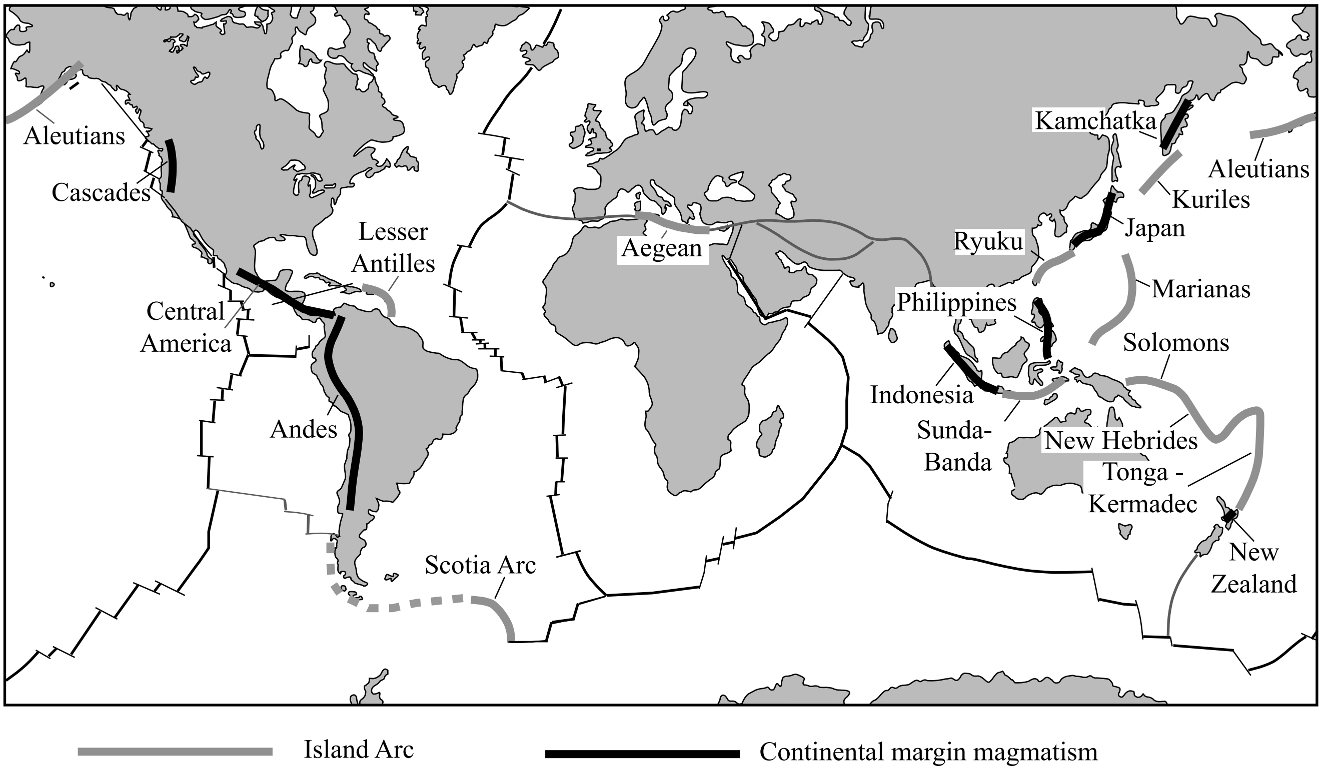
Chapter 7

Convergent Margin Magmatism

7.1 Introduction

Subduction produces some of the major topographic features on Earth and consumes large amounts of oceanic crust each year. At modern rates it would take only 160 million years to subduct an area equal to that of the entire surface of Earth. Regardless of whether the overriding plate is oceanic or continental, convergent plate margins share many of the same characteristics. This includes a deep (six thousand to eleven thousand meters deep) oceanic trench marking the plate boundary, chains of volcanoes on the overriding plate located about 100–200 kilometers inboard from the trench, and a dipping zone of seismicity called the Benioff zone, which includes shallow, intermediate, and deep-focus earthquakes. This marks the plane of descent of the oceanic lithosphere into the mantle. The volcanoes and plutonic rocks above the Benioff zones are constructed of magmas that range from basalt to rhyolite, with andesite the dominant composition. Volcanism in this tectonic setting is frequently highly explosive. This, coupled with the fact that large population centers are located in the shadow of many of these volcanoes, makes study of arc magmatism important for hazard prediction. The volcanic and plutonic rocks formed at convergent margins are also relevant to the study of the growth and evolution of the continental crust. Insofar as convergent margin magmas transfer material from the mantle to the crust, they represent a mechanism by which continents form and grow. The volume and composition of crust formed at subduction zones is therefore of considerable interest to geologists interested in the formation and development of continental crust over Earth's history.

This chapter introduces the main features of oceanic and continental arc magmatism using well-studied examples of arc volcanic and plutonic complexes. The petrography and geochemistry of island and continental arcs provide important clues to the petrogenesis of arc magmas, although the details of the process remain poorly understood.



Map 7.1 World map showing active island arcs and continental margin magmatism.

7.2 Oceanic and Continental Arcs

We can divide convergent margin volcanism into two groups, even though the overall tectonic setting is similar in each. First, **island arc magmatism** generates melts in response to subduction which are injected into oceanic crust with little contamination by crustal melting. The second is **continental arc magmatism**, wherein subduction zone magmas ascend through and interact with continental crust. Although many of the magmatic processes are the same in both environments, the resulting magma suites have somewhat different compositions that relate to whether the magmas traversed continental crust during their ascent into and through the overriding plate.

7.2.1 Island Arc Magmatism

Subduction of one oceanic plate beneath another has produced currently active oceanic island arcs, including the Aleutian, Kurile, Marianas, Ryuku, Sunda-Banda, Solomon, New Hebrides, and Tonga-Kermadec arcs of the western Pacific; the Lesser Antilles of the Caribbean; and Scotia in the southern Atlantic Ocean (Map 7.1). In these young island arcs the plutonic rocks are rarely exposed, so that most of the petrologic information available comes from extrusive materials. In some island arc terranes, erosion has exposed their plutonic roots. A good example is Tobago in the West Indies, where the crust has tilted to expose a cross-section that includes arc basement, and plutonic rocks underlying a volcanic sequence (Frost and Snoke, 1989; Snoke et al., 2001).

7.2.2 Continental Arc Magmatism

Whereas oceanic island arcs are formed by the subduction of one oceanic plate beneath another, continental margin magmatism results from the more complex tectonic environment in which the overriding plate is continental. Magmas generated in this environment today occur along the west coast of North and South America, Japan, New Zealand, and along the Aegean Sea (Map 7.1). The eruptions of both continental and

BOX 7.1 VOLCANIC HAZARDS

There are approximately 600 active arc volcanoes in the world. When these volcanoes erupt they may cause loss of life and damage to property by a number of different processes. Some destruction is a direct result of the eruption: ash falls, pyroclastic flows, debris avalanches, explosions, and emission of volcanic gases and acid rain all may cause damage and death. Other hazards are indirect: the volcanic eruptions may trigger earthquakes, tsunamis, and post-eruption famine. Fortunately, volcanic eruptions are relatively infrequent events and they involve less economic loss and human casualties than other natural hazards such as floods, hurricanes, and earthquakes. Nevertheless, there have been thirty-two eruptions since 1000 CE that killed more than 300 people. Moreover, approximately 10 percent of the world's people live near potentially dangerous volcanoes (Tilling, 1989).

The Volcanic Explosivity Index (VEI) was developed to provide an estimate of the magnitude of volcanic eruptions. It is a logarithmic index based upon the volume of material ejected by an eruption (Newhall and Self, 1982). The scale ranges from zero for small, nonexplosive eruptions of lava to eight for huge, paroxysmal eruptions of pyroclastic material and injection of significant amounts of ash into the stratosphere (Table 7.1). As one might expect, the larger the eruption the less frequent it is likely to be. Mason and colleagues (2004) identified five eruptions with a VEI of seven or greater in the last ten thousand years, the most recent being Tambora in 1815. There has been no eruption with a VEI of eight in that time. The entrainment of ash from Tambora into the stratosphere caused the following summer to be much cooler than usual. In the past two million years, only six eruptions with VEIs of eight or greater have occurred, and they were cataclysmic. Eruptions on this order of magnitude may have caused "volcanic winters" with significant effects on life on the planet.

Table 7.1 Volcanic Explosivity Index

VEI	Volume	Plume	Frequency	Example	Death toll
0	$< 10^4$ m^3	< 100 m	constant	Kilauea	4 since 1900
1	$> 10^4$ m^3	100–1000 m	daily	Nyiragongo (2010)	245
2	$>10^6$ m^3	1–5 km	weekly	Galeras (1993)	9
3	$> 10^7$ m^3	3–15 km	few months	Nevado del Ruiz (1985)	23,000
4	> 0.1 km^3	10–25 km	≤ yr	Eyjafjallajökull (2010)	0
5	> 1 Km^3	20–35 km	≤ 10 yrs	Mount Saint Helens (1980)	57
6	> 10 km^3	> 30 km	≤ 100 yrs	Mt. Pinatubo (1990)	700
7	> 100 km^3	> 40 km	≤ 1,000 yrs	Tambora (1815)	92,000
8	> 1,000 km^3	> 50 km	≤ 10,000 yrs	Toba (70,000 yrs BP)	Unknown

BOX 7.2 PORPHYRY COPPER DEPOSITS

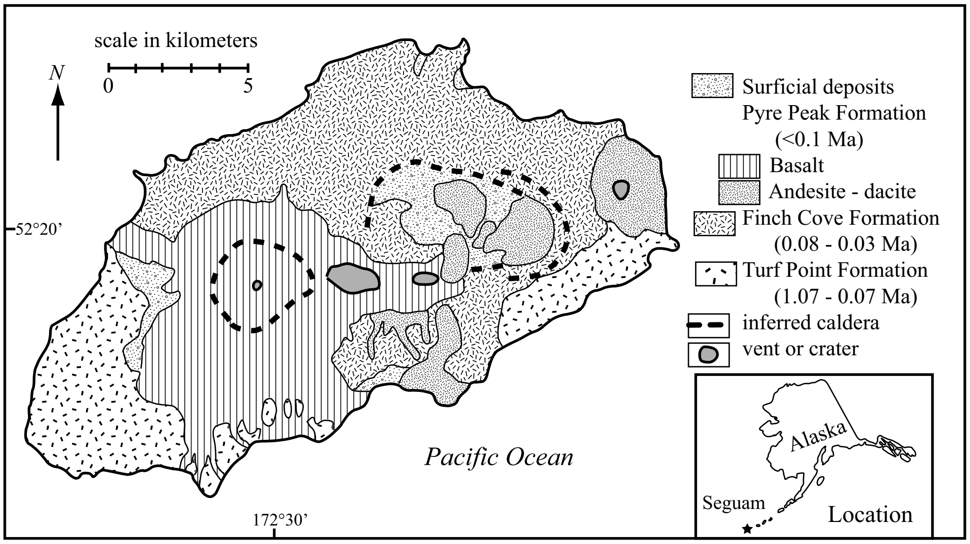
A major economic characteristic of arc magmatism is the occurrence of porphyry copper deposits. These deposits supply nearly three-fourths of the world's copper, half of the molybdenum, and around one-fifth of the gold (Sillitoe, 2010). Porphyry copper deposits are associated with shallow intrusions in arc settings. Typical examples include the Bingham mine in Utah, El Teniente in Chile, and the Ok Tedi Mine in Papua New Guinea. There is no consistent relationship between porphyry deposits and the composition of the host rocks, which may range from diorite to granodiorite in calc-alkalic suites and from diorite to syenite in more alkalic suites (McMillan and Panteleyev, 1988). Instead, the common feature of the host plutons for porphyry Cu deposits is their shallow level of emplacement. The shallow emplacement level means that, during crystallization of the igneous pluton, the aqueous fluids exsolved from the magma undergo a large volume increase (Figure 3.2). This causes hydrofracturing of the rocks within, above, and around the intrusion, allowing circulation of fluids through the rock. Because transition metals such as Cu, Mo, and Au and elements such as Cl and S behave incompatibly in silicate melts, these become enriched during the fractionation of the melt and will, in turn, fractionate into the exsolving fluids. The metals, which are dissolved in the fluid as chloride complexes, are transported through the fractured rocks and precipitated as the fluids become neutralized by reaction with the country rock (see Chapter 17).

island arc volcanoes represent a significant geologic hazard (Box 7.1).

Not only are volcanic edifices common in continental arcs, some arcs have been eroded deeply enough to expose granitic batholiths that formed beneath the volcanoes. These batholiths represent some of the most voluminous granitic intrusions in the world. Late Mesozoic subduction along the western margin of North and South America produced several large granitic batholiths, including the Coast Range batholith of western Canada, the Sierra Nevada batholith of California, and the Peninsular Ranges batholith of California and Baja California. The magmatic arc along the western margin of North America has been more deeply eroded than the corresponding arc in South America: huge andesite volcanoes still cap much of the Andes. These large batholiths, known as Cordilleran batholiths after the extensive mountain chains along western North and South America, are not single intrusions of granite but rather composite bodies made up of numerous plutons that range in composition. Arc batholiths are important as a source of metals, including copper, molybdenum, and gold (Box 7.2).

7.2.3 Structure of Island and Continental Arcs

Cross-sections through island and continental arcs can be divided into four regions: the trench, fore-arc, arc, and back-arc. Arcs are marked by a distinctive negative gravity anomaly over the trench that is paired with a positive anomaly over the fore-arc (Figure 7.1). The negative gravity anomaly near the trench is caused by the presence of relatively light, water-saturated sediments in the fore-arc, whereas the positive gravity anomaly over the fore-arc reflects the presence of cold dense subducted lithosphere beneath the arc. The trench and fore-arc are marked by low heat flow, while the arc and back arc are characterized by high heat flow. The low heat flow over the fore-arc is produced by the cold slab that lies beneath it. The high heat flow over the arc and back-arc is caused by the heat carried to high crustal levels by hot magma. The down-going slab in subduction zones is marked by the Benioff zone earthquakes along its plunging surface.



Map 7.2 Geologic map of Seguam island, central Aleutian arc, Alaska, USA. From Singer, Myers, and Frost (1992).

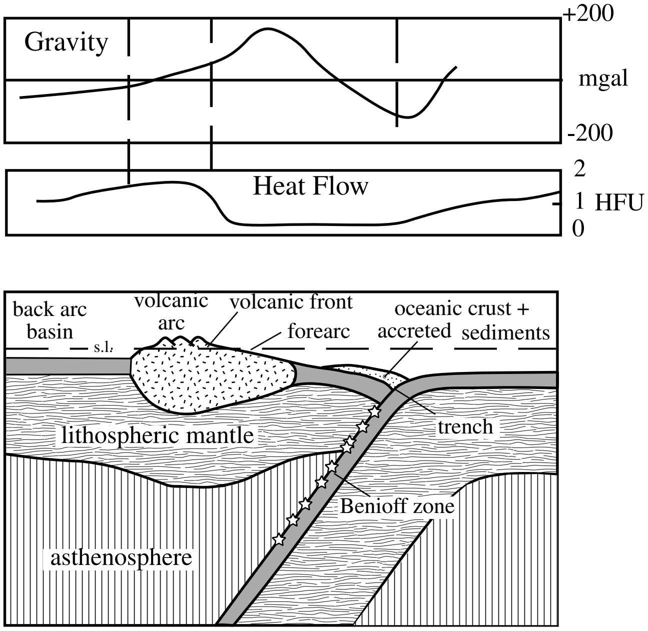


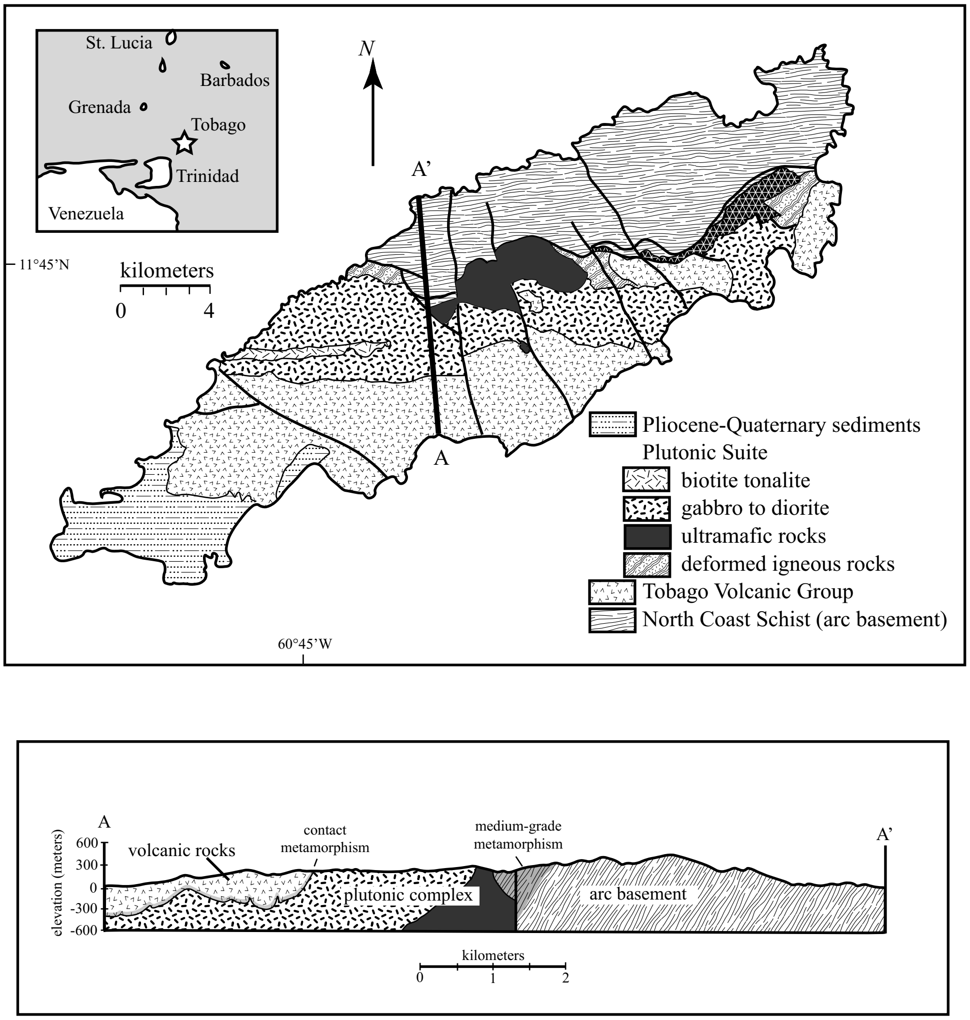
Figure 7.1 Schematic cross-section of a typical island arc. The graphs above show the gravity and heat flow profiles across the arc. Stars indicate locations of earthquake epicenters. s.l. = sea level, HFU = heat flow units. Modified from Gill (2010).

Figure 7.2 Photo of Pyre Peak, Seguam Island, Alaska. Note characteristic steep-sided cone of the composite volcano breeched by a summit caldera. Photo by Brad Singer, used with permission.

7.2.4 Examples of Island and Continental Arcs

7.2.4.1 Island Arc Volcano – Seguam, Aleutian Islands, Alaska

Seguam, an island in the middle of the Aleutian chain, is dominated by Pyre Peak, the highest of the young volcanic edifices on the island (Figure 7.2). In this portion of the chain, modern volcanoes are built atop Eocene to Miocene arc crust (Singer, Myers, and Frost, 1992). The subaerial lavas of Seguam consist of three major eruptive phases (Map 7.2). The oldest of these three units is the Turf Point Formation, which consists of flows that range from 1.1 to 0.07 million years old. Overlying this, the Finch Cove Formation ranges in age from 0.08 to 0.03 million years old. The deposits from the youngest eruptive phase compose the Holocene Pyre Peak Formation, which occupies the western half of the island. The most recent volcanic activity on Seguam occurred in May 1993.



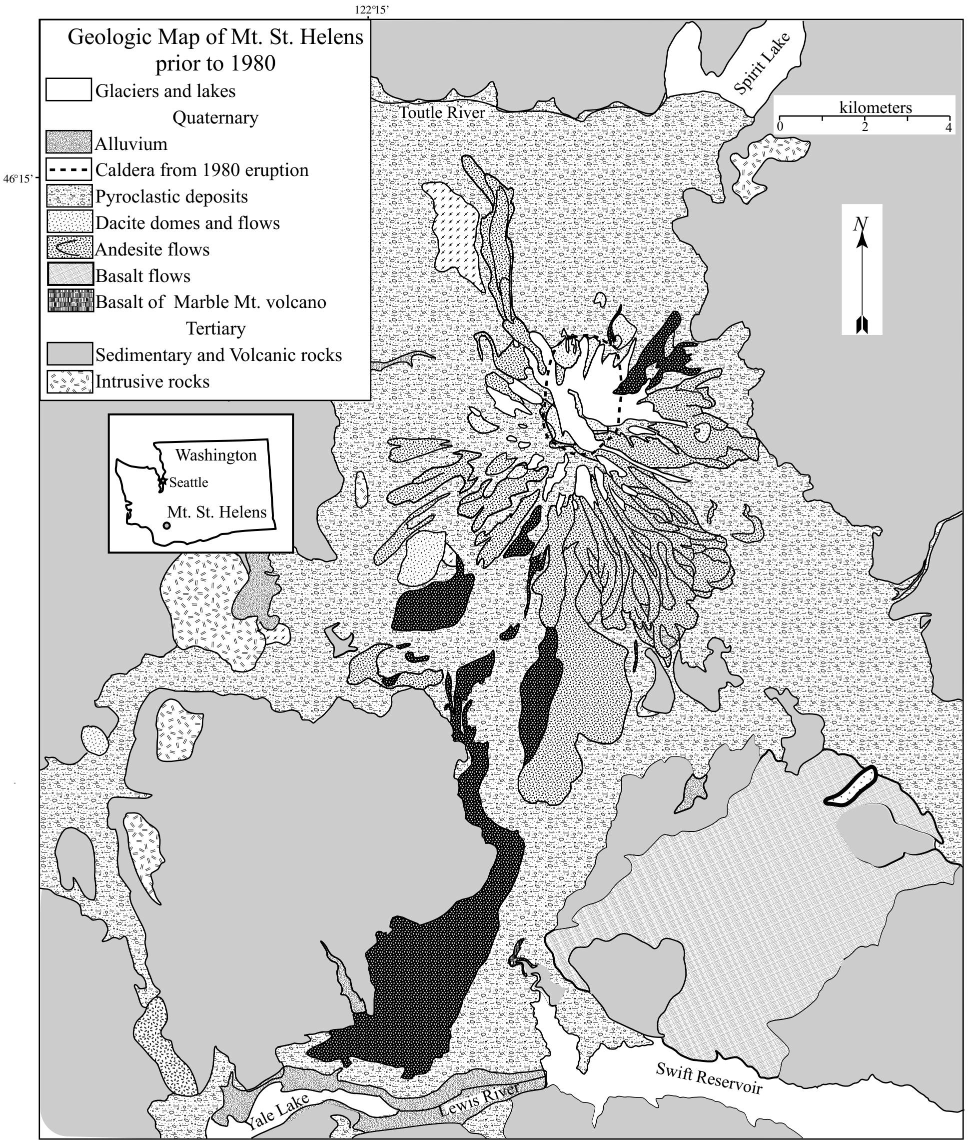
Map 7.3 Geologic map of Tobago, West Indies, showing a cross-section through the Cretaceous oceanic arc complex that exposes both plutonic and volcanic rocks. From Frost and Snoke (1989).

The geochemical studies of Seguam were conducted on the Turf Point formation where the wave-cut cliffs on the island shore expose a cross-section through the eruptive sequence. The Turf Point Formation consists of about 70 percent basalt, 15 percent andesite, and 15 percent dacite. Similar abundances of these rocks are found in both the Finch Cove and Pryor Peak Formations.

7.2.4.2 Island Arc Plutonic Complex – Tobago, West Indies

The island of Tobago lies at the northeast corner of the South American shelf in the southern Caribbean. The island preserves a crustal cross-section through a 105–103-million-year-old (Albian) oceanic island arc (Snoke et al., 2001). The arc is built on older, metamorphosed, and deformed Cretaceous arc rocks referred to as the North Coast Schist (Map 7.3). Both plutonic rocks and volcanic rocks of the Albian arc are exposed. The plutonic rocks of the oceanic arc include ultramafic rocks, gabbro and diorite, and a small volume of tonalite. The ultramafic rocks include dunite, wehrlite, olivine clinopyroxenite, and hornblendite. The gabbroic rocks include olivine melagabbro, hornblende gabbro, and gabbronorite. Mineralogical layering in the gabbro unit has been interpreted to result from crystal accumulation, and texturally the ultramafic and gabbroic rocks appear to be cumulate rocks.

Parts of the plutonic complex intruded and contact metamorphosed the volcanic rocks of the Tobago plutonic-volcanic complex, which include volcaniclastic breccias and lava flows. Volcanogenic mudstone, sandstone, and grit are also found within the volcanic sequence. Both plutonic and volcanic rocks are cross-cut by a suite of mafic



Map 7.4 Geologic map of Mount Saint Helens, Cascade Range, Washington, prior to the 1980 eruption. Heavy dashed line shows the extent of the caldera produced by that eruption. Inset shows location in the state of Washington. Modified after Hopson (2008).

dikes interpreted by Frost and Snoke (1989) as similar in composition to the basaltic parent magmas from which the Tobago plutonic and volcanic rocks formed.

Figure 7.3 Mount Saint Helens prior to the eruption of May 1980. Photo from the USGS.

7.2.4.3 Continental Arc Volcano – Mount Saint Helens, Washington

Before its explosive eruption on May 18, 1980, Mount Saint Helens, located in southern Washington state, was a stratovolcano rivaling Mount Fuji for its symmetry (Figure 7.3). The geologic map of Mount Saint Helens before the eruption displays many of the features distinctive of continental arc volcanoes (Map 7.4). One characteristic is that the Mount Saint Helens volcano erupted basalt, andesite, and dacite lavas. The basalt flows extended

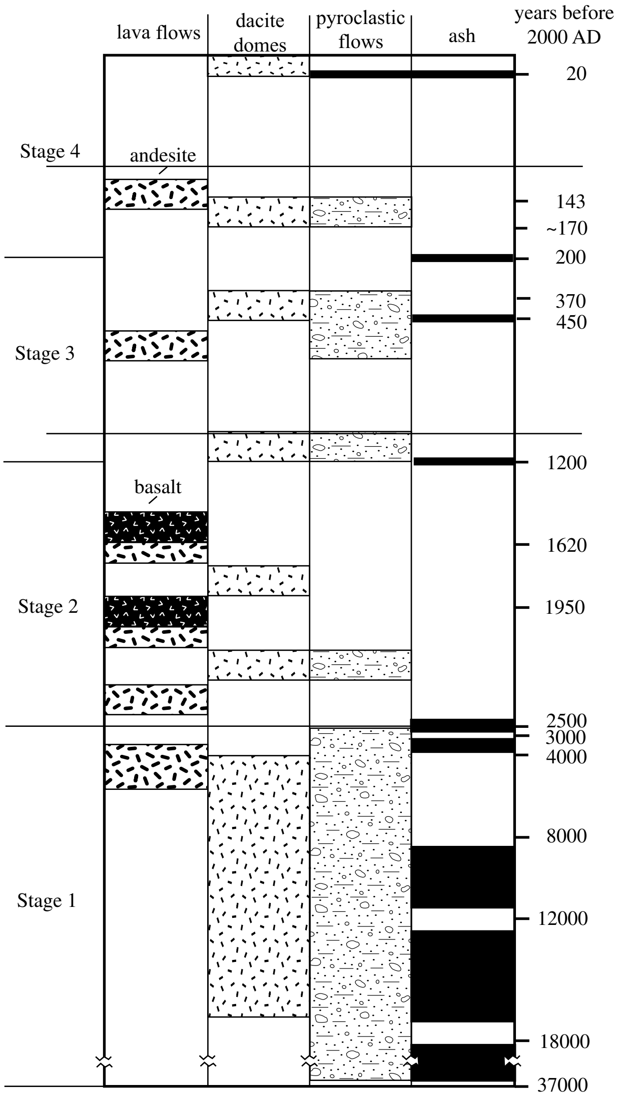


Figure 7.4 Diagram showing the geologic history of Mount Saint Helens volcano. Modified after Hopson (2008).

Figure 7.5 Granodiorite of the Tuolumne pluton in Yosemite National Park, California. Photo by Arthur W. Snoke.

up to twenty kilometers from the vent (Map 7.4). The fluid basalt formed lava tubes that flowed through a thick forest of large trees typical of the Pacific Northwest rain forest, solidifying around the tree trunks. After the trees rotted away, the flow was littered with huge holes, several feet in diameter, where the trees used to stand. The andesite flows were much more viscous than the basalt flows. Most andesite froze on the slopes of the mountain, although a few flowed about eight kilometers from the vent. Dacite volcanism formed domes, which seldom exceed a kilometer in diameter. In addition to forming domes, the dacite volcanism and, to a lesser extent, the andesite volcanism produced pyroclastic flows that flowed down the mountain and into the valleys of the Toutle and Lewis rivers, which drain the north and south sides of the volcano, respectively.

Even before a magnitude 4.1 earthquake on March 15, 1980 marked the awakening of Mount Saint Helens, the volcano was recognized as the most active volcano in the Cascades arc, which extends from northern California to southern British Columbia. Geologists had determined that over the past forty thousand years Mount Saint Helens had erupted lavas, emplaced dacitic domes, produced pyroclastic flows, and emitted ash (Figure 7.4). Several events had occurred within the last 200 years. Because of extensive petrologic study and an extensive monitoring program, the 1980 eruption of Mount Saint Helens was predicted successfully, minimizing loss of life (Box 7.3).

7.2.4.4 Continental Arc (Cordilleran) Batholith – The Tuolumne Pluton

A classic example of a Cordilleran batholith is the Tuolumne pluton in the Sierra Nevada batholith, which is spectacularly exposed in Yosemite National Park in California (Figure 7.5). The Tuolumne pluton makes up only a small portion of the immense Sierra Nevada batholith, which is over 500 kilometers long by 50 to 80 kilometers wide, and is composed of up to 200 separate plutons. The majority of exposed rock in the Tuolumne pluton is granodiorite, rather than true granite (Map 7.5). Many other Cordilleran batholiths are similarly dominated by granodiorite. Another important feature of the Tuolumne pluton is that it is composite, meaning that it formed from multiple intrusive episodes (Map 7.5). Earlier, relatively mafic phases including

BOX 7.3 VOLCANIC HAZARDS ASSOCIATED WITH CONVERGENT MARGIN MAGMATISM: EXPLOSIVE VOLCANISM AND PYROCLASTIC DEPOSITS

The intermediate to felsic magmas of magmatic arcs are characterized by high water contents and high viscosity (see Chapter 4). These magmas lead to explosive volcanism, in contrast to the relatively quiescent basaltic volcanism of oceanic magmas. Explosive magmatism produces pyroclastic deposits, which may form by multiple mechanisms. One mode of origin is collapse of a growing lava dome. Growing lava domes are unstable, and commonly break up to form landslides. If the melt is close to water saturation at the time the landslide forms, sudden decompression of the underlying magma can lead to explosion, which triggers an avalanche of hot blocks, ash, and gas. Transported individual blocks can reach tens of meters in diameter. The pyroclastic flow deposits of Mount Saint Helens associated with the climactic eruption on May 18, 1980 formed by this mechanism (Christiansen and Peterson, 1981).

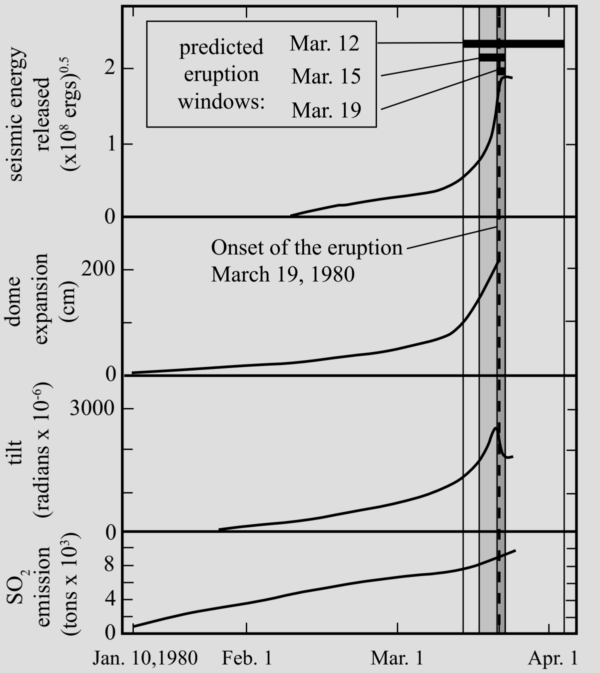
Pyroclastic flow deposits also may form by collapse of a vertical eruption column. Magma is disrupted by expanding gases within the conduit and discharges pumice, ash, and gases as a mixture into the air. A turbulent jet structure is formed, mixing cold air into the sides of the column. This air is heated by the ash, expanding the column, and lowering its density. The mixture of ash and gas is almost always denser than the surrounding atmosphere when first discharged. In addition, the amount of kinetic energy available from gas expansion is only enough to discharge the mixture to a few kilometers height at most. To produce a column thirty to fifty kilometers high, as is typical for continental arc volcanoes, the discharged mixture must absorb and heat enough air to lower the density of the mixture to less than that of the atmosphere. The mixture is then buoyant and rises as a convective plume, like smoke from a forest fire or an exhaust pipe. In columns where the whole or part of the mixture is still denser than the atmosphere by the time all kinetic energy is lost, collapse occurs and forms a density current of ash and hot gases. Because gases have very low viscosity and density, the particles settle rapidly to form a dense avalanche or pyroclastic flow. These flows can travel several tens of kilometers at velocities up 10 to 300 m/sec. The July 22, 1980 eruptions of Mount Saint Helens included pyroclastic flows of this origin (Christiansen and Peterson, 1981).

Arc volcanoes, including Mount Saint Helens, have produced massive eruptions (VEI scale five and six; see Box 7.1), many of which have resulted in extreme loss of life. Relatively recent eruptions on this scale include Krakatoa in 1883, Katmai in 1911, and Mount Pinatubo in 1990. Because volcanic eruptions can have disastrous consequences for people living near the volcano, petrologists and volcanologists seek to understand the plumbing of volcanoes to characterize and mitigate volcano hazards. Because Mount Saint Helens was so close to population, geologists studied the development of the volcanic edifice attentively. Researchers established seismographs around the volcano to sense the movement of magma and tiltmeters around the edifice to recognize how the mountain inflated as the magma moved into the shallower plumbing. These measurements provided the basis for a series of successively narrowing predictive windows that proved remarkably accurate (Swanson et al., 1985; Tilling, 1989; Box 7.3).

The information obtained from the eruption of Mount Saint Helens became indispensible in predicting the eruption of Mount Pinatubo ten years later. Scientists from the Philippine Institute of Volcanology and Seismology, working closely with those from the United States Geological Survey, were able to monitor emissions of volcanic gases and to use earthquakes to follow the movement of magma into the volcano from a depth of thirty-two kilometers. They used these data to predict the eruption far enough in advance that people living on the volcano's slopes were able to evacuate before the eruption. These

(continued)

BOX 7.3 (CONT.)



Box 7.3 Evidence of potential volcanic activity at Mount Saint Helens became increasingly compelling through the early months of 1980, when seismic activity, dome expansion, inflation of the edifice, and SO_2 emissions increased. Geologists issued series of warnings of a volcanic eruption with successively narrowing predictive windows, all of which accurately predicted the March 19 event. Modified from Swanson et al. (1985).

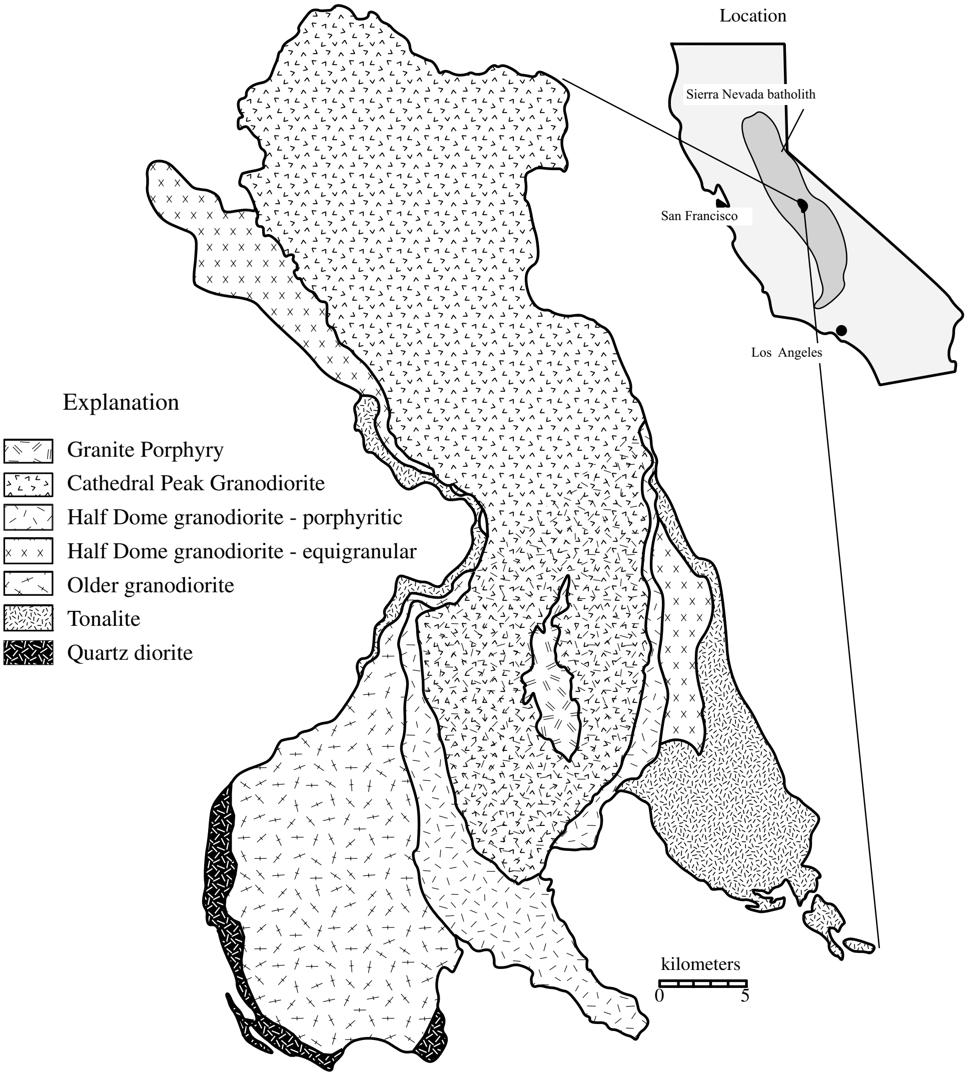
efforts saved an estimated five thousand lives and at least $250 million in property (Newhall, Hendley, and Stauffer, 1997). These results indicate that in the future, geologists will be able to predict volcanic eruptions with sufficient accuracy that eruptions of arc volcanoes threatening cities from Seattle to Tokyo. Hazard forecasts could give the millions of people who live in the shadows of these beautiful mountains enough time to avoid the immediate effects of volcanic eruptions.

quartz diorite and tonalite form a discontinuous annulus around the batholith. Progressively younger and more evolved intrusions are nested within the interior of the pluton. Field relations indicate that the sheets and blocks of the earlier quartz diorite and tonalite were incorporated into the younger, more evolved magmas as they were emplaced in the interior portions of the batholith (Bateman and Chappell, 1979; Miller, Miller, and Paterson, 2005).

7.3 Petrographic Characteristics of Island and Continental Arc Rocks

7.3.1 Petrography of Island Arc Rocks

The Turf Point Formation lavas on Seguam are a calcic island arc suite that span a compositional range from basalt to rhyodacite. This suite consists of an anhydrous phenocryst assemblage of plagioclase, olivine, clinopyroxene,



Map 7.5 Geologic map of the Tuolumne pluton (after Bateman and Chappell, 1979). Inset shows the location of the batholith within the Sierra Nevada batholith, and the location of the Sierra Nevada batholith in California.

orthopyroxene, magnetite, and rare ilmenite. The proportions of the phenocryst phases vary between basalts, basaltic-andesites, andesites, and dacites, but even the dacites and rhyodacites lack hydrous minerals such as hornblende and biotite (Singer, Myers, and Frost, 1992).

The calcic lavas of Seguam differ from those of other Aleutian volcanoes and from most of the volcanoes of the Pacific and Lesser Antilles arcs, which tend to be calc-alkalic. Many calc-alkalic island arc suites are dominated by voluminous, two-pyroxene andesites. Such rocks are typically phenocryst rich, containing an assemblage of hypersthene, augite, and plagioclase. Plagioclase usually is andesine and commonly shows complex zoning. Olivine phenocrysts may occur, but they are rarely in equilibrium with the pyroxenes and may be xenocrysts from the mantle. Some andesites may contain phenocrysts of hornblende in addition to, or even to the exclusion of, the pyroxenes. In addition to andesite, calc-alkalic island arcs commonly erupt small volumes of evolved dacite. Like the andesites, dacitic lavas from these suites are phenocryst rich. The key phenocryst for dacite is quartz, which occurs with complexly zoned andesine. Ferromagnesian minerals may include pyroxenes, hornblende, cummingtonite, or biotite.

Alkali-calcic to alkalic, high-K series island arc rocks are around 50 percent basalt, 40 percent andesite, and 10 percent dacite. They are distinguished from calc-alkalic suites by a higher abundance of biotite. Alkalic island arc suites occur in Fiji and Sunda in the Pacific, and in Grenada in the southern Lesser Antilles.

The plutonic rocks associated with modern island arc volcanoes are rarely exposed, but older complexes, such as

Tobago, indicate that the plutonic roots of island arc volcanoes are composed of ultramafic to gabbroic cumulate rocks with lesser amounts of more siliceous tonalite (Frost and Snoke, 1989). Some mafic layered intrusions appear to represent the roots of arc volcanoes. The Duke Island mafic-layered intrusion in southeastern Alaska, described in Chapter 9, is interpreted as a sub-arc intrusion. Other examples include the Proterozoic Mullen Creek and Lake Owen complexes of southeastern Wyoming, which are composed of mafic and ultramafic cyclic units that suggest repeated intrusion of mafic magma into a sub-arc magma chamber (Premo and Loucks, 2000). Other plutonic arc rocks, such as the Jurassic Smartville complex of northern California, are dominated by unzoned gabbros or zoned plutons composed of olivine gabbro in the core with quartz diorite rims (Beard and Day, 1988). A common feature in all these examples of island arc plutons is the preservation of both cumulate and differentiated rocks in the complexes.

7.3.2 Petrography of Continental Arc Rocks

Magma series erupted along continental margins are compositionally similar to those erupted in island arcs, except that arcs erupting through continents have a greater abundance of silica-rich rock types, such as dacite and rhyolite. Much of this felsic material occurs as pyroclastic flow deposits. Continental margin magmatism contains significant amounts of andesite and dacite, which are petrologically similar to rocks of those compositions erupted in island arcs. Continental margin magmatic arcs may also contain rhyolite, which may be distinguished from dacite by the presence of phenocrystic sanidine.

Plutonic rocks are more commonly exposed in continental margin magmatic arcs than in island arcs. Rock types are generally gabbro, diorite, tonalite, granodiorite, and granite. The minerals characteristic of these rocks are plagioclase, alkali feldspar, quartz, amphibole, biotite, and magnetite and ilmenite. Pyroxenes, both clinopyroxene and orthopyroxene, may be found locally. Sphene and apatite are common accessory minerals, even in the mafic rocks, whereas allanite is common in highly differentiated granites. As with most slowly cooled rocks, there is evidence of subsolidus growth of minerals such as biotite, amphibole, and chlorite due to the interaction of solid rocks with high-temperature hydrothermal fluids. Grain boundaries also may be altered by post-crystallization reactions resulting in a sutured texture.

Pyroxene is dominantly augite, sometimes joined by hypersthene in intermediate composition plutonic rocks. In many diorites, clinopyroxene is rimmed by hornblende. Amphibole is mainly hornblende and, unlike in the volcanic rocks, it is abundant and often well-formed in plutonic rocks, reflecting that the plutonic rocks crystallized with higher water activity than the volcanic rocks. The color of the hornblende ranges from green to brown and tends to correlate with increasing amounts of TiO_2. Biotite is a common mafic mineral in granitic rocks. Plagioclase is the major rock-forming mineral in nearly all plutonic rocks. It is often complexly zoned, and myrmekite is common. Alkali feldspar is found only interstitially in mafic granitic rocks, but becomes more abundant in more felsic rocks. Orthoclase is the most common alkali feldspar, whereas microcline is found in the most differentiated rocks and forms under volatile-rich conditions. Exsolution textures are common, and magmatic fluid may be the cause of perthite coarsening (Parsons, 1978). Granophyric intergrowths are characteristic of the most differentiated granitic rocks, which form from the most volatile-rich magmas. Granophyres may form under conditions of supercooling, either by reduction in temperature as the magma rises in the crust, or by sudden loss of volatiles from the system (Vernon, 2004). Magnetite and ilmenite are the major opaque oxides.

7.4 Geochemical Characteristics of Convergent Margin Magma Series

7.4.1 Comparison of Oceanic and Arc Differentiation Trends

The tholeiitic basalts from oceanic and island arc environments are similar in terms of major element composition, but they follow different differentiation trends. This is best illustrated on a plot of Fe* versus SiO_2 (Figure 7.6). During differentiation, tholeiitic melts from oceanic environments become enriched in Fe relative to Mg. The ferromagnesian silicates in the lavas become increasingly enriched in their iron end members as differentiation progresses. Only late in the differentiation history of oceanic tholeiites do the melts undergo silica enrichment (see data for the Galapagos and Iceland in Figure 6.9). In contrast, most arc magma suites show strong enrichment

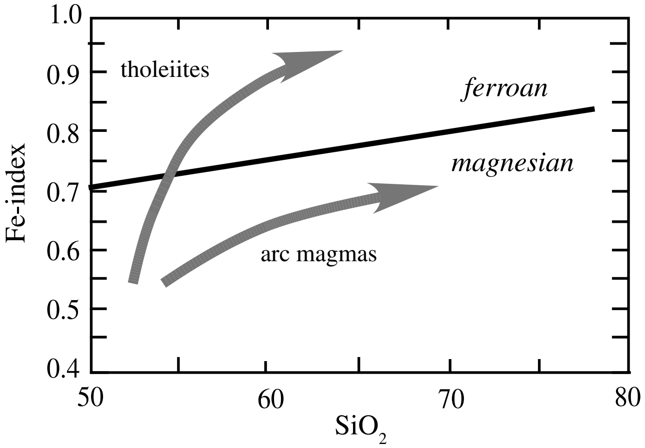


Figure 7.6 Plot of $FeO^{tot}/(FeO^{tot}+MgO)$ showing the different differentiation trends for arc magmas and oceanic tholeiites.

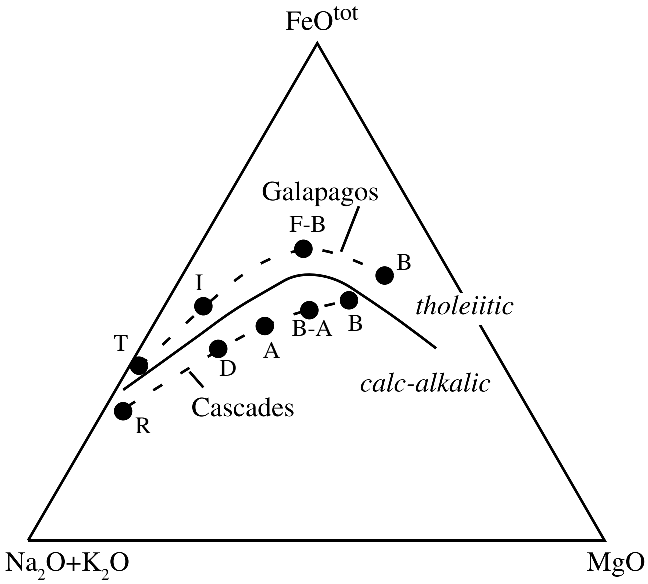


Figure 7.7 Alkalis-FeO^{tot}-MgO (AFM) diagram comparing the differentiation trends of tholeiitic rocks (as indicated by the lavas of the Galapagos) and calc-alkalic rocks (as indicated by the lavas of the Cascades). CA = calc-alkalic, TH = tholeiite, A = andesite, B = basalt, B-A = basaltic andesite, D = dacite, F-B = ferrobasalt, I = icelandite, R = rhyolite, T = trachyte. From Irvine and Barager (1971) and Wilson (1989).

in silica with increasing differentiation, but the ferromagnesian silicates show only moderate increases in the Fe/(Fe+Mg) ratio.

In terms of the classification discussed in Chapter 5, oceanic magmas are typically ferroan, whereas those from magmatic arcs are magnesian. These different trends are caused by the fact that the oceanic tholeiitic magmas tend to be more reducing than the arc magmas, and as a result Fe-Ti oxides crystallize relatively late in the former. The crystallization of olivine extracts Mg preferential to Fe and this causes the melts to become iron enriched, a feature noted earlier in the formation of oxide gabbros in oceanic crust. In contrast in arc magmas, Fe-Ti oxides crystallize relatively early, inhibiting the iron enrichment of the residual magma and causing the evolving magmas to become enriched in silica (Frost and Lindsley, 1992).

The two differentiation trends are often shown in a ternary diagram plotting (Na_2O+K_2O) – $FeO^{(total)}$ – MgO (Figure 7.7). On such a diagram differentiation drives the oceanic magmas (magmas from the Galapagos as an example) toward the iron apex before alkalis become enriched. In contrast the magmatic arc magmas (often called "calc-alkalic," *senso lato*), as exemplified by magmas of Mount Saint Helens and other Cascade volcanoes, evolve toward the alkali apex without increases in FeO.

7.4.2 Comparison of Island and Continental Arc Magma Series

Although island and continental arc magma series both tend to be magnesian, there are some important differences in alkali content. This is shown in Figure 7.8, where fields for Seguam, Tobago, Mount Saint Helens, and Tuolumne all follow magnesian differentiation trends, but Seguam and Tobago are calcic whereas Mount Saint Helens and Tuolumne are calc-alkalic (Figure 7.8B). Arc volcanoes also may be characterized according to their trends on a plot of K_2O versus silica (Figure 7.9). A few arc volcanoes, such as St. Kitts, are poor in K_2O. These magmas are referred to in Figure 7.9 as the low-K series and are calcic by the MALI classification. Some arcs, such as those of the Solomon Islands, are potassic and define a high-K series. These are alkali-calcic by the MALI classification. Most arc volcanoes, including Mount Saint Helens and the more differentiated lavas of Seguam, fall into what we refer to as the medium-K series. As noted in Figure 7.9, some researchers have called this medium-K group the "calc-alkalic" series even though Seguam is calcic (Figure 7.8). Volcanic rocks of this composition are so common in arcs that the term "calc-alkalic" commonly is used to describe island arc magmas in general. However, because the term has a strictly defined geochemical connotation and because some arc suites are calcic and some

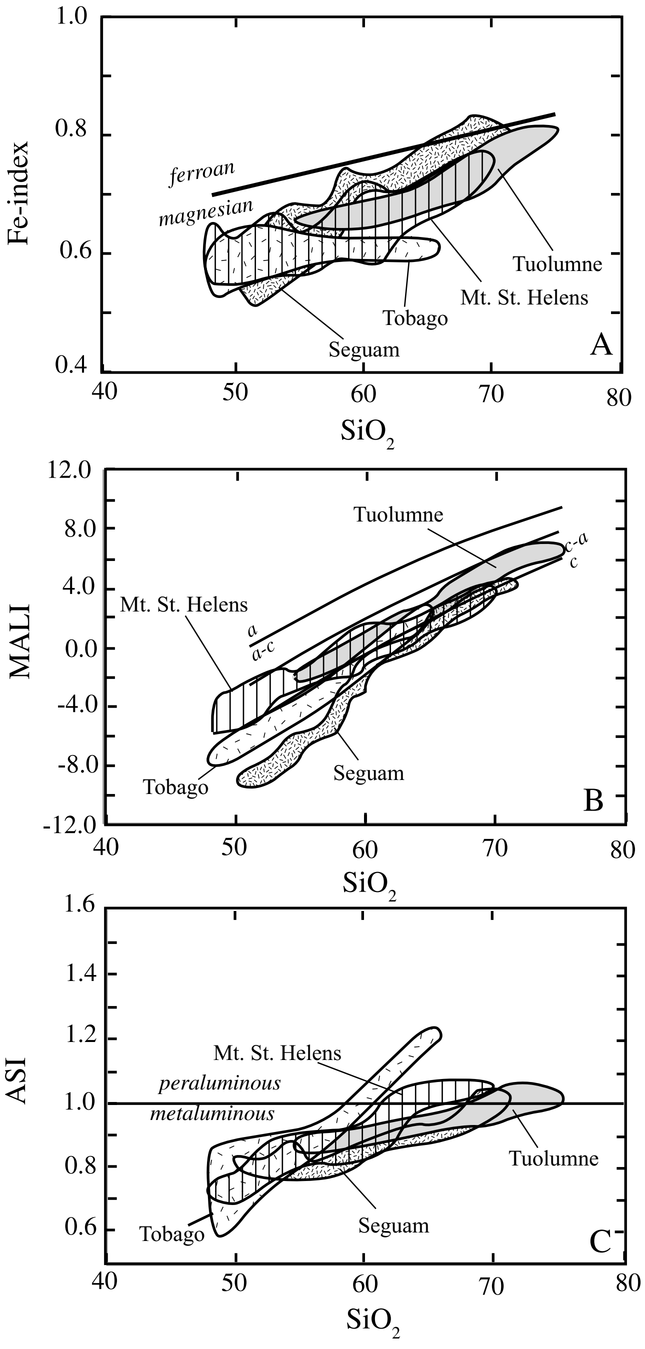


Figure 7.8 The chemical trends of island arc rocks, represented by Seguam, compared to continental arc rocks from Mount Saint Helens and Tuolumne. Data from Bateman and Chappell (1979), Halliday and colleagues (1983), Singer, Myers, and Frost (1992), and Smith and Leeman (1993).

are alkali-calcic, it is not advisable to use the word "calc-alkalic" loosely to refer to island arc magmatism.

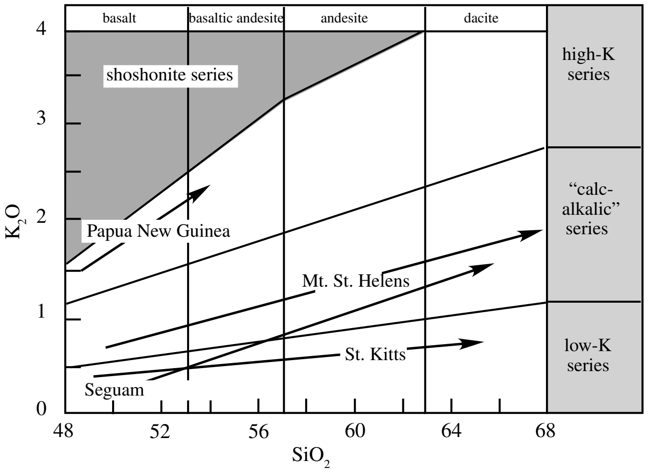


Figure 7.9 Plot of weight percent SiO_2 versus weight percent K_2O showing the composition variation of volcanic rocks from various island arcs. b.a. = basaltic andesite. Data from Brown et al. (1977), Johnson, Mackenzie, and Smith (1978), Halliday and colleagues (1983), Singer, Myers, and Frost (1992), and Smith and Leeman (1993).

There are several explanations for the variations in K_2O in arc lavas. One is based on the observation that in some arcs there is a spatial pattern along the axis of the arc. In the Lesser Antilles, for example, the lavas vary from low-K magmas at St. Kitts at the northern end of the arc, to "calc-alkalic" magmas in the center of the island chain, to high-K lavas at the southern end at Grenada (Brown et al., 1977). This variation correlates with the amount of sediment, which is a rich source of K_2O, being carried into the trench, which increases southward toward South America.

Another pattern observed in some arcs is a correlation between K_2O content and a volcano's distance from the subduction zone. The alkali content of volcanoes in an island arc tends to increase with increasing depth to the Benioff zone. Volcanoes erupting close to the trench (i.e., from relatively shallow melting depths) tend to be calcic in terms of the Peacock classification (see Chapter 5). Volcanoes erupting further away from a trench (i.e., relatively deep melting) are calc-alkalic, whereas those that are erupted farthest from a trench are alkali-calcic. Most of this change is related to an increase in K_2O in the magma with increasing depths of melting (Marsh and Carmichael, 1974).

In comparison to island arcs, calcic suites are uncommon along active continental margins. Instead, calc-alkalic suites are most typical. As with island arcs, the K_2O content of continental margin volcanism increases inland from the coast, with alkalic suites occurring on the landward side of the volcanic front. A good example of a high-K magmatic suite occurs in the Absaroka Mountains, which lie on the eastern margin of Yellowstone National Park in Wyoming. The Absaroka Mountains lie more than a thousand kilometers inboard from the west coast of North America and host an unusually potassic suite that has provided the names *absarokaite* and *shoshonite* and given the name to the shoshonite series (see Figure 7.9).

7.4.3 Comparison of Oceanic and Continental Arc (Cordilleran) Plutonic Complexes

As the Tobago plutonic complex documents (Map 7.2), island arc plutonic rocks are dominated by ultramafic and gabbroic cumulates with only small volumes of tonalite. By contrast, continental arc plutons are composed mainly of granodiorite with subsidiary granite and quartz diorite. On the QAP diagram the oceanic arc plutons like Tobago define a slightly different differentiation trend from the continental arc batholiths such as Tuolumne (Figure 7.10). Tuolumne follows a differentiation trend of quartz diorite to granodiorite, with minor granite, with minor early gabbro or diorite (the trend marked C-A). Oceanic arc plutons like Tobago have lower abundance of alkalis; they are less likely to contain granodiorite or granite and typically follow a trend from gabbro and diorite to quartz-diorite to tonalite (marked C in Figure 7.10).

The divergent differentiation trends of oceanic and continental arc plutonic complexes illustrated on the QAP diagram are also evident on plots of Fe-index and MALI (Figure 7.11). Although both Tobago and Tuolumne are magnesian, Tobago is dominated by calcic rocks and Tuolumne by calc-alkalic ones. The ultramafic and gabbroic cumulates exposed on Tobago account for the lower silica contents of that island arc's plutonic complex compared to the continental arc rocks that extend to more siliceous compositions.

Also shown in Figure 7.11 is the compositional range of the Sierra Nevada batholith, of which Tuolumne is a small part. The granitic rocks of the batholith are dominantly magnesian, although a few of the most siliceous granites are ferroan. The granitic rocks define a large field on a MALI diagram that covers the range from calcic to alkali (Figure 7.11B). This broad range in

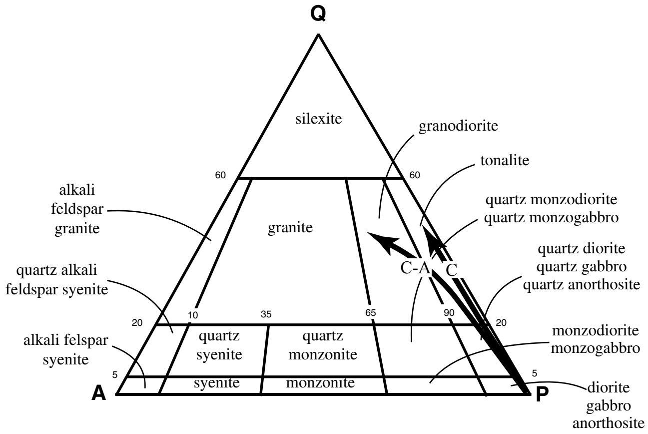


Figure 7.10 QAP diagram showing the compositional ranges of rocks found in calcic (C) and calc-alkalic (CA) batholiths (after Frost and Frost, 2008).

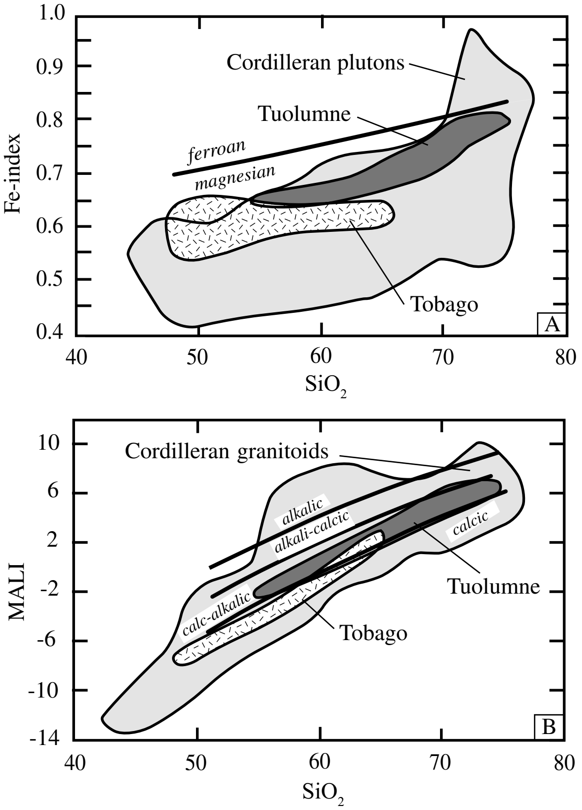


Figure 7.11 The chemical trends of plutonic island and continental arc rocks as represented by Seguam and Tuolumne. Also shown is the field for Cordilleran batholiths. Data from Bateman and Chappell (1979), Halliday and colleagues (1983), Singer, Myers, and Frost (1992), Smith and Leeman (1993), and Frost and colleagues (2001).

composition correlates to geographic location. Plutons on the western part of the Sierra Nevada tend to be calcic, those in the core Sierra Nevada are calc-alkalic, and those lying in the eastern Sierra Nevada are alkali-calcic or alkalic. As was observed for arc volcanic rocks, this change in composition may reflect a shift to more alkalic compositions farther inboard from the subduction zone. In addition, the inboard plutons may have incorporated more continental crust, which also is indicated by their increase in initial Sr isotopic composition from west to east (Figure 4.12).

7.4.4 Geochemical Identification of Contrasting Processes Forming Seguam and Mount Saint Helens

Although both Seguam and Mount Saint Helens have erupted basalt, andesite, and dacite, the two rock suites developed by very different processes. Geochemical studies (Halliday et al., 1983; Smith and Leeman, 1992) strongly suggest the range of rock compositions from Mount Saint Helens formed from mixing two melts: a mantle-derived basaltic melt and a crustally derived dacite melt. In contrast, Singer, Myers, and Frost (1992) concluded Seguam formed by closed-system fractional crystallization.

Evidence for these different processes is seen in geochemical variation diagrams (Figure 7.12A, B). The plots of TiO_2 and FeO^{tot} abundances from Seguam define a distinct inflection at 60 percent SiO_2, and TiO_2 increases with increasing silica up to this inflection point. The inflection indicates the appearance of Fe-Ti oxides (ilmenite or titanomagnetite) on the liquidus, after which point iron and titanium are removed from the melt by incorporation into crystallizing oxides. In contrast, the TiO_2 and FeO concentrations in rocks from Mount Saint Helens form straight trends on variation diagrams, a feature explained by mixing basaltic and dacitic magma. This hypothesis is supported by Sr isotopic data (Figure 7.12C). As described in Chapter 4.6, in a closed system $^{87}Sr/^{86}Sr$ will increase over time as ^{87}Rb decays to ^{87}Sr. The decay rate for ^{87}Rb is slow enough that the $^{87}Sr/^{86}Sr$ ratio for a magma varies little over the lifetime of a volcano. Figure 7.12C shows that the $^{87}Sr/^{86}Sr$ of lavas from Seguam remains constant regardless of the silica content of the rock, a pattern consistent with closed-system fractionation of a magma with a particular $^{87}Sr/^{86}Sr$. By contrast, the $^{87}Sr/^{86}Sr$ for rocks from Mount Saint Helens increases with increasing silica. This pattern would be expected if a dacitic melt with a relatively high $^{87}Sr/^{86}Sr$ ratio mixed with a basaltic melt with a low $^{87}Sr/^{86}Sr$ signature.

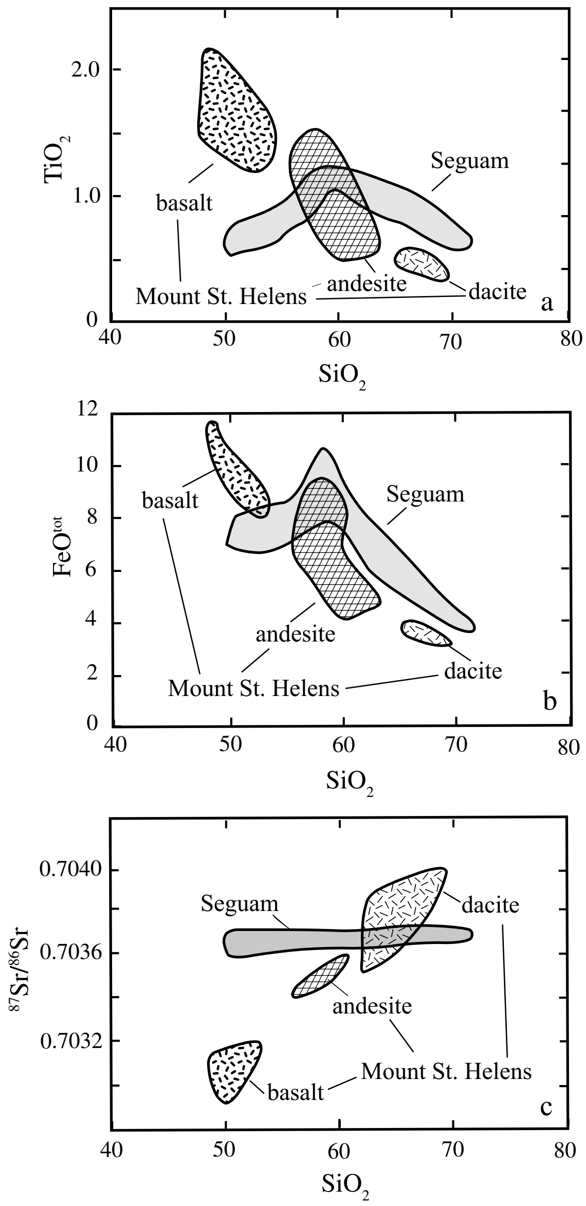


Figure 7.12 Variation diagrams showing the differences in trends exhibited by Seguam and Mount Saint Helens volcanic rocks, which reflect different processes of magmatic differentiation. Data from Singer, Myers, and Frost (1992), Halliday and colleagues (1983), and Smith and Leeman (1993).

This evidence led Halliday and colleagues (1983) and Smith and Leeman (1993) to conclude that the various rock types on Mount Saint Helens formed from mixed magma. Intrusion of hot basaltic magma melted mafic country rock to produce a dacitic melt. The two initial melts, the crustal dacite melt and the basalt mantle-derived melt, then mixed in various proportions to produce the andesites. On the other hand, Singer, Myers, and Frost (1992) concluded that Seguam formed from mafic melt that differentiated in a closed system to form the more evolved rocks, including the andesites, dacites, and rhyodacites.

7.5 Magma Generation at Convergent Margins

The sources of arc magmas are the subject of long and continuing debate. Compared to oceanic magmas at ridges or within oceanic plates, a more diverse combination of materials may be involved or in some way, influence the magmas in arc settings (Figure 7.2):

1. *Seawater* is the ultimate source for most of the H_2O that appears in island arc magmas. It is trapped in pore spaces in sea floor sediment and and gets incorporated into oceanic crust during metamorphism, and is subducted along with the oceanic crust.
2. *Oceanic crust* consists of basalt, gabbro, and sea floor sediments including clays, carbonates, and chert. Oceanic crust may be incorporated into arc magmas in two environments. Subducted oceanic crust could melt at depth, or the oceanic crust on which the arc volcano is built could melt as magmas pass through it. During subduction, the cold crust is heated by the surrounding mantle and possibly also by frictional heating at the surface of the slab.
3. *The mantle wedge above the subducted slab* consists of two components. One is the mantle lithosphere, forty to seventy kilometers thick, which is depleted in some constituents because MORB melts have already been extracted. These depleted rocks are unlikely to melt readily. The other component is the asthenospheric mantle, which consists of lherzolites likely to be more fertile than those in the lithosphere and that could melt if they were to interact with fluids discharged by the subduction zone.
4. *Continental crust*. Unlike island arc magmas, magmas by subduction along continental margins must pass into and through continental crust. Many of the differences between continental margin magmas and island arc magmas can be attributed to the fact that continental margin magmas must pass through a ~50 km thick section of continental crust. Almost without exception these magmas appear to interact with the crust through which they pass, both assimilating that crust and undergoing fractional crystallization as they cool. In some places, the effects of assimilation are easily recognized. If the overriding continental plate contains Precambrian crust, the distinctive isotopic characteristics of those ancient rocks will be imprinted in the contaminated magmas. In areas where the overlying crust contains young metasedimentary rocks, which are not isotopically distinguishable from mantle-derived magmas, crustal assimilation is harder to identify.

The thermal regime of the subduction zone is very important in controlling magma production. Generally speaking, the system will be hotter if the convergence rate is slower, since this will minimize the depression of isotherms where cool lithosphere is subducted into the mantle. Likewise, if the subducted slab is young, it will be warmer and the system will be hotter. Numerical models by Peacock (1991) suggest that young, warm, oceanic crust and its veneer of sediment may partially melt rather than dehydrate as it descends into the mantle. On the other hand, older, cooler crust may dehydrate and release fluids that flux the overlying mantle wedge, lowering its melting point such that the mantle partially melts.

Recently, investigators have recognized that at subduction-zone pressures and temperatures, hydrous fluids polymerize, not unlike silicate melts, which enhances their ability to dissolve solutes, particularly silica and alkalis. Because of this behavior of aqueous fluids, at high enough temperatures there is a continuum between aqueous solutions and hydrous melts (Manning, 2004). Thus, depending upon conditions, the down-going slab releases fluids that range from silicate melts to aqueous fluids. Polymerized aqueous fluids can dissolve and transport a wide variety of chemical compounds into the overlying mantle. These fluids can produce partial melting of the mantle wedge and these magmas may carry a geochemical signature of the slab, even if the slab itself didn't melt.

Arc magmas may rise diapirically and pond in magma chambers at depths of thirty kilometers or less, accumulating at the base of the crust or within it. Some magma chambers appear to form within a few hundred meters of the surface. Here magmas may differentiate and may assimilate the surrounding crustal wall rocks. Evidence for high-level magma chambers comes from several observations. The existence of craters at the summits of volcanoes is evidence of shallow magma chambers. They are formed by eruption of large volumes of magma and the subsequent foundering of the overlying rock into the space previously occupied by the magma. In addition, many andesite flows contain inclusions of cumulate plutonic autoliths. These autoliths typically are gabbro or diorite in composition, and provide evidence that crystals were accumulating within a magma chamber before eruption. The presence of plagioclase restricts their formation to depths shallower than thirty kilometers, since plagioclase does not usually crystallize at greater depths. The attenuation of S-waves, shallow volcanic tremors, and the deformation of the ground surface associated with the filling of shallow magma chambers all reinforce petrographic indications from mineral assemblages of low-pressure crystallization.

Finally, the composition of continental arc magmas may be affected by assimilation of crust during magma ascent and emplacement. As described earlier in this chapter, because the isotopic composition of mantle-derived magmas commonly is distinct from that of crustal melts, the interaction of mantle and crust sources may be identified isotopically. Section 7.4.4 described the interaction of crustal melts with more mafic arc magmas at Mount Saint Helens, as evidenced by the contrasting Sr isotopic compositions between basalts and dacites (Figure 7.12C). In another example, the incorporation of Precambrian crust in magmas of the Sierra Nevada batholith is indicated by higher $^{87}Sr/^{86}Sr$ isotope ratios of the granitic rocks in the eastern portions of the batholith (Section 7.4.3 and Figure 4.12). Partial melts of continental crust tend to be felsic and are a major reason continental arcs contain more siliceous rocks on average than island arcs.

Summary

- Oceanic and continental arcs form on an overriding oceanic or continental plate, respectively, above a subducting oceanic plate.
- Magmas from arcs typically follow a magnesian differentiation trend in contrast to the ferroan trend exemplified by oceanic tholeiites.
- Island arc magmas may be calcic, calc-alkalic, or alkalic. The K_2O content correlates spatially either with position along the arc (as in the Lesser Antilles), or with increasing distance from the subduction zone (as in the Sierra Nevada batholith).
- The common volcanic rock types associated with arcs are basalts, andesites, dacites, and minor rhyolites. Magmatic arcs on continental margins tend to produce magmas that are more siliceous than arcs in oceanic environments.
- Arc volcanism is commonly associated with explosive eruptions, which form pyroclastic deposits. These pose considerable hazards to human and other life.
- Oceanic arc plutonic complexes typically contain ultramafic and gabbroic cumulates as well as differentiated rocks such as tonalites.
- The plutonic roots of continental arcs are exposed as Cordilleran granitic batholiths, dominantly granodiorite. Cordilleran batholiths tend to be magnesian, calcic to calc-alkalic, and metaluminous. The most siliceous rocks may be peraluminous, mainly due to interaction with continental crust.
- A combination of sources may contribute to arc magmas, including the oceanic crust of the down-going slab and its carapace of subducted sediment, the overlying mantle wedge, and the oceanic or continental crust of the overriding plate. Variations in the thermal regime of the subduction zone system and the characteristics of the fluid or melt released from the subducted slab, as well as the composition and amount of interaction with the overriding plate, may account for the petrologic, geochemical, and isotopic differences observed in arc magmas.