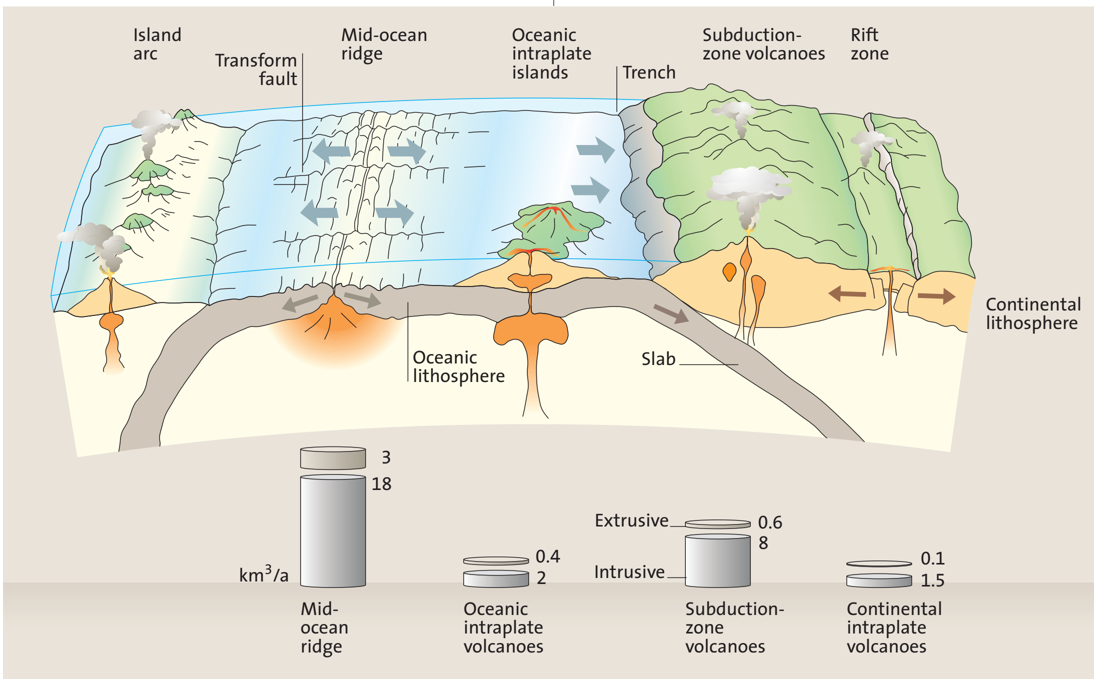
Plate Tectonics

In 1912, Alfred Wegener took the scientific community by surprise in postulating that the present continents had once been united in a megacontinent named *Pangea* that broke up about 200 million years ago into smaller fragments – the present continents –, which drifted apart and still do so today. This went against all contemporary scientific belief of the permanence of ocean basins and continents. A fundamental argument was the very good morphological and structural fit of South America and Africa and many other geological similarities between the southern continents. Wegener's revolutionary vision of a mobile dynamic Earth continued to be opposed by most scientists for almost fifty years. His ideas were dramatically revived during the 1960s. The hypothesis of *continental drift* was then greatly expanded and superseded by the models of *seafloor spreading* and *plate tectonics*, both of which have come to revolutionize all of Earth sciences. This new view of a dynamic planet also heralded a new phase in our understanding of the location and origin of volcanoes. The striking difference in their eruptive behavior could now be related to different magma sources, processes of magma generation and thus magma compositions. The time was passed to view volcanoes such as Surtsey or Mauna Loa as isolated local phenomena.

> **Don't be alarmed at the heat, my boy.**
> *Jules Verne, Journey to the center of the Earth, 1864*
> *Translated from the French*

Alfred Wegener did not regard volcanoes, their composition and the origin of magmas as fundamental to his model. While his conception of a mobile Earth turned out to be correct, the models of seafloor spreading and plate tectonics are based on geological and geophysical observations in the present ocean basins, where the crust is entirely volcanic (Fig. 2.1). These hypotheses constitute the most important change in geological paradigm of the last 100 years. The story of the development of these ideas has been recounted numerous times and is part of basic general geological education. I will here focus on those aspects relevant for understanding the origin and evolution of magmas beneath volcanoes –

▼ Fig. 2.1. Major lithospheric plates and global distribution of some active and dormant volcanoes



▶ Fig. 2.2. Divergent (mid-ocean ridges) and convergent (subduction or Wadati-Benioff zones) plate margins (after 269). Annual magma production rate (km^3/a) after several sources (303).

processes that occupy a central position in the new global view of Earth science.

Below, I will briefly review fundamental geodynamic relationships between volcanoes and the structure of the Earth, as well as dynamic processes in the Earth's crust and the mantle, prior to discussing more specific aspects of volcanoes and volcanic eruptions. Causes of volcanic eruptions and volcanic processes in general cannot be understood without a rudimentary understanding of the composition of magmas and gases and the distribution of volcanoes on the planet. In other words the entire framework of the magma-volcano system needs to be laid out before treating the volcano itself.

Fundamental is the observation that not only the ca. 550 active subaerial volcanoes (340), but all Quaternary, Tertiary, and older volcanoes and volcanic fields are not distributed haphazardly on the surface of the Earth.

The Conveyor Belt of the Mid-Ocean Ridges

One of the breakthrough discoveries made during the 1960s was the recognition that changes in the orientation of the magnetic field of the Earth occurred every few hundred thousand to million years. In other words, the *magnetic* North Pole (to which compass needles currently point) changes position from the *geographical* North Pole (or close to it) to the *geographical* South Pole. These opposite orientations, occupied by the magnetic field of the Earth in irregular intervals of its history, can be well-documented because they are, so to speak, frozen into lava flows. When hot lava flows cool, magnetic minerals crystallize and the submicroscopic magnetic domains in the mineral phases align along the direction of the prevailing orientation of the magnetic field.

When magnetic orientations were measured in volcanic and plutonic rocks of the ocean floors, scientists were struck by a major puzzle; the oceanic crust turned out to be characterized by stripes with alternating opposite magnetic orientations. These stripes of normal and reverse polarity paralleled the mid-ocean ridges (Fig. 2.2). Why should the ocean floor show parallel belts of opposite orientation, when, according to the prevailing idea, the ocean floor was very old? Frederick Vine and Drummond Matthews from England discovered in 1963 that the magnetic zebra patterns on the sea floor on either side of a mid-ocean ridge are symmetrical, with the mid-ocean ridge representing the mirror plane. When comparing the relative widths of these normally and reversely magnetized stripes, it became apparent that relatively narrow stripes corresponded to short time intervals and larger ones to longer periods of constant orientation of the Earth's magnetic field.

These discoveries provided compelling evidence that the oceanic crust of the deep sea (three quarters of the entire Earth's surface) could not be billions of years old; it must have formed in the recent geological past. And this crust was apparently not formed where it is today but rather along welts in the middle of the ocean basins. Hence it had to migrate away from this zone, as on a constantly moving conveyor belt. Moreover, it soon became apparent that the contrasting widths of these stripes corresponded to periods of normal and reverse polarity preserved in deposits on land as discovered a few years earlier. All this combined to show that the Mid-Atlantic Ridge (roughly central in the Atlantic basin) and the asymmetrically located East Pacific Rise, are young geological features where new oceanic crust is being formed day by day. These revolutionary concepts necessitated an expansion and major modification of the conventional view of a layered Earth.

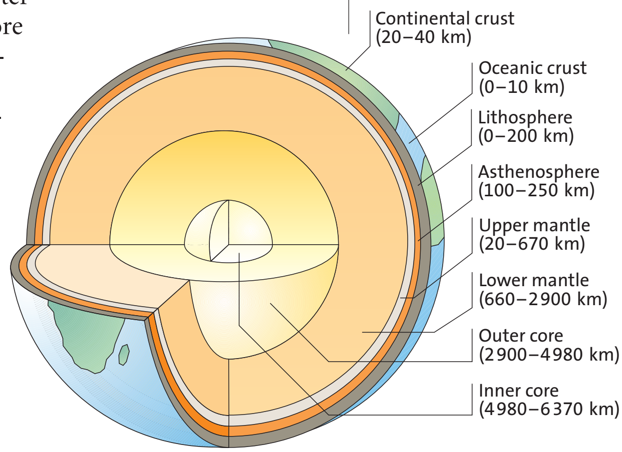
The Layered Earth

The velocity of seismic waves depends mainly on the density of a rock. Acoustic compressional waves, generated during earthquakes or artificial explosions, and which migrate through the Earth, increase their velocity with depth in a stepwise fashion. These abrupt changes in velocity allowed geophysicists to subdivide the Earth into three main layers or shells of different density (Fig. 2.3):

- The Earth's crust, the thin outer rind of the Earth with a mean density of 2.67 g/cm^3, averages about 25 km thick in the continents, but can reach up to 70 km beneath some mountain ranges. The mainly basaltic crust in the ocean basins is only 5 to 7 km thick, with a mean density of 2.8 g/cm^3. The crust is distinguished from the underlying mantle along the so-called *Mohorovičić discontinuity* (Moho), a surface defined by a sudden increase in wave velocity from about 7 to over 8 km/s.
- The Earth's mantle underlying the crust consists of Fe- and Mg-rich silicates, chiefly olivine in the upper 660 km. At greater depth the high pressure forms of olivine with closer packing of the atoms dominate. The mantle is about 2 870 km thick and has a mean density of 4.6 g/cm^3.
- The core, probably consisting largely of nickel and iron, has a radius of 3 480 km and a mean density of 10.6 g/cm^3. Its outer shell is liquid, its interior core solid.

How have these layers of different density developed? Current consensus is that the Earth originally aggregated from cold cosmic dust, about 4.6 billion years ago. This protoplanet was melted by meteorite impacts, radioactive decay and gravitational energy, causing differentiation of the Earth's core. The end result was a more or less homogeneous planet. In the gravity field of these masses, the shells probably developed by density separation. This was via the process of partial melting, which was not only active in the early history of the Earth, but is continuing today, as shown by many volcanic eruptions each year.

Because the Earth is very much hotter in its core than the outer mantle or the crust, heat migrates along thermal gradients to the Earth's surface and is then radiated into space. The thermal gradient does not, however, increase linearly downward. If the measured crustal temperatureincrease of about 3 °C per 100 m would be constant to the center of the Earth, the core would have the unbelievably high temperatures of almost 200 000 °C, instead of the likely 5 000 to 6 000 °C. For comparison, the surface temperature of the Sun is estimated to be about 5 500 °C.

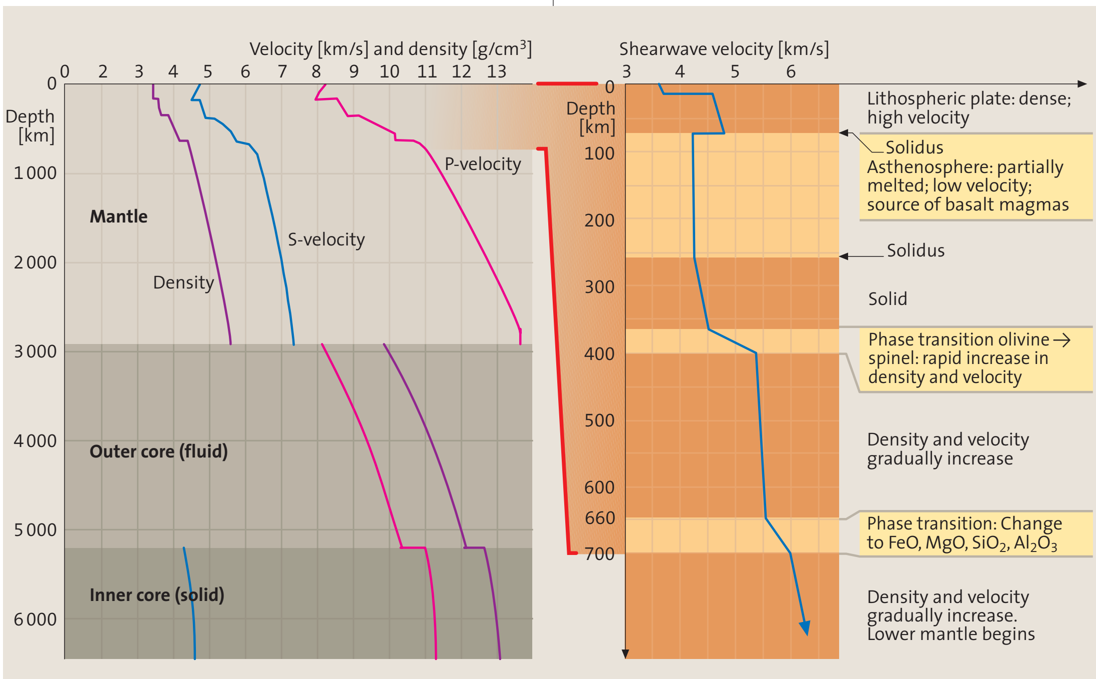


▼ Fig. 2.3. Subdivision of the Earth into several shells based on the density differences as determined by differences in seismic velocities

Dynamic Subdivision of the Earth

When looking at a globe, one is struck by the contrast between continents and ocean basins. The belts of seismic and volcanic activity stand out strongly. Jason Morgan (241) subdivided the outer rind of the Earth into a number of "plates", whose boundaries are characterized by earthquakes and often also by volcanic activity. These plates are constantly moving against one another (Fig. 2.1). Many plate boundaries do not coincide with the boundaries between continental and oceanic crusts. Some, like the Mid-Atlantic Ridge, are roughly parallel to the continent-ocean boundaries, while others do not, such as the East Pacific Rise, which impinges on the North American continent at an acute angle.

Because the Earth does not expand, the constant production of new crust must be compensated by destruction of crust at some other place. Wadati-Benioff zones (Chap. 8), recognized since the 1930s, are characterized by planes of earthquake foci (hypocenters), dipping beneath continents or island arcs (such as the American continent and the Japanese Islands, respectively). These Wadati-Benioff zones became recognized as counterparts to the axial zones. Ocean plates, composed of igneous ocean crust and underlying mantle, dip downward along these zones characterized morphologically by deep-sea trenches alongside convergent continental margins or island arcs. A major portion of the sediments deposited on top of the igneous crust in the ocean and shed from land is also dragged down into the mantle.



▶ Fig. 2.4. Distribution of P (*red*) and S (*blue*) velocities of seismic waves and density (*violet*) and a cross-section through the Earth (*left*). Subdivision of the upper mantle by shear wave velocity at *right* (269)

These new concepts necessitated the introduction of a more dynamic subdivision of the outer rind of the Earth (Figs. 2.3 – 2.5). The crust and the uppermost part of the mantle are mechanically coupled and are termed *lithosphere*. The lithospheric plates of plate tectonics are visualized as relatively cool rigid, highly viscous outer rinds of the Earth, being underlain by the more mobile, weaker *asthenosphere*. There are several different definitions of lithosphere, however (11).

The *seismic lithosphere* is defined by a zone of higher seismic velocity, contrasting with the underlying *low velocity zone* (LVZ). Its thickness increases in the ocean basins from less than twenty km at the mid-ocean ridges, to more than sixty km along passive continental margins (the oldest oceanic lithosphere being about 180 Ma old). Beneath the so-called *cratons* (the old shields of the continents) the lithosphere reaches thicknesses in excess of 200 km. The temperature at the base of the lithosphere is estimated as 600 – 650 °C.

The *elastic lithosphere* is derived from the measured rise and sinking of the Earth's surface when subjected to loading and unloading (such as by huge volcanic edifices as in Hawaii – Chap. 6 – or by mountain ranges). The elastic lithosphere in the ocean basins is similar in thickness to that of the seismic lithosphere, but is a little thinner (30 – 40 km) under continents. In the ocean basins, the base of the elastic lithosphere roughly corresponds to a temperature of about 500 °C for dry olivine rheology (Chap. 4). The lower sharp boundaries of the seismic and elastic lithosphere are probably due to a change in the mineral composition of mantle rocks and/or due to a phase change.

The *thermal lithosphere*, i. e. the cool outer rind or thermal boundary layer (TBL), is determined by a conductive gradient with a basal temperature of about 1 280 °C. In other words, the thermal lithosphere is about twice as thick as the seismic and elastic lithosphere. In the ocean basins, its thickness increases from a few kilometers in the center to about 100 km at the margins, thickening to about 150 km beneath the continents.

Plates along active continental margins that descend beneath continents or island arcs are called *slabs*.

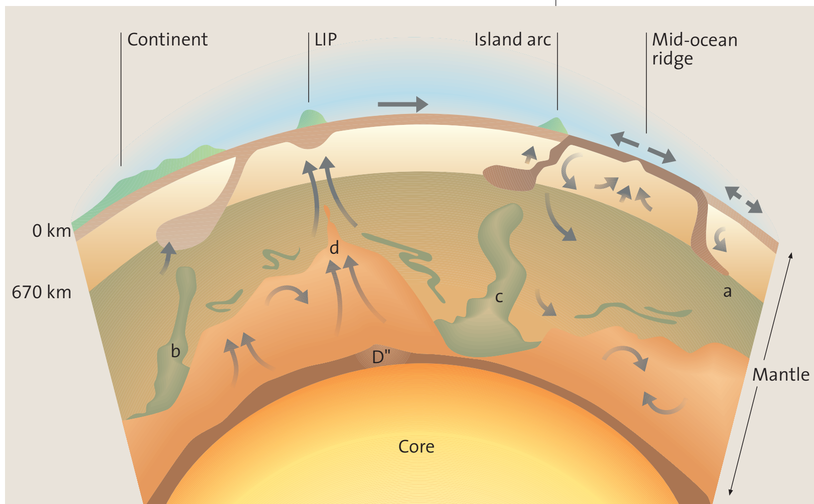
A *low velocity zone* (LVZ) is almost universally recognized to be characterized by up to 2 % wave velocity decrease beneath the lithosphere. Beneath cratons, it begins at about 150 km and locally as deep as 400 km. The LVZ is roughly equivalent to the asthenosphere, the "soft" layer beneath the rigid lithospheric plate. The low seismic velocity is commonly explained by an increase in temperature approaching the melting point of mantle peridotite. Hence, partial melts (magma) may be present in this zone, although recently it is also interpreted as a decrease in H_2O concentrations, caused by partial melting (e. g. 169). The asthenosphere is widely thought to be the source region for geochemically depleted basaltic magma, which intrudes and erupts along mid-ocean ridges (Chap. 5).

A second layer that has recently attracted much scientific attention is the D-region – called

D double prime (D'')–at the base of the mantle above the outer core. This layer, typically 200–300 km thick, is characterized by enhanced scattering of seismic waves. Locally the layer may be very hot and even contain traces of magma.

The lithosphere consists of about 16 larger and many smaller, relatively rigid plates, which move against each other. Most large plates, such as the North American and the Eurasian plates, comprise continental as well as oceanic lithosphere (Fig. 2.1).

These discoveries provided robust evidence that continents and ocean basins were not formed at one time, remaining stationary for billions of years. Continents have drifted apart, became welded together and broken up repeatedly. The large mountain chains, such as the Alps in Europe or the Himalayas, are the crumple zones between giant colliding plates. Energy accumulating during such collisions is released in earthquakes, as in Afghanistan, Armenia, Iran, India or Turkey, sometimes with catastrophic results. The present Atlantic Ocean basin, which started to form only about 200 million years ago when a large supercontinent called *Gondwana* broke up, widens by about 2 cm/year. The migration of the lithospheric plates, their constant formation along mid-ocean ridges and their plunge into the mantle along Wadati-Benioff zones, are governed by deep-reaching motions in the Earth's interior (Chaps. 6–8).



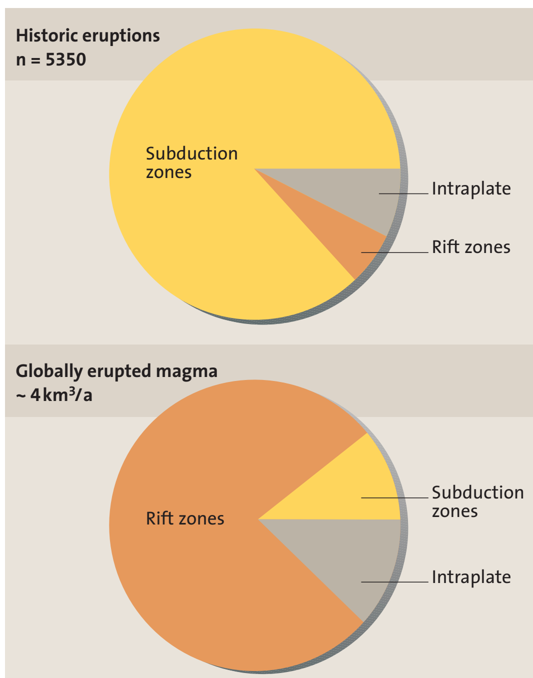
▲ Fig. 2.5. Model of plate dynamics and magma sources. Volcanoes erupted along mid-ocean ridges are fed by magmas from the asthenosphere (depleted mantle). Volcanoes above subduction zones derive their magma chiefly from the overlying mantle wedge, melting being triggered by hydrous fluids released from the descending slab. Magmas in oceanic and continental intraplate volcanoes (LIP) may be generated in rising mantle diapirs (plumes). Some downgoing lithospheric slabs may become subducted to the boundary between upper and lower mantle at 670 km (a). Others may penetrate deep into the thick intrinsically dense layer in the lower mantle (b) or to the core-mantle boundary (c), eventually forming a major magma source for intraplate magma systems (oceanic volcanic islands, LIPs, continental intraplate volcanic fields). Plumes are thought to start at high spots (d) of the dense layer in the lower mantle and consist of mantle peridotite variably mixed with recycled lithosphere. The core is separated from the mantle by the D" layer that may be the starting point for plumes (395)

Distribution of Volcanoes on the Earth's Surface

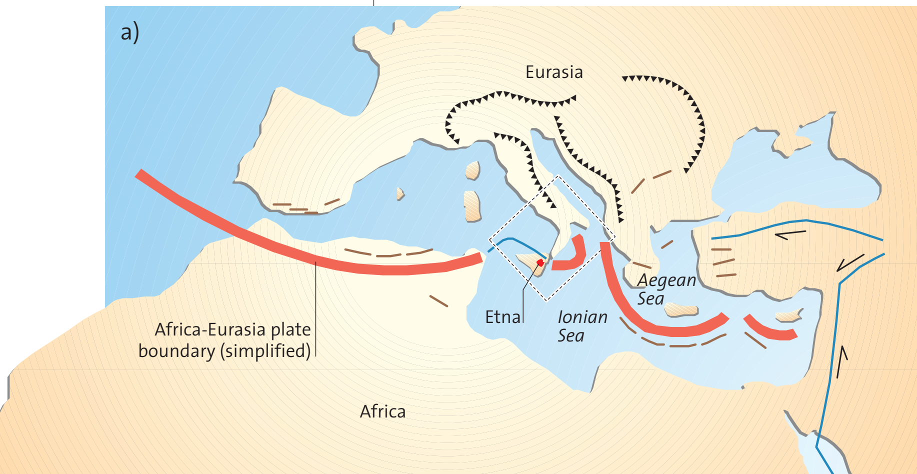
Alexander von Humboldt (163) noted that geologically young Quaternary and Tertiary volcanoes and volcanic fields are not distributed evenly or randomly on the surface of the Earth. He considered that the concentration of volcanoes was due to deep-reaching causes, an idea that strongly contrasted with that of his teacher, Abraham Gottlob Werner, and disciples of the Neptunist school, who thought that volcanoes had shallow sources and only grew late during Earth history.

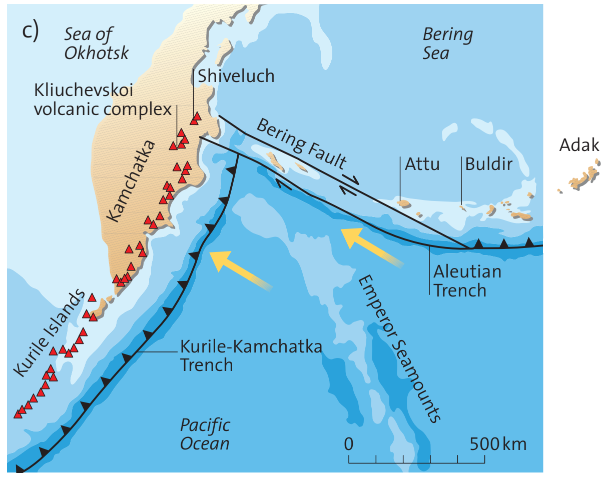
Humboldt's view has been confirmed time and time again. In some areas, such as geologically old shields or *cratons*, in which the crust is maybe more than 1 billion years old (e.g. Central Canada, Sweden, Finland and Western Australia), almost no volcanic eruptions have occurred in the recent geological past. Young volcanoes preferably occur in specific zones. These are foremost island arcs or convergent continental margins, such as around the Pacific Ocean or in the Mediterranean, in rift zones and their uplifted shoulders, such as the Rio Grande Rift, the Rhine Graben or the East African Rift or, by far most abundantly, in the ocean basins. Today, this geographic subdivision can be interpreted in a geodynamic framework, which greatly helps us to better understand eruptive rates, chemical compositions of magmas, or contrasting explosivity in volcanoes.

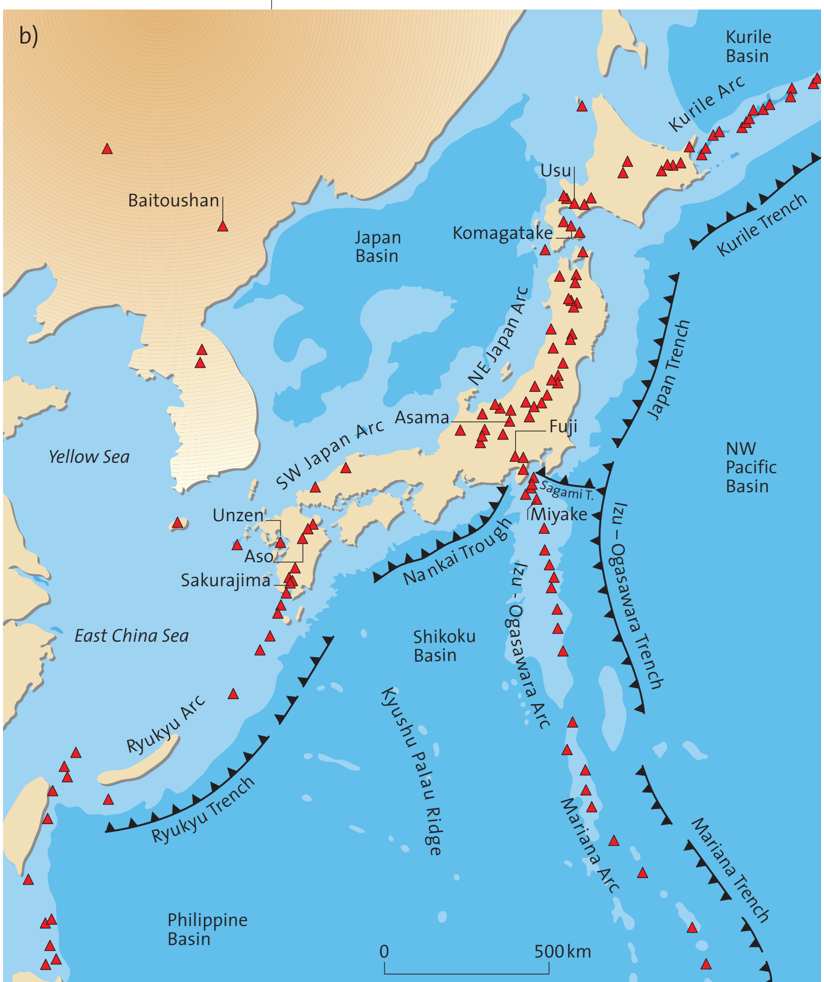
Diverging or constructive plate margins are the oceanic axial zones with the highest production and eruption of magmas on Earth and the largest number (although unknown precisely) of active submarine volcanoes (Fig. 2.6). Iceland is a mid-



▶ Fig. 2.6. Comparison of the number of historic eruptions and mass of annual global volcanic production in three different plate tectonic settings: subduction zones, intraplate environments and rift zones, including mid-ocean ridges (339)







▲◀▲ Fig. 2.7. Three examples of highly productive basaltic magma – volcano systems in *slab-edge tectonic settings*. a) Simplified tectonic schemes of Mt. Etna in the Mediterranean (135). b) Distribution of major volcanoes in Japan, eight very active and/or famous volcanoes being highlighted, and the trench position along the Wadati-Benioff Zone in Japan and adjoining arcs (several sources). The location of Mt. Fuji at the triple junction between three plates is shown in detail in Fig. 8.4. c) Kliuchevskoi/Tolbachik volcanic complex (Kamchatka) close to the edge of the subduction zone where it is cut off by the complex Bering fault zone. Note oblique subduction (yellow arrow) along the Aleutian Trench. The island of Adak, type locality for adakite magmas interpreted as slab melts, just outside frame (Smithsonian). Frame in a shows area detailed in Figs. 2.8 and 2.9

ocean ridge volcano, in which particularly high magma production and lava eruption rates above a plume (Chap. 6) have generated a large volcanic island.

Convergent or destructive plate margins are zones along which oceanic lithosphere descends into the Earth's mantle. Most presently active *subaerial* volcanoes are formed above these *subduction zones*. Even though eruptive volumes of magmas along subduction zones comprise less than 10 % of the global production or about 4 km^3 per year, they represent more than 80 % of the roughly 5 350 eruptions recorded in historic times.

Intraplate volcanoes or volcanic fields are subdivided into oceanic ones, such as Hawaii, and continental ones, such as the volcanic fields of Michoacán-Guanajuato in Mexico, San Francisco in Arizona (USA), Eifel in Germany, or Chaîne des Puy in France.

Hybrid Tectonic Settings

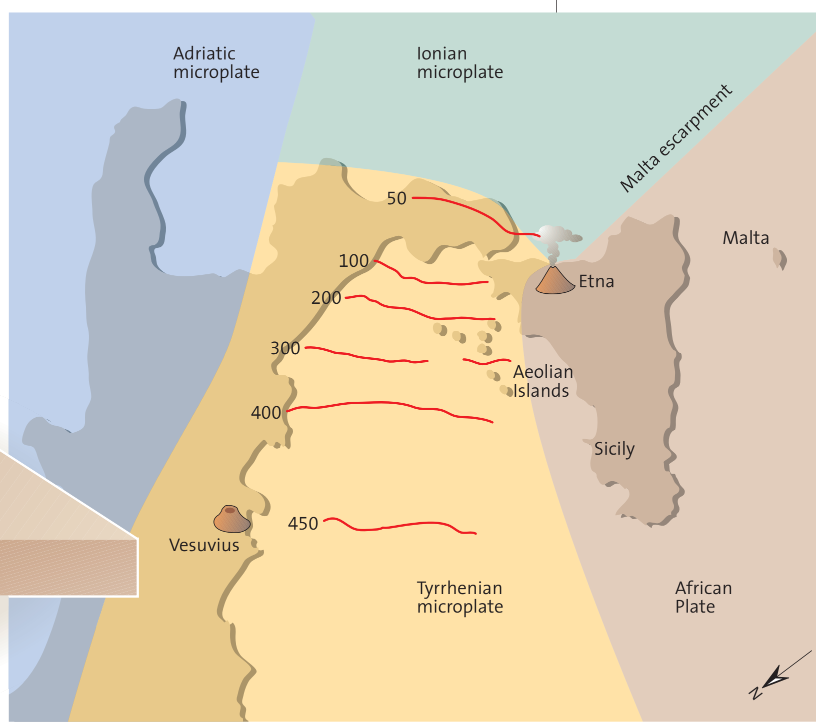
As can be expected, not all volcanoes fit neatly into the plate tectonic pigeonholes. For example, some particularly productive basaltic volcanoes occur at complex junctions between subduction zones, or at or near the edge of a downgoing slab (Figs. 2.7 – 2.9). Prominent examples are Mt. Etna, the largest active volcano in Europe rising to 3 350 m a. s. l., Mt. Fuji, the famous landmark towering over wide stretches of Honshu (3 776 m a.s.l.) and the more remote Kliuchevskoi volcanic complex, the highest (4 835 m a.s.l.) and most active volcano on Kamchatka. The chemical signatures of the mafic magmas of some of these *slab-edge volcanoes* are most similar to intraplate magmas but they also show some characteristics of subduction zone-related magmas, Mt. Etna being a prominent example of this hybrid magma source. Etna and Mt. Fuji volcanoes appear to have developed in a tensional environment between subducting plates. Mt. Fuji has developed at a triple junction at the southern end of the downgoing Pacific Plate (Fig. 8.4) and the Kliuchevskoi/Tolbachik complex at the northern end of the Honshu-Hokkaido-Kurile-Kamchatka arc system (Fig. 8.17). Here, a 1 000 km long strike slip fault borders the downgoing slab to the north connecting this region to the Aleutian Arc. A major reason for foci of high mafic magma production rates in slab-edge settings may be the fact that fertile asthenosphere may be able – or is forced – to rise sideways of the edges of downgoing slabs, partially melting as it rises and decompresses. The magmas of both Mt. Fuji and the big northern Kamchatka magmas show subduction signatures, however. Magma genesis above downgoing slabs is discussed in more detail in Chap. 8. Examples of volcanoes in other plate tectonic settings that do not fit easily into the simple three-fold plate tectonic subdivision are back arc magma-volcano systems (Chap. 8) and ocean islands or island groups such as Iceland and the Azores showing weak to strong intraplate magma compositional characteristics but have grown above or along the Mid-Atlantic Ridge.

Summary

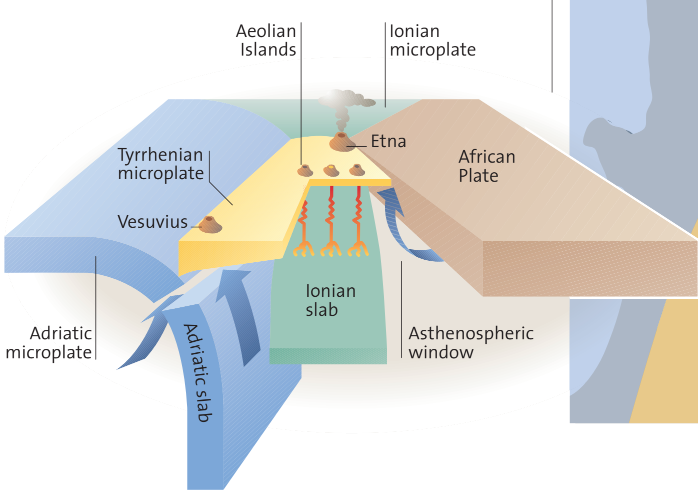
The volumes, heights and forms of volcanoes mainly depend on the physical properties and composition of the magma and thus processes in, and composition of, the root zones of volcanoes, whose dynamics are governed by their plate tectonic setting. Hence, a single volcano does not only contain information about its local origin. An andesitic stratocone is typical for a subduction zone tectonic setting. Morphology and architecture of a volcano by itself is not diagnostic, however. For example, caldera volcanoes can form in very different types of tectonic environments. Increasing numbers of calderas are now recognized to occur even in submarine volcanoes both, on seamounts as well as along mid-ocean ridges. Some types of volcanoes, such as maars, whose form is basically governed by near-surface processes (e.g. the interaction of magma and water) (Chap. 12), are particularly unsuitable to infer a particular tectonic setting.

Most volcanoes on Earth form either along divergent or convergent plate margins or in the continental or oceanic plate interiors. The divergent and convergent plate margins and the plate interiors can be characterized by a number of physical parameters (crustal and plate thickness, heat flow, stress field, earthquakes, etc). The mag-

▼ Fig. 2.8. Map of the south Tyrrhenian subduction zone with north and south reversed for easier visualization. The Ionian microplate (*green area*) descends northward under the Tyrrhenian microplate, contours in km (5 – 450) representing the depth to the top of the downgoing slab. The Aeolian islands (*dots*) form a volcanic arc (134)



▼ Fig. 2.9. Three-dimensional model of the south Tyrrhenian subduction zone looking southeast from a point above the Tyrrhenian Sea (see Fig. 2.8). *Red lines* represent magma pathways from the top of the slab to the arc. *Arrows* represent local patterns of asthenospheric mantle flow driven by slab motion. Etna volcano is located outside the Aeolian arc and above asthenospheric mantle rising sideways from beneath the African plate. The Adriatic microplate dipping steeply west of Vesuvius is thought to be broken.



mas of volcanoes in each of these major plate tectonic setting are characterized by specific chemical compositions comprising major and trace elements, isotope ratios and composition of mineral phases. Different volatile contents of the magmas are particularly well reflected in contrasting modes of eruptions. For example, volcanoes grown above subduction zones where water-rich sediments and ocean crust are dehydrated at depth are typically highly explosive because the processes of magma formation in subduction zones are strongly governed by fluid release from the subducted slab. Magma compositions and types of volcanoes in hybrid plate tectonic settings commonly show more complex characteristics.

Soon after the theory of plate tectonics revolutionized Earth science, attempts increased to infer paleotectonic settings based on the composition of older volcanic rocks. This is sometimes problematic because volcanic rocks change their composition during alteration. However, the number of publications that attempt reconstructions of paleotectonic settings based on a comparison with modern plate tectonic characteristics still increases.

Before I discuss the main plate tectonic settings of volcanic activity on Earth in detail (Chaps. 5–8), I will treat the material of volcanoes, the magma (i.e. the melt) and the volcanic rocks formed by cooling of the magma in more detail.