

THE EARTH
Its Origin, Structure
and Evolution

edited by M.W. Mc Elhinny

The Earth: Its Origin, Structure and Evolution

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M. W. McELHINNY

*Research School of Earth Sciences,
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Preface and Dedication

This volume was written to honour two outstanding scientists who have been responsible for the development of Earth Sciences at the Australian National University. John Conrad Jaeger became the foundation Professor of Geophysics in January 1952, and established the Department of Geophysics. Under his guidance, the Department expanded greatly and achieved a wide degree of international recognition in a remarkably short time, firstly in several fields of geophysics, and subsequently, in areas of geochemistry. Following Jaeger's retirement in December, 1972, the decision was reached to separate the Department from its parental Research School of Physical Sciences and establish a new, autonomous, and more broadly based Research School of Earth Sciences. Anton Hales was the first Director of the new School. Under his leadership, existing research activities were strengthened and new research groups established in geophysical fluid dynamics, economic geology and global geodynamics.

Jaeger and Hales were scientists of great distinction and breadth prior to joining the A.N.U. Despite their administrative responsibilities, their continuing ability to produce good science was an inspiration to their younger colleagues. These men possessed other qualities to a rare degree—deep concern and interest in the problems, both scientific and personal, of all their staff, creative leadership, unselfishness and also a degree of courage that enabled them to take difficult decisions, both within and outside the School, where necessary. It was this combination of human qualities and professional distinction that won the affection, loyalty and respect of all their colleagues, subordinates and students.

The book has been written exclusively by present and past members of the Faculty of the Research School of Earth Sciences and associates. The topics

cover aspects of the major research interests of the Research School in a way that enables them to be placed together in a volume about the Earth. Indeed in many respects the contents of this volume reflects the view of the Earth as seen from the A.N.U. and represents an overview of the developments planned and pursued by Jaeger and Hales. Starting from the beginning it is appropriate to discuss the origin of the Earth and its composition as seen from a geochemical standpoint. A chapter on the rotation of the Earth is followed by aspects relating to the core through to the crust in sequence. The various chapters demonstrate the successful merging of geophysics and geochemistry that has been one of the hallmarks of the Research School.

As Faculty members under Jaeger and Hales the authors are proud to present this volume in their honour. Writing about the science that has been carried out under their leadership is undoubtedly the sincerest compliment that can be paid to them. As editor I could not have asked for a more pleasant or easier task.

M. W. McElhinny

Canberra, June 1978.

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1. Composition and Origin of the Earth

A. E. RINGWOOD

Abstract

The composition and constitution of the mantle are reviewed in detail. The pyrolite chemical composition of the upper mantle is found to be applicable throughout the entire mantle when the effects of phase transformations on density and seismic velocity distributions are considered. The abundance patterns of major and minor elements in pyrolite provide key boundary conditions relating to the cosmochemical environment in which the Earth accreted. Compared to the primordial abundances, pyrolite is depleted in a wide range of volatile elements to degrees which are correlated with the volatilities of these elements in the solar nebula. The abundances of many siderophile elements (e.g. Ni, Co, Re, Au) in pyrolite are 10–1000 times higher than would be expected if pyrolite had ever equilibrated with a metallic iron phase which had subsequently sunk into the core. Likewise, pyrolite is much more oxidized than would be expected if it had accreted in equilibrium with metallic iron. The abundances of many crystallographically compatible elements (e.g. Mg, Fe, Ni, Co, Mn, Zn) appear to display remarkably low dispersions in mantle rocks. These elements display extremely diverse degrees of volatile, involatile and siderophile behaviour in the cosmochemical environment of the solar nebula. The uniformity of these distributions within the mantle implies that accretion was accompanied by, or preceded by, a very efficient mixing process, and also that the mantle was not extensively melted and differentiated during accretion.

Although the core is mainly composed of iron, its anomalously low density requires the presence of 5–15 per cent of a light element in solution. If the light element is sulphur, it would imply that the Earth accreted about half of the primordial abundance of this extremely volatile element, whilst at the same time becoming much more strongly depleted in a wide range of elements which are much less volatile than sulphur. This appears highly improbable and we conclude that sulphur is not the principal light element in the core. Calculations based upon experimental data show that large quantities of FeO would dissolve in molten iron under the P, T conditions prevailing in the core. It seems most likely that the anomalously low density of the core is caused by the presence of about 10 per cent of oxygen.

The bulk composition of the Earth is estimated from inferred compositions of mantle plus core. It is found that the relative abundances of major elements, Mg, Fe, Si, Ca and Al, in the Earth are similar to the primordial relative abundances of these elements in Type 1 carbonaceous chondrites. There is no evidence which requires that significant degrees of fractionation of metallic iron from silicates, or of high-temperature condensates (CaO, Al_2O_3) from intermediate-temperature condensates (MgO, Fe) occurred during the formation of the Earth. It appears that formation of the Earth was a more simple cosmochemical process than is proposed by many current theories.

The origin of the Earth is discussed in the light of the boundary conditions obtained from its present composition. A wide range of geochemical evidence is found to contradict hypotheses involving heterogeneous accretion. The composition of the Earth can be explained satisfactorily if it accreted homogeneously from a mixture of 15 per cent of low-temperature solar nebula condensate similar in composition to Type 1 carbonaceous chondrites, and 85 per cent of a high temperature, devolatilized, metal-rich condensate. The entry of ferrous oxide into solution in the core combined with disproportionation of Fe^{2+} into $\text{Fe}^{3+} + \text{Fe}^0$ deep in the Earth's interior causes a large increase in oxygen fugacity of the mantle-core system. This may be responsible for the high abundances of siderophile elements and the high oxidation state of the mantle. The bulk composition of the Earth including its depletions in volatile elements can be readily interpreted in terms of accretion from planetesimals which became chemically isolated from the solar nebula over a wide range of temperatures in an environment somewhat resembling that of a modern infra-red cocoon protostar.

1. Introduction

The last thirty years has witnessed an enormous advance in our knowledge of the composition and constitution of the Earth's interior. It is now possible to provide reasonable estimates of the chemical and mineralogical composition of the mantle and to place constraints upon the extent of possible chemical zoning. Corresponding advances have been made in our understanding of the structure and composition of the Earth's core. As a result of these developments, many new and important boundary conditions for the origin of the Earth have emerged. I do not believe that these boundary conditions, mainly of a geochemical nature, have been adequately recognized in many recent discussions of the origin of terrestrial planets in general and of the Earth in particular.

This paper will present an outline of current knowledge relating to the internal composition and constitution of the Earth, with particular emphasis upon key properties which are relevant to its origin. We will then discuss the bearing of these properties upon theories of origin of the Earth.

Because of the complexity of the subject, it is not possible, in a review of this length, to provide complete documentation and references for many of the conclusions stated. For further detailed discussion of matters related to

the composition and structure of the mantle, the reader is referred to my book (Ringwood, 1975). The composition of the core is considered in a recent detailed paper (Ringwood, 1977). Finally, the entire subject matter covered in this paper is treated more exhaustively in another paper now in press (Ringwood, 1978).

2. Constitution of the Mantle

The *crust* represents the product of extremely complex and efficient differentiation processes acting over geologic time, which have concentrated a large portion of the Earth's inventory of certain key incompatible elements (e.g. U, Ba, La) into this thin surficial region. Since we are primarily interested in the geochemical properties of the mantle in its primitive state, before being affected by the differentiation processes which formed the crust, detailed discussion of the properties of the crust is not necessary.

We will be concerned chiefly with the mantle, representing about 68 per cent of the mass of the Earth, and the core, about 32 per cent. The principal physical information on the structure of the mantle and core is given by the variation of seismic P- and S-wave velocities with depth (Fig. 1). These provide the basis for subdividing the Earth's interior into a series of layers (Fig. 2).

2.1. The Upper Mantle

The upper mantle extends from the Moho to a depth of 300–400 km (Figs 1, 2). It is characterized generally by rather low P- and S-wave velocity–depth gradients, except perhaps in the vicinity of the low-velocity zone, and by the existence of pronounced lateral variations in velocity distributions. In most regions of the Earth, the S-wave velocity and possible the P-wave velocity pass through a minimum between depths of about 70–150 km. This minimum may be caused by the occurrence of a small degree (~ 1 per cent) of partial melting along grain boundaries in this region. It is of considerable importance as a zone of low “viscosity” and tectonic decoupling of the overlying rigid lithosphere from underlying more mobile asthenosphere regions of the mantle.

The P-wave velocity of most regions of the uppermost mantle beneath both continents and oceans is in the range $8.2 \pm 0.2 \text{ km s}^{-1}$. This property, together with certain broad petrological and chemical limitations, effectively restricts the mineralogical composition of this region to some combination of olivine, pyroxene(s) and garnet. The principal rock types carrying these minerals are peridotite (olivine–pyroxene) and eclogite (pyroxene–garnet). Complete mineralogical transitions between these two rock types are rare.

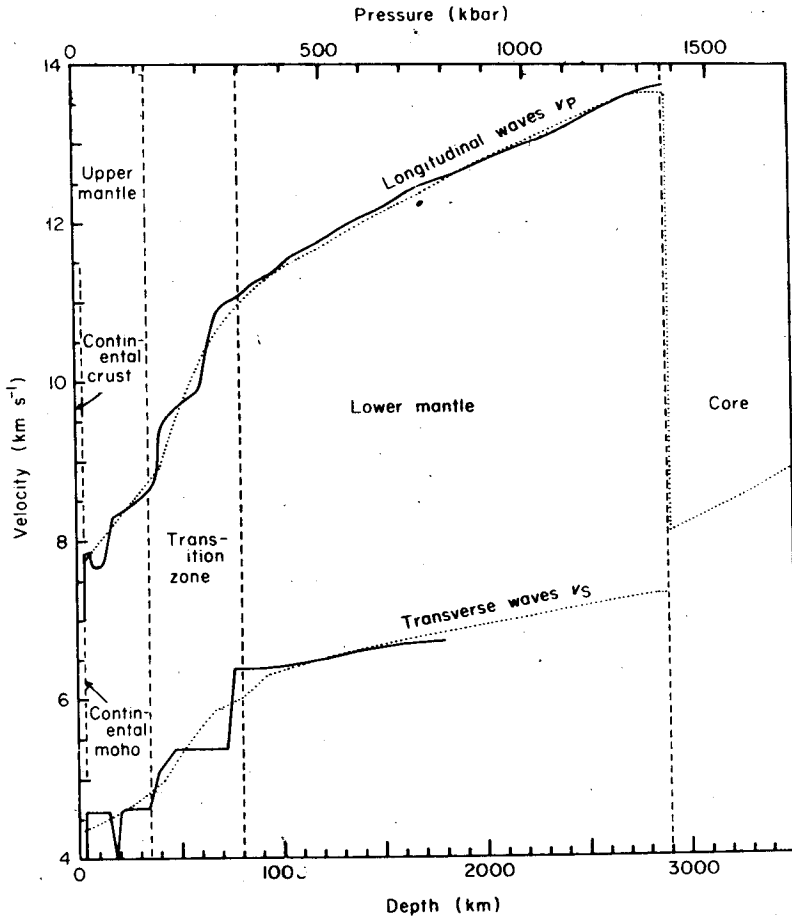


Fig. 1. Variation of seismic P- and S-wave velocities throughout mantle and outermost core. P-waves: solid line, Johnson (1967, 1969). S-waves: solid line, Nuttli (1969); dotted lines, Jeffreys (1939).

A wide range of evidence, reviewed by Ringwood (1975), shows that the uppermost mantle or lithosphere is dominantly composed of peridotite, with eclogite widely distributed as local segregations but relatively small in total amount. The vast majority of naturally occurring peridotites are strongly depleted in low-melting point components, so that they are unable to produce basaltic magmas when partially melted. On the other hand, we know that magmas of the basaltic suite have been erupted in copious volumes throughout geological time at localities scattered all over the Earth's surface, both continental and oceanic. It appears, therefore, that

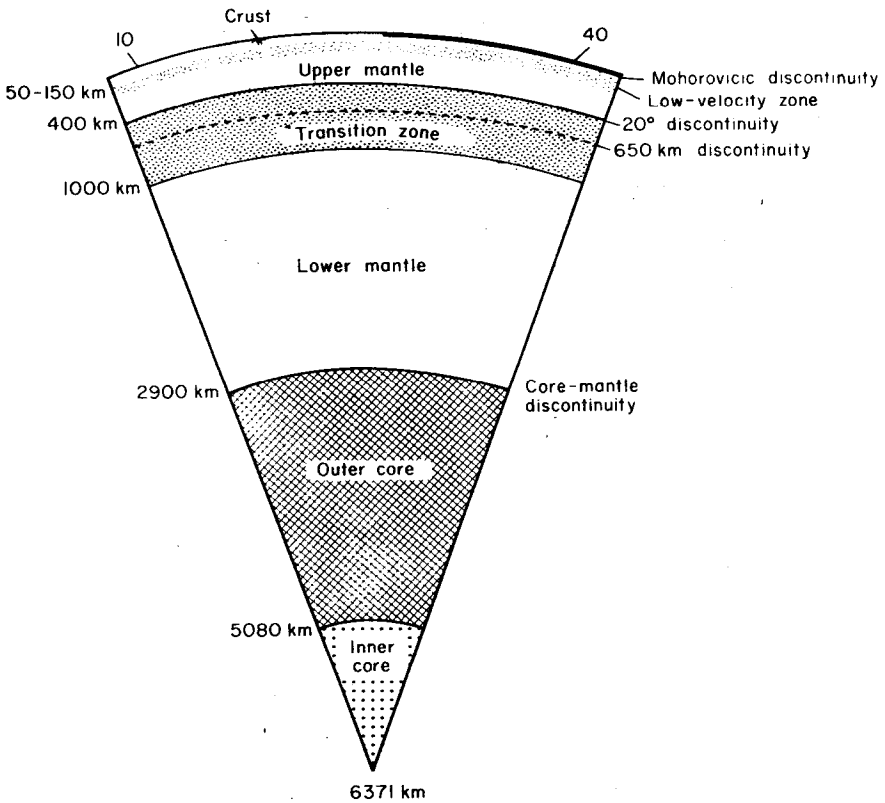


Fig. 2. Principal internal subdivisions of the Earth.

beneath the refractory peridotite layer there must exist a more primitive source region from which basaltic magmas have not been extracted. This primitive source material has been denoted by the term "pyrolite", implying a non-specific pyroxene-olivine rock, capable of yielding basaltic magmas on partial melting. Peridotite is interpreted to represent the refractory residue remaining behind after the basaltic magma has been removed. We thus arrive at a chemically zoned model for the upper mantle, as indicated in Fig. 3. Material of pyrolite composition is believed to be the dominant constituent of the upper mantle (Ringwood, 1975).

In a general sense, the composition of pyrolite must lie between those of basalt and peridotite. This composition may be obtained from the study of chemical equilibria between the various classes of basaltic magmas and their respective peridotitic residues, using the techniques of experimental petrology at high pressures and temperatures. This approach is combined