Composite Volcanoes

Jon Davidson
UCLA

Shan De Silva
Indiana State University

Glossary

composite volcano Relatively large, long-lived constructional volcanic edifice, comprising lava and volcaniclastic products erupted from one or more vents, and their recycled equivalents.

compound volcano Volcanic massif formed from coalesced products of multiple, closely spaced, vents.

debris avalanche Catastrophic landsliding of gravitationally unstable volcano flanks resulting in a widely dispersed deposit at the foot of the edifice, typically characterized by a hummocky surface.

edifice Constructional volcanic mass.

planezes Triangular, flat-faced, facets on volcano flanks formed by the intersection of two master gullies in the upper reaches of a cone.

ring plain Region surrounding a volcano beyond lower topographic flanks, over which tephra and mass-wasting products are radially distributed.

satellite (or flank, or parasitic) vents Small monogenetic volcanic features (domes, cinder cones) distributed over the flanks of a larger composite edifice.

steady-state or equilibrium profile Shape of the edifice (cone) once an active volcano has become well established—follows the initial cone building, precedes long-term erosional degradation, and represents a balance between construction through mass addition (eruption) and degradation through erosion.

topographic inversion Process whereby through time valleys become ridges and vice versa—can occur on volcanoes as volcanogenic products such as lavas are channeled down valleys, focusing subsequent erosion along their edges.

vent Surface opening at which volcanogenic material is erupted.

Ask a small child to draw a volcano. Chances are that child will draw a composite cone. These are the most common types of volcanic edifice, the sites of the most well-known historic eruptions, and the sources of a wide array of volcanic products. Composite volcanoes occur in all regions of volcanic activity across the Earth. Human populations are drawn to composite volcanoes, attracted by the fertile and frequently renewed volcanic soils generated by the volcanoes, while at the same time threatened by the hazards associated with their frequent eruptions.

I. INTRODUCTION

A. Definition of Composite Volcanoes

Surprisingly, the definition of a composite volcano is neither straightforward nor uniformly agreed upon. Most volcanoes are constructional features—they build an edifice from erupted material that extends above the original topography in the region of the vent. Exceptions to this are maars and calderas. Among constructional edifices, there are variations in shape and size (Fig. 1). Shape is largely a function of slope angle; at the one extreme are very shallow slopes that characterize shields, and on the other are the steeper slopes that characterize cones and domes. Among the smaller edifices are cinder cones and domes, which are typically monogenetic (formed from a single eruption episode). Shield volcanoes and composite cones are the products of multiple eruptions spanning tens to hundreds of thousand of years, and, as a result, are larger and more diverse in terms of their products (types and compositions). Composite volcanoes are therefore defined as relatively large and long-lived volcanic edifices comprising both lava and volcaniclastic erupted products. Note that our definition is intended to be descriptive and not a rigid classification; composite volcanoes clearly overlap with many other edifice types and may incorporate smaller volcano types (cinder cones and lava domes) in their architecture. Composite cones are commonly taken as synonymous with stratovolcanoes; the latter term is preferred in many introductory texts. We choose to avoid the term stratovolcano, as it conveys an implication (albeit not necessarily intentional, but certainly perpetuated in diagrams from introductory texts) of regularly interlayered pyroclastic deposits and lavas. The term "composite" has been used to describe volcanic cones from the Andes that have a composite growth history, punctuated by one or more episodes of sector collapse, and the term "compound" to denote edifices comprising multiple cones, resulting from limited vent migration over time within a restricted area. Both composite and compound volcanoes in these senses are included under our definition of composite cones.

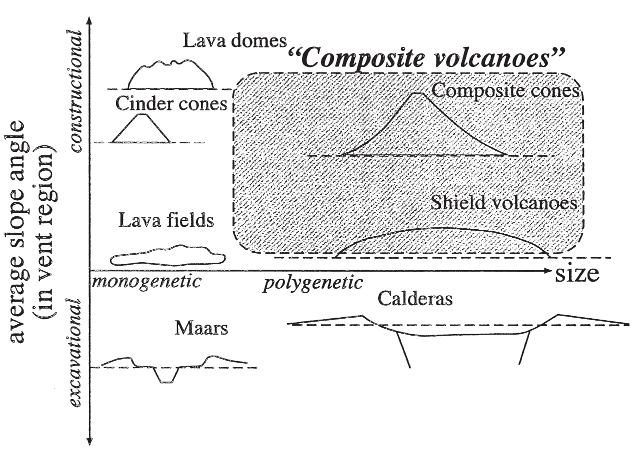


FIGURE 1 Variations in volcanic landforms as a function of size and "steepness." The diagram is intended for illustrative purposes rather than a rigorous classification. The composite volcanoes discussed in this article are constructional features, each with a reasonably protracted history of eruptions. The erupted products typically comprise both lavas and pyroclastic materials, associated with reworked deposits.

B. Distribution of Composite Volcanoes

Composite volcanoes are found globally in nearly all regions of volcanism, although their abundance relative to classic shield volcanoes, lava fields and domes, calderas, and cinder cones varies considerably. At convergent plate margins, composite volcanoes are arguably the type edifices (Fig. 2). Indeed subduction zones are perhaps most dramatically characterized by classic cone-shaped basaltic andesite to andesite volcanoes such as Mount Fuji in Japan. In fact, most well-known historic eruptions have occurred at composite cones located along convergent plate margins (Table I). Although some convergent margin environments where extension occurs in intra-arc grabens or backarc rifts are dominated by cinder cone fields, the magmatic expression of a convergent plate margin is generally a chain of composite volcanoes, subequally spaced, comprising a volcanic arc. The arc is subparallel to the trench and constructed on the upper plate approximately 100–150 km above the upper surface (known as the Wadati–Benioff zone—see "Plate Tectonics and Volcanism") of the subducted slab. The spacing of the volcanoes along the arc is subregular, varying from 30 to 100 km among different arcs, although most arcs may be characterized by an average spacing. The control on volcano spacing is unclear and may reflect the spacing of Rayleigh–Taylor diapiric instabilities in a melt zone above the subducted slab or periodic variations in the stress state of the upper plate lithosphere that impede or allow melt ascent.

Composite volcanoes are not common at divergent plate margins, although examples can be found. Along oceanic divergent margins (midocean ridges) they are effectively absent, although on Iceland, where the midocean ridge lies over a mantle plume, composite cones

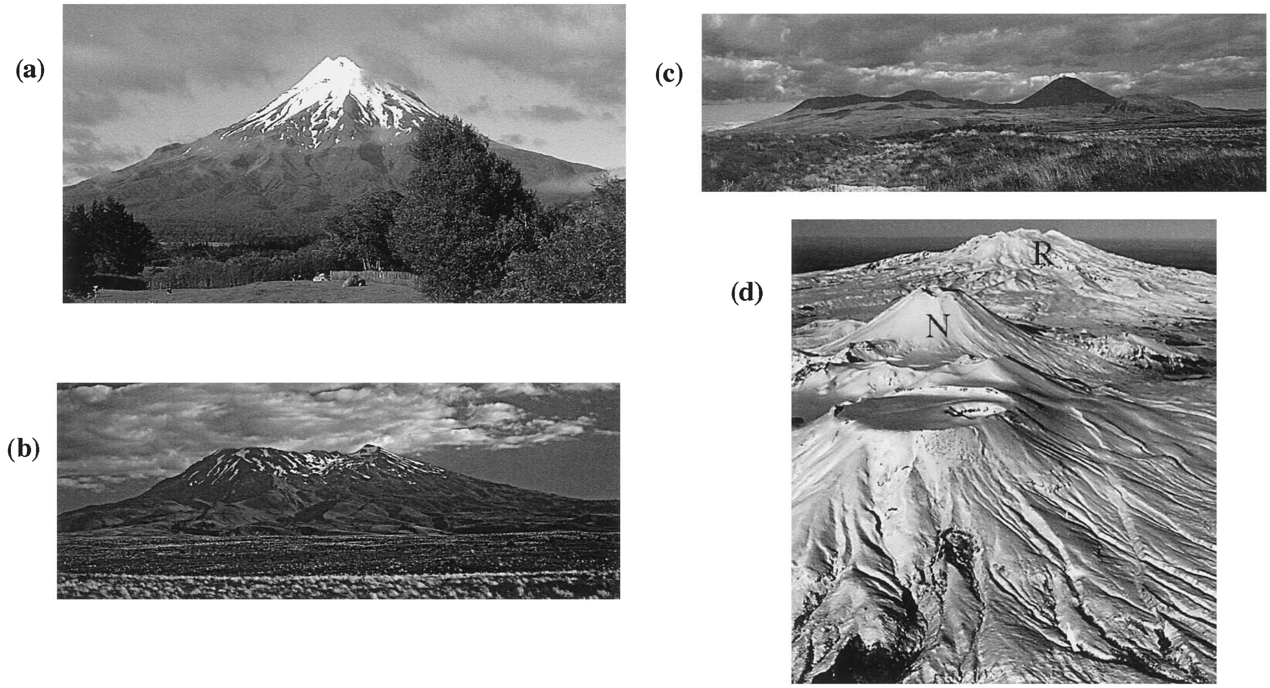


FIGURE 2 Examples of different composite volcano forms from a convergent plate margin setting, the North Island of New Zealand: (a) Mount Taranaki, a "classic" cone shape; (b) Mount Ruapehu, a compound volcano; (c) Tongariro, a compound volcano with numerous Holocene vents (the youngest being the symmetrical cone of Mount Ngauruhoe with a single active vent). Photograph d is an aerial view of Tongariro (N = Ngauruhoe) looking south to Ruapehu (R) in the distance, for comparison. The variation from (a) to (c) reflects an increasing tendency for vent location to migrate over time. Although they are cluster or composite edifices (Table II), Ruapehu and Tongariro might be considered twin volcanoes (to each other) in a broad sense.

are present, such as Hekla and Askja. In the early stages of divergent margin development (continental rifting), composite volcanoes do occur, although they are typically off-axis. Along the East African Rift, for instance, huge composite volcanoes (e.g., Mount Kilimanjaro) are found at the rift shoulders. Intraplate volcanism, perhaps by virtue of the high heat (and therefore magma) flux over a protracted time period, typically gives rise to large composite volcanic edifices. Many, particularly in the ocean basins, are dominated by basaltic effusion and are classic shield volcanoes. Composite intraplate volcanoes may, however, be found in both oceanic and continental environments. They are effectively indistinguishable morphologically from those found at convergent plate margins (Fig. 3), differing only in terms of the rock chemistry and petrography.

What factors determine the surface expression of magmatism, that is, the construction of composite volcanoes rather than other volcano landforms? Two factors at least promote the formation of composite volcanoes: (1) the composition of magma erupted and (2) the style of eruption. Magma compositions at convergent plate margins are largely the result of differentiation and volatile concentration. These factors are, of course, not unconnected, as volatile concentration is typically a consequence of differentiation (cf. "Volatiles in Magmas"). Styles of eruption are controlled more by the physical structure and stress environment of the lithosphere through which magmas ascend (although this also influences the extent of magma differentiation). In order to produce compound volcanoes, eruptions at a given vent are frequent and small to moderate in size.

Differentiation increases SiO_2 content and increases magma viscosity, leading to high aspect ratio lavas and impeding lateral distribution. Thus there is a distinction between shield volcanoes, at which low-viscosity basalts can flow large distances from the vent, and cones, at which lava flows are shorter and construct a steeper sloped edifice around the vent. The combined increase in volatile content and magma viscosity also increases the propensity for explosive eruption and the production of pyroclastic material. Convergent margin magmas are characterized by high H_2O contents, and, at least by the time they reach the surface, they tend to be differentiated (basaltic andesites and andesites). Because magma ascent is fundamentally dictated by the buoyancy con-

(a) (b) (c)

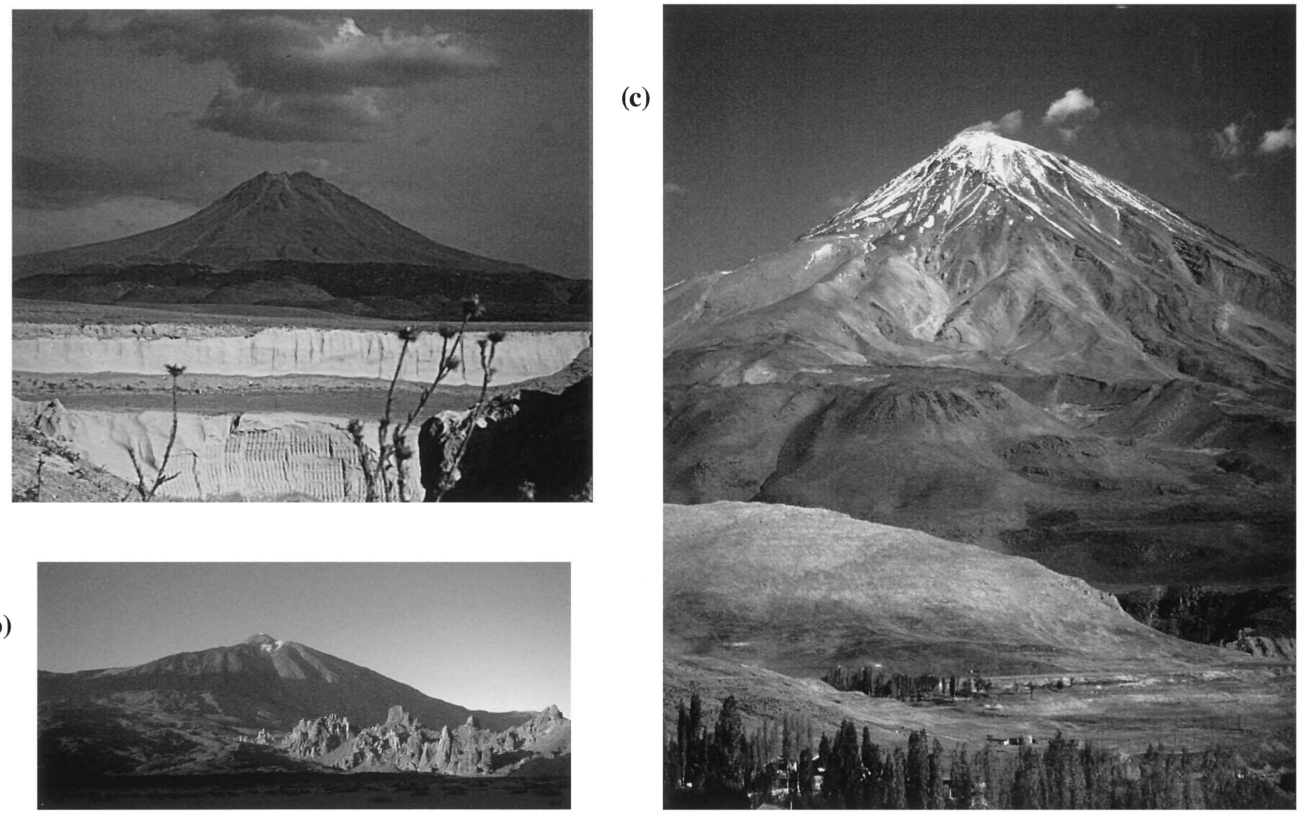


FIGURE 3 Large composite volcanoes from intraplate settings: (a) Hasandag volcano, Cappadocia, Turkey; (b) Teide volcano, Tenerife; (c) Mount Damavand in northern Iran (5671 m) (see also color insert). Both continental (a, c) and oceanic (b) crustal substrates are represented.

trast between magma and the lithosphere, ascent through thick, low-density continental crust will be impeded unless extensive differentiation occurs to reduce the magma density. Protracted differentiation can ultimately produce large volumes of rhyolite in continental regions, which, in turn, may be erupted in caldera-forming events (cf. "Calderas").

The association of calderas with precursor composite volcanoes is common. Smaller, less differentiated caldera systems such as Crater Lake in Oregon may represent the cataclysmic evacuation of a silicic magma chamber from beneath a simple composite cone. Larger caldera-forming eruptions (such as at Long Valley in California and Valles in New Mexico) are typically preceded, albeit by a few million years, by magmatism expressed as clusters of composite volcanoes concentrated in the region of the future caldera. Composite volcanoes and calderas may also be contemporaneous, varying only slightly in location along and across zones of magmatism, such as the Taupo Volcanic Zone of New Zealand. These associations suggest a further complex balance between magma/heat flux and the rheological state of the crust in determining the morphological expression of volcanism.

In summary then, relative to shield volcanoes, composite volcanoes are characterized by the eruption of more differentiated, silica- and volatile-rich magma. Compared with caldera systems, composite volcanoes erupt smaller volumes more frequently and less explosively, which likely inhibits the long-term extreme differentiation, which typifies caldera-forming magmas.

II. Morphology of Composite Volcanoes

A. Introduction

Morphology is one of the most fundamental properties of a volcano, and yet surprisingly little work has been

TABLE I Selection of Notable Eruptions from Composite Volcanoes Since A.D. 1500 Involving 1000 or More Fatalities[a]

Volcano	*Country*	*Year*	*Explosive eruption*	*Lava flow*	*Debris flow*	*Tsunami*	*Famine*
Kelut	Indonesia	1586			10,000		
Huaynaputina	Peru	1600	>1,000				
Vesuvius	Italy	1631		18,000			
Etna	Italy	1669		10,000			
Unzen	Japan	1792				15,190	
Mayon	Philippines	1814	1,200				
Tamabora	Indonesia	1815	12,000				80,000
Galunggung	Indonesia	1822	1,500		4,000		
Mayon	Philippines	1825			1,500		
Awu	Indonesia	1826			3,000		
Cotopaxi	Ecuador	1877			1,000		
Krakatau	Indonesia	1883				36,417	
Awu	Indonesia	1892			1,532		
Peleé	Martinique	1902	29,000				
Santa Maria	Guatemala	1902	6,000				
Kelut	Indonesia	1919			5,110		
Merapi	Indonesia	1930	1,300				
Lamington	Papua, New Guinea	1951					
Agung	Indonesia	1963					
El Chichón	Mexico	1982	1,700				
Nevado del Ruiz	Columbia	1985			25,000		

[a] Modified from Report by the Task Group for the International Decade of Natural Disaster Reduction. (1990). *Bull. Volcan. Soc. Jpn. Ser. 2* **35,** 80–95. Numbers refer to fatalities, listed under column for cause of deaths.

done since the seminal work of Cotton in the 1940s. One of the reasons for this may be the general perception that the morphological evolution of a composite volcano is simple; they are positive (constructional) topographic features, with steep flanks and a general conical shape, and they result from local accumulation of erupted products. However, this simple view ignores the fact that while many composite volcanoes are simple cones with a single summit vent and radial symmetry, many are more complex, compound volcanoes with convoluted histories involving cone collapses, rebuilding, and changing vent locations through time (Table II). Nevertheless, they still display a conical profile normal to the length axis, suggesting a consistency to the "normal" conical shape of a single composite cone.

Another fact that is ignored is that the simple conical shape is the result of a complex evolution that is controlled by the interplay of aggradation and degradation. Short-term aggradation by constructive processes of eruption and emplacement of volcanic materials is opposed by degradation as the longer period destructive processes of erosion, punctuated by catastrophic events such as gravity-driven avalanching (cf. "Debris Avalanches") and posteruption mass wasting. The fact that active composite volcanoes maintain a simple conical shape suggests that the average rate of aggradation must exceed the "punctuated equilibrium" of degradation.

B. Evolution of Morphology

Most composite volcanoes around the world have very similar characteristics. These volcanoes are characterized by a concave-upward profile, which should be considered as the equilibrium or steady-state profile of an active composite cone. Classic textbook volcanoes such as Mount Mayon in the Philippines, Mount Fuji in

TABLE II Summary of Morphological Types among Composiite Volcanoes

Morphological type	*Description*	*Examples*
Simple cone	Classic "textbook" radially symmetric shape; tend to be young	Fuji (Japan), Klyuchevskoy (Kamchatka), Mount Mayon (Philippines), Osorno (southern Chile), Shishaldin (Aleutians, United States), Taranaki (New Zealand), Cotopaxi (Ecuador)
Shieldlike	Shallow-sloped flanks, common craters/calderas in summit region, greater diversity of magmas (include evolved types such as dacite/rhyolite)	Newberry (Cascades, United States), Okmok (Aleutians, United States), Gorely (Kamchatka)
Compounds	Limited vent migration—typically resulting in an elongate ridge, more occasionally a large equant massif	Ruapehu (New Zealand), Zhupinovsky (Kamchatka), Lascar and Irruputuncu (northern Chile), Tatara–San Pedro (southern Chile)
Twins	Distinct neighboring volcanoes, considerably closer together than average volcano spacing along an arc; typically there is an age difference between the two edifices (a younger active and an older cone)	Avachinsky–Koryaksky (Kamchatka), Parinacota–Pomerape and San Pedro–San Pablo (northern Chile), Colima (Mexico)
Clusters	Groups of more than two distinct polygenetic edifices	Tongariro (New Zealand), Bromo (Java)
Collapse-scarred	Severe recent modification of morphology by sector collapse, resulting in large summit bowl or amphitheater	Mount St. Helens (Cascades, United States), Bezymianny (Kamchatka), White Island (New Zealand)

Japan, and Mount Taranaki (formerly Egmont, New Zealand) exemplify this (Fig. 4). While this is a useful general observation, it is instructive to note that more youthful or nonequilibrium volcanoes have a more pure conical shape with a more restricted base (Fig. 4b). At most composite volcanoes, it is clear that this shape is produced by early lavas being more voluminous and extensive than later lavas (Fig. 4b, parts iii and iv). Certainly, there is a slight concavity to the flanks, but these volcanoes lack the extensive aprons of talus that accentuate the concavity of the slopes. This suggests that mass transfer through destructive processes modifies the shape of a volcano with time from a cone with simple slopes and a restricted base to one with a more concave-upward profile and a wider base (Fig. 4c). Most active volcanoes are equilibrium or steady state.

C. Factors Controlling Morphology

Notwithstanding the complexities discussed above, the primary shape of a composite volcano is conical. Many of the controls on this shape can be understood by considering the geometry of a cone. The volume v of a simple cone is given by

$$v = \tfrac{1}{3}\pi r^2 h, \qquad (1)$$

where r is the radius of the base and h is the height of the cone. For a typical steady-state volcano with the concave-upward profile, a more complex exponential form is needed:

$$r = Be^{Mh}. \qquad (2)$$

B and M are constants and the volume has to be found by integration. Below we address the main factors that control the morphology of composite volcanoes.

D. Aggradation

While there is a strong dependency of edifice height on the volume of a composite cone, there also appears to be a limit to the size of composite cones. Edifice heights (base to summit) of composite volcanoes rarely exceed 3000 m and the vast majority of arc-related composite volcanoes are between 2000 and 2500 m. Volumes are similarly restricted; notwithstanding the difficulty in measuring accurate volumes, maximum volumes for arc-related composite volcanoes are around 200 km^3 (e.g., Mount Adams and Mount Shasta in the Cascades of the United States). Intraplate composite cones may attain larger volumes.

One explanation for this is that the conical form exerts a fundamental control on the growth of a volcano. The relationships in Eqs.(1) and (2) suggest that if the conical form is to be maintained, every additional increment in height requires a huge additional increase in volume—the additional volume has to be distributed all over the cone. At some point, this becomes prohibitive to further growth. However, closer examination of volcanoes reveals that the height increment does not necessarily always involve the large volume increment suggested by the relationships described in Eq. (2), because in many cases the increase in height is achieved by adding material to the uppermost parts of the edifice only. In many cases the uppermost parts of composite cones are characterized by small and stubby lava flows or domes reflecting their evolved nature and attendant high viscosity and yield strength (Fig. 4c, part iv). Effusion of these lavas builds up the edifice without much new volume being added and results in the steep slopes that characterize the uppermost slopes.

The consistency of edifice heights and volumes in comparable tectonic settings around the world suggests that some simple geophysical relation must exist to limit the size of composite volcanoes. Several factors can affect the height to which a composite volcano can grow. Among these are the nature of the volcanic products, the duration of magma supply, differentiation of the magmas, and the crustal density profile. Magma supply is certainly an important control because the largest composite volcanoes are intraplate volcanoes such as Mount Ararat, Turkey; Mount Damavand, Iran; and Mount Kilimanjaro, Kenya. Here magma production and supply rates are higher than those associated with arcs and the resulting edifices are much larger. However, even though magma supply rates and other factors are likely to be different between regions or arcs, they may be close to constant for a given region, arc, or portion of an arc. Mature composite volcanoes in comparable tectonic settings are still similar in size the world over.

Most eruptions from composite volcanoes are driven by the hydrostatic "head" or, more appropriately, the overpressure (that in excess of lithostatic (Fig. 5)) in the magma reservoir. Geophysical studies of active volcanoes commonly reveal the presence of shallow (5–10 km) magma storage zones beneath active volcanoes. Petrologic studies confirm shallow reservoir depths as most composite volcanoes are characterized by eruptions of porphyritic magmas dominated by plagioclase. Furthermore, most volcanic products also show evidence of extensive magma mixing—a phenomenon that is best understood in the context of shallow magmatic systems. While it is debatable whether a shallow magma reservoir exists throughout the entire lifetime of the volcano, it is clear that one must exist during the actively erupting stages. Therefore it is reasonable to assume that most eruptions from composite volcanoes occur from shallow magma reservoirs and therefore that the overpressure required to erupt material from the chamber is unlikely to vary much. The consistency of the ballistics of volcanic bombs from composite volcano eruptions supports this contention.

As a volcano grows, two factors may conspire to decrease the eruption rate. First, the growing mass of the volcano increases the lithostatic load on the shallow magma chamber and eventually overcomes the hydrostatic head. Inflation and deflation of volcanic edifices are often modeled as the result of a shallow source of deformation (a Mogi source), suggesting strong feedback between the edifice and the magma reservoir. Second, the distance the magma has to ascend to the surface increases. It should be clear from Fig. 5 that if h and the load are increased, there will be a limit (observational evidence suggests this is about 3000 m of edifice height) above which it will be physically unlikely that further lava can be erupted from the summit. Two general observations support this reasoning. First, early lavas tend to be more voluminous and extensive than later lavas. Second, early lavas are commonly less evolved than later lavas. The first directly relates growth to changing effusion rate, and the second implies that the critical overpressure ($P_{ex}>P_{lith}$) can only be maintained if the reservoir magma becomes more evolved and consequently less dense, but more viscous as the volcano grows. Only the higher viscosity of the lower density, evolved lavas permits the condition $P_{ex}>P_{lith}$ to be maintained—the more evolved lavas typically have lower magma densities due to removal of dense crystalline phases and can sustain greater overpressures on vesiculation since the higher viscosities impede volatile outgassing.

This control is well illustrated in Fig. 4b, parts iii and iv. Here, the youthful cone of Licancabur is built from shorter younger flows radially disposed around the vent, overlying older more extensive flows. The true equilibrium profile has not yet developed because there has been insufficient time to significantly degrade the flanks and develop a talus apron. A dramatic decrease in density (with consequent increase in overpressure) can also be achieved by vesiculation of the magma. This condition will depend on magma composition (volatile species, solubility, and content) and on its capacity to achieve supersaturation through depressurization, which is ulti-

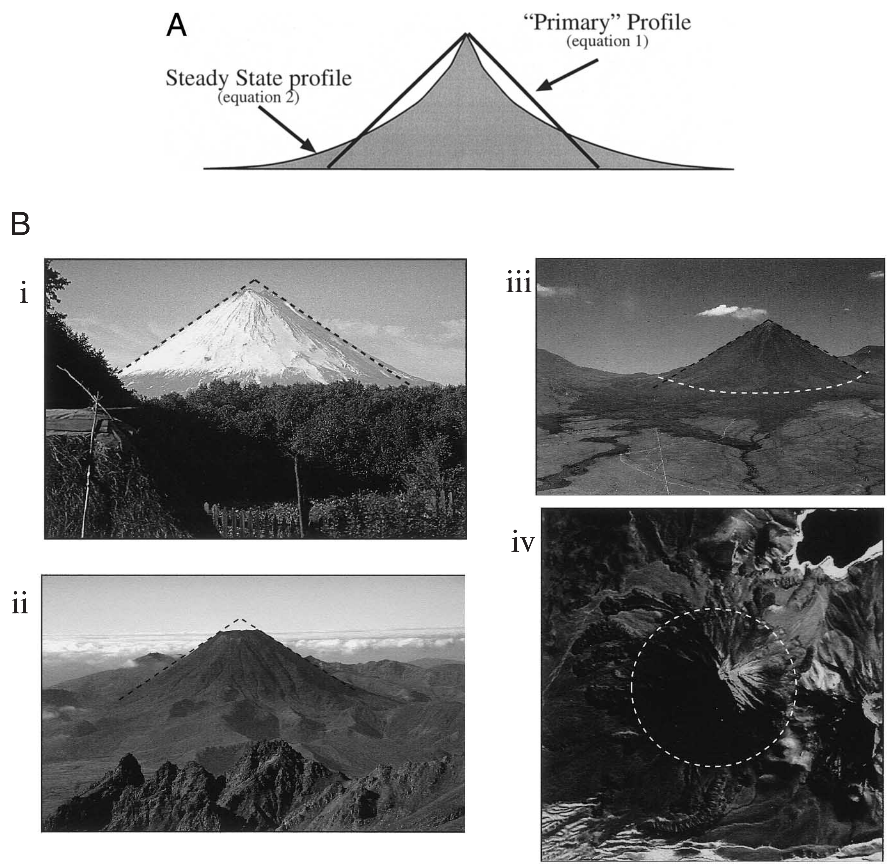


FIGURE 4 (A) Idealized evolution of the shape of a composite volcano. Initially, a pristine volcano will form a pure conical form with constant slopes and a volume given by Eq. (1). Mass wasting results in transfer of mass from the upper parts of the edifice to the lower flanks, building out a talus apron. The edifice evolves to a steady-state profile with concave-upward slopes and a volume given by Eq. (2). Compare with examples of profile evolution given in (B) and (C), respectively. (B) Young nonequilibrium conical profiles: (i) Klyuchevskoy volcano, Kamchatka, one of the world's most active subduction zone volcanoes and $<$10,000 years old (view from north); (ii) Nguaruhoe cone (ca. 2500 years old), New Zealand (cf. Fig. 2); (iii) Licancabur volcano, view from west together with (iv) Landsat TM image of Licancabur. Photographs iii and iv show the early more extensive lava flows around the base and a more restricted cone formed from later more restricted lavas, outlined in a white dashed line.

mately also controlled by the parameters illustrated in Fig. 5.

E. Degradation

In a heuristic and phenomenological sense, the history of a composite cone can be thought of as the interplay of short-term eruptive phenomena that construct volcanoes periodically and the longer term erosive processes of degradation that conspire to bring them down (Table III). However, while this is a useful working hypothesis, it is important to recognize that the while the averaged rate of degradation on composite volcanoes suggests longer term equilibrium, in reality degradation is highly variable, consisting of a regional "background" rate modulated by more rapid erosion and mass-wasting events. The high degradation rates often accompany and closely follow eruptions and punctuate the equilibrium. For instance, observations after the 1980s eruptions of Mount St. Helens in the USA and the 1991 eruption of Mount Pinatubo in the Philippines showed that peaks of erosion follow closely on peaks of eruption as pyroclastic material is rapidly (months to years) removed from the cone. Catastrophic processes such as landsliding/avalanching further conspire to accelerate degradation.

Long-term erosion depends on climate and the composition of the volcanic edifice. Given comparable rates of production and cone growth, volcanic cones are better

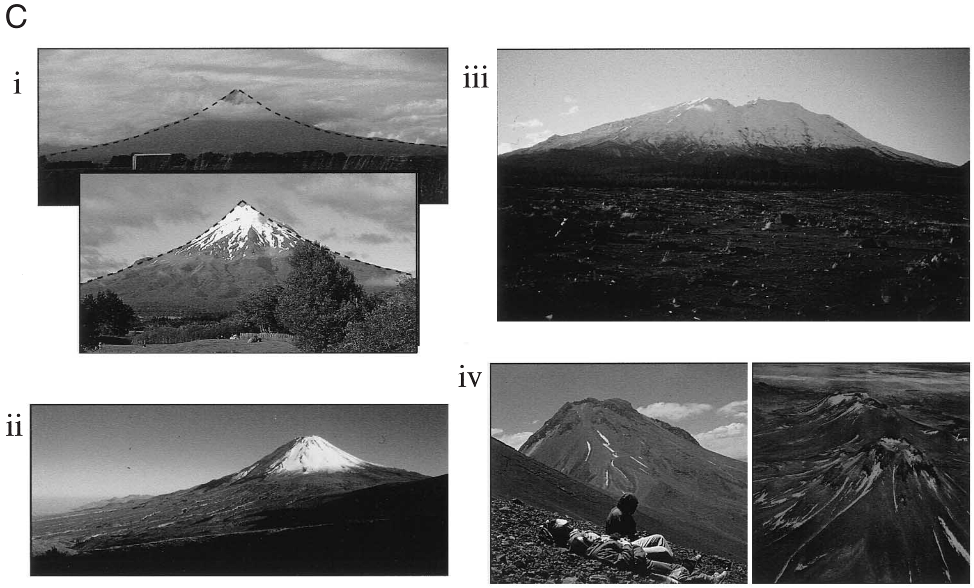


FIGURE 4 (*continued*) (C) Equilibrium profiles: (i) Taranaki volcano, New Zealand (two views from the north emphasizing classic extensive equilibrium profile of concave-up flanks); (ii) Volcan Misti (Peru) from southeast showing extensive ring plain or talus apron and a developing equilibrium profile; (iii) lahar deposits of the ring plain or talus apron (foreground) of Mount St. Helens. Low-angle aprons of this type of material extend out to several kilometers from the base of the cone. View is from the southeast. (iv) Aguas Calientes from Lascar (central Andes), showing the short, stubby lava flows that have built up the steep upper portions of the cone.

preserved in arid/cool climates rather than humid equatorial climates. For instance, climatic differences between the hyperarid central Andes and the tropical northern Andes are highlighted by pristine morphologies of Pleistocene volcanoes in the former and degraded morphologies in the latter. In response to eruptive events that produced large volumes of unconsolidated material and greatly disturbed local topographic equilibria, at Mount St. Helens, 10-m-deep gullies were cut into the pyroclastic deposits within a few months of the

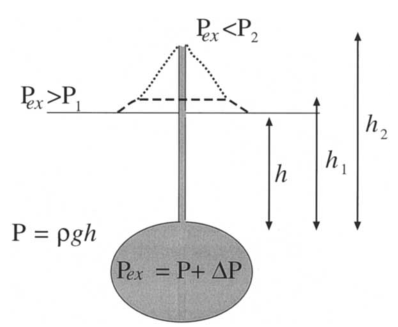


FIGURE 5 Schematic diagram showing the relation between lithostatic pressure P and eruption driving overpressure P_{ex} in the magmatic system of an active volcano. The lithostatic pressure P changes with the mass of the growing volcano and the depth to the magma chamber h. Eruption can take place as long as P_{ex} remains greater than P. At h_2, the edifice has grown to the critical height beyond which P_{ex} is less than lithostatic and therefore eruption from the summit is no longer viable.

TABLE III Stages in the Erosional History of Composite Volcanoes

Stage	*Geomorphic signature*
1	Fresh, young cones, often dark, pristine lava flows and summit crater visible, sharp profile; not glaciated
2	Small gullies on flanks, lavas visible and crater may exist, but degraded; cone still sharp, dark apron gone; moraines present
3	Individual lava flows barely visible, no crater, well-established gullies, constructional surfaces dwindling; planezes initiated
4	No lava flows visible, deeply incised gullies, large planezes, little original cone surface left; considerable relief; major U-shaped glacial valleys in glaciated regions
5	Barely recognizable, low relief; radial symmetry the only clue to volcanic origin

eruption. At Mount Pinatubo, the 1991 pyroclastic flows had similar gullies within a matter of days. On the other hand, pyroclastic deposits at Katmai (Alaska), where the climate is somewhat cooler and drier, are only moderately eroded nearly 100 years after eruption.

The composition of the edifice is an equally important control on degradation styles and rates. Clearly, unconsolidated pyroclastic material will be more readily eroded. Lava is less porous than scoria and will encourage runoff. Porosity and permeability will therefore be important in controlling if runoff or percolation dominates. Since extensive gullying is common on composite volcanoes, we can surmise that runoff dominates. Gullying is the most common indication of degradation of composite cones and occurs in several stages. One of the most significant stages of gullying involves the formation of planezes (Table III). These are the result of two master gullies intersecting in the upper reaches of a cone and isolating a triangular, flat-faced, facet.

The biggest single obstacle to the growth of a volcano is gravity and the hackneyed cliche "what goes up must come down" is nowhere better exemplified than in the catastrophic debris avalanches (cf. "Debris Avalanches") that are now recognized as being part of the normal mode of activity of composite volcanoes. The mass transfer associated with these events is largely responsible for modifying the shapes of volcanoes to the steady-state concave-upward profile as the deposits from these events extend the talus apron of the lower flanks out to several tens of kilometers from the summit.

As a volcano grows, its slopes become steeper and therefore gravitationally unstable. Further, asymmetry resulting from unequal distribution of mass on an edifice adds to the instability. Edifices built on slopes are inherently unstable. Gravitational collapse requires a trigger, and many events of this type probably involve earthquake-triggered flank failures (e.g., Bezymianny, 1956; Mount St. Helens, May 1980). The growing volcanic load may reactivate local basement faults that may penetrate up into the volcanic edifice (e.g., Socomopa, Chile, 7500 a). Finally, inflation of the cone due to a recharge event or degassing may trigger the collapse of an unstable flank (e.g., Tata Sabaya, Bolivia).

The most spectacular examples of gravitational collapse involve the failure of 25–30% of a volcanic cone in a matter of minutes.

The morphologic signatures of collapse are invariably a collapse amphitheater and hummocky topography on the avalanche deposit; the May 18, 1980, eruption of Mount St. Helens (see "Debris Avalanches") provides a typical example. Several other amazing examples have also been recognized around the world, but nowhere more so than in the central Andes. The studies in the central Andes highlight several key features. First, collapsed portions may vary in scale from relatively small (10–15%) portions of the edifice as at Irruputuncu on the Bolivia/Chile border to quite large (30%) portions of the edifice as at Tata Sabaya in Bolivia. Second, regardless of how extensively an edifice is eviscerated, the conical shape is reestablished very rapidly. This may explain why there are currently few clear examples of collapse-scarred volcanoes (Table II). At Parinacota in Chile, reconstruction since a massive collapse 13,000 years ago has virtually rebuilt the entire edifice (Fig. 6e; see also color insert). Only very careful examination of aerial photographs reveals the trace of the amphitheater. At Bezymianny in Kamchatka, a dome growing since the 1956 sector collapse has nearly filled the amphitheater (Fig. 6f). Third, the deposits from these collapses can form a significant portion of the talus apron of volcanoes (e.g., Volcan Misti, Peru).

Gravitational collapse is therefore a significant mechanism of mass transfer on composite volcanoes. The reduction of steep slopes of the upper and middle flanks by collapse and deposition of these materials far from the flanks results in extensive low-angled aprons (commonly referred to as *ring plains*; vide infra) extending to several tens of kilometers out from the edifice. Subsequent "healing" of the cones results in reestablishment of steep middle and upper flanks, perpetuating the steady-state profile.

Also important in determining the volcano morphology resulting from degradation are the effects of hydrothermal alteration. Mature conduits can provide a sufficient heat flux to drive groundwater through a hydrothermal circulation system, with the consequence that the rock volume affected by the system is altered and weakened, making it more vulnerable to erosion by both long-term, slow-mass-wasting, glacial or fluvial processes and catastrophic failure. In volcanoes with well-established hydrothermal systems, the vent region can occupy an enormous bowl of altered volcanic material (such as Mutnovsky volcano, Kamchatka) that may resemble—or on occasion coincide with—a sector collapse amphitheater. The occurrence of hydrothermal activity and the influence of consequent alteration can extend long after magmatic addition to the edifice has effectively ceased and exert considerable control on its morphological degradation.

F. Changes in Vent Locations through Time

The classic conical shape owes its form to the constancy of vent location over a protracted period of time. This

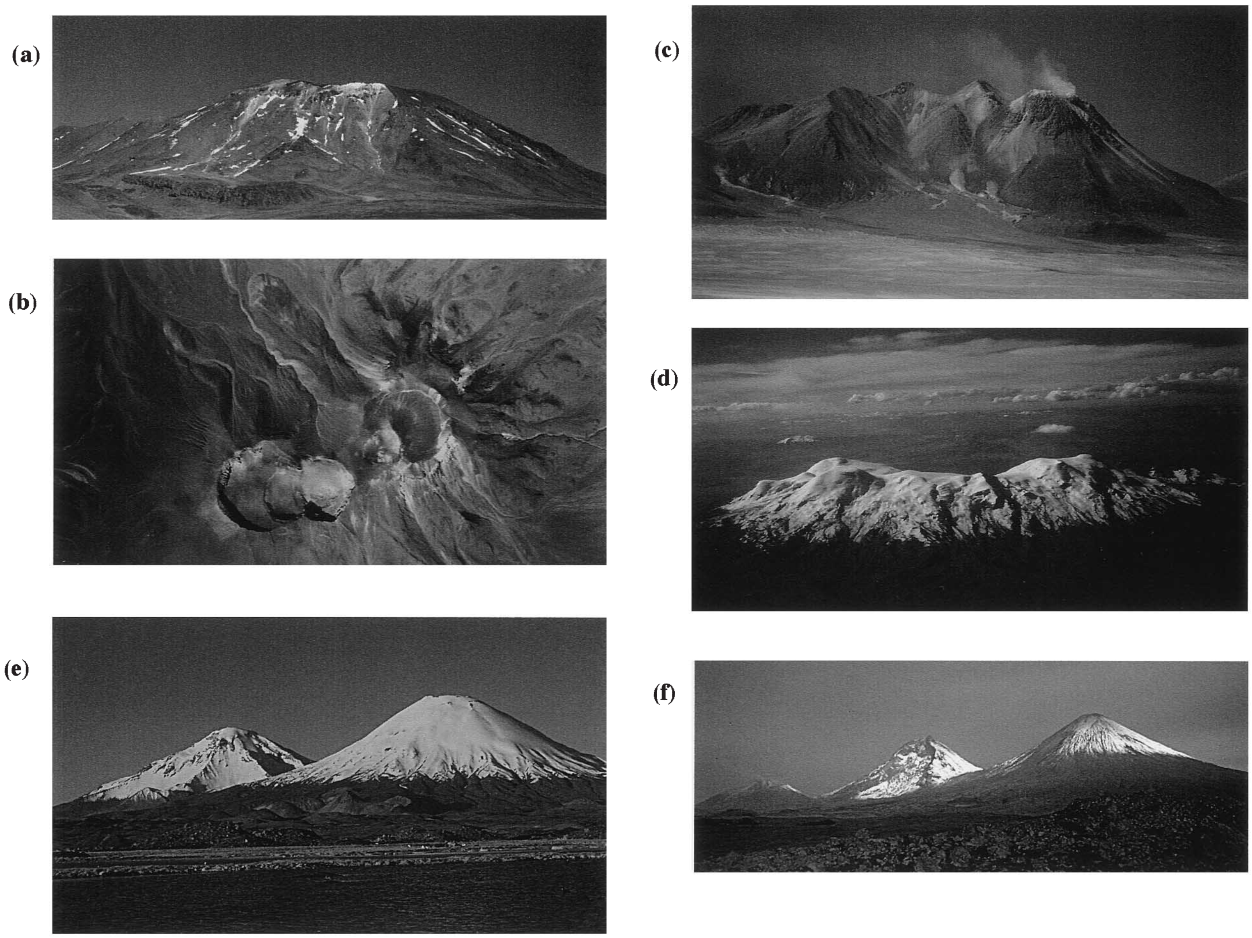


FIGURE 6 More complex or compound composite cones, illustrating effects of local vent migration through time. (a) Lascar from the north, an extensive composite cone that is elongate east to west due to migration of the vent region. (b) Aerial photograph of Lascar clearly showing the nested craters resulting from vent migration (north to top of page). (c) Irruputuncu (Chile/Bolivia), another typical nonconical, ridgelike composite cone (view from the west). The oldest part of the cone is the left. (Photograph courtesy of Gerhard Worner; see also color insert.) (d) Coropuna, Peru, a compound volcano made up of at least five different overlapping cones. (e) Nevados de Payachata, central Andes, comprising twin volcanoes (view from southwest). The older glaciated Pomerape cone is to the north (left), while Parinacota is the young, more symmetrical cone. The hummocky terrane in the foreground is a debris avalanche deposit. (See also color insert.) (f) Klyuchevskoy group volcanoes, Kamchatka, view from the south east. The symmetrical Klyuchevskoy cone in the foreground and the vapor-shrouded Bezymianny volcano (which collapsed in 1956 and now consists of a large active dome in the amphitheater) in the distance are both active, while the central peak (Kamen), which shows the scarp of a collapse event, is inactive.

ensures that volcanic products, and therefore mass, are always added from the summit area and decrease radially away from it. However, many volcanoes show evidence that activity has migrated with time (Table II, Fig. 6). Several interesting questions arise. For instance, it is not clear whether activity migrates in the same direction with time throughout the region, in response to migration of the volcanic front as a whole, or whether it is segment specific or even random.

Some volcanoes are twin systems comprising two quite distinct but neighboring composite volcanoes. Examples include San Pedro–San Pablo and the Nevados de Payachata in the central Andes (Fig. 6e). Typically, twin volcanoes reflect a vent shift such that one of the two is active, leaving its twin extinct. Examples are found, however, such as Bezymianny and Klyuchevskoy volcanoes in Russia (Fig. 6f), where neighboring volcanoes are concurrently active. Others are elongate amalgamated edifices with a migrating summit complex. Examples of these include the following: in the central

Andes, Aucanquilcha, Lascar (Figs. 6a and 6b), Irruputuncu (Fig. 6c), Coropuna (Fig. 6d), and Ojos del Salado, the world's highest active volcano; in New Zealand, Ruapehu (Fig. 2); in Turkey, Ararat; in Kamchatka, Zhupinovsky. Tongariro (Fig. 2) is an extreme example of this as it is a cluster of as many as 30 relatively small edifices. These compound volcanoes offer even greater challenges of interpretation than on "simple" cones. The complex geometries of nested and overlapping cones make determination of individual cone volumes difficult as we commonly do not see basement exposed and the preexisting topography is unknown. Volcanic stratigraphy is similarly problematic to unravel, particularly in light of the close proximity (in both space and time) of potential source vents.

Subsidiary vents, commonly called satellite, parasitic, or flank vents, are common features at many composite volcanoes. The general use of the term parasitic should, however, be discouraged as it implies an often-false dependence on the main volcano. These subsidiary vents are typically in the form of small monogenetic volcanoes like cinder cones or domes (Figs. 1 and 7). Such features are commonly arranged along lineaments and are interpreted as reflecting the influence of faults along which magma can migrate laterally away from the main magma chamber or, more commonly, vertically from a separate magma batch. In some cases, these satellite vents occur as part of an areally extensive field spatially associated with the main volcano as at Mount Adams in Washington state or Payun Matru in Argentina. Geochemically, the erupted products of flank eruptions are commonly found to be significantly different from those of the main vent. Typically, they are more primitive but they can show a wide range in compositions—those of the main vent tend to be more restricted in their range. These observations suggest that in these systems the main vent is supplied by a steady-state magmatic system, whereas flank eruptions might be supplied by separate small magma batches that do not intercept the main magma chamber. In the case of the volcanic fields peripheral to the main cone (e.g., Mount Adams, Washington, U.S.A.; Payun Matru, Argentina; Mount Ararat, Turkey), the more mafic magmas that typically erupt from the satellite vents are probably prevented from ascending beneath the main cone by its subjacent magma storage system.

(a) (b) (c) (d)

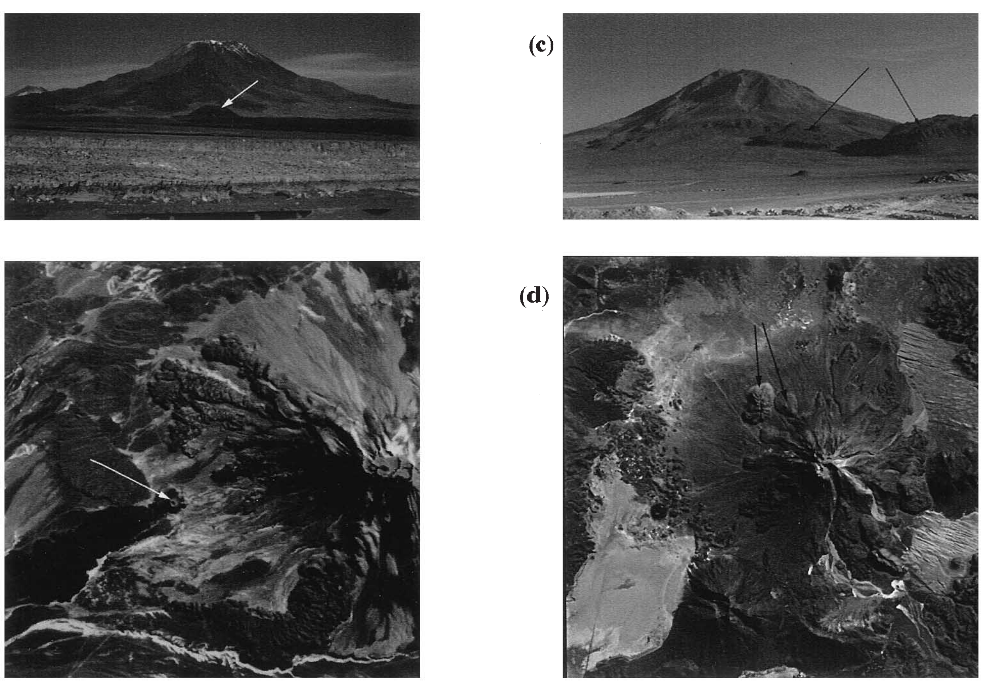


FIGURE 7 Examples of satellite centers and their relation to composite volcanoes: (a) San Pedro composite volcano (central Andes) and La Poruna cinder cone from west (arrowed), together with (b) thematic Mapper image of San Pedro and La Poruna (arrowed). Note the very large lava flow that erupted during the formation of La Poruna. North is to the top, and the image is 15 km × 15 km. (c) Ground view (from the north) of monogenetic dacite flank domes (arrowed) on Ollague volcano and (d) Landsat image of Ollague volcano, central Andes, with dacite flank domes of (c) arrowed.

III. Lifetimes of Composite Volcanoes

It is important at the outset to distinguish the active life of a volcano from its longevity as a topographic entity. A volcano can exist as a topographic entity for a considerable time after its active life—defined as the time span over which volcanic eruptions occur—is over. The time span over which it remains recognizable is largely a function of degradation rate (the "background erosion" of Section IIE), which is a function of climate. In arid regions such as the central Andes, 20-Ma-old volcanoes are well preserved and easily recognizable. In more temperate climates, this time span is considerably shorter. The discussion below focuses on the active lifetime of a composite volcano.

The general impression from the sparse and largely poorly constrained geochronological data on composite volcanoes is that these are long-lived. Observational evidence suggests that during this long lifetime periods of rapid aggradation punctuate the slow background of degradation. Unfortunately, these data do not address more detailed questions that are critical to really addressing the time scales over which volcanoes operate. For instance, does a composite volcano form in one continuous episode or multiple episodes with periods of repose? How long are the eruptive episodes and the repose periods? What are the rates of eruption that characterize periods of aggradation? To answer these questions, one must address issues such as eruption rates during eruptive episodes vs background eruptive rates, episodic cone growth rates vs average long-term cone growth rates, length of repose intervals, eruption recurrence time scales, time–volume–composition relationships, and even the meaning of "active" and "dormant."

The paucity of knowledge exists because addressing these questions requires detailed high-precision geochronology tied to detailed stratigraphy and few studies that have attempted this. The seminal work on the Mount Adams volcanic field in the USA distinguishes itself as a standard, which has recently been complemented by studies of Tatara–San Pedro in central Chile and Tongariro on the North Island of New Zealand. These detailed studies afford a general framework (see Table IV) within which many of the questions above can be addressed. Some of the main observations are

1. *Composite volcanoes grow in spurts.* The main cone of Mount Adams was built in three main episodes between ~520–490, 460–425, and 40–10 ka at eruption rates of 1.6–5 km^3/ka. At Tatara–San Pedro the two youngest

TABLE IV Volume–Time Relationships for Well-Studied Active Composite Volcanoes

	Volume (km^3)	*Inception of activity of the volcanic system (ka)*	*Age of cone-building events (ka)*	*Peak eruption rates (km^3/ka)*	*Background eruption rates (km^3/ka)*
Mount Adams	~200	940	520–490 460–425 40–10	1.6–5.0	0.05–1.0
Tatara–San Pedro	~55[a]	930	183-83, Pellado 90-19, Tatara–San Pedro	0.2–0.3	0.06[b]
Tongariro	~50	250–275	0-2.5, Ngauruhoe 65-110, Tongariro Trig 70-115, SW Oturere 120-190,Pukekaikiore 200-210, Tama 2 90-250, NE Oturere 215-275, Tama 1	0.88 0.27 ± 0.11 0.11 ± 0.05 0.09 ± 0.02 1.00 ± 0.02 0.37 ± 0.07[c] 0.03 ± 0.02	0.17–0.2

[a] Volume of lavas preserved. Original volume assuming 50–95% of material erupted between 930 and 200 ka has been removed by erosion due to glaciation is much higher.
[b] Based on preserved volume. If no erosion is assumed, rate would be 0.2–0.3, which is similar to peak rates.
[c] Applies to main period of cone growth, 110–130 ka.

composite cones of Pellado and Tatara–San Pedro formed between 188–83 and 90–19 ka, respectively. So these two composite cones formed during ~100 ka of eruptive activity at a minimum rate of ~0.2–0.3 km^3/ka. At Tongariro, seven large cones of 2–17 km^3 were built in periods ranging from 2.5–270 ka (or 2.5–70 ky) at rates of 0.09–1 km^3/ka. These data suggest that the length and rate of cone-building episodes are quite variable.

Less comprehensive data from other places confirm this variability. The 250-km^3 Kluchevskoy volcano (Kamchatka) has been built in the past 7000 years at an extremely high rate of 8–35 km^3/ka, whereas the similarly symmetric cone of Mount Fuji (Japan) appears to have been constructed in two phases from 80 to 10 ka and from 5 ka to the present. At Mount St. Helens the 79-km^3 cone has been built in the past 40 ka at a rate of 2 km^3/ka, whereas the 76-km^3 cone of Parinacota (Chile/Bolivia) is thought to have formed in the past 250 ka at peak rates of around 0.6 km^3/ka. Santa Maria and Fuego (Guatemala) are thought to have been constructed entirely in the past 100,000 years.

These reasonably short (generally <100 ka) cone-building episodes might be considered the typical timescales to reach "maturity"—an approach to the steady-state equilibrium after which overall size is maintained roughly constant by the opposing effects of construction and erosion discussed earlier and the physical controls outlined in Fig. 5. Increases in the volume of the overall edifice beyond this are typically a function of subsequent vent migration.

2. *Composite volcanoes stay active for periods of up to 500 ka.* Mount Adams in the Cascades dates back to ~520 ka and appears to be typical of other large composite cones in the Cascade arc of North America. Although the data are sparse, Mounts Baker, Rainier, Hood, Jefferson, Mazama, and Shasta are thought to have lasted >300 ka. Once a steady-state edifice has been constructed, there appears to be no clear relationship between volume and longevity.

The observations from the Cascades are ratified from other regions. Tongariro (New Zealand) had been active since ~250–275 ka. In the southern volcanic zone of the Andes, composite volcanoes are thought to have been active for periods of up to 300 ka. Volcan Parinacota, in the central Andes, was initiated ~250 ka, after the vent shifted slightly southward from its older twin cone Pomerape (Fig. 6e).

3. *Volcanic systems may remain active between widely spaced pulses of peak activity.* At Mount Adams, the main volcanic field remained continuously active from 940 to 10 ka with an average rate of eruption of 0.05–1 km^3/ka with breaks in activity up to 30 ka. At Tatara–San Pedro, the system was active from ~930 to 19 ka at an overall eruption rate of 0.09–0.12 km^3/yr (adjusted for glaciation associated volume reduction. At Tongariro, the background rate of activity since inception ~250–275 ka is 0.17–0.2 km^3/ka and the background rates of activity are considerably lower than the peak rates of activity discussed earlier (Table IV).

4. *Recurrence time intervals between eruptions at historically active composite volcanoes display a wide range.* Volcanoes such as Sakurajima (Kyushu) and Sangay (Ecuador) have been erupting *persistently*, on an almost daily basis for decades. More typically, composite volcanoes erupt on the *0.1 to 10-year timescale*, as exemplified by Fuego (Guatemala), Klyuchevskoy (Kamchatka), Lascar (Chile), Pavlof (Alaska), and Arenal (Costa Rica). Activity at these volcanoes consists of clusters of minor outbursts, commonly vulcanian, of varying frequency. The next characteristic timescale is the hundred to hundreds of years timescale that characterizes many of our best-known recently active volcanoes such as Mount Pinatubo (Luzon), Mount St. Helens (Cascades), and Mount Fuji (Honshu). Lastly, volcanoes such as Mounts Baker, Hood, Rainier, and Adams that have had few true eruptions in the Holocene may typify a class of composite volcanoes that operate on the timescale of *millennia*.

No doubt our understanding of composite volcano behavior and evolution is biased by the historical record (Table IV), which may be too truncated relative to the timescales of cyclic volcanic activity to be representative.

IV. Characteristics and Distribution of Volcanogenic Products at Composite Volcanoes

A. Introduction

Composite volcanoes are characterized by a greater diversity of volcanogenic products than any other volcanic landform (Fig. 8). The controls on the nature and distribution of erupted products are twofold—magmatic differentiation processes and syneruptive modulation by interaction with the surface environment. In the former category are included the melting and differentiation processes discussed earlier in this volume (e.g., "Composition of Magmas," "Origin of Magmas," "Volatiles in Magmas," and "Magma Chambers") that determine

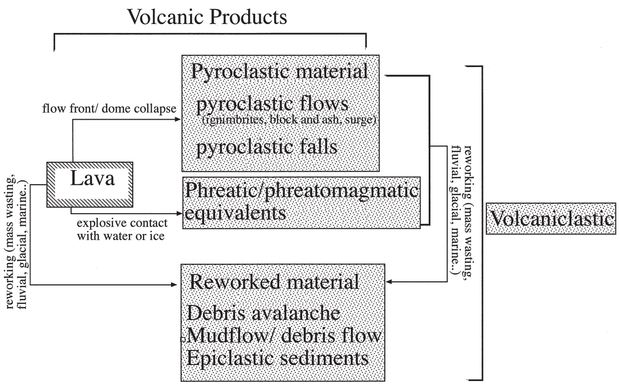


FIGURE 8 Broad classification of volcanogenic products (lavas vs volcaniclastic rock types, distinguished by shading of boxes) at composite volcanoes.

the physical properties—density and viscosity—of the magma. In this respect, the role of volatiles is critical ("Volatiles in Magmas"). High volatile concentrations increase the propensity for eruption as fragmented magma (pyroclastic) relative to lava, although the influences of effective magma viscosity and ascent rate will ultimately determine the occurrence and extent of explosivity. In the latter category, the surface morphology controls the distribution of lava flows. As gravity-driven phenomena, both pyroclastic and lava flows are typically channeled into valleys, producing a complex interplay of erosion and construction that leads to frequent topographic inversions on volcano flanks.

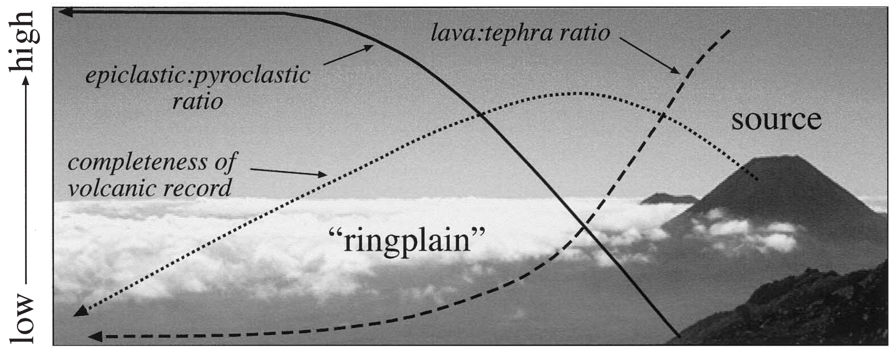
The morphology of the summit region can have a significant effect in directing volcanogenic flows, particularly if there are distinct crater breaches. Lava domes, a common feature of evolved composition volcanoes, may dominate vent region morphologies over long periods of time—occupying either craters (e.g., Soufrière and Montserrat) or sector-collapse scar amphitheaters (e.g., Mount St. Helens). The domes are commonly active, growing by slow addition of magma to the interior and periodically gravitational collapse—which may or may not be accompanied by explosions. Dome talus landslides or avalanches may on occasion supply more extensive block-and-ash flows. Lava flows in steep summit regions or on upper flanks may also sustain gravitational instability collapse of their flow fronts, producing hot block avalanches. Sustained dome growth can result in a significant fraction of the upper part of a composite cone being formed entirely of one or more domes (e.g., Bezymianny).

Finally, the effects of surface conditions (climate/weather), discussed in the previous section, will have a profound effect on the redistribution of volcanogenic material. In fact, perhaps the single most important element in defining volcano morphology is the balance between construction (a function of magmatic flux to the surface) and erosion/weathering (a function of local climate). The control on the distribution of volcanogenic products is largely a result of this competition and is illustrated schematically in Fig. 9a.

While Fig. 9a usefully summarizes the distribution of volcanogenic products around a composite cone, perhaps the most helpful way to discuss the materials themselves and how they vary in nature and distribution relative to vents and topography is by use of the facies concept traditionally used to describe sedimentary environments. The specific associations that characterize a composite cone can be defined largely on the basis of distance from the vent, which accounts for both the relative predominance of immediate volcanic products near the vent, versus recycled or mixed (with water) volcaniclastic material, and topographic effects with slope steepness typically decreasing away from vents (Fig. 9b). A summary is provided in Table V.

B. Main Vent Association

This association is defined as lithologies related to long-term vents at which volcanic products are erupted to the surface. Typically, for a simple cone this would be a central/summit vent, but in cases where compound cones have been developed, this may be an inaccurate description. The most important defining characteristic is that it is a long-term feature, and for a given volcano, it may change location several times during the history of activity. At the cone surface, the lithofacies found associated with the main vent are of two main types. On the one hand, if the vent takes the form of a crater, it is commonly surrounded by (1) vent-filling breccia comprising disaggregated wall rock material from the vent and (2) coarse primary tephra, commonly welded due to proximity to the vent. The distribution of this material is concentric to the vent, thinning rapidly away from the vent region, where it may simply pinch out (interfingering with proximal cone-building facies association) or grade into well-defined tephra layers or even lava flows of the upper cone. In cases where the vent crater is filled by a crater lake, additional deposits such as lacustrine sediment, intracrater lahars, and phreatic/phreatomagmatic deposits may be an important element of the main vent lithofacies. On the other hand, the vent at the cone surface can be occupied by a lava plug or dome that forms a steep-sided morphological feature

(a)


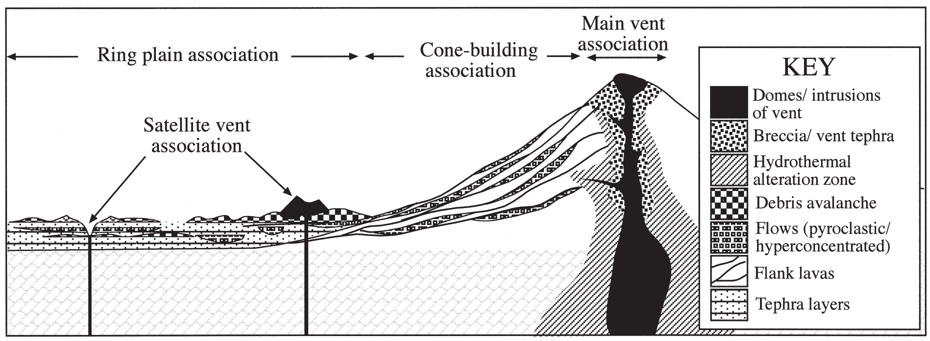
(b)


FIGURE 9 (a) Schematic illustration of the distribution of deposits relative to vent for a composite volcano. "Completeness of volcanic record" refers to the number of events recorded in a succession at a given location. The most complete record is preserved in tephra that are deposited over wider areas. However, on the slopes of the volcano, tephra are rapidly reworked and may be washed away. Thus a more complete, albeit condensed, section is typically found in the region immediately surrounding the volcano—the ring plain. (b) Schematic illustration of lithofacies associations for a typical composite cone, showing *types* of deposits-compare with *distribution* of deposits in (a).

occupying or completely overfilling and obscuring a preexisting crater depression. Main vent domes are vulnerable to collapse if they overfill the summit crater [e.g., Mount Unzen (Japan), Soufrière (Montserrat)]. They are also vulnerable to destruction during later eruptions when located over the volcano's main vent. The lava dome itself is commonly surrounded by carapace breccia and breccia aprons—which again may be continuous with upper cone slope facies. In either case, the subsurface vent association is defined by a concentration of brecciated material and by an intensity of hydrothermal alteration. The latter reflects both the intense supply of heat and volcanic gases that define the vent and the permeability of the vent lithologies to vapors and fluids over long periods of time—commonly extending beyond the period of eruptive activity for the cone. Shallow intrusions comprising various geometries, including plugs, dikes, and sills, reflect the focusing of magma into the vent conduit and its movement upward through the edifice. The main vent association at shallow subvent depths (referred to as "hypabyssal") may also host concentrations of metal ores (cf. "Mineral Deposits Associated with Volcanism"), which can be exposed by modest erosion in the deeper portions of the edifice and in the subedifice basement between the surface and the original magma chamber.

C. Cone-Building Association

The lithofacies of this association are those that build and define the edifice itself. They include a diverse array of volcanic products ranging from lava flows to pyroclastic flows to the products of flow transformations or reworking, involving mixing of water with volcaniclastic material. The relative distribution of lithofacies is largely dependent on (1) the style of activity—which we

TABLE V Lithofacies Associations for Typical Composite Volcanoes

Association	*Main lithofacies and architecture*	*Other features*
Main vent	Coarse tephra, commonly welded; breccia Poorly bedded, commonly disturbed/slumped Domes may fill vent at surface	Hydrothermal alteration common Shallow intrusives below vent
Cone building	Lava flows, pyroclastic flows, hyperconcentrated flows Radial from main vent—may grade into vent facies or not be connected Ribbon-like bodies to narrow wedges	Distribution of deposits strongly influenced by erosional topography
Ring plain	Fall tephra, debris fans from lower cone slopes, lahars, debris avalanche deposits Deposits tend to be more continuous and widely dispersed than on cone	Distribution of tephra strongly influenced by wind Preservation of deposits/completeness of record decreases if ring plain is restricted/eliminated by encroachment of surrounding topography
Satellite vent	Cinder cones, with lava flows and tuff ring/maar associations Dome/coulees Distribution may be controlled by basement structures—e.g., aligned along faults	Phreatomagmatic features more likely on lower flanks and ring plain

have seen is determined mainly by the composition of the magma supplied to the volcano—and (2) the balance between the supply of volcanogenic material (eruption frequency) and the rate of erosion. If erosion is able to produce a well-developed drainage pattern between eruptions, then many of the erupted products will be channelized and form ribbon-like bodies radial to the main vent(s). As a result, there may be common stratigraphic inversions—younger flows occupy valley floors while older flows form the canyon walls at higher elevations. Topographic inversions may also occur—if valleys are effectively filled by lava flows that are resistant to erosion, then subsequent incision may take place on former ridges.

If erosion is less effective and the edifice is a relatively smooth-surfaced cone, then, at least for low-viscosity erupted products (basaltic lavas, pyroclastic flows, and hyperconcentrated flows), more widely distributed wedge-shaped veneers will form, again focused at the vent(s) of origination. The distribution of fall tephra is less influenced by the cone topography, but rather will form a veneer with a thickness that is greatest near the vent and strongly influenced by wind directions during eruption.

Lava flows, and their associated autobreccias, originate principally from the main vent, where, in the case of basaltic flows, they are typically the result of quiet effusion from a summit crater (overspill of a lava lake) or rapid accumulation and congelation of fire fountain spatter (clastogenic flows). More silicic andesite and dacite flows form more prominent radial ridges by virtue of their greater viscosities and tend to be topography-formers rather than topography-fillers, as in the case of their more fluid basaltic counterparts. They may be short, stubby coulees, connected to main vent domes, or may be rootless if the steep uppermost portions of the cone cause detachment of the main mass of the flow from its source.

Pyroclastic flows are also dispersed radially from the main vent. Given a well-established topography—that is, deep radial valleys—they will tend to become valley fills; otherwise they may form veneers over quite large angular segments of the flanks. Such flows may originate as column collapse from vulcanian or plinian eruptions or as dome/plug collapses in the vent region. Mixing with stream water in channels or snow and ice on the cone surface may lead to flow transformations, so that the ratio of primary pyroclastic flow deposits to hyperconcentrated flows (lahars and debris flows) typically decreases away from the vent (Fig. 9a). Unmodified pyroclastic flow deposits, as with pyroclastic fall tephra, are also rapidly reworked and removed from the upper parts of the cone to be redeposited low on the cone or on the ring plain.

D. Ring Plain Association

The lithofacies of the ring plain are dominated by fall tephra and by the tephra that has been rapidly reworked from the cone. The ring plain is defined as the area immediately surrounding the volcano, but not including the constructional edifice itself. In cases where the cone is isolated from neighboring volcanoes or other mountainous terrain (e.g., Taranaki and Ruapehu, Fig. 2), the definition is quite obvious. However, in many volcanic terranes, individual edifices merge with their neighbors, including ancestral degraded volcanoes, and the surrounding topography is far from flat so that classic "ring plain" deposits as discussed here will rather be concentrated into drainages, reworked and removed from the system quite rapidly. Furthermore, for many oceanic composite cones such as those of island arcs, the immediate edifice is surrounded by ocean and a true ring plain does not exist—although quite complete records of activity can be recovered from the tephra mantling the nearby ocean floor.

As emphasized in Fig. 9, the ring plain is potentially where the most complete record of explosive activity is preserved. It is sufficiently close to the volcano that the products of volcanism are not too widely dispersed, yet it is beyond the edifice, which, through its topography, has the effect of promoting rapid removal of volcanic products and concentrating them into narrow drainages. Lithofacies include numerous tephra layers—pyroclastic fall material that may be correlative with flow-forming events on the cone but that has been dispersed over much larger areas. The thicknesses of individual tephra layers reflect both the flux and duration of an eruption and the dispersal control by wind. Lateral variations in the thicknesses of individual layers (isopachs) and in the grain sizes of tephra within the layers can be used to accurately reconstruct eruption histories (cf. "Plinian Eruptions" and "Tephra Fall Deposits").

Interbedded with fall tephra are the fluvial and laharic deposits, which may form the distal edges of wedgelike fans of debris from the lower cone slopes or may be concentrated along well-established drainage channels through the ring plain. The distal edges of the most extensive of flows (lava and pyroclastic) from the cone may also reach as far as the ring plain (e.g., Fig. 4b, parts iii and iv).

A typical, albeit occasional, product of composite volcano activity is the debris avalanche—the widely dispersed large-volume product of large-scale gravitational instability, or sector collapse (cf. "Debris Avalanches"). Debris avalanche deposits are a common ring plain lithofacies, distinguished by a hummocky topography, with the size of hummocks decreasing away from the edifice from large toreva blocks at the slope base to the more subtle topography of flow transition lahars and debris flows that drain the deposit far out on the ring plain (e.g., Fig. 6e). The hummocks consist of blocks mobilized from the cone slopes, which have suffered various degrees of disruption. At the base of the deposit, the lithologies are strongly disrupted and smeared, whereas in the interiors of many blocks disruption is minimal and a jigsaw texture is observed among the components reflecting intense fracturing but no turbulent mechanical mixing.

E. Satellite Vent Association

While by no means ubiquitous at composite cones, satellite vents are nevertheless common. As pointed out above, the magma compositions erupted at such vents are commonly distinct from those of the main vent that characterize the bulk of the edifice. The eruptions are also typically monogenetic—a single eruptive episode rather than prolonged and repeated eruptions of the main vent. It should come as no surprise then that there may be distinct lithofacies associations at satellite vents.

Scoria cones are defined by the steep piles of scoria that are accumulated at the angle of repose about the vent crater. A high flux of pyroclast accumulation around the vent can lead to the formation of spatter ramparts or even limited clastogenic lava flows. However, most lava flows associated with scoria cones (and some may be quite extensive; Fig. 7b) breach the cone and may raft large fragments of the cone walls along on the flow.

If a basaltic satellite vent interacts with near-surface water, then maars and tuff rings may form during phreatomagmatic eruptions. The water may occur as shallow groundwater reservoirs or in standing bodies of water such as lakes. In either case interception of shallow water by ascending magma is more likely to occur on the shallow slope lower reaches of the edifice, or on the ring plain, rather than on the cone itself. The common occurrence of accretionary lapilli in such phreatomagmatic deposits is also consistent with the important role for water.

Lava domes may also occur as monogenetic eruptions at satellite vents (e.g., Figs. 7c and 7d). These occurrences, by virtue of their location, have a higher preservation potential than those emplaced at the main vent. Silicic magma batches supplied to flank locations are typically small and degassed, resulting in slow and passive effusion of lava. The earliest phases of emplacement may be volatile-charged, resulting in emplacement within a pumice cone—an effect analogous to effusion of basalt lava from a cinder cone. As with basaltic equivalents, tuff cones of silicic tephra may also be found where silicic magma supplied to flank vents intercepts shallow near-surface water reservoirs.

V. Concluding Remarks and Future Research Directions

We are only beginning to understand the complex behavior of composite volcanoes through detailed studies of their histories (erupted products), their subsurface conduits (geophysically imaged), and their occasionally witnessed eruptive activity. In recent years, physical volcanology has made considerable advances enabling the characteristics of individual deposits to be interpreted in terms of eruption styles and magnitudes. At the same time, geochemical techniques examining both rocks and volatiles have enabled us to better understand magma generation and evolution from source to eruption. A major challenge of the next decade is to integrate geological, geochemical, and geophysical approaches in order to decipher the processes occurring in magma chambers, the timescales over which they occur, and the consequences for volcanic eruptions. Such an understanding not only will enable us to address important aspects of magmatism such as mass fluxes between the mantle, lithosphere, and atmosphere but will also have tremendous predictive value, aiding the mitigation of volcanic hazards.

See Also the Following Articles

Calderas • Debris Avalanches • Plate Tectonics and Volcanism • Pyroclast Transport and Deposition • Volatiles in Magmas • Volcanic Soils

Further Reading

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