Chapter 1

Understanding the physical behavior of volcanoes

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Introduction

Volcanism is a spectacular display of the complex way in which energy and materials are exchanged between three major components of our planet: the solid Earth, oceans, and atmosphere. Mankind has long been both fascinated and terrified by erupting volcanoes. Yet throughout history people have been drawn to their fertile slopes and have developed a unique symbiosis. In many cultures, volcanoes symbolize a source of tremendous power that must be placated by worship or sacrifice. Volcanologists, on the other hand, strive to understand how volcanoes work in order to better predict their behaviour and reduce the hazards to people who live near them. But volcanoes are not merely destructive and need to be viewed as an integral part of the dynamic Earth system. They create new land, replenish soil, and provide essential water and other gases to our oceans and atmosphere. Much of this book will focus on the relationship of volcanoes to the environment and to mankind. However, before these topics are addressed we need to begin with some fundamental concepts about the causes and processes of volcanism. In this chapter we explore how volcanoes work by examining the complex path that must be taken before an eruption takes place at the Earth's surface. This includes the generation of magma at depth, its rise, storage and evolution within the Earth's crust, and finally the factors that determine the nature of the eruption at the surface.

Each eruption represents a unique culmination of this complex series of steps, making the prediction of volcanic eruptions one of the most challenging tasks in the geosciences.

The science of volcanology draws from many different fields, including petrology, geochemistry, seismology, and sedimentology. It began with mainly qualitative observations about the distribution of volcanoes, their eruptive behavior, and the types of products they create. In AD 79, Pliny the Younger made the first written description of a volcanic eruption in two letters describing the death of his uncle, Pliny the Elder, during the eruption of Vesuvius volcano in Italy. During the past two decades the field of volcanology has undergone revolutionary changes in the understanding of volcanic activity. This has resulted from a more quantitative approach to the analysis of volcanic processes through the application of physics, chemistry, and fluid dynamics. In many instances, strides in the field were spurred on by observations of major eruptions such as Mount St. Helens, USA, in 1980, El Chichón, Mexico, in 1982, Nevado del Ruiz, Colombia, in 1985, and Mt. Pinatubo, Philippines, in 1991 (described further in Chapter 2). These eruptions often provided the opportunity to observe volcanic processes that had not previously been documented quantitatively and led to the ability to interpret such processes from deposits in the geologic record (this will be discussed further in Chapter 3). With the advent of Earth-observing satellites, the remote sensing of volcanoes from

space has led to a new appreciation for the global impact of some large-scale eruptions and provided volcanologists with new tools to assess the relationship of volcanoes to the environment (e.g. Rose *et al.*, 2000). A particularly exciting breakthrough has enabled the mapping of the ocean's bathymetry from satellites by measuring subtle changes in the elevation of the seasurface, allowing for the recognition and mapping of volcanic features on the seafloor with high resolution. As a result of land-based, marine, and space observations there is now an excellent documentation of the distribution of volcanic activity on Earth.

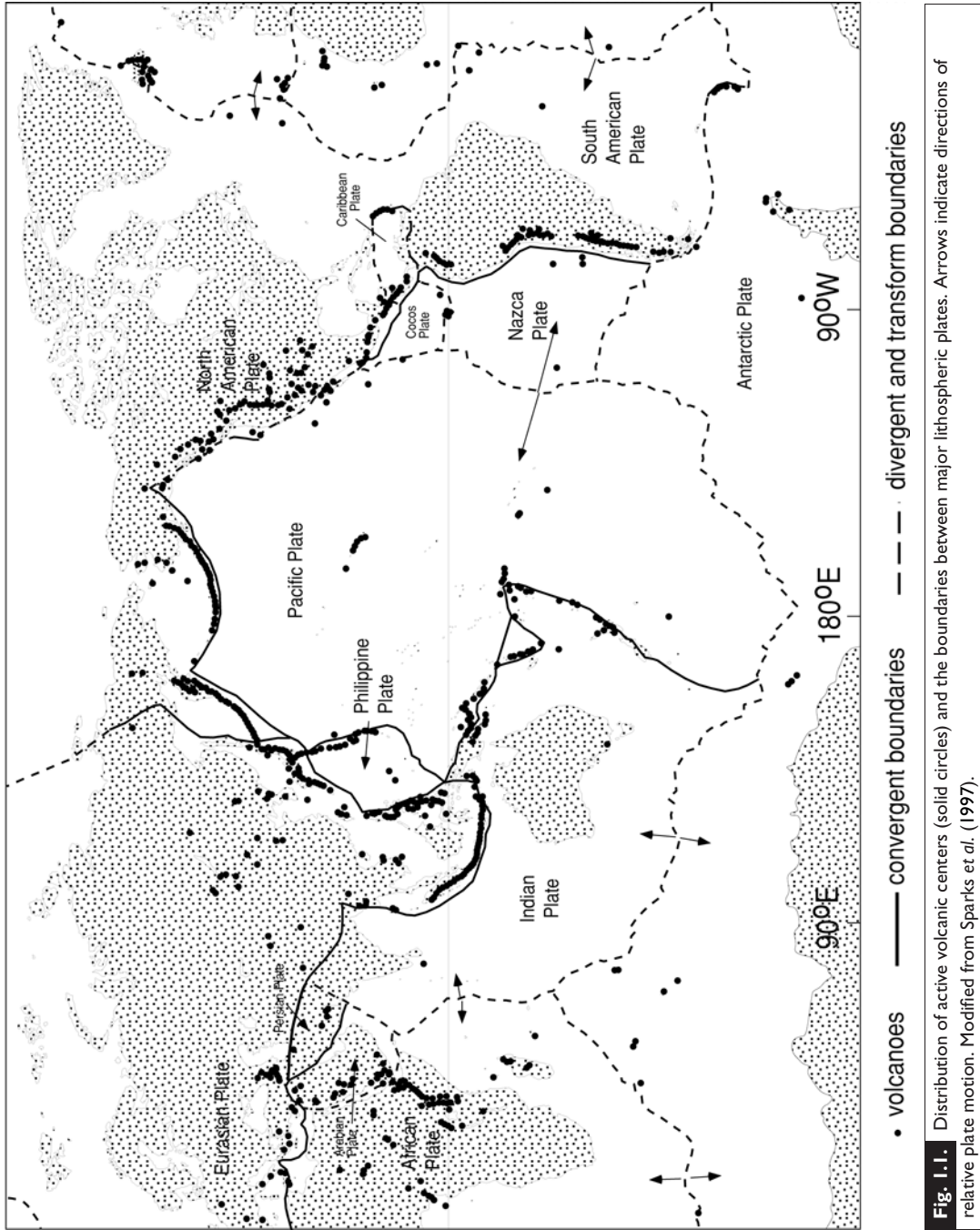## Distribution of volcanic activity: the plate tectonic framework

The distribution of volcanoes on the Earth's surface provides important information about the underlying causes of volcanism, yet making a global inventory of volcanoes is not a simple task. Simkin (1993) notes that it is difficult to define precisely the number of active volcanoes on Earth. During historic times there have been some 538 with documented eruptions and over 1300 have erupted during the last 10 000 years. However, two-thirds of the planet's surface is covered by water and thus observations of volcanic activity are strongly biased towards the continents and islands. We now know that virtually all of the seafloor is composed of volcanic rock and that most volcanic activity occurs far removed from sight in the depths of the ocean.
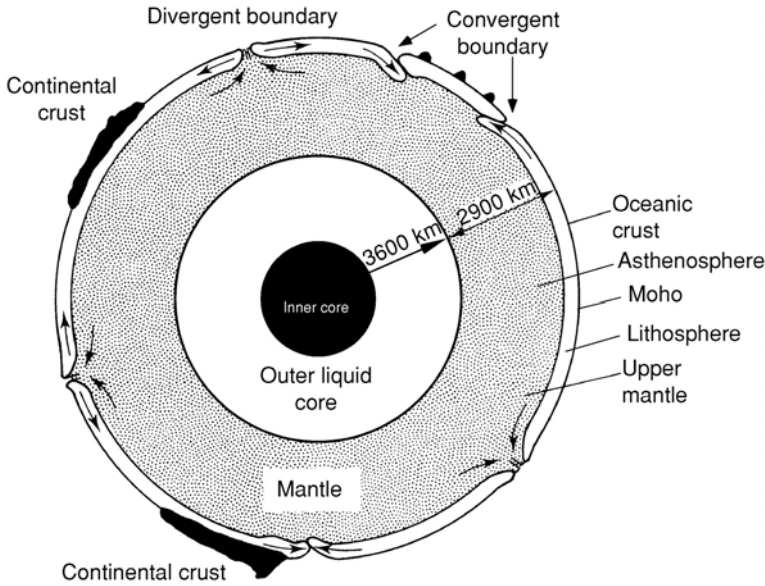
Early workers who documented the distribution of volcanoes realized that they did not occur randomly but tended to run in belts or linear segments. This is particularly evident when one looks at the present location of volcanism on the Earth's surface (Fig. 1.1). A large majority of the Earth's active and conspicuous volcanoes can be found along a belt that rims the Pacific Ocean beginning at the southern tip of South America, proceeding north along its western coast across Mexico into the western United States (Fig. 1.1). From there it winds into Alaska, across the Aleutian islands to the western Pacific, where the line continues southward all the way to New Zealand. This remarkable clustering of volcanoes is known as the "Ring of Fire." Large earthquakes are also concentrated along this belt adding to the hazards associated with the volcanoes. Other significant belts of subaerial volcanoes occur in the Indonesian Archipelago, the Mediterranean region and in the Lesser Antilles islands of the West Indies.

It would take one of the major revolutions in the earth sciences, that of plate tectonics, to provide the unifying explanation for the distribution of volcanoes on the Earth. It has now been demonstrated that the surface of the Earth consists of numerous large plates that are constantly in motion relative to one another and relative to the deep interior of the Earth (Fig. 1.1). The theory of plate tectonics provides the fundamental linkage between our understanding of the Earth's surface and its interior (Keary and Vine, 1990; Canon-Tapia and Walker, 2003). A cross-section through the planet reveals a strongly layered internal structure (Fig. 1.2). Much of our knowledge of the Earth's interior has been derived from the study of how earthquakes are transmitted in different types of materials. By studying the arrival of different types of seismic waves, such as P- and S-types, at various positions around the globe, it is possible to infer the nature of the deep Earth. This remote-sensing approach is necessary because direct sampling of the deep Earth by drilling is usually limited to depths of about 5 km. Some deeper samples are brought to the surface naturally by volcanic eruptions. These xenoliths have been critical for determining the chemical composition and physical nature of the source areas of volcanism.

From the center of the Earth to a distance of 1228 km lies the inner core, a dense solid consisting mostly of iron with lesser amounts of nickel and sulfur. Surrounding the solid inner core out to a distance of 3500 km is a liquid outer core, also consisting of iron and sulfur. The presence of a liquid region deep in the Earth is inferred from the blocking of earthquake shear waves (S-waves), which are unable to propagate through a liquid. Within this layer, convective movement of material is responsible for the

Fig. 1.1. Distribution of active volcanic centers (solid circles) and the boundaries between major lithospheric plates. Arrows indicate directions of relative plate motion. Modified from Sparks et al. (1997).

Fig. 1.2. Cross-section of the Earth's interior showing the major concentric regions. Arrows indicate the motions of the major lithospheric plates. Thickness of the lithosphere is exaggerated for viewing purposes. Modified from Frankel (1996).

generation of the Earth's magnetic field. At a distance of 3500 km from the Earth's center there is an abrupt transition to the largest volumetric component of the solid Earth, the mantle. Extending to less than 100 km from the surface, the mantle consists of silicate minerals and is the source of most magma for volcanism on the planet. As a result of gradients in pressure and temperature throughout the mantle, the assemblage of minerals changes as a function of depth. In the lower mantle, dense phases such as perovskite, magnesiowustite, and stishovite predominate, whereas above 670 km (upper mantle), minerals such as pyroxene, olivine, and an aluminum-bearing phase are stable. The mantle represents 80% of the solid Earth by volume and 67% by weight (Ringwood, 1975).

Overlying the mantle is a thin veneer, or crust, on which we live. In simple terms, the crust can divided into two principal types: oceanic and continental. Oceanic crust is relatively thin (up to 15 km), dense (3.0 g/cm^3), consists of rocks rich in iron and magnesium called basalt, dolerite, and gabbro, and underlies most of the ocean basins. In contrast, continental crust is thicker (up to 50 km), less dense ($\sim$2.8 g/cm^3), consists of rocks that are richer in silica, sodium, and potassium, such as granite, and forms most of the continental masses. The plates that are in constant motion over the Earth's surface are termed the lithosphere, a combination of crustal rocks and upper mantle material (Fig. 1.2). They are of the order of 100 km thick and are considered to behave in a generally rigid form. Lithospheric plates ride over an underlying asthenosphere that consists of mantle rocks at higher temperatures and pressures. These conditions allow the asthenosphere material to deform under stress in a ductile fashion and to accommodate the movement of the overriding plates.

The boundaries between plates can be subdivided into three main types: divergent, convergent, and transform (Fig. 1.2). Each one represents a different sense of motion between plates. At divergent boundaries plates are moving away from one another and magma wells up from the mantle along fissures, so creating new oceanic crust and lithosphere. An example of a divergent boundary is the one between the North American and the Eurasian plates centered roughly in the middle of the Atlantic Ocean (Fig. 1.1). Convergent boundaries represent the opposite sense of motion where plates are coming together. In these areas one plate moves under another in a process called subduction (Fig. 1.2). The descending plate is typically bent downwards as it is returned to the mantle, producing a deep area, or trench, near the boundary. Earthquakes occur along the descending plate as it returns to the mantle and their location can be used to define

the slope of the downgoing slab, referred to as the Benioff Zone. In the Pacific Ocean, the deepest oceanic depth of 13,000 m is associated with the trench of the Mariana subduction zone. Convergent margins can be produced by subduction of oceanic lithosphere beneath other oceanic lithosphere (island arc) or oceanic lithosphere beneath continental lithosphere (active continental margin). Finally, transform boundaries are areas where plates slide past one another, such as along the San Andreas fault system of the western United States, where the Pacific plate is moving northward relative to the North American plate (Fig. 1.1). Significant earthquake hazards are associated with this type of boundary when plate motion occurs by rock failure. At transform boundaries, there is not, however, significant volcanic activity.

Volcanoes and earthquakes are largely confined to the boundaries between lithospheric plates and are a direct consequence of plate motion. The style of volcanism, the composition of the erupted products, and the nature of volcanic features that are produced vary considerably between different boundaries and reflect the fundamental influence of tectonic forces on volcanism.

## Mid-ocean ridge volcanism (divergent boundary)

Volcanism at divergent boundaries has produced a globally encircling mountain range known as the mid-ocean ridge system. It extends throughout the major ocean basins of the world for a total length of some 70 000 km. Discovery of this undersea mountain chain and its recognition as a primary volcanic feature was one of the most important advances in the field of marine geology. Dredging of rocks from the ridge and direct observations by submersibles confirmed that fresh volcanic rock is being emplaced along this boundary, forming new seafloor that progressively moves away from the ridge axis. The rate of production has been determined by dating magnetic anomalies in the oceanic crust that are arranged in symmetrical fashion on each side of the ridge (Vine and Matthews, 1963). These anomalies record times when the Earth's magnetic field changed polarity direction by 180°.

Spreading rates are generally low by human standards, averaging only a few centimeters per year. However, over long periods of geologic time movements of plates can produce or consume entire ocean basins.

There is considerable variation in the rates of spreading along different segments of the mid-ocean ridge system. In the Atlantic Ocean the spreading along the mid-Atlantic ridge is only about 2 cm/year, whereas along the East Pacific Rise the rate is up to 18 cm/year. It should be emphasized that the spreading rates are based on calculations that average the production of new seafloor over hundreds of thousands or millions of years. There is not necessarily an addition of a few centimeters of new oceanic crust all along the mid-ocean ridge every year. Eruptions are likely to be episodic, occurring on the timescale of hundreds to thousands of years, and affecting only parts of the ridge at any given time. Only recently has there been an actual eruption detected along the mid-ocean ridge system. It occurred in 1993 when an event was recorded from a 6-km-long section of the Juan de Fuca spreading center off the northwest coast of the United States (Chadwick *et al.*, 1995).

The crest of the ridge is generally located at a depth of several thousand meters. Topographic profiles across ridges exhibit distinctive morphologies that relate to spreading rate. The slow-spreading mid-Atlantic ridge consists of a well-defined axial valley surrounded on each side by steep, fault-bounded ridges, whereas the fast-spreading East Pacific Rise is defined by a broad elevated ridge with only a small-scale axial valley (Fig. 1.3).

Although they are primarily confined to the seafloor there are areas, such as Iceland and the African Rift Valley, where divergent boundaries are exposed on land, providing a unique opportunity to directly observe volcanic processes. Iceland is an example where an anomalous rate of magma discharge along the mid-Atlantic ridge has elevated the spreading center above sea level. The island is being enlarged through volcanic activity occurring along its neovolcanic zone that extends from the southwest to the northeast (Fig. 1.4). Along this zone is a set of prominent central volcanoes that rise to elevations up to
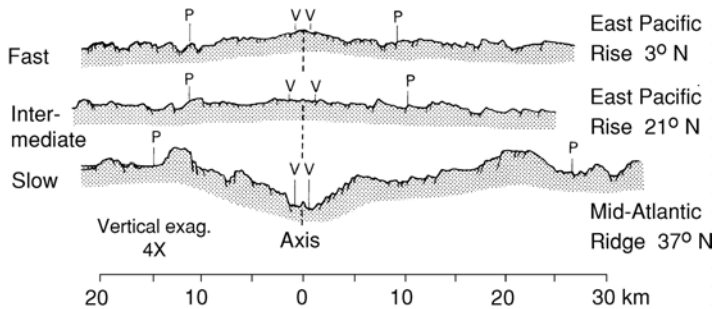
Fig. 1.3. Bathymetric cross-sections across the East Pacific Rise at 3° N and 21° N, and the mid-Atlantic ridge at 37° N showing the differences in morphology between fast, intermediate, and slow-spreading ridges. Modified from Brown et al. (1989).
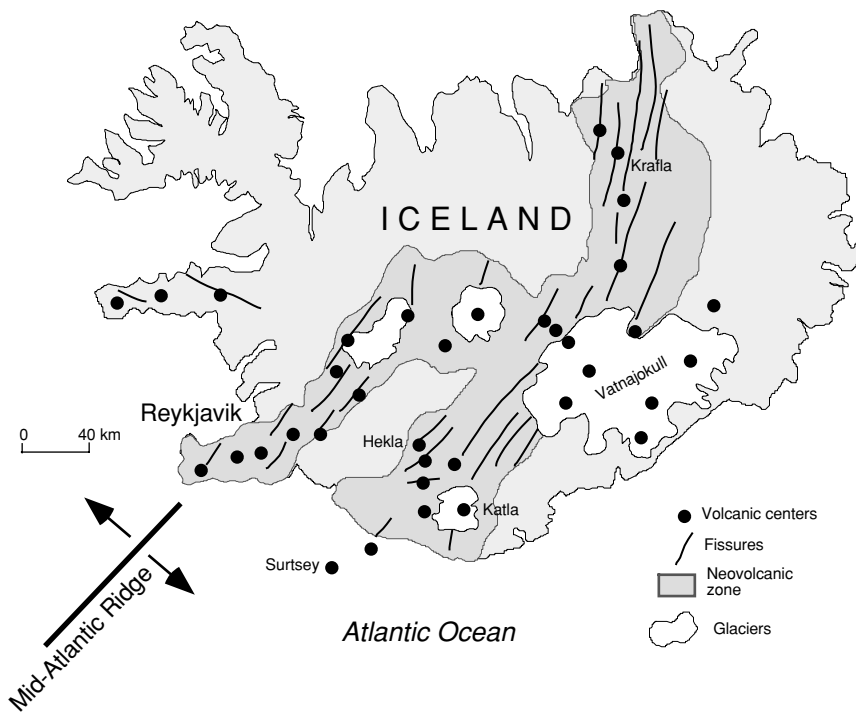
Fig. 1.4. Location of the neovolcanic zone (<7 Ma volcanism) in the central part of Iceland. Hotspot volcanism centered along the mid-Atlantic ridge has led to the emergence of Iceland above sea level. Modified from Gudmunsson (1996).

2000 m and are often glaciated. Between these centers are zones of fissures (rift zones) where magma can travel laterally from storage areas beneath the central volcanoes. In eastern Africa a nascent divergent boundary has created a 4000-km-long rift zone that extends from the intersection of the Red Sea and the Gulf of Aden, south to the latitude of Madagascar. This rift valley is home to some of Africa's largest volcanoes such Mt. Kilimanjaro and Mt. Kenya.

The global importance of divergent boundary volcanism can be appreciated by considering the annual budget of volcanic activity on Earth. Estimates of the total annual volcanic output from all volcanoes is about 4 km^3 of magma. Of that, 3 km^3, or about 75%, can be attributed to the mid-ocean system (Crisp, 1984). Thus, a large fraction of the global volcanic activity occurs at great depth in the ocean, out of view.

Subduction zone volcanism
Most of the documented volcanic eruptions occur along convergent plate boundaries, or subduction zones, such as the ones that make up the Pacific

Fig. 1.5. Mount Rainier stratovolcano in Washington state, elevation 4392 m. The volcano is dominanted by lava flows and breccias which are mostly andesitic in composition. Explosive eruptions have also produced pumice and ash deposits on the slopes of the volcano. Photograph by S. Carey.

"Ring of Fire" (Fig. 1.1). These eruptions are often explosive in nature, result in immediate threats to human populations, and consequently attract our attention. Many of the world's most famous volcanoes such as Krakatau, Mt. Pelée, Mount St. Helens, and Mt. Fuji are related to the subduction process. Their structure is often what we consider as a "typical" volcano; a high, steep-sided mountain with a crater at the summit (Fig. 1.5). But as we've seen, the dominant and thus more "typical" type of volcanic landform is that occurring beneath the sea in the form of mid-ocean ridges.

A striking feature of the global distribution of subduction-related volcanism is that it's highly asymmetrical, with most of it occurring around the rim of the Pacific Ocean (Fig. 1.1). The Atlantic Ocean has only two short segments of subduction volcanism; the Lesser Antilles island arc at the eastern boundary with the Caribbean Sea, and the South Sandwich island arc off the southern tip of South America. Other major subduction zones occur in the Indian Ocean (Indonesian island arc) and the Mediterranean Sea (Aeolian and Hellenic island arcs).

Just as there were significant differences in the morphology of divergent plate boundaries (Fig. 1.3) there are also marked differences in the types of convergent boundaries. Uyeda (1982) has suggested that there are at least two distinct types represented by the Mariana island arc in the western Pacific and the Andean active continental margin of South America (Fig. 1.6). A cross-section through the Marianas arc shows that subduction of oceanic crust is occurring along a steeply dipping Benioff Zone. The lack of great thrust earthquakes during historical times suggests that the mechanical coupling between the downgoing and the overriding plate is relatively weak. Volcanic activity in the Marianas occurs as a narrow, curved array of individual volcanic islands positioned about 120 km above the top of the descending plate. The curvature of the island chain is merely a reflection of the geometrical constraints of subducting a rigid plate into the surface of a sphere. In detail, however, some island arcs show distinct linear segmentation of volcanic centers along the subduction trend (e.g., Marsh, 1979; Carr, 1984). Behind the line of volcanic islands in the Marianas is a series of small oceanic basins called back-arc basins. These basins are inferred to form by spreading, in a manner similar to mid-ocean ridges, but on a smaller scale (Karig, 1971). The Marianas arc is thus considered as an example of a typical island arc involving the subduction of oceanic crust beneath other oceanic crust.

A cross-section through the west coast of South America shows a very different type of subduction process (Fig. 1.6). Here, oceanic crust is descending beneath thick continental crust at a shallow angle. The frequent occurrence of strong thrust earthquakes suggests that, unlike in the Mariana arc, there is strong coupling, or resistance, to the subduction of the plate beneath South America. Volcanism occurs as a line of individual volcanoes that typically is located at a position about 120 km above the top of the descending plate. However, because the slope of the Benioff Zone is much shallower than in the Marianas, the location of the volcanic front in the Andes occurs further back from the trench (Fig. 1.6). Another important difference is that the Andean subduction zone exhibits compression in the area behind the volcanic front and consequently this type of margin lacks the extensional back-arc basins that are characteristic of the western Pacific.

The differences in these two modes of subduction have been related to factors such as the age
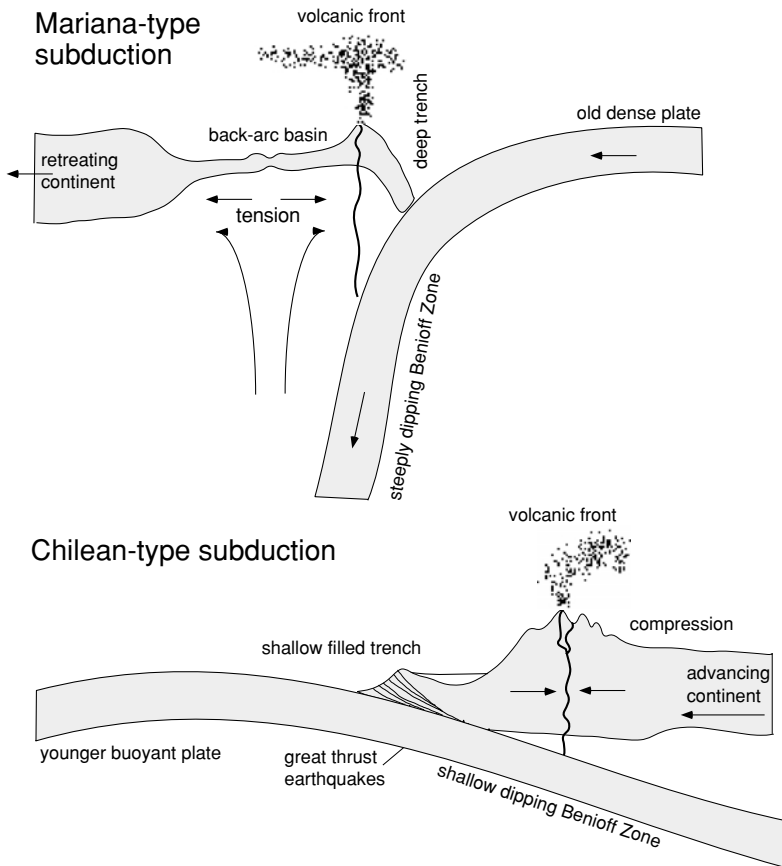
Fig. 1.6. Summary of the differences between the Mariana-type and Chilean-type subduction modes based on the model of Uyeda (1982). Mariana-type subduction involves steeply descending plates with few great thrust earthquakes, whereas plate subduction in the Chilean-type zones is much shallower and typically more seismically active.

of the subducting slab and the absolute motion of the overriding plate relative to the trench (Molnar and Atwater, 1978; Uyeda and Kanamori, 1978). Subduction of the Mariana type is thought to take place when old dense seafloor descends beneath oceanic crust and the overriding plate is moving away from the active trench. In the Andean type of subduction the descent of the plate is more difficult because it is younger and more buoyant. The absolute motion of the overriding plate is also towards the trench, resulting in compression behind the volcanic front.

Subduction is a process of recycling where oceanic crust is returned to the mantle. The size of the Earth has remained relatively constant and therefore the production of new seafloor at the mid-ocean ridges must be balanced by the subduction of crust at convergent margins. As discussed earlier, volcanism at mid-ocean ridges accounts for about 75% of the annual volcanic

output of the Earth (Fisher and Schmincke, 1984). The volcanism associated with subduction is only 15%, and thus, even though subduction volcanism poses the largest threats to the human population and is the most conspicuous type of activity, it still represents a relatively small proportion of the annual volcanic production.

Intraplate volcanism

There are many areas of the Earth's surface where volcanism is occurring that is unrelated to a major plate boundary. These can be found both in the ocean basins and on the continents. Focused, persistent areas of volcanic activity such as these that remain active for millions of years are known as hotspots, or mantle plume volcanism (Wilson, 1973). They are areas of anomalously high volcanic production that are related to the rise of mantle plumes from deep within
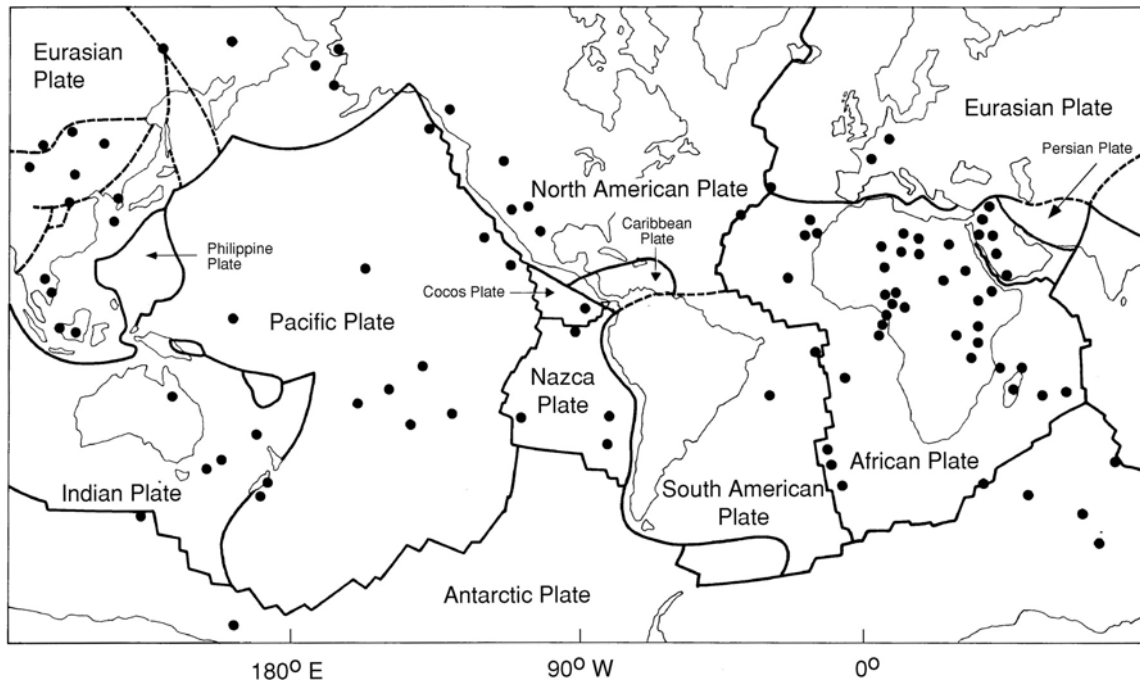
Fig. 1.7. Location of the major volcanic hotspots (solid circles) in the ocean basins and on the continents. Modified from Wilson (1989).

the Earth. There are currently between 50 and 100 active hotspots, depending on the factors that are used to define them (Fig. 1.7). Common features include voluminous outpourings of basaltic magma, higher than normal heat flow, thinning of the overlying crust, and development of a broad topographic high.

Because the source of magma for hotspots is derived from a long-lived source beneath the lithosphere, plate movement over millions of years results in the formation of linear volcanic features. Hotspots are thus extremely useful for inferring the absolute motions of plates relative to the deep interior of the Earth. An excellent example of this can be found in the middle of the Pacific plate where the Hawaiian islands form a distinctive linear group that trends from the southeast to the northwest. The Hawaiian islands are actually a small part of a much larger submarine linear feature that includes the Hawaiian ridge and Emperor seamount chain (Fig. 1.8).

Formation of this large-scale feature is attributed to hot spot volcanism currently located beneath the southeast flank of Hawaii. During the past 70 million years, volcanic activity from this hotspot has built a series of islands that are continually moved to the northwest by the motion of the Pacific plate. This is confirmed by the systematic increase in island age from the southeast to the northwest along the chain (Clague and Dalrymple, 1987). As the islands age, they subside and are eroded below sea level. A pronounced shift in the orientation of the Hawaiian–Emperor seamount chain occurred about 44 Ma ago when the motion of the Pacific plate changed to a more westerly direction of motion (Fig. 1.8). The most recent island associated with the Hawaiian hotspot is Loihi, now forming under water on the southeast flank of the big island of Hawaii. Other examples of linear chains of islands and seamounts includes the Tuamotu and Austral groups of the South Pacific. These chains show a similar kink associated with the major change in Pacific plate motion.

In the ocean basins some hotspots coincide with divergent plate boundaries. Iceland is an example of a hotspot that is centered along the
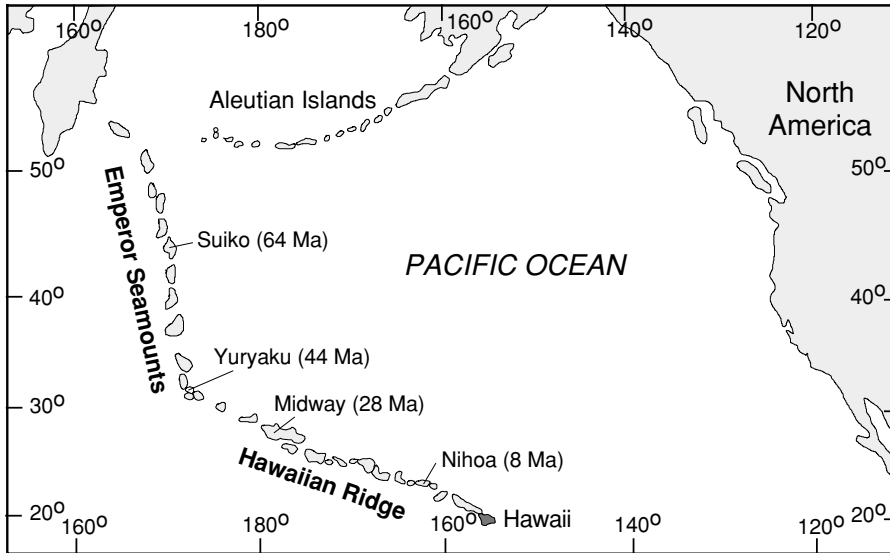
Fig. 1.8. Orientation of the Hawaiian ridge and Emperor seamount chain in the Pacific Ocean. Ages of various islands are shown in parentheses. Note the change in alignment of the two seamount chains at Yuryaku, corresponding to an age of 44 Ma. Modified from Clague and Dalrymple (1987).

mid-Atlantic ridge axis. The excess volcanic output of the hotspot results in the elevation of the ridge above sea level and the formation of elevated submarine ridges on each side of the Iceland Plateau. Other hotspots are located beneath the continents, especially Africa (Fig. 1.7). Plate motion of continental masses can also produce linear traces of past volcanic activity like those in the ocean basins. For example, volcanic activity beneath Yellowstone National Park in the western United States has been attributed to the location of an active hotspot. A belt of volcanic rocks ranging from Recent to 15 Ma old (Eastern Snake River Plain) can be traced from Yellowstone back across Wyoming into Idaho. This is likely to represent the record of volcanism as the North American plate migrated to the southwest (Greeley, 1982).

Large igneous provinces (LIPs)
Much of the previous discussion has centered on describing the current distribution of volcanic activity on the Earth's surface. However, there are examples of spectacular volcanic activity that have occurred in the geologic past for

which there are no modern analogues. Many continents and ocean basins contain widespread accumulations of basaltic lava flows that represent massive outpourings of magma. These are collectively referred to as large igneous provinces, or LIPs (Coffin and Eldholm, 1994). Included in this category are continental flood basalts and submarine basalt plateaus (Fig. 1.9). The Deccan Traps of India is an example of one of the largest continental flood basalt provinces on Earth. When it was formed 65 millions years ago it may have covered an area of 1.5 million km^2 with an average thickness of at least 1 km. Such provinces are noteworthy because of the large areas affected by volcanism and the relatively short times of formation. An estimate for the emplacement of the Deccan Traps basalts is of the order of 1 Ma (Duncan and Richards, 1991; see also Chapter 7). Such durations imply volumetric discharge rates that are up to an order of magnitude larger than those of modern volcanic provinces, such as mid-ocean ridges. As a result of the high eruption rates this type of activity does not tend to produce high individual volcanoes, but instead, eruptions from many vents leads to the accumulation of laterally extensive flows into a thick plateau. The Ontong–Java plateau, located in the western Pacific (Fig. 1.9) is an example of a large submarine flood basalt province that was formed 124 Ma ago. It is three times the area of the Deccan Traps and was produced in about 3 Ma.