THE EARTH'S INNER CORE

Revealed by Observational Seismology

The inner core is a planet within a planet: a hot sphere with a mass of 100 quintillion tons of iron and nickel that lies more than 5000 km beneath our feet. It plays a crucial role in driving outer core fluid motion and the geodynamo, which generates the Earth's magnetic field. This book is the first to provide a comprehensive review of past and contemporary research on the Earth's inner core from a seismological perspective. Chapters cover the collection, processing, and interpretation of seismological data, as well as our current knowledge of the structure, anisotropy, attenuation, rotational dynamics, and boundary of the inner core. Reviewing the latest research and suggesting new seismological techniques and future avenues, it is an essential resource for both seismologists and non-seismologists interested in this fascinating field of research. With electronic supplements, including inner core-sensitive datasets and 3D visualisations, it will also form a useful resource for courses in seismology and deep Earth processes.

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Preface

> "Every day is a journey, and the journey itself is a home."
>
> Matsuo Bashō, *Narrow Road to the Interior* (Bashō, 1694)

In Jules Verne's novel, *Journey to the Centre of the Earth* (Verne, 1864), a forest of giant mushrooms grows on the shores of a large subterranean sea, ichthyosaurs and plesiosaurs clash for survival in its murky waters, and the heavy strata of the atmosphere permeates the gigantic cavern that must have somehow collapsed inwards from the surface. One and a half centuries later, our imagination for the deepest of the depths does not cease to exist and 'the people of perpendiculars',[1] like Professor Lindenbrock from Verne's novel, whose only wish is to slide down the Earth's radius, are luckily still among us. Verne's phantasmagorical landscapes, however, get washed away by the scientific rigour of the deep Earth images that emerge from seismological studies. This is not to say that the Earth's centre in our contemporary view is featureless. Quite to the contrary, the inner core is a planet within a planet: a hot sphere with a mass of one hundred quintillion tons of iron and nickel that lies about 5150 kilometres beneath our feet, still waiting to be 'discovered'. Its surface seems to be rough and mushy in places, and its interior deformed by internal stresses. It might contain heterogeneity at various scales, and host another smaller shell more elusive to our seismological probes. Despite its small volume (less than 1 per cent of the Earth's volume), the Earth's inner core contains about 10 per cent of the total magnetic field energy. It plays a crucial role in outer core fluid motions and the geodynamo, which generates the Earth's magnetic field. Without the magnetic field, life on Earth would be impossible. Embedded in the liquid outer core with a strong magnetic field and exposed to large gravitational pulling from the surrounding mantle, it spins faster than the mantle, and, at times, it slows down. But how do we know all this?

[1] The term used by William Butcher to refer to Jules Verne himself, in an introduction to *Journey to the Centre of the Earth*, Oxford University Press, 1992.

This book attempts to answer that question as it skips a significant part of 'the journey' and arrives by means of seismic waves at our destination – the inner core – right from the start. As seismic waves produced by earthquakes, explosions, and other natural phenomena reverberate through the solid Earth, they are reflected or scattered from discontinuities within and between the crust, mantle, and inner and outer core. Changes in the composition and temperature of Earth's minerals cause the waves to change their speed, bend, and even reverse their paths, all of which is manifested in recorded seismograms. The waves that traverse the inner core are thus the only direct probe available, and they become a subject of study.

Due to the exponential growth of geophysical data in recent years, it has become possible to image the Earth's deep interior, albeit not quite to the level of detail obtained for structure near the Earth's surface. Seismological observations have been the pivotal points for major advances in our understanding of the deepest Earth structure, which more often lead than follow geodynamical predictions. Indeed, global observational seismology is a powerful tool that serves as an inverted telescope with which we can probe the deepest parts of the Earth's interior, including the inner core. However, probing the inner core with seismic waves is similar to looking at a distant object in the universe through an imperfect lens that distorts the image. Imperfect knowledge of the rest of the Earth's layers is projected to the centre as a challenge that will be overcome only by innovative ideas and methods, some of which are presented in this book. Indeed, most seismologists would confirm that we are still in a discovery rather than mapping stage in our pursuit of understanding the deep Earth. This makes studying the Earth's inner core a fascinating subject.

Despite the fact that seismology leads the observational efforts, major advances in our understanding of the Earth's inner core would have not been possible without combining seismological observations with the results from geodynamics, magnetohydrodynamic modelling, mineral physics, and mathematical geophysics. However, interactions between researchers from different disciplines are often limited to special sessions on the Earth's core at international meetings and conferences. The geophysical values derived from seismological analyses (e.g. the inner core to outer core density ratio, the strength of anisotropy in the inner core, or the amount of differential rotation with respect to the mantle) are often utilised in geodynamical considerations or modelling without sufficient scrutiny and clear understanding of how these quantities were derived. This is in part because the inner core is buried deep below our feet and is difficult to scrutinise due to a lack of experimentally controlled conditions. It is also because of the level of specialisation required and a perceived lack of data visibility. Despite the importance of the subject, the communication among various groups of researchers still remains relatively undeveloped. We live in times when science can no longer thrive when fragmented into a large number of sub-disciplines. Studies of the Earth's inner core are no exception. Hence, there is a need more than ever for specialists from various disciplines to collaborate and share seismological data in our common quest to elucidate Earth's inner core.

Understanding inner core structure and dynamics, including energy exchange across the liquid core boundaries, helps Earth and Planetary Scientists to better understand planetary formation, the workings of the Earth's magnetic field, and the age of the inner core, the time capsule to understanding Earth's past, present, and future. During the past several decades, our understanding of the inner core's internal structure and dynamics has completely changed owing to modern observational seismology and the expansion of worldwide seismographic stations. Yet, there are no contemporary monographs available that place emphasis on the Earth's inner core from a seismological perspective. The *AGU Geodynamics Series on Earth's Core, Dynamics, Structure, Rotation*, vol. 31, published 14 years ago, is a collection of review papers on the subject, but they focus on selected aspects of the Earth's core, and therefore, a connection among the presented material is difficult to establish. A number of major advances have been made since its publication. Some basic facts about the inner core are present in a number of seismological books at various levels, but the inner core has never been presented as a stand-alone subject in spite of its importance and great interest among students.

My intention has been to look at the Earth's inner core from the perspective of an observational seismologist and present the methods and seismological data that have been used to determine its structure and dynamics. This hopefully provides a useful account on how seismology is used as a tool to probe a specific part of the Earth's interior, its inner core, to both a seismological and a non-seismological readership. The book thus might serve as a supplementary text to general geophysics or seismology books in various graduate or advanced undergraduate courses.

There was occasionally a need to present the basic physical and mathematical principles guiding seismologists in their observation and interpretation of physical properties and dynamics of the Earth's inner core despite the existence of more specialised books on seismology. Most mathematics is moved to appendices to allow a smoother presentation in the main part of the book, and most of it is limited to the derivation of main principles used heavily in the papers on the inner core not yet derived elsewhere. I attempted to give a comprehensive review of all data and observations that have played a significant role in shaping contemporary conceptual frameworks about the inner core. Some of these datasets are included in electronic form as supplementary material to the book.

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More Information

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