

Preface

The Earth's mantle is not homogeneous. This has become more than evident from the analysis of seismic waves, which are strongly affected by changes in temperature, mineralogical phase, and chemical composition as they travel through Earth's mantle. The message from geochemistry is similarly complex. For instance, analysis of geochemical isotopes showed that the plumes from which Ocean Island Basalts are thought to originate are sampling at least two distinct chemical reservoirs. Recovering detailed maps of mantle heterogeneities at the various scales of interest to Earth scientists, for the purpose of unraveling their nature and origin, raises several challenges that Earth scientists attempt to solve by combining data, observations, theoretical and numerical models, and experimental results from several fields including geophysics, geochemistry, geodynamics, and mineral physics. This monograph aims to discuss recent developments that have contributed to improved understanding of the physico-chemical structure and dynamics of Earth's mantle through a series of topical reviews and original research contributions with emphasis on interdisciplinary studies. *In fine*, our ability to impose constraints on accretion, differentiation, and early evolution of our planet hinges crucially on our ability to elucidate its internal structure.

Over the past decade, considerable observational and experimental evidence from seismology, geochemistry, mineral physics, and geodynamical studies have accumulated attesting to the presence of radial and lateral heterogeneities that permeate Earth's mantle. These heterogeneities cover length scales from microscopic (chemistry) over patches of lithospheric slabs that scatter seismic waves in the lower mantle (~10–100 km) to cold subducted lithosphere, transition-zone topography, and large low shear-wave velocity provinces in the deep mantle (~1000 km) and are evidence of the dynamic evolution that Earth's mantle has undergone and continues to undergo. Variations in composition, temperature, and mineralogy are all believed to play a role in explaining the observed heterogeneity, but their relative contributions remain elusive. However, recent advances in creating comprehensive mineral physics databases combined with improved geophysical imaging techniques, greater accuracy of geochemical analyses, and more complex

geodynamic models, has greatly improved our ability to make quantitative inferences on the thermo–chemical state of Earth’s mantle, which ultimately holds the key to understanding the evolution of our planet.

Of all methods available to Earth scientists seismology has proved the most important because it affords the highest resolution. Accordingly, seismology has been the main source of information on mantle structure. For decades radial seismic profiles have formed the basis for inferring structure and constitution of the Earth. The variations in seismic wave-speed of the upper mantle and transition-zone have been recognized as arising from phase transformations undergone by the silicate minerals that constitute the mantle as pressures and temperatures increase. However, the role and extent of any compositional layering between upper and lower mantle, is yet to be fully resolved. The question of whether phase transitions in the olivine system alone are sufficient, or indeed, whether a chemical change is needed to explain the observed discontinuous increase in, e.g., seismic wave-speeds, remains to be understood.

Seismic tomography has provided information on both lateral and radial structure of Earth and has done much to advance our understanding of its dynamics. The large-scale global velocity structure is relatively well-resolved, as is apparent from the current consensus among studies that employ different data and modeling techniques, and correlates well with surface tectonics. This is demonstrated in the opening chapter of this monograph by Schaeffer and Lebedev, who present a global surface-wave tomographic model of the upper mantle and compare it to existing models. Increased resolution in seismic imaging on regional scales has been made possible through analysis of data from high-density seismic networks. An example of such a regional model is presented and discussed in Chap. 2 by Rawlinson and coauthors who address the seismic wave-speed structure of the upper mantle beneath Australia. Heterogeneities in the upper mantle associated with discontinuities that arise as a result of phase changes are identified and discussed by Schmerr in Chap. 3.

In spite of advances in tomographic techniques and a tremendous increase in the volume of seismic data that has become available, accurate mapping of mantle structure is still mired by a number limiting factors including trade-off between seismic heterogeneities and topography of interfaces, separation of isotropic and anisotropic anomalies, finite-frequency effects, and details of wave propagation. In Chap. 4, Bodin and coauthors consider the trade-off that occurs between radial anisotropy and small-scale radial heterogeneities, and show how this problem might possibly be solved by adding high-frequency data.

In the lowermost mantle, tomographic models published since the 1990s show that the dominant structures are two large low shear-wave velocity provinces (LLSVPs), whose detailed nature is still debated. In the past decade, waveform modeling and travel-time data from specific seismic phases provided interesting details on LLSVPs structure. Besides LLSVPs, small-scale heterogeneities are also present in the deep mantle and may be detected using scattered seismic waves as shown by Rost and coauthors (Chap. 12).

Another challenge related to imaging the lower mantle is detection of the mineral post-perovskite (pPv), a high-pressure phase of perovskite (pv) discovered experimentally in 2004. Laboratory experiments and ab-initio calculations indicate that the stability field of pPv is likely to oscillate around the depth of the core-mantle-boundary because of local variations in temperature and composition. Therefore, pPv may only be present on local or regional scales, but is unlikely to make up a global layer at the bottom of the lower mantle. Seismology, however, has yet to identify such pPv-dominated regions unambiguously, although D'' figures as a prominent candidate. In Chap. 13, Cobden and coauthors review the different seismological data and techniques used to detect the pv-pPv phase transition, its properties, and discuss the seismic observations that point to its presence.

Seismic data and models are capable of imaging mantle heterogeneities, but can only provide clues about the nature of these heterogeneities. Interpreting seismic data and models in terms of variations in mantle composition, thermal state, phase transitions, water content, or a combination thereof, as sources of seismic heterogeneities, requires additional information. This missing information is supplied in the form of mineral physics data, which encompasses a wide range of data determined both experimentally or from first-principles (ab initio) numerical computations, including phase equilibria and stability regions of mantle minerals, sensitivities of thermodynamical, thermo-elastic properties, and transport properties of mantle rocks to changes in pressure, temperature, chemical composition, and water concentration. Data for most of the upper and lower mantle minerals are now available and gathered in thermodynamic databases that, when combined with equation-of-state modeling, allow us to construct elastic and transport properties (e.g., seismic wave-speeds, density, and electrical conductivity) in the mantle at pressure and temperature conditions spanning most of the mantle. In turn, these “synthetic” profiles can be compared to field-derived estimated and thereby provide a means of testing various hypotheses for the structure, constitution, and chemical make-up of Earth’s mantle.

As an illustration of this approach, Kawai and Tsuchiya (Chap. 8) use recent data determined from *ab initio* calculations to estimate the seismic signature of recycled granitic material in the mid-mantle (400–1200 km depth), and subsequently compare it to the seismic signature of other mantle materials as a means of assessing the possible origin of heterogeneities in the mid-mantle. In a related approach Khan and coauthors (Chap. 5) employ a free-energy minimization method to interpreting seismic surface-wave dispersion data for the thermochemical structure of the mantle beneath the Australian continent. The advantage of free-energy minimization methods is that profiles of physical properties (e.g., seismic wave-speeds and density) can be computed self-consistently as a function of temperature, pressure, and composition. This allows for joint interpretation of diverse geophysical, petrological, and mineral physics data sets as considered in the contribution of Khan and coauthors.

Interpretation of seismic observations in terms of mantle chemistry and thermal state is nonunique and notoriously difficult to separate. An illustration of this concerns the nature of LLSVPs observed in the deep mantle. Two hypotheses are

discussed in the present volume. The purely (or mostly) thermal origin scenario, which possibly involves the presence of the mineral pPv, is reviewed by Davies and coauthors in Chap. 14, while a different explanation for the LLSVPs is offered by Deschamps and coauthors (Chap. 15), who favour a thermochemical origin.

An alternative means of addressing mantle heterogeneity is to investigate transport properties such as electrical conductivity that, in principle, are more sensitive to parameters such as composition and temperature than is elasticity. The importance of electrical conductivity arises because of the strong dependence on temperature, major element composition, water content, partial melt, and oxygen fugacity. This is illustrated in Chap. 6, where Katsura and Yoshino consider variations in electric conductivity observed in the oceanic upper mantle to show that the high conductivity observed beneath mid-oceanic ridges could be caused by partial melting. The contribution by Khan and coauthors in Chap. 5 provides another example of using electrical conductivity to recover the thermo-chemical structure beneath Australia.

Geochemistry, like geophysics, has provided a wealth of data that bear on mantle heterogeneities, albeit at different scales. Important insights on the chemical and dynamical processes that rocks have undergone during their formation, and the physical conditions under which rocks have formed are obtained from analysis of rocks originating in the uppermost mantle. A good example of this approach is given in Chap. 7 by Ma and coauthors, where a suite of spongy clinopyroxene and melt-pockets from the Al Ghab volcanic field is investigated. Their analysis shows that compositional heterogeneities occurred at micro-scale, and suggests that the spongy clinopyroxene and melt pockets were formed as a result of decompressional melting most probably associated with the recent development of the pull-apart basin in this region. Several hints point to distinct reservoirs coexisting in the deeper mantle, including recycled oceanic crust and a source of undegassed material. In Chap. 11, Caro presents updated results for the Sm–Nd, Lu–Hf, and Rb–Sr systems suggesting that Earth accreted from non-chondritic material depleted in incompatible elements, and that pristine material may be preserved in the deep mantle up until now. Kaminski and Javoy also challenge the chondritic model of the Earth in Chap. 10 by proposing that Earth's mantle may have formed from enstatite chondrites. Combined with a two-stage formation scenario involving a giant impact, their compositional model result in a large-scale chemically heterogeneous deep mantle.

Finally, geodynamics is a key ingredient to understand the formation and evolution of mantle heterogeneities. Earth's mantle is continuously being stirred by convection, which is the dominant mechanism for heat and mass transport throughout the mantle. However, the detailed mode of mantle convection is still a matter of debate. In this context, it is unclear whether stirring induced by the flow is able to efficiently mix large-scale chemical heterogeneities with ambient mantle. Several parameters may influence mantle flow and its ability to mix (or non-mixing), including viscosity and density contrasts between heterogeneous regions and ambient mantle. One obvious source of chemical heterogeneity is the continuous recycling of oceanic crust through slab subduction. In Chap. 9, Ishikawa and coauthors

investigate the influence of the water content on slab subduction. Another possible source of heterogeneity, which may have survived until now, is early partial differentiation of the mantle. In Chap. 15, Deschamps and coauthors investigate the stability of an initial basal layer of dense material and identify important parameters controlling this stability. If, by contrast, convection is efficient enough to mix chemical heterogeneities, the mantle may appear isochemical at medium-to-large scales. As a result, mantle dynamics may be described by purely thermal models of convection, of which a few examples are discussed in Chap. 14 by Davies and coauthors.

This monograph is divided into two parts: Part I focuses on the upper mantle and transition zone, while Part II is dedicated to the lower mantle. As will become clear to the reader, many contributions collected in this monograph are based on multidisciplinary approaches, blending results from several fields. Since data, numerical modeling techniques, and analyses typically differ depending on the region addressed and on the scale of the heterogeneities investigated, it was deemed more appropriate to group contributions according to the part of the mantle being addressed rather than topically. In closing, we would like to acknowledge all of the people who contributed to the development and production of this volume. Above all, we would like to thank all the contributing authors for their participation. Without their efforts this volume would clearly not have been possible. We are also indebted to the numerous reviewers for their crucial assessment of the various contributions making up this volume. Finally, we would like to thank the editorial staff at Springer, in particular Naomi Portnoy and Elodie Tronche, who contributed to making this volume possible.

Amir Khan
Frédéric Deschamps