The Earth's Mantle

The Earth's mantle plays a crucial role in a variety of geologic processes and provides researchers important insights into the development of our planet. Interdisciplinary in scope, this book is a comprehensive overview of the composition, structure, and evolution of the mantle layer.

Written by internationally recognized scientists from the Research School of Earth Sciences at the Australian National University, and dedicated to the memory of A. E. ("Ted") Ringwood, this book draws on perspectives from cosmochemistry, isotope geochemistry, fluid dynamics and petrology, seismology and geodynamics, and mineral and rock physics.

The book begins with a discussion of the accretion and differentiation of the Earth, including the cosmochemical initial conditions, scenarios for core segregation, constraints on the age of the Earth, the dating of core formation, and the subsequent differentiation and outgassing responsible for both the continental crust and the atmosphere. It also reviews the evolution of the Earth, emphasizing the 'plate' and 'plume' modes of mantle convection. Finally, the book describes experimental constraints on magma genesis and the structure and physical properties of the modern mantle.

Striking a balance between matters of consensus and continuing controversy, *The Earth's Mantle* will provide researchers and graduate students with an authoritative review of this important part of our planet.

The Earth's Mantle

Composition, Structure, and Evolution

Edited by
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Dedication

Questions concerning the origin and evolution of the Earth have inevitably been of special significance to our species and accordingly have occupied the minds of many of our most influential thinkers. During the past four decades, phenomenal progress has been made towards answers to these fundamental questions, and the late Professor A. E. ("Ted") Ringwood was consistently at the forefront of this research. He participated in, and capitalized upon, the progressive development during this period of equipment now capable of reproducing in the laboratory the extreme conditions of pressure and temperature that prevail within the Earth's interior. He boldly exploited the opportunities offered by these technological developments to explore key aspects of the chemical behaviour of geological materials. Perhaps foremost amongst his achievements was the demonstration of the occurrence and importance of pressure-induced phase transformations. He combined such findings with insights emerging from increasingly detailed seismological probing of the internal structure of the Earth, as well as with the perspective offered by exploration of the solar system, in imaginative and compelling new models to describe the chemical composition, internal structure, origin, and evolution of our planet and its Moon. Preparation of a volume on *The Earth's Mantle: Structure, Composition, and Evolution*, written by his colleagues at the Australian National University (ANU), therefore seemed a fitting tribute to this brilliant earth scientist who will be long remembered for his many seminal contributions in this field of intellectual endeavour.

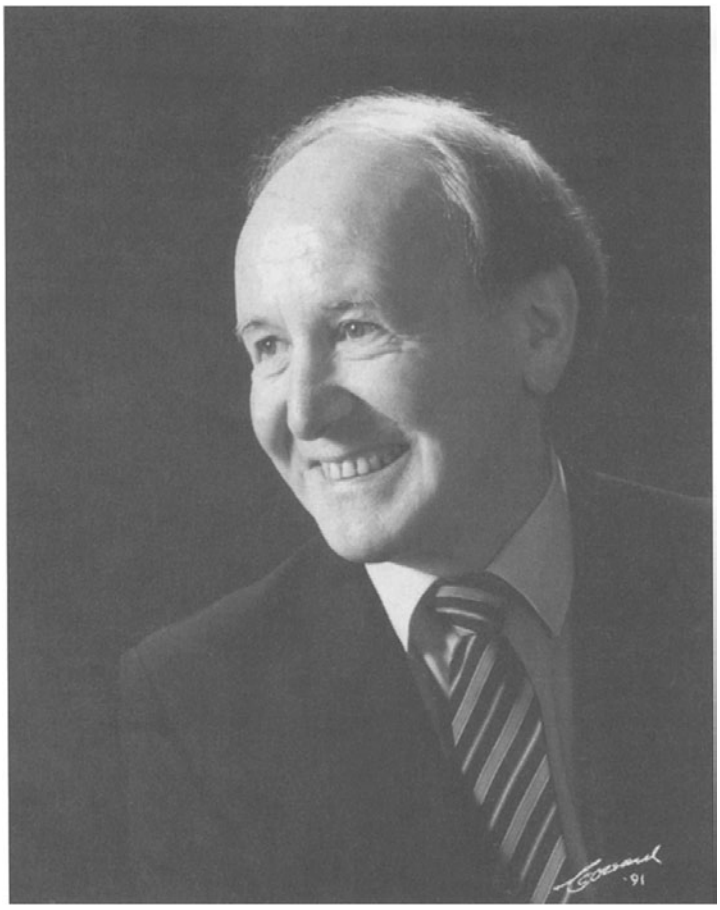
Ted Ringwood was born in Melbourne, Australia, in 1930 and was educated at the Geelong Grammar School and the University of Melbourne, graduating with his Ph.D. in 1956. He was amongst the first generation of distinguished Australian scientists to be educated to Ph.D. level within Australia. After a postdoctoral fellowship with Francis Birch at Harvard University, Ted joined the Department of Geophysics at the ANU as a Senior Research Fellow in 1959. His rapidly growing stature was recognized through his appointment in 1963 as Personal Professor, and in 1967 as Professor of Geochemistry, a position he filled with distinction until his premature death in 1993.

During the late 1960s and early 1970s, with the support of the late Professor J. C. Jaeger, then head of the Department of Geophysics and Geochemistry of the Research School of Physical Sciences at ANU, Ted Ringwood argued the ultimately successful case for the formation of a new Research School of Earth Sciences (RSES). The new school's mandate was to expand into carefully selected new areas such as geophysical fluid dynamics, ore genesis, and environmental geochemistry, all of which are now integral parts of the school's research activity. Ringwood also recognized and promoted opportunities for the enhancement of existing research activities, notably in mineral/rock physics and noble-gas geochemistry. Jaeger and Ringwood were responsible for the inspired appointment in 1973 of Professor A. L. Hales as foundation director of RSES. Ringwood himself later served a term (1978–83) as director of the school.

There was a close and instructive symbiosis between Ringwood's research into the chemical composition, origin, and evolution of the Earth and Moon and his applied-research interests. The same crystal-chemical principles and experimental methods that elucidate the high-pressure behaviour of silicate materials in the Earth's deep interior provided the basis for the Synroc strategy for safe immobilization of high-level nuclear wastes in a durable ceramic wasteform. He also patented procedures for the fabrication of new cutting-tool materials in the form of diamond- and boron-nitride-based composites.

The impact of Ringwood's research, as reported in more than 300 papers, two books, and several patents, has been recognized through frequent citation and many awards, including Fellowship of the Australian Academy of Science (1966), the American Geophysical Union (AGU) (1969), and the Royal Society of London (1972). He was a recipient of the Bowie Medal of the AGU (1974), the Day Medal of the Geological Society of America (1974), the Holmes Medal of the European Union of Geosciences (1985), the Wollaston Medal of the Geological Society of London (1988), the Feltrinelli Award of the Italian National Academy (1991), and the Hess Medal of the AGU (1993), amongst others.

Above all, Ted Ringwood will deservedly be remembered as a bold, original, and lateral thinker and an excellent communicator. He was a powerful, often irresistible, advocate for the causes to which he was committed, and a feisty debater. He was supportive of and loyal to those who worked closely with him, impatient with mediocrity, and intensely proud of his country and the life-style that it offers. It is with a real sense of loss that his colleagues in the Research School of Earth Sciences at the Australian National University dedicate this volume to his memory.



PHOTOGRAPH BY DAVID COWARD

A. E. ("Ted") Ringwood (1930–93)

Preface

It has been our goal in assembling this volume to produce an overview of the composition, structure, and evolution of the Earth's mantle that will be authoritative, up-to-date, and forward-looking, yet thoroughly readable. It is our hope that it will prove useful to all those interested in the Earth's mantle and its workings, from beginning graduate students to experienced researchers. The volume consists of 11 chapters contributed by the staff of the Research School of Earth Sciences at the Australian National University and their collaborators, arranged into three parts, as follows:

Accretion and Differentiation of the Earth
Dynamics and Evolution of the Earth's Mantle
Structure and Mechanical Behaviour of the Modern Mantle

Recent progress towards consensus on many of the major issues surrounding the composition, structure, and evolution of the Earth's mantle makes this volume particularly timely. This Preface is intended to provide the reader a brief connected account of the topics addressed in this volume, not necessarily in their order of appearance, and an indication of the general philosophy adopted in assembling the material.

It is now widely accepted that the planet Earth was accreted from a hierarchy of planetesimals that formed in our solar nebula over a range of radial distances from the Sun. Through studies of chondritic meteorites, which display uniform relative abundances of refractory elements and systematic depletions of volatile species, the bulk composition of the silicate Earth can be constrained, albeit within significant residual uncertainties, especially in the important Mg/Si/Al ratios. The abundances of the siderophile elements in the Earth's mantle differ markedly from those that would be expected on the basis of the metal–silicate distribution coefficients measured at low pressure. Thermodynamic equilibrium between the core and the mantle in a homogeneously accreted Earth would therefore be excluded, unless

the distribution coefficients should prove to have a particular pressure dependence. It is suggested in this volume that it is more likely that the Earth was formed by heterogeneous accretion. In this scenario, core formation began with the sequestering into the core of almost the entire siderophile-element inventory of the early, volumetrically dominant, highly reduced, strongly devolatilized component of the proto-Earth. This was followed by incorporation into the core of siderophile elements derived from a subsidiary, more oxidized, volatile-rich component. Following the completion of core formation, at about 4.5 billion years ago (4.5×10^9 years ago, or 4.5 Ga), a late-stage 'veneer' of chondritic material was added to the Earth's mantle.

Isotopic constraints indicate that another 200 million years probably elapsed before it became possible to preserve a continental crust enriched in light rare-earth elements (LREEs). It seems that part of the Earth's mantle was at least as LREE-depleted in the early Archaean (before 3.8 Ga) as are the source regions for modern mid-ocean-ridge basalts (MORBs) and that the continental crust probably has grown progressively, albeit episodically, through geological time, with recycling of continental crust back into the mantle playing a subsidiary role. Studies of the crust/mantle distribution of incompatible trace elements and of the Earth's inventory of radiogenic argon (^{40}Ar) suggest that about half of the Earth's mantle has been stripped of its incompatible and volatile elements. Studies of noble-gas isotopes (particularly Ne, Ar, and ^{129}Xe) indicate that much of the degassing to form the atmosphere must have occurred within the first few hundred million years of the Earth's history. A striking contrast between the correlated He and Ne isotopic ratios in MORB and ocean-island-basalt (OIB) source regions provides strong evidence of continuing outgassing from the OIB source region of a primordial (solar) noble-gas component.

Convection within the Earth's present-day mantle is also becoming increasingly well understood as the superposition of two main modes. The dominant plate-scale flow is driven mainly by the gravitational instability of the cold, stiff upper thermal boundary layer or lithosphere. Plumes represent the second, subsidiary mode of mantle convection, arising from instabilities in a bottom-heated lower thermal boundary layer. The dynamics of both the plate-scale and plume-related flows are becoming increasingly accessible to study through a combination of laboratory experiments and numerical modelling, although complete three-dimensional calculations, with realistic Rayleigh numbers and appropriate temperature- and depth-dependent rheologies that incorporate the complicating effects of phase transformations, melting, and chemical differentiation, remain to be performed.

Considerations of the relative magnitudes of mid-ocean-ridge topography and hotspot-swell topography suggest that plumes originate from the core–mantle boundary (CMB), rather than from another thermal boundary layer at the base of an upper mantle strongly heated from below. It has been argued that plume-head diameters comparable to those of continental flood-basalt provinces provide additional evidence of a CMB origin for mantle plumes. However, recent modelling

indicates that the highest temperatures may be strongly localized in the near-axial region of the uppermost layer of the plume head. Under these circumstances, an explanation of flood-basalt eruptions in terms of laterally extensive partial melting of plume heads seems to require a major-element chemistry for plumes that is substantially enriched relative to pyrolite – consistent with previous inferences from enriched trace-element signatures. Alternatively, a mechanism would be required that would allow ascent of plume-head material to shallower levels, especially within the continental lithosphere.

Increasingly detailed knowledge of the relevant phase equilibria and of the elastic properties of mantle minerals suggests that phase transformations in an isochemical (pyrolite) model mantle provide an adequate explanation for the seismologically well constrained radial structure, within the residual uncertainties in the temperature and pressure dependence of elastic (especially shear) moduli. Strong compositional layering, with its implication of an additional pair of thermal boundary layers in the mid-mantle, separating convection above and below, not only is not required but also would be difficult to reconcile with the radial velocity models. The superimposed large-scale lateral variability in wave speeds, as revealed by seismic tomography, is most pronounced in the outer few hundred kilometres of the mantle, where it is closely correlated with surface tectonics and probably is primarily of thermal origin. On smaller scales, compositional heterogeneity and anisotropy probably are more important. Tomographic studies suggest that most subducting lithospheric plates penetrate into the lower mantle, but not without significant distortion and deflection within the transition zone, plausibly explained by interactions with the viscosity structure of the mantle and by the effects of chemical layering within the down-going slab and the influence of trench migration.

The likelihood that the Clapeyron slopes for the phase transformations in the normative pyroxene-garnet component of the mantle are comparable in magnitude, but of opposite sign, to those for the relatively well understood olivine $\rightarrow$ wadsleyite and ringwoodite $\rightarrow$ perovskite + magnesiowüstite transformations suggests that transformational buoyancy probably does not strongly perturb the dominantly thermal convection of the mantle. Chemical buoyancy associated with the basaltic layer of subducting oceanic lithosphere and any such material ascending in plumes might be at least equally as important as transformational buoyancy; its effect would be to resist the descent of slabs, but to promote the ascent of plumes.

According to recent analyses of sea-level changes consequent upon deglaciation, the effective viscosity of the mantle increases about 30-fold with increasing depth, from a minimum value of about 3×10^{20} Pa · s in the upper mantle to 10^{22} Pa · s in the deep mantle. The rheology of the dominant upper-mantle mineral olivine is becoming increasingly well understood through detailed laboratory experimentation. Of particular interest is the possibility of a transition from dislocation creep to diffusion creep in lithospheric shear zones and deep in the upper mantle, and there is evidence for significant weakening produced by small amounts of melt or water. However, the weakening effects of small degrees of partial melting might

actually be more than offset by the hardening effects induced by strong partitioning of dissolved water-related defect species from olivine into the melt. There are also preliminary indications of the relative strengths of the key high-pressure minerals of the transition zone and lower mantle, and there have been some intriguing insights into transformation mechanisms and their consequences for the origin of deep-focus earthquakes. Microphysical rheological models for the deep mantle, based on extrapolation of experimentally determined flow laws for analogue materials, are most readily reconciled with those derived from analyses of glacial-rebound phenomena within a whole-mantle convection scenario in which there are no mid-mantle thermal boundary layers.

All of these inferences are consistent with a model of whole-mantle convection in which old cold slabs descend well into the lower mantle, though at speeds substantially less than those for the upper mantle, because of the higher viscosity. In this scenario, plumes rise from the thermal boundary layer at the base of the mantle, with narrow conduits or tails feeding large mushroom-shaped heads that grow by entrainment of surrounding mantle. The small relative motions of 'hotspots' require that their sources be located within a region of relatively high viscosity, most plausibly the very deep mantle. The inferred substantial increase in viscosity with depth in the Earth's mantle results in much longer circulation times, and less effective mixing, for material transported along streamlines penetrating deep into the lower mantle. Long residence times and ineffective mixing are necessary to explain the survival (on timescales of $\sim$2 billion years) of chemical and isotopic heterogeneity, including the observation that the degassing of primordial He and Ne and of radiogenic ^{40}Ar is far from complete.

This unifying view of the composition, structure, and dynamics of the modern mantle is a persistent theme throughout much of this volume. However, there remain substantial areas of uncertainty and controversy, which are also addressed. Some of the areas of residual uncertainty have already been mentioned in the preceding summary. One that is central to the admissibility or exclusion of the model of whole-mantle convection is the efficiency of mixing. The noble-gas data mentioned earlier and the evidence for the extraction into the continental crust of only about 50% of the Earth's budget of incompatible elements require the presence of a reservoir (or regions having a significant volume) that is essentially inaccessible to the processes of melt extraction and outgassing on timescales comparable to the age of the Earth. Strictly layered convection, in which the circulation patterns of the upper mantle and lower mantle would be separated by a pair of thermal boundary layers impermeable to matter, but conductive of heat, obviously would provide an effective mechanism for the chemical and isotopic isolation of the lower mantle. The upper mantle, with its substantially lower average viscosity and its direct participation in the processes of mid-ocean-ridge volcanism, would be both more homogeneous and much more depleted. However, strict layering is difficult to reconcile with the wide range of geophysical evidence summarized earlier. Nevertheless, it remains to be

demonstrated conclusively that whole-mantle convection in a mantle with depth-dependent viscosity is compatible with the survival of chemically and isotopically distinct materials for timescales on the order of 2 billion years.

Another issue of central importance for an understanding of the evolution of the Earth is the possibility that even if whole-mantle convection is currently operative, it may not always have been so. There may have been episodic layering of the mantle in the past, as well as involvement of the cool upper boundary layer of the early Earth in processes distinctly different from those of modern plate tectonics. The proportion of the basaltic layer within the differentiated lithosphere, as well as the equilibrium and kinetic controls on its successive transformations to denser assemblages, may be very influential in deciding the fate of oceanic lithosphere. These factors might be important in determining whether all or part of the lithosphere can sink into the mantle, how and where any such subduction is initiated, and whether or not subduction can be sustained through the transition zone and into the lower mantle.

Also presented here are the very different implications of two alternative views of magma genesis in mid-ocean-ridge, ocean-island, and flood-basalt settings. The advocates of one model consider that the parental magmas for MORBs are olivine tholeiites derived at relatively low pressure from passive upwelling and melt pooling along a ~1,300°C adiabat. The common presence of picrites in ocean-island settings could then be interpreted as evidence for the substantially higher potential temperatures expected of deep-seated plumes. The alternative view, that MORBs are generally derived from picritic precursors, is also argued in some detail in this volume. Under these circumstances, the potential temperature for the typical upper mantle would be much higher (~1,450°C), indistinguishable from that for hotspot magmatism. Hotspots would be attributed not to higher temperatures, but rather to melting that was fluxed by locally higher concentrations of volatiles, derived ultimately from old subducted lithosphere deep in the upper mantle.

The mixture of emerging consensus and continuing vigorous debate, represented by the contributions that follow, seems appropriate for a volume in honour of Ted Ringwood. Moreover, this blend faithfully represents a living science in which the prevailing hypotheses are subject to continual testing against new observations, followed by revision or replacement as appropriate.

Finally, I thank the following individuals outside the authorship group for their thoughtful reviews of the various chapters: Bill Compston, Steve Eggins, Oli Gudmundsson, Anton Hales, Sue Kesson, Mervyn Paterson, Malcolm Sambridge, John Stone, Geoff Taylor, Sharon Webb, and Greg Yaxley. The editorial assistance of Kay Provins, and the enthusiastic involvement of Catherine Flack from CUP, are greatly appreciated.

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