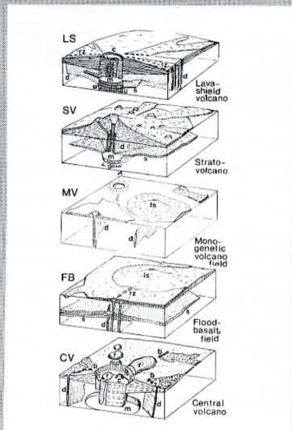

Basaltic Volcanoes and Volcanic Systems

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Glossary

central volcano A volcano that erupts magmas of various compositions, for example, basalt and rhyolite. These volcanoes frequently have calderas in their central parts.

decollement A detachment structure resulting in differential movement of rock above and below.

lava shield volcano A low-angle volcano constructed principally of basalt lava flows.

monogenetic volcano A volcano that erupts only once.

polygenetic volcano A volcano that erupts repeatedly, often in an episodic manner.

stratovolcano A volcano constructed of alternating layers of lava flows and pyroclastic rocks. Stratovolcanoes are steeper than shield volcanoes.

I. Introduction

More than half of all volcanoes consist wholly or largely of basalt. Basaltic volcanoes are found in all tectonic settings. They follow both convergent (volcanic arc) and divergent (oceanic rift) plate boundaries, occur at hot spots and areas where crustal extension is taking place, and are developed on a vast scale on the ocean floors. This chapter describes their occurrences on land.

A basic relationship is that some volcanoes (called *polygenetic*) erupt repeatedly, whereas other volcanoes (called *monogenetic*) are born, erupt once only, and then die. Polygenetic volcanoes have a sufficiently large and persistent magma supply rate that an ascending magma batch will preferentially follow the still-hot pathway of the preceding batch. Conversely, a volcano is monogenetic if the magma supply is so small or episodic that any pathways have cooled down and are no longer favored routes for the next magma batch.

Polygenetic volcanoes are generally considered to possess a magma storage chamber at a neutral buoyancy level. Magma ascends into this chamber mainly because of its positive buoyancy (but sometimes aided by tectonic forces). Processes in the chamber, such as the exsolution of gases, modulate the output.

When describing volcanoes it is of great merit to recognize the existence of a larger entity, namely, the volcanic (or magmatic) system. A system may embrace the melting anomaly at the magma source, the conduits through which magma rises toward the surface, the magma chambers, intrusions, and geothermal zones, and the volcano itself.

A volcanic system may be crudely compared with a civilization system (a city), with the extensive infrastructure of transportation, water and power supply, waste disposal, and communications on which a city depends. Both systems are sustained by an input of energy (as hot magma and gases, or in the city system as fossil fuels, electric power, and food). Very roughly, a city of 1 million people requires about the same annual power input as an average-sized volcanic system having an annual magma input of 1 million cubic meters.

In this chapter a fivefold grouping of basaltic volcano systems is presented (Fig. 1). The two main parameters that control volcano type are the time-averaged magma supply rate and the frequency of incoming magma batches, as shown by Fig. 2.

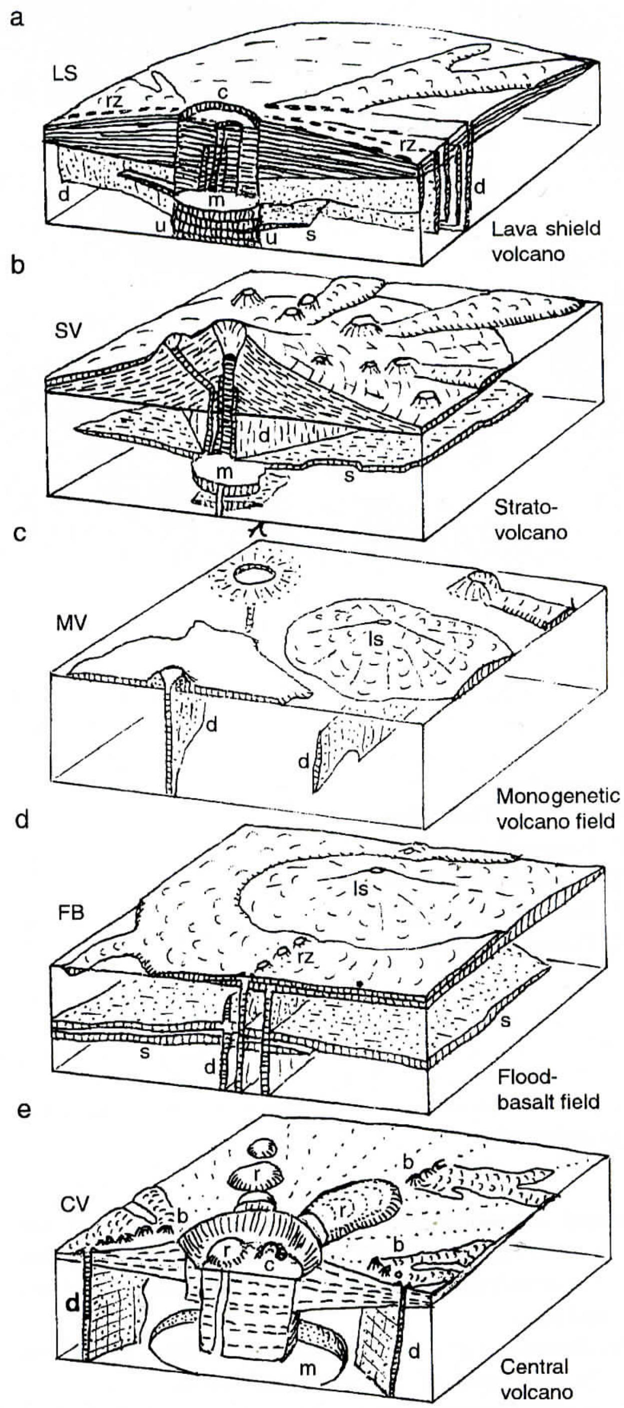

FIGURE 1 The five types of basaltic volcano systems illustated schematically by block diagrams. *Key:* b, basaltic vents; c, caldera; d, dike; is, lava shield of scutulum type; m, magma chamber; rz, rift zone; r, rhyolitic lava dome; s, sill or intrusive sheet; u, plutonic, gabbroic, or ultramafic rocks. (1993, Geological Society of London.)

II. LAVA SHIELD VOLCANOES

Examples of lava shield volcanoes are Mauna Loa and Kilauea in Hawaii. They consist largely of thin lava flows, with minor pyroclastic layers. Their subaerial slopes are mostly 4–8 degrees (less on coastal lava deltas). They have steep-walled summit calderas (Fig. 1a) and also pit craters that are similar to calderas in form but smaller. Mauna Loa, at 40,000 km^3 the largest volcano on Earth, stands 4169 m above sea level and 8 km above the ocean floor, plus an additional 4 km where the base of the volcano has sagged because of its huge mass. Mauna Loa and Kilauca are the most productive volcanoes on Earth, having a combined lava output of about 8 km^3 per century.

The low-angle shield form results from the low lava viscosity, the commonly high effusion rates that drive lavas fast and far, the high proportion of lava that issues from flank vents and not from the summit, and the spreading (widening) and subsidence of the volcano that occurs in the summit area and rifts.

A point of confusion is that lava shields occur on two scales. The name is applied to mainly large polygenetic structures, but also to mainly small monogenetic structures. The latter may be termed shields of scutulum

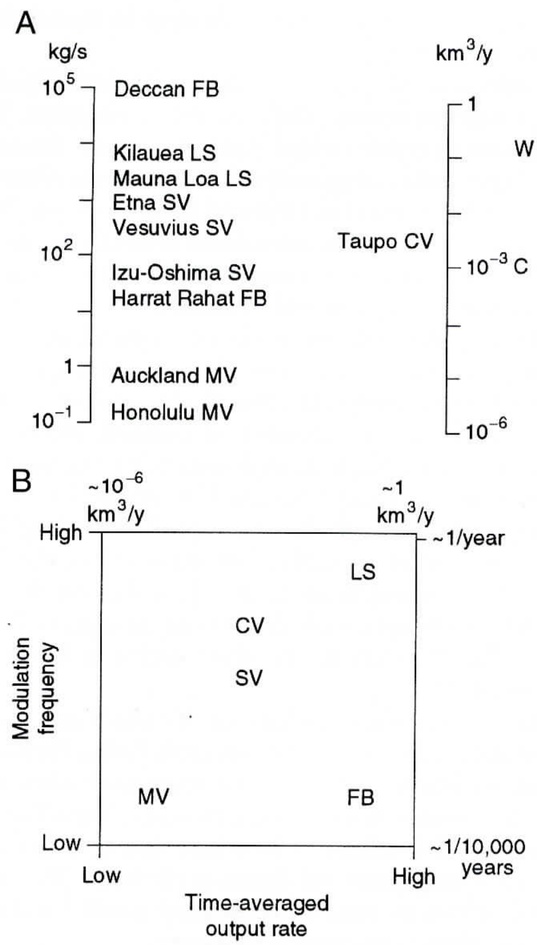

FIGURE 2 (A) Time-averaged output rates of selected volcanic systems in kilograms per second and in cubic kilometers per year. Note that the greatest outputs are by flood basalt and lava shield systems, and the smallest by monogenetic volcano systems. *Key:* W, equivalent world energy consumption by mankind, excluding food; C, equivalent energy consumption, including food, by city having a population of 1 million. (B) Plot of the time-averaged output rate against modulation frequency (i.e., eruption frequency), the two main inferred controls on volcanic system types, showing the approximate average positions occupied by the five kinds of basaltic volcano systems. Semiquantitative scales are shown along the top and right-hand side. (1993, Geological Society of London.)

type (from Latin *scutulus*, the diminutive of *scutus*, meaning "shield").

Each large Hawaiian shield volcano has two narrow and well-defined colinear rift zones extending to as far as 250 km from the summit. Some volcanoes also have a third and less well defined rift. Eruptions are concentrated at the active rift zones. Vent edifices range from low ramparts consisting of highly expanded scoria and spatter formed when magma viscosity was least, to cinder cones up to 200 m high when viscosity was appreciably higher. Spheroidal and spindle bombs are common at cinder cones.

Two main morphologic types of lava flows occur. One, called *pahoehoe*, is smooth surfaced. The other, called *aa*, has a thick upper zone of loose clinkery or rubbly debris. Pahoehoe results when the volumetric flow rate of lava is low, and aa forms when it is high. Viscosity is indirectly involved, because aa still flows strongly after significant cooling, to the point where lava viscosity is too high for breaks in the surface crust to be healed.

Volcanic eruptions are mostly from fissures, and intense complexes of intrusive dikes (the subsurface manifestation of eruptive fissures) underlie the caldera and rift zones. A traverse across the Koolau volcano (Oahu, Hawaii) contains an estimated 7400 dikes, totaling in aggregate 4.5 km wide. It is inferred that coarse plutonic (gabbroic) rocks may underlie the dike complex.

Shouldering aside of the preexisting volcanic edifice by dikes is largely responsible for the seaward movement, by decimeters per year, of the southern flank of Kilauea. Movement is thought to occur on a decollement—a low-angle fracture zone on which lateral movement occurs—in slippery subvolcanic marine sediments. Major prehistoric volcano collapses, some involving as much as 1000 km³ of rock, have occurred repeatedly in the history of some volcanoes. They include catastrophic rock avalanches that carried debris 200 km over the ocean floor. A surface limestone breccia reaching to 326 m above sea level on Lanai (Hawaii) is widely thought to be the deposit of a tsunami generated by a catastropic collapse event.

Shield volcanoes elsewhere may deviate somewhat from the Hawaiian model. Some in the Galapagos Islands of Ecuador have radial dike swarms; also their shield culminates in a steep dome and deep summit caldera; a circumferential (annular) rift zone occurs around the caldera rim. Piton des Neiges (Reunion Island, Indian Ocean) is cut by swarms of flat-lying intrusive sheets in lieu of dikes. Maderia and Tahiti are dissected by profound erosional canyons.

A few shield volcanoes have persistent active lava lakes in their summit caldera. The most famous lava lake was that in Halemaumau pit crater (Kilauea), which persisted for more than a century until it drained into fissures in 1924. Drainout was accompanied by violent groundwater explosions. Others are found in Erta Ale (Afar, Ethiopia), Mount Erebus (Antarctica), and Nyiragongo (Congo). Lakes are sustained by strong magma convection in the conduit that joins them to their magma chamber.

The escape of a flood of highly fluid lava from Nyiragongo lava lake in 1977 gave rise to remarkably fast-moving (ca. 60 km/hour) lava flows that killed many people. Elephants were also overcome, and in a bizarre twist their carcasses were coated by a thin layer of lava.

Hawaiian lava shields at the peak of their activity erupt tholeiitic lava derived by a high degree of partial melting from mantle peridotite source rock. With declining activity, alkali basalts are erupted from scatters of flank vents as the summit magma chambers solidify and rift zones are no longer preferred pathways. Later, highly alkalic (e.g., nephelinite) lava derived by a low degree of partial melting may erupt in a "rejuvenation stage" of volcanism that builds small fields of monogenetic volcanoes.

III. STRATOVOLCANOES

Stratovolcanoes consist of explosively erupted cinders and ash interbedded with lava flows. They tend to a steeply conical form (Fig. 1b), and in their upper part stand at the repose angle of loose rock (about 35 degrees measured from the horizontal). Among the largest are Huzi (Fuji) in Japan and Klyuchevskoy in Kamchatka, which rise 3700 and 3000 m, respectively, above their surroundings and have estimated volumes exceeding 1000 km^3.

The birth and growth of two stratovolcanoes has been observed. One, Izalco in El Salvador, was born in 1769 or 1770 and was almost continually active until 1966 by which time it had built to 650 m high. The other, Cerro Negra in Nicaragua, was born in 1850 and in the 17 eruptions since then grew to a similar height. Both began as cones of cinders and ash and became buttressed by lava flows.

A few volcanoes, notably Etna and Stromboli in Italy, display very persistent activity, and molten lava resides in their summit crater for decades or longer. Stromboli has many small explosions daily that throw up incandescent lava clots, and evidently it behaved similarly to at least as far back as ancient Roman times when it was referred to as the "Lighthouse of the Mediterranean."

Some stratovolcanoes such as Oshima in Japan erupt at fairly regular intervals (their activity is time predictable), or the volumes of erupted lava are proportional to the lengths of the preceding repose periods (their activity is volume predictable). From a broader perspective, such volcanoes exhibit steady-state conditions, consistent with the notion that magma feeds steadily into the magma chamber, but enough must be stored there before it can erupt.

Basalts in arc settings are tholeiitic or calcalkaline and merge with increasing silica content to andesites. The prevalence of rather violent explosive activity, the occasional generation of pyroclastic flows as were observed on Lopevi (Vanuato) in 1960 and Ulawun (Papua New Guinea) in 1978, and the prevalence of rough rubbly and blocky lava surfaces point to magma viscosities generally higher than those of shield tholeiites.

Many of the volcanic rocks of stratovolcanoes are porphyritic, that is, they contain macroscopic crystals (called phenocrysts) that grow in the cooling magma, likely in the magma chamber or conduit. Phenocryst minerals include plagioclase olivine and pyroxenes. Phenocrysts in the highly fluid shield tholeiites have commonly settled through the lava to produce striking local (decimeter-scale) concentrations. In contrast, the phenocrysts in stratovolcanoes are suspended in the lava and tend to be uniformly distributed through each lava flow. The phenocrysts are, thus, useful indicators of lava viscosity.

Many stratovolcanoes have cinder cones and craters of parasitic (adventive) vents on their flanks. Hundreds occur, for example, on Etna. Alignments of vents mark eruptive fissures. In some volcanoes these linear features have a radial distribution. In others they tend toward a parallel arrangement and delineate rift zones. Rift zones in arc volcanoes tend to be aligned parallel with the tectonic plate-convergence trajectory.

Many stratovolcano cones have been truncated by caldera collapse. Vesuvius in Italy is an example. The caldera in this case is asymmetric and is horseshoe-shaped in plan. The rim is called Monte Somma. Many stratovolcanoes have a lake in their crater. On the more active volcanoes the lake is steaming hot and muddy. It is also strongly acidic, due to the influx of hot acidic gases (SO_2, HCl) from the magma chamber. When hydrothermal and phreatic explosions occur they eject mud and strongly weathered rocks. In the less active lakes the water often has brilliant blue or green colors, attributed to minute particles of sulfur in the water.

IV. MONOGENETIC VOLCANO FIELDS

These are clusters or scatterings of small monogenetic volcanoes, each of which erupts once only. Many of the volcanoes comprise a cinder cone, commonly with associated lava flows (Figs. 1c and 3). Some are small lava shields. Others are tuff rings or maars cored out by phreatomagmatic explosions (where lava exploded in contact with water) at vents on low-lying ground or under water. The shields are of the scutulum type, for example, Rangitoto Island in the Auckland field (New Zealand), which is 5.5 km in diameter, 140 m high, and 1.0 km^3 of it occurs above sea level.

A typical monogenetic field may contain 10–100 volcanoes of aggregate volume about 10 km^3, and may span 50 ka to 5 Ma. The Michoacan-Guanajuato field in Mexico is much larger than average; it contains more than 1000 volcanoes, but merges into and partly consists of flood basalts. It had two historic eruptions. One saw the birth of El Jorullo in 1759–1774, a line of four or five cones along 3.4 km of fissure, and a lava field covering 12 km^2. The main cone rises about 330 m above its base.

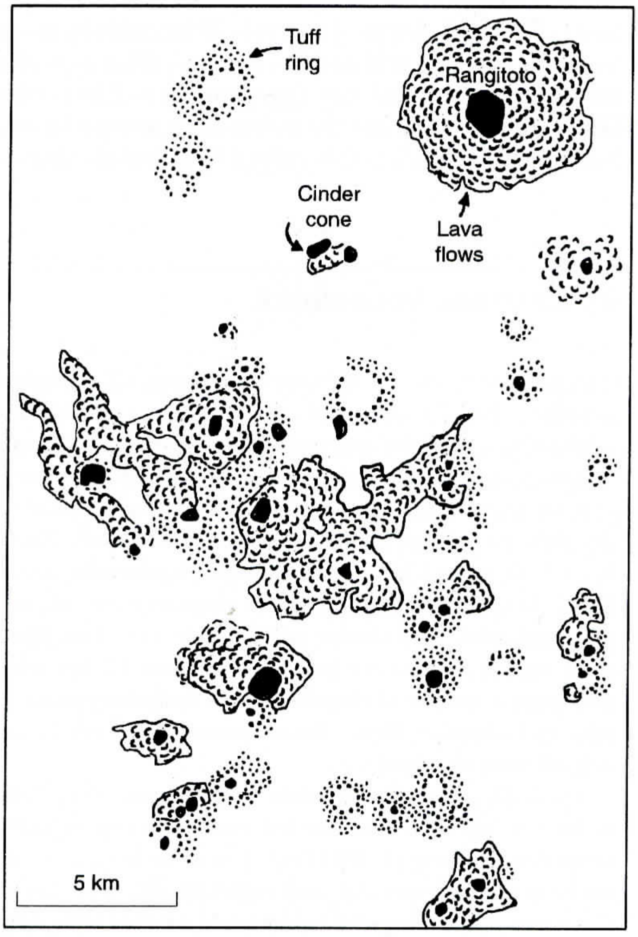

FIGURE 3 Sketch map of the Auckland, New Zealand, monogenetic field, simplified by deleting the coastline. (1993, Geological Society of London.)

The other eruption, that of Paricutin in 1943–1952, was andesitic.

Deeply eroded monogenetic fields are known in many places, for example, in East Fife (Scotland) where about 100 volcanic vents, the roots of monogenetic volcanoes, occur over an area 25 km across. Some vents are plugs of basalt. Others are diatremes, which are vertical pipes filled with explosively fragmented volcanic tuff and other debris. Dikes occur in other fields.

Monogenetic fields occur in volcanic arcs, where the basalt is associated with andesites, and they also occur in hot spot settings where the basalt is alkalic. A feature of the latter is that the basalt contains included fragments of mantle-derived ultramafic rock, often loosely referred to as olivine nodules. The presence of these inclusions indicates that the magma rose without pause from the mantle: if the magma had paused, the inclusions would have dropped out.

Rarely, the pipes in monogenetic fields contain diamonds. Diamonds form under very high pressures, equivalent to depths of 200 km or more. Their survival depends on being transported very rapidly from the mantle to the surface, otherwise they oxidize and are destroyed.

V. FLOOD BASALT FIELDS

These consist of voluminous and extensive spreads of lava flows erupted from scattered monogenetic fissure vents. They tend to flood the landscape and generate a new landscape of subdued relief (Figs. 1d and 4). They occur at hot spots where significant crustal spreading has occurred, for example, the Snake River Plain (Idaho), Iceland, and the fields in Arabia and Syria that parallel the Red Sea/Dead Sea rift system. Individual fields cover 3×10^3 to 5×10^5 km^2. Outpourings of particularly large "giant" fields such as the Deccan in India have punctuated Earth's history, and are approximately coincident with mass bioextinction events.

Many individual lava flows have volumes exceeding 10 km^3. Youthful examples include the 1783 Laki lava in Iceland, which covers 565 km^2 and has a volume of 10–15 km^3; and the Toomba flow in Queensland, Australia, which flowed 120 km down an average gradient of only 0.2 degrees. Giant fields such as the Columbia River Plateau in Washington state (USA) contain flows exceeding 1000 km^3 in individual volume. Vents are marked by crater rows of spatter, agglutinate, and cinders. Commonly, fissure vents evolved to point

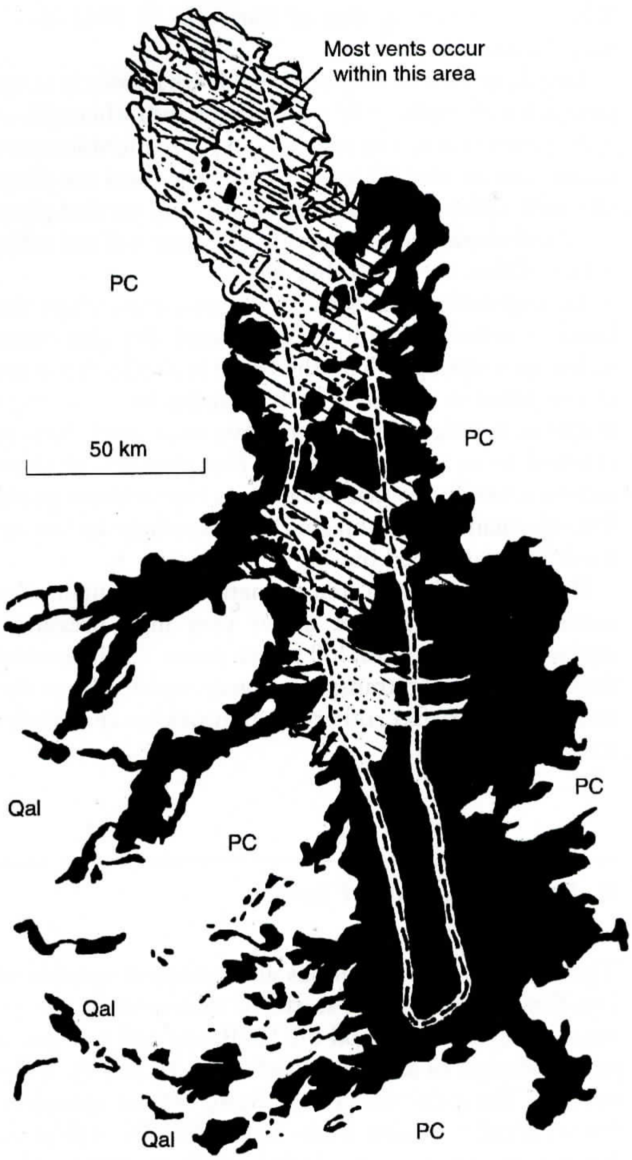

FIGURE 4 Sketch map of a moderate-sized flood basalt field: Harrat Rahat in Arabia. Solid black, lava 10–1.7 Ma; open diagonal shading, 1.7–0.6 Ma; dots, vents; closed diagonal shading, lavas under 0.6 Ma including those of historic eruptions in A.D. 641 and 1256; dashed line, approximate limit of vents; PC, Precambrian basement rocks; Qal, Quaternary sediments near Red Sea coast. (1993, Geological Society of London.)

sources where vent widening by localized wallrock erosion was concentrated.

Many lava flows are compound, meaning that they are divided into flow units, each unit having chilled margins against its neighbors. Great accumulations of pahoehoe flow units form shields of the scutulum type typically sloping at 1–7 degrees. A fine example from Iceland is Skjaldbreid, 8 km in diameter and rising about 500 m above its base. Flood basalt fields in Iceland consist of many overlapping low-angle shields. Many of the compound lavas exhibit structures caused by endogenous growth as freshly erupted lava injected under and lifted up the surface crust, and lava tubes formed where lava drained out from under the crust.

Flow units are thickest where erupted on shallow slopes. They then commonly exceed 10 m thick. They exhibit distinctive pipe vesicles (elongate gas bubbles) and segregation bodies (vesicle cylinders and segregation veins). Lavas ponded in depressions may rest on lignite coal deposits (the fossilized contents of former marshes) and lake sediments. They show columnar jointing.

Eroded flood basalt fields are normally seen to have inwardly directed dips due to subsidence that are greatest where the lava pile is deepest. They are cut by linear dike swarms that locally comprise 5–20% of total rock. Good examples occur in the Hebridean Volcanic Province in Scotland. A typical swarm is 20 km wide by more than 100 km long, and in cross traverses dikes typically number hundreds and may aggregate up to 2 km wide. Dikes are narrowest and the swarm most intense where, locally, a flood basalt field is capped by a central volcano.

VI. CENTRAL VOLCANOES

Central volcanoes are volcanoes that erupt silicic as well as mafic (basaltic) magmas. Commonly, the composition is bimodal, and silicic and mafic rocks may each be more voluminous than intermediate rocks. The broad central part of the volcano is mainly or exclusively made of rhyolitic rocks, and flanks consist of flood basalt. Newberry Volcano in Oregon, for example, has basaltic lower flanks 20 km wide, sloping at 1–3 degrees outward, and scattered with 400 cinder cones (Fig. 1e). The main cone and caldera occur in a central zone 12 km wide and consist mainly of rhyolitic rocks including pumice, ash, and obsidian flows. Some pumice and ash layers extend onto the flanks.

Typically, multiple rhyolitic vents occur. They tend to be monogenetic because intervals between rhyolitic eruptions are long (1–1000 ka). The zone in which they occur is crudely circular and typically about 10 km in diameter, embracing the caldera and caldera rim. This zone reflects the width of the inferred underlying silicic magma chamber from which the rhyolitic eruptions stem.

This central area is a shadow zone from which basaltic vents are excluded. This is because of the general inability of basaltic magma to pass up through a chamber that is at least partially molten and is less dense than basaltic magma.

It is envisaged that basaltic magma ascending beneath the shadow zone, being denser than silicic magma, is trapped at the base of the silicic chamber; being hotter it heats silicic magma and by reducing its viscosity and promoting gas exsolution, it mobilizes silicic magma and may trigger eruptive activity.

The coexistence of rhyolitic and basaltic magmas in central volcanoes is manifest as composite dikes (having basaltic rims and rhyolitic center), streaky mixed pumice, mixed lavas (having fluidal-shaped inclusions of basalt in rhyolite), and hybrid rocks.

Central volcanoes generally have one or more calderas, where subsidence of the magma chamber roof occurred as large silicic eruptions, caused partial evacuation of the chamber. Occasionally, rhyolitic vents occur along arcuate lines, for example, around Valles caldera in New Mexico.

Eroded central volcanoes commonly display granitic plutons (inferred to be solidified magma chambers). Ring intrusions and ring faults delineate cauldrons wherein piston-like subsidences of chamber roof occurred. These occurrences are called *ring complexes*. The type examples are found among the roots of a 400-Ma volcanic field in Scotland.

Many central volcanoes host ore deposits (of Ag, Au, Cu, Mo, Sn, W), including many of the porphyry copper type. The ore metals were transported and deposited by hot volcanic fluids. An unusual gold deposit occurs in the hot caldera floor of Lihir volcano, (Papua New Guinea). Ore deposits in central volcanoes are more closely associated with the silicic than with the mafic volcanism, and likewise the spectacular geothermal manifestations (geysers, hot springs, and geothermal power plants) as seen in the Taupo Zone of New Zealand, the Yellowstone Park (Montana), and Iceland.

See Also the Following Articles

Basaltic Volcanic Fields • Calderas • Flood Basalt Provinces • Lava Flows and Flow Fields • Magma Chambers

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