

Chapter 2

Our Haven, Planet Earth

Abstract Planet Earth was formed from the agglomeration of solid bodies. Earth's iron-nickel enriched core segregated from a silicate mantle as early 30 million years after its formation 4.1–4.7 billion years ago. Earth is the third planet in our solar system circling around the Sun in an elliptical orbit at a distance of 147–152 million kilometers. Such a distance from the Sun enables our planet's temperature to be hospitable to animal and plant life. Among the nine planets of our solar system, Earth is the only one whose surface environment is adapted for water to exist in its three states: solid, liquid and gas. The elements necessary for life consisting essentially of oxygen, carbon, hydrogen, nitrogen and sulfur, are also found in comets, stars and probably on other planets in the Universe. 71 % of the Earth's surface is covered by water, which means that when seen from space, our home could be called the “Blue Planet”.

The universe has expanded and cooled from an extremely hot and dense state after the “Big Bang” occurred about 15 billion years ago (Hazen 2012). The term “Big Bang” refers to the beginning of the Universe, when a release of energy triggered a rapid expansion of primordial elementary particles. The regions with particles having a high density also had a gravitational potential to attract more matter from their surroundings and to grow even denser. Thus, the beginning of the galaxies started as matter began to accumulate in various confined regions of the universe. Today, our universe is also littered with blocks of dead stars. The larger and more massive stars have exploded in supernovas and now form relics of denser stars. Some of these massive stars have even become black holes. Other blocks and dust have agglutinated together and contracted under gravitational forces to form hot fireballs like the Sun. Our Sun and our solar system are located at the edge of the Milky Way Galaxy.

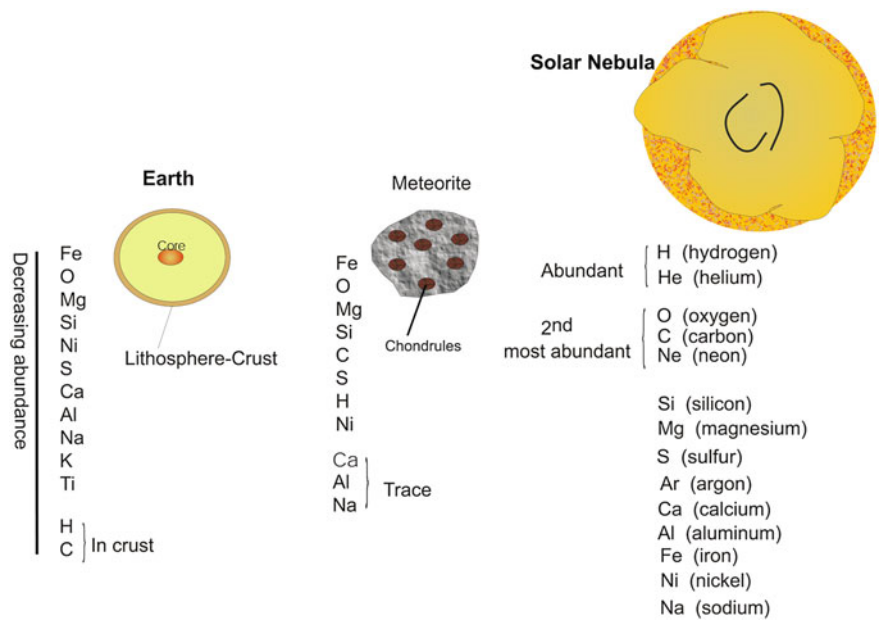


Fig. 2.1 The schematic representation infers the creation of planet Earth from our Solar Nebula. The major-element compositional distribution with their relative abundance is shown (after White 2013)

The Birth of Planet Earth

About 4.7 billion years ago, dust and rocky blocks gravitated around the Sun and formed spherical bodies of variable size (Fig. 2.1). Our home planet, Planet Earth, must have begun to be formed with the accretion of dust and large blocks that collided and agglomerated together. This agglomerated sphere attracted more material from the stellar system and its gravitational forces generated heat so the material began to melt. As melting occurred, particle differentiation began, therefore the heavier components such iron (Fe), magnesium (Mg) and nickel (Ni) sank into a magma pool towards the center of the planet while a silicate liquid made up essentially of silicon (Si), aluminum (Al) and sodium (Na) rose towards the surface.

There are many similarities between our planet and others in distant galaxies, called exoplanets, because they are planets located beyond our solar system that are orbiting around other stars. In terms of similarities, we could consider a planet's density. In our own solar system, for instance, Mercury (5.42 g/cm^3), Venus (5.25 g/cm^3) and Earth (5.52 g/cm^3) have similar densities when compared to that of Mars (3.94 g/cm^3). The average density of a planet depends on its mass. The bulk density of a planet is the ratio of the mass of a planet compared to its volume. The variation in density between planets of similar size is related to a change in the

composition of the material forming each planet. The relationship between density and mineralogical and/or chemical composition is related to the way the atomic structure of the matter is arranged (Broecker 1985).

Since the density of a planet depends on its mass, the “denser” or “heavier” a planet is, the stronger its gravitational pull will be. Thus, since Venus and Earth are larger than Mercury, gravity’s attraction on their surface will also be greater. The pressure generated by a planet’s gravity will cause the atoms forming the planet’s interior to contract in size. If a planet’s mass is increased, then its gravity will increase and the contraction of the atoms forming the planet’s material will also increase.

The information we have concerning the composition of the stars, planets, their satellites (or moons) and comets has been obtained from astronomical observations conducted from Earth and, more recently, from observations obtained by spacecraft launched from Earth to explore our galaxy. The astronomical observations on the elements composing other celestial bodies are based on studies of light refracted by a prism, in order to separate the light’s different colors into a spectrum. Each color of the prismatic light characterizes an element. Laboratory experiments to define the various elements consist in calibrating the passage of light from an electrical arc through a known gas mixture.

The most abundant elements in a star’s interior are hydrogen (H) and helium (He), and the second most abundant elements are oxygen (O), carbon (C) and neon (Ne) (Fig. 2.1). Volatiles in comets consist essentially of water and minor amounts (about 1 %) of other constituents such as CO (carbon monoxide), CO₂ (carbon dioxide), methanol, formaldehyde, ammonia and hydrogen sulfide (HS₂).

Compared to stars or comets, the most abundant elements forming the largest planets are oxygen, magnesium, silicon and iron with nickel, sulfur, calcium, aluminum, sodium, potassium, and titanium, in decreasing abundance. The abundance of other elements drops rapidly, and becomes so insignificant that all the other elements represent no more than one percent of a planet’s entire composition (White 2013). Due to these compositional variations, it is not surprising to observe that when we are on Earth, we are walking around on a solid crust which is mainly made up of elements such as O, Fe, Mg, Si and Al forming crystalline compounds, which we call minerals and rocks.

Another direct source of knowledge about the composition of our planet comes from the meteorites, which have fallen on Earth. These “space rocks” are essentially made up of nickel, iron, silica, magnesium and oxygen, formed from molten liquids which also contain small amounts of long-life radio-isotopes, which can be used like a clock. By measuring the concentration of the radioactive elements and the time necessary for one radioactive isotope to decay and change into another element, it is then possible to define the date of the meteorites’ formation. It was determined that the meteorites from our galaxy were formed about 4.6 billion years ago (Myers and Crowley 2000). No rocks as old as this have as yet been discovered on Earth, but analyzing a zircon compound in a metamorphic formation in Canada, some scientists have determined an age of 4.1 billion years (Myers and Crowley 2000). If, as according to astronomers, the age of the

Universe is around 15 billion years, then the Earth was probably formed 4.1 billion years ago from the same matter as that found on other planets (Dalrymple 2001). The continued exploration of our planet can provide us with an opportunity to better understand the extraterrestrial bodies in the rest of our universe.

Recently, more information on the composition of our galaxy has come from spacecraft sent into space to collect data and make in situ measurements of meteorites and comets. For example, the Comet Wild 2 images and dust samples collected from the NASA Stardust and Deep Impact missions gave us some information on the nature of the solid material in comets (From Internet: news.com.au). The presence of minerals called fosterite (Mg_2SiO_4) and enstatite (MgSiO_3) along with other phases have been detected in meteorites (Brownlee 2008), and these minerals are similar to the mineral composition found in our own Earth's mantle.

Our nearest neighbor, planet Mars with its lower density, is also one of the smallest planets in our solar system. It has been explored by robots carrying out geological and biological experiments. So far, little has been achieved to determine the existence of water (H_2O) such as we know it on Earth. Mars' atmosphere has a low density and it is very cold (-93°C to 13°C), so it is unlikely that water could exist in its liquid form.

In 2004, based on satellite observations on Mars, scientists detected the existence of an ice cap located on the South Pole of this planet using a spectrometer capable of detecting images in the range of infrared sensors. This ice cap is not made of water, but is formed of frozen CO_2 (Pappalardo et al. 1998). If liquid water (H_2O) could have been present on Mars in the past, this might suggest the existence of life on the planet. However, the thin CO_2 -rich atmosphere does not prevent incoming UV (ultra violet) radiation from the Sun, which is fatal for living organisms.

On the other hand, on Europa, which is a moon circling around Jupiter, we have observed a liquid ocean covering its surface. Is this ocean similar to that of our Earth? The Galileo space probe permitted us to observe patchy structures on the surface of Europa that were interpreted by scientists as representing floating icebergs (Pappalardo et al. 1998).

It was in 2004 that the Cassini-Huygen spacecraft entered Saturn's orbit. Landing on Titan, one of the largest moons of Saturn, scientists interpreted evidence of frozen methane as being flat and rounded slabs (Pappalardo et al. 1998). NASA scientists have announced that they were able to photograph features resembling lakes of liquid hydrocarbons more than 200 km long and 70 km wide.

The Solid Earth's Interior

Probably the Earth's interior today does not reflect the composition and the structure that it must have had at the beginning. During the creation of the solar system, crystalline solids condensed from the solar nebula. These solids were swept up by gravitational attraction after which intense heating and melting took

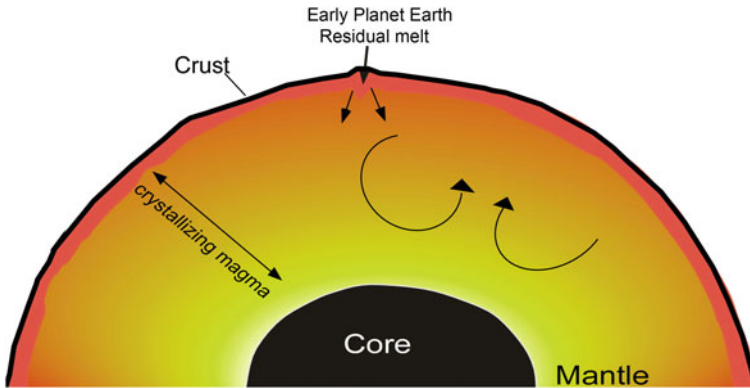


Fig. 2.2 Early-solidifying Earth after its formation shows thermal convection mixing the composition of lower and upper mantle from the base of the mantle upward. Various elements (mainly incompatible) will be diffused and transferred throughout the solidifying layers composed of different crystallizing phases. A reservoir of enriched heavy elements distilled from the early “magma ocean” resides within today’s Earth, probably in the area of the core-mantle boundary at about 2900 km depth (after Boyet and Carlson 2005)

place on Earth. Based on isotopic element ratios measured on primitive meteorites and compared to present terrestrial samples, it was found that the Earth’s mantle was a deep ocean magma during its first 30 million years (Boyet and Carlson 2005) (Figs. 2.2 and 2.3).

The early molten Earth most probably crystallized from the base of the mantle upward and Earth’s surface was the residue of molten liquid sitting under a primordial crust. Similar to the other solid planets, the early dense iron contained in the molten magma settled at the center forming the metallic core overlaid by a peridotite (silica, aluminum, iron, magnesium and calcium) enriched mantle.

As the mantle continued to solidify, convection currents were generated and they were able to mix the upper and lower mantle material (Boyet and Carlson 2005). Reservoirs of enriched elements such as potassium, sodium, uranium, thorium and rare gases such as He (helium), Ne (neon), Ar (argon) and Xe (xenon) and their isotopes now mostly reside in a region found at the mantle-core boundary, at 2900 km depth. The heat generated by these radioactive elements and the heat within the molten core are responsible for creating the mantle’s convection currents and for supplying energy and matter to hot magma plumes upwelling towards Earth’s surface. Also, the early differentiation of the Earth’s mantle interior must have been the result of at least two different sources to produce the most common volcanic rocks, which are mid-ocean ridge basalts (MORBs), and ocean island basalts (IOB) (Mukhopadhyay 2012).

Our present knowledge of the Earth’s interior suggests that it is roughly like an onion made of successive concentrically arranged layers with increasing density towards its interior (Fig. 2.3). The deep Earth’s interior is beyond our visual observation; the only evidence of its composition comes from meteorites falling on

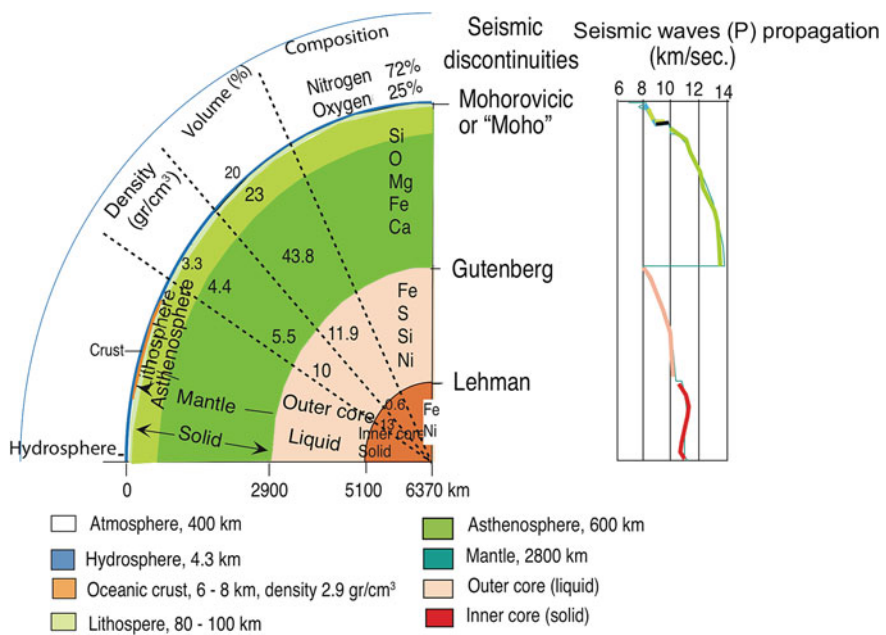


Fig. 2.3 The internal structure of the Earth shows different compositional layers. Seismic study reveals several discontinuities encountered in the interior of the Earth. Each discontinuity relates to physical, chemical and mineralogical changes (after Hekinian and Binard 2008)

Earth's surface, or from interpreting seismic wave propagation within rocks. Also, we have learned about our Earth's interior due to laboratory experimental work on the stability of mineral phases at different pressure and temperatures. Thus, laboratory experiments exerting high pressure and high temperatures on minerals in order to change their stability have permitted us to determine the density distribution at the interior of the planet (Green and Ringwood 1970). Another way of determining the composition of the Earth's interior is by measuring the density differences of the material encountered and then comparing this information to that obtained from laboratory experiments. The density differences can be gathered during earthquakes and/or any extensive man-made explosive activity (bomb testing) where the release of energy at a known source produces waves, which radiate in all directions and are identified on seismographs (from the Greek words *seismic* meaning earthquake and *graphos* meaning writing). The seismograph measures time and the ground motion of the Earth's interior. The ground motion is transmitted into the Earth by "wave propagation", similar to what is observed on the sea's surface when dropping a stone. A seismograph will measure the propagation of certain seismic waves called P-waves (Primary waves), which are compression waves, as well as expansion waves, like sound and other S-waves, which vibrate at right angles to the direction of travel, as do light waves. The P waves travel through both solids and liquids while the S-waves only travel through

solid material. A geologist reads and interprets the reading of a “seismogram”, just as a doctor is able to interpret our heartbeat when reading a cardiogram.

When comparing the seismic sound wave velocity transiting through a rock formation in relation to the density differences encountered, a seismologist is able to infer the composition of the material. Three major discontinuities have been found inside our Earth: (1) Core, (2) Mantle and (3) more rigid Lithosphere-crust (Fig. 2.3).

The Core

A 2,900 km deep “discontinuity”, also called the *Gutenberg discontinuity*, at the border of the inner mantle and the outer edge of the core, is made up essentially of a mixture of iron and magnesium silicates. This discontinuity marks the separation between the Earth's mantle and its core. Earth's core is composed mainly of iron and lesser amounts of nickel (3–6 %), and is revealed by a sharp drop in the P-wave velocity from about 12 km/s to about 8 km/s which then increases again up to 10–11 km/second at the inner core boundary (5,100 km depth), also called the *Lehman discontinuity* after the Danish seismologist, Inge Lehman. The inner core, at 5100–6130 km depth, is solid and essentially made up of nickel and iron. Its density is around 9–13 g/cm³ (Fig. 2.3). This solid inner core was formed during the accumulation of heavy metal material that sank from the outer core, which is less dense and is still in a molten state. It was Descartes, in 1644, who first proposed that Earth must have a liquid core or center.

The outer core consists of liquid metallic material made up of siderophile (iron loving) components. The siderophile elements such as the platinum group of elements (rhenium, osmium, iridium, palladium and ruthenium) are likely to be associated with the nickel-iron core. They are also called High Strength Elements (HSE) because they prefer to be associated with metals rather than silicates. Hence it is likely that they are more prevalent in the liquid outer-core than in the Earth's mantle.

Convection currents may have allowed material from the outer-core to be mixed into the lower mantle, and will later enhance the distribution of the platinum group elements towards the upper mantle and then enable them to appear in erupted lava on the Earth's surface. However, this hypothesis assumes that the platinum group elements were differentiated during the early formation of the solid inner-core to the liquid outer-core. Furthermore, we do not know about the real composition of the liquid outer-core and the crystalline inner core. In addition, if elements have fractionated from the inner to the outer-core, this must have happened at the very beginning of Earth's formation due to what is observed by the long-lasting half-life of the platinum radioisotope (¹⁹⁰Pt). In fact, these chemical hypotheses are in conflict with geophysical theories based on Earth's heat flow history, which is used in order to explain the evolution of the inner-outer core

system and which suggested that the core was formed later than Earth's beginning, and only occurred about 1 billion years ago (Labrosse et al. 2001; Melbom 2008).

The lower boundary between the core and the mantle is called the D" layer and is about 200–300 km thick. This is the area where the temperature of the Earth has the highest gradient and changes from 2200 °C at its base, closest to the solid, cooler core center, to 3400 °C at the top of the Core's D" layer. This is the region where iron-rich liquids interact with oxides and silicates in the mantle. It is an unstable and heterogeneous region responsible for generating the hot mantle plumes capable of rising towards the Earth's surface to form hotspot volcanoes. (See Chap. 9) (Fig. 2.3).

If the core were leaking, we should be able to retrace this fact through the presence of the High Strength Elements (HSE), which have accumulated inside the Core. The isotopic fingerprint of these HSE sometimes accompanies magmatic upwelling in some of the larger plumes generating hotspot volcanism, such as on the Hawaiian volcanoes. It has been determined that mantle derived materials exposed through volcanic eruption are heterogeneous in their radio-isotopes and in their light-incompatible-element contents, which are more similar to the material found in lithosphere-mantle volcanism and which do not seem to require material or energy input from the deeper-lying outer-core.

The Mantle

The Earth's *upper and lower mantle* occurs above the major seismic *Gutenberg discontinuity* located at 2,900 km deep at the Earth's core boundary (Fig. 2.3). The mantle reveals another seismic discontinuity at 640–700 km depth separating the *upper mantle* from the *lower mantle*. The *upper mantle* is subdivided into the *lithosphere* (>100 km deep) and the *Asthenosphere*, whose lower limit is at about 670–700 km deep. The temperature at the base of the mantle is around 3000–3700 °C but is <1200 °C in the upper mantle region.

The composition of the interior of our layered Earth has been extrapolated from laboratory experiments on minerals that form rocks as well as from what we have observed in meteorites landing on Earth from outer space. Thus, it is inferred that the upper mantle must have a composition close to the mineral association of olivine–spinel (and/or garnet)–pyroxene forming a rock called a *lherzolite* as well as to the composition of the mineral known as peridotite, which is stable within the first 50–100 km depth inside the Earth.

At about 670 km depth in the lower mantle, there is a mineral phase change where synthetic perovskite (Mg, Fe, CaTiO₃) becomes stable until about 2,900 km depth. This perovskite could be the most abundant mineral phase found on Earth and is similar in composition to the enstatite mineral found in comets.

Most minerals of the Earth's upper mantle contain hydrogen, which is structurally bound as hydroxide (OH). The OH concentration in each mineral species is variable, so in some cases it may reflect the geological environment of

a mineral's formation. Of the major mantle minerals, pyroxenes are the most hydrous, containing from 200 to 500 parts per million (ppm) H_2O by weight (Bell and Rossman 1992) while garnet and olivine contain only 1–70 ppm (written as $\text{H}_2\text{O} = 1\text{--}70$ ppm).

The Lithosphere-Crust

The interior of the Earth is further subdivided into the *lithosphere*, which is about 60–100 km thick. The *lithosphere* (from the Greek words *lithos* meaning rock and *sphere*, meaning ball) includes the outside layer, called the *crust*, which is a more rigid layer and the underlying *asthenosphere*, which is more ductile (See Chap. 4) (Fig. 2.3). In the outer part of the asthenosphere, the rocks are colder ($<1000^\circ\text{C}$) and more rigid therefore they deform elastically under loads and eventually break due to brittle failure. The continents consist essentially of granitic crust. Granite consists of quartz (a pure silica oxide), plus grey feldspar (K and Na aluminum silicate) and white colored plagioclase (Ca, Na, aluminum silicate) as well as darker iron-magnesium bearing minerals, which could include pyroxene and mica or amphibole. The granitic crust under the continents could be as much as 60 km thick. Underneath the oceans, the outside layer of crust is $<6\text{--}10$ km thick and consists of *extrusives* (volcanic rocks) or *intrusives* (dykes or sills).

The lower part of the lithosphere that intrudes into the upper mantle at about 100 km deep consists of peridotite (see Chap. 4). The lower boundary of the lithosphere (called the asthenosphere) is composed of a less rigid and more plastic (ductile) material than the upper-crust lithospheric layer.

In 1909, a Croatian seismologist named Andrija Mohorovicic discovered a seismic discontinuity located at about 35 km under the Balkan mountains, during his study of earthquakes. This has been called the *Mohorovicic discontinuity* and is commonly thought to be the lower level of the *crust*. The difference between the crust and the deeper lithosphere is observed by differences in seismic wave travel-times, which are related to the composition of the rocks.

Underneath the ocean, the difference between the lithosphere and the crust is arbitrarily defined. Generally the *crust* is defined as the portion of the most outer layer of the Earth, about 6–10 km thick, that is created during the upwelling of magma originating from the partial melting of the mantle. The magma transiting through conduits and magma reservoirs will undergo crystal-liquid fractionation and give rise to a solidified volcanic shell (see Chap. 5).

Crustal thickness varies between what is beneath the continents (estimated at about 60–80 km thick) to underneath the ocean where it could vary from 6 to 25 km depending on the constructional features. In the oceans, the thicker crust is located under islands, which have been built during repeated volcanic eruptions, enabling seamounts to rise to the ocean's surface. The lithosphere is really two different zones: a more ductile asthenosphere and the solid crust. In geology, the two zones are often combined together to represent the outermost shell of our

planet. The crust's relative rigidity (brittle nature) corresponds to a relatively cooler region, and is involved in the mechanisms of tectonic plate motion. The lithosphere's crust has broken up into several rigid plates, which move with respect to each other according to a common pole of rotation. Each rigid plate is like a "raft" that is floating on the more ductile layer of the lithosphere, i.e. the asthenosphere.

The lithosphere-crust has changed continuously over geological time. This is due to the slow convective flows carrying mantle material and heat, which are responsible for the renewal of the Earth's outer layer (See [Chap. 5](#)). These changes have also been called the *Wilson Cycle* in honor of Tuzo Wilson (1972) who developed the concept that continental masses have been formed by the opening and closing of the Earth's oceans as a natural consequence of plate motions. How many times have the oceans and continents been recycled? How far back in Earth's history can the surface evidence of this convective cycle be extended? This has certainly occurred many times, but it is hard to be more specific on the basis of our present geological record.

Water on Earth

Water abounds in the Universe, however the origin of water on Earth is speculative. On Earth, 96.5 % of the planet's surface water is found in the oceans, 1.7 % in groundwater, 1.7 % in glaciers and the ice caps of Antarctica and Greenland, a small fraction in other large water bodies, and 0.001 % is found in the air as vapor or clouds, formed of solid and liquid water particles suspended in air (Fig. 2.4) as well as in precipitation. Only 2.5 % of the Earth's water is fresh water, and 98.8 % of that water is found in ice and in groundwater. <0.3 % of all fresh water is located in rivers, lakes, and the atmosphere, and an even smaller amount of the Earth's freshwater (0.003 %) is contained within biological bodies and manufactured products.

How this water formed the oceans is not easy to grasp. Convay's hypothesis (1943) claims that water condensed from the primeval atmosphere. Thus, the genesis of the air and ocean is due to planetary gas release during the capture, concentration and accumulation of particles forming a layered Earth composed of solid, liquid and gas. The blue color of the ocean is due to the fact that the red wavelengths of sunlight are absorbed quickly while the blue rays are transmitted through the water column.

Another hypothesis is that the hydrosphere was formed at the beginning of the Earth's formation from degassing during volcanic activity and then by gravitational differentiation, when volatiles concentrated on the surface. It is also evidenced that the release of volatiles from the Earth's mantle is another source of gas and liquid in the hydrosphere and atmosphere. Furthermore, it must be noted that the volatile release, which could condense and form the oceans, will react

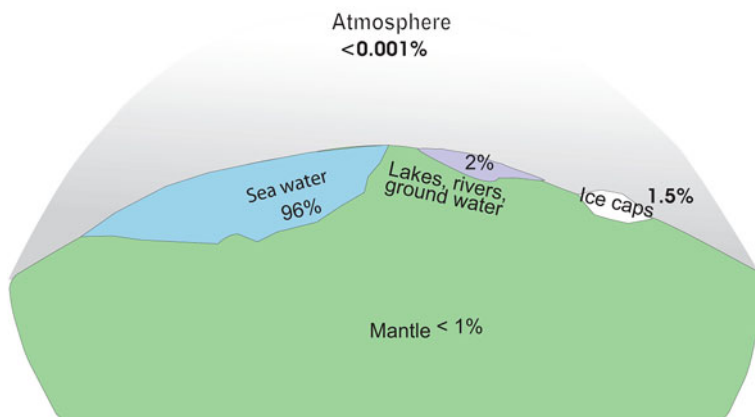


Fig. 2.4 Global distribution of water in the Earth shows that a small portion of water is stored in the atmosphere in the form of confined vapor. This vapor is essentially in the lower atmosphere. 96 % of the Earth's water is in the oceans, and <2 % in the solid mantle and lithosphere. About 2 % is found in lakes and rivers and 1.5 % makes up the ice caps. (The drawing was inspired after Broecker 1985, p. 203.)

with the alkali components (i.e. K^+ , Na^+ , ammonia, Cl^-) of the crust to form the atmosphere.

Volcanic eruption is one way for the Earth to release volatiles (gases) and various elements such as sulfur, methane, hydrogen, carbon dioxide, hydrogen chloride, and hydrogen sulfide that are present in magma (See Chap. 5). Whether volcanic activity has provided sufficient water to account for all the hydrosphere is a matter of speculation.

For any planet to be able to sustain life in any form, liquid water must be available in abundance. Most of the water on Earth is found in the Oceans and about 2 % in solid Earth (See Chap. 5), while the rest is located in rivers, lakes and ground water (3 %), and in ice caps (1.3 %) (Fig. 2.4). Only a very small content (<0.001 %) of water in the form of vapor is stored in the Asthenosphere. Seawater contains gas in solution such as carbon dioxide, hydrogen sulfide, oxygen, nitrogen, helium, argon, and neon, in order of their abundance. In addition, seawater has dissolved more than fifty elements and compounds of which the major constituents consist of Na^+ , Sr , K^+ , Mg^{2+} , Ca^{2+} , Br , SO_4^{2-} , HCO_3^- , F^- and Cl^- , with a pH of about 7.8.

The origin of seawater and other volatiles such nitrogen, carbon dioxide and chloride ions may be two fold:

(1) These compounds are not abundant in the rocks forming our planet. Carbonaceous chondrites (meteorites) contain minerals that have water in their lattice; hence, by analogy, we believe that the rocks in the interior of our mantle must also have bonded-water in their mineral lattices. In order to understand their origin, we must turn to an extraterrestrial source. The sun and extraterrestrial material such as comets and meteorites could give us some clue on the origin of

these compounds. It is known that the tails and the cores of comets traveling in space are formed of frozen ice and rock debris. During the formation of our solar system from extragalactic clouds, the condensation and differentiation of interstellar matter made up of gas, mostly ice-water, and solid dust took place in the *solar nebula*. During a gravitational collapse and heating of a solar nebula, water could be formed from the reaction of hydrogen and oxygen. Eventually the increasing concentration and agglomeration of the solid dust made up of silicates and iron must have initiated the accretion of the planets.

Thus, from the extraterrestrial hypothesis, it is possible to explain the concentric layering of matter forming the atmosphere, hydrosphere and solid Earth.

(2) Another hypothesis for the origin of the seawater is the slow release of water trapped in the solid Earth over geological time. Water was trapped in the solid-Earth during the early formation of our planet. Even if the solid interior of the Earth's mantle has in average of $<2\%$ water trapped in its different mineral phases, because of its volume ($>40\%$ of the total Earth) the mantle remains the most important reservoir of water. The Earth's mantle contains more than 5 times the amount of water found in the oceans. The fragments of meteorites, mainly the carbonaceous chondrites found on earth, contain water in their minerals such as clay, hydrated silicate and carbon oxides forming organic compounds. These meteorites have a close composition to that of the Earth's mantle. If such material was heated during the early formation of our planet, water would have been released. During episodic geological events due to radioactive heating and or gravitational forces generating heat, water could be released from the lattice of the silicate minerals and from other compounds of iron bearing phases in addition to forming the raw material for our air, our oceans and life (Turikian 1968).

A study of zircons has found that liquid water must have existed as long ago as 4.4 billion years, very soon after the formation of the Earth. This requires the presence of an atmosphere.

Why Seawater is Salty

The main salt compounds found in seawater have originated from the slow alteration and decomposition of rocks. Rivers running into the ocean carry some of the constituents such as sodium, potassium and silica. Other elements such chlorine (hydrochloric acid) and magnesium are likely to be of volcanic origin. The fact that its salinity and seawater's composition has not changed considerably over time is due to the balance of material entering the ocean with that which is precipitating into sediment or is ingested by various organisms. Excess sodium will form zeolite and clay minerals in sediment. Chlorine forms complexes with silica and other nutrients (potassium, nitrogen, carbon) that are essential for life and can be ingested by organisms. Chlorine forms chlorite-bearing minerals such as apatite and sodalite, which are found in sedimentary rocks containing organic material as well as in volcanic rocks.

Seawater also conducts electricity because of its diluted-salt content. It is a good sound propagator, which helps us to use sound-propagation to map the ocean floor and to conduct underwater seismic experiments. Because of the dissolved salts and mineral contents, seawater freezes at about -4°C . The composition of seawater with its major dissolved compounds is: Cl^{-} (55.05 %), SO_4^{2-} (7.68 %), HCO_3^{-} (0.41 %), Na^{+} (30.61 %), Mg^{2+} (3.69 %) and Ca^{2+} (1.16 %).

How Deep Can Seawater Penetrate into the Earth's Lithosphere?

The penetration of seawater into the solid lithosphere is inferred from seismic data given during earthquakes generated in the ductile portion of the lithosphere. By analogy, the solid lithosphere is like a thick piece of wood that dries and breaks. Under some constraints it can generate fissures through which liquid penetrates. Generally such depths are <20 km deep in most submarine regions except in the subducting trench area where the depth of penetration could be several 100 km. The study of tectonic processes taking place in converging margins, such as underneath island-arcs and in the active margins bounding oceanic regions, can help us to understand continental accretion. It is under the modern Oceans that the internal structure of the Earth can best be studied without taking into consideration the constraints of the large tectonic events taking place during continental growth.

Hydrosphere-Atmosphere Interaction

The interaction between the ocean and the atmosphere has a direct implication on the climate changes observed on the Earth's surface. It is a dynamic process depending on many factors such as convection currents carrying deep water to shallow levels, the flow of rivers to the ocean, and the wind carrying various sized particles. Thus, the gas escaping from the crust and mantle is introduced into seawater and transported to the surface where it will eventually be discharged into the atmosphere. Helium, carbon dioxide, hydrogen and methane gas are found in the water column and then released into the atmosphere above their site of production. When measuring the content of seawater at different depths in the water column, chemists are able to find the exact source of the gas escaping on the ocean floor. These sources are multiple. They are due to the alteration of oceanic rocks, to the circulation of magmatic melts that give rise to volcanic eruptions as well as to hydrothermal fluid discharge into the seawater.

Between the hydrosphere and the atmosphere, it is necessary to maintain an equilibrium in order for life to exist. This equilibrium is due to the so-called carbon cycle, which involves carbon oxide (CO_2), the bicarbonates (HCO_3^{-}) and

the organic carbon forming animal tissues. Also sulfur dioxide (SO_2) is added to the atmosphere due to biological activity in seawater.

The oceans are the major reservoir for carbon storage ($>4 \times 10^{13}$ tons) while the atmosphere has much less (8×10^9 tons). The study of ocean water circulation is a difficult task because the time of mixing between different water masses is longer (thousands of years) than in the atmosphere. Thus the study of the water masses and the input of gaseous phases inside the ocean is a vital issue for humanity in order for us to understand and eventually prevent pollution and the green house effect.

Because of the numbers of their atoms and their lattice configuration, gases such as CO_2 and H_2O have a larger capacity for retaining the infrared rays from the sun than do oxygen and nitrogen. The equilibrium between them will be perturbed if the concentration of these gaseous phases is modified. It appears that for about a century this equilibrium has been being modified because of the massive introduction of CO_2 into the atmosphere due to human activities. However, the ocean has the capacity to absorb a large quantity of carbon from the atmosphere in the form of organic material, which can be stored away from the atmosphere in sediment for long geological periods. However, in subaerial regions the various forms of carbon compounds will stay in contact with the atmosphere and might influence climate change.

Formation of Continents

The Earth is in constant motion and has continued to change since its creation 4.7 billion years ago. Some of this evolution is witnessed during a human's lifetime, such as when volcanic eruptions, earthquakes or tsunamis disrupt daily activities or create major catastrophes.

It is difficult to draw the shape of early-formed continents. When the molten Earth solidified, solid crust started to form isolated pieces of landmass called "cratons". The cratons are thick portions of today's continent formed from older pieces of continents. The oldest rock formations or cratons exposed on the surface of the Earth are Archean in age (3.8–4.4 billion years and older) (Myers and Crowley 2000). Archean (2,500 million years ago) rocks have been seen in Greenland, on the Canadian Shield, in Western Australia, and in South Africa. These first continental-size land mass are also called "Ur" (Hazen 2012). At the beginning of Earth's creation, there were no solid landmasses until late in the Archean period, when small "proto-continents" were formed. These proto-continents probably formed as "patchy hotspots" during the cooling and differentiation of the "magma ocean" giving rise to mafic and felsic rocks.

The world's oceans have probably existed from the beginning of our planet's history. Evidence suggesting the presence of ancient oceans has been gathered from the discovery of metamorphosed sedimentary rocks from Canada and Australia (Wilde et al. 2001). Sediments containing fossils are deposited on the sea floor and

solidified with time. The study of our modern sea floor will help scientists understand what happened in ancient oceans, traces of which can now be found on Earth's older continental with areas of exposed sedimentary rocks.

The “modern sea floor” is younger than 180 million years. Today's present continents and oceans have not always had the same appearance and the attachment and breaking-up of *Pangaea* and *Gondwanaland* might not have been a unique event. Indeed, it is not excluded that other continents previously existed and subsequently disappeared into the interior of the Earth. This may have occurred several times prior to formation of *Pangaea*. Extrapolating from our knowledge of the present arrangement of our planet's landmasses, we might be able to predict what will happen to Earth's continents in the future. For instance, if we imagine that the process of continental drift continues in the same pattern as now, it is not excluded that the re-closing of the oceans and seas will create another unique continent, or in other words, we may one day have a second *Pangaea*.

In geology, sometimes we refer to the continents as being the “granitic crust”. The term granite is used to define the assemblage of silica-enriched rocks that are lighter in weight (or less dense) than basalts or fresh peridotites; granite is what constitutes the main component of the continental lithosphere-crust. The origin of a “granitic crust” is related to the melting and upwelling of mantle material which first gives rise to a basaltic liquid. The basaltic melt resides in large magma chambers where the differentiation between heavy and light elements forming the compounds will take place (See [Chap. 5](#)). The lighter compounds, made up essentially of silica, potassium and sodium, will move upward inside the magmatic reservoir and upon crystallization, they will form quartz (silica oxide) and feldspar (silicates of calcium, sodium, potassium and aluminum) which are the primary minerals found in a granite crust.

At the beginning of its formation, the Earth was a molten ball that slowly solidified. The early solidification of our planet began at the base of the mantle near the core, and continued upward. The various compounds found in the mantle were diffused and transferred throughout the solidifying layers as “blobs” of agglomerated solids floating on top of denser partially molten material ([Fig. 2.2](#)).

The age of the earliest continental material is hard to evaluate and it is often related to the presence of life on Earth. However, the fossil records on continental terrain have sometimes been obliterated during rock alteration due to weathering or metamorphism (rock transformation). Indications of the age range for a primitive continent have been found among preserved fossil records to vary from 0.1 to about 3.8 billion years in Canada ([Schidlowski 2001](#)). Metamorphosed sedimentary rocks from western Australia have given an age of 4.4 billion years based on age dating of a detrital zircon found in metamorphosed sediment from the Narryer Gneiss Terrain ([Wilde et al. 2001](#)). Using “age dating”, which can be calculated by measuring the rate of decay of radioactive isotopes (i.e. $^{187}\text{Re} - ^{187}\text{Os}$ decay) and on carbon (CO_2) isotopes, and also based on stratigraphic observations, scientists have concluded that the major granite-forming activities in continent building have been cyclic and episodic.

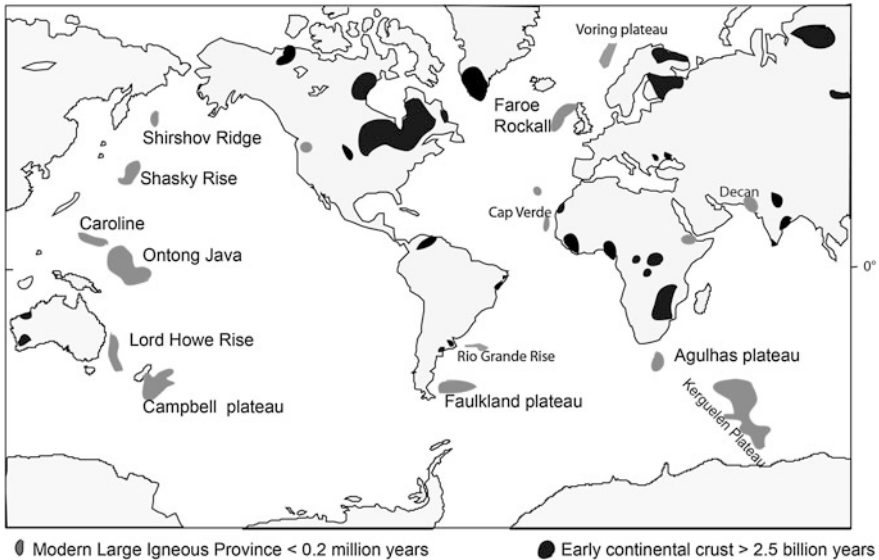


Fig. 2.5 The ancient (>0.2–2.5 billion years old) subaerial exposure of continental crust (*black*) is compared to younger (<0.2 billion years old) Large Igneous Provinces (*grey*)

The continental growth rate has been calculated to be about 3 km^3 a year during a period about 4–3 billion years ago but this rate of growth decreased to 0.8 km^3 a year after the early high growth-rate period (Dhuime et al. 2012). A decrease in the rate of continental accretion is probably due to the increase in subduction of newly formed lithospheric plates. The major granite-forming events have taken place sequentially with intermittent, quieter geological periods. When reading backward from the present, the major granite-forming events for building the crust can be dated in millions of years: 100, 400, 1,100, 1,500, 1,900, 2,600 and 3,400 million years (Gastil 1960; Engel and Engel 1964; Pearson et al. 2008). For example, the Alps in Europe, and the Andes, Rocky, Cascade and Appalachian mountains in the Americas are among the youngest examples of continental crust, since they are only about 100–200 million years old. The oldest granite crust which has been found in south Greenland, North America, Scandinavia, South Africa and in western Australia is older than 2.6–3.8 billion years (Hanika et al. 2012) (Fig. 2.5).

Wilde et al. (2001) used evidence from age dating on a detrital zircon (ZrSiO_2 —zirconium silicate) found in the Narryer Gneiss Terrain, in Yilgarn Craton, in Western Australia, and have determined that this part of the Earth has an age of 4.4 billion years old. The Narryer Gneiss Terrain contains sedimentary rocks suggesting the presence of early water that interacted with ancient continental crust. The zircon's isotopic age goes back to the time when the zircon's magma separated from the mantle, at which point it crystallized. The oxygen isotope measurements on this zircon suggest that the crystal grew in a liquid environment. Thus, the presence of water implies that the surface temperature was

cool enough to permit the evolution of life on Earth. In fact, life has been traced back to the Archean period, 3.5 billion years ago. Probably the early appearance of continental crustal nuclei as “blobs” of solid plates is comparable to what has been observed on ancient terrains exposed on all the larger continents, which are more than 3.5 billion years old (Fig. 2.5).

Large Igneous Provinces (LIP) as a Nucleus for Continent Accretion

It is likely that ancient rocky outcrops existed at the early stage of the Earth's formation when the “magma mantle” started to solidify and convective heat currents began to move matter from one part of the mantle to another (Fig. 2.5). These convective currents were the driving mechanism to bring lighter material to the surface and form crustal embryos of “continental islands”. The early conditions for the formation of silica-rich continental rocks took place about 4 billion years ago (4000 Ma) and were probably comparable to the more recent (63–200 Ma) mechanisms giving rise to the Large Igneous Provinces (LIPs) observed on the Earth's surface.

LIPs are due to the upwelling of lava from large, hot mantle plumes. From geological records it is known that these LIP must have been the result of huge amounts of volcanism associated with the emission of deadly gases such as sulfur dioxide (SO₂) and carbon dioxide (CO₂) and coinciding with long periods of acid rain. Even if the toxic gases were eventually lost or consumed during rock weathering over the next few thousand years, nevertheless significant environmental damage must have occurred because of the large quantity of toxic elements emitted over a relatively short period of time during the closely spaced periods of volcanic eruptions.

These LIP are found today in the Kuroo volcanic region of South Africa (190 Ma), in the Deccan Trapp in India (63 Ma), in Uruanu in Japan (26 million years), in the Yellowstone area in northwestern USA (2.2 Ma), on the Kerguelen Plateau in the southern Indian Ocean (110 million years), and in the Parana region (128 Ma) on the South American continent as well as in the Edenteka trap in Namibia (Southwest Africa). All these continental Large Igneous Provinces are covered by flood basalts accompanied by large amounts of silica-rich volcanic rocks forming great volumes ($>10^4$ km³) of eruptive material, which was later uplifted at the tectonic (lithospheric) plate margins to form continental crust.

Other, even older continental crust can be found in the Finno-Scandinavian provinces of Pechenga (2500 Ma), in South America (Uruguay) in the Rio de la Plata Craton (1790 Ma), and in Siberia (250 Ma). In today's ocean, Cretaceous (70–120 millions years old) and Jurassic (up to 168 Ma old) Large Oceanic Plateaus covered by extensive amounts of flood basalts, are found in today's submarine environments such as near Ontong, Java, and in the Maniki and Hikurangi

plateaus, plus the Shatsky and the Chatham Rises in the southwest Pacific, and in the Caribbean igneous province (Ben-Avraham et al. 1981). In the eastern Caribbean, silica-enriched volcanism has been observed on the Aves Ridge off the northern coast of Venezuela.

These Large Oceanic Plateaus seem to be similar to the Large Igneous Provinces (LIP), thus they could be interpreted as being precursors of future continents. Seismic studies done on these Large Oceanic Plateaus indicate that they are made of a thicker crust (25–60 km in thickness), which is comparable to that found underneath continental regions. Other Large Oceanic Plateaus with “granitic” crust but which are much older, such as the Seychelles Islands in the Indian Ocean, which are Precambrian in age (>540 millions years), and the Aghulas Plateau south of Cape Town in South Africa, are considered as being submerged continental fragments.

In summary, silica-rich igneous rocks are an integral part of all continental Large Igneous Provinces (LIP), which erupted a great amount (>6500 km³) of lava from the oldest Precambrian (>3000 millions years ago) period to the youngest Cenozoic times when the Large Oceanic Plateaus were created. Continental crust has been formed during several cycles of accretion around a more ancient or primitive «granitic nucleus» at different periods of Earth’s history up to today. Eventually, the formation of continental crust and Large Igneous Provinces has contributed to depleting the Earth’s mantle of its primordial incompatible (mostly lighter) elements.

Volcanic Arcs: Possible Sites of Crustal Accretion

Once mantle convection began and early “silica-rich” crust was created forming isolated nuclei (or patches of landmasses), the mechanism of continental crust formation continued to evolve as the rigid plates began to drift. Evidence of the existence of ancient intra-continental arcs is now lacking within the continents. It is however possible that the earliest continental crust was first constructed during the subduction of ancient lithosphere as early as the Precambrian period (more than 500 million years ago) because during plate tectonics and “continental drift”, when the plates spread apart from the ridge axes, the crust along with its sediment, basaltic rocks and a portion of the upper mantle’s intrusive rocks will be carried away until it encounters less dense material where it could be subducted (pushed underneath) the lighter material after a collision (see Chap. 10). If we look at the fore-arcs of today’s subduction zones, we can see the accumulation of drifted sediment, which could later be uplifted during tectonic events. Modern volcanic formations (<150 million years old) have formed above subduction zones where volcanic plates are recycled back into the Earth’s interior.

The total length of the arc margins where oceanic crust is being constructed is about the same as the length of the volcanic arcs themselves, and this length is estimated to be about 43,500 km (von Huenen and Sholl 1991).

Continental Drift

“Continental drift” is the movement of the Earth’s continents in relationship to each other. When looking at the Earth’s globe one is tempted to fit the South American continent with the West coast of Africa, and when looking closer towards the northern hemisphere, Europe and North America could also fit together with a small rotation with respect to each other.

The first hint of a theory for the drift of the continents was mentioned in 1620 by Francis Bacon, who suggested that the western hemisphere was once attached to Europe and Africa. However, the idea that the continents were once joined together was first put forward by the Flemish cartographer, Abraham Ortelius, in 1596. These ideas were more fully developed by the German astronomer, Alfred Wegener, in 1912. He proposed that all the continents were attached together 200 million years ago and he called this super-continent “Pangaea” (Fig. 2.6). Wegener also used paleontological records, which reported that fossils of some animal species found on both the American and African continents had similarities. It was also in the nineteenth century that Eduard Suess, a geologist from Austria, noted a close correspondence between certain geological formations on the southern hemisphere continents of Australia, Antarctica, southeast Asia and India. Based on his observations, Suess suggested that these areas were once part of an original, large landmass he named *Gondwana*.

Scientists did not accept Wegener’s concept of continental drift until after his death, which occurred during an expedition to Greenland, in 1930. In fact, many scientists were not convinced about the drift of continents even up to the 1960’s. However, the final irrefutable verification that the continents have been drifting apart came in 1963 when two British scientists, Vine and Matthews, reported the result of their investigations on the magnetic imprint left by the Earth’s magnetic field at spreading ridge axes (See [Chap. 7](#)). It was at this point that the theory of Continental Drift was finally accepted.

Plate Tectonics

The “theory of plate tectonics”, which involves the movement of the rigid segments (plates) of the Earth’s lithosphere, was inspired by and evolved from Wegener’s earlier hypothesis concerning continental drift. This theory has considerably changed our perception about how we view our living planet. The Plate Tectonic Theory was first presented in 1967 at the American Geophysical Union (AGU) meeting in Washington DC by Jason Morgan. According to his explanation, the surface of our planet is divided into several rigid plates that are moving with respect to each other. These rigid plates, which include the Crust and the Lithosphere, move above a less rigid substratum called the asthenosphere (Fig. 2.3). Jason Morgan and Xavier Le Pichon wrote and published the first

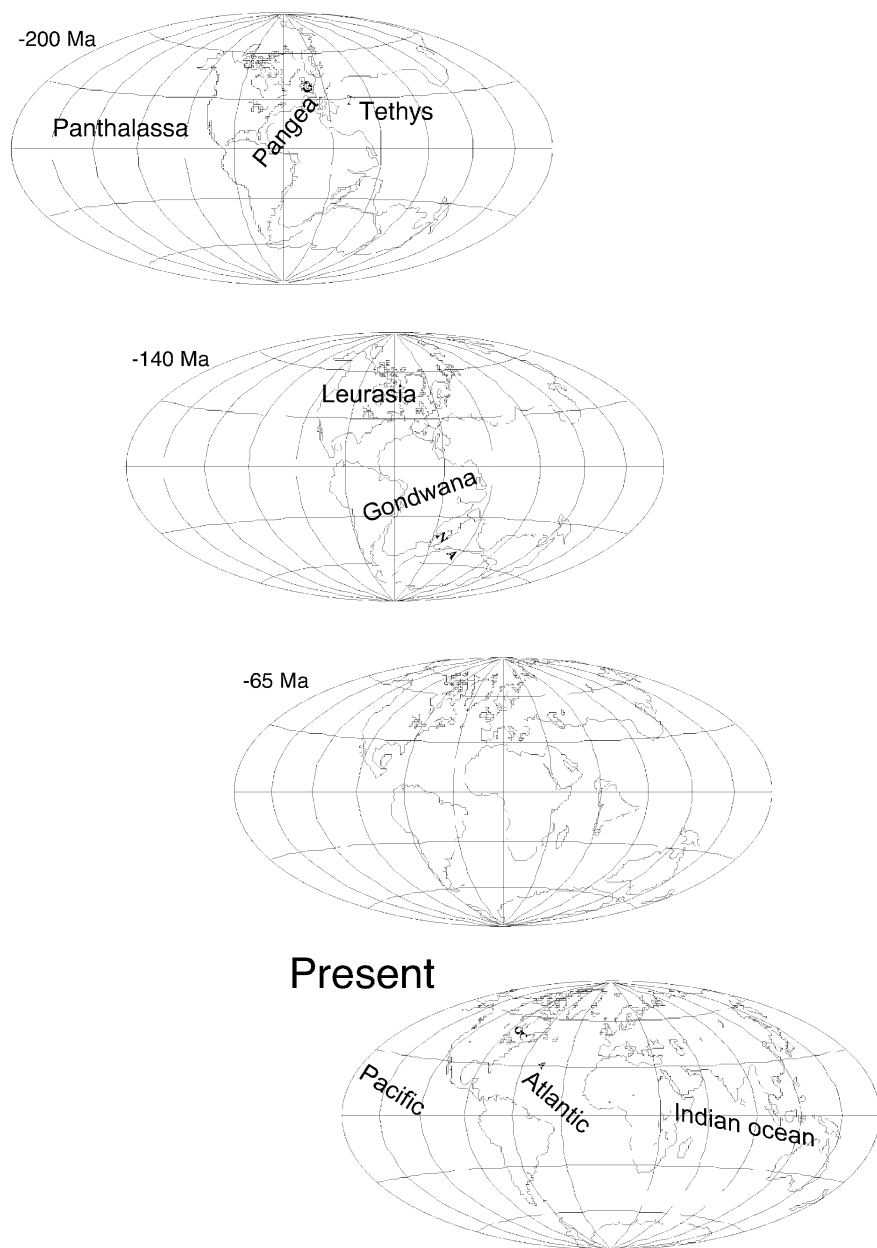


Fig. 2.6 The continents are formed from light material of granitic composition drifting on top of the asthenosphere. Early records show that the continents once formed a unique block that started to fragment under the effect of convection currents in the mantle. The continents become a giant puzzle that assembled themselves periodically, such as 200 million years ago. A unique ocean called *Pantalassa* surrounded the original continent called *Pangaea*

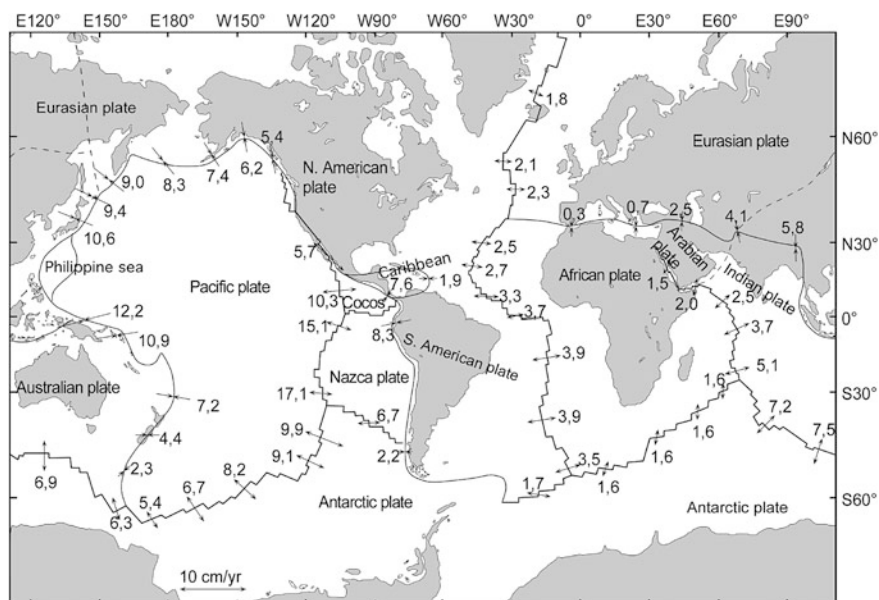


Fig. 2.7 Spreading ridge segments, major faults and subducting zones separate twelve major “rigid” plates. The *arrows* show the direction of tectonic plate motion and the spreading rates (after Hekinian and Binard 2008)

papers on plate tectonics in 1968. Spreading ridge systems, subduction zones and large fracture zones make up the boundaries of these plates (Fig. 2.7).

However the theory of plate tectonics does not explain, nor does it take into account, the interior of the oceanic basins (or “intraplate” regions) where volcanic activities have also formed large islands and underwater volcanoes called “seamounts”. According to the “hotspot hypothesis”, the motion of the lithospheric plates are the reason that many volcanic seamounts and islands are formed in a linear direction because the plates are sliding above and across huge sources of magma called “mantle plumes” (Morgan 1972) (See Chap. 9). Hotspot volcanic activity has triggered large eruptions throughout geological time and now scientists are certain that a good portion of the Earth’s volcanic activity has been taking place in the ocean basins, also referred to as intraplate regions, which are found at a distance from the diverging plate boundaries (also referred to as “accreting plate boundaries” since volcanic material is accreting there, and as “spreading ridge axes” since the plates are “spreading apart from each” other in these areas).

Thus, volcanic activity is responsible for the processes involved in the movement of the lithospheric plates and this mainly takes place under the oceans, where volcanism is much greater than on the emerged continents. Every year more than 3 km^3 and as much as 18 km^3 (Hekinian and Binard 2008) of oceanic crust is created along the 70,000 km of spreading ridge axes around the world. So far we have counted <1,500 active volcanoes above sea level, and most of them are

located in island arc provinces or on the continental margins of the circum-Pacific region. This number would have to be multiplied by 10,000 in order to have a close estimation for the amount of recent volcanism on the sea floor.

Oceanic crust is brittle and easily broken, especially in the areas of extensive fractures cutting 8–15 km deep within the lithosphere, as indicated by bathymetric studies and from monitoring seismic epicenters around the World. Earthquakes are a common phenomenon related to the readjustment of material during lithospheric stress. The material discharged in the water column during undersea volcanic eruptions such as helium, carbon dioxide and carbon monoxide, hydrogen, sulfur, methane etc. are carried by currents and/or absorbed by marine organisms. This volcanic discharge is of primary importance for determining the volcanic budget of our planet. Certain primary compounds such as carbon, hydrogen, and oxygen are the building blocks for a viable planet, which can support various life forms. Also, these discharge products could be of assistance in many aspects of human life. For example, if we consider the discovery that natural methane gas is seeping out onto the sea floor through bottom sediment, this could be of great interest since it is a large, new source of untapped energy. Because we have only limited knowledge concerning our ocean, it is expected that scientists will make many more new discoveries as sea floor exploration continues.

Mantle Convection Currents

Since its initial formation and subsequent cooling, our planet's interior has been transformed by means of convective currents of heat within the mantle. The heat flow (convective currents) is affected by heat lost across cold boundary layers inside the mantle and as well as through the lithosphere-crust sequences (outer shell of the Earth) (Figs. 2.3, 2.8). The convection currents form "rivers" of flowing matter and energy inside the mantle and will carry hotter and more viscous material towards the surface. The force driving this phenomenon of mantle convection is primarily due to the downward pull of gravity on the cold and dense lithosphere and the upward motion of hotter matter rising to the Earth's surface.

The increase of temperature with depth has been calculated to be about 20–25 °C/km below the plate boundary regions. The difference in temperature combined with the effect of density differences in the mantle is responsible for generating convection currents. The core-mantle boundary is about 3,500–3,700 °C, while the upper mantle-lithosphere is <1,000 °C. The convective flows inside our planet are comparable to what happens in the atmosphere where air currents are formed when an upward movement of hot air and a downward movement of cold air take place. Because of the constant changes inside the interior of the Earth, nothing has remained the same since the early formation of our planet. Convection currents are the driving force for generating various processes such as plate motion and mountain building.

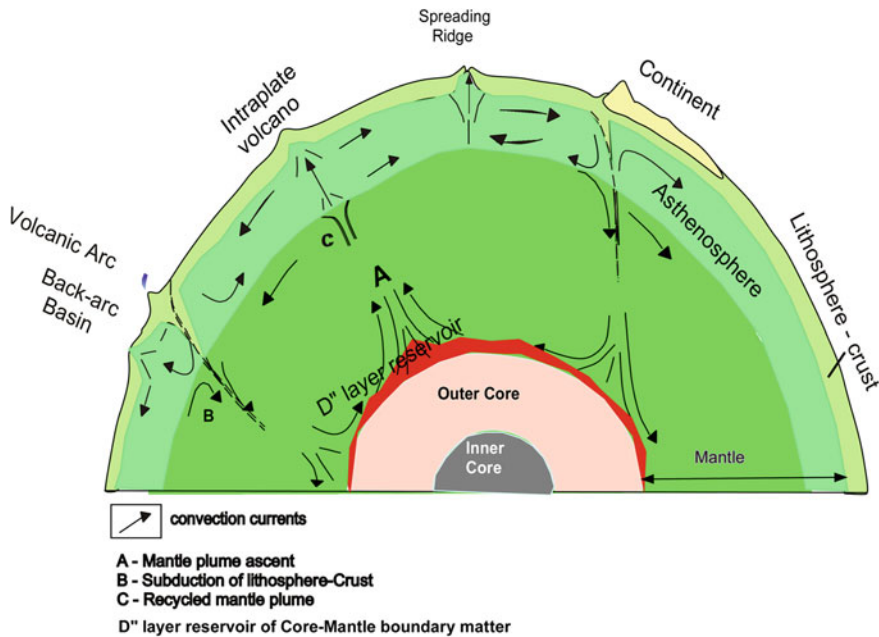


Fig. 2.8 Convection currents in the interior of the Earth show (A) the ascent of matter and energy forming hot mantle plumes, (C) recycled mantle plumes and magma creating spreading ridge segments as well as moving the lithospheric plates that will eventually plunge into the subduction zone (B) underneath continents and island arcs, which is where the lithosphere created at the spreading ridge axis descends into the mantle. A transition zone called the *D''* Layer marks the boundary between the Earth's mantle and the core, and is apparent due to the change in mineral crystalline structure

The temperature driven convection indicates that the interior of the earth is still extremely hot. This heat has been preserved since the early formation of the Earth and it is continuously being alimanted by the energy release due to the radioactive decay of long-lived radioactive isotopes such as ^{236}U , ^{235}U , ^{238}U , ^{232}Th and ^{40}K . The average air temperature on the Earth's surface is about 13 °C. In the Earth's interior, the temperature differences between the core (inner and outer core) at 5,000–7,000 °C, the lower mantle at about 2,000 °C and the upper mantle at about 500–600 °C are responsible for generating the mechanism of heat convection and the subsequent transfer of matter throughout the Earth's interior (Wilson 2005; White 2013). The temperature increases with depth and there is also a relationship with the interior's increasing pressure. When critical depth has been reached, the rocks will approach their melting point (about 1000 °C) near the upper mantle (in the lithosphere), so they will become ductile and have lower seismic wave velocities. This coincides with the beginning of what is known as the *asthenosphere*, at 670–700 km depth, where convection currents are the dominant mode of heat repartition and heat flow. The thermal energy radiating from the core will be

dissipated during its ascent in the mantle so it is not the same everywhere. In other words, thermal flux (heat flow) is irregularly distributed within the mantle before being dissipated through the lithosphere and the continental crust.

The ascent of deep-seated energy and matter is accompanied by a phenomenon of decompression. This decrease in pressure will increase the melting point temperature of the matter (mineral phases). Depending on the mineral structure and the surrounding temperature gradient, even just a small variation of only 10–30 °C is sufficient for enabling a rock to melt and become a liquid magma. The density decrease caused by heating will enhance the melted material's ability to rise to shallower depths and eventually to the surface. The melting takes place at the junction between mineral grains. The ability of a melt to ascend will depend on the porosity and the degree of fissuring of the surrounding area. Near the surface, a rising melt will accumulate in pockets forming large reservoirs (called magma chambers) at shallow depths of <500 m under spreading centers (see [Chap. 5](#)).

Probably not all the mantle's thermal energy is liberated at the surface of the Earth. Thermal energy and matter transfer could also flow laterally along major physical discontinuities marked by the boundary between the lithosphere and upper mantle. This generates weaknesses underneath the lithosphere, which could subsequently break and give rise to the observed major oceanic provinces such as fracture zones, spreading ridges and hotspots in oceanic basins.

Sea Floor Renewal

The major oceanic provinces are created along diverging plate boundaries at the spreading ridge axes, but also, to a lesser extent, in marginal basins formed behind island arcs, also called back-arc basins (see [Chap. 10](#)) (Figs. 2.8 and 2.9). The lateral dissipation of energy and matter driven by the mantle convective currents can move the lithosphere (tectonic plates) away from the heated region at spreading ridge axes towards a margin of colder and lighter density continents and/or older lithosphere at convergent margins where the heavier plates will sink back into the mantle to begin another new cycle of magma creation and subsequent volcanism.

The lithosphere (crust) moves away from its site of formation at a speed of a few centimeters per year (at a rate of <1 to more than 9 cm/year). The plates will cool progressively and will become thicker by incorporating a portion of the underlying asthenosphere. As the lithosphere moves and ages, it will become denser and eventually sink into the mantle at the subduction zones.

There is a geodynamic cycle of sea floor renewal. This cycle is relatively fast, over a period of about 346 million years. That is why the oceanic rocks are relatively young. The oldest oceanic sea floor located in the western Pacific is about 173 million years old, which is the geological Jurassic period. The renewal of the oceanic lithosphere occurs when a portion of the subsided lithosphere sinks into the Earth's mantle, regenerates itself and later reappears forming new material

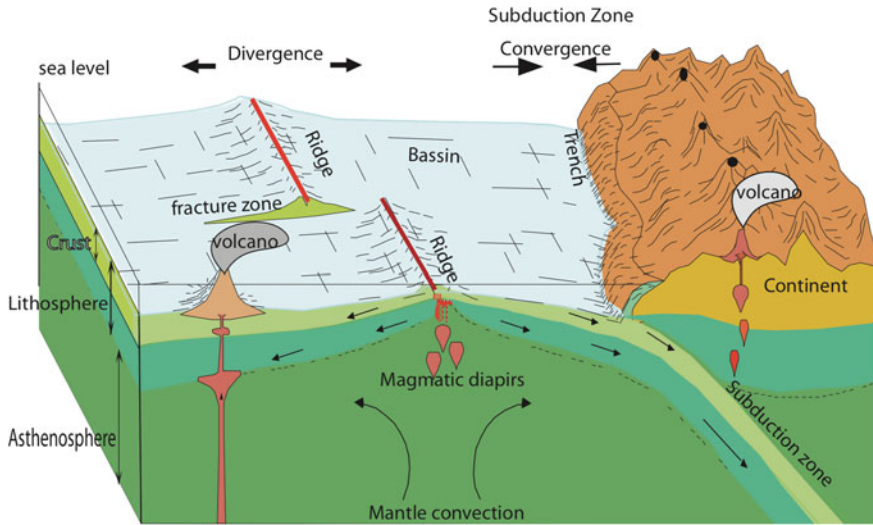


Fig. 2.9 The cycle of sea floor accretion and subduction shows that the sea floor created at the spreading ridge axis progressively ages as it is moved away from its point of origin (Hekinian and Binard 2008). At the same time the lithosphere cools, thickens and sinks into the mantle in the subduction zone. Convection cells (Fig. 2.8) drive the motions of matter and heat inside the mantle

on the surface of the Earth. This takes place during partial melting, which occurs during the extraction of upper mantle material found in the region of the asthenosphere. The magma that reaches the Earth's surface produces about $2\text{--}3 \text{ km}^3$ of volcanic rocks (mainly basalts) and about $15\text{--}20 \text{ km}^3$ of intrusive rocks (gabbros and various cumulates) per year along the planet's $70,000 \text{ km}$ of spreading ridges. There is in equilibrium between the creation of new lithosphere at ridge axes and the subduction of the old lithosphere in oceanic trenches (subduction zones). For this reason, the Atlantic Ocean, which is bounded by accreting passive margins with no trenches or subduction zones, except for the region of the Caribbean with the Lesser Antilles arc, is considered as being an ocean "in expansion", while the Pacific Ocean, which is bordered by active margins (tectonically active subduction zones), is "decreasing its size" by about 0.5 km^3 per year. In other words, the Pacific is an ocean closing in on itself.

The underwater structures covered by the oceans comprise mainly the deep ocean basins ($>4500 \text{ m}$ depth) which represent about 30 % of the sea floor, the spreading Mid-Ocean Ridge segments ($<4000 \text{ m}$ depth) which cover about 60 % of the sea floor, and a smaller proportion (10 % of the total undersea provinces) which is the location of the back-arc basins associated with subduction zones and island arcs.

The exploration and description of these different oceanic provinces as presented in this book will help the reader to better understand the formation of our planet. The upper portion of the lithosphere with a solid crust that is $<10 \text{ km}$ thick

(on the average) in oceanic regions is the most accessible to direct observations and thus is best known by marine geologists. During the last 120 years of investigations on land and in the deep sea, scientists have recognized several oceanic features based on their different types of environment and setting, and also based on their rock compositions. These major underwater structures include (1) spreading ridge systems, (2) fracture zones, (3) islands, underwater volcanoes and seamount chains, (4) deep trenches associated with subduction zones, (5) large volcanic plateaus which form the outer shell of our planet (see [Chap. 4](#)).

Thanks to deep-sea drilling operations, plus direct field observations of deep fracture zones and/or based on the upwelling of deep-seated molten material giving rise to volcanism on the surface, geologists have managed to probe the composition and structure of the lithosphere. Also, extrapolations have been made based on indirect studies involving seismic profiles and gravity anomaly measurements. However, we need to be careful when trying to define the stratigraphy of the crust. It is often found that the sequential variation of rock types is not uniformly distributed and sometimes the rocks recovered may vary considerably within the same structure. This is due to tectonic activities such as fracturing and fissuring as well as to the rheology (deformation) of the material forming the lithosphere and exposing different types of material. Diapiric upwelling of deep-seated material locally intruding the crust (see [Chap. 4](#)) gives rise to a large amount of tectonic instability and rock composition differences. In order to generalize the sequential compositional variation of a section of the lithosphere, it is necessary to have a good knowledge of the geological setting and the compositional variability of the rocks found within a given area.

Earth's Magnetism

Sailors are familiar with the effect of Earth's magnetic field and the preferential direction shown by the needle of a compass. The property of the magnetized needle in relationship to the Earth's magnetic field and the invention of the compass was probably first used by Chinese navigators and in fact, the first person recorded to have used the compass as a navigational tool was Zheng He (1371–1435), from the Yunnan province in China, who made seven ocean voyages between 1405 and 1433. (Mary Bellis, About.com Guide). William Gilbert wrote the earliest scientific treatises on magnetism in Latin, in 1600. However, the earliest evidence of Earth's field magnetization is likely to date back to the eleventh century (Jacobs [1967](#)).

In modern science, the geomagnetic field has been used to explore the dynamics of the Earth's interior and for mapping mineral deposits. Furthermore, scientists have learned that the magnetic poles have jumped from north to south and vice versa several times during the Earth's history. Thus, the study of paleo-magnetism has given indications about the location of the poles during the emplacement of iron rich lava.

What is the Source of the Earth's Magnetic Field?

The natural magnetic field is generated by the Earth's electric-dynamo system. It is believed that 99 % of the Earth's magnetism and its energy is the result of the fluid motions in the Earth's core. The molten nickel and iron spread spinning in the outer core are capable of generating electrical currents where the mechanical energy is transformed into electromagnetic energy. This is the same as in a car battery where the generator transforms mechanical energy into electricity, and this is called the dynamo effect. A switch of polarity in a dynamo will flip the direction of the current. This also happens in the interior of our planet and it is called the reversal of the magnetic field when the poles change polarity from north to south. We do not know why the field changes its polarity. The last switch of polarity occurred about 780,000 years ago and it is not known when the next one will take place. The flip of the magnetic field could be due to the change in direction of the convection currents moving the molten Fe–Ni-enriched matter in the Earth's core (Olsen and Manda 2008).

The first striking evidence of sea floor spreading was observed when analyzing the magnetic data obtained by magnetic sensors (called magnetometers) towed by the a research vessel in order to measure the fields of magnetic intensity on the sea floor. Vine and Matthews published this finding in 1963. Their paper talked about the *existence of long stripes* of normal and reversed magnetization running parallel to each other on each side of the spreading ridge, like a mirror image. Molten material containing magnetite and titanomagnetite had magnetized and upon solidification these elements pointed towards the direction of the Earth's magnetic field. This observation on the magnetism that was seen on the mirror image stripes is a way of showing that the solidified material is moving away from the axis of the ridge as more magma is injected to take its place. The magnetized formations reported by Vine and Matthews consist essentially of dykes and basaltic flows. It is believed that the Earth's magnetic field reverses itself (the North Pole becomes the South Pole and vice versa) about once every one million years. Therefore, the width of the stripes of magnetized anomalies will depend on the extent of the magmatic material injected into the crust and will be comparable to the rate of lithospheric opening (Harrison 1968).

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