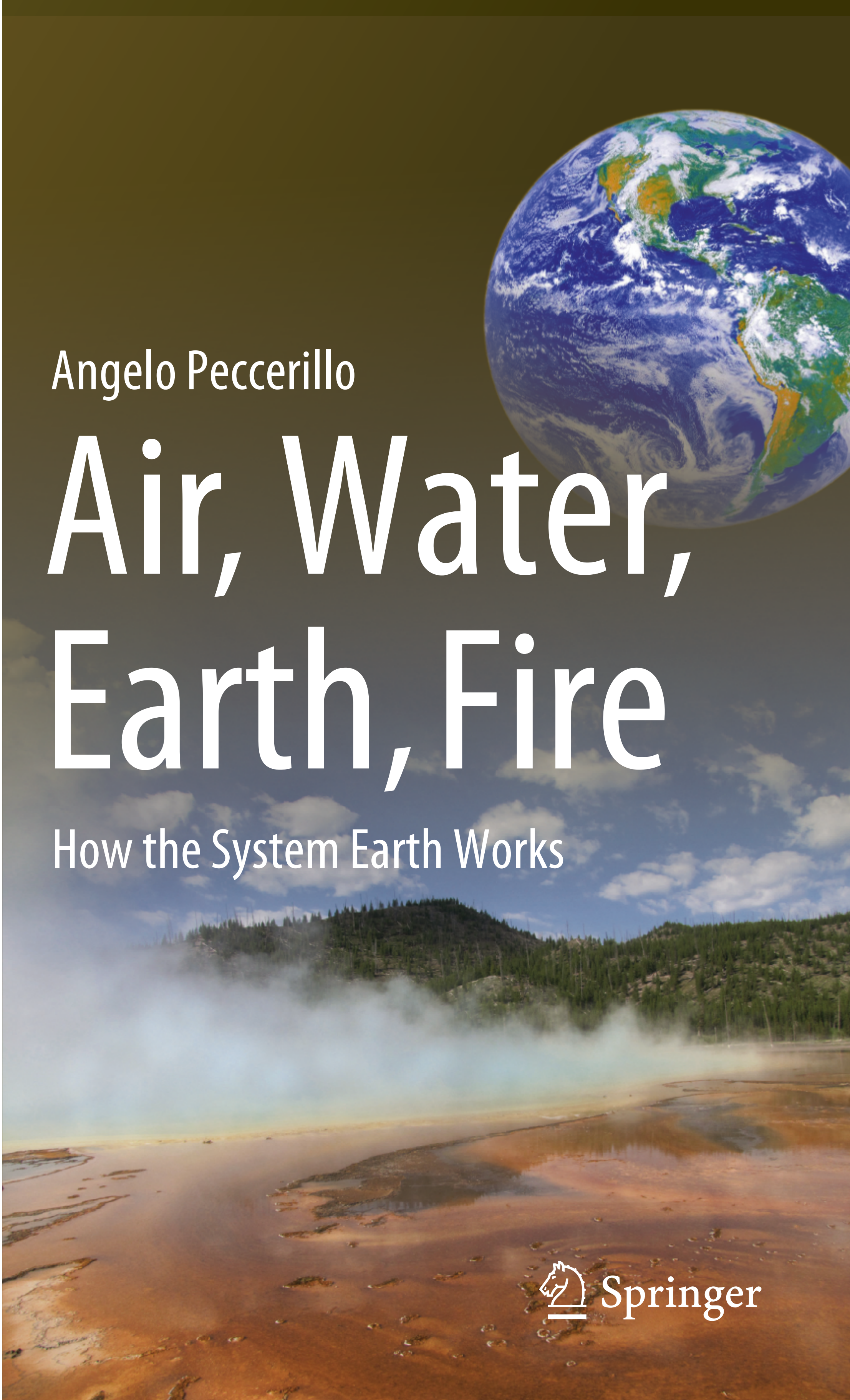

Angelo Peccerillo

Air, Water, Earth, Fire

How the System Earth Works

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Preface

From time to time, it happens that scientific discoveries go beyond the restricted circle of discipline specialists, being widely disseminated through the mass media. The news of science most frequently reported by the press and television generally deal with medicine, biology, and physics, particularly astronomy. By contrast, discoveries in the Earth Sciences rarely attract media attention, although they involve natural phenomena that directly impact the environment.

Recently, a team of British and Italian researchers demonstrated a temporal relationship between some crucial changes of life on Earth and intense modifications in the strength of the geomagnetic field. Geomagnetism provides protection to living organisms against the solar wind. The occurrence of a strong magnetic field enveloping our planet has allowed the development of the first microorganisms and might also have facilitated the so-called *Cambrian explosion*, i.e. the rapid diversification of multicellular animal life that occurred around the beginning of the Cambrian period at about 540 million years ago. In short, without the presence of an intense magnetic field, life on Earth would not exist.

One might expect that such important news would find adequate space in the public media; however, this was not the case, at least in Italy. As a result, most people ignore the paramount role of the geomagnetic field for the birth, evolution and survival of all organisms living on Earth, including the human species.

The same fate has befallen many other geological topics, including the long-running dispute about the increase of CO_2 in the Earth's atmosphere over the last century, a geological process of primary significance that, although much considered in the media, is rarely framed in its proper scientific context, that is, within the framework of the global geochemical cycle of carbon.

These and many other considerations have led me to conclude that the spread of scientific education does not value much the geosciences, a group of disciplines that investigate many crucial topics such as the chemical-physical characteristics, dynamics, and evolution of the Earth, and their role in constructing an external environment suitable for complex life, a unique case in the universe—as far as we presently know. Typically, geological phenomena are worthy of media attention only during natural disasters such as earthquakes, tsunamis, and volcanic eruptions.

In contrast with the dominant trend, I decided to write this book about the basics of geology, illustrating without pretension of completeness and originality some of the main geological processes that have shaped our planet, making it friendly for complex life. These notions are the standard cultural background of geologists, but I have reason to believe they are little known, if not wholly unknown, across the public at large. Therefore, this book aims at giving some basic scientific information on how our planet works, something that should belong to the cultural background of any conscious individual, in the author's opinion. Geologists will not find much interesting in the book, except perhaps the attempt to frame the most disparate of geological processes in a holistic context, and the particular perspective with which the various topics are addressed, sensibly oriented towards geochemistry.

Giuseppe Tomasi di Lampedusa (1896–1957), a highly regarded novelist from Sicily, stated:

> *Writing his memories and experiences at a certain age should be a duty imposed by the State to everyone. The material that would accumulate after three or four generations would be invaluable: many psychological and historical problems that beset humanity would be solved. There are no memories, although written by common people, which do not contain first-order values.*

If this is true for the personal experiences of ordinary people, the same should apply, and perhaps even more so, to scientists. Therefore, the great Sicilian novelist can be paraphrased by saying that if every scientist decides to write his experiences to transmit discoveries and illustrate what he understood about his science, then the spread of scientific culture would receive a decisive impetus.

This book consists of nine chapters and an Epilogue. The first three chapters provide the foundation by presenting the structure of the Earth, and by describing the sedimentary and magmatic processes that respectively operate at the surface and inside our planet. Chapters 4 and 5 focus on the physics of the Earth system, in particular on geomagnetism and seismicity. Chapters 6– 8 synthesise the information from the previous chapters to present the plate tectonics theory and the global geochemical cycles, exploring their impact on the external environment and life. Chapter 9 reviews the history of Earth from its formation in the solar nebula to the present time. The Epilogue contains a few informal philosophical-scientific considerations about the unique nature of our planet and discusses how knowledge and thinking of the geological past can lead us to make sound choices in the future. A geological time scale aimed at guiding the reader through the Earth's deep time is reported at the end of the book.

A complete reading of the book, from beginning to end, provides a full picture of how our planet works. However, the various chapters are organised to be read in isolation and not necessarily in sequence. This choice requires repetition, which makes the text redundant at times. Moreover, since "*life is short and great is the prolixity of the world*" (Josè Saramago), I thought it appropriate to add a summary at the end of each chapter. A preliminary reading of the summaries may help get an overview of the book, a first step in reading individual chapters. Detailed information boxes are added at the end of all chapters to go somewhat deeper into some key topics. These are not indispensable in understanding the essence of geological processes, but are intended to satisfy the curiosity of those who want to know more about specific subjects. Although the presentation is general in nature, various references to specialist publications are reported as footnotes to guide those who wish to investigate particular concepts in detail. Suggestions for further reading are reported at the end of the book.

A necessary price to pay for using a popular scientific approach and language is to lower the rigour of the discussion, leave out many important details, and insert elements that may appear purely ornamental. The following pages do not escape this rule, although I have done my best to make the tribute to simplification minimal, at least from the standpoint of scientific accuracy.

I express my deepest thanks to the colleagues and friends Russell S. Harmon and Carlo Bartolini for the critical reading of the manuscript and for suggestions and corrections.

I dedicate this work to my grandson, Alessandro Leonardo. It will be up to his generation to face the consequences on the environment of our choices and behaviours.

Firenze, Italy
Angelo Peccerillo

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About the Author

Angelo Peccerillo graduated in Geology cum laude, has been full professor of Petrology at the Universities of Messina, Cosenza and Perugia, where it has been teaching courses of Igneous petrology, Volcanology and Geochemistry (retired 2013). He has been editor or member of the editorial board of several international and national journals such as the European Journal of Mineralogy, Lithos, Journal of Volcanology and Geothermal Research, Open Mineralogy Journal, Journal of Virtual Explorer, and Journal of the Italian Geological Society. He has been topic editor, for Igneous and Metamorphic Petrology, of the Encyclopedia of Life Support System (EOLSS) printed by UNESCO. His scientific research has been focused on petrology, geochemistry and geodynamic significance of igneous processes and their role in the evolution of the Earth. For his activity he has been awarded the Feltrinelli Medal by the Accademia Nazionale dei Lincei, Rome, for the year 2006. He is author or co-author of some 250 scientific papers, mostly published on peer review international journals, several popular and didactic publications and scientific books, published with both national and international printers. He is Member of Academia Europaea and Honorary Member of the Geological Society of Italy.

1

The World Hidden Beneath Us—Structure and Composition of the Earth

Imagine there's no heaven
No hell below us
Above us only sky.
John Lennon - Imagine (1971)

1.1 Introduction

Elementa dum quattuor sunt: *aer, aqua, tellus, ignis*[1]: this is the aphorism with which scholars summarised the composition of the world, until a few centuries ago. Today, we know that the number of naturally occurring chemical elements is much higher; even so, this simplistic idea of ancient naturalists is still valid when applied to the Earth system as a whole.

The Earth can be viewed as consisting of four fundamental "ingredients" or spheres: the atmosphere (*aer*), hydrosphere (*aqua*), rocks and soil (*tellus*), and hot liquid materials such as magmas (*ignis*). However, the sphere of fire is not located between the Terrestrial Paradise and the Sky of the Moon, as envisioned by the Medieval cosmology, but is instead seated deep inside the Earth and gives continuous proof of its existence through volcanic activity.

While much is known about the atmosphere and hydrosphere (the so-called **fluid Earth**), the interior of the planet has been, and largely remains,

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[1] Elements then are four: air, water, earth, fire.

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unknown. Its inaccessibility has given rise to myths and phobias throughout the ages, from the Hades of Greek mythology and the Medieval Christian hell to the world of the Cimmerians and the mysterious realm of Agartha. For a long time, the dominant idea of a “Hollow Earth” thoroughly crossed by underground voids through which an internal fire rushed about in interconnected channels, was popular among ordinary folk, scientists and poets, as indicated in the writings of the Greek Homer, the Roman Pliny the Elder, Martianus Capella in the fifth century, Athanasius Kircher in the 17th and Jean-André Deluc in the eighteenth century, and into the early nineteenth century as postulated in Sir Humphrey Davy’s model of volcanism.

Studies conducted in the last century got rid of these ideas by demonstrating that the body of the Earth is made up entirely of closely packed and compact rocks and liquids subjected to high pressure and temperature, progressively increasing with depth. The planet is stratified according to physical and chemical properties, especially density, and each layer or shell has its unique features. Such a structure is the outcome of a combination of geological processes, which have affected the Earth since its birth about 4.5 billion years ago, and are still going on today.

The various layers are not steady and isolated from each other, but rather move and continuously exchange matter and energy, making the Earth an active and continually evolving planet. Underground cavities and rivers do exist, but they only occur in certain rocks near the surface: a scientific revolution that has radically changed the view of the world hidden beneath us.

Knowledge of the interior of the Earth is a prerequisite for understanding geological processes. Since a large part of the Earth is formed of rocks (the so-called **solid Earth**), which, in turn, are composed of minerals, it is also necessary to have essential information on these crucial natural objects, which is summarised in Box 1.1.

The present structure of the Earth is the outcome of a countless number of events that have been going on for billions of years, from the aggregation of the planet about 4,600 million years ago to the present. Such a long history has been subdivided into various intervals on the basis of key geological events and their time of occurrence. The sequence of chronological units and subunits are grouped in the Geological Time Scale. A simplified version is reported at the end of the book and discussed in Chap. 9.

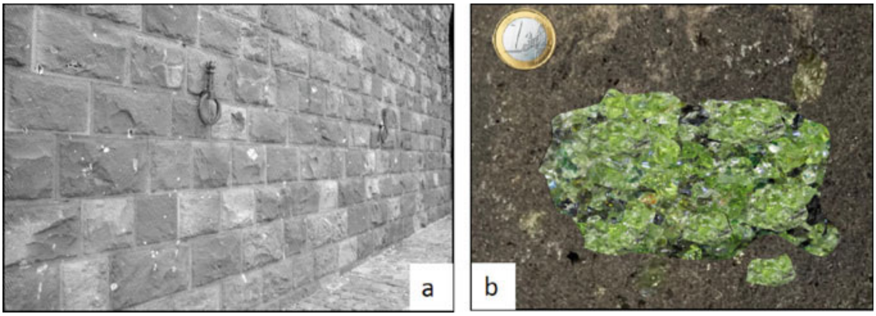

Fig. 1.1 **a** Xenoliths in volcanic rock at Torre Alfina, Province of Viterbo, Central Italy. Xenoliths are visible on the castle walls built with volcanic rocks quarried from a local eruptive centre. The xenoliths of Torre Alfina include a wide variety of rock types, such as peridotite, shales, schists, sandstones, limestone, and marls that represent samples torn out from the subsurface by rapidly ascending magmas; **b** Peridotite xenolith enclosed in a basalt

1.2 Xenoliths, Meteorites, Earthquakes: Witnesses of the Underground World

Most of the information on the structure and composition of the Earth's interior comes from studies of rocks and meteorites, and from the behaviour of the seismic waves that propagate through the planet during earthquakes. Direct observation of rocks is only possible for materials cropping out at the surface or residing at shallow depths where they can be accessed by mining, tunnelling, or drilling.[2] There is, however, a natural process that picks up rocks from the interior of the Earth and takes them to the surface, allowing us to obtain direct knowledge into deep regions that would otherwise be inaccessible. This "service", so to speak, is provided by a particular type of magma that originates at depths of 100–200 km and rises quickly to the eruption sites, tearing away and bringing to the surface fragments of rocks encountered during the ascent. These fragments are called **xenoliths** (from the Greek words ξένος λίθος, xénos lithos = foreign rock) and are easily distinguished from the host volcanic rock because of their contrasting colour and texture. Examples are reported in Fig. 1.1.

A particularly relevant class of xenoliths is called **peridotite**. This is a beautiful green crystalline rock (Fig. 1.1b), consisting of transparent green-coloured olivine crystals (or peridot), plus deep-green pyroxene and minor amounts of other minerals, mainly colourless plagioclase, black spinel

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[2] The Kola Superdeep Borehole in the Kola Peninsula of Russia is the deepest yet hole made into the Earth's crust. It reached 12.2 km, which is only one third of the average thickness of the Earth's crust.

($MgAl_2O_4$) or red garnet [$Mg_3Al_2(SiO_4)_3$], and sometimes diamond (see Box 1.1). These latter four minerals are stable, i.e. they can crystallise and remain unmodified, within rather narrow pressure ranges. Plagioclase is stable at pressures below one gigapascal[3] ($P < 1$ GPa); spinel occurs between 1 and 2 GPa; garnet and diamond are stable at higher pressures. Considering that pressure inside the Earth increases with depths by about 0.1 GPa (1 kbar) every 3.3–3.5 km due to the weight of the overlying rocks (**lithostatic** or **load pressure**), it is easy to deduce that xenoliths containing plagioclase come from depths ranging from a few metres down to 35 km, those with spinel come from 35–70 km, and those with garnet and diamond from even greater depths. More accurate information on the source of xenoliths can be obtained by detailed chemical and structural studies of individual minerals; but this is a specialists' subject well beyond the scope of this book.

The numerous studies carried out on xenoliths from various volcanoes around the world have shown that they mostly come from relatively shallow depths, with a maximum of 100–200 km. Xenoliths are, therefore, messengers that bring information about the outermost shells of the Earth.

Further evidence on the composition and structure of the Earth's interior is provided by **meteorites**. These are extra-terrestrial bodies that range from metallic (Fe–Ni) to silicate or mixed (metals plus silicates) in character. Some meteorites represent fragments of planets similar to the Earth that disintegrated due to collisions during the early life stages of the solar system. Their study tells us much about the internal structure and compositions of these ancient bodies and, thereby, also of our planet. Evidence from meteorites is somewhat elusive, yet it is critical for placing constraints on Earth composition, as it will be discussed soon.

The third important source of knowledge comes from geophysics, particularly from the study of seismic waves that cross the Earth during earthquakes. Seismicity will be reviewed in Chap. 5. For the scope of the present discussion, it is enough to know that earthquakes occur when rocks undergo a sudden fracturing under the effect of stress. Like any rigid body that breaks, rocks emit vibrations or **seismic waves**, which originate at the focal point or **hypocentre**, propagate quickly in all directions across the body of the Earth, and return to the surface, where they can be registered by seismographs (Fig. 1.2).

There are two types of seismic waves originating from the hypocentres: **P-waves** (*Primae*) and **S-waves** (*Secundae*), characterised by different energy, speed, and propagation mechanisms. P-waves can pass through solid and

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[3] The pascal (Pa) is the unit of measurement of pressure, recommended by the *Système International* (SI). One gigapascal (GPa) is one billion Pa. Pressure values are also given in atmospheres (1 atmosphere = 101,325 Pa) or in bars (1 bar = 100,000 Pa).

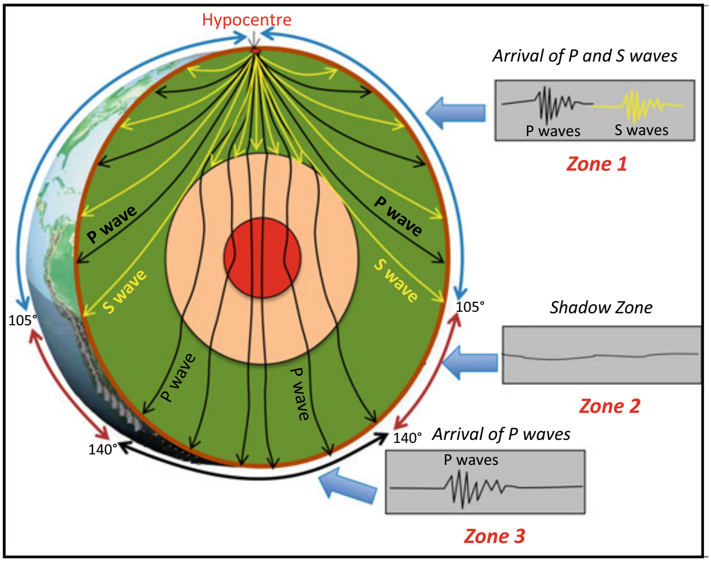

Fig. 1.2 An earthquake generates energy that spreads across the body of the Earth as vibrations or seismic waves. There are two types of seismic waves originating at the hypocentres, the P-waves and S-waves. They follow curvilinear paths and can be recorded at remote monitoring stations by seismographs. Seismic stations situated between 0° and 105° from the hypocentre (Zone 1) record both the P-waves and S-waves. In the range between 105° and 140° (Zone 2 or Shadow Zone), neither P-waves nor S-waves are recorded because the former are refracted, and the latter are unable to pass through the Earth's liquid outer core. Stations located more than 140° from the hypocentre (Zone 3) only record P-waves, but not S-waves that are shielded by the outer liquid core

liquid materials, are fast and reach the recording stations first. S-waves are slower and, notably, cannot propagate through liquids.

The speed of P- and S-waves across the Earth ($\mathbf{V_P}$ and $\mathbf{V_S}$) is variable, depending on the physical–chemical characteristics of the material through which they pass. Their values across minerals and rocks are well known, owing to the many experiments carried out in the laboratory at high pressures and temperatures. Comparison of experimental values with seismic wave velocities measured worldwide during earthquakes[4] allows us to determine what kind of material is present in the Earth's interior, between the hypocentre and the recording stations.

The paths of the seismic waves across the Earth are schematically outlined in Fig. 1.2. Stations located near the hypocentre only record waves that cross (and then can give information on) the shallower levels of the planet. In

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[4] Values of V_P and V_S at a given locality are calculated by dividing the distance from the hypocentre by travel time, i.e. the time for seismic waves to reach the recording place.

contrast, more distant seismographs record the waves that penetrate deeper into the Earth. The composition of the materials resting at different depths is inferred by monitoring, at the seismic stations scattered around the world, the medium to large earthquakes that frequently occur at various sites of the planet.

1.3 The Structure and Composition of the Earth

Creating a model of the structure and composition of the Earth's interior has engaged philosophers and naturalists for centuries. The idea that the planet has a stratified structure was anticipated in the seventeenth century by René Descartes (1596–1650) and Gottfried Wilhelm von Leibniz (1646–1716), but a couple of centuries had to pass before being translated into a scientifically grounded model by the German geophysicist Emil Johann Wiechert (1861–1928).

A robust initial surge towards a scientifically supported model was made when Isaac Newton calculated that our planet has a mean density of about 5.51 g/cm^3, much higher than any rock occurring at the surface that rarely exceeds 2.7 g/cm^3. It was then obvious that the internal body of the Earth should consist of much heavier stuff. However, the very nature of these materials remained a matter of speculation.

Peridotite xenoliths and metal meteorites were the most plausible candidates because of their high density of about 3.3–3.5 g/cm^3 and 7–8 g/cm^3, respectively. Based on this evidence, geologists of the 19th and early twentieth century hypothesised that there were layers of peridotite and metals, under an external shell of relatively light rocks. The Austrian geologist Eduard Suess (1831–1914) gave the name of **Sial** to the outer rocky shell of the Earth, being composed of aluminium silicates; **Sima**, the intermediate layer, made up of more dense magnesium silicates; and **Nife** the nickel–iron core. A combination of silicates and metals was a brilliant solution to the density conundrum of the bulk Earth. However, the thickness, the state of aggregation (solid or liquid), and the exact composition of the individual layers remained obscure. Such problems had to be solved later in the twentieth century.

Integrated petrological[5] and geophysical investigations were decisive for working out a robust model of the interior of the Earth.[6] Seismic study

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[5] Petrology (from the Greek words: πέτρος λόγος, pétros lógos = rock study) is the branch of geology that studies the texture, composition, physical characteristics and origin of rocks.

[6] Birch [1], Ringwood [2].

during earthquakes furnished values of V_P and V_S for materials residing at different depths; laboratory experiments provided critical data on the physical properties of minerals and rocks. A comparison of geophysical and petrological data obtained in the laboratories and in nature placed substantial constraints on the kind of materials within the Earth's interior and established the depth at which the transition from one type of material to the other occurred.

One of the most striking findings was that V_P and V_S changed with the depth, supporting the hypothesis of variable compositions for materials inside the Earth. Moreover, it was also discovered that there are some abrupt changes of seismic wave velocities at some particular depths (Fig. 1.3). These "jumps" are referred to as **seismic discontinuities** and were correctly interpreted as marking the boundary between layers with different mineralogical and/or chemical compositions, and/or distinct state of aggregation (solid–liquid).

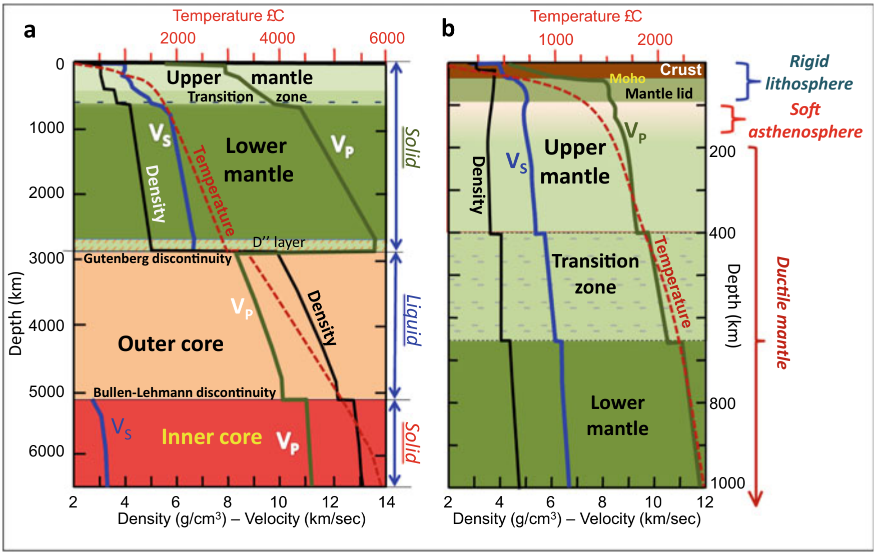

Fig. 1.3 **a** Simplified model of the internal structure of the Earth[7]; **b** Model of the crust-mantle system to 1000 km depth. Lines indicate the variation of seismic wave velocities, density, and temperature with depth. Density stratification is the consequence of the tendency of heavy material to sink below and the lighter one to float. Temperature variation with depth—called the **geothermal gradient**—is much higher in the crust (on average 30 °C/km) than in the mantle and core, reducing to about 1 °C/km in the centre of the Earth

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[7] Dziewonski and Anderson [3].

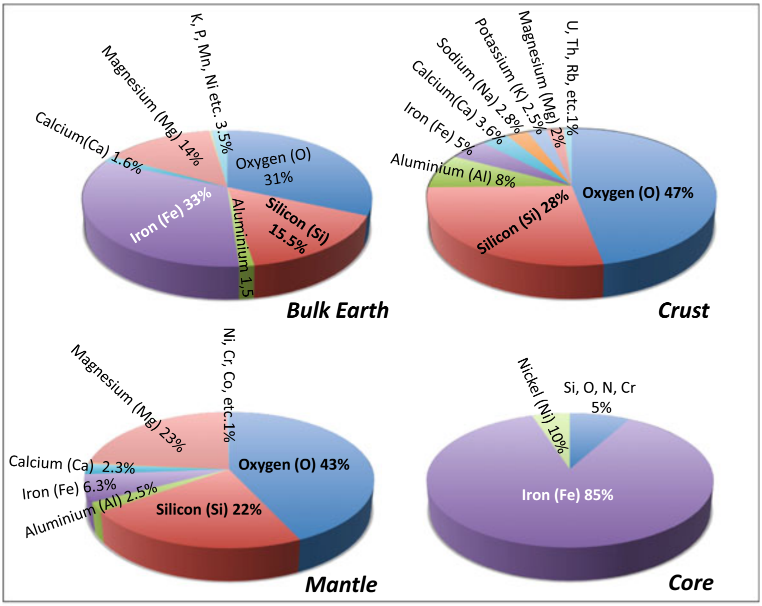

Fig. 1.4 Chemical composition of the bulk Earth, crust, mantle, and core. Element concentrations are expressed as per cent (%) by weight

The first jump of V_P and V_S occurs about 8 km beneath the ocean floor and at very variable depth (about 10 to 70 km; average 35 km) beneath the continents. This boundary is called the **Mohorovičić discontinuity** or **Moho**, after the Croatian geophysicist Andrija Mohorovičić (1857–1936), who discovered it in 1909. Above the Moho, V_P is around 6.5 km/sec, but it increases to more than 8.0 km/sec below the Moho. These values are consistent with a transition from aluminium silicate rocks in the upper domain to magnesium silicate rocks similar to the peridotite xenoliths below the Moho.

A much stronger discontinuity lies at a depth of about 2900 km. It is known as the **Gutenberg discontinuity**, named after the German-American geophysicist Beno Gutenberg (1889–1960), who discovered it in 1913. Below this discontinuity, a strong decrease of V_P and a loss of S-waves ($V_S = 0$) highlights the most dramatic change in the structure and composition of the Earth's interior, i.e. the transition from a solid rocky upper layer to a liquid metallic mass through which the P-wave velocities are strongly retarded, and S-waves are not allowed to pass (Fig. 1.2).

A third major discontinuity is present at about 5150 km, where V_P increases from about 10 to 11 km/sec. This is the **Bullen-Lehmann discontinuity**, named after the Danish seismologist Inge Lehmann (1888–1993), who hypothesised its existence in 1936, and New Zealander geophysicist Keith Edward Bullen (1906–1976), a prominent scholar of seismology.

The studies summarised above resulted in the recognition of various compositionally distinct concentric spherical layers or shells inside the Earth, as Suess had suggested in the late nineteenth century. However, the situation is somewhat more complex. In essence, three layers—crust, mantle and core—can be distinguished from a chemical point of view; by contrast, when mechanical characteristics are considered at least four different shells are recognised—the inner core (solid), the outer core (liquid), the convective mantle (solid ductile) and the lithosphere (solid rigid). Mechanical and chemical layers do not match and both types are to be considered to explain many first-order geological processes such as geomagnetism, seismicity, ocean basin formation, and mountain building.

1.3.1 The Compositional Layering: Core, Mantle, and Crust

The **core** extends from the centre of the Earth—situated at a depth ranging from 6357 km at the poles and 6378 km at the equator—to the Gutenberg discontinuity. It consists of an inner sphere of solid metal enveloped by a thick liquid layer, separated by the Bullen-Lehmann discontinuity. Core composition is dominated by iron, with lesser amounts of nickel (the so-called *Nife* of Suess) and small contents of light elements such as silicon, nitrogen, sulphur and water (Fig. 1.4).

The **mantle** is placed between the Gutenberg discontinuity and the Moho. It is subdivided into three distinct concentric layers by second-order seismic discontinuities: the **upper mantle** (extending down to 400 km), a **transition zone** (400–650 km), and the **lower mantle** (650–2900 km). A distinct irregular domain, a few hundred kilometres thick named the **D” layer** (D-double-prime layer), is located at the core-mantle boundary. The mantle is believed to have a relatively homogeneous chemical composition dominated by oxygen, silicon, and magnesium that resembles the *Sima* of Suess. However, mineralogical composition changes vertically, as a response to the progressive increase in pressure and temperature with depth. Seismology and experimental petrology suggest that the upper mantle is formed of peridotite. By contrast, the transition zone and the lower mantle are made up of some exotic high-density minerals that are stable at very high pressures,

Table 1.1 Mass, volume, and density of the Earth and its main structural units

	Mass (Tons)	Volume (km^3)	Percent of Earth mass	Percent of Earth volume	Density (g/cm^3)
Bulk Solid Earth	5.97×10^{21}	1.13×10^{12}	100	100	5.5
Atmosphere*	5.10×10^{15}	2.6×10^{10}	0.00008	2.3	$0–1.2 \times 10^{-3}$
Hydrosphere	1.40×10^{18}	1.40×10^{9}	0.023	0.12	1.03
Bulk Crust	2.59×10^{19}	9.25×10^{9}	0.43	0.09	2.8
Oceanic Crust	5.91×10^{18}	2.0×10^{9}	0.1	0.04	2.9
Continental Crust	20×10^{18}	7.25×10^{9}	0.33	0.05	2.7
Mantle	4.06×10^{21}	9.5×10^{11}	68.05	84.15	3.3–6.0
Bulk Core	1.89×10^{21}	1.78×10^{11}	31.5	15.76	11
Outer Core	1.79×10^{21}	1.7×10^{11}	30	15	10
Inner Core	9.7×10^{19}	7.6×10^{9}	1.5	0.7	13

*Troposphere + stratosphere

such as wadsleyite, ringwoodite, Fe-periclase, perovskite, Mg-Si-perovskite, and Mg-wüstite.[8]

The **crust** is the external rocky shell extending from the surface of the solid Earth down to the Moho. Its thickness is variable, ranging from an average of about 8 km under the ocean basins to a maximum of about 70 km under some mountain chains. The composition and density of the crust change significantly from oceans to continents (Table 1.1). The **oceanic crust** is made up of a dense layer of igneous rocks (basalt and gabbro; Box 1.1) covered by a veneer of sediments; this rock suite extends rather uniformly over vast areas, flooring the Earth's oceans. Its chemical composition consists predominantly of oxygen, silicon, aluminium, and calcium with considerable iron, hosted in a small number of minerals, namely plagioclase feldspar, pyroxene, olivine and Fe-oxides.

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[8] Wadsleyite and ringwoodite make up the transition zone; they have the same composition as olivine $(Mg,Fe)_2SiO_4$ but atoms are more closely packed, resulting in a higher density; phases of the lower mantle are Fe-periclase (Mg,Fe)O, Mg-Si-perovskite $(Mg,Fe)Al_2SiO_6$, perovskite and post-perovskite $CaSiO_3$, and Mg-wüstite (Mg,Fe)O.