Contractional theory, continental drift and plate tectonics

Plate tectonics – a change in the paradigm of the geosciences

Earth's tectonic system concerns the movement of the lithosphere, the relatively brittle outermost solid Earth, which consists of a mosaic of independent plates. The boundaries of these plates are the most dynamic areas in the world and are the locations of most orogeneses, a word from the classical Greek meaning mountain building. The concepts embraced above define the field of geodynamics – energy, forces, and motion of a changing Planet Earth; mountains are the most obvious results of this system. Although nearly all geologically recent and many ancient mountain ranges are at obvious plate boundaries, all continental crust was at some time generated at plate margins, an observation that clearly relates the global phenomenon of mountain building and plate tectonics.

The formation and evolution of mountain ranges has been a major concern of geologists since the inception of the field of geology. Insights from hundreds of years of investigations are involved in the paradigm of plate tectonics. However, Wegener's theory of continental drift, which was published in 1915 and is regarded by many as the direct precursor of modern plate tectonics, contributed astonishingly little to the understanding of mountain building processes. Only the theory of plate tectonics was capable of combining all dynamic phenomenons to one unifying and explanatory theory. This major change in paradigm was formulated in the 1960's, revolutionized the geosciences, and blazed the trail towards a process-oriented consideration of geodynamic processes.

Early history of geodynamic thought

The French philosopher and naturalist René Descartes (1596–1650) was one of the first scientists to consider the composition of the interior of the Earth. In his "Principia philosophiae" (1644) he proposed that Earth contains a core with a liquid similar to that of the sun and wrapped by layers of rock, metal, water and air (Bonatti, 1994). The Danish naturalist Niels Stensen, alias Nicolaus Steno (1638–1686), recognized that rocks are deformable and that the original position of deformed rocks can be reconstructed (Steno, 1669).

Peter Simon Pallas (1777), James Hutton (1795), and Leopold von Buch (1824), who together can be regarded as the founders of tectonics as an independent branch of science, considered the forces of rising magmatic rocks as the main cause of mountain uplift. They noted that granitic rocks are common along the central axis of many mountain ranges. The opposing theory of horizontal forces, which suggested that resulting compression and folding of the crust created mountains, was championed by numerous geologists and also had several variations. De Saussure (1796) and Hall (1815) were the first to propose that horizontal forces were the prime drivers of mountain building. The existence of strong horizontal forces has later been verified by the discovery of large nappe thrusts in the Alps.

Horizontal forces generally were considered to be a consequence of Earth's contraction and the results were a compression of the Earth's crust (Élie de Beaumont, 1852). The contractional hypothesis was based on the concept of an original liquid Earth followed by long-term cooling and shrinking. A variation of contractional tectonics is manifested in the geosynclinal theory of Dana (1873), which assumed that sedimentary rocks, now folded in a mountain range, were deposited in large, linear subsiding marine troughs, the so-called geosynclines. The sedimentary accumulation in a geosyncline is typically several kilometers thick and is many times thicker than sedimentary accumulations of the same age deposited on cratons. Dana considered the subsidence of the troughs as well as the later folding and uplifting to be the result of a shrinking of the Earth. The geosynclinal theory was later widely extended (e.g., Stille, 1913) and a large number of different types of geosynclines was defined. The contractional theory, which was supported far into the 20th century, is not accepted today because it conflicts with most modern hypotheses that concern the origin and early history of Earth. In fact, instead of shrinking, the diameter is actually slowly increasing due to tidal friction that slows down the velocity of rotation, which at present, is about 16 millionths of a second per year. At the beginning of the Cambrian approximately one-half billion years ago, a day was two and a quarter hours shorter and one year had 400 days.

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The concept that mountain building occurs in phases, which globally act at the same time, was supported by Élie de Beaumont (1852) although Lyell (1833) had previously argued resolutely against it. This theory assumes that tectonic events that deform rocks and lead to folding in mountain ranges occur globally in temporally very limited phases. It was insistently advocated and improved by Stille (1913 and later publications). The concept of tectonic phases is not accepted today in its original, rigid form; however, it is well known that plate-tectonic events tend to create widespread, relatively synchronous mountain-building events.

The scientific dispute as to whether vertical or horizontal forces are the primary drivers of mountain building is today clearly settled in favor of the horizontal forces. However, these forces have their origin in the dynamics of plate tectonics and not in a shrinking Earth. The uplift of a mountain range is a secondary process that is induced by the horizontal movement of crustal blocks.

At the beginning of the 20th century, a significant advancement in tectonics developed through studies of large geologic structures in the Alps (Lugeon, 1902; Termier, 1904). Outcrops displayed rock patterns with kilometers to tens of kilometers of overthrusting that had formed during mountain building processes. These overthrust units are called nappes and are characteristic of nearly all mountain ranges. This proved that mountain ranges are zones of extreme compression and crustal shortening; furthermore, results from geophysical investigations indicate that the continental crust beneath mountain ranges is significantly thickened and shortened. Because this thickened stack of continental crust below the mountains is significantly less dense than the displaced mantle below, according to the principle of isostasy, a buoyancy develops that leads to increase in topographical elevation. The relations between crustal shortening and thickening are complex and critical to the understanding of the tectonics of mountain building.

From continental drift to plate tectonics

Since the end of the 16th century, naturalists have noted the similarity of the coastlines on both sides of the Atlantic and concluded an original unity followed by later drift of the continents. The English philosopher Francis Bacon (1561–1626), who had access to the first accurate maps of the continents, was the first to make this point. Early explanations were sought, but at this point were in vain. The Flemish cartographer Abraham Ortelius (1527–1598) stated in 1596 that America was torn off from Europe and Africa by earthquakes and floods (Braun and Marquardt, 2001) – an interpretation, though without evidence when Ortelius wrote it, that stands today. In 1756 the German theologian Theodor Lilienthal found the biblical confirmation of this observation: “And unto Eber were born two sons: the name of one was Peleg; for in his days was the Earth divided” (First Book of Moses, 10:25).

From 1910 until his early death in 1930 the German meteorologist Alfred Wegener published works that attempted to add credibility to his theory of continental drift (**Fig. 1.1**; Wegener, 1912, 1915, 1929). Although his observations were supported by geographic fit, fossil evidence, and geologic patterns across the Atlantic, he was never able to convince a skeptical audience who demanded more proof – and especially an explanation for the mechanism that propelled the continents long distances. But he kept trying; his publications suggested that the continents were composed of lighter, less dense materials that he termed sial – an acronym that reflects the prevailing elements silicon and aluminum. The lighter continents drifted across the denser material of the Earth’s mantle and the ocean floor, his sima – an acronym for silicon and magnesium. Sial was able to drift or plow through sima. He proposed that the driving forces behind continental drift were derived from known forces such as the rotation of the Earth, precession (a small conical rotation) of the Earth’s axis, or tidal friction. The rotation of the Earth would produce polar escape, the slow drifting of the continents away from the poles, and the westward drift of the continents. Wegener used these forces to explain specific mountain ranges and the folding associated with them. Polar escape formed the mountain ranges that extend from the Alpine-Mediterranean area across the Iranides and into the Himalayas and Southeast Asia; they formed due to the convergence of Eurasia, which was drifting southward from the North Pole, and the southern continents Africa and India. The western drift from the Earth’s rotation formed the high mountain ranges along the western coast of the Americas by frontal compression. Coincidentally and independently, similar ideas were expressed by the American geologist F. B. Taylor (Taylor, 1910).

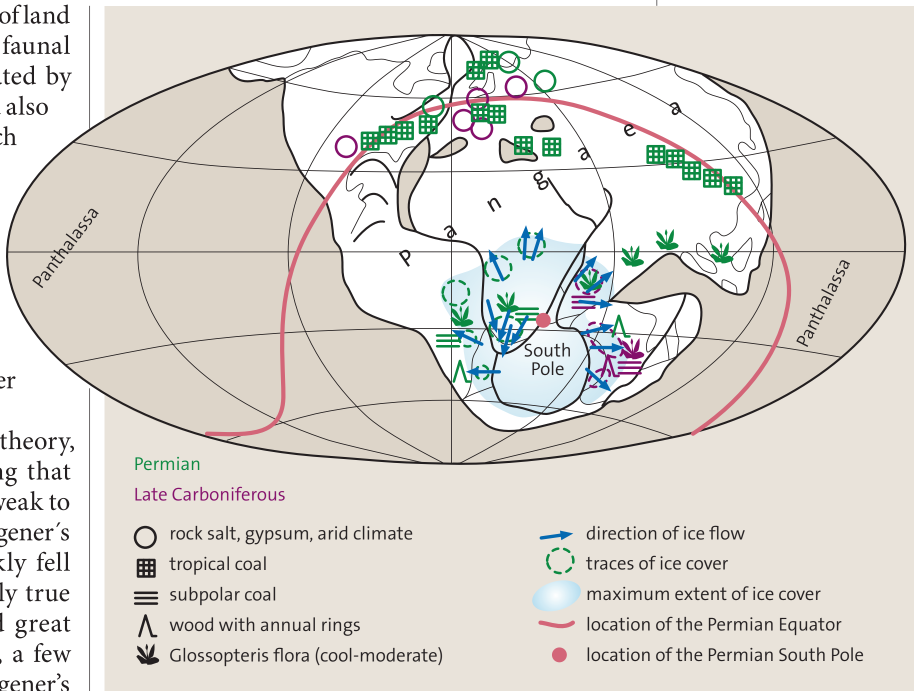
Wegener’s theory of continental drift could explain a number of problems that existed during his time: (1) the fit of the coastlines along both sides of the Atlantic, (2) the linear and narrow shape of the mountain ranges (the contractional theory in fact should produce much wider orogens), (3) the dominance of two levels of global altitude, the deep-sea abyssal plains and the broad continental lowlands (each reflects the two types of crustal material – oceanic and continental; **Fig. 1.2**), (4) the otherwise inexplicable appearance and disappearance of land bridges that were necessary to explain the faunal exchange between continents now separated by large oceanic areas. Continental drift could also explain why indicators of warm climates, such as Carboniferous coals, are today found near the poles. He postulated that all large continental blocks were unified at the end of the Paleozoic and beginning of the Mesozoic into one large continent that he named *Pangaea* (*Greek* all the land). His paleogeography followed similar illustrations of Pangaea published by Antonio Snider (1859) and Howard B. Baker (1911).

In spite of a seemingly comprehensive theory, physicists rejected Wegener's ideas stating that the forces suggested by him are much too weak to explain the drift of the continents. After Wegener´s death, the continental drift theory quickly fell out of scientific favor. This was particularly true in America where Wegener had aroused great scientific hostility. Meanwhile in Europe, a few scientists continued to examine some of Wegener's ideas – ideas that would lead eventually to the theory of plate tectonics.

While many of the geologists mentioned above were looking at rocks exposed at the surface of the Earth, several Alpine geologist began to look deep into the Earth for answers regarding the origin of mountains. Eduard Suess, in his magnificent and revolutionary multi-volume work "Das Antlitz der Erde" (The Face of the Earth), suggested that the deep-sea trenches along the border of the Pacific are zones where the ocean floor plunges beneath the continents (Suess, 1885–1909). Otto Ampferer (1906) presented the theory of undercurrents (*German: Unterströmungstheorie*) which postulated that compression and nappe transport were forced by mass currents beneath the mountain ranges. Robert Schwinner (1920) took these ideas to develop a more far-reaching theory that assumed that currents in the Earth's interior are produced by convective heat transport. Subduction replaced the older German term "Verschluckung" that was used by Ampferer; André Amstutz (1951) used the term subduction in conjunction with the development of tectonic nappes in the Swiss Alps. The term was later adopted and used by plate tectonicists (White et al., 1970). Many of the above concepts were amalgamated into a mobilistic model of geodynamics by the British geologist Arthur Holmes (1931, 1944), who proposed that convection currents were the driver of the Earth's tectonic system.

The mechanisms proposed by Ampferer, Schwinner, and Holmes suggested that rising currents underneath continental extensional structures and oceanic ridges, mountain building above descending branches of currents and continental drift on top of the horizontal parts of the currents drove the Earth's tectonic engine. Their ideas are not far from those of modern plate tectonics. Interestingly, if Schwinner and Wegener, who were both professors at the university of Graz (Austria) in the 1920's, would have communicated, they could have unified the drift theory with the correct theory of driving mechanism thus accelerating the development of the theory of plate tectonics. Meanwhile, German research vessels discovered the large, long-stretched submarine mountain ranges that today are known as mid-ocean or mid-oceanic ridges and are a key to the concept of modern plate tectonics. But scepticism to all of this persisted well into the 1960's, especially in America, where a geologist is purported to have said: "I only accept the theory of continental drift if the head of a fossil will be found in Africa and the tail in South America".

The general acceptance of continental drift was achieved in the 1960's with the development of the theory of plate tectonics (for compilations of the most important early literature on plate tectonics see: Bird and Isacks, 1972; Cox, 1973). Modern investigations of the previously inaccessible ocean floor and in particular the discovery of the striped pattern of magnetic polarities (see below) at both sides of the mid-ocean ridges led to the concept of "sea-floor spreading", the dispersion of ocean floor from the mid-ocean ridges. Now for the first time,



▲ **Fig. 1.1** Reconstruction of the supercontinent Pangaea after Wegener (1915). The diverse geological and climatological data from different continents fit like a jig-saw puzzle on this reconstruction. Panthalassa was the giant ocean that stood opposite to Pangaea.

data supported a firm base on which to build the theory of plate tectonics and geologists had a single unifying model, which as it developed in the following years, could unify all basic geological and geophysical phenomena. The vast accumulation of data and knowledge since the inception of the basic model, have tweaked the original, but the basic tenants remain steadfast 50 years later. Plate tectonics remains the first and only global geodynamic theory which orchestrates all known tectonic phenomena including earthquake zones, mountain building, structural patterns, nature of sedimentary basins, magmatism, and metamorphism – plate tectonics is an elegant and comprehensive synthesis of Earth's geodynamics.

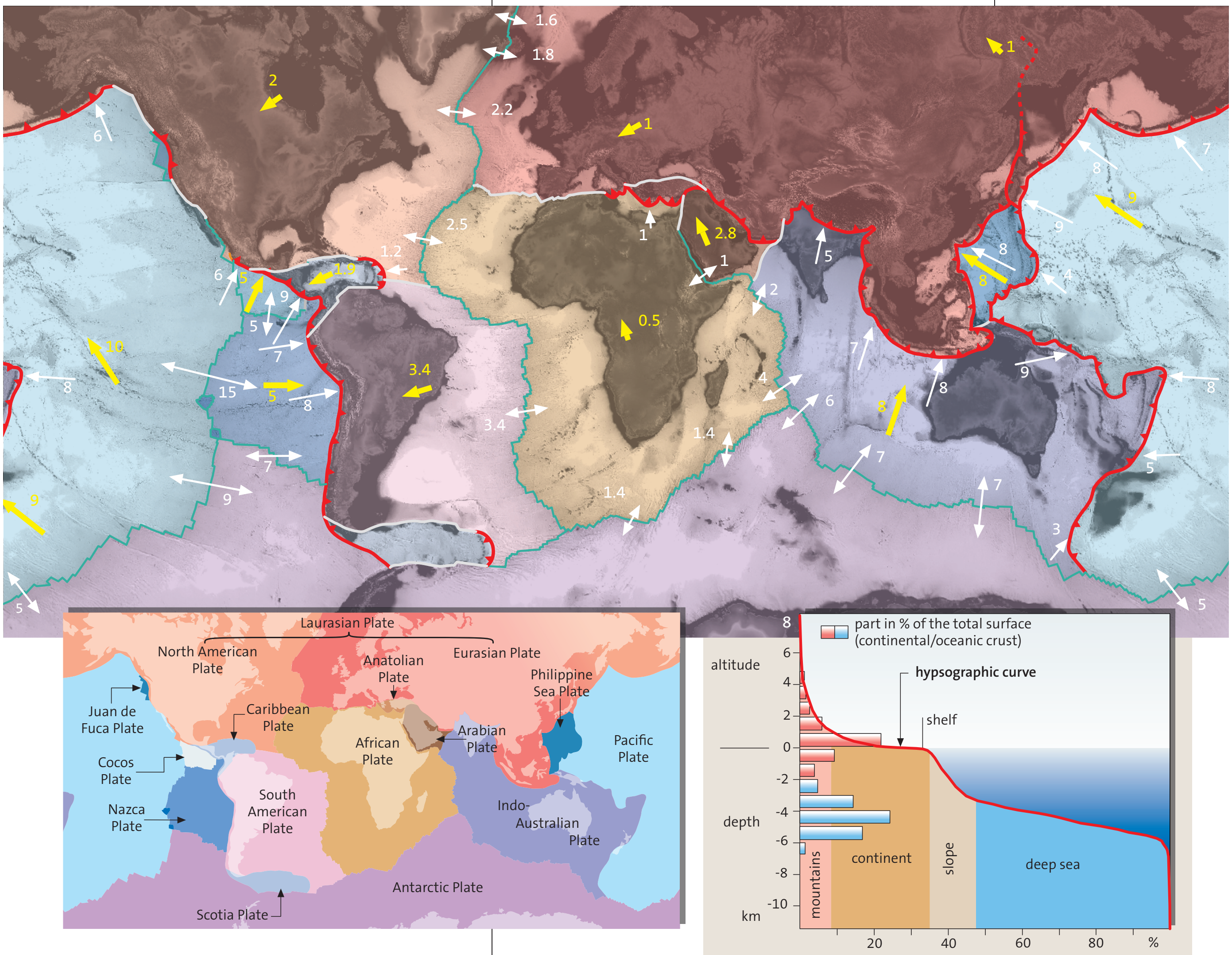
One of the strongest tenants of the theory of plate tectonics is that it is based on the tectonics of present Planet Earth (e. g., Hess, 1962; Vine and Matthews, 1963; Wilson, 1965; Isacks et al., 1968; LePichon, 1968; Morgan, 1968; McKenzie and Morgan, 1969; Dewey and Bird, 1970). Therefore, plate tectonics is an actualistic model. Geologists attempt to apply this concept to mountain building throughout Earth history. This application has been successful in most cases over the last 2 billion years of Earth history. Of course numerous older mountain ranges have generated contrasting hypotheses regarding the details of their origin as much original information has been destroyed during later mountain building processes. Also, all ocean crust older than ca. 180 million years has been destroyed so detailed reconstructions of oceans older than this are not directly possible. Furthermore, mountain building older than 2.5 Ga (*Giga anni* – billions of years ago) does not straightforwardly conform with modern plate tectonics because the outer layers of the Earth – the place where plate tectonics is manifested – were somewhat different back then (Ch. 11).

The plate tectonic concept

The outermost two layers of Planet Earth, the lithosphere and asthenosphere, are directly involved in plate tectonics and are the only parts of Earth described in detail here. The term plate tectonics takes its name from the rigid lithospheric plates that form the outermost shell around the entire Earth. The size of individual plates is significantly different (**Fig. 1.2**). The lithosphere (*Greek* shell of rock) ranges in thickness from 70 to 150 km or more, thicker below the continents, thinner below the oceans. Beneath some mountain ranges it may exceed 200 km in thickness. It consists of two components – the crust (oceanic or continental), and the lithospheric part of the mantle (**Fig. 1.3**). The lithospheric mantle behaves in brittle fashion and contrasts in this regard from the underlying "plastic-like" *asthenosphere* (*Greek* weak shell). The asthenosphere behaves in ductile fashion and locally contains pockets of molten rock. These attributes point out the significant difference between Wegener's theory of continental drift and the theory of plate tectonics – the former suggested that continental blocks somehow plowed through the oceans but the latter documents that rigid plates, containing both continental and oceanic crust, move on top of ductile mantle.

Earth's crust, which forms the uppermost 5–60 % of the plates, is generally divided into two types, continental and oceanic. Continental crust has an average thickness of 30–40 km but ranges up to 70 km under mountain ranges and high plateaus like the Andes or the Tibetan Plateau. Unlike the pure geographic definition, continents consist of both land and their adjacent shelf areas covered by shallow seas. Oceanic crust is markedly thinner with typical thicknesses of 5–8 km and forms the ocean floor. The top of oceanic crust lies an average 4–5 km deeper than that of the continental crust (**Fig. 1.2**). This stunning bimodal distribution of Earth's surface defines the first-order aspect of topography and controls the primary pattern of land versus sea – most land and continental shelf areas lie within several hundred meters of sea level and most ocean floor lies 5 km below sea level. In fact, the fit of the continents across the Atlantic, the prime piece of evidence to Wegener's continental drift, is nearly perfect at the 500 fathom (~1000 m) contour – the famous Bullard fit (see **Fig. 4.7**; Bullard et al., 1965).

The bimodal elevation of Earth is a direct reflection of the difference in composition and density between continental and oceanic crust. Continental crust consists of relatively light (less dense) material that consists of acidic (rich in silicic acid, > 65 weight percent SiO_2), granitic and metamorphic rocks (granites, granodiorites, gneisses, schists); hence the expression that continental crust is granitic. Primary mineral components include potassium and sodium feldspar, quartz, and mica, especially in the upper portions of the crust. In deeper parts of continental crust, the amount of basic (poorer in SiO_2) minerals such as hornblende and amphibole increase and rocks types include diorite and gabbro. The average density of the continental crust is 2.7–2.8 g/cm³, and the average chemical composition is that of an andesite or diorite, magmatic rocks with an intermediate content on SiO_2 (about 60 % SiO_2). Oceanic crust consists of basic basaltic rocks (~50 % SiO_2), mostly basalts and gabbros; density averages about 3.0 g/cm³, and calcium-rich feldspar and pyroxene are the most important minerals.

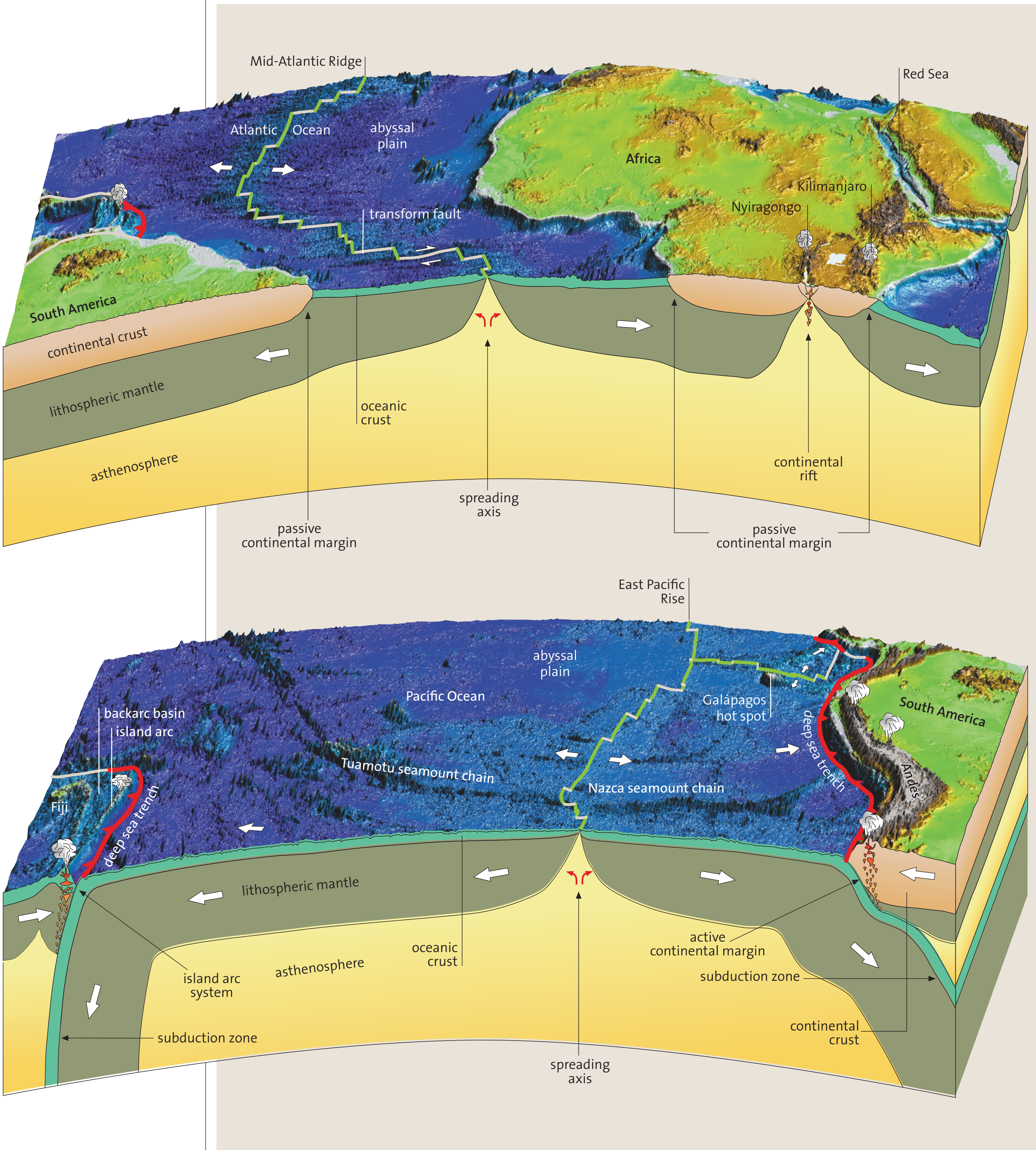


▲ **Fig. 1.2** Map showing the present plate configurations and plate motions on Earth; plate names shown on insert. White arrows indicate relative motion along plate boundaries (see Ch. 2) and yellow arrows indicate absolute plate motions related to a reference system based on stationary hot spots (see Ch. 6; DeMets et al., 1994). Constructive plate boundaries (mid-ocean ridges) are marked by green lines, destructive plate boundaries (subduction zones) by red lines (teeth point towards the upper plate), and conservative plate boundaries (transform faults) by gray lines. The hypsographic curve (box in the lower right) indicates the percentage of different topographic levels on the continents and under the sea. Continental and oceanic crust are characterized by different topographic levels.

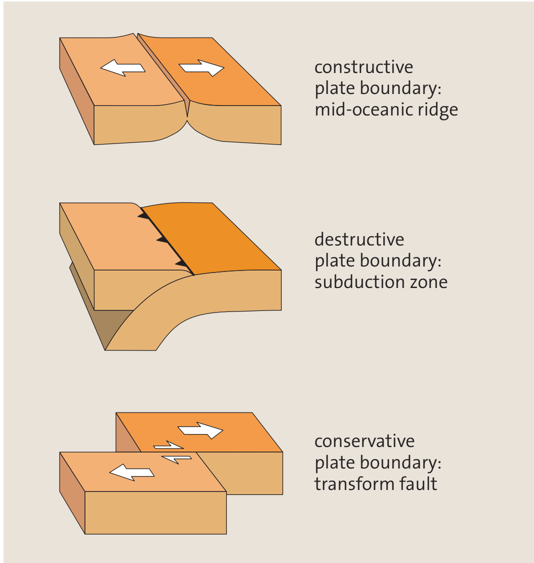
The mantle lithosphere is composed of ultrabasic peridotites (~42–45 % SiO_2) that have a density of 3.2–3.3 g/cm^3; the main mineral components are olivine and pyroxene.

The lithospheric plates move against and towards each other with different velocities in different directions (**Fig. 1.2**). This raises the question of how a balance is possible within a closed system of plates across the sphere of the Earth. According to the Euler theorem of 1770 the movement of an object at the surface of a sphere occurs by rotation around an axis that passes through the center of the sphere. Therefore, all plate motions are defined by a rotation around such an axis plus an angular velocity (see Ch. 2). Plate motion results in three types of plate boundaries: constructive, destructive, and conservative (**Fig. 1.4**).

Constructive plate boundaries are characterized by diverging plates – commonly referred to as divergent plate boundaries. The developing gap along the line of separation is immediately filled by newly formed lithospheric material including oceanic crust; hence the term constructive plate boundary. Constructive plate boundaries are represented by the *mid-ocean ridges* – the under sea mountain ranges that circle the Earth like seams on a baseball. Ridges are formed by rising basaltic melts generated from the mantle asthenosphere, that solidify to brittle ocean crust. The topographic mid-ocean ridge (spreading axis in **Figs. 1.3, 1.5**) reflects the



▲ Fig. 1.3 Block diagrams of the outer shells of the Earth in the Atlantic and the Pacific region. Shown are the three types of plate boundaries, passive and active continental margins, island arcs, volcanic chains fed by hot-spot volcanism, and a graben system (strong vertical exaggeration). The plates consist of crust and lithospheric mantle. Relief data are from etopo30 (land surface) and gtopo2 data by Smith and Sandwell (1997), and etopo1 data by Amante and Eakins (2009).



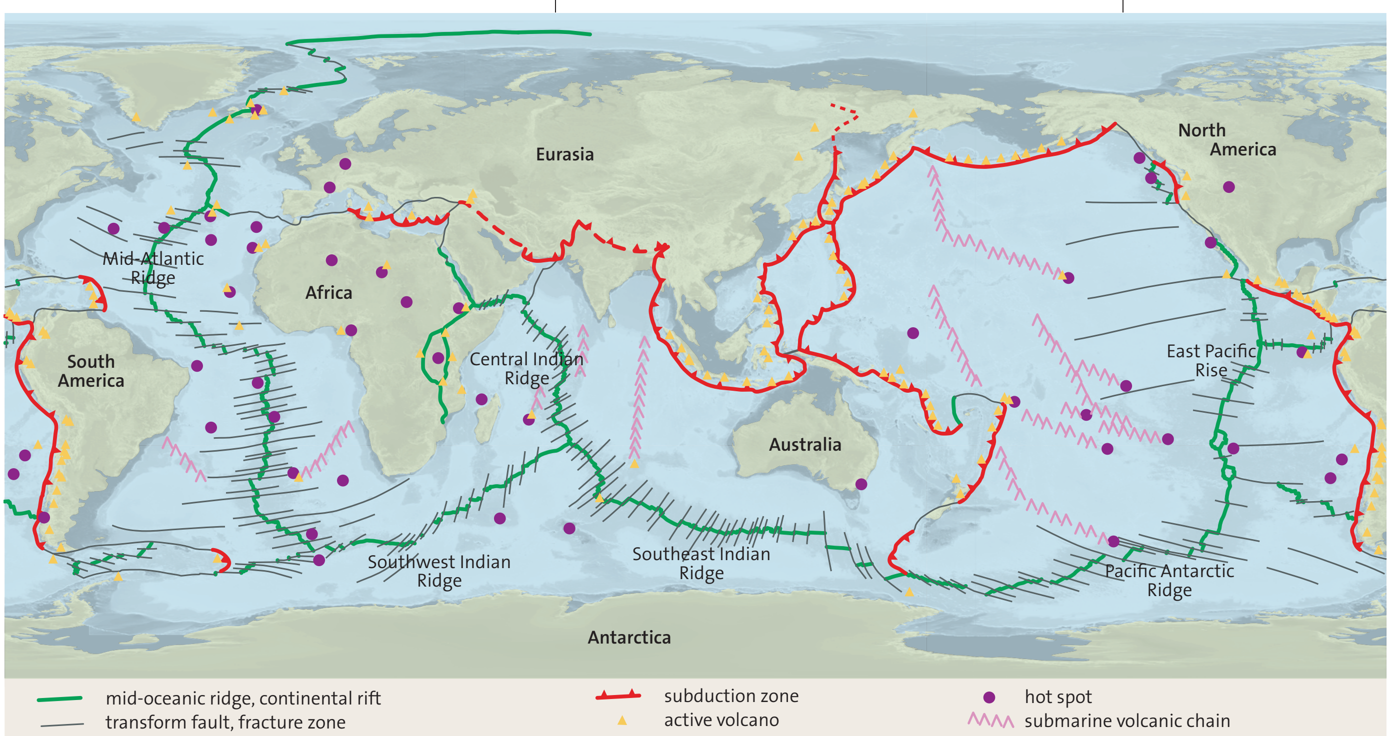
◀ **Fig. 1.4** Block diagrams showing the three types of plate boundaries.

warm, less dense lithosphere that underlies it (older oceanic lithosphere is more dense and expresses the low topography of the abyssal ocean plains). The ocean floor spreads from constructive plate boundaries, hence "sea-floor spreading".

Destructive plate boundaries are characterized by converging plates. Where two plates move towards each other, the denser plate is bent and pulled beneath the less dense plate, eventually plunging downward at an angle into the depths of the sub-lithospheric mantle. Such areas are called *subduction zones*. Eventually the subducted plates become recylced into the mantle and thus destroyed. At convergent boundaries as they are commonly termed, only dense, oceanic lithosphere can be diverted into the sub-lithospheric mantle in large quantities; thicker, less dense continental lithosphere can not subduct very deeply – this explains why old continental crust, billions of years old exists today while no ocean crust greater than ca. 180 Ma (*Mega anni* – millions of years ago) is present – older ocean crust has all been recycled. Surface expression of subduction zones is manifested in the deep-sea trenches, common features around the Pacific Ocean (**Figs. 1.3, 1.5**).

Conservative plate boundaries occur where two plates slip past each and little or no crust is created or destroyed in the process. These boundaries are also characterized by strike-slip or *transform faults* and are commonly called transform margins. Transform faults are rare in the purely continental realm. Mid-ocean ridges on the other hand are cut by numerous, mostly relatively short transform faults (**Figs. 1.3, 1.5**). Such faults connect two segments of the ridge that are apparently shifted relative to each other. The prolongation of oceanic transform faults contain *fracture zones* with little tectonic activity that in many cases can be traced for long distance on the ocean floor. Where oceanic transform faults intercept continental crust at oblique angles, the faults can penetrate deeply into the adjacent plate and create large distances of

▼ **Fig. 1.5** First-order tectonic elements of Earth. Each of the present plates is readily discernable.



lateral offset; the San Andreas Fault of California is such an example (Ch. 8).

The motions of the individual plates can be described by their relative movements along the plate boundaries. As a geometric constraint, the sum of the movements of all of the plates must result in zero (Ch. 2). From a global perspective, the drifting apart of the plates at constructive boundaries must be compensated by the opposite movement and destruction of lithosphere at destructive boundaries.

The pattern of magnetic polarity stripes

The discovery and interpretation of the striped pattern of magnetic polarities (**Figs. 1.6, 1.7**) led to the concept of sea-floor spreading. Although generally ascribed to Vine and Matthews (1963), L. W. Morley submitted a paper a year before that was rejected because the reviewers considered the idea absurd (Cox, 1973).

Minerals and the rocks in which they are contained acquire a magnetic signature as a given mineral cools below a certain temperature, its Curie temperature. Below the Curie temperature, named after the physicist Pierre Curie, a given mineral acquires the magnetic signature of the Earth's magnetic field that was present at that time. As an example, magnetite has a Curie temperature of 580 °C. Three signatures of magnetism are generally infused into magnetic minerals: inclination, which reflects latitude; declination, which reflects direction to the poles; and normal or reversed polarity, which indicates magnetic reversals (by convention, the current situation is defined as "normal"). Magnetic signatures in minerals are maintained for hundreds of millions of years, although some overprinting from subsequent geologic events does occur so that samples must be "cleaned" to eliminate younger events. Also, the perturbing effect of the current magnetic field must be compensated for during the analysis of the sample.

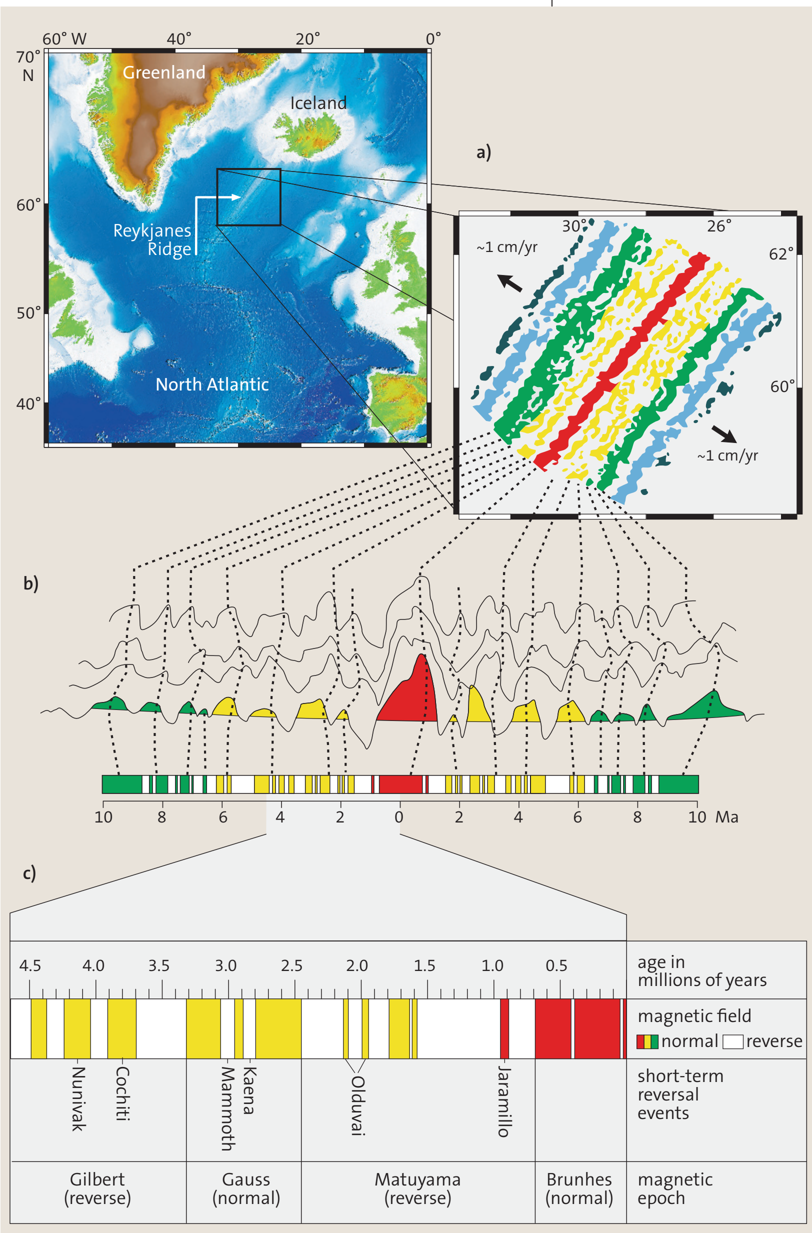
The magnetic pole moves around the geographic pole (the rotational pole of the Earth) in an irregular, sinuous manner to produce what is called secular variation. However, averaged over a period of several thousand years the two poles coincide. Therefore, the orientation of earlier geographic poles can be detected using paleomagnetics if the mean value is calculated from enough samples. The present magnetic South Pole is located near the geographic north pole. This has not alwas been the case. At very irregular intervals over periods of variable duration, the polarity reverses and the earlier South Pole becomes the North Pole and the other way round.

Using dated basaltic and other rocks with magnetic signatures on land, a magnetic time scale has been defined that displays the periods and epochs with normal (like today) and reversed magnetization. These patterns of magnetization are found parallel and symmetrically aligned to the oceanic ridges (**Fig. 1.6**). Based on the characteristic patterns of normal and reversed magnetization, the stripes can be dated by comparing them with known sequences. This is very strong proof for sea-floor spreading because the method shows that variable magnetic stripes of oceanic crust are formed parallel to the ridges and that they become older with increasing distance to the ridge (**Fig. 1.7**). It was the discovery of this symmetric pattern parallel to the ridges that proved in the early 1960's the concept of sea-floor spreading and associated drifting of continents, two of the most basic tenants of plate tectonics. Magnetic reversals in oceanic rocks only yield data back to approximately 180 Ma, the Early Jurassic (see **Fig. 2.12**) – all older oceanic crust has been subducted. A paramount reason for this fact is that older ocean crust is colder and more dense, and therefore subducts more readily; for example, if 20 Ma ocean crust and 150 Ma ocean crust collide, the older will be subducted (Ch. 4).

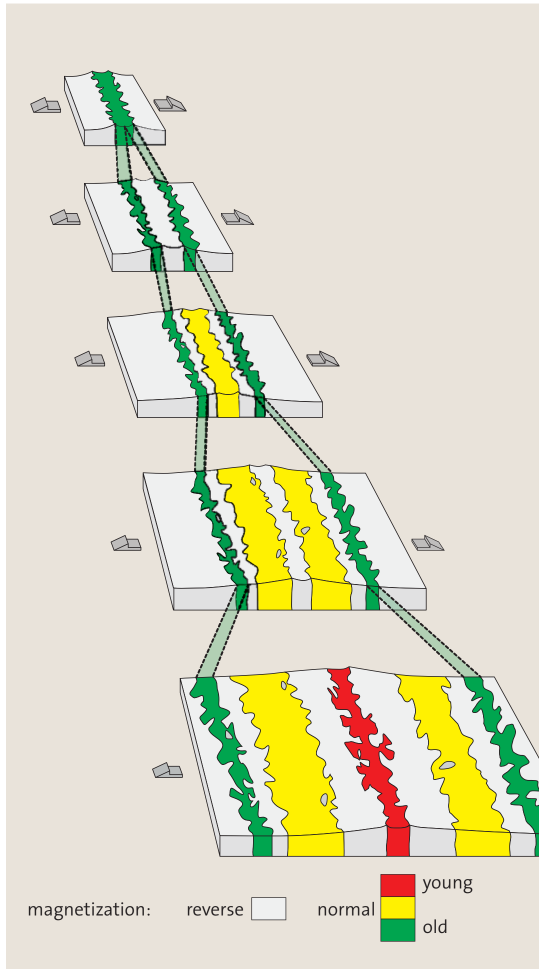
Plate motions and earthquake zones

Convectional currents in the sub-lithospheric mantle are interrelated to overlying plate motions. Based on the propagation behavior of earthquake waves, it is known that the Earth's mantle is primarily in a solid state. Nevertheless, it is able to flow on the order of several centimeters per year; this value is close to the velocity of plate motion. The flow motion is facilitated by gliding processes along mineral grain boundaries, a condition accentuated by the high temperature conditions in the Earth's mantle. The Earth's mantle contains relatively small but important areas where molten material forms a thin film around and separates the solid mineral grains. The mobile asthenosphere directly beneath the lithosphere is assumed to contain a few percent of molten material.

The pattern of convection cells movement in the Earth's mantle is extremely complex and has even been "photographed" using seismic tomography, which is a technique based on methods used in the medical industry (Ch. 2). Probably, the outermost system of convection cells in the upper mantle (down to about 700 km depth) is separated from a second system in the lower mantle; both systems, however, are strongly interrelated and induce and influence each other. Tomography suggests that rising and descending currents in both parts of the mantle commonly have the same spatial distribution. The Earth's core, which consists predominantly of iron and nickel, has an outer liquid shell



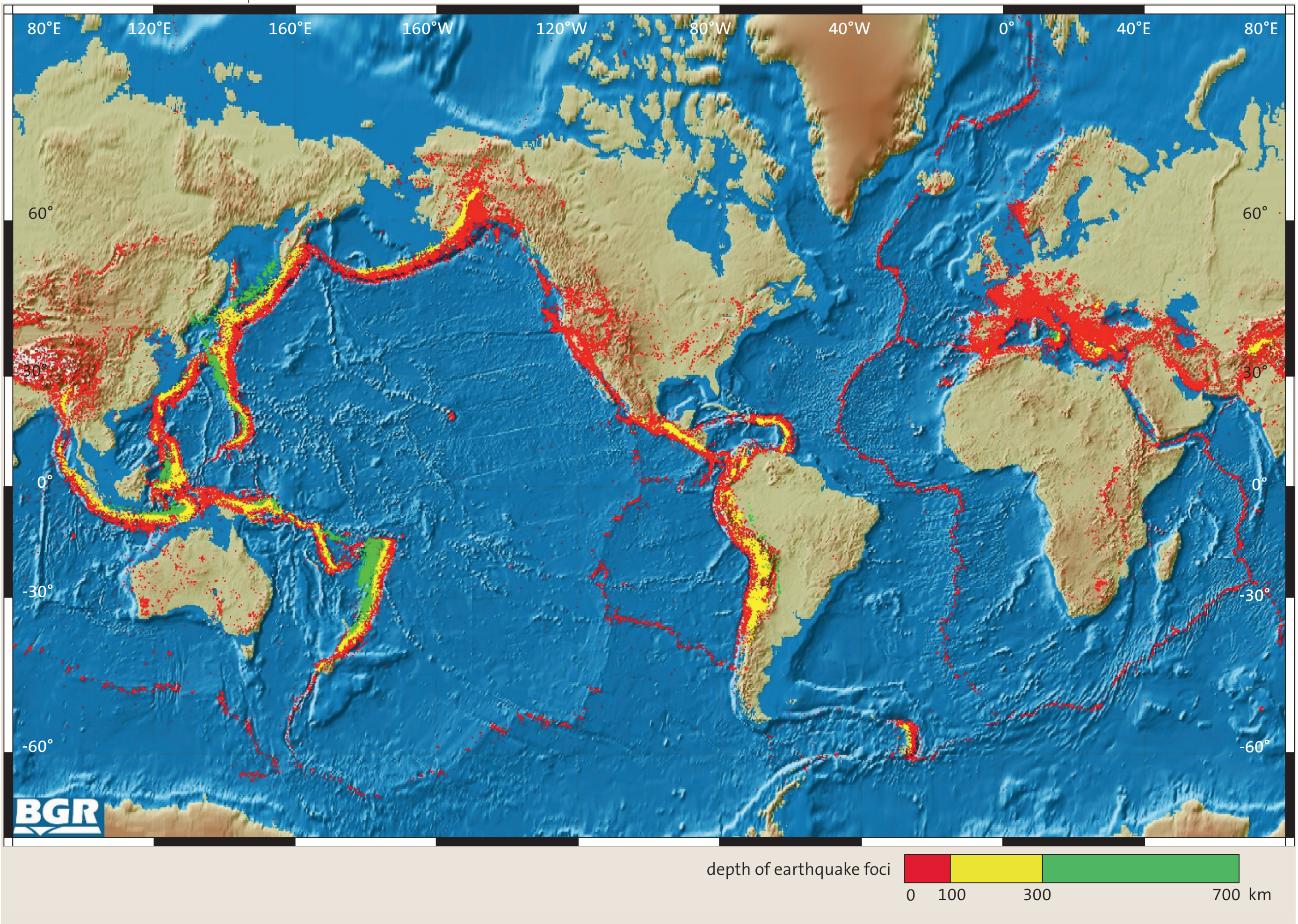
◀ **Fig. 1.6** **a)** Stripe pattern of magnetic polarities on the ocean floor at the Reykjanes Ridge, part of the Mid-Atlantic Ridge southwest of Iceland (Heirtzler et al., 1966). **b)** Curves representing the magnetic field strength measured along the track of ships crossing the ridge. Normal (in colors) and reverse magnetization can be obtained from these curves. **c)** Graph showing detailed magnetic stripe pattern for the last 4.5 Ma. By comparison with measured profiles, the ocean floor can be dated.



▲ **Fig. 1.7** Simplified sketch showing development of the magnetic stripe pattern along the spreading axis. The pattern is caused by repeated reversals of the Earth's magnetic field. Irregularities of the stripes are caused by submarine extrusion of basaltic lavas that adapt to the existing, commonly rough topography.

that surrounds an inner solid sphere. The relations of the core to convection cell currents and plate motions are still under investigation. However, it can be assumed that interactions and material transfer occur.

Relative movements of the plates along the plate boundaries induce earthquakes. The gliding process between the plates produces great but variable stress. Stress is induced along slip planes within rocks, which to a certain degree are elastically deformable, and is released in a jerky movement when a limiting value is reached. Looking at the distribution map of earthquake epicenters (points at the Earth's surface directly above the earthquake center) it impressively shows that earthquakes are mainly restricted to narrow zones around the globe (**Fig. 1.8**), the present plate boundaries. Distribution of earthquakes varies at different types of plate boundaries. Deep earthquake centers occur only along subduction zones, whereas shallow earthquakes occur at all plate boundaries. Moreover, distributed earthquake centers can be found elsewhere indicating that the plates are not free of deformation in their interior parts that may be cut by large fault zones. The rates of movement at intra-plate fault zones are generally less than a



▲ **Fig. 1.8** Global distribution of earthquake centers with epicenters mapped according to their depth. Note how the epicenters define plate boundaries (Fig. 1.5); also note that most earthquakes occur within 100 km of the surface except along subduction zones where they deepen under the upper plate (produced with the kind support of Mrs. Agneta Schick, Federal Institute of Geosciences and Resources, BGR, Hannover, Germany).

few millimeters per year when averaged over long geologic periods of time; this tends to be an order of magnitude less than rates at plate boundaries.

Globally, earthquakes are strongly concentrated along destructive plate boundaries and are especially notable ringing the Pacific Ocean. Zones of epicenters are relatively wide (**Fig. 1.8**) because the subducting plates that produce the earthquakes plunge obliquely into the mantle. Subduction zones can be traced downward, using earthquake foci (the location and depth of the earthquake) to depths of approximately 700 km. The map view of the plate boundary is located at the trench side of the earthquake belt where the centers are at a shallow depth; the boundary plunges downward at different angles. Earthquake foci at shallow depths, with epicenters mostly near the surface of the plate boundary, may have devastating consequences – these are the locations of the Earth's most destructive earthquakes.

Along transform faults the epicenters of earthquakes are much more concentrated near the surficial trace of the plate boundary because the fault zones are vertical. Where transform faults cut through continental crust, they may also cause devastating earthquakes similar to the shallow earthquakes at subduction zones. Friction is generated by the thick, stiff plates and is dependent upon the motion velocity between the plates. Examples of continental transform faults include the San Andreas Fault in California and the North Anatolian Fault in Asia Minor.

Earthquake activity is much less at mid-ocean ridges. Uprising currents transport molten rock material to the Earth's surface and the stiff shell that accumulates and releases stresses is quite thin. Hot and recently solidified rock material is more likely to deform plastically. Therefore, only small, shallow earthquakes occur. Nevertheless, the constructive plate boundaries are also clearly visible on the earthquake map (**Fig. 1.8**).

Young mountain ranges like the Alps-Himalaya belt or the Andes-Cordillera belt, which are still tectonically active, are also characterized by frequent earthquakes. Because of the diffuse collision of large continental masses, wide zones of deformation with numerous slip planes develop. Therefore, exceptionally wide belts of shallow earthquakes occur in these zones (**Fig. 1.8**). Occasional deeper earthquakes testify to the preceding subduction activity.

Two kinds of continental margins

Nearly all of the presently existing plates contain areas with both continental and oceanic crust. A good example includes the large plates on either side of the Mid-Atlantic Ridge, one of Earth's most prominent plate boundaries. This plate boundary separates the two American plates from the Eurasian and African plates, all of which have large amounts of both continental and oceanic crust (**Figs. 1.2, 1.5**). The Indo-Australian, the Antarctic and many smaller plates also contain both crustal types. In contrast, the huge Pacific Plate which extends westward from the East-Pacific Rise to the eastern Asian island arc systems, contains only very small amounts of continental crust, mostly in California and New Zealand. The Philippines, Cocos, and Nacza plates – smaller plates that surround the Pacific Plate – only contain oceanic crust.

The fact that most plates contain both crustal types means that some boundaries between oceans and continents occur within a given plate; hence, two types of continental margins exist. Where continental crust merges with oceanic crust, shelf areas generally slope towards the abyssal plains – thus the ocean-continent boundary is an intra-plate feature. Continental and oceanic crust belong to the same plate. Such continental margins are widespread around the Atlantic Ocean. Here only slight (mostly vertical) movements occur; therefore, they are commonly called *passive continental margins* (**Fig. 1.3** upper part). Passive continental margins do not represent plate boundaries.

On the other hand, *active continental margins* are those margins where a plate boundary exists between continent and ocean. Two types occur – subduction margins and transform margins. At subduction margins, a part of a plate with oceanic crust is being subducted beneath the continental crust. At transform margins, the oceanic plate slides laterally along the continental margin. A deep sea trench forms along subduction zone plate boundaries. This type of continental margin is today prominent along the Andes (**Fig. 1.3** lower part) and along numerous subduction zones around the Pacific Ocean that are characterized by island arc systems. The margin of the upper plate in these cases is characterized by chains of volcanic arcs, built either on continental crust or on continental pieces that were separated from the neighboring continent.

Magmatism and plate tectonics

Magmatic belts as well as earthquake activity are closely related to plate boundaries. The average yearly production of magmatic (volcanic and plutonic) rocks formed at destructive plate margins is slightly less than 10 km^3 (Schmincke, 2004). The melting that produces magmatism is caused by complex interrelations between the asthenosphere and the subducting plates plunging into it. These melts, which are marked by specific chemical characteristics, intrude into the upper plate and feed volcanic chains above subduction zones (**Figs. 1.3, 1.5**) to produce subduction related magmatism. Modern examples include the eastern Asian island arcs (island arc magmatism) and the Andes (magmatism at an active continental margin).

Mid-ocean ridges are the location of major production of basic magmatites, namely basalts and gabbros. High temperature and pressure release beneath the ridges combine to generate partial melting of up to ~20 % the rocks of the mantle (peridotite). Oceanic crust develops from these melts and annually more than 20 km^3 of new crust is formed (Schmincke, 2004). Therefore, mid-ocean ridges generate more than twice the amount of melts than are generated above subduction zones. At transform faults significant melting does not occur so magmatic processes are unimportant.

Although constructive and destructive plate boundaries are responsible for the formation of most of Earth's magmatic rocks, annually approximately 4 km^3 of magmatic rocks are produced in intraplate settings. This intraplate magmatism is mostly related to hot spots (**Fig. 1.5**). Hot spots are point-sources of magma caused by mantle diapirs and occur on either the continents or oceans. Diapirs are hot, finger-like zones of rising material within the mantle. When they reach the upper asthenosphere beneath the plates, melting is induced that creates volcanic eruptions and doming of the surface over long time periods. Hot spots are less commonly superimposed on constructive plate boundaries.

Modern continental hot spots include the Yellowstone volcanic field in North America, the French Central Massif and the volcanic Eifel Mountains in Europe, and the Tibesti Mountains and the Ahaggar (Hoggar) in North Africa (**Fig. 1.5**). Modern oceanic hotspots include the active part of the Hawaiian Archipelago and the Canary Islands; Iceland is an example of a hotspot superimposed on a mid-ocean ridge. As plates drift over hot spots, long volcanic chains develop with the hot spot located at the active end; Hawaii is a good example of this (**Fig. 1.5**). On continents, hot spots are commonly related to graben structures characterizd by extensive, deep fault systems that cut through the entire thickness of continents; the best known example are the volcanoes of the East African graben system. Graben structures are characterized by crustal extension and bordered by faults; such areas cause thinning of the lithosphere and provide the opportunity for magma to rise along fault zones. If extension continues, new ocean can be formed at these structures. An example for such a newly developing ocean is the northern part of the East African graben system (Afar) and the Red Sea (Ch. 3). The so-called Afar triangle is also characterized by a hot spot. Graben structures may be transferred into constructive plate boundaries where the hot spot commonly plays an important role.

What drives the plates and what slows them down?

The growing plate boundaries at mid-ocean ridges always forms new oceanic lithosphere because the basaltic/gabbroic oceanic crust is a product of partial melting directly from the mantle; on the other hand, continental crust forms by much more complicated melting and recycling processes above subduction zones (Ch. 7). Only oceanic lithosphere can be completely reintegrated into the mantle at subduction zones whereas subducted continental crust experiences strong buoyancy and accretion to the overlying plate. Plate movements are thus mainly controlled by the formation of oceanic lithosphere at the oceanic ridges, and its subduction and reintegration into the Earth's mantle at destructive margins. Oceanic lithosphere, therefore, forms the conveyor belt of plate tectonics whereas the continental blocks go along for the ride.

In fact, the driving forces for the plate movement are to be found under the mid-ocean ridges and in the subduction zones – at the plate boundaries. Plate motion is thus orchestrated by rising magma at the mid-ocean ridges and sinking dense lithosphere at the subduction zones (Bott, 1982). These processes are called "ridge push" and "slab pull". Ridge push is caused by the upward movement of hot and relatively light rock melts at the mid-ocean ridges where, in the area of newly forming lithosphere, the vertical movement is transferred into a horizontal vector that pushes the plates apart. Slab pull arises because of the higher density of cooled lithosphere with respect to the mantle underneath. Of the two driving forces this is the more important one. Mineral changes to denser species that, because of lower temperatures in the descending plate, occur at shallower depth as compared to that of the surrounding mantle, intensify this process. An earlier idea that suggested that the carrying of middle parts of plates on top of the horizontal currents of the asthenosphere may, however, not be important in plate motion and, in contrast, actually hinder the process in certain regions.

Ridge push and slab pull act in accord with the state of stress in the plate interiors. They produce compression near the mid-ocean ridge and extension near the deep sea trenches. If plates were actually carried by currents, the state of stress would be the other way round. Also, from a thermodynamic view, it is logical that rising hot and descending cold material supply the driving forces. These considerations are supported by the following observations. The velocities of plate movements are independent of the size of the plates, and plates with subduction borders move faster than those without subduction borders; this emphasizes the importance of the slab pull as the driving force. Plates with a large percentage of thick continental crust move more slowly, an observation that suggests that dragging at the bottom of the plates (like the keel of a boat on sand) negatively influences the movement (Kearey and Vine, 1990).

Collision and mountain building

Subduction zones tend to form in locations with mature (older), cool, and thus denser lithosphere. These conditions exist at the edges of large oceanic basins like the present Pacific Ocean. If an oceanic basin is not bounded by subduction zones, it will widen as is the case with the present Atlantic Ocean. Spreading rates at middle oceanic ridges range from a low of 1 cm/yr to a high of 15 cm/yr (**Fig. 1.2**). The rate of subduction (at present up to 9 cm/yr – in the past probably faster) in an ocean basin can exceed the rate of new crust formation at a ridge, especially if opposite sides of the basin both contain subduction zones. In such a case, the oceanic basin shrinks and adjacent continental blocks move closer together. Continuing convergence finally leads to the collision of the continental blocks and the passive continental margin of the subducting (lower) plate is dragged beneath the active boundary of the upper plate. The low density of the subducted part of the continent prohibits extensive subduction and it cannot be dragged down to great depths. Rather, it buoys up on the surrounding denser mantle material and rises, following the principle of isostasy.

Buoyancy and strong frictional forces following collision of two continental blocks eventually brings the subduction of continental crust to a standstill. During this process, complex tectonic structures such as folds and nappes develop and rocks are deeply buried and heated; metamorphism and partial melting typically occur. After convergence ceases, the attached subducted oceanic lithosphere breaks off under its own weight ("slab breakoff"). The lessening of slab pull due to the release of the counterweight induces isostatic uplift of the continental crust, which has been thickened to double its normal thickness. The Alpine-Himalayan mountain chain was created by such processes and forms sharply protruding edifices on the surface of the Earth.

Collisional orogens are something like a Janus head: both an interior and an exterior sight, different, but closely related. The interior processes of mountain building or orogenesis consist of the collision of the continental parts of the plates where large blocks of crust are stacked and thrust upon each other, deformed, and metamorphosed. These processes occur at depth and are not necessarily immediately accompanied by the formation of a high mountain range. The exterior of a mountain range is characterized by topographic expression at the surface. Mountain building in this sense is the uplift and dissection of rock masses to form a high mountain range. Although the geological mountain building process in the Earth's crust causes the topographical uplift of a mountain range, the coupling, however, is complex and not always directly related in time. Uplift commonly follows with a considerable delay of several millions of years the internal mountain building process at depth.

The Alps are a product of the collision of the Adriatic Plate, which at the northern edge of the African Plate formed a protrusion, with Europe. During this collision, Europe was shoved beneath the Adriatic Plate along a southward-dipping subduction zone. The Himalayas formed by the collision of India, which previously separated from Africa as an independent plate, with Central Asia. But here, the subduction zone was dipping northward, thus pulling India beneath Asia. In both cases the collision happened in the early Tertiary at about 40–50 Ma. Ensuing uplift and the formation of the high mountain ranges, however, began millions of years later.

Not all mountain ranges form strictly through continental collision. Cordilleran-type mountain ranges form after immensely long periods of subduction of oceanic crust under continental crust. In the case of the Andes and the North American Cordillera, long-term subduction and accompanying volcanic and plutonic activity along the active margin caused crustal thickening, thrusting, metamorphism, and ultimately mountainous uplift. In fact, the North American Cordillera may be the world's greatest concentration of plutonic and volcanic rocks over the last 300 million years.

Subduction at complex plate tectonc junctions such as those currently in the western Pacific may induce the formation of several chains of island arcs. Collision of these island arcs, with each other and with adjacent continents, leads to the formation of mountain ranges and new continents.

Another variation at plate margins that results in mountain building occurs when dense, cold, old ocean crust is rapidly subducted. This results in a tearing away of the lower (subducted) plate from the upper plate. The locus of the trench moves away from or "rolls back" from the upper plate, much like slowly tearing masking tape off of a ceiling. The upper plate extends and thins to fill the space left by the trench roll-back. In one type of scenario, thin ribbon-like island arcs migrate with the trench as backarc spreading creates new crust to fill in the gap. In another common case, the trench roll-back occurs next to a continent and rifts and rafts a ribbon of continental crust from the adjacent continent. Backarc spreading and new oceanic crust occur in the rift zone. In both cases, the island arc or rifted continental ribbon tends to follow the rapidly rolling-back trench. These ribbon-like wedges eventually collide with other continents forming accreted terranes. Many ancient mountain ranges including the Appalachians, Alps, and Himalayas are replete with such accreted terranes. Each phase of terrane accretion formed another phase of orogeny. Presently, the rapidly eastward migrating Antilles arc and Caribbean plate provide an example.

Long lasting subduction and subduction related magma generation leads to the creation of new continental crust. Today about one third of the Earth's surface is covered by areas of continental crust. Continental crust has not grown at a continuous rate throughout the geological past. It was particularly rapid during the late Archean about 2.5–3 billion years ago (Ch. 10). Since that time, continental crust has probably formed at a fairly steady rate.