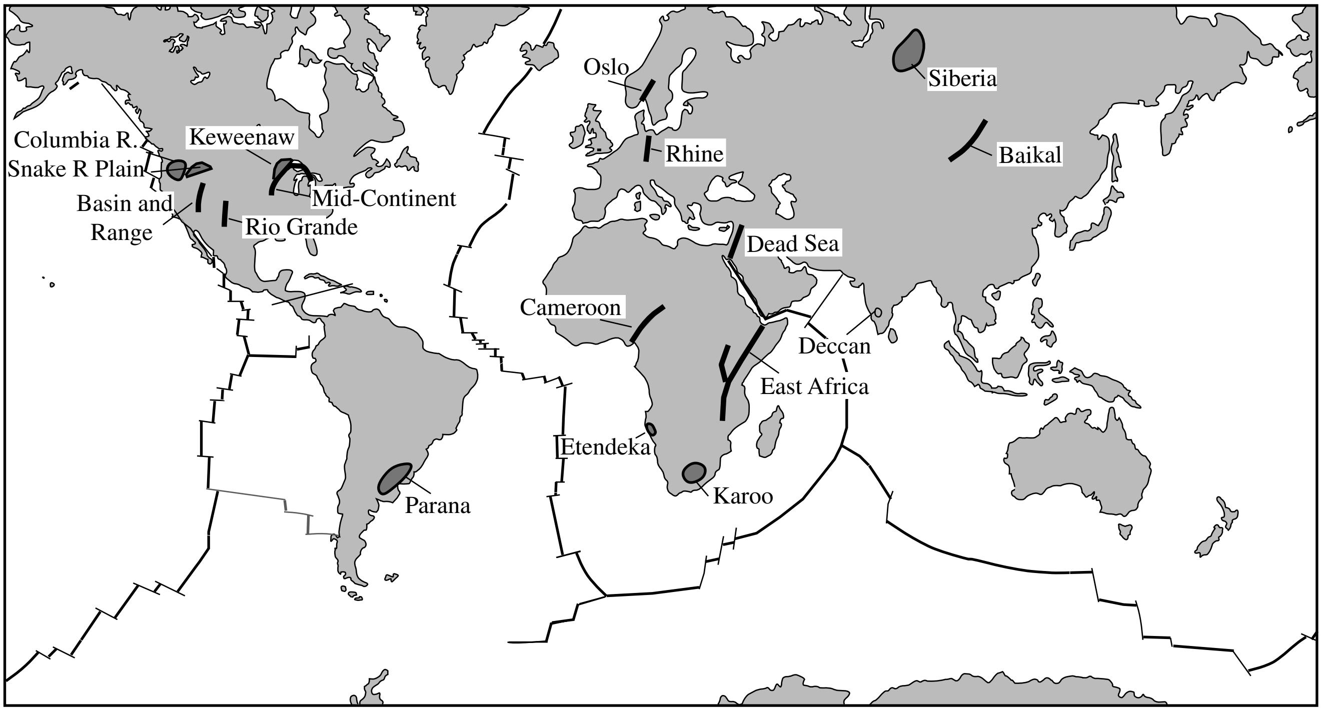
Chapter 8

Intracontinental Volcanism

8.1 Introduction

Although continental intraplate magmatism produces only a small proportion of the igneous rocks erupted on Earth, it produces the largest variety of rock types. This diversity of intracontinental igneous rocks results from various combinations of mantle, continental lithosphere, and crustal sources. Different combinations and proportions of these sources, together with processes of magmatic differentiation, create a broad spectrum of igneous suites. Intracontinental magmatism is addressed in this and the following chapter. This chapter is concerned with intracontinental volcanism, whereas the next chapter describes plutonic rocks that formed in an intraplate environment. The discussion of volcanism precedes that of plutonism because the tectonic environment of young volcanic rocks is typically the most straightforward. The information assembled in this chapter is then used to address the origin of intracontinental plutonic rocks, the tectonic environments of which are not always definitive. It is important to keep in mind that in many instances intrusions are spatially related to coeval volcanic rocks, and hence the division of this topic into two chapters is somewhat arbitrary.

Intracontinental volcanism is typically associated with mantle plumes or rifts. Plume-related magmatism in intracontinental settings is analogous to that in oceanic environments: volcanic centers define tracks of progressively younger magmatism approaching the present site of the plume. The plume track along the Snake River Plain in Idaho is comparable to the one that produced the Hawaii-Emperor island chain in the Pacific Ocean. Intracontinental volcanism associated with active continental rift zones includes the Basin and Range province and the Rio Grande rift of the southwestern United States, the Rhine graben of Europe, the East African rift zone (including the Red Sea), and the Cameroon volcanic line of Africa, the Baikal rift in Siberia, and the southeast Australia rift zone (Map 8.1). Of these, the East African rift system involves the greatest volumes of magma (500,000 km^3 compared to 12,000 km^3 in the Rio Grande rift). Continental rift zones form above areas of local lithospheric extension and are characterized by a central depression, uplifted flanks, and a thinning of the underlying crust. These structures are associated with high heat flow, broad zones of regional uplift, and magmatism. The rift zones are usually tens of kilometers wide and tens to a few hundred kilometers long. The Basin and Range province is unusual among continental rifts in that it extends hundreds of kilometers in both length and breadth. Some rift zones, such as the East African rift, represent continental crust undergoing the first stages of continental breakup. These may eventually evolve into Atlantic-type, rifted continental margins. Other rift zones are the products of "escape tectonics." In these zones, the continent outboard of a continental collision extends in response to that collision. Examples include the Rhine graben, which formed in response to the Alpine collision, and the Baikal rift, which formed in response to the Himalayan collision.



Map 8.1 Locations of major continental flood basalt provinces (shaded areas) and of major continental rifts (heavy lines).

It is difficult to generalize about the composition of lavas erupted in continental rifts. In some environments, rifting involves eruption of huge volumes of tholeiitic basalt as flood basalt, such as in the Rio Grande rift. In other areas, such as the East African rift, magmatism involves the formation of individual, point-source volcanoes that may range in composition from tholeiitic to alkaline. Most alkaline rocks are rich in sodium, rather than potassium, although potassic alkaline rocks are present as well. This chapter examines this wide range of primary magmas, their origin, and their differentiation to form a wide range of derivative magmas.

8.2 Continental Flood Basalt Provinces

Perhaps the most dramatic examples of continental volcanism are flood basalts. Large areas of the continents have been covered by great thicknesses of basaltic magma that appear to have been fed from fissures rather than from central vents. Some of these flood basalts, such as the Keweenawan basalts in the north central United States, are clearly related to rifts; for others the relationship is cryptic. Continental flood basalt provinces, together with oceanic plateau (see Chapter 6), are sometimes referred to as **large igneous provinces** (LIPs). The volume of lava produced in these provinces is far greater than any continental volcanism occurring today. Most continental flood basalts are tholeiitic, and they appear to form in extensional environments. Although they form lava sequences one to ten kilometers thick, the surface upon which the lavas flowed never seems to have developed much relief. Apparently, the underlying rocks subsided to form a basin of about the same extent as the lavas that flowed out, so that mass was simply transferred from depth to the surface.

Map 8.1 shows the distribution of major continental flood basalt provinces in the world; the ages and dimensions of the provinces are given in Table 8.1. Many of the flood basalts erupted during continental breakup or during failed continental rifting. The Karoo, Paraná, and Deccan provinces evolved in tensional environments associated with the breakup of Gondwana during the Jurassic and Cretaceous. These provinces form a band that parallels the Atlantic margin of Gondwana. A plume source is implicated in the origin of other occurrences of continental flood basalts. The Columbia River basalts and the lavas of the Snake River Plain and Yellowstone may be the product of a single plume (Camp, 1995). Mantle plumes are commonly associated with divergent plate margins;

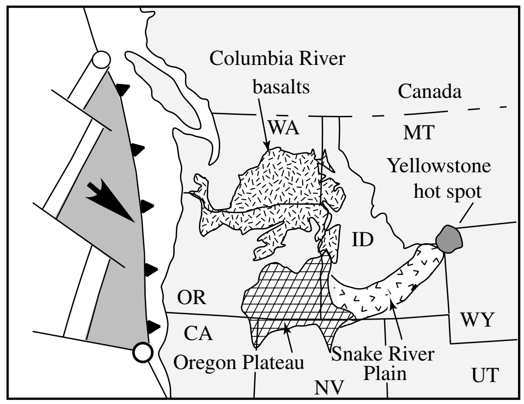
Table 8.1 Ages and Dimensions of Major Continental Flood Basalt Provinces

Flood basalt	Location	Age (Ma)	Area (km^2)	Thickness (m)
Snake River Plain	Idaho, USA	16–present	$.5 \times 10^5$	up to 1,200
Columbia River	WA, ID, OR, USA	16–6	2.0×10^5	>1,500
Deccan Traps	India	65–50	$>5.0 \times 10^5$	>2,000
Paraná Plateau	Brazil	149–119	12×10^5	1,800
Karoo	S. Africa	206–216	$>1.4 \times 10^5$	9,000
Siberian Traps	Russia	245–216	$>15 \times 10^5$	3,500
Keweenaw	Lake Superior, USA	1200–1050	$>1.0 \times 10^5$	12,000

many ocean islands, including Iceland, the Galapagos, Bouvet, and Tristan da Cunha are located on mid-ocean ridges. Continental flood basalt provinces may be related to rifting and to plume activity. For example, the Etendeka and Paraná flood basalt provinces were formed over the Tristan hot spot during the opening of the South Atlantic Ocean (Mohriak et al., 2002).

8.2.1 The Columbia Plateau – Snake River Plain Province

One of the youngest and best preserved continental flood basalt provinces in the world is the Columbia Plateau – Snake River Plain province of Washington, Oregon, and Idaho. The basaltic volcanism composes part of a swath of Miocene and younger basaltic (and minor rhyolite) volcanism that extends across the northwestern United States, including the Columbia Plateau, the Oregon Plateau, and to the east, the Snake River Plain and Yellowstone (Map 8.2). Between six and seventeen million years ago, approximately 200,000 km^3 of relatively aphyric basaltic lavas covered an area of about 200,000 km^2 in the Columbia Plateau. Since the Miocene, a much smaller volume of basaltic lava has been erupted in the Snake River Plain, where the last eruption took place only two thousand years ago.



Map 8.2 Map showing the relation between the Colombia River basalts, the Oregon Plateau volcanic belt, the Snake River Plain, Yellowstone, and the direction of movement of the Juan de Fuca plate relative to North America.

The Columbia River basalts have been divided into four major units, which are, from oldest to youngest, the Imnaha, Grande Ronde, Wanapum, and Saddle Mountains basalts (Figure 8.1). The Picture Gorge basalt is a smaller unit coeval with the Grande Ronde basalt. The Grande Ronde flow is by far the largest by volume, and was erupted over a narrow time interval of 0.42 million years beginning at 15.79 million years ago (Barry et al., 2010). This age is somewhat younger than the 16.5 million year age for the Steens basalt, one of the major basalt flows of the southeastern Oregon Plateau that is considered part of the Columbia River Basalt Group (Brueseke et al., 2007; Baksi (2010). Like the Grande Ronde basalt, the Steens basalt was erupted over a very short time of 0.2 million years (Baksi, 2010). The origin of the Columbia River basalts is the subject of ongoing debate. Some authors emphasize the location of the basalt province east of the Cascades arc in a back-arc setting and propose a magma source in the shallow mantle akin to that supplying arcs. Alternatively, the fact that huge volumes of basalt were erupted over a very short period of time has led others to conclude that the eruption of the Steens basalt marked the onset of hotspot volcanism in western North America (see discussion and reply in Hooper et al., 2007). Hooper and colleagues (2007) proposed that one edge of the plume died out over

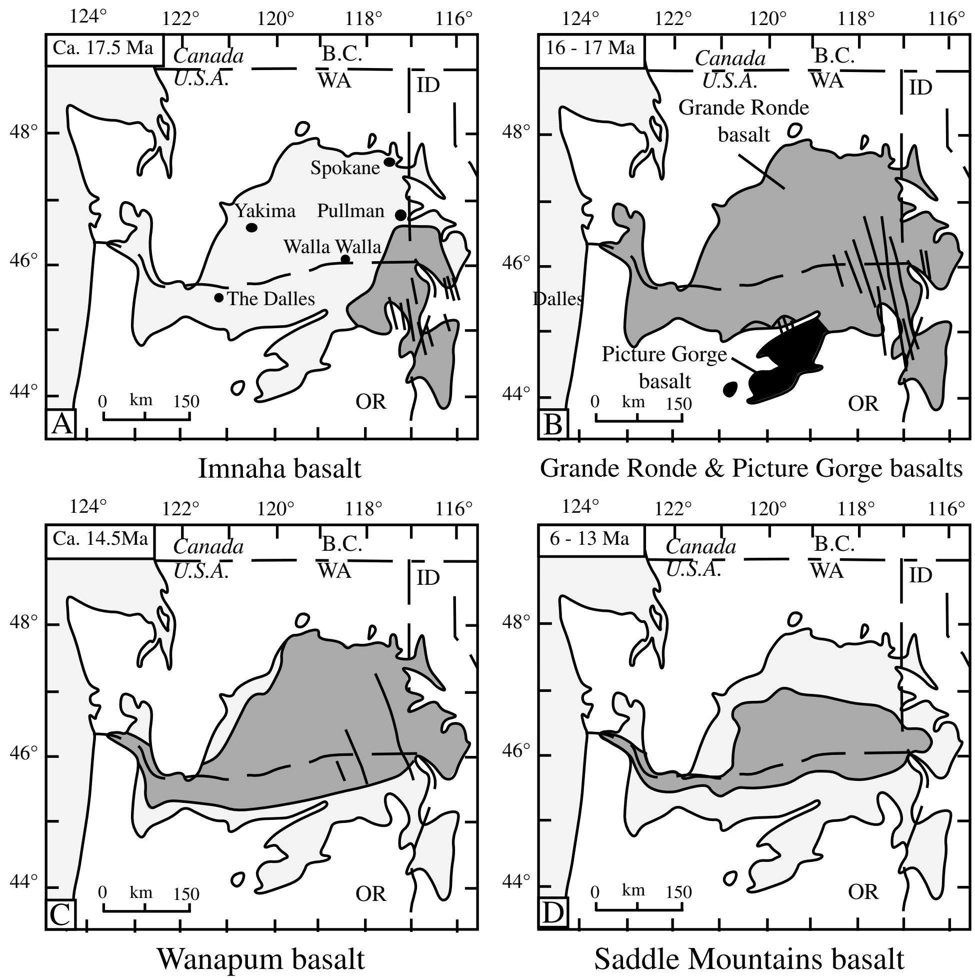


Figure 8.1 The aerial extent (in dark shading) of the four units of the Columbia River basalts. Light shading gives the modern extent of the Columbia River basalts. The location of the fissures are marked with heavy lines. From Swanson and colleagues (1979).

six million years ago after the eruption of the Columbia River basalts, while the main portion of the plume produced the basaltic and rhyolitic volcanism of the Snake River Plain. The rhyolite volcanism of the Snake River Plain becomes younger to the east as the North American plate drifted westward over the head of the plume. The locus of the plume-related volcanism is now centered over Yellowstone and the eastern Snake River Plain.

Chemistry of the Columbia River basalts. The Columbia River basalts show a differentiation trend typical of tholeiitic suites, with moderate increases in SiO_2 accompanied with considerable decreases in CaO and decreases in MgO (Figure 8.2). Figure 8.2 shows that as the suites differentiate to lower MgO, they display an increase in silica. However, at any value of MgO there is a considerable range in SiO_2 among the eruptive suites. This suggests each suite experienced a different degree of crustal assimilation. The well-defined trend on the CaO versus MgO diagram is consistent with fractionation of clinopyroxene and plagioclase, which produces residual lavas poorer in both of those two oxides. The increase in K_2O with decreasing MgO indicates that potassium was behaving incompatibly; no K-bearing phase, such as K-feldspar, was crystallizing in these basalts. TiO_2 behaved incompatibly in the Imnaha, Grande Ronde, and Picture Gorge basalts, indicating that the Ti-bearing phase, such as Ti-magnetite or ilmenite, was not crystallizing. In both the Saddle Mountains and Wanapum basalts, the TiO_2 reaches a maximum at MgO ~ 5.0 percent, which indicates the composition where ilmenite or Ti-magnetite began to crystallize.

A key point indicated by the data shown in Figure 8.2 is that each formation in the Columbia River Basalt Group has a distinct geochemical signature. The oldest unit, the

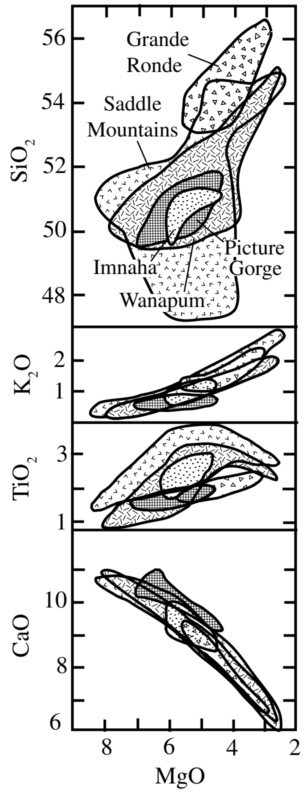


Figure 8.2 Major element compositions of the Columbia River Basalt Groups. From Hess (1989) and Hooper and Swanson (1990).

Imnaha basalt, has a relatively restricted compositional range, and SiO_2 and MgO compositions are near those of primitive mantle-derived basalts. Despite the huge volume of basalt erupted in the Grand Ronde basalts, these basalts have a rather restricted range in composition, which is richer in SiO_2 and poorer in MgO than the Imnaha basalt. Compared to the Grande Ronde, the time-correlative Picture Gorge is less evolved chemically and has lower SiO_2 and higher MgO (Figure 8.2). The smaller lava volumes of the Wanapum and Saddle Mountains formations were erupted with highly variable chemical compositions.

Two end member models describe the formation of the Columbia River basalts: either each eruption represents a new batch of mantle-derived magma, or the basalts formed from a single large batch of magma that ponded and differentiated in a chamber at depth from which eruptions tapped magma periodically. Since the lavas do not systematically become more evolved with decreasing eruptive age, the geochemical data best support the first alternative.

8.2.2 Petrography and Chemistry of Continental Flood Basalts

Flood basalt lavas typically are aphyric and phenocrysts are scarce. When phenocrysts are present, plagioclase is the most abundant mineral; it is accompanied by augite + pigeonite and Ti-magnetite and lesser amounts of olivine. This mineral assemblage is indicative of shallow-level crystallization. There are some distinct differences between continental flood basalts and MORB. In both rock types, plagioclase is the dominant phenocryst phase, but in MORB, olivine and Mg-Cr spinel are very common, whereas in continental flood basalts, augite and sometimes pigeonite are the main ferromagnesian minerals.

In terms of major element chemistry, continental flood basalts are similar to MORB. One important difference is the Fe-index, which is typically higher in continental flood basalts ($FeO^{tot}/(FeO^{tot} + MgO) = 0.7–0.8$; Hooper, 2000) than in MORB ($FeO^{tot}/(FeO^{tot} + MgO) = 0.5–0.6$; Stakes, Shervais, and Hopson, 1984). Either continental flood basalts are generated from sources that have more Fe than N-MORB-source mantle, such as E-MORB mantle (see Figure 6.7), or magmatic differentiation lowered the Mg content.

8.2.3 Models for the Generation of Continental Flood Basalts

The petrography, major and trace element chemistry, and isotope geochemistry suggest fundamental differences between continental flood basalts and oceanic basalts, some of which may be due to subcontinental lithospheric mantle and continental crust contamination of flood basalts(Hooper et al., 2007).

Continental flood basalts contain a low-pressure phenocryst assemblage. Consequently, it is reasonable to assume that at least part of the differentiation that produces continental flood basalts takes place at shallow depths, and that gabbroic and ultramafic cumulates lie beneath the flood basalt provinces. Cox (1980) envisions a two-stage process: basaltic sills near the base of the crust that undergo partial crystallization. The residual magmas, which are now less MgO rich, rise through a network of dikes toward the surface. The magmas may pond again near the surface and undergo further fractional crystallization to produce the low-temperature phenocryst assemblage.

Ascent through a system of dikes provides ample opportunity for crustal contamination. The extent of contamination will vary with the temperature of the magma, the flux of magma through the dikes, the width of the dikes, and the composition (and solidus temperature) of the crust through which they pass. Where flow in the dikes is turbulent, magma will erode its walls and become more contaminated than if flow were laminar. The Columbia River basalts appear to have been contaminated at two levels: first, at the base of the crust by the subcontinental lithosphere or lower crust, and second at shallower crustal levels where assimilation of continental material occurred during magma ascent (Hooper et al., 2007).

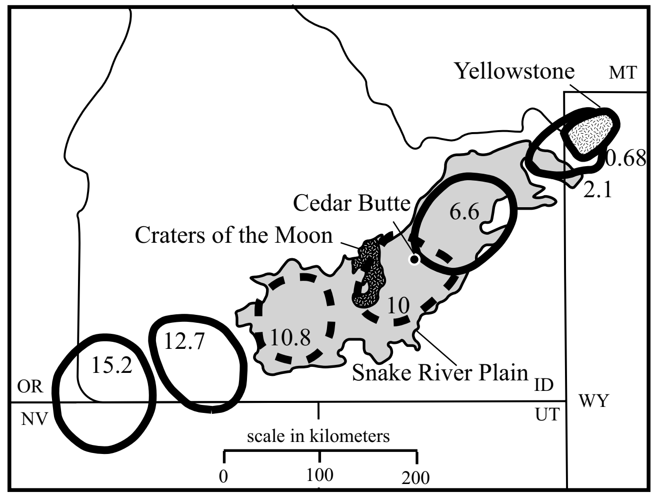


Figure 8.3 A portion of the northwestern United States showing the location of the Snake River Plain, Craters of the Moon volcanic rocks, Cedar Butte rhyolite volcano, the Yellowstone Caldera, and the calderas formed by the Yellowstone hot spot as it moved across Idaho, dashed where approximate. Numbers give the ages for the caldera eruptions in millions of years. Modified after Perkins and Nash (2002) and McCurry et al. (2008).

8.3 Bimodal Volcanism

The Columbia River flood basalt province contains essentially no coeval rhyolites, but most flood basalt provinces and many tholeiitic volcanoes in rifts erupt rhyolite as well as basalt (Bryan et al., 2002). In fact the association of basaltic rocks and rhyolite with a comparative lack of intermediate rocks is common enough in rifted areas to carry its own term – **bimodal volcanism**.

8.3.1 Bimodal Volcanism in the Yellowstone – Snake River Plain Province

A good example of bimodal volcanism is seen in the Snake River Plain – Yellowstone system, which, as noted earlier, appears to be located along a continuation of the plume track that may have formed the Columbia River basalt and Oregon Plateau (Figure 8.3). The Yellowstone – Snake River Plain province erupted in a two-stage process. The first event involved rhyolitic caldera eruptions that migrated from west to east across Idaho during the past fifteen million years (Perkins and Nash, 2002). This age progression is caused by the westward migration of North America over a stationary hot spot. Indeed, the fact that the apparent eastward migration of the calderas matches the rate of the westward movement of the North America plate is one of the strongest arguments that the Yellowstone – Snake River Plain volcanism is caused by a mantle hot spot. The famous thermal features of Yellowstone National Park are the result of the magmatic heat that remains after the most recent eruption in this series, a massive eruption that formed the Yellowstone Caldera six hundred forty thousand years ago. The second series of events involved the eruption of extensive flood basalts that filled most of the calderas formed by the rhyolitic eruptions.

The eruptions of the Yellowstone Caldera produced voluminous deposits of fayalite-bearing, high-silica rhyolitic tuffs, which record some of the world's most catastrophic volcanic events (Box 8.1). The presence of fayalite in these tuffs indicates that the magma was iron enriched. The remnants of similar iron-enriched, high-silica rhyolites, found on the margins of the Snake River Plain across southern Idaho and northern Nevada, were used to determine the locations and ages of the calderas that have long been buried by the basaltic Snake River Plain lavas.

The Snake River Plain volcanism is dominated by olivine tholeiite, but locally, including at Cedar Butte, the plain is dotted with small rhyolite volcanoes. Like the rhyolite from Yellowstone, the rhyolite from the small rhyolite volcanoes in the Snake River Plain is iron enriched. Additionally, the rhyolite is isotopically indistinguishable from the basalts of the Snake River Plain, causing McCurry and colleagues (2008) to conclude that the rhyolite was produced by extreme differentiation of the Snake River Plain tholeiitic basalt. This association of rhyolite with basalt is typical of bimodal volcanism. In many

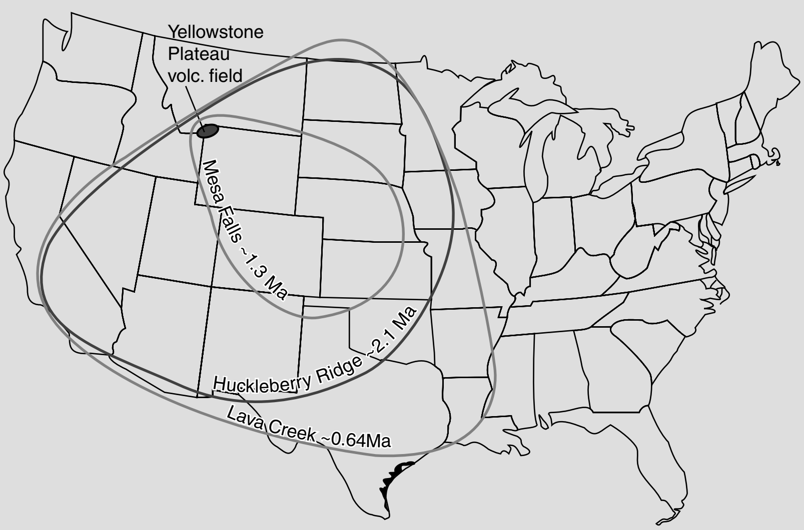
BOX 8.1 VOLCANIC HAZARDS IN INTRACONTINENTAL ENVIRONMENTS

Arc volcanoes account for more eruption-related fatalities in the past thousand years than eruptions in any other tectonic setting (Box 7.1). However, some of the largest volcanic eruptions derive from intracontinental volcanoes. The Yellowstone volcanic field has erupted catastrophically three times over the past 2.1 million years:

Eruption	Date	Volume of ejecta
Huckleberry Ridge	~2.1 Ma	2,500 km^3
Mesa Falls	~1.4 Ma	280 km^3
Lava Creek	~0.64 Ma	1,000 km^3

Each eruption produced extensive blankets of hot rhyolitic ash that covered much of western and central North America (Box 8.1). Each eruption also resulted in the formation of a caldera when the ground collapsed above the partially emptied magma chamber.

Eruptions on this scale are rarest, but the hazards they pose are the most significant. Each eruption at Yellowstone probably lasted for a day to weeks. The area closest to the volcanic centers was overrun by ash flows, and a larger area was affected by ash falls. Fine ash encircled the globe, cooling climate for several years. The U.S. Geological Survey estimates that the probability of another major, caldera-forming eruption in Yellowstone is so small as to be below the threshold of calculation (Christiansen et al., 2007). However, the area remains geologically active, and the hydrothermal features – including geysers, hot springs, and fumaroles – draw millions of visitors to Yellowstone National Park each year.



Box 8.1 The extent of ash fall deposits from the three major caldera-forming eruptions of the Yellowstone Plateau volcanic field: the Huckleberry Ridge ash bed (~2.1 Ma), the Mesa Falls ash bed (~1.3 Ma), and the Lava Creek ash bed (~0.64 Ma). From Christiansen and colleagues (2007).

rift environments, only basalt and rhyolite are found and lavas with intermediate silica contents are conspicuously missing. In the Snake River Plain, lavas with intermediate silica contents are found in the four-hundred-thousand-year-old lava flows from Cedar Butte, which record a complete geochemical transition from basalt to rhyolite in the Snake River Plain magmatic system (Figure 8.4).

8.3.2 Geochemistry of the Yellowstone – Snake River Plain Bimodal Suite

The differentiation trends of intracontinental, plume-related magmas (Figure 8.4) are distinctly different from those of arc magmas (Figure 7.8). The notable increase in the Fe-index with only a minor change in silica is probably an indication that magnetite and ilmenite didn't begin crystallizing until late in the fractionation history of the lavas. The lack of Fe-Ti oxides in the initial crystallizing assemblage leads to the formation of rhyolites that are strongly enriched in iron over magnesium (Figure 8.4A). Similar to the iron index, MALI of Snake River Plain basalts shows a strong increase with only a minor change in silica before following a trend parallel to the alkalic – alkali-calcic boundary (Figure 8.4B). This trend is probably caused by fractionation of clinopyroxene at relatively high pressures, conditions that suppress plagioclase crystallization (Frost and Frost, 2011). Crystallization of clinopyroxene extracts CaO from the melt without changing the K_2O or Na_2O contents, unlike crystallization of plagioclase.

The rhyolitic tuffs of Yellowstone lie at the silica-rich margins of the Snake River trends in Figure 8.4. The Yellowstone rhyolites, however, are a little less iron enriched than the rhyolites of Cedar Butte: they border on being calc-alkalic instead of alkali-calcic. In addition, the Yellowstone rhyolites are slightly peraluminous instead of metaluminous (Figure 8.4C). Isotopic studies of the intracaldera Yellowstone rhyolitic rocks indicate that they formed dominantly by differentiation of tholeiitic basalt but may contain up to 15 percent crustal components (Hildreth, Halliday, and Christiansen, 1991). The compositional differences between the Yellowstone rhyolites and those of Cedar Butte can be explained by this crustal contamination. The continental crust in the area, as indicated by the gneisses exposed in the adjacent Wind River Mountains, is dominated by magnesian calc-alkalic granitic rocks (Frost et al., 1998). Melting of these granitic rocks likely produces mildly peraluminous

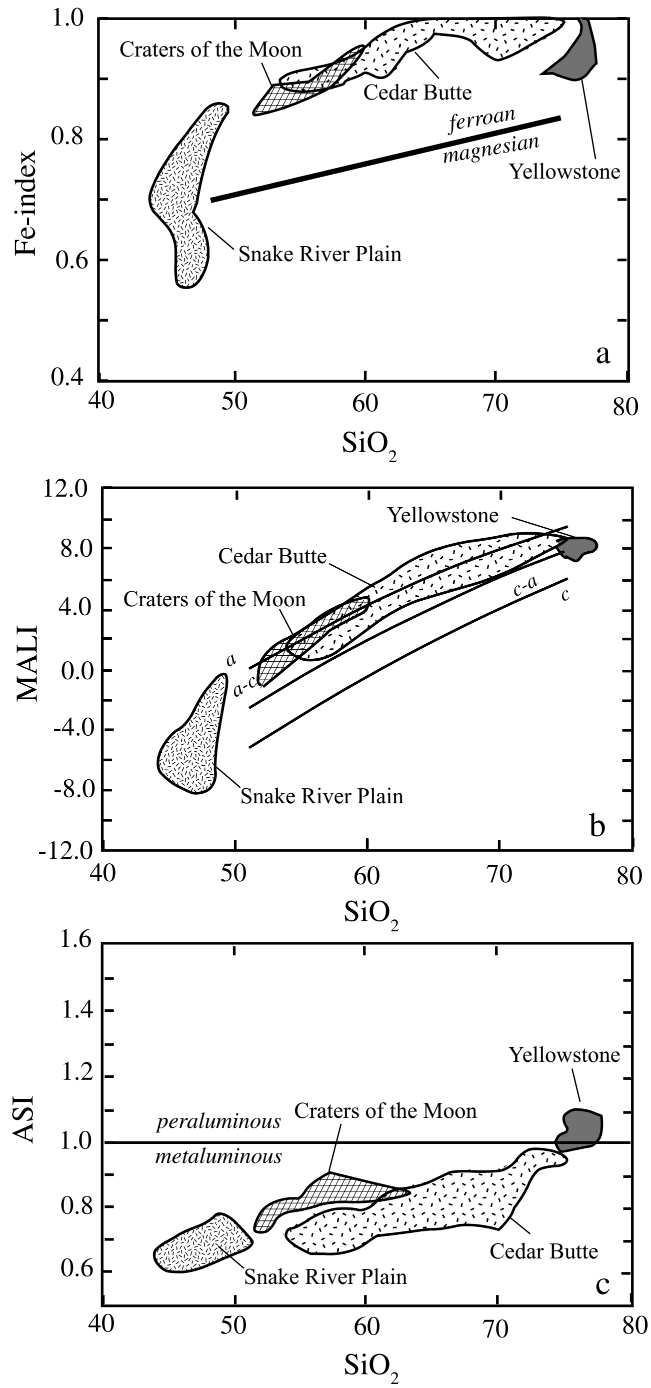


Figure 8.4 Geochemical trends in the volcanic rocks of the Yellowstone – Snake River Plain province. In Figure 8.4 A: c = calcic, c-a = calc-alkalic, a-c = alkali-calcic, a = alkalic. Data from McCurry et al. (2008), McCurry (unpublished data), and Hildreth, Halliday, and Christiansen (1991).

magnesian calc-alkalic melts that, when added to the melts of Cedar Butte composition, could produce the magmas of Yellowstone.

8.3.3 Models for the Generation of Bimodal Volcanism

Models for the origin of bimodal volcanism must both identify the sources of the basaltic and rhyolitic magmas and also explain the near absence of intermediate composition lavas. The source of the basaltic components in bimodal suites is the least controversial aspect of the problem; a mantle source is almost certainly required. Mantle-derived tholeiitic basalt may be produced either when the asthenosphere upwells during rifting or when a mantle plume ascends. This tholeiitic basalt may pond at the base of the crust, where it would differentiate along a tholeiitic trend, producing magmas enriched in FeO/(FeO + MgO). Contamination of the primary magma by subcontinental lithosphere and the continental crust may occur in bimodal associations, just as it does in flood basalts. Eruption of these magmas accounts for the basalt flows in bimodal associations.

The origin of the rhyolitic rocks in bimodal associations is more contentious. One possibility is that the basaltic magma stalled at depth continues to differentiate until producing andesitic to rhyolitic magmas. These magmas may assimilate continental crust as they evolve, and crustal contamination may be reflected in their isotopic compositions. As the magmas become more siliceous and accordingly more buoyant, triggering ascent to shallower depths or eruption at the surface. This hypothesis is favored for the eastern Snake River Plain, where an unusual continuum of magma compositions is preserved in a few Quaternary volcanic centers (McCurry et al., 2008; Figure 8.4).

To explain the lack of intermediate compositions typical of bimodal associations, Frost and Frost (1997) proposed that partial remelting of earlier formed differentiates could produce granitic melts. These, too, could assimilate felsic crust prior to eruption on the surface. Hildreth, Halliday, and Christiansen (1991) identified partial melts of Cenozoic basalt as a possible source of Yellowstone rhyolites and were able to quantify varying amounts of crustal assimilation using Sr, Nd, and Pb isotopic data.

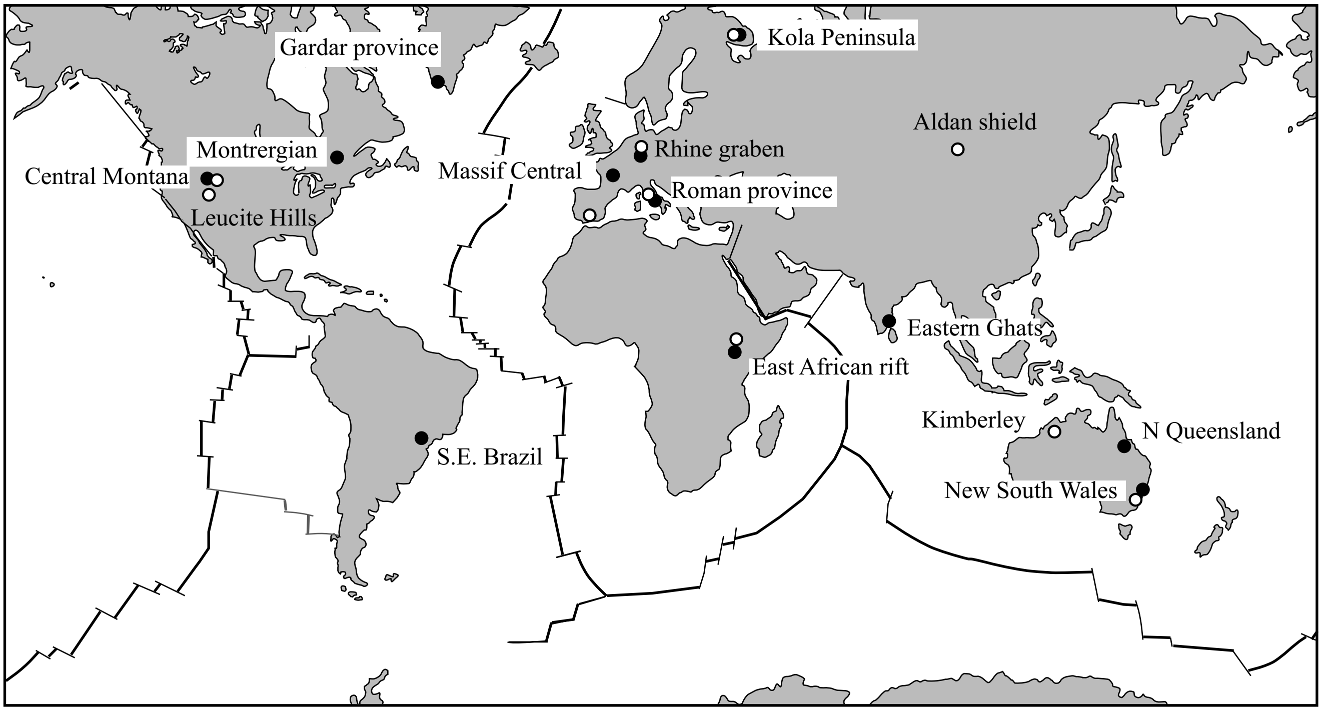
A third mechanism to produce the rhyolitic magmas in bimodal associations is partial melting of felsic crust in response to heating by tholeiitic magma. This mode of origin accounts for the lack of intermediate rocks. However, as Christiansen and McCurry (2007) pointed out, rocks formed by crustal melting tend to be magnesian and calc-alkalic, whereas the silicic volcanic rocks in bimodal associations are typically ferroan and alkali-calcic to alkalic. Nevertheless, it seems likely that rhyolites formed in extensional environments associated with tholeiitic basalt may include a spectrum from those that are formed exclusively by fractionation or partial melting of basalt and its subsequent differentiates, to those that were produced largely or entirely by partial melting of felsic crust.

8.4 Alkaline Volcanism

Small volumes of alkaline volcanic and intrusive rocks occur in intracontinental settings (Map 8.3). Alkaline rocks are so named because they have relatively high abundances of (Na + K). Most commonly, alkaline rocks are unusually rich in sodium; however, potassic alkaline rocks do occur. As noted in Chapter 4, three broad classes of alkaline rocks exist: nepheline-bearing rocks that are metaluminous (i.e., there are enough alkalis to stabilize nepheline, but not enough to make sodic amphiboles and pyroxenes); nepheline-bearing rocks that are peralkaline (i.e., there are enough alkalis to form sodic pyroxenes and amphiboles); and quartz-bearing rocks that are peralkaline (Figure 4.11). The rocks associated with alkaline magmatism range from mafic to felsic silicate rocks and carbonatites.

Alkali and nepheline basalts. These basalts typically contain plagioclase, olivine, and augite rich in titanium and sodium. The absence of orthopyroxene in the groundmass allows one to distinguish alkali basalt from tholeiite. Many alkali basalts do not contain nepheline as a modal phase; it is a normative component hiding in the glass phase. Nepheline is a groundmass phase in the nepheline basalts. These rocks include basanite, where olivine is present with nepheline, and tephrite, where olivine is absent.

Trachyte. The primary mineral in trachyte is alkali feldspar. Metaluminous trachyte may contain minor phenocryst phases including calcic pyroxene, iron-rich olivine, hornblende, and Fe-Ti oxides. In peralkaline trachyte, the groundmass phase is sodic pyroxene and sodic amphibole. Trachyte is close to SiO_2 saturation, and so trachyte can be either quartz bearing or nepheline bearing. With



Map 8.3 World map showing the major alkaline magmatism provinces. Sodic alkaline rocks are shown in filled circles; potassic alkaline magmatism is shown in open circles.

increasing silica, quartz trachyte grades into rhyolite; with decreasing silica trachyte grades into trachytic phonolite.

Phonolite. Phonolite is a felsic volcanic rock that contains nepheline and alkali feldspar. The groundmass minerals include alkali feldspar, pyroxene, and amphibole. In peralkaline phonolites, the pyroxenes and amphiboles are Na rich (aegirine or riebeckite/arfvedsonite).

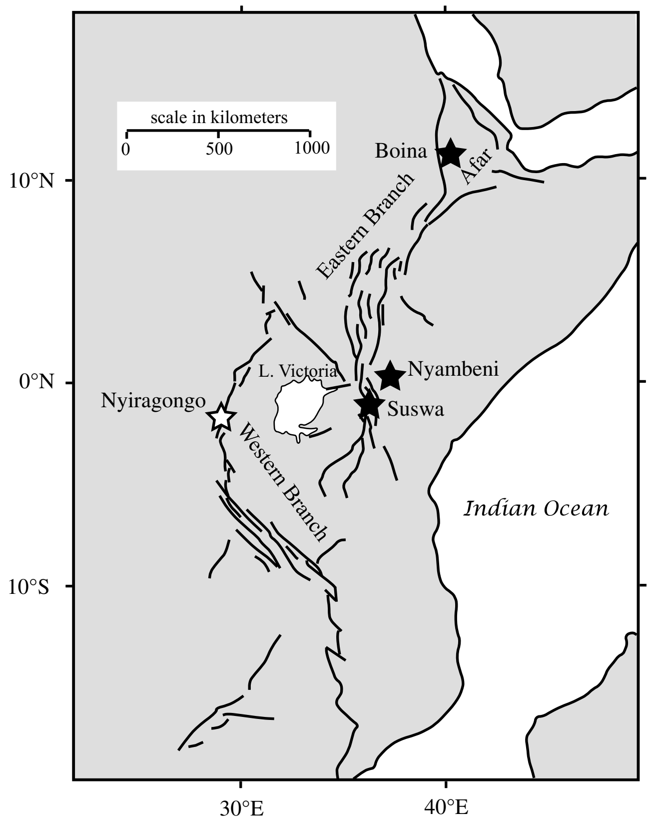
Peralkaline rhyolites. Peralkaline rhyolites contain alkali feldspar and quartz as the main phenocryst phase. The presence of sodic pyroxenes and amphiboles distinguishes peralkaline from metaluminous rhyolites.

*Carbonatite*s. Carbonatites contain at least 50 percent carbonate minerals, mostly calcite, although Ol Doinyo Lengai, a volcano of the East African rift in Tanzania, has erupted sodium carbonate. Other minerals include sodic pyroxenes and amphiboles, and Mg-rich biotite, which may form by unmixing of a carbonate-rich melt from phonolite or alkali basalt.

8.4.1 Sodic Alkaline Magmatism of the East African Rift

The East African rift, one of the great alkaline provinces in the world, extends sixty-five hundred kilometers from the Red Sea to Mozambique (Map 8.4). Volcanoes in the rift, which have been erupted from the Miocene to Holocene, include compositions that range from tholeiitic to highly alkaline basalts. Most of the volcanoes in the East African rift have erupted sodic lavas, although a few, such as Nyiragongo, are potassic. Three volcanoes from the East African rift are described to provide examples of the range in compositions present and some of the different differentiation processes capable of producing those compositions. One is the Quaternary Boina volcano from the Afar region, which consists of mildly alkaline olivine tholeiite, ferrobasalt, trachyte, and peralkaline rhyolite (Barberi et al., 1975). The Nyambeni range consists of multiple volcanic centers in Kenya that have been active from Pliocene to Holocene. These have erupted a series of lavas ranging from highly alkaline basalts (basanite and tephrite) to phonolite with minor peralkaline phonolite (Brotzu, Morbidelli, and Piccirillo, 1983). Mount Suswa is a Quaternary volcano in Kenya that has erupted peralkaline trachytes and phonolites; basaltic rocks are absent (Nash, Carmichael, and Johnson, 1969).

Trends on the Fe-index and MALI diagrams. During differentiation, the basaltic rocks of the Boina volcano



Map 8.4 Map of the East African rift showing the locations of the Boina, Nyambeni, and Suswa volcanoes, all of which are sodic alkaline rocks (filled stars), and Nyiragongo, which is a potassic alkaline volcano (unfilled star).

show a strong increase in the iron ratio with only a minor change in silica content (Figure 8.5A), defining a trend very similar to rocks from the Snake River Plain (compare Figure 8.5A to Figure 8.4). This early iron enrichment probably indicates that substantial differentiation took place before magnetite began to crystallize. Nyambeni shows an iron enrichment trend similar to Boina, but because the primary magma was undersaturated with respect to silica, differentiation never led to significant silica enrichment and Nyambeni. The rocks from Suswa are restricted to an iron-rich composition. Because iron-rich melts are never derived directly from the mantle, the melts from Suswa must have formed from differentiation of a parent melt that was not erupted.

On a MALI diagram (Figure 8.5B), the lavas of Boina form a narrow trend that initially increases until the rocks lie in the alkalic field and then plateau at high silica. The increase at low silica can be explained by substantial

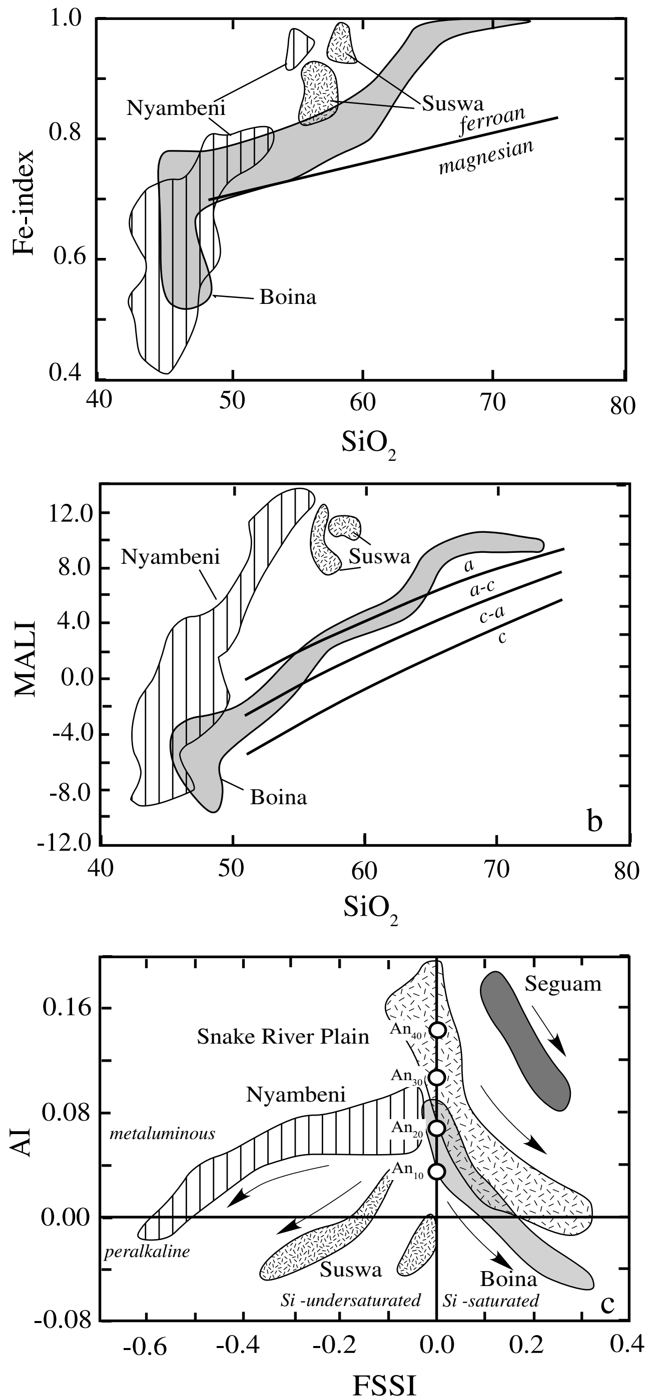


Figure 8.5 Geochemical trends for the Boina, Nyambeni, and Suswa volcanoes. a. Fe-index versus silica, b. MALI versus silica (a = alkalic, a-c = alkali-calcic, c-a = calc-alkalic, c = calcic). c. AI versus FSSI. Trends for Craters of the Moon and Seguam are shown for comparison in data from Barberi et al. (1975), Brotzu, Morbidelli, and Piccirillo (1983), Nash, Carmichael, and Johnson (1969), Singer, Myers, and Frost (1992) and from references cited in Figure 8.4.

fractionation of augite, which extracts CaO from the melt, while the plateau at high silica may be produced by the fractionation of aegerine and sodic amphibole, which extract Na_2O from the melt. Rocks from Nyambeni form a broad field with a very steep increase in relative MALI with minor change in silica.

Trends on the AI – FSSI diagram. On a plot of alkalinity index versus FSSI (feldspathoid silica-saturation index) (see Figure 4.11), compositional data from each of the three volcanoes define separate fields that radiate from FSSI = 0.0, which represents the albite thermal barrier (Figure 8.5C; c.f. Figure 2.10). As noted in Chapter 2, fractional crystallization of magmas slightly to the right of this barrier can move the composition of a melt farther to the right (toward higher silica contents). In the same way, a magma slightly to the left of this barrier may differentiate to compositions farther to the left (toward lower silica contents), but in neither case can the melt composition cross this barrier. The rocks from Boina become increasingly silica rich during differentiation (as indicated by the arrow in Figure 8.5C), but also become more alkaline. In contrast, the rocks from Nyambeni reflect a decrease in silica with differentiation. The rocks from Suswa define two groups, each of which show increasing alkalinity and decreasing silica abundance with increasing differentiation. These trends of increasing alkalinity with increasing differentiation are not unique to alkaline rocks, as indicated by the fact that the lavas from the Snake River Plain and Seguam show similar trends. These trends are a manifestation of the crystallization of plagioclase, because, as indicated in Figure 2.11A, crystallization of plagioclase will extract Ca from a melt, enriching it in alkalis. In a Ca-bearing melt that is sodium-rich, CaO will preferentially enter plagioclase, leaving the pyroxene enriched in Na_2O. This effect, called the "plagioclase effect" by Bowen (1945), means crystallization of plagioclase can drive a melt that was originally metaluminous into the peralkaline field. The positions of An_{10}, An_{20}, An_{30}, and An_{40} are shown in Figure 8.5 to show how extraction of plagioclase of these compositions could have caused the trends observed (although the differentiation was certainly more complex than that).

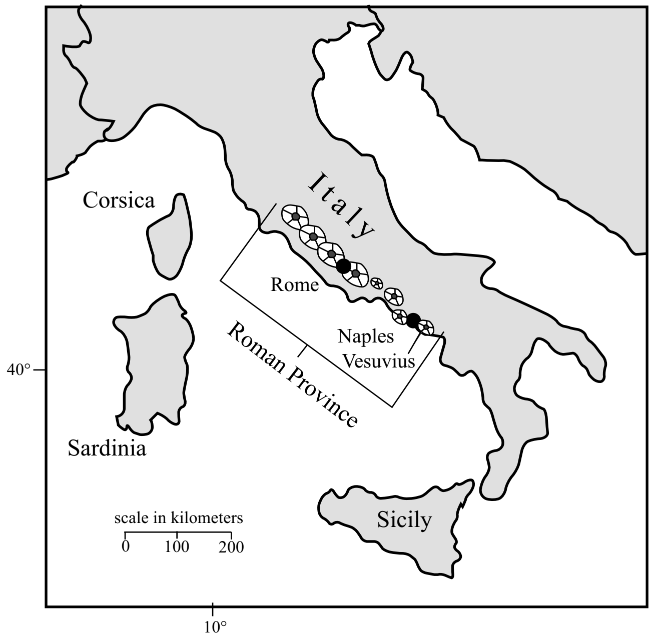
Figure 8.5C shows a suite of rocks derived from a basaltic parent will evolve to become peralkaline through fractional crystallization depending on the relative abundances of CaO and Na_2O in the parent rock. Rock suites such as Seguam, which are relatively calcic, do not become peralkaline during differentiation. In contrast those that are sodium rich may become peralkaline if significant amounts of plagioclase fractionate.

Implications for the evolution of Boina, Nyambeni, and Suswa volcanoes. As noted in Chapter 4, geochemical variation diagrams such as those in Figure 8.5 cannot prove a suite of rocks evolved through fractional crystallization, but the fact that the rocks from Boina and Nyambeni form tight trends strongly supports this contention. The fact that Sr isotopes are similar for the basaltic and rhyolitic rocks of Boina and that the trace elements behave in a manner consistent with fractional crystallization (Barberi et al., 1975) is strong corroboration that the suite of rocks erupted by Boina evolved through fractional crystallization. Similarly the well-defined trends on major and trace variation diagrams in the Nyambeni lavas suggest derivation through fractional crystallization (Brotzu, Morbidelli, and Piccirillo, 1983). The same cannot be said for the rocks from Suswa because they occupy two separate fields in the discrimination diagrams, particularly in Figure 8.5. Based on whole rock and trace element chemistry, Nash, Carmichael, and Johnson (1969) argued that Suswa volcano erupted melts from different sources at different times, although each of the individual batches of melt may have evolved toward increasing peralkalinity and decreasing silica activity.

8.4.2 Potassic Alkaline Volcanism

Although most alkaline rocks are sodic (i.e., have $Na_2O > K_2O$), a number are potassic. In some localities, such as in the East African rift, potassic alkaline magmas are clearly rift related. In other localities, such as the Roman province, the tectonic environment is cryptic at best. In this section, Mount Vesuvius from the Roman province exemplifies potassic alkaline volcanism. Another group of mafic potassic alkaline rocks, kimberlites and lamproites, forms small bodies (often a kilometer or less across) that are important as hosts of diamonds. This section also discusses the origins of kimberlites and lamproites and the diamonds they contain.

Mount Vesuvius and the Roman Province. Mount Vesuvius is the southern-most volcano in the Roman province, a group of potassic alkaline volcanoes that extends for more than 500 kilometers along the west coast of Italy (Map 8.5). Mount Vesuvius is a recent cone (less



Map 8.5 Geologic sketch of the Roman province in Italy showing the location of major eruptive centers. Modified after Corticelli and colleagues (2002).

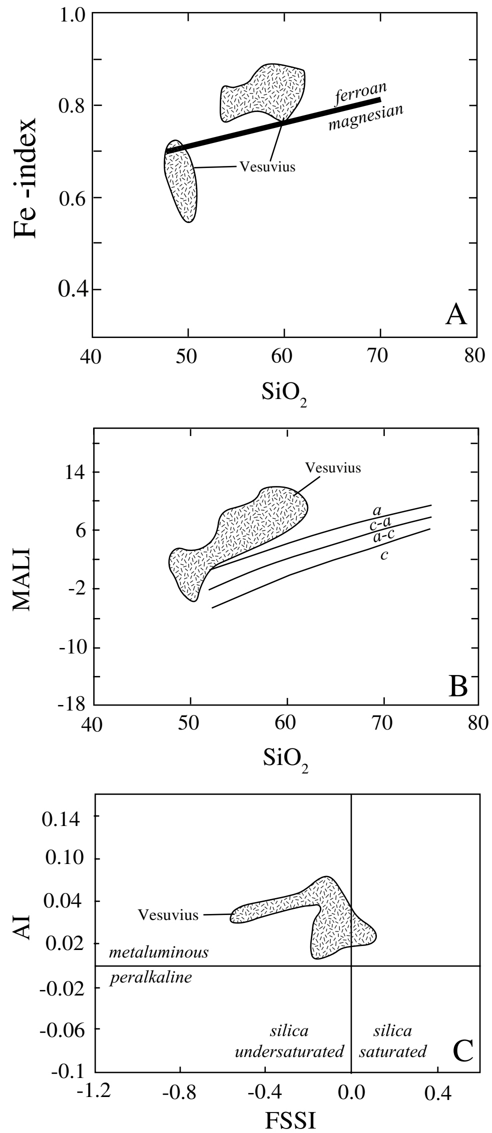
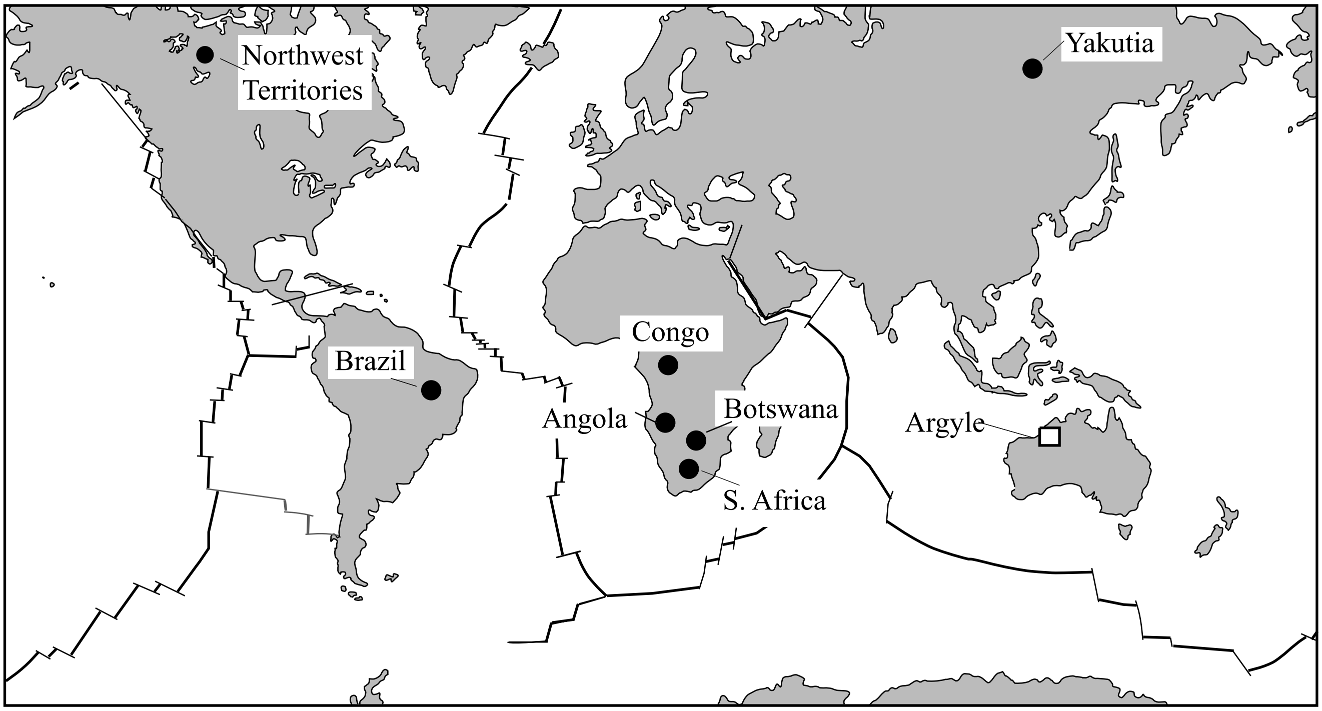


Figure 8.6 Geochemical trends for the rocks from Mount Vesuvius. Data from Di Renzo and colleagues (2007).

than nineteen thousand years old) built in the caldera of Mount Somma, an older volcano active from thirty-nine thousand to nineteen thousand years ago. Long periods of quiescence punctuated by explosive eruptions characterize the activity of Vesuvius (Di Renzo et al., 2007). One of these eruptions buried Pompeii in 79 CE, an event witnessed by Pliny the Younger. His letters on the eruption of Vesuvius (*Epistulae* VI.16 and VI.20) are certainly some of the earliest geologic descriptions of a volcanic eruption. Because of Pliny's letters, eruptions such as those of Vesuvius are called "plinian."

Over the last nineteen thousand years, Vesuvius has erupted about 50 km^3 of magma with wide ranging composition. Trachyte from Vesuvius may be either nepheline- or quartz-normative, whereas phonotephrite and phonolite are both nepheline- and leucite-normative (Di Renzo et al., 2007). The rocks from Mount Vesuvius do not form any clear trends on chemical discrimination diagrams (Figure 8.6), which is not surprising considering that both quartz-saturated and nepheline-saturated rocks are involved. Lack of a simple trend indicates the evolution of the rocks from Vesuvius did not involve simple fractional crystallization. In fact, Di Renzo and colleagues (2007) postulate that the melting of a heterogeneous source area, crustal contamination, and magma mixing could all have been involved in the evolution of the lavas from Vesuvius.

Kimberlites and lamproites. Kimberlites and lamproites occur almost exclusively within continental plates, typically erupting through Precambrian crust (Dawson, 1967; Mitchell and Bergman, 1991) (Map 8.6). Kimberlites and lamproites have similar major element compositions and the two rock types are often grouped together (Mitchell and Bergman, 1991). Both are potassic ultramafic rocks that contain olivine and phlogopite. The tectonic environment that produces such rocks is often enigmatic, and



Map 8.6 Major diamond-producing regions of the world. Filled circles = diamonds sourced from kimberlite, open square = diamonds sourced from lamproite.

may be different for different occurrences. These potassic mafic rocks are interesting because 1) they may bear xenocrystic diamond, and 2) they have exotic mineralogies (and names) that give petrologists important information about the mantle.

Kimberlites are products of continental intraplate magmatism, confined to regions of the crust underlain by ancient cratons; no occurrences have been described from oceanic environments or young fold belts. Kimberlites don't appear to be associated with continental rifts, although in some cases their location can be correlated with zones of weakness in the crustal lithosphere. Kimberlites cluster in small volcanic diatremes, sills, and dikes. Some kimberlite provinces have experienced multiple episodes of kimberlite magmatism – southern Africa, Wyoming, and Russia in particular.

Kimberlites appear to originate at depths of 100–200 kilometers and ascend into the crust as a kimberlite magma. At relatively shallow depths (maybe around two kilometers), they exsolve a CO_2-rich fluid and the fluid-rich magma erupts explosively to the surface (Dawson, 1967; Mitchell, 1986). This rapid emplacement results in brecciation of the host rock as well as fragmentation of the conduit up which the melt moves. As a result, kimberlites consist of a fragmented and altered groundmass containing olivine, phlogopite, diopside, apatite, spinel, and ilmenite. Many of these minerals have been partially or completely altered to serpentine and carbonate. Kimberlites also often include lithic fragments and xenocrysts from crustal and mantle rocks through which they ascend. The diamonds commonly present in kimberlites are usually found within garnet peridotites or eclogite xenoliths; rarely they are found as xenocrysts within the kimberlite itself.

Lamproites occur mainly as dikes, minor intrusions, and flows (Mitchell and Bergman, 1991). Like kimberlites, lamproites are associated with lineaments that may reflect zones of lithospheric weakness. Some of the classic lamproite occurrences include the Leucite Hills, Wyoming; Smoky Buttes, Montana; and occurrences in Antarctica, southern Spain, and western Australia (Map 8.6). Most lamproites are Cenozoic, in contrast to kimberlites, which are exclusively pre-Cenozoic. Like kimberlites, lamproites may host diamonds.

Lamproites are characterized by major phases of phlogopite, olivine, diopside, sanidine, and leucite. In most rocks, olivine is partially or totally pseudomorphed by serpentine, iddingsite, carbonate, or quartz. Fresh leucite is also rare, commonly replaced by sanidine, analcite, quartz, zeolite, or carbonate. Lamproites may contain diamonds, but the diamonds tend to be much smaller than those found in kimberlites. One explanation for this size disparity is that lamproites are emplaced at a slower velocity than the explosive emplacement of kimberlite. Whereas kimberlites can carry the larger xenoliths and the larger diamond xenocrysts to crustal levels, in lamproites, those diamonds and larger xenoliths will sink into the mantle before arriving at shallow crustal levels.

8.5 Origin of the Chemical Diversity of Intracontinental Basaltic Magmas

The preceding sections illustrated how a wide variety of mantle-derived rocks of basaltic composition erupted in continental settings. These intracontinental mafic rocks range from voluminous tholeiitic flood basalts through alkali basalts to highly alkaline sodium-rich or potassium-rich mafic magmas. A reasonable question to ask is: What causes this extreme variability of magma compositions? As noted in Chapter 5, alkali basalts could form by small degrees of partial melting of a normal mantle. However, it is difficult to adopt this explanation for the origin of the highly alkaline basaltic rocks, such as those that formed the Nyambeni eruptive centers, or for potassic magmas such as those that the feed the Roman province. These highly alkaline melts must have been derived from a mantle whose composition was different from the "normal" mantle that produces tholeiites.

This process by which the composition of the mantle has changed is called **metasomatism**, which technically describes any metamorphic process that changes the composition of a rock. Metasomatized mantle is increasingly recognized as a precursor for alkaline magmatism, both in the East African rift (Rosenthal et al., 2009) and in the Roman province (Bianchini, Beccaluva, and Siena, 2008, Nikogosian and Van Bergen, 2010). Movement of Na-bearing fluid through the mantle will produce hornblende-rich veins, whereas K-bearing fluids will produce phlogopite. Preferential melting of these veins will produce sodium-enriched and potassium-enriched alkaline magmas. Mantle xenoliths brought up in alkali basalts provide compelling evidence for metasomatism (Dawson and Smith, 1988; Meshesha et al., 2011). The mineralogical composition in these veins and their abundance in the mantle are likely to be irregularly distributed. Thus melting of a metasomatized mantle is likely to produce a wide variety of magmas. This explains why areas such as the East African rift and the Roman province erupt such a wide variety of lavas (Bianchini, Beccaluva, and Siena, 2008; Nikogosian and Van Bergen, 2010).

Having established how highly alkaline magmatism can derive from a heterogeneous, metasomatized mantle, the next question concerns the source of the fluids that metasomatized the mantle. Because both Na_2O and K_2O are enriched in the crust over the mantle, one reasonable source is through subduction (Bianchini, Beccaluva, and Siena, 2008; Markl, Marks, and Frost, 2010). If a subduction zone entrained substantial sea floor sediment, dewatering of these rocks may produce a K-rich fluid that could metasomatize the overlying mantle. Alteration of basaltic rocks on the sea floor causes albite to form from calcic plagioclase. Subduction of these rocks provides a source for sodium-rich fluids that can affect the composition of the overlying lithosphere (Markl, Marks, and Frost, 2010). It is important to emphasize that this type of metasomatism must have occurred before (in some areas millions of years before) alkaline melts generated. The thermal event that produced the alkaline melts is in no way directly related to subduction.

The fact that metasomatized mantle enriched in K_2O or Na_2O melts to produce alkaline rocks may explain observations from the Roman province. The Roman province lies above a steep east-directed subduction zone (Bianchini, Beccaluva, and Siena, 2008), in an area where one would expect broadly calc-alkalic volcanism. Indeed calc-alkalic magmas are found locally in the Roman province (Boria and Conticelli, 2007). One proposal to explain why the magmatism in the Roman province is highly potassic suggests that, unlike most arcs, the mantle under the Roman Province had been previously invaded by K-rich fluids derived from an earlier subduction event (Bianchini, Beccaluva, and Siena, 2008). Thus, although this book describes igneous rocks in the context of the tectonic environment where they are most frequently occur, it is important to note that the factors controlling the composition of mantle melts are many and include mantle composition, degree of melting, and temperature and pressure conditions of melting. The tectonic environment usually controls the conditions of melting, but not the composition of the mantle that partially melts in these environments. For this reason, a variety of magma compositions may be produced by mantle melting in any given tectonic environment.

Summary

- Intracontinental volcanism includes continental flood basalts, bimodal associations of basalt and rhyolite associations, and alkaline rocks.
- Intracontinental volcanism is usually associated with mantle plumes or rifts.
  - Hotspot-related magmatism in intracontinental settings defines tracks of progressively younger volcanic centers recording the movement of the plate over a plume.
  - Rift-related volcanism may be associated with broad areas of extension, such as in the Basin and Range in southwestern United States, or in narrower rifts such as the East African rift.
- A wide range of lavas is erupted in continental rifts.
  - Flood basalt provinces are dominated by large volumes of tholeiitic basalt.
  - Bimodal associations are composed of tholeiitic basalt and ferroan rhyolite.
  - Rift-related volcanism may range in composition from tholeiitic to alkaline.
  - Kimberlites and lamproites are unusual mafic, high-potassium magmas that may transport diamonds to the surface.
- The wide range of mantle-derived rocks of basaltic composition, from tholeiitic basalt, through alkali basalt, to alkaline sodium or potassium-rich mafic magmas, may reflect:
  - different degrees of partial melting of the mantle, and/or
  - variations in the composition of the mantle sources.
- Alkaline rocks are commonly attributed to partial melting of mantle that is compositionally heterogeneous as a result of metasomatism.

Questions and Problems

Problem 8.1. Compare and contrast oceanic plateau and continental flood basalt provinces.

Problem 8.2. Calculate the approximate plate velocity for the North American plate from the age of volcanic centers along the Snake River Plain and Yellowstone shown in Figure 8.3. What is the direction of plate motion?

Problem 8.3. Provide at least two explanations for the absence of intermediate compositions of volcanic rocks found in bimodal volcanic suites.

Problem 8.4. What is metasomatism?

Problem 8.5. What are the similarities and differences between kimberlites and lamproites?

Further Reading

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