinary advances to date ensuing from interpreting deep mantle seismological structures and dynamical processes in the context of the experimentally and theoretically determined properties of the post-perovskite phase change; the last silicate phase change likely to occur with increasing pressure in lowermost mantle rocks.

INTRODUCTION

The importance of mineralogical phase transitions in the deep Earth was anticipated in the 1950s by Francis Birch, and over the past half century interpretation of seismological structures by mineralogical phase equilibria has guided compositional, thermal and dynamical models of the planet’s interior. Confident seismological detection of the occurrence of a specific predicted phase change at depth enables a cascade of constraints to be placed on deep properties that can otherwise only be loosely bounded. Earth’s transition zone, the depth region from 410- to ∼800-km with complex seismological discontinuities and multiple associated phase changes, has now been characterized in substantial detail. However, important attributes of the underlying lower mantle, such as absolute temperature, have been inferred only by large depth extrapolations from conditions established by phase changes in the transition zone or at the inner core boundary. Demonstration of the presence of a well-characterized lower mantle phase change raises the prospect of revolutionary improvements in our understanding of lower mantle properties and dynamics.

Following the discovery of silicate perovskite by Liu [1974], MgSiO₃ perovskite has become recognized as the principal mineral occurring in Earth’s lower mantle. For several decades, MgSiO₃ perovskite has been extensively studied to clarify its physical properties, crystal chemistry, and role in mantle dynamics. After a workshop in Bisbee, Arizona, held in 1987, a monograph exploring this important mineral entitled “Perovskite: A Structure of Great Interest to Geophysics and Materials Science” edited by A. Navrotsky and D. J. Weidner, was published by the American Geophysical Union in 1989. Observation of seismological discontinuities in the lowermost mantle (Wright and Lyons [1975], Lay and Helmberger [1983]) motivated investigation of very high-pressure and high-temperature properties and stability of perovskite. This has been a subject of some controversy in the high-pressure mineral physics community. It was suggested at one time that orthorhombic perovskite transforms to cubic structure with increasing temperature. Dissociation of perovskite into mixed simple oxides was also suggested to occur in the mid-lower mantle. However, these possibilities were not verified by subsequent studies. The likelihood of perovskite transforming into a denser MgSiO₃ polymorph was not generally anticipated, primarily because perovskite is an ideal close-packed structure.
that is favorable for high-pressure conditions. The notion that perovskite is the ultimate stable form of silicates in the Earth’s mantle thus began to take hold, although awaiting confirmation by advances in experimental and theoretical mineral physics.

This notion of perovskite stability clearly could not account for the observed seismic discontinuities in the lowermost few hundred kilometers of the mantle (the D" region), and the possibility of some phase transition occurring there was proposed on the basis of seismological and geodynamical considerations [e.g., Sidorin et al., 1999]. The D" region has long been enigmatic because its seismological properties are distinct from relatively homogeneous overlying lower mantle. With improving characterization of seismological properties of D", it became clear that some combination of mineralogical, compositional, and thermal heterogeneity is required to account for the observed structures [Lay and Garnero, 2004].

As experimental techniques advanced to span the full range of pressure and temperature (P-T) conditions of the lower mantle, a phase transition from MgSiO₃ perovskite to post-perovskite was discovered and confirmed by several laboratories. This was first reported in 2004, 30 years after silicate perovskite was first synthesized. This new mantle mineral has profound implications for the nature of and dynamics in the D" region. The occurrence of the phase change and the distinct properties of post-perovskite now provide a viable explanation for several major seismological characteristics of the D" region, along with having important implications for the dynamics of the lower mantle boundary layer. The specific properties of the phase change, together with seismological observations, also provide the first direct constraints on absolute temperature and temperature gradients in the lowermost mantle, eliminating the need for vast extrapolations of temperature estimates over large depth ranges.

Several long-term enigmas may be reconciled by occurrence of post-perovskite in the lower mantle. However, the D" region, by virtue of its location above the boundary between the liquid iron core and the rocky silicate mantle, is still expected to have complex thermal and chemical structures. Strong radial and lateral temperature gradients should exist in the boundary layer caused by heat flowing out of the core and by mantle convection. Chemical heterogeneity is likely to exist in this boundary layer due to the huge density contrast at the core-mantle boundary (CMB) and the long history of chemical differentiation in the interior, with ancient residues of mantle differentiation and/or subsequent contributions from deep subduction of oceanic lithosphere, partial melting in the ultra-low velocity zone (ULVZ) just above the CMB, and core-mantle chemical reactions. The complexity of a thermo-chemical boundary layer in D" was extensively documented in the 1998 American Geophysical Union monograph “The Core-Mantle Boundary Region” edited by M. Gurnis, E. Knittle, M. E. Wysession, and B. A. Buffett. This context indicates that extensive characterization of the thermal and chemical influences on the post-perovskite phase transition is critical to our ability to relate seismological observations to the behavior of the new mineral.

The current monograph presents a full span of post-perovskite attributes, including characterization by experimental and theoretical mineral physics, seismological interpretations and dynamical considerations. The papers are grouped by disciplinary emphasis, but all of the geophysical attributes are interconnected. It should quickly become evident why this last silicate phase transition in the mantle is eliciting such excitement and concentrated effort.

**EXPERIMENTAL MINERAL PHYSICS PAPERS**

The deep lower mantle is a challenging region to quantify mineralogically, in part because experimental investigations at relevant P-T conditions are very difficult. Recent developments at synchrotron radiation facilities and advances in laser-heated diamond-anvil cell (LH-DAC) techniques now enable experimentation at relevant high P-T conditions with in-situ X-ray measurements of deep mantle minerals. The phase transition from MgSiO₃ perovskite to post-perovskite was discovered through a change in X-ray diffraction spectra above 125 GPa and 2500 K [Murakami et al., 2004], corresponding to conditions near the top of the D" region. In addition, electronic spin-pairing transition of iron in perovskite and magnesiowüstite was found to occur in the lower mantle, based on X-ray emission spectroscopy measurements [e.g., Badro et al., 2003]. These new findings in experimental mineral physics have significant implications for structure, seismic heterogeneity, dynamics and chemistry of the middle to deep lower mantle.

Interpreting the cause of seismic discontinuities in the mantle has long been a central subject of high-pressure experimental studies. Yagi reviews the progress of high-pressure experimental techniques and studies of mantle phase transitions since the 1950s. The olivine to spinel phase transformation was first observed in Fe₂SiO₄ at 5 to 6 GPa [Ringwood, 1958]. With advances in generating higher pressures by using newly designed apparatus, phase relations on the join Mg₂SiO₄-Fe₂SiO₄ were systematically investigated. Modified-spinel (so called β-phase) was found on the Mg-rich part on this join, but the crystal structure was not known at that time. In the early 1970s, the pressure of the 660-km seismic discontinuity was beyond the capability of any existing high-pressure apparatus. Liu [1974] first synthesized silicate perovskite using LH-DAC, inferring that the 660-km seismic discontinuity is caused by formation of the dense
perovskite-structured phase. MgSiO$_3$ perovskite was subsequently found to have great stability, leading to speculations that it may persist in this form all the way to the CMB.

Hirose reviews the discovery of MgSiO$_3$ post-perovskite and subsequent experimental studies on perovskite to post-perovskite phase transition in both simple and natural multi-component systems. While XRD patterns indicated the phase transition in MgSiO$_3$, the crystal structure of post-perovskite was obtained with the aid of theoretical calculations. The MgSiO$_3$ post-perovskite phase transition boundary has been experimentally determined using several different pressure standards. Most results show that the transition occurs within the mantle but the experimentally estimated transition pressure varies by as much as 15 GPa, due primarily to uncertainty in $P-V-T$ equations of state of pressure standards. The MgO pressure scale currently appears to be the most reliable, and the results based on the MgO scale indicate that the transition pressure matches the general depth of the seismic discontinuity observed near the top of D$''$ [e.g., Wysession et al., 1998] for a plausible mantle temperature of 2500 K. The post-perovskite phase transition occurs in a natural pyrolic mantle composition at pressures very similar to that in pure MgSiO$_3$, when the MgO scale is used. Al-bearing (Mg,Fe)$_3$SiO$_5$ perovskite is the most abundant mineral in subducted MORB crust. The post-perovskite phase transition occurs in MORB materials at shallower depths, by about 70-km, than in pyrolite at the same temperature. Hirose also discusses how several long-term seismological enigmas may be reconciled by the properties of post-perovskite without the need for invoking chemical heterogeneities; these include the D$''$ discontinuity, strong seismic anisotropy in the D$''$ region, and anti-correlation between anomalies in S-wave and bulk sound velocities in the deep mantle. Some remaining unsolved problems in the lowermost mantle are summarized.

Iron is the most important impurity in MgSiO$_3$ post-perovskite, and may significantly affect post-perovskite stability, density, and elastic properties. Mao, Campbell, Prakapenka, Hemley, and Mao report new experimental data on the volumes of (Mg$_{0.8}$Fe$_{0.2}$)SiO$_3$ post-perovskite at high $P-T$ and an estimate of the thermal expansivity at lowermost mantle conditions. The incorporation of iron significantly increases its mass but only moderately expands the volume, resulting in a large increase in density. They also review the previous research on Fe-bearing post-perovskite, inferring that iron lowers the perovskite to post-perovskite transition pressure, increases bulk modulus, and lowers the sound velocities. Nuclear resonant inelastic X-ray scattering (NRIXS) measurements on Fe-enriched post-perovskite (40% FeSiO$_3$) at 130 GPa and 300 K demonstrate that compressional and shear wave velocity estimates are consistent with seismological observations for the ULVZ. However, the extent of any iron enrichment at the base of the mantle is controversial. The effect of iron on the stability of post-perovskite is also still an open issue.

The electronic spin state of iron in magnesiowüstite, perovskite, and post-perovskite may affect the physical properties of the lower mantle. Li reviews the recent studies on spin crossover (high-spin to low-spin transition) of iron in these major lower mantle minerals. Both experiment and theory show that the spin crossover occurs in magnesiowüstite around 60 GPa at 300 K, resulting in remarkable changes in volume and sound velocities. Note that the iron spin transition takes place over a much broader pressure range at high temperatures and therefore these changes should be gradual in the mantle. In contrast, the spin crossover in perovskite is currently controversial. The nature of spin transition is complicated in perovskite because iron has multiple valence states and crystallographic sites to be incorporated. The pressure and sharpness of spin crossover in perovskite and its temperature and compositional dependence are still poorly known.

Seismic anisotropy is observed in the D$''$ region, with an increase in strength across the D$''$ seismic discontinuity. Since post-perovskite is possibly a predominant mineral in this region, the seismic anisotropy may be caused by lattice-preferred orientation (LPO) of post-perovskite. Yamazaki and Karato review experimental and theoretical studies on the deformation mechanism of post-perovskite. They discuss the experimental results on an analogue material, CaIrO$_3$ with post-perovskite structure, obtained at high temperature under modest stress conditions, which may be applicable to the deformation occurring in D$''$. These experiments show that the layering plane (010) is a dominant slip plane. Yamazaki and Karato calculate the S-wave splitting for post-perovskite aggregates under horizontal flow and conclude that the sense of splitting is consistent with the seismological observations ($V_{SH}$ is faster than $V_{SV}$), but the magnitude is less than observed. A contribution from LPO of magnesiowüstite may be important as an additional source of S-wave splitting observed in the D$''$ layer.

THEORETICAL MINERAL PHYSICS PAPERS

The role that computational mineral physics had in the discovery, acceptance, and recognition of the importance of the post-perovskite phase in the Earth cannot be overstated. Although it was experimental evidence of the perovskite to post-perovskite transformation that first stirred the computational mineral physicists into action, the fact that the experimental evidence was quickly confirmed by ab initio results gave tremendous credence to it. Moreover, computational mineral physics was immediately used to provide estimates of the Clapeyron slope - with which the variation in the depth of the D$''$ seismic velocity discontinuity could be compared - and
estimates of the elasticity to compare with the observed seismic anisotropy. A flurry of further papers quickly provided high temperature elastic constants of post-perovskite, together with estimates of the effect of chemistry on its stability and elastic properties.

The paper by Wentzcovitch, Tsuchiya, and Umemoto addresses the stability of post-perovskite relative to perovskite using ab initio lattice dynamics. As long as the anharmonicity is not too large, ab initio lattice dynamics is able to provide accurate high temperature properties. Wentzcovitch et al. present, therefore, a full range of thermodynamic properties such as the heat capacity and entropy, as well as thermoelastic properties such as the Gruneisen parameter. One of the major benefits of lattice dynamics over other molecular dynamics is that the free energy at a finite temperature is more readily available. This allowed the authors to calculate the Clapeyron slope, which they find to be about 7.5 MPa/K at a temperature of 2500 K and a pressure of about 100 GPa.

They also find the Clapeyron slope to be relatively insensitive to a temperature of 2500 K and a pressure of about 100 GPa. They also examine the possibility of post-perovskite (2500 K) and at temperatures ranging from 0 to 4000 K in 500 K intervals. They then compare their results with those previously obtained using lattice dynamics and find that the two sets of results start to diverge at high temperatures (greater than about 2500 K). Although the cause of this is not certain, it may be due either to a break down in the quasi-harmonic approximation used in lattice dynamics or, alternatively, due to the choice of pseudopotential or exchange-correlation functional. The divergence in high temperature elasticity particularly affects the seismic anisotropy and, unfortunately, at high temperatures the two methods predict completely different polarizations for the same crystal orientations. For instance, for a crystal aggregate developed with slip in the (010) plane (the slip plane intuitively expected from the layered octahedra), the MD results predict about a 2% shear-wave anisotropy, with the horizontal S-wave propagating faster than the vertical one; the lattice dynamics results on the other hand, show the exact opposite polarity. This makes the interpretation of the observed anisotropy in Dv somewhat uncertain. Stackhouse and Brodholt also use their elastic constants, together with estimates for other phases and chemical components, to show that a post-perovskite bearing Dv matches PREM to within 1%.

The last paper in the Theoretical Mineral Physics section is by Caracas and Cohen who use density functional methods to look at the effect of Fe and Al on the physical properties and stability of perovskite and post-perovskite. They find that the effect of iron is to decrease considerably the transition pressure between the two phases. The FeSiO3 end-member perovskite is in fact stable at all pressures relative to perovskite. Aluminium, on the other hand, increases the transition pressure, but to a lesser extent that iron. Due to its high atomic mass, Fe strongly increases the density of perovskite and post-perovskite, and, therefore, strongly decreases seismic velocities. Fe is also found to slightly decrease the seismic anisotropy. Al2O3 also affects the seismic velocities, but generally to a lesser extent than Fe. It does, however, strongly increase the seismic anisotropy. In order to characterize the effect that iron has on the width of the phase transition, Caracas and Cohen use a non-ideal solution model to construct a pressure-temperature-composition phase diagram for Fe2+ bearing MgSiO3. They find that the effect of Fe can be quite considerable, especially in a colder mantle. For instance, in a very cool mantle of 1500 K (i.e., in a subducting slab), the phase transition could begin at a depth 150 km shallower than in a 3000 K mantle. In addition, they find a very wide two-phase loop in the cool case, and for about 10% Fe, the transition takes place over about 170 km depth. In contrast, the width of the transition at 3000 K is only 50 km. The exact width depends on the concentration of iron.

SEISMOLOGICAL PAPERS

Analyses of seismic waves that traverse Earth’s interior provide direct constraints on material properties of the mantle such as its elastic wave velocities and density, with geochemical and petrological models being guided by and tested against the seismic observations. The transition zone velocity discontinuities discovered in the 1960s have played a major role in developing mineralogical and petrological models for the upper mantle, and it is not surprising that lower mantle velocity discontinuities discovered in the 1970s and 1980s are now playing a similar role in advancing models of the deep mantle as mineral physics experiments progressively reveal high pressure properties of major mineral types.

The presence of a mineralogical phase change in the mantle can produce observable changes in material properties. Lay and Garnero review the complex suite of seismological observations of deep mantle velocity discontinuities, exploring the viability of attributing some features to the perovskite to post-perovskite phase transition in a chemically and thermally heterogeneous environment. Interpretation of an observed seismic velocity discontinuity as the result of a particular phase transition is not unique, so the variability of the
seismic observations is considered in order to evaluate the likelihood that a phase transition to post-perovskite structure occurs in the deep mantle. Attributes of the seismic discontinuity observations such as the depth, size, and sharpness of $P$- and $S$-wave discontinuities, and their relationship to surrounding volumetric velocity heterogeneity, are considered. Inconsistencies with the phase change predictions for end-member compositions motivate consideration of the possible effects of variable chemistry and temperature compatible with the seismic heterogeneities. The observation of multiple seismic velocity discontinuities in some regions is discussed, with attendant implications for multiple intersections of the geotherm with the post-perovskite phase boundary being considered. The importance of expanding seismic wave data sets, new waveform stacking and migration algorithms, and 2D and 3D waveform modeling methods is discussed. The overall emphasis of this contribution is on the variable nature of the seismic velocity structures in the lowermost mantle, and the need to avoid simplification generalizations about the occurrence of post-perovskite. While the existence of post-perovskite in the deep mantle cannot yet be conclusively demonstrated, it is shown that its presence is plausible and many attributes of the deep structure revealed by seismology can be reconciled with the phase change occurring in a thermally and compositionally heterogeneous environment.

Sun, Helmberger, Song, and Grand assume that post-perovskite is present and that large-scale tomographic seismic velocity variations are primarily thermally controlled to make predictions of the lateral position of the phase boundary. Higher velocity regions are assumed to be cooler, giving rise to shallower occurrence of the phase-transition than in lower velocity, presumably warmer regions. Detailed seismic waveform analysis is then used to constrain the properties of the thermally modulated phase boundary. The use of tomographic models provides constraints on the lower mantle velocity models that were not available when the first $D^\ast$ discontinuity models were developed, and this allows improved resolution of the overall velocity models and discontinuity depths. Strong lateral variations in the phase boundary are predicted by the strong gradients in tomography models and in independent travel time observations, and these variations can be reconciled with seismic reflections from the phase boundary. Large low velocity provinces are recognized to involve chemical heterogeneity in addition to having warmer temperatures. Internal convection of these provinces results in localized regions where lower temperatures can support post-perovskite even if most of the chemically distinct province is too warm for the phase to be stable. The conclusion is again that many attributes of the lowermost mantle seismic velocity structure can be accounted for by predictable variations in the phase boundary when thermal and chemical heterogeneity are allowed for.

Wookey and Kendall consider the seismic velocity anisotropy expected for post-perovskite, demonstrating how this provides another observational approach to detecting and potentially exploiting the presence of post-perovskite to constrain deformational processes in the lower mantle boundary layer. Observations of seismic shear wave splitting are summarized and considered in the context of predicted anisotropic effects for end-member mineralogies involving perovskite, MgO, and post-perovskite, including variations with Fe and Al components. Uncertainties in the slip planes that will actually be activated in lower mantle boundary layer flows preclude a definitive conclusion at this time, and alternatives such as shape-preferred anisotropy associated with liquid inclusions cannot be ruled out. However, the possibility of lattice preferred orientation in post-perovskite accounting for seismic observations is demonstrated for some viable slip systems.

Observation of the weak reflections from a phase boundary are difficult to seek on a global basis, so to constrain large-scale structures Reif explores long-period travel time constraints on models with and without phase boundaries. Normal mode observations are shown to provide some weak constraints, precluding the existence of a global, thick layer of high density post-perovskite, but not the possibility of a strongly laterally varying layer as suggested by the velocity discontinuity studies. Carefully measured long-period arrival time patterns are used to characterize the variable slope of the first-arrival time curve, finding only limited first-arrival time support for a rapid velocity increase like that expected for a phase boundary. Further comparison of $P$- and $S$-wave tomography models in terms of thermal, compositional and phase change effects demonstrates that the additional degrees of freedom upon including a phase change further complicates the inversion for separate compositional and thermal effects. As in the chapters on seismic velocity discontinuities, it is recognized that progress in mapping the presence of post-perovskite hinges upon more thorough calibration of the effects of composition on the phase change itself, if the inversion trade-offs are to be overcome.

GEODYNAMICAL PAPERS

From a geodynamical vantage point, the $D^\ast$ layer has long been recognized as the site where instabilities are likely to develop because of the presence of the thermal boundary layer right above the CMB [Jones, 1977; Yuen and Peltier, 1980; Loper and Stacey, 1983]. The dynamical implications of the post-perovskite interpretation of the $D^\ast$ layer having a steep positive Clapeyron slope are quite profound for the dynamics of the deep mantle, since the rheology of post-perovskite may also be non-Newtonian and lower than the adjacent perovskite because of the large-stresses present at the boundary layers of mantle convection.
Peltier gives an historical account of the dynamics of the D″ layer from a purely thermal perspective. He reminds the reader that the interpretation of the D″ layer in terms of chemical heterogeneity [e.g., Trampert et al., 2004] was originally invoked to explain properties of this layer that may be adequately explained now by the post-perovskite phase transition. This motivates a review of the plausibility of the end member of chemically homogeneous models of mantle convection. Peltier stresses that the post-perovskite transition may force geophysicists to reconsider the idea that the chemical heterogeneity that is associated with D″ may be entirely derived from the core rather than from slabs piling up at the CMB. Such a scenario may fit very nicely with the idea of infiltration of iron into the post-perovskite phase advocated in Petford et al. The relative importance between thermal and chemical buoyant forces in the deep mantle relies critically on the knowledge of equation of state of subducted oceanic basalt and pyrolite for different compositions of iron. The differences in the bulk moduli with depth [Tan and Gurnis, 2005] being traded off with the reduction of the coefficient of thermal expansion with depth must be examined quantitatively by detailed equation of state calculations and not by extrapolations of thermodynamic data.

Tackley, Nakagawa, and Hernlund examine the influence of post-perovskite transition on both thermal and thermal-chemical mantle convection. They study the dynamical effects arising from the complex interplay of variations in temperature, composition and the post-perovskite transition. Figure 1 shows the situation that arises for two Clapeyron slopes that depend on composition and how they would be crossed by the temperature curve labeled $T$ associated with a thermal boundary layer above the CMB. Because of uncertainties of the physical parameters, such as depth variations of thermal expansivity and the differences in the bulk moduli with depth, it is extremely difficult to ascertain the relative dynamical importance of each of these factors. Tackley et al.'s calculations reveal that the lateral variations in the occurrence of post-perovskite contribute the most to the long wavelength lateral shear-wave anomalies in the deepest portion of the mantle. With a post-perovskite transition dependent on composition, a great variety of complex behavior may ensue, producing structures such as multiple crossings of the temperature curve by the two different types of post-perovskite transition (see Figure 1, where $t_1$, $t_2$, $b_1$ and $b_2$ are the four crossings due to compositionally dependent phase boundaries).

Figure 1. Schematic diagram showing the temperature curve and the phase boundaries in the D″ layer. The temperature $T$ curve represents the temperature profile as it approaches the CMB. Two phase boundaries depending on composition have been included and the Clapeyron slopes are given by $\gamma$, and the temperature-intercept at the CMB by $T$-int. The temperature of the CMB is designated by $T$-CMB. The levels $t_1$, $t_2$, $b_1$, and $b_2$ are the depths where the temperature curve is intersected by the two phase boundaries. The thermal expansivity $\alpha$ is dependent on $P$, the pressure. The thermal conductivity $k$ depends on temperature, pressure and iron content Fe. The non-Newtonian viscosity of post-perovskite depends on the stress $\tau$, temperature, pressure and Fe content.
Yuen, Matyska, Cadek, and Kameyama focus on the dynamical effects from the physical properties in the lower mantle on the post-perovskite transition within the framework of thermal convection in Cartesian geometry. They investigate the influences on lower mantle plume dynamics of strongly depth-dependent coefficient of thermal expansion and radiative thermal conductivity (see Figure 1) acting in concert with the post-perovskite transition. Double-crossing of the post-perovskite boundary only takes place when the CMB temperature is higher than the temperature intercept of the phase change \( T_{\text{int}} \) (see Figure 1). Both radiative thermal conductivity and strongly decreasing thermal expansivity conspire to induce partially layered convection with slabs stagnating in the transition zone and to develop multiple scale mantle plumes, with superplumes in the lower mantle and smaller scale secondary plumes emerging from 670 km depth. From the same thermal expansivity, they deduce the 3-D density anomalies from the seismic velocity anomalies inferred from seismic tomographic inversion. They then deduce the lateral viscosity variations above the CMB by solving the inverse problem dealing with the long-wavelength geoid anomalies computed for viscous responses to the mantle flows excited by the 3-D density heterogeneities. They find that the region underneath hot spots has significantly higher viscosity in the lower mantle than the region below subduction zones. They suggest that the bottom portions of lower mantle perovskite superplumes are stiffer than the adjacent post-perovskite deep mantle and the fixity of these plumes is due to the constraints imposed by the surrounding horizontal flow of post-perovskite with cold downwelling origins.

Petford, Rushmer, and Yuen consider the material transfer of iron into the D\(^\text{+}\) layer from the core, as proposed in Peltier. They view this phenomenon as a multiscale problem, both spatially and temporally. On the microscale they used pure and simple shear deformation mechanisms which produce transient pressure gradients to drive local fluid flow. They emphasize that the mesoscale non-Newtonian flow associated with the D\(^\text{+}\) boundary layer is a possible trigger of small-scale convection within this sub-layer, while the macroscale flow comes from lower-mantle circulation. They also discuss in detail the microscale physical processes and the coupling to geochemistry. Ideas on core-mantle interaction and melt migration under large stresses are drawn from experimental deformation studies under moderate temperature and high strain-rate conditions. The rheology of post-perovskite is an important ingredient for this filtration process to work efficiently.

**CONCLUSION**

Any compilation of results such as this book provides only a snap-shot of knowledge at a given time, and there will be steady advances in our understanding of post-perovskite properties and occurrence in the Earth. But all scientific revolutions have an initial phase of dramatic changes, followed by long-term adjustments. This book documents the remarkable discoveries and advances of the first three years of the post-perovskite revolution.

**REFERENCES**


