CHAPTER 10

Magma Extrusion: Field Relations of Volcanic Rock Bodies

FUNDAMENTAL QUESTIONS CONSIDERED IN THIS CHAPTER

1. How is magma extruded onto the surface of the Earth?
2. What factors govern explosive eruptions versus quiet effusion of lava?
3. How can the fabric and field relations of volcanic rocks be used to decipher their manner of emplacement?

INTRODUCTION

Extrusive processes are more amenable to direct observation and study than processes of magma ascent and intrusion, which were discussed in Chapter 9. This is not to say, however, that geologists fully understand everything about extruding magmas and the rocks formed from them. Although some magma extrusions, such as low-viscosity, gas-poor basalt lavas, can be observed safely from within a few meters, one can only observe explosive eruptions from distances of many kilometers. Interpretation of the products of these exceedingly dangerous explosive eruptions can be challenging.

This chapter delves into processes of magma extrusion and the rock bodies and volcanic edifices so produced. The emphasis here is on the field relations of the entire volcanic rock body—the whole genetic entity. The rock fabrics that were considered in Chapter 7 and are observed in a single outcrop or on smaller scales than the whole body are not sharply distinct from larger scale field relations. Despite their treatment in separate chapters, *both* fabric and field relations of volcanic rocks record the character of formative processes; they cannot and should not be divorced from one another if the petrologist is to understand fully the origin of the rock body. For example, identical porphyritic aphanitic fabrics could have originated in a thin dike or in the margin of a small stock, in a shallow crustal environment, or in a lava flow, or as a clast in a volcanic debris flow. Only by means of the field relations can the true origin be ascertained because the cooling rate (thermal kinetic path) was similar in each environment and as a result the same fabric developed.

In this textbook, only a very brief summary of the rapidly growing field of volcanology as it relates to rock-forming processes and the fabric and field relations of rock bodies can be provided. More extensive general treatments are those by Williams and McBirney (1979), Cas and Wright (1987), Francis (1993), and the monumental *Encyclopedia of Volcanoes* edited by Sigurdsson et al. (2000). Since Fisher and Schmincke (1984), an explosion in works on pyroclastic topics has been edited by Sparks et al. (1997), Freundt and Rosi (1998), and Sparks and Gilbert (1999). A useful brief summary is Walker (1993).

10.1 OVERVIEW OF EXTRUSION: CONTROLS AND FACTORS

Two magma properties are of supreme importance in processes and products of extrusion: dissolved volatile concentration in the melt fraction and rheology of the magma. Rheology is expressed in Newtonian and non-Newtonian viscosity and depends not only on the concentration of dissolved volatiles in the melt, but also on major element composition of the melt (especially concentration of silica), magma *T,* crystallinity, and strain rate. In this chapter, apparent viscosity (Section 8.2.2) is used to denote magma rheology.

Volatile phenomena and rheology are involved in moving magmas to the surface from buried chambers and feeding conduits; they are also involved in the processes of extrusion from the vent and emplacement of the magma onto the surface.

10.1.1 Moving Magma to the Surface: What Allows Extrusion

Basically two requirements must be satisfied if magma is to extrude, either directly from its source in the deep crust or upper mantle where it was generated or from a staging chamber in the shallower crust. First, there must be an opening to the surface from the buried magma body. Second, magma must be able to move and be propelled through the opening. These are not necessarily independent of one another and, in fact, are usually related. Several mechanisms, all of which depend on development of overpressure in the subterranean magma body, allow venting of magma:

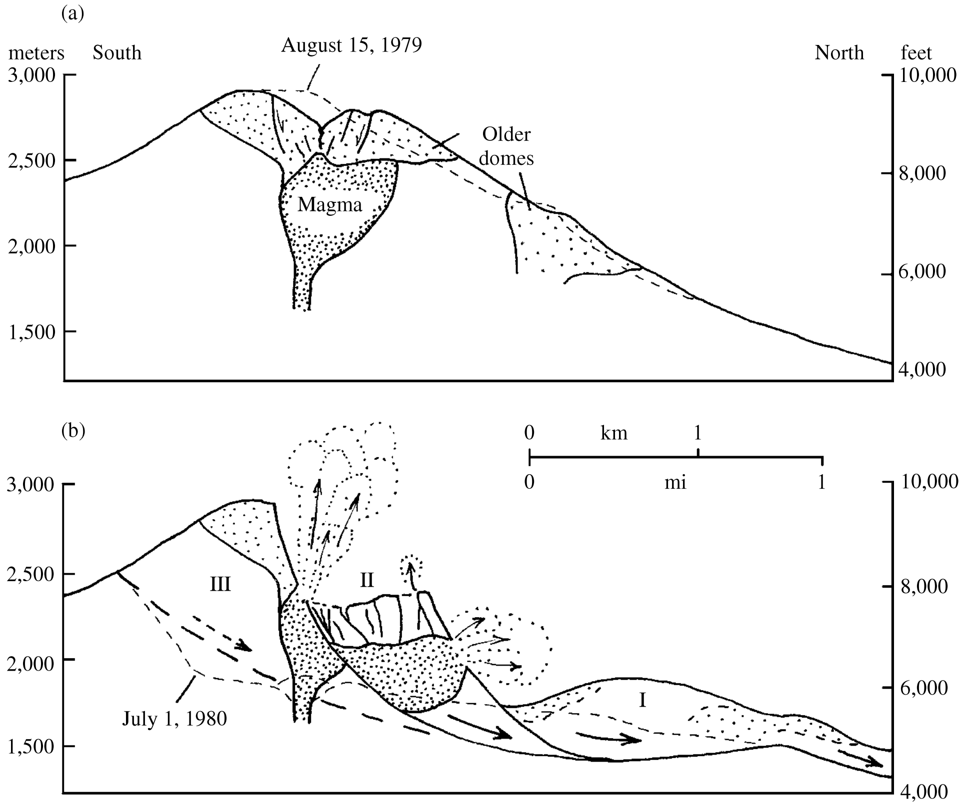
1. Independently of any exsolving and expanding volatiles, a buried mass of magma may have the capacity to rise and even fracture the overlying rocks by virtue of its buoyancy. Thus, in extensional tectonic regimes basaltic magma in upper mantle or deep crustal reservoirs can invade subvertical fractures of its own making, ascend to the surface, and extrude. This mechanism probably accounts for most extrusions of basaltic magma.
2. After buoyant ascent from its source through dikes or as diapirs, magma stored for a time in a shallow crustal chamber can subsequently erupt once its volatile fluid pressure or buoyant force exceeds the tensile strength of the roof rock overlying the chamber, causing the roof to rupture and then allowing the gas-charged magma to erupt. This can happen in the following ways:
   (a) As a stationary magma cools and crystallizes feldspars, pyroxenes, and so on, the residual melt becomes saturated in volatiles. The resulting volatile fluid pressure or the buoyancy of the bubbly magma can drive eruption.
   (b) The magma may rise to still shallower crustal levels, causing more volatiles to exsolve and expand in the decompressing system. Exsolution and bubble growth may be retarded in rapidly ascending, viscous magmas so that eventual pressure release is greater and explosive eruption more violent. Instead of the magma's rising to shallower levels to cause decompression, a stationary magma system may be unroofed. The catastrophic May 18, 1980, explosive eruption of Mount Saint Helens, Washington (Lipman and Mullineaux, 1981), furnishes an example. After 2 months of seismic activity, steam-blast explosions at the summit, and bulging of the northern summit and flank area at a rate of about 2 m/day, a magnitude 5+ earthquake triggered a massive landslide in the unstable bulge, unroofing the buried growing body of dacite magma (Figure 10.1). The sudden decompression of the overpressured magma system produced a violent explosion.
   (c) Mafic magma may be injected into the base of a chamber of cooler, less dense, more silicic magma (Figure 8.24; Sparks and Sigurdsson, 1977). Transfer of heat to the intruded resident silicic magma may create enough additional buoyancy to cause eruption. But probably more significantly, cooling and crystallization of the mafic magma cause volatile saturation and exsolution. Released volatiles float into the overlying silicic magma, oversaturating it and increasing the volatile pressure and magma buoyancy.
   (d) External water in the ground or in lakes or ocean may come into contact with buried magma, absorb heat, and expand explosively, blowing off the shallow cover over the magma body.

Changes in an extruding magma system can arrest further eruption. Deeper levels of evolved silicic crustal chambers tapped during continued extrusion are commonly poorer in volatiles and are more crystalline: both characteristics create greater apparent viscosity of the magma and less eruptibility. A decrease in ascent velocity, caused by whatever process, can allow more cooling, crystallization, and potential loss of exsolved volatiles through permeable wall rock.

Magma is extruded either from a central vent or from a fissure. In a **central eruption,** magma vents from a more or less subvertical cylindrical feeding conduit and builds a conical volcano (Figure 10.2). Other magmas, commonly of basaltic composition, extrude from a long crack in the crust and constitute a **fissure eruption** (Figure 10.3); the subterranean feeder is a subvertical dike. For thermal reasons (Section 8.4.1), eruptions that begin from a fissure commonly become localized into a central vent as extrusion continues.

10.1.2 Two Types of Extrusions: Explosive and Effusive

Depending on whether or not near-surface magmas blow apart into separate pieces, either of two types of extrusion, **explosive** or **effusive,** can result. These contrasts in the dynamics of extruding magma are linked to vesiculation phenomena that depend on volatile con-



10.1 Cross sections showing catastrophic unroofing and consequent explosion of the Mount Saint Helens magma-hydrothermal system on May 18, 1980. (a) Situation just before the earthquake-induced 2.3-km^3 rockslide. Intrusive dacitic magma had perceptibly bulged and destabilized the north side of the volcano (compare August 1979 topographic profile, dashed line). (b) Three successive unstable masses of rock slipped northward on May 18. Movement of I and II caused a lateral blast, pyroclastic surge, and plume (vertical eruption column) of ash and steam. Movement of III further beheaded the magma body. See Figures 10.20 and 10.21 for distribution of explosive deposits. The dashed line shows the July 1, 1980, topographic profile. (Redrawn from Moore and Albee, 1981.)

centrations in the magma and its rheology, and to whether magma comes into contact with external water.

In *exploding* magmas, juvenile particles of melt and crystals, together with possible accidental rock and single crystal fragments (xenoliths and xenocrysts, respectively), are blown from the volcanic vent, dispersed through a medium of air or water, and finally deposited on the surface of the Earth. All of these particles and fragments, collectively called **pyroclasts, tephra,** or **ejecta,** accumulate subaerially on dry ground and subaqueously on the floors of lakes and oceans.

Nonfragmented but commonly bubble-bearing magmas pour *effusively* from volcanic vents as coherent overflows of **lava.** The morphological characteristics and style of movement of lava reflect the ways magma composition and heat loss and gas loss impact magma rheology. Apparent viscosity dictates whether lava spreads as a thin sheet or stream with an **aspect ratio** (thickness/horizontal dimension) as small as 10^{-4} in the case of some basaltic lava flows (Figures 10.3 and 10.4) or as a bulbous dome with a ratio near 1 in the case of many silicic lavas (Figures 10.2 and 10.5). To some degree, the rate of discharge of lava from the vent also influences aspect ratio; rapid discharge can reduce effects of cooling on lava mobility and lengthen the flow. Apparent viscosity as well as other factors such as the vent diameter and volume of the magma supply influence the rate of discharge of lava from a vent; less viscous lava generally extrudes faster. Figure 10.2 illustrates some of the variety of extrusive forms that can occur in one local volcanic field.

Some lava finds its way into topographic depressions, such as stream canyons, where it moves as a confined flow. On surfaces lacking pre-existing channels, lava moves as an unconfined flow and, because of a greater surface area exposed to the atmosphere, tends to cool faster by radiant and convective heat transfer. Locally, rootless lava flows may be produced by coalescence of molten blobs of magma falling around the base of lava fountains.

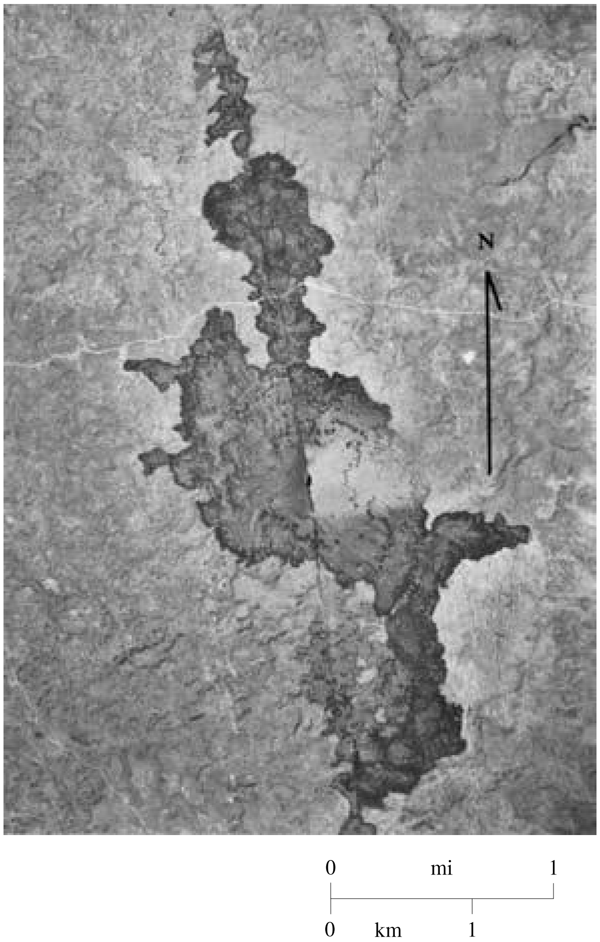
During the history of a particular long-lived volcano the mode of magma extrusion commonly fluctuates between explosive and effusive. Single episodes of volcanic activity after a period of repose that can last from months to hundreds of years commonly begin explosively and then, as the supply of more volatile-enriched

10.2 Mount Shasta, a **composite volcano** in the Cascade Mountains of northern California, and nearby lava extrusions. See also Figure 10.44. View is looking southeast up Whitney Creek. Extruded magmas with differing apparent viscosities created a range of lava-flow morphological characteristics. The most viscous lava produced Haystack dome in left foreground, which is 150 m high and 900 m in diameter, and snow-covered Shastina, a **parasitic cone** just to the right of the summit of Mount Shasta. Note the lobate tongues at the toe of the youthful flow to the right of Haystack and the well-developed **lava levées** along the flow margins that testify to viscoplastic flow behavior. Lava flows and volcanoclastic deposits built Mount Shasta, which rises almost 3 km above Haystack dome and about 16 km away. (Photograph from Shelton JS. Geology Illustrated, New York, W.H. Freeman, 1966. Used with permission of John S. Shelton, who holds the copyright.)

magma at the top of the preeruption chamber is exhausted, evolve into effusive activity. Large composite and shield volcanoes, such as Mount Saint Helens and Mauna Loa (Hawaii), respectively, are built on time scales of $<10^6$ y (Figure 10.6) by episodic eruption of magma at repose intervals of $1–10^2$ y. Such recurring activity reflects an interplay of many factors, including the rate of replenishment of the magma in the staging chamber from deeper sources; rate of cooling and crystallization of magma in the chamber, which depends largely on chamber size and shape; apparent viscosity of the magma and its composition, especially volatile content; and other factors.

In contrast to these long-lived, large, polygenetic volcanoes, some eruptions consist of only one episode, lasting perhaps months to years, after which activity ceases at that vent system. This **monogenetic** activity forms small simple volcanic edifices, such as a cinder cone and its associated lava flow (Figure 10.4) or a rhyolite dome nestled in its precursory pyroclastic crater (Figure 10.5).

Contrasts between explosive and effusive processes and products are strongly influenced by magma composition. Pyroclastic basaltic deposits are typically only of local, minor volume around source vents. Far more energetic and explosive activity, which reflects generally greater volatile contents and especially greater apparent viscosity in silicic magma, can create vast, thick pyroclastic deposits tens of kilometers distant from the vent and dispersal of finer tephra worldwide. Basaltic lavas a few tens of meters thick can spread tens, even hundreds, of kilometers from the vent, building enormous shield volcanoes (Figure 10.6) and larger flood-basalt plateaus. Some low-silica trachytic and phonolitic magma extrusions are comparable to basaltic extrusions with regard to mobility. Increasingly more silicic lava of greater apparent viscosity forms small thick flows and domes piled high over the vent (Figures 10.2 and 10.5). Intermediate-composition magma extrusions behave in some intermediate manner between rhyolitic and basaltic end members and yield more or less intermediate lava flow morphological characteristics.



10.3 Youthful Kings Bowl basaltic **fissure eruption** in the eastern Snake River Plain, Idaho. Note subparallel fissures in older underlying basaltic flows (paler gray in photograph) on each side of major feeder fissure. Mantle of ash (lightest gray) covers the east-central part of the youthful flow. Irregular white line crossing photograph from east to west is a road. (Photograph by U.S. Department of Agriculture.)

10.2 EFFUSIONS OF BASALTIC LAVA

Basalt is the most widespread magmatic rock on Earth. More than half of the world's volcanoes are of basalt or include basalt. It forms most of the oceanic crust that covers about three-fourths of the Earth and huge continental flood-basalt plateaus as well as smaller local fields. Basalt is found in virtually all tectonic settings.

Effusions of basaltic magma from fissure and central vents vary in size, rate of discharge, surface morphological features, and internal structure. The aggregate volume of one subaerial lava flow, commonly composed of many gushes of lava extruded during a single eruptive event lasting hours to perhaps a year or more, is generally 0.01–1 km^3, although volumes on the order of 10^2–10^3 km have apparently occurred in a single plateau flood. A relatively high extrusion rate for the 12.3-km^3 Laki, Iceland, fissure eruption during 28 days in 1783 was about 5000 m^3/s (~0.5 km^3/day). Higher rates of extrusion allow lava to flow farther, as much as 40 km at Laki, because heat transfer and consequent cooling and immobilization are less important factors. Thickness of a single flow is generally 10–30 m but can be as little as a few centimeters for a low-viscosity lava.

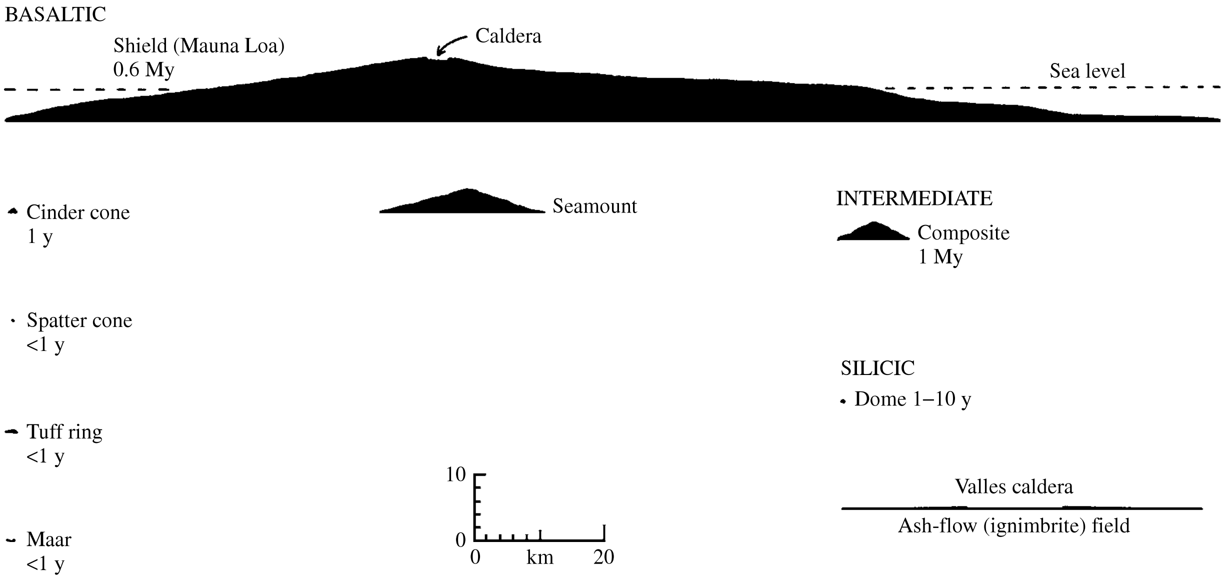
10.2.1 Types of Basaltic Lava Flows

Basically, four end-member types of basaltic flows can be recognized among a wide spectrum of forms. Three are typically subaerial, for which two have names from the native Hawaiian tongue: *aa* and *pahoehoe* (pronounced "ah'-ah" and "pa-ho'-e-ho'-e"). The fourth flow type is subaqueous pillow lava. The main subaerial aa and pahoehoe flows differ in surface morphological characteristics and in the dynamics of emplacement.

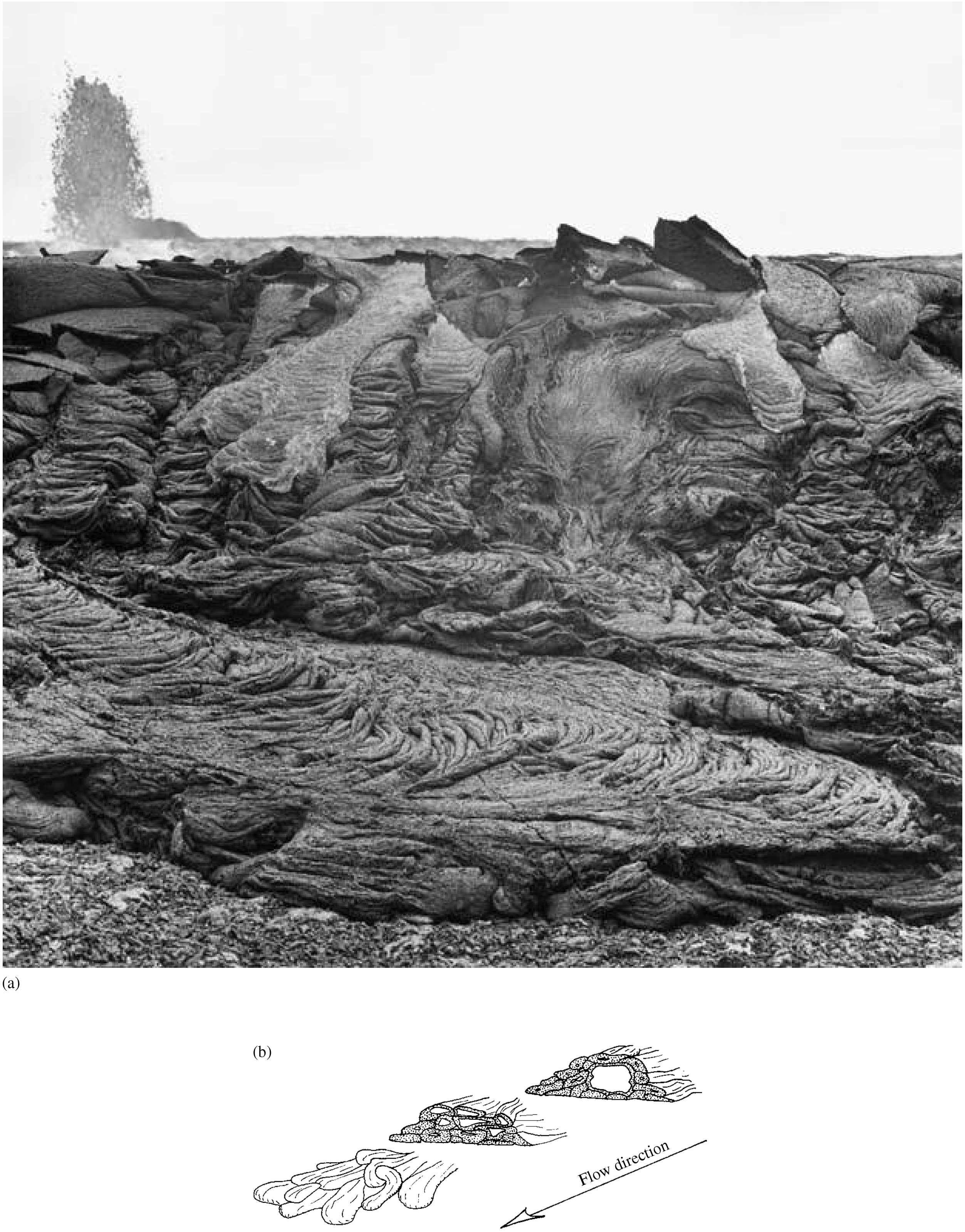
Pahoehoe Flows. Low-viscosity lava, especially basalt but also carbonatite, can produce **pahoehoe flows** that consist of thin, glassy sheets, tongues, and lobes, commonly overlapping one another. A quickly congealed vesicular glassy skin insulates the interior and blocks the escape of exsolved gas bubbles from the typically slowly moving lava (10–100 m/h). Eruptive *T* and gas content can just about be maintained in the lava, even during flow over several kilometers. Restrictions in downslope flow cause the glassy skin of the flow tongue to wrinkle into ropelike festoons (Figure 10.7a). Downslope, lava pressure builds up within the rubbery skin, inflating the sheet or tongue and causing breakouts of a new tongue. The hotter interiors beneath the skin of pahoehoe flows form an intricate network of **lava tube** distributaries so the lava advances in multiple "fingers." Major feeding tubes in upstream parts of the

10.4 SP Mountain, a basaltic cinder cone and associated lava flow in the **monogenetic lava field** 45 km north of Flagstaff, Arizona. Sharply defined, symmetric **cinder cone** with crater at top lies at head of lava flow. Age is about 0.07 Ma. Older cinder cones and a **tuff cone** (upper right) are also visible in distance. (Photograph courtesy of John S. Shelton.)

10.5 Mono Craters silicic **lava domes** in east central California. Note circular **tuff cone** almost 1 km in diameter of pyroclastic material surrounding low lava dome in right foreground. Southward (to left) are additional low lava domes and lava flows or coulees. Sierra Nevada underlain mostly by a Mesozoic batholith in background. (Photograph from Shelton JS. Geology Illustrated, New York, W.H. Freeman, 1966. Used with permission of John S. Shelton, who holds the copyright.)



10.6 Comparative sizes of volcanoes and their life spans in years (y) and million years (My). Although composite volcanoes are impressive edifices that can tower some 3 km above their base, they are smaller than seamounts (submerged oceanic volcanoes) and about two orders of magnitude smaller than the large Hawaiian **shield volcanoes.** Monogenetic basaltic tephra volcanoes and silicic domes are two to three orders of magnitude smaller than composite volcanoes.



10.7 Pahoehoe lava flows. (a) Corded glassy pahoehoe tongues 1 m or so in width formed during the 1974 eruption of Mauna Ulu, Hawaii. An active **lava fountain** playing in the left background over the vent feeds actively moving incandescent lava flow tongues that are somewhat lighter colored in this photograph. (U.S. Geological Survey photograph courtesy of Robin T. Halcomb.) (b) Schematic serial sections through a tube-fed pahoehoe flow showing major upstream lava tube and multiple smaller downstream distributary tubes. (Reproduced by permission from Rowland SK, Walker GPL. Pahoehoe and aa in Hawaii: Volumetric flow rate controls the lava structure. Bull. Volcan. 52:615–628, 1990; copyright © 1990 by Springer-Verlag.)

flow can be several meters in diameter and many kilometers long. If, as commonly happens, the lava drains downslope from beneath the crusted skin, the tube becomes an open cavity; these characterize exposed subvertical sections through the interiors of solidified pahoehoe flows (Figure 10.7b). On gentle slopes, elongate **pressure ridges** and more equidimensional, domelike tumuli are elevated segments of pahoehoe flows inflated by more lava input or stranded highs between drained segments. Crestal clefts or tension gashes are commonplace.

Though commonly developed on land, pahoehoe flows can also form subaqueously.

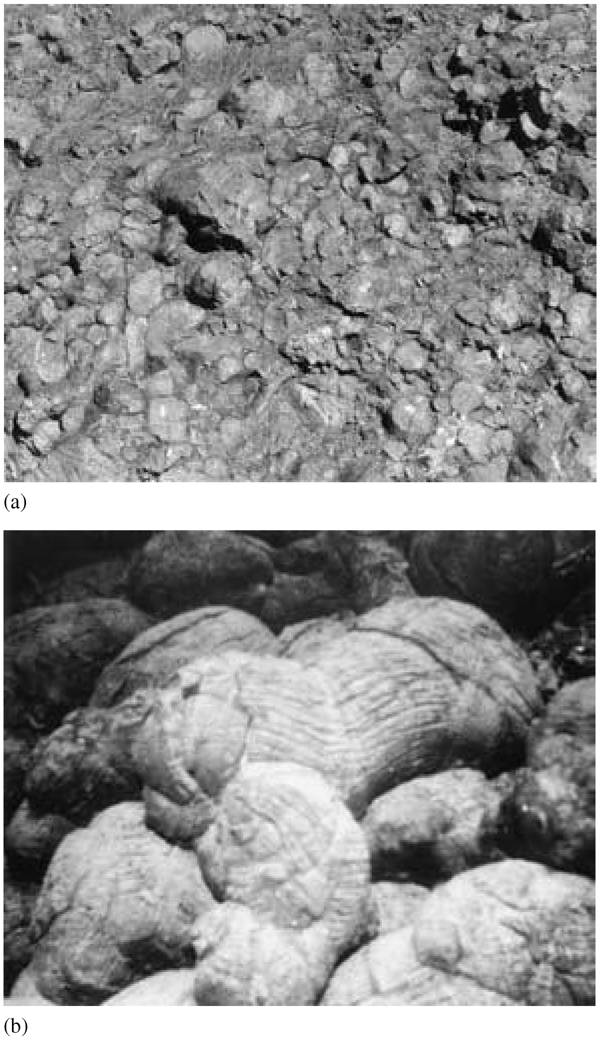
Aa and Block Flows. **Aa flows** are thicker than pahoehoe and have exceedingly rough, treacherous surfaces of irregular, clinkerlike scoriaceous fragments (Figure 10.8). A complementary but thinner rubble layer lies at the base. Flow advance is faster than pahoehoe so that the tensile strength of the cool rigid crust is overcome by the applied stress, causing autoclastic breakup. Heat loss is also higher from the discontinuously exposed incandescent core, causing increased downslope crystallinity in the groundmass (Polacci et al., 1999), which is another striking contrast from glassy pahoehoe. Increasing crystallinity produces more irregularly shaped vesicles than the smooth-walled subspherical vesicles of more glassy pahoehoe. Non-Newtonian rheology in more crystalline lava may be manifested in plug flow (Figure 8.13) and lava levées along channel margins (Figure 10.2).

Block flows resemble aa but have a mantle of more regularly shaped polyhedral chunks rather than jagged, highly vesicular, scoriaceous clinker. Block flows range from basaltic to highly silicic obsidian.

The contrasting morphological characteristics, as well as observed transitions from pahoehoe to aa, *never the reverse,* suggest that greater apparent viscosity promotes development of aa (Wentworth and Macdonald, 1953). Any downslope loss of heat and gas (causing increasing crystallization) allows near-vent pahoehoe to become aa farther downstream. Degassing and increasing nucleation and crystallization are promoted by stirring; consequently lava flows plunging over steep escarpments and lava produced by more vigorous fountaining may change from pahoehoe to aa. More viscous aa that is flowing faster with greater strain rate (Peterson and Tilling, 1980) results in fragmentation of the surface. Calm eruption and slow advance result in pahoehoe.

10.8 Toe of **aa lava flow** in the Black Rock Desert monogenetic basalt field, west central Utah.

Pillow Lavas. Pillow lavas are usually of low-viscosity basaltic magma formed where it comes into contact with water or water-saturated sediment, even in shallow intrusive situations (Walker, 1992). Their most widespread occurrence is on the seafloor where they have developed by extrusion along spreading ridges and on seamounts. Although having the appearance in most exposures, such as roadcuts (Figure 10.9a), of a pile of discrete, independent ellipsoids of pillow shape and size, submarine pillow lavas in some outcrops and especially those viewed on the seafloor in three dimensions consist of a tangled mass of elongate, grooved, interconnected flow lobes that are circular or elliptical in cross section (Figure 10.9b). Flattening of the still hot, not quite rigid pillows produces convex upward tops and cusped bottoms that fill openings between underlying pillows. Such forms are useful indicators for the field geologist of stratigraphic "right-side-up" direction in deposits that have been tectonically tilted. Pillows may resemble pahoehoe toes in cross section; they can be distinguished by the lack of open ellipsoidal internal tubes and the presence of fewer vesicles and radial contraction cracks. Pillows typically have a concentrically zoned fabric (Figure 7.3) reflecting decreasing inward rate of cooling. They may also be progressively encrusted with Mn-Fe oxides as the glassy envelope "weathers" subaqueously to palagonite (Section 7.1.1). Shattering of the hot glassy rinds of pillows in water creates vitroclasts, discussed later.



10.9 Basaltic **pillow lavas.** (a) Roadcut at Nicasio Dam in the Mesozoic Franciscan Complex north of San Francisco. (Photograph courtesy of Mary Hill.) (b) Submarine pillows at a water depth of about 2 km along the Puna Ridge east of the island of Hawaii. (Photograph courtesy of Hank Chezar and D. J. Fornari.)

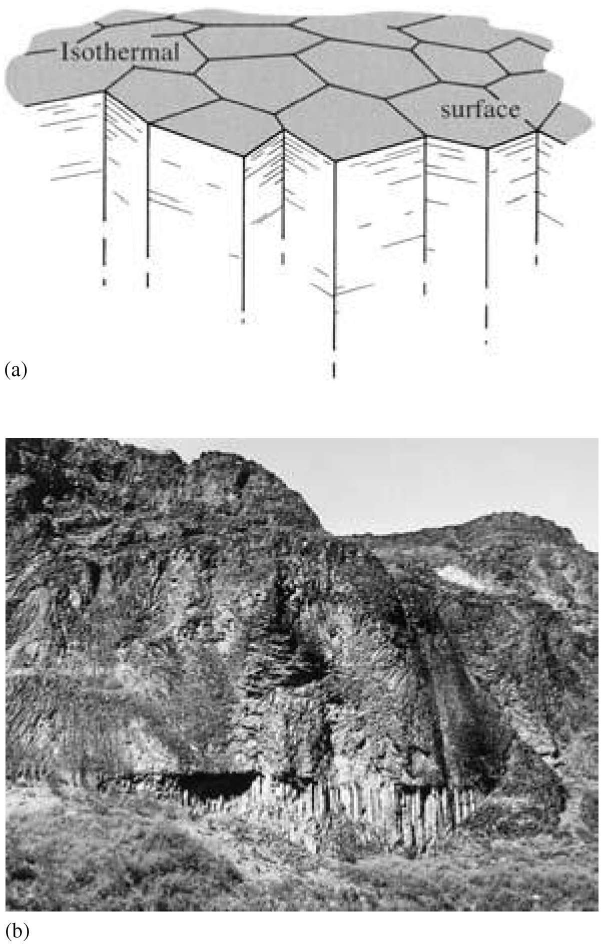
Moore (1975) observed submarine pillows forming off the 20°-sloping coast of Hawaii in tens of meters of water. Toothpastelike protrusions of fresh lava squeeze out of trapdoorlike openings in an upslope pillow; the newly protruded pillow tongue may then detach and roll away or, if it remains connected, may bud a new protrusion. Pillow formation on flatter slopes has not been observed.

Smooth-surfaced sheet lava flows and lava lakes along oceanic rifts are apparently formed in deep water by more rapid extrusion rates than those that create pillow lavas.

10.2.2 Columnar Joints

All rocks are fractured, mostly because of tectonic forces. However, most tabular bodies of magmatic rock, especially aa lava flows and thin sheet intrusions of basalt, have uniformly spaced **columnar joints** formed by shrinkage during cooling (Figure 10.10). Thermal contraction creates tensile stresses that exceed the brittle strength of the rigid magmatic body. Resulting extensional cracks nucleate at more or less equidistant points on the upper and lower margins of a uniformly cooling tabular body. At each of these nucleation points, a randomly oriented planar crack, or perhaps a three-prong crack, forms and propagates away from its point of origin along the essentially isothermal surface of the flow until it intersects an extensional crack propagating from a neighboring nucleation point. The network of cracks so formed consists of rather regularly sized polygons with four, five, six, or seven sides that resemble desiccation cracks in a thin layer of drying, shrinking mud. As cooling and contraction advance into the tabular body, the polygonal cracks likewise propagate inward, forming mostly hexagonal joint columns; these represent the "least-work" configuration of thermally induced tensile-stress fractures in the magma body.

Joint columns have more than aesthetic appeal. Because they develop perpendicular to isothermal cooling surfaces parallel to the margins of a cooling tabular body, the configuration of the body, though its defining margins are now possibly missing as a result of erosion,



10.10 Columnar joints. (a) Schematic view of joint columns oriented perpendicular to an isothermal surface in a cooling magma body. See also Figure 8.19c. (b) Multitiered columnar joints in a remnant of a 100-m-thick, ponded basalt lava flow now exposed just above the Colorado River in the western Grand Canyon, Arizona. Abruptly overlying a basal "colonnade" of thick columns is the "entablature" of thinner columns. Though seemingly haphazard, two radially oriented arrays can be discerned on the left in the entablature. Many lava flows find their way into drainage channels and are subsequently overtopped by water, which penetrates down into the fractured cooling lava flow. Margins of the radial arrays may delineate where the water entered, locally depressing isothermal surfaces. (Photograph courtesy of W.K. Hamblin.)

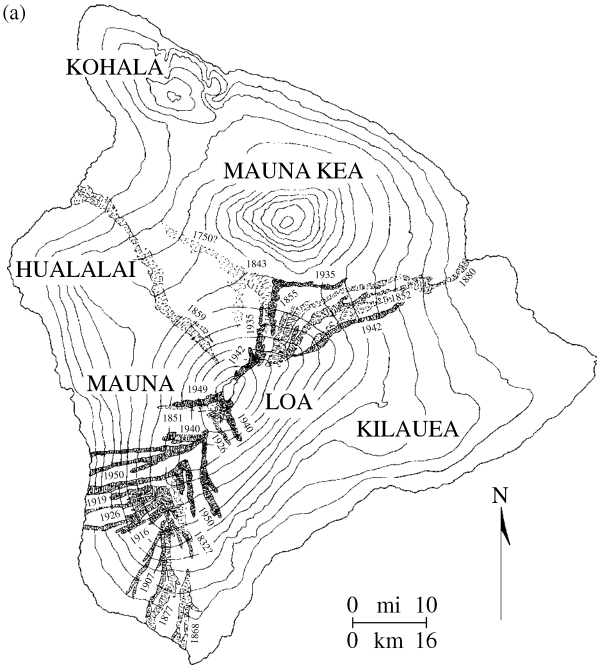
can be inferred (Figure 8.19c). The pattern of jointing is useful in delineating individually emplaced cooling units in a succession of volcanic deposits.

10.2.3 Subaerial Lava Accumulations

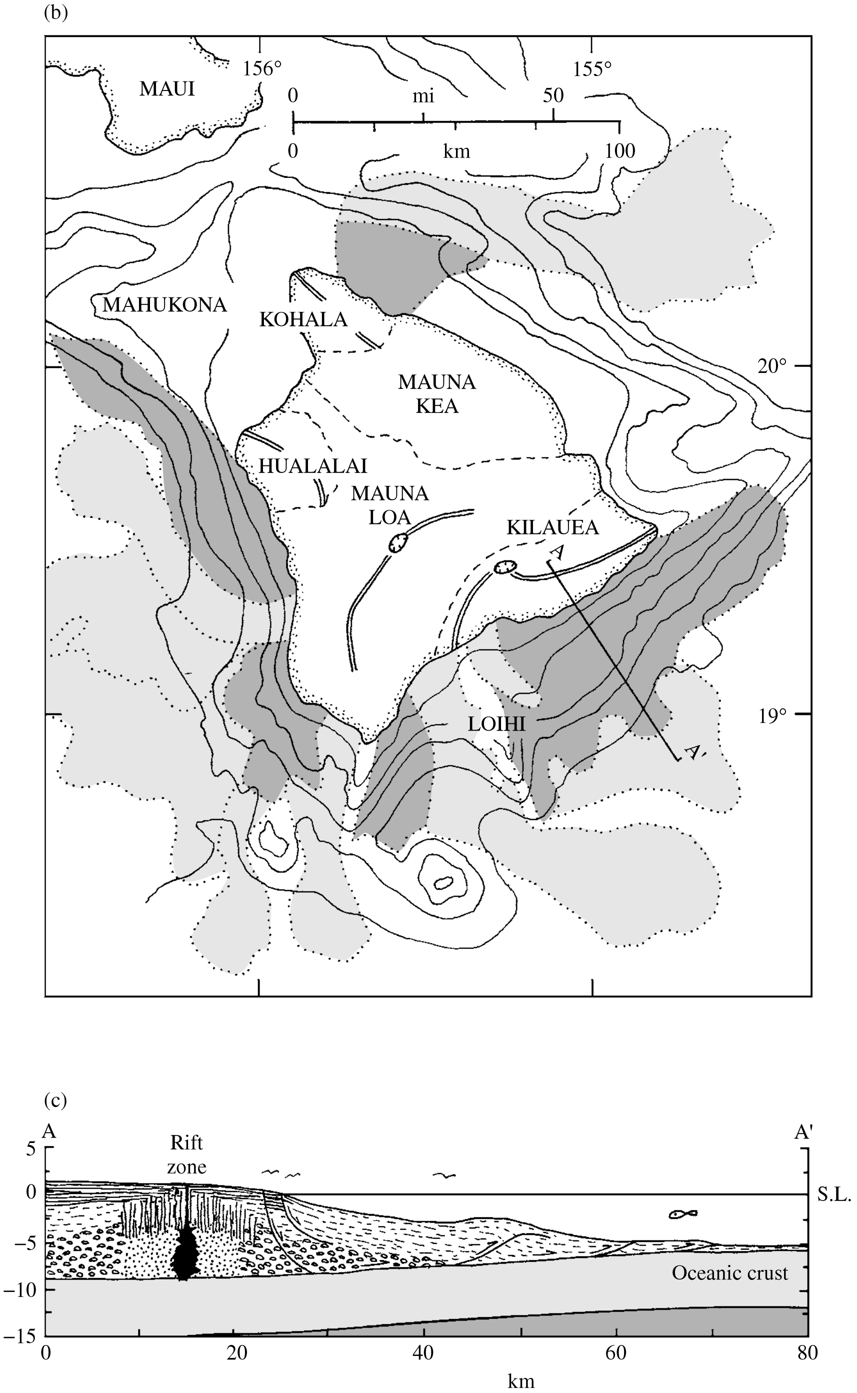
On land, the three most important types of basaltic lava-built accumulations are, in terms of increasing volume, small basalt fields, shield volcanoes, and plateau-forming floods.

Basalt fields form on flanks of larger composite and shield volcanoes, within large calderas, and in other continental areas. Vents may be localized along extensional faults. Generally small (<1 km^3), monogenetic extrusions produce simple tonguelike lava flows and associated cinder cones (Figures 10.3 and 10.4). Where rising basalt magma encounters water-saturated sediment or surface bodies of water (lakes), hydromagmatic explosions produce tuff rings and maars (discussed later). In some places, a few lava flows may be superposed but no thick pile is produced as in basalt plateaus. The activity of a field may last a few millions of years and create hundreds of volcanic edifices.

Shield volcanoes are built by innumerable extrusions of low-viscosity basaltic lava flows from a central



10.11 The island of Hawaii is built of seven coalescing **shield volcanoes.** See also Figure 9.8. Four of these—Hualalai, Mauna Loa, Kilauea, and Loihi—are active. Loihi seamount south of Kilauea has not yet emerged above sea level. Extinct Mahukona northwest of Hualalai has submerged isostatically (Moore and Clague, 1992). Each shield grew over about 0.6 My. (a) Aa and pahoehoe lava flows, such as the historic flows of Mauna Loa (patterned and labeled), build the subaerial parts of the shields. These flows are extruded from flank fissure (rift) systems and from a summit central vent complex. Deeply eroded older shield volcanoes on older islands reveal extensive feeder-dike swarms marking the fissure systems. Topographic contours are thousands of feet above sea level. (Redrawn from Stearns, 1966.) (b) Offshore bathymetry (depth contours in km) and major submarine slumps (dark shade), and debris avalanches (light shade). Double lines through subaerial shields are rift zones through which most of basaltic lava is extruded. AA′ line is line of cross section in (c). (c) Enlarged cross section along AA′ in (b) of slump south of east rift zone of Kilauea shield volcano showing subaerial lava flows (subhorizontal lines), hydroclastic debris (dashed lines), pillow lava (ellipses), sheeted feeder dikes (vertical lines), gabbro (dotted pattern), and magma (black). Dark shaded in lower right is mantle. (Redrawn from Moore et al., 1994.)



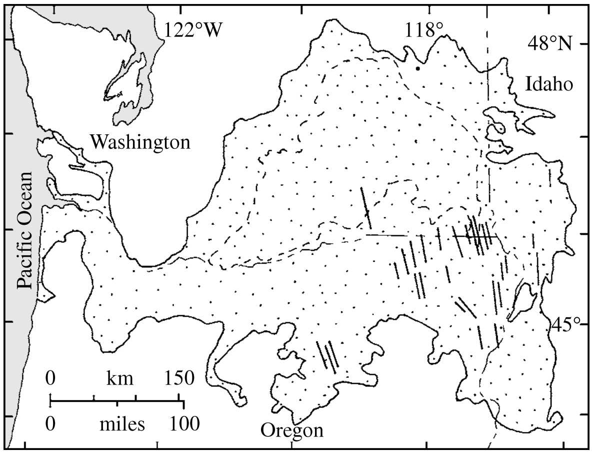
10.11 (*Continued*).

vent complex and locally one or more fissure systems radially disposed from it; the resulting edifice shape resembles a warrior's shield (Figures 9.8, 10.6, and 10.11). Small shields, as in Iceland and many continental areas, have diameters of a few kilometers. Shield volcanoes find their greatest development in the Hawaiian Islands. These gigantic edifices grew from the seafloor by submarine extrusions (discussed later) for tens to hundreds of thousands of years before eventually becoming subaerial. They are the largest volcanoes on Earth, have diameters of over 100 km, and rise as much as 10 km above their base on the seafloor. (Mount Everest is only 8.85 km above sea level!) So great is their weight that the oceanic lithosphere is flexed downward, resulting in greater ocean depths immediately around the isostatically subsiding island mass. The largest island, Hawaii (Figure 10.11), has grown over the past 0.6 My and is composed of seven coalesced shield volcanoes, the oldest of which is submerged to the northwest; the youngest, to the southeast, has not emerged above sea level. Gravitational instability of the flanks of the compound shield edifice causes recurrent landslides (Figure 10.11b, c). These are more or less coherent slumps of a flank sector whose slope is >3° as well as fast-moving chaotic debris avalanches on gentler slopes, some of which have gigantic volumes on the order of 5000 km^3—the largest avalanches known on Earth.

Plateau-forming, fissure-fed **flood basalts** are the most voluminous subaerial lava extrusions of any composition known on Earth. Many **continental plateaus** occur around the globe, including the Jurassic Karroo-Ferrar in southern Africa and Antarctica, Paraná-Etendeka in South America and southwestern Africa, and the late Cretaceous-early Paleocene Deccan in India (Figure 10.12). The Columbia River Plateau of the northwestern United States (Figure 10.13) consists of more than 100 flows emplaced in a remarkably brief period of the Miocene—almost entirely 17–15 Ma (Reidel and Hooper, 1989). Their aggregate volume is about 180,000 km^3, covering an area of 160,000 km^2 to a depth as much as 3 km. By comparison, the large Mauna Loa shield volcano on the island of Hawaii has one-sixth this volume.

Individual large lava flows, literally floods, whose stratigraphic correlation has been facilitated by "chemical fingerprinting" using particular element concentrations and ratios, range in volume from 90 km^3 to perhaps as much as 3000 km^3. Some flows traveled hundreds of kilometers down gentle slopes of 1 m in 10 km (1/10,000). On the basis of a model of lava transport in inflated pahoehoe flows, Self et al. (1997) propose that the gigantic compound Roza flow field (Figure 10.14) was emplaced over a period of 6–14 y and individual flows in 5–50 months. Lava was able to travel great distances because it did so under an insulating pahoehoe crust and the only place where the hottest mobile lava became exposed was at local breakouts feeding new pahoehoe tongues. Calculated effusion rates are about 4000 m^3/s, which is comparable to that of the 1783 Laki, Iceland, fissure eruption cited previously. Though such discharge rates seem extraordinary, the rate for the peak 2-My plateau-forming episode is about 0.08 km^3/y, comparable to discharge rates of Hawaiian shield volcanoes and oceanic rifts.

10.12 **Plateau flood basalts** exposed in the Western Ghat escarpment of the Deccan Plateau, India. Photograph provided courtesy of Peter R. Hooper. [Reproduced by permission from Hooper PR. Flood basalt provinces. In Encyclopedia of Volcanoes, Sigurdsson H, Houghton B, McNutt SR, Rymer H, Stix J, eds. 345–359:2000; copyright © 2000 by Academic Press (a division of Harcourt Brace and Company).]

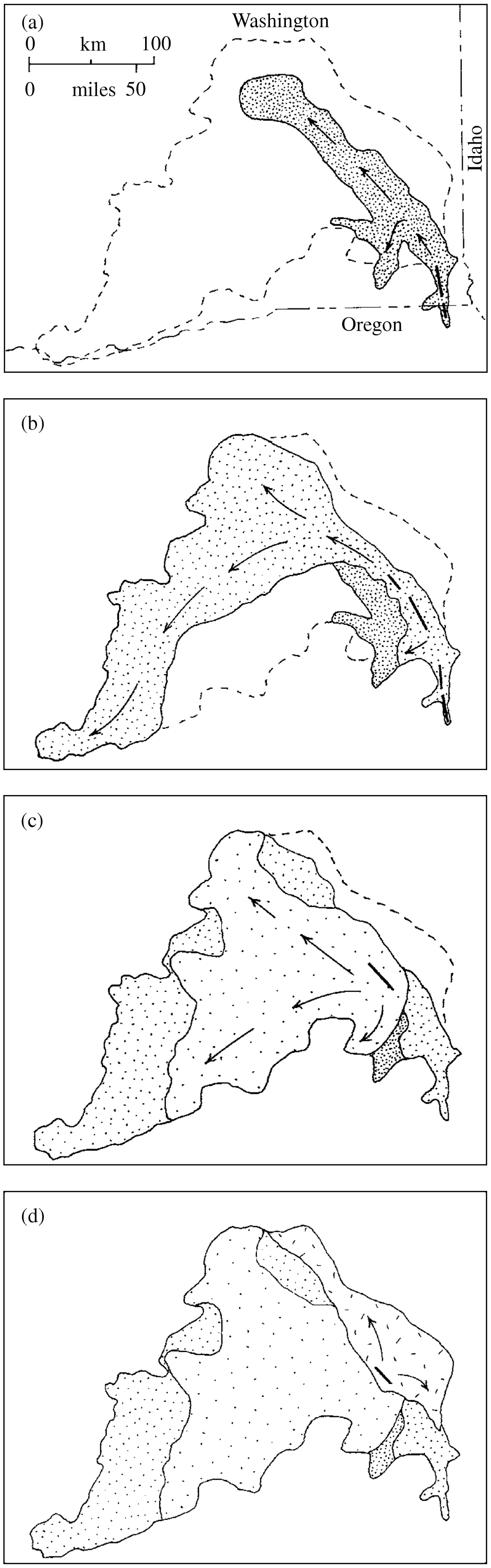


10.13 Columbia River **plateau flood basalts,** northwestern United States. Subparallel north-northwest-trending lines show the approximate location and orientation of known groups of feeder dikes that number in the thousands. Extent of Roza flows (Figure 10.14) indicated by dashed line. (Redrawn from Reidel and Hooper, 1989.)

In flood basalt plateaus, geologically rapid withdrawal of 10^2-10^3 km^3 of magma did not result in caldera collapse, as in silicic ash-flow eruptions of comparable volume (discussed later). Roofs over shallow crustal silicic chambers tend to be thinner than their spanning diameter and hence readily collapse. In contrast, roofs over magma reservoirs feeding basalt floods that lie in the upper mantle, possibly the lower crust, have sufficient thickness and strength to resist collapse and merely subside over time. Discharge of huge volumes of compositionally relatively uniform basalt magma from the mantle raises questions regarding magma generation and storage.

10.2.4 Submarine Basaltic Accumulations

Most submarine extrusions are of basaltic lava and account for most of global volcanism (Figure 1.1). Most submarine activity involves fissure eruptions at oceanic ridges, whereas more localized central eruptions have built in excess of one million basaltic volcanoes dotting the seafloor (Plate I). Most of these volcanoes are sub-



10.14 Schematic development of the Roza compound pahoehoe flow field in the Columbia River plateau (Figure 10.13). Arrows indicate direction of travel of basalt lava from fissure vent source (heavy line) beneath the insulating pahoehoe crust. (Redrawn from Self et al., 1997; Martin, 1989.)

merged **seamounts** >50–100 m high; others have grown from a submarine base (Figure 10.11c) into subaerially exposed volcanic islands such as Hawaii.

The confining pressure exerted by seawater and especially the relatively low volatile concentrations in basalt magmas preclude explosive eruptions in all but the shallowest water depths. Because hydrostatic pressure increases by about 1 bar (= 10^5 Pa) for every 10 m of water depth and because oceanic ridge basalt magmas typically have small water concentrations of <0.5 wt.%, exsolution is limited to water depths of <500 m (Figure 4.7). Ocean ridge basalt magmas may contain concentrations of CO$_2$ comparable to that of water but, because of its much lower solubility (Figure 4.10), may exsolve below the seafloor. Moreover, explosive fragmentation of magma due to bubble growth cannot take place until some critical bubble volume fraction develops, and this requires shallower depth for bubble expansion. After a volcano has grown from the deep seafloor to shallower depths of perhaps <200 m, explosive fragmental deposits can be formed.

Magmatism along the 65,000-km-long system of oceanic spreading ridges around the world (Frontispiece and Plate I) is the most prolific on Earth (Figure 1.1). In concert with seafloor spreading, the entire present-day oceanic crust has been produced in <200 My.

Extrusions along oceanic ridges at water depths of a few kilometers typically produce pillow lava and,

Special Interest Box 10.1 Speculative triggering of El Niño by submarine basalt extrusions

In the last two decades of the 1900s, a major anomaly in the weather pattern in some large continental areas surrounding the Pacific Ocean gained considerable attention. This so-called El Niño is caused by episodic perturbations at irregular recurrence intervals among sea surface temperatures, sea level anomalies, and atmospheric wind stress. Shaw and Moore (1988) have proposed a novel but controversial hypothesis that El Niños might be triggered by extrusion of large-volume submarine basalt flows along the East Pacific Rise off the northwest coast of South America. This is the fastest oceanic spreading ridge in the world and is the area where El Niños seem to be spawned. Shaw and Moore speculate that some of these submarine flows may have volumes and extrusion rates comparable to those of the flood basalt lavas that formed continental plateaus. Every 1 km^3 of submarine basalt that cools to ambient ocean temperatures within the time of an El Niño cycle, they calculate, accounts for about 1% of the anomaly.

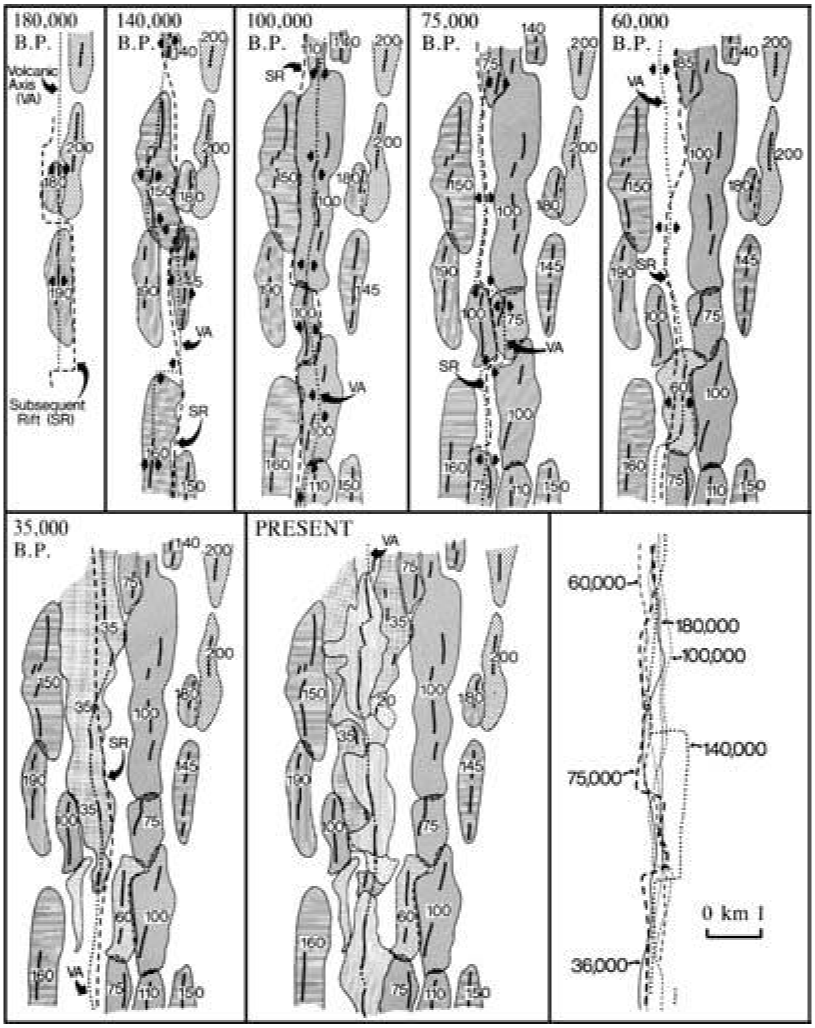
where extrusion rates are greater, sheet lava flows, locally pahoehoe. Along the Mid-Atlantic Ridge, a crestal rift valley, 20 to 30 km wide and 2 km deep, has extensional fault-controlled terraces flanking a narrow inner valley only a few kilometers wide and 100 to 400 m deep. Topographically controlled lava flows on the inner valley floor are elongate (Figure 10.15). Along the faster-spreading East Pacific Rise, lava lakes have ponded on low-relief flanks. One youthful flow discovered by side-looking sonar covers 220 km^2 and has a volume estimated at 15 km^3 (Shaw and Moore, 1988).

Counterparts of the huge continental flood-basalt plateaus were discovered during investigations of the ocean floors in the late decades of the twentieth century (Mahoney and Coffin, 1997). **Oceanic plateaus** are broad topographic highs rising 1 km or so above the surrounding seafloor and underlain by a crust as much as 40 km thick, five to six times typical oceanic crust. Little is known of these plateaus.

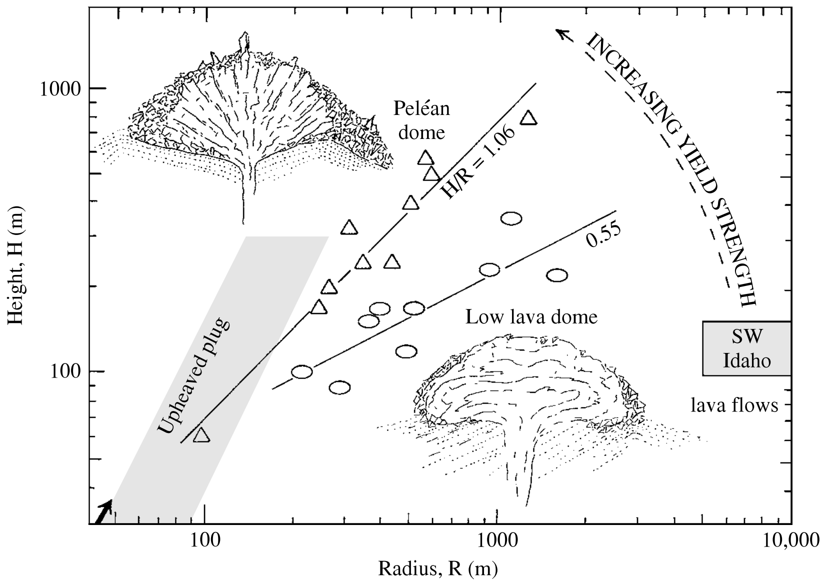
10.3 EFFUSIONS OF SILICIC LAVA

10.3.1 Morphological Characteristics and Growth

The most crystalline and, especially, the most silica-rich lavas are the least mobile because of their high apparent viscosities. Accordingly, silicic effusions have much larger aspect ratios (thickness/length) than typically sheet-like basaltic lava flows. A spectrum of shapes can



10.15 Evolution of the inner rift valley in the northern Mid-Atlantic Ridge at 36° 50′N latitude during the past 0.2 My. Shaded areas show volcanic edifices built along the active volcanic axis (VA) that are later cut by a subsequent rift (SR). Lower right diagram combines all of these rifts. Small numbers give ages of volcanic edifices in thousands of years. (From Ballard RD and van Andel TH, Morphology and tectonics of the inner rift valley at lat 36° 50′N on the Mid-Atlantic Ridge. Geol. Soc. Am. Bull. 88:507–530, 1977; Reproduced with permission of the publisher, The Geological Society of America, Boulder, Colorado USA. Copyright © 1977 Geological Society of America.)



10.16 Shapes of silicic effusions. Cross sections through typical low **lava dome** and **peléan dome,** both resting on precursory pyroclastic deposits, shown as dotted lines. (Redrawn from Williams, 1932.) Note aprons of mostly block-size talus. Measured dome height, *H*, versus dome radius, *R,* of selected low lava domes (ellipses) and peléan domes (triangles) around the world are plotted with a best-fit line representing the indicated aspect ratio, *H/R*. (Redrawn from Blake, 1990.) The aspect ratio of peléan domes is similar to the tangent of angles of repose of the talus pile of unconsolidated fragments that typically surround them. Note that these talus accumulations are significantly less around low lava domes. Shaded rectangle on right represents large-volume (as much as 200 km^3), high-*T* rhyolite lava flows in southwestern Idaho. (From Bonnichsen and Kauffman, 1987.) Shaded band on left represents possible aspect ratios for high-yield-strength upheaved plugs. As silicic lava emerges from a vent (arrow, lower left), with increasing height, *H*, it may grow into a lava flow, low lava dome, peléan dome, or upheaved plug depending on increasing yield strength.

be recognized (Figure 10.16). The most mobile with the smallest aspect ratio is the lava flow (Figure 10.17). The more viscous mushroom-shaped **lava dome** (Figures 10.2, 10.5, 10.18) has a larger aspect ratio. The still larger-aspect-ratio **peléan dome** resembles an artichoke and grows by expansion from within, pushing slabs of rigid lava out of and away from the vent in fan fashion or along sled-runner-shaped ramps. Although most silicic effusions have blocky fractured tops and surrounding aprons of blocky talus (Figure 7.33), these are more pronounced in peléan domes. Slender **spines** may be elevated above the remainder of the peléan dome before being shattered by steam explosions or thermal stresses or collapsing under their own weight. Least mobile, rigid lava is extruded as an **upheaved plug,** which is an elongate cylindrical mass roughly the diameter of the vent conduit so that its aspect ratio is >1; a plug resembles a cork in a narrow-necked wine bottle.

Many domes grow in craters (Figure 10.5) produced by preceding explosive eruption of more volatile-rich magma from the top of the supply chamber. Explosive activity may continue during the slow continuous or episodic effusion of lava, which advances from the vent at velocities of meters per hour to meters per day. The duration of lava effusion can be many decades in the case of large domes, such as the 1-km^3 growth of Santiaguito, Guatemala, since 1922 (Rose, 1987). In some effusions it is clear that new lava is slowly added in an **endogenous** manner (Figure 10.19), inflating the interior beneath a more rigid carapace or cover of closely packed blocks of lava. Other effusions are **exogenous** and grow by addition of lava onto the surface.

Dome growth may be modeled in two ways, as a brittle shell enclosing pressurized magma or as viscoplastic lava. In the viscoplastic model (Blake, 1990; see also Section 8.2.2), the chilled carapace of a low lava dome has yield strengths of 10^5–10^6 Pa, whereas a steeper-sided peléan dome, whose form is dictated as much by its talus apron as by the rheology of the lava core, has a yield strength $>10^6$–10^7 Pa.

Autoclastic fragments, generally of block size, mantle flows and domes and form talus aprons around them (Figure 7.33). Fragments are created by movement of the rigid carapace, thermal stresses, or internal gas pressure, or by collapse under their own weight. As the effusion advances laterally, the clastic apron may be pushed aside or overridden and possibly engulfed within the flow. Larger-volume crumbling of sectors of the steep dome and plug margins on summits or on slopes of larger volcanoes creates avalanches of considerable runout, as in the Chaos Jumbles in Figure 10.18. More explosive shattering generates devastating pyro-

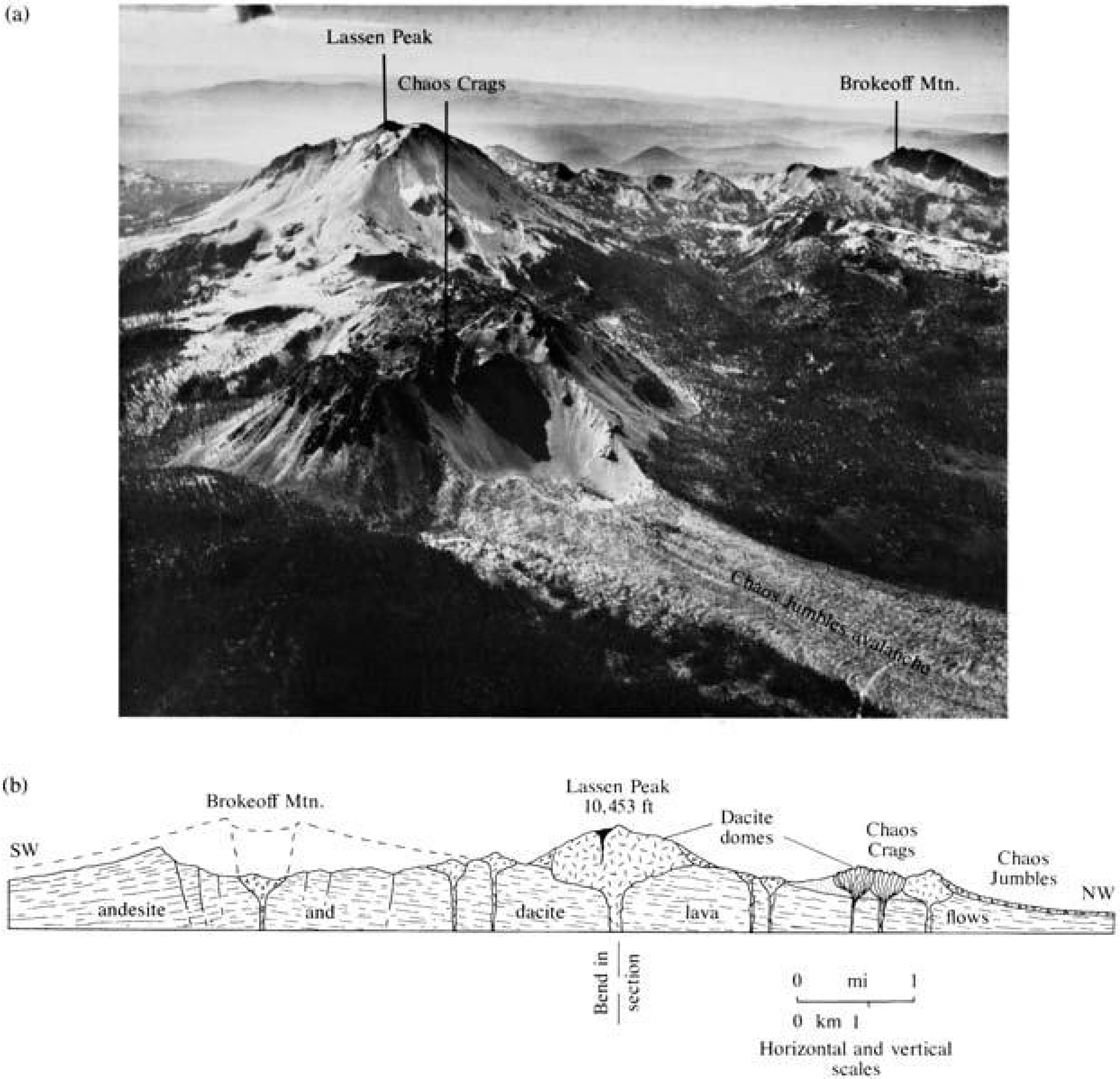
10.17 Vertical aerial photograph of Big Glass Mountain rhyolite obsidian flow east of Mount Shasta, California. Main tongue toward upper left is nearly 3 km long, has a thickness of about 75 m, and flowed down an approximate 9° slope from the vent near photo center. Arcuate **pressure ridges** in flow surface transverse to flow direction that are spaced about 60 m apart with amplitudes averaging 8 m possibly originated through compressional drag forces exerted in the more rigid flow surface by the underlying hotter, more mobile flowing interior. Note east-northeast trending line of extrusive vents beginning at lower left corner and ending at upper right that were probably controlled by a fissure. (Photograph by U.S. Forest Service.)

clastic avalanches that cascade with hurricane speed downslope.

10.3.2 Internal Fabric

Planar and linear fabric elements are widespread in silicic effusions and constitute markers of the pattern of internal flow in the body during emplacement. More or less planar flow layering (Figures 7.4 and 7.41) expressed by textural variations (crystal size, crystallinity, vesicularity) in a wide range of lava viscosities reflects laminar flow. Contorted and folded flow layers reflect local changes in flow velocity or drag, particularly near flow margins. Grooves and striations, which resemble slickenlines on fault surfaces, and associated transverse open tension gashes also develop on shear surfaces in viscous lava.

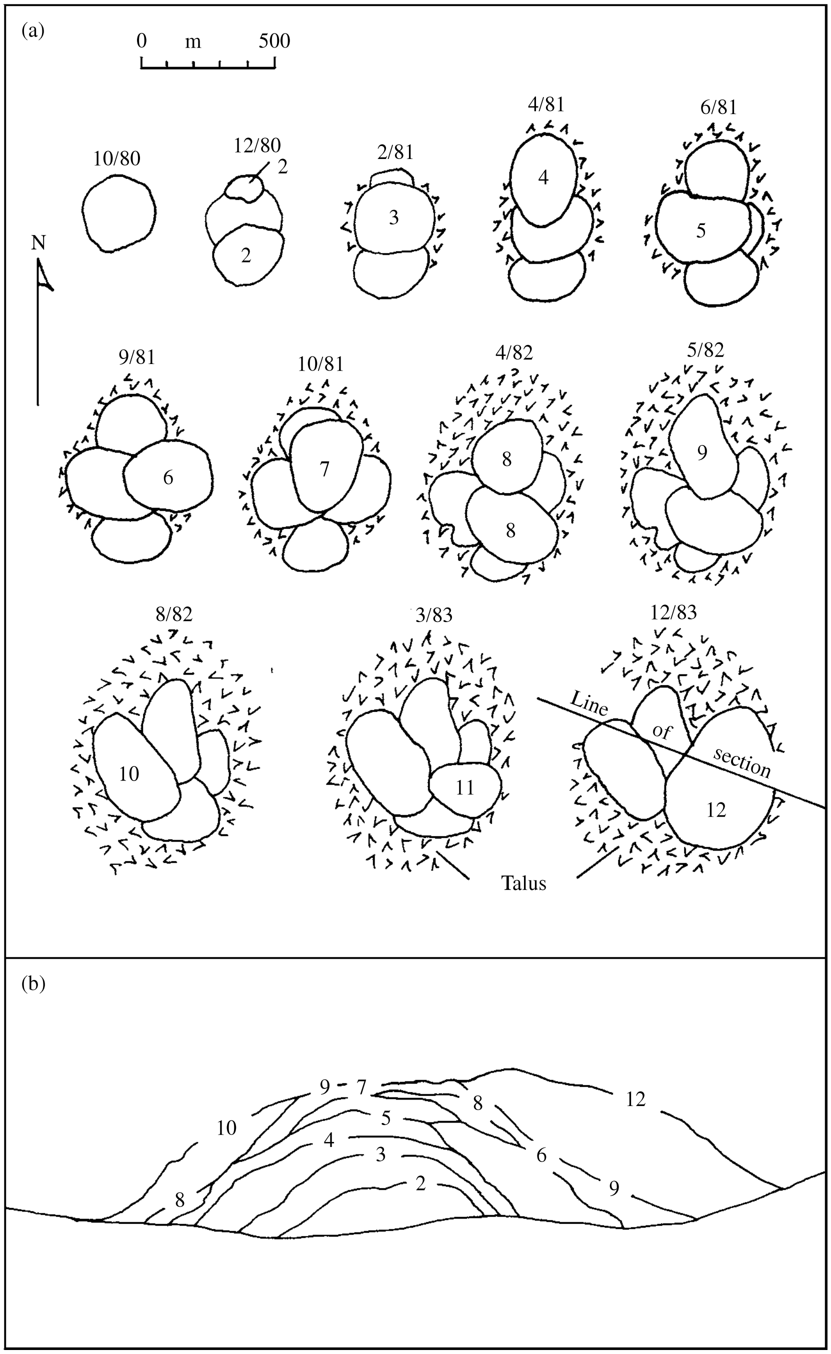
Rhyolite flows and domes have a more or less consistent vertical internal zonation of fabric developed by variable vesiculation, fragmentation, and devitrification superposed on rheologic flow. This zonation serves as a useful field guide in the interpretation of poorly exposed old flows. Thicknesses of zones vary considerably, and a particular zone may not be everywhere present. Tops and bottoms of the extrusion are of autobreccia that is variably vesiculated, as are local internal seams representing brecciated flow margin material engulfed during flow or zones of rigid magma that were fragmented. Interiors are flow-layered. Young effusions



10.18 Aerial photo (a) and cross section (b) of a part of the Lassen volcanic area, northern California. Brokeoff Mountain is an erosional remnant of a large composite volcano (dashed lines). Collapse of a sector of Chaos Crags dacite peléan dome, possibly in the 19th century, produced the Chaos Jumbles avalanche. A prominant talus apron extends around the dome complex on each side of the sector that collapsed. A small eruption of dacite lava, black in (b), from the summit of Mount Lassen occurred in 1915 and spawned a major debris flow. (Cross section redrawn from Williams, 1932; photograph courtesy of John S. Shelton.)

less than a few million years old generally have obsidian interiors, but with increasing age, glass gradually hydrates and devitrifies, developing perlitic and crystalline textures, respectively. Early devitrification produces spherulites strung along flow layers, which, in cross sections, resemble beads on a string. In the more slowly cooled interiors of some thick flows, devitrification begins during effusion, whereas quenched flow margins are glass. Ultimately, all glass devitrifies and becomes a felsitic mass of aphanitic feldspar and quartz. Interacting crystallization and release of volatiles creates lithophysal zones.

During flow of silicic to intermediate composition lavas, platy feldspar microlites in the groundmass become aligned to form trachytic fabric; volatile bubbles may be drawn out and similarly oriented. The foliation thus produced creates a pervasive parting that, particularly after accentuation by weathering, is manifested in platy fragments a few centimeters in thickness forming aprons of talus around flow margins.



10.19 Mainly endogenous growth of the composite dacite **lava dome,** Mount Saint Helens, Washington. (Redrawn from Swanson et al., 1987.) The dome grew as new magma inflated the more rigid carapace. It is sited in a crater formed by the catastrophic explosions of May 18, 1980 (Figure 10.1) and was modified somewhat in succeeding months when numerous pyroclastic flows were erupted. Until August 1982 (8/82) the dome is portrayed in schematic map views (a) at end of each growth episode. During 1983 growth was continuous and only two arbitrary stages are represented in March 1983 (3/83) and December 1983 (12/83). (b) Schematic cross section at larger scale viewed southward shows topographic profiles of the composite dome at times when individual domes formed, from (a). Talus omitted.

❊10.4 EXPLOSIVE ERUPTIONS

The complex sequence of interrelated processes whereby magma near the surface of the Earth explodes and becomes a clastic deposit is not completely understood. For purposes of discussion, the continuum of interrelated processes can be considered in terms of the initiating explosive production of pyroclasts and their subsequent transport and deposition. Explosive discharge produces a volcanic plume from which pyroclasts are eventually deposited.

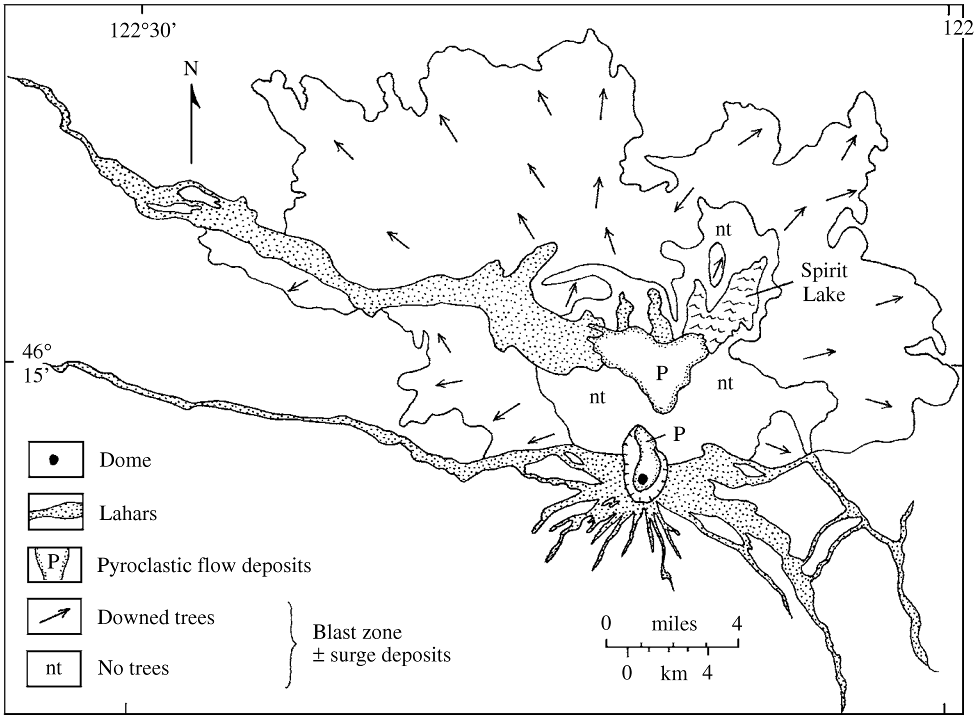
Despite accelerated research in the last two decades of the 20th century due to increasing application of fluid dynamic modeling and detailed observations of many eruptions, more new questions seem to have been created than old ones answered.

10.4.1 Explosive Mechanisms: Production of Pyroclasts

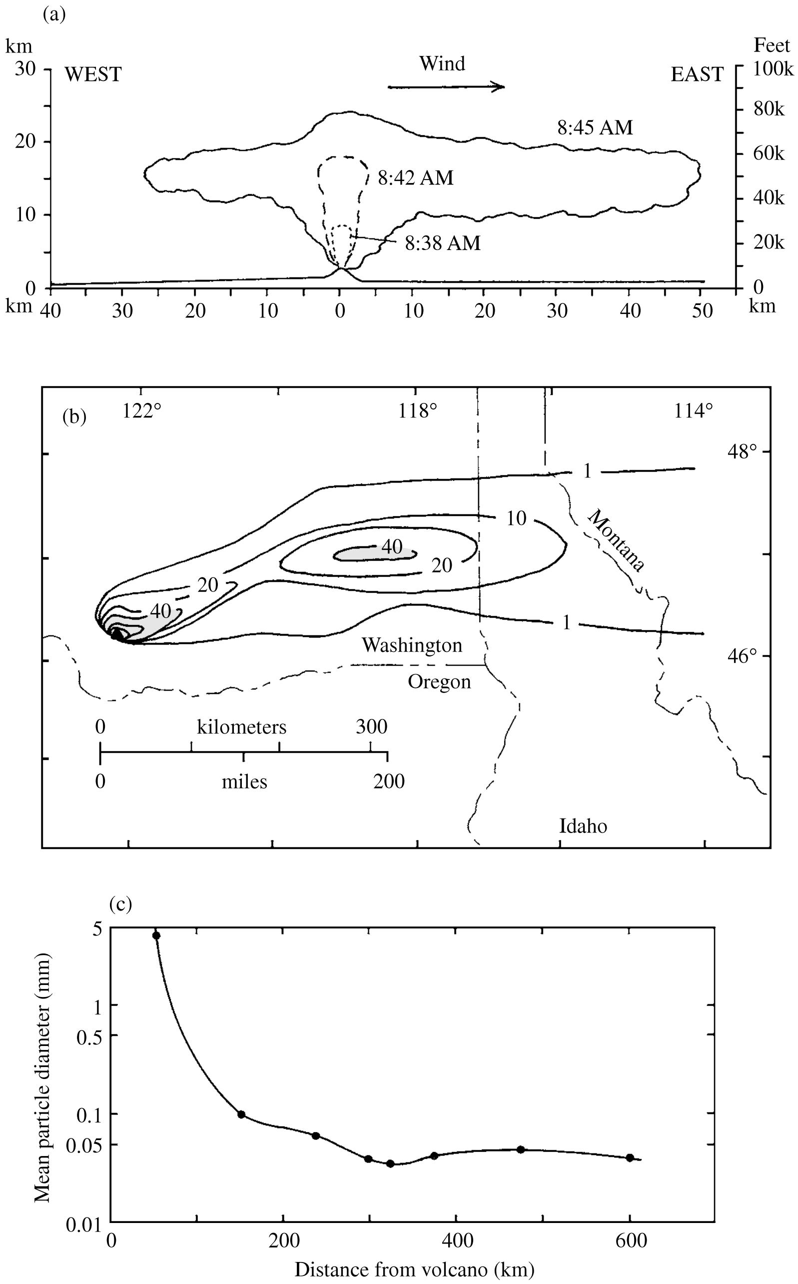
Explosive production of pyroclasts (tephra or ejecta) involves the expansion of volatiles—whether contained in magma or external water in the environment or in combinations of these (Section 7.7).

Exsolution and Expansion of Dissolved Volatiles. Fragmentation of magma caused by the volatiles dissolved within the melt follows a sequence of events beginning with exsolution of volatiles in an oversaturated melt. After nucleation, bubbles grow by continued exsolution and possible volumetric expansion, culminating in explosive rupture of the bubble walls, converting thermal energy into kinetic energy. The mechanism through which bubbles rupture their walls and explode is poorly understood (Figure 4.13; see also Section 6.7.2); it is obviously related to melt viscosity and/or water content because these are greatest in the most explosive silicic magmas. Excessive internal pressure in volatile bubbles may not be the only factor. The rate at which the bubbly melt expands upward in the volcanic conduit may play an important role; localized faster expansion strains the bubble walls faster so that they rupture as brittle glass rather than slowly stretching as a viscous melt.

There have been countless witnessed explosive eruptions. A well-documented one is that of Mount Saint Helens on May 18, 1980 (Figures 10.1, 10.20, 10.21). Though the pyroclastic material produced was small



10.20 The variety of mainly volcaniclastic products from the explosive eruption of Mount Saint Helens, Washington, May 18, 1980 (Figure 10.1). Only deposits proximal to the volcano are shown. More distal ash-fall deposits are shown in Figure 10.21. In the 600-km^2 lateral blast zone where local minor surge deposits occur, trees as much as 2 m in diameter were blown down (arrows indicate tree orientation) and were completely blown away closer to the volcano in the "no tree" (nt) area. Some three dozen steam-blast explosion pits in the pyroclastic flow (P) are also not shown; they were produced as the hot deposit vaporized overridden bodies of water. Note that lahars were mostly confined to existing stream channels; on the upper steep slopes of the volcano on the east, south, and west, loose rock and soil were scoured away to feed lahars farther downslope. The lava dome emerged and grew months after the May 18 eruption (Figure 10.19) within the elliptical crater shown as line with tick marks. (Redrawn from Lipman and Mullineaux, 1981, Plate 1.)



10.21 Ash-fall deposit from the 20-km-high volcanic plume of the explosive eruption of Mount Saint Helens, Washington, May 18, 1980. (a) Thirteen-minute growth of plinian plume beginning at 8:32 AM. (b) Distribution of ash. Isopach lines of constant uncompacted thickness in millimeters. Innermost two isopachs immediately surrounding the volcano are 100 and 200 mm. Anomalously thick area in eastern Washington probably reflects clumping of fine ash and premature fallout. (c) Mean particle diameter plotted on logarithmic scale against distance along axis of fallout in (b). Note change in horizontal distance scale from (a) to (b) and (c). (Redrawn from Sarna-Wojcicki et al., 1981.)

(<1 km^3), the accompanying blast devastated a large area and debris flows (lahars) created considerable downstream damage. Airborne ash traveled around the Earth, and as much as 1 cm of ash was deposited 500 km distant.

Magma-Water Interactions. **Hydromagmatic explosions** can occur wherever magma contacts external water. Because of the ubiquity of water on the surface of the Earth these explosions occur in a wide variety of geologic environments. Ascending magma can encounter shallow water along coasts of islands and continents as well as water-soaked ground, rocks containing water in fractures, and lakes (Figures 10.22 and 10.23). Because water is common in volcanic craters, recurrent rise of magma into volcanoes can trigger hydromagmatic ex-

10.22 **Surtseyan** eruption of Capelinhos volcano, Azores. The central black plume choked with basaltic ejecta is estimated to be about 400 m high. A ring-shaped **base surge** has formed at its base and a white steam cloud lies behind and to the right. (Photograph courtesy Richard V. Fisher from Othon R. Silveira of Horta, Azores; from Waters AC, Fisher RV. Base surges and their deposits: Capelinhos and Taal volcanoes. J. Geophys. Res. 76:5596–5614, 1971; Published 1971 by the American Geophysical Union.)

plosions. Lava extruded from subaerial vents can flow into the sea, lakes, and rivers and over water-soaked ground. On high volcanoes or at high latitudes, magma can contact snowfields and glaciers.

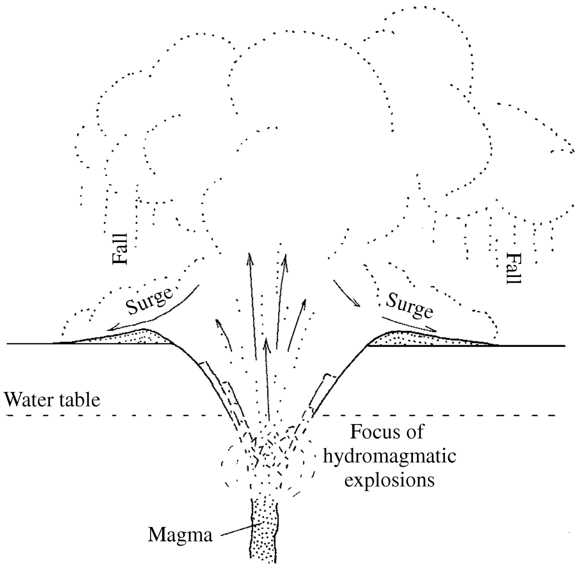
Because of their high *T* and large heat capacity, magmas contain a vast amount of thermal energy that can be transformed into PV energy (Section 3.2.2) as external water is vaporized to high-pressure steam. Explosive yields of rapidly vaporized water can be as much as one-third the yield of an equivalent mass of TNT (Francis, 1993). A kilogram of magma that contains 1.6×10^6 J of energy converting a fixed (confined) volume of water from 0°C to 1000°C produces a pressure of 500 MPa (Sparks et al., 1997, p. 14). This pressure exceeds the brittle breaking strength of rock by as much as two orders of magnitude. It is little wonder that some of the most explosive volcanic eruptions involve magma-water interactions.

However, not all magmas contacting water produce explosions. For example, lava entering the water at depths of less than a few tens of meters along the coast of Hawaii produces pillows (Moore, 1975) and only minor explosive activity. Other factors obviously control the intensity of hydromagmatic explosions. One appears to be "premixing" of large surface areas of magma with water. Explosive activity along the coast of Hawaii is more common where aa flows rather than pahoehoe enter the sea. The irregularly shaped, vesicular chunks of lava in aa provide for more heat transfer to water than smaller-surface-area pahoehoe and pillow lavas insulated by a smooth skin of glass.

It may also be that many hydromagmatic eruptions occur because magma contacting external, near-surface water is independently vesiculating and perhaps fragmenting because of exsolving volatiles in the magma; this is another way of premixing large-surface-area magma with water. Fine-scale fragmentation is apparently required to create high rates of heat transfer and energy release. This may happen (Wohletz, 1986) as an expanding layer of vaporized water develops at the interface between magma and water; in some, not well understood, manner, cyclic collapse and regeneration of this layer on short time scales (microseconds) explosively fragment the magma, typically into ash-size granules.

Processes and products in magma-water interactions range widely, depending chiefly on the water/magma ratio. Ratios of about 0.3–0.4, depending on magma composition, appear to be optimal for conversion of the thermal energy of the magma into the work of magma fragmentation, ejection/dispersal of pyroclasts, and possible crater excavation into underlying rock.

Hydroclastic refers to any fragmental material created by interactions between magma and water. Such deposits that are principally vitroclasts are referred to as **hyaloclastites.** These form by nonexplosive spalling and granulation of glassy rinds on pillow and pahoehoe flows in contact with water and by explosive hydromagmatic processes in a wide range of subaqueous and subaerial geologic environments. Where magma invades unconsolidated sediment near the surface of the



10.23 Schematic cross section through a **hydromagmatic explosion** system. Focus of explosion is the area where ascending column of magma contacts external water. Pyroclastic surge and fall deposits, including ballistic clasts, build a low **tuff ring** around the deepening **maar** crater.

Earth, water lodged in pore spaces expands and creates a situation where the magma can produce complex physical mixtures with sediment; the resulting rock is called **peperite.**

10.4.2 Pyroclasts in Volcanic Plumes

Most pyroclasts are ejected from a vent into a **volcanic plume**—a mixture of pyroclasts and hot expanding gas, chiefly steam, that is discharged explosively into the atmosphere (Sparks et al., 1997). On the basis of ballistic clast trajectories (discussed later), plumes exit volcanic vents at velocities as high as 600 m/s (a supersonic 2160 km/h). Higher velocities correspond with higher exsolved volatile concentrations in the erupting magma, whereas the height of the plume, to as much as 50 km, is controlled mainly by magma discharge rates (mass flux) from the vent. Discharge rates as high as about 0.1 km^3/h have been determined for historic eruptions, but they may have been at least an order of magnitude greater for colossal prehistoric eruptions. Discharge rates are in turn largely governed by the radius of the vent. (Most explosive vents can be considered to be more or less circular as the explosive process reams out fractured wall rock, eliminating inward projecting irregularities and creating a minimal area of circumferential surface.) Once formed, plumes can be sustained for hours to months if the magma supply is not exhausted and if the ascent rate of the material in the plume is less than the discharge rate. Other plumes accompany single instantaneous bursts.

Plumes are of many types. Those that are produced by hydromagmatic explosions are shown in Figures 10.22 and 10.23. Other types of plumes that depend on the water content of the erupting magma and vent radius are shown in Figures 10.24a and 10.24b. High-energy **plinian plumes** are created by blasting of gas-rich magma from smaller vents (Figure 10.25). (Pliny the Younger was an eyewitness to and described the 79 AD eruption of Vesuvius in southern Italy.) Above a gas-thrust region, turbulent plinian plumes engulf and heat atmospheric air, become buoyant, and rise convectively to tens of kilometers above the vent, forming the giant, visually impressive "cauliflower" ash-laden clouds accompanying explosive eruptions. Where the cloud becomes neutrally buoyant, it spreads horizontally, creating an umbrellalike form. Plinian plumes disperse pyroclasts over wide areas in ash-fall deposits. Lower-energy **collapsing columns,** resembling water fountains, are created by eruption of less-volatile-rich magma from larger vents. Discharge rate is so great that the plume contains more pyroclastic mass than can be lifted buoyantly; consequently the eruptive column collapses under its own weight. Collapsing columns produce ground-hugging pyroclastic flows and surges that move radially away from the base of the fountain at hurricane speeds. Such flows can themselves generate secondary **coignimbrite plumes** that are produced as fine ash is flushed out of the flow by buoyantly rising gas.

Some pyroclastic deposits (Figure 10.26b) indicate that low-energy fountains and high-energy plumes can alternate over a period of days to months from the same localized vent system. Other systems may begin, for example, with a plinian plume and end with a collapsing column.

10.4.3 Pyroclast Transport and Deposition

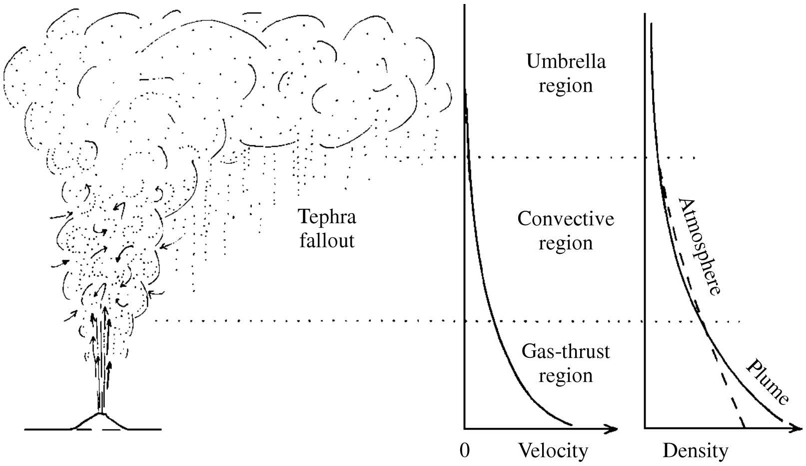
Pyroclasts blown from a volcanic vent, mostly in an explosive plume, are then transported by pyroclastic fall, flow, and surge and eventually deposited. The fabric and field relations of these three types of deposits are generally distinctive, but (as usually happens when humans impose a classification on nature) some pyroclastic deposits have hybrid aspects, emphasizing the need for caution and an open mind in interpreting them. For example, strong near-vent winds accompanying plinian fall can produce reworking of pyroclasts so that the deposit may resemble a surge deposit. In many localities, fall, surge, and flow deposits are interlayered in complex fashion (Figure 10.26b). Finally, nonvolcanic, or epiclastic, processes can rework tephra to produce features resembling those of primary pyroclastic deposits.

Pyroclastic flows are gravity-driven hot avalanches of mostly juvenile pyroclasts and gas that sweep downhill and across the landscape with hurricanelike speed; deposits are *unsorted* accumulations of ash and pumice lapilli and blocks that fill in topographic features as a flood of water does. Pyroclastic flows are of such great importance in the volcanic record that they are treated separately in Section 10.4.5.

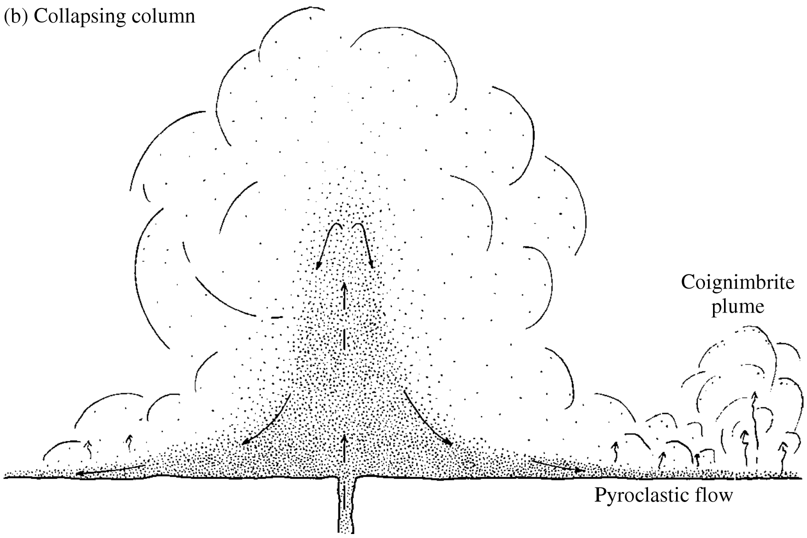
Pyroclastic Fall. Gravity-induced fallout of ejecta from explosive volcanic vents, principally the overlying convecting volcanic plumes, creates **pyroclastic-fall deposits,** also called **ash-fall deposits.** Their extent, thickness, sorting, particle size parameters, especially maximal and mean sizes, and other characteristics depend on the nature of the preeruption magma chamber and conduit/vent geometric characteristics, discharge rate and duration, style of eruption, and nature of the associated eruption plume, especially its height, wind characteristics, and the aerodynamic properties of the pyroclasts. Careful measurements of fall deposit properties allow plume character and duration to be estimated (Sparks et al., 1997).

The largest fragments commonly ejected from volcanic vents are approximately >10 cm in the bomb- and block-size range and are called **ballistic clasts** because they are hurled on ballistic trajectories from the vent, resembling projectiles shot from a cannon. They can land as far as 25 km from the vent but most fall closer. Ballistic trajectories are essentially unaffected by

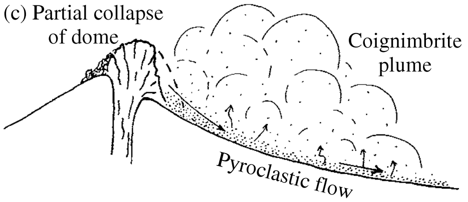
(a) Sustained plinian plume



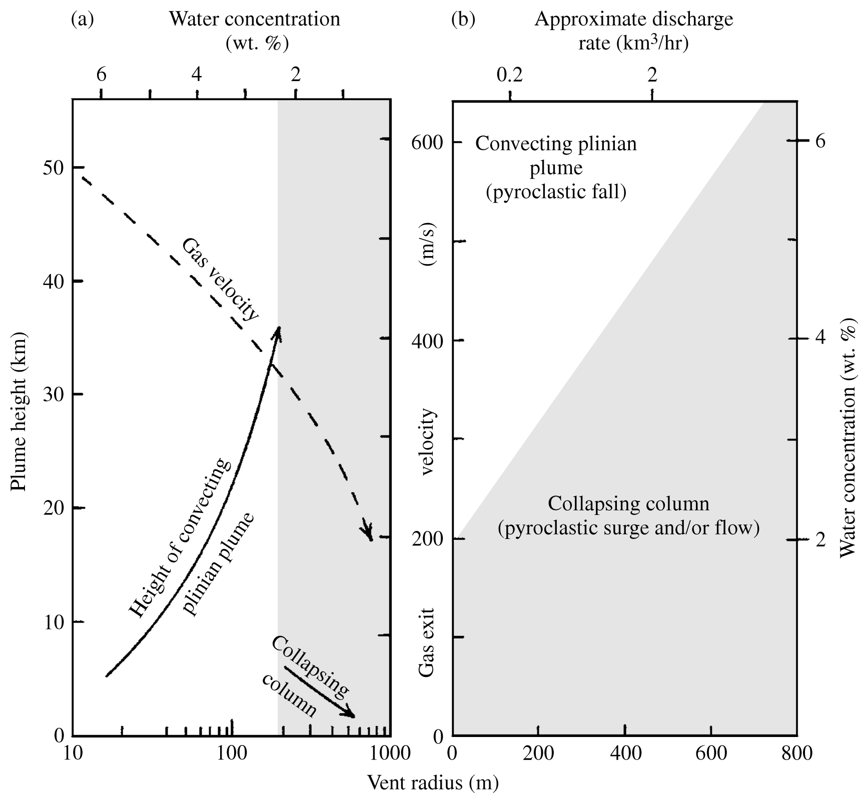
(b) Collapsing column



(c) Partial collapse of dome



10.24 Volcanic plumes. Three diagrams are not at the same scale. (a) Sustained **convecting plinian plume** showing three dynamic regimes and their relation to column height, velocity, and density of plume and atmosphere. (Redrawn from Sparks et al., 1997.) In the gas thrust region, the expanding volatile fluid exsolved from the magma imparts upward-directed momentum to the plume, much as exploding gun powder propels shot from a gun barrel. In the convective region, thermal energy contained in the turbulent plume heats entrained atmospheric air, decreasing the density of the plume to less than that of the normal atmosphere and providing buoyant lift. In the umbrella region, the density of the expanding, convecting plume matches that of the density-stratified atmosphere so the neutrally buoyant plume spreads horizontally. Nonetheless, the upward momentum of the plume in the convective regime causes it to overshoot the level of neutral buoyancy so that the umbrella region can have a substantial thickness. Although the overall height of the plume is chiefly a function of magma discharge rate correlated with vent radius, other factors such as atmospheric *T* and humidity and wind velocity also influence height. **Ash-fall deposits** form by fallout from the plume hundreds to thousands of kilometers from the vent. (b) A **collapsing column** forms if the upward momentum of the plume exiting the vent is incapable of lifting it more than a few kilometers. The mass of ejecta is too great to be lifted buoyantly and, consequently, the pyroclasts fall back to the ground, where their kinetic energy gained during fallback propels them away from the fountain as **pyroclastic flows.** However, an overlying convecting buoyant plume is formed by mixing of atmospheric air with fine pyroclasts in the outer part of the plume. A **coignimbrite plume** develops over the pyroclastic flows. Collapsing columns and plinian plumes may be less symmetric in nature than shown here. (c) Collapse of a sector of a peléan dome producing a small **block-and-ash pyroclastic flow** and overriding **coignimbrite plume.** Compare with Figure 10.36.

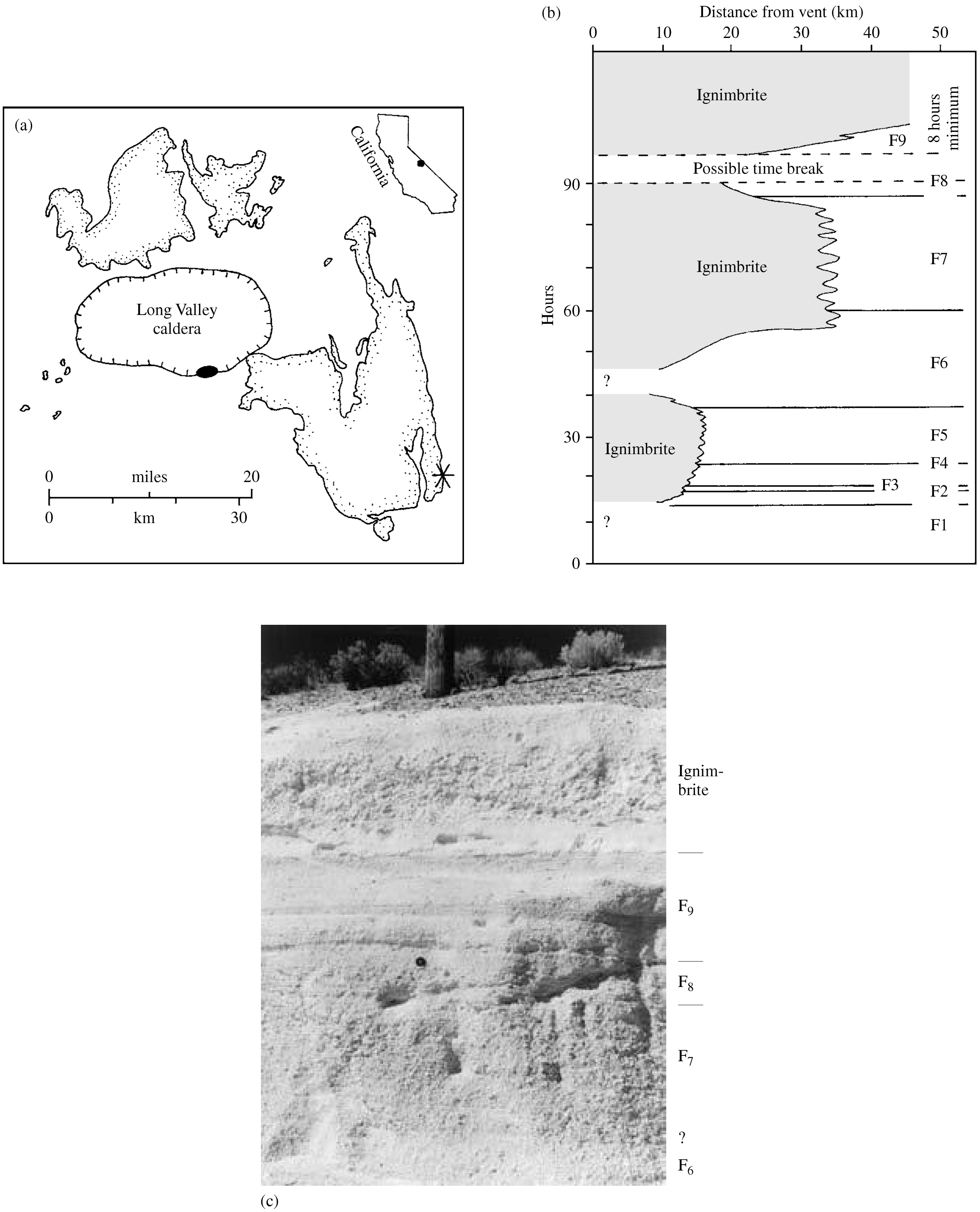


10.25 Fluid dynamic models of controlling factors in volcanic plumes. (a) A specific dynamic model for silicic magma in which $T = 1200\text{K}$, lithostatic pressure prevails in the conduit, and water is the only volatile. Decreasing water concentration in the erupting magma (from a zoned chamber in which the magma initially has about 6 wt.%) reduces the exit velocity of the plume gas at the vent. With increasing vent radius (due to erosion during explosive eruption), the height of the convecting plinian plume first increases as a result of increasing magma discharge rate and thermal energy available to heat entrained air to provide buoyancy; however, as this rate reaches a critical value at a vent radius of 200 m and water concentration near 2.4 wt.% the erupting mass is too great to be lofted higher by influx of heated air and the plume collapses (shaded part of diagram). (b) General model conditions showing that convecting plinian plumes are favored if the magma has a high water concentration and a high exit velocity at a small-diameter vent, whereas collapsing fountains occur for the opposite conditions. Note that a particular eruption can be stabilized or sustained in one or the other plume regime—either convecting or collapsing. A geologically likely transition is from a convecting plume to a collapsing column. (Redrawn from Wilson et al., 1980.)

wind or convection in the plume; thus, ejection velocities can be calculated. In contrast, smaller pyroclasts approximately 1–10 cm that include coarse lapilli and small blocks and bombs are mostly lofted by turbulent suspension in a convecting volcanic plume but will fall if their terminal velocity exceeds convective updraft in plume margins. Smallest pyroclasts are <1 cm and include fine lapilli and ash, which commonly account for most of the ejecta; they are also suspended by turbulence but can be dropped from the umbrella part of the plume as convective energy dissipates. Settling velocities of the finest ash particles may be smaller than wind currents, in which case they may circle the Earth several times before eventually settling. These can be responsible for multihued, pastel sunsets worldwide for years after a major pyroclastic eruption.

Particle size and density control terminal velocity (Stokes's law; Section 8.3.3) so that larger and denser clasts are preferentially dropped nearer the vent (Figure 10.21). Consequently, a pyroclastic fall deposit at any one location consists of particles of similar size: That is, deposits are well sorted. However, fine ash can clump into larger particles in the turbulent plume, if it is wetted by water condensed from cooling steam, forming accretionary lapilli. Other clumps form because of electrostatic attraction, forming porous "ash snowflakes." Both aggregates of fine ash fall closer to the vent. Fine ash can also fall prematurely if it is entrapped by falling raindrops or by larger falling particles. For these reasons, fallout deposits may not be as well sorted as expected, but the mean and maximal sizes of particles generally decrease with distance from the vent.

Fresh, unconsolidated pyroclastic-fall deposits of ash and highly vesiculated pumice fragments are best preserved in marshes, lakes, and deep oceans; where reworking by wind and water currents is limited; or where they are immediately covered by other deposits.

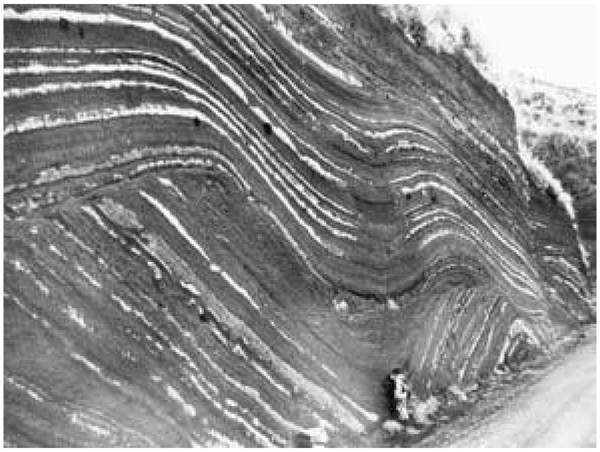


10.26 Pyroclastic deposits derived from the Long Valley magma system, eastern California, at about 0.76 Ma. (a) Distribution of the Bishop Tuff, consisting of ignimbrite and interlayered fall and surge deposits, chiefly in two lobes north and southeast of the Long Valley source caldera. (b) Stratigraphy of the interlayered proximal ignimbrite (shaded) and fall deposits (F1, F2, etc.) southeastward from the source vent (solid ellipse) on the caldera ring fracture in (a). Note that the total sequence of approximately 600 km^3 was deposited in about 100 h. (c) Proximal fall deposits of sorted pumice and ash capped by unsorted ignimbrite. See stratigraphic relations in (b). Photograph taken at locality marked by asterisk (*) in (a); Camera lens cap for scale. ([a] and [b] reproduced by permission from Wilson CJN, Hildreth W. The Bishop Tuff. New insights from eruptive stratigraphy. J. Geol. 105:407–439, 1997; Copyright © 1997 by the University of Chicago Press.)

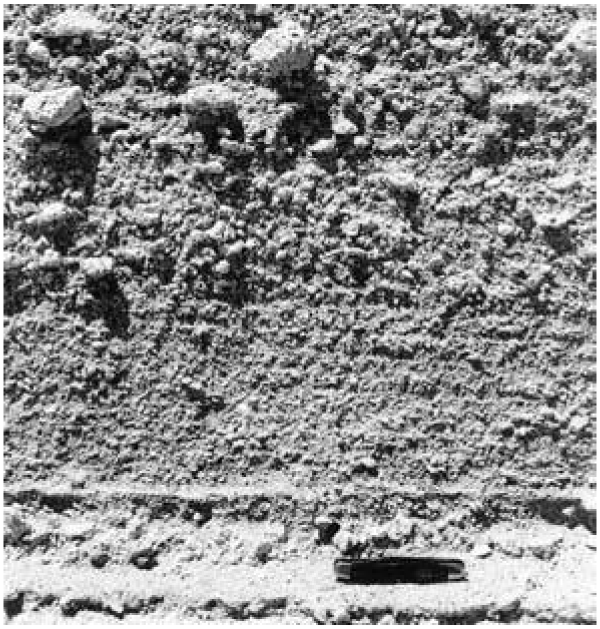
Characteristics of pyroclastic-fall deposits include the following:

1. Generally they are better sorted than surge and flow deposits.
2. Plane parallel beds form unless they are modified by erosion.
3. Unabraded vitric clasts form; if they are inequant in dimensions, they lie flat in the bedding plane.
4. **Mantle bedding** is created as the tephra showers uniformly over the ground surface, whether hill or valley, as in snowfall (Figure 10.27).
5. **Reverse-graded** beds form, in which increasingly coarser clasts occur upward, rather than normal-graded beds, in which the coarsest particles are at the base (Figure 10.28). Reverse grading might be caused by shifts in wind currents and speed, but another explanation stems from the dynamics of plinian plumes. A plume may rise to greater height, possibly because of increased magma discharge rate related to increased vent radius as the conduit is reamed out by the discharging magma. Consequently, larger pyroclasts are carried convectively to greater heights and distances before being released in fallout, in which their terminal fall velocities overcome convective lift.

Ash-fall beds are useful in **tephra chronology** because a widely dispersed ash-fall layer (Figure 10.21) can serve as a correlatable time stratigraphic horizon. Crystal and vitric particles have distinctive compositions inherited from the magma and can be dated isotopically. Tephra studies can be a valuable resource for archeology. However, differential sorting due to contrasting size and density of the pyroclasts and derivation from different parts of compositionally zoned chambers precludes using the bulk composition of any fall deposit as an accurate indicator of preeruption magma composition.



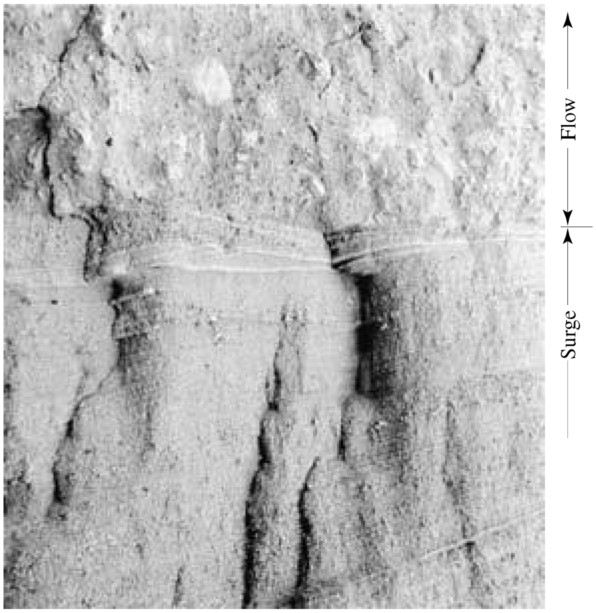
10.27 **Mantle bedding** of ash-fall layers, Oshima Volcano, Japan. The beds in the roadcut partly covered by snow are not folded, but dips are primary and mimic the configuration of the depositional surface on which they rest. Note unconformity where erosion cut into older underlying sequence. Geologist for scale at bottom of photograph. (Photograph courtesy of Jack Green.)



10.28 **Reverse grading** in **ash-fall deposit.** Note upward-increasing size of rhyolitic pumice fragments. Pocket knife 8 cm long.

Pyroclastic Surge. Like pyroclastic flows, **pyroclastic surges** are devastating mixtures of hot gas and solid particles that move laterally away from the base of a collapsing pyroclastic plume at hurricanelike speed (Figure 10.23). However, unlike flows, surges are dilute mixtures that have low concentrations of particles. Surges travel in turbulent manner to less than a few kilometers at most from a vent because they have less momentum, as they are mostly gas. Surges can develop bed forms similar to those in water- and wind-transported sediment. As in these modes of sediment transport, surges move particles by surface traction in a bed load and by turbulent suspension. Unlike water- and wind-transporting media, surges have density and viscosity that can vary during travel, thus creating variations in bedforms. **Surge bedforms** (e.g., Figures 10.29 and 10.30) include the following:

1. Poorly to moderately sorted, planar to pinch-and-swell strata that are 1 cm or so thick. Plane parallel beds may resemble pyroclastic fall deposits but can grade laterally into more typical surge bedforms, and flat clasts can be imbricated (dipping toward the source).
2. Low-angle, cross-bedded to wavy beds are common.



10.29 Silicic **pyroclastic deposit.** Poorly sorted **pyroclastic flow** deposit in Snake River Plain, Idaho, which contains light gray pumice blocks to as much as 12 cm, overlies **pyroclastic surge** deposit. **Surge bed forms** include climbing dune cross-beds and pinch-and-swell beds. Lowermost part sequence of thin-plane parallel beds may be also be surge material.

3. Climbing duneforms lie transverse to the surge direction.
4. Scoured bed contacts are due to local erosion.
5. **Bedding sags** are caused by impacting ballistic clasts depressing soft underlying layers; asymmetric sags can be interpreted to determine direction to vent.
6. Penecontemporaneous downslope slumps of water-saturated beds are also created.

Most surges are of the type known as **base surges** created by hydromagmatic explosions of mafic magma; gravitational collapse of a steam-saturated eruption column creates a ring-shaped surge traveling outward along the ground from the vent (Figures 10.22 and 10.23). Less common surges are related to steam blast eruptions, and some are jetted from toes of advancing pyroclastic flows. Whether surges are distinctly different from pyroclastic flows, or whether one grades into the other, is debatable. Some volcanologists consider a pyroclastic surge to be simply a dilute pyroclastic flow.

If most of the thermal energy in a hydromagmatic eruption is consumed in converting water to steam, the so-called wet surge may be near 100°C and consist of pyroclasts, steam, and water. Accretionary lapilli, soft-sediment deformation structures, and plastering of mud onto upright objects, such as trees that are not burned, indicate a wet surge. Other surges are hotter (able to carbonize trees) and are dry (steam only).

10.4.4 Explosive Style

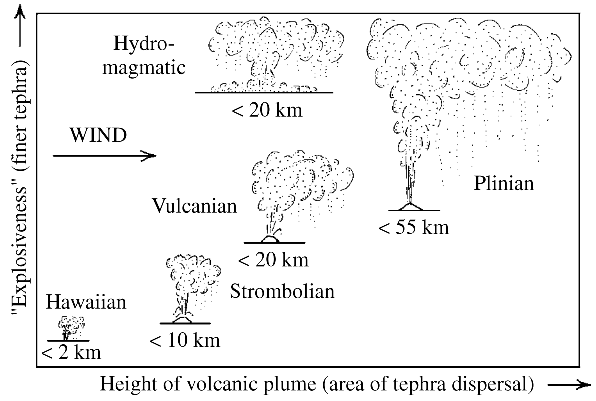
Because of the myriad factors involved, there is a wide and continuous spectrum of **explosive style** that defies straightforward categorization. Styles range from small vents harmlessly "burping" low-viscosity basaltic spatter a few meters to the colossal, high-energy catastrophic explosions of silicic magma that create enormous convecting plumes or collapsing columns and deposit thick blankets of pyroclastic material over thousands of square kilometers and finer ash globally. During the course of a particular eruptive episode the style may change or alternate. Widely accepted names for particular styles are taken from geographic locales and famous exemplifying volcanoes. Associated with this spectrum of eruptive styles are a variety of volcanic plumes (Figure 10.31).

As with earthquakes, the frequency of volcanic explosions depends on their magnitude. The smallest explosions occur roughly every month somewhere on Earth, whereas the largest occur on a time scale of millions of years. Volcanologists employ various parameters to measure the **"explosiveness"** of a volcanic eruption; these include intensity (rate of magma discharged from the vent, or mass flux), magnitude (total volume or mass of material vented), explosivity index (ratio of pyroclastic deposits to all other volcanic material), and dispersive power or violence (area of dispersal of pyroclasts).

Eruptive styles are now discussed in order of increasing explosiveness. Characterizing properties of the resulting deposits are emphasized.

Hawaiian Eruptions. Typically, basaltic magma in **Hawaiian eruptions** takes the form of low viscosity lava flows and mildly effervescing **lava fountains,** less

10.30 **Surge** deposit 0.4 km northeast of Sugarloaf Mountain rhyolite dome, San Francisco Peaks volcanic field, Arizona. Climbing dune cross-beds indicate surge moved from right to left; note bedding sag to left of shovel below crest of dune. (From Sheridan and Updike, 1975; photograph courtesy of M. F. Sheridan.)



10.31 Highly generalized classification of **explosive eruption style** based on explosiveness and height of volcanic plume. Diagrams not to same scale. More explosive eruptions tend to have smaller mean size of pyroclasts. Higher plumes are capable of wider dispersal of fallout pyroclasts so that ash-fall deposits occur farther from the vent. (Redrawn from Cas and Wright, 1987.)

appropriately called "fire fountains." Expanding bubbles within a rising magma column propel fragments from the vent to form the incandescent lava fountain (Figures 10.7a and 10.32). The relatively large ejecta (centimeters to meters in diameter) retain their high eruptive *T* because the surface area for dissipation of heat is small compared to the enclosed mass. Hence, relatively little heat is transferred into the air, convective updrafts are minimal, and only the smallest pyroclasts are transported out of the fountain by the wind. Since most pyroclasts are large and unaffected by convecting air currents, they follow nearly ballistic trajectories in the collapsing fountain. Still hot, molten clots accumulate at the base of the fountain, where they form deposits of **welded spatter,** or **agglutinate.** Aerodynamic streamlining of the low-viscosity spatter during flight creates bombs and smaller Pele's tears and hair (Figure 7.29). Depending upon wind conditions, vent geometric features (central versus fissure), and possible obstructions in the vent that deflect the ejecta from the vertical, this welded spatter can form a more or less symmetric **spatter cone** around the vent or a less symmetric one-sided spatter rampart or mound. Spatter accumulations may be hundreds of meters in diameter, but most are smaller. Lapilli- and block-size fragments of scoria (vesicular basalt) that are cool and solid upon deposition accumulate as cinder deposits. Alternations of cinder and spatter create **cinder-and-spatter cones.** High-discharge-rate fountaining can produce sufficient accumulations of molten spatter at the fountain base that the mass recombines into a mobile lava that can move downslope as a rootless lava flow. Accumulation of lava in a depression can form a **lava lake.** Lava lakes also appear at the top of the magma column in the vent and can overtop a crater rim or undermine and rupture a tephra cone, rafting away sectors of the cone on the flowing lava. Contemporaneous lava fountaining and lava effusion from the same or nearby vents can occur.

Strombolian Eruptions. More explosive **strombolian eruptions** that build monogenetic volcanoes of basaltic or andesitic magma involve bursting of large gas bubbles, as much as 10 m in diameter, near the top of a magma-filled conduit. Most of the ejecta are lapilli-size cinders and lesser larger blocks (Figure 10.33), which are solid upon deposition around the vent, forming a **cinder cone,** also called a **scoria cone** (Figure 10.4). Variable amounts of congealed spatter and streamlined bombs can be mingled with the cinders.

Vulcanian Eruptions. Vulcanian eruption activity occurred at Vulcano, another volcano on a Mediterranean island like Stromboli, but has taken place at many other subduction-related volcanoes erupting intermediate-composition magma. Typically, **vulcanian eruptions** begin with cannonlike, steam-blast explosions (discussed later) at intervals of minutes to hours that disintegrate rock plugging the vent over a magma-filled conduit. Blocks are ejected ballistically, whereas finer clasts fall out of convective plumes and accumulate in moderately sorted to well-sorted beds that are more widespread than those of strombolian eruptions. Once the rock cap on the magma column is removed, continued eruptions discharge juvenile pyroclasts ranging from vitric and crystal ash to bombs and breadcrust blocks. Pyroclastic surges and flows accompany

10.32 Incandescent 1959 Kilauea Iki, Hawaii, **lava fountain.** Diffuse plume of cooler black ash and cinder fanned from the fountain and carried downwind (to left) forms a crescent-shaped cinder rampart (not visible) and more distant beds of finer ash. Below the collapsing fountain, rapidly accumulating clots of magma merge into a rootless lava flow that feeds an incandescent lava river draining into a partly crusted **lava lake** that is barely visible in lower left corner of photograph. (U.S. Geological Survey photograph by G. A. Macdonald.)

10.33 Internal crude stratification and moderate degree of sorting in basalt **cinder cone.** Quarry face reveals blocks and mostly lapilli-size vesicular cinders that have been variably oxidized while hot in the oxygen-rich atmosphere. Essentially nonoxidized are black, whereas slight oxidation of the Fe-rich glass creates an iridescent coating. More thorough oxidation creates minute pervasive hematite grains that pigment cinders red-brown. Note hammer in lower left for scale.

some vulcanian eruptions. Effusion of highly viscous, less gas-rich lava commonly terminates the eruptive episode.

Steam-Blast Explosions. Water contacting hot rock is vaporized to expanding steam, which blows the rock to pieces in **steam-blast explosions.** Because the term *phreatic* refers to groundwater, explosions caused by contact between groundwater and hot rock may be called **phreatic explosions.** No juvenile magma is ejected, although in many cases it lies not far below and is responsible for the heating of the rock. Some explosions occur in areas of geothermal activity overlying active hydrothermal systems (Figure 4.12) where temperatures are increased as a result of magma recharge. Other explosions occur where hot lava or pyroclastic flows override or otherwise interact with bodies of water or water-soaked ground. Explosions produce steam-rich plumes laden with lithic ash as well as larger ballistic clasts. In certain cases, the nonjuvenile tephra has suffered mineral alteration as a result of prolonged prior hydrothermal and fumerolic processes. Many explosive volcanic episodes begin with steam blasts and later evolve into other styles of eruption.

Hydromagmatic Eruptions. One such style of activity that follows preliminary steam blasts is the **hydromagmatic eruption,** in which magma makes actual contact with external water (Figure 10.23). Basaltic eruptions in lakes and ocean are typical, such as that at Surtsey, Iceland, in 1963–1965; this eruptive style is appropriately called **surtseyan** (Figure 10.22).

Mostly juvenile fragments are ejected in hydromagmatic explosions. Shattering of quenched basaltic melt creates poorly vesicular, blocky juvenile vitric ash, which is caught up in a steam-rich plume. Finer ash in the convecting plume can aggregate into accretionary lapilli. Fallout from the high plume produces thinly bedded, sorted ash-fall deposits many kilometers from the vent in quiet water or on nearby land. Multiple surge beds numbering in hundreds to thousands, together with ballistic clasts, form wedge-shaped (in cross section) accumulations near the vent and tapering away from it. As the body of water is blocked from the vent by these encompassing accumulations, continued rise of magma erupts in strombolian or hawaiian style and may fill the crater with magma, forming a lava lake.

Monogenetic hydromagmatic eruptions produce low-rimmed edifices having bowl-shaped craters including tuff cones, tuff rings, and maars. Morphologically, these edifices form a continuum with cinder cones. In strombolian-generated **cinder cones,** the aspect ratio (edifice height/basal diameter) is approximately 1 : 3 and the constructional crater is small relative to the volume of the cone. In **tuff rings,** at the opposite end of the spectrum, the ratio is $<1:5$ and the volume of crater space is larger than the volume of ejecta (Figure 10.34). **Tuff cones,** the typical edifice formed by surtseyan eruptions, are intermediate in shape. Where lava erupted on land enters the sea, as on the island of Hawaii, hydromagmatic explosions may create a **littoral cone.** Such edifices are of unconsolidated tephra and can be called ash rings or ash cones, but most are fairly well cemented because of extensive and surprisingly rapid palagonitization (Section 7.1.1) of the warm wet vitric ash. A **maar** is a tuff ring in which the crater floor lies below the general elevation of the preeruption land surface. Maars form by excavation of older rock material by hydromagmatic explosions that occur just below the preeruption land surface (Figure 10.23). The surrounding rim of ejecta

10.34 MacDougal Crater in the Pinacate area of northwestern Sonora, Mexico. The **tuff ring** is about 1.5 km in diameter. (Photograph courtesy of John S. Shelton.)

therefore includes a significant proportion of accidental lithic material in addition to juvenile. In the Eifel, Germany, region, maars and cinder cones are closely associated, even along the same fissure system. But cinder cones tend to form on hills, whereas maars form in the valleys, where there was access to the shallow water table.

Diatremes are narrow, funnel-shaped masses of breccia underlying maars. They are discussed in Section 9.4.3 and shown in Figures 9.25 and 9.26. The origin of diatremes involves an ascending convecting fluid-rich magma system. However, some basaltic maars are underlain by what is interpreted to be a downward-growing diatreme that was produced by hydromagmatic processes (Lorenz, 1986).

Plinian Eruptions. Highly explosive plinian eruptions are characterized by plinian plumes (Figure 10.24a). **Plinian eruptions** involve volatile-rich silicic magmas (dacite-rhyolite) of high apparent viscosities, although andesitic and even basaltic eruptions have been documented. Eruptive velocities are hundreds of meters per second and eruptions last from tens of minutes to several days or intermittently for years where magma supply can be maintained. Plinian eruptions commonly, but not invariably, initiate silicic volcanic activity. Many of the most destructive eruptions of recorded history began as plinian, including that of Vesuvius, which inundated Pompeii and Herculaneum with several meters of a pumice fall in 79 AD; Krakatoa in 1883; and Mount Saint Helens on May 18, 1980.

In plinian eruptions, pyroclasts are as large as blocks, but lapilli-size pumice and vitric ash predominate. Most of the properties listed for pyroclastic fall deposits apply to characteristically sheetlike, moderately sorted to well-sorted plinian accumulations.

The 180 AD eruption of Taupo in New Zealand was the most powerful known plinian eruption, creating a layer as much as 12.5 cm thick of rhyolite ash 200 km from the vent; the plume is estimated to have had a height of >50 km. Some of the Taupo eruptions (130–186 AD) occurred where vesiculating silicic magma encountered lake water; such **phreatoplinian** eruptions are the silicic counterpart of basaltic surtseyan eruptions and produce widely dispersed, thin beds of very fine ash that has abundant fine vesicles and blocky shapes.

10.4.5 Pyroclastic Flows and Deposits: Overview

Large, widespread silicic pyroclastic-flow deposits in the western United States were an enigma to early geologists because of their superficial lavalike appearance but thin sheetlike aspect ratio (Figure 10.35) uncharacteristic of silicic lava flows. Beginning in 1902 with the tragic eruptions of Mount Pelée on Martinique (Figure 10.36) and La Soufrière on Saint Vincent, both islands in the Caribbean, and continuing with hundreds of similar eruptions in many parts of the world, volcanologists have gained much insight into the nature and origin of these puzzling deposits. Observations from safe distances have been integrated with laboratory experiments on model systems, computer simulations, and

10.35 Sheets of **ash-flow** tuff **(ignimbrite)** deposited outside the Valles caldera near Los Alamos, New Mexico (see Figure 10.41). Contrast aspect ratio of these sheets with a typical rhyolite lava dome (e.g., Figure 10.16). (U.S. Geological Survey photograph courtesy of Robert L. Smith.)

10.36 Pyroclastic eruption at Mount Pelée, Martinique. **Coignimbrite plume** rising above an inconspicuous pyroclastic flow dominates photograph. The remains of the town of Saint Pierre, devastated by an earlier eruption on May 8, 1902, which took 28,000 human lives, lie in the foreground. Compare Figure 10.24c. (Photograph courtesy of The Geological Museum, London.)

fluid dynamic studies to provide considerable insights, but no complete solutions. The classic exposition on pyroclastic eruptions and deposits in the western United States is by Ross and Smith (1961).

Nomenclature and Types. The French petrologist Alfred Lacroix, who was at the site of some of the 1902 Caribbean eruptions, called pyroclastic flows *nuées ardentes,* meaning "glowing" or "hot clouds." *Glowing avalanches* is a more accurate, sometimes used label for flows because the depositional agent is not a cloud of dispersed ejecta, as Lacroix believed, though these are invariably associated. **Ash flow** and **ash-flow tuff** are names commonly used by U.S. geologists for the eruptive agent and its deposit, respectively, even though pumice clasts of lapilli size are typically present with ash. Locally, blocks of pumice also occur, together with a wide size range of lithic clasts. **Welded tuff** is a nonporous rock made chiefly of vitric ash particles that are stuck together because of the high *T* at emplacement. For the Plio-Pleistocene rhyolite deposits on the North Island of New Zealand, Peter Marshall in 1935 coined the term **ignimbrite,** from Latin *ignis,* meaning "fire," and *bris,* meaning "cloud," hence, fiery cloud rock. The term *ignimbrite* has been widely adopted for pyroclastic flow deposits.

A **pyroclastic flow,** our preferred generic term, is a highly mobile, hot avalanche of pyroclasts and gas that is denser than ambient air and moves swiftly (as much as 300 m/s) along the ground surface away from its source. Resulting deposits are massive poorly sorted beds that can be hundreds of meters thick. Rheologic properties of a pyroclastic flow vary with respect to distance of transport from the vent. As it moves along the ground, denser particles may sink and lighter ones rise, buoyed up by the hot gas, forming an overlying dilute, turbulent ash cloud, commonly referred to as a *coignimbrite plume* (Figures 10.24b and 10.36). Flows tend to be confined to topographic lows but can cascade over tops of hills. Flows denser than water travel along the floor of lakes and oceans, whereas less dense ones travel over the water surface. Some pyroclastic flows have dilute ground surges propelled from their toe.

Many different types of pyroclastic flows have been recognized, but they fall essentially into two basic categories depending on the process of origin and character of the flow and flow deposit; these are block-and-ash flows and ash flows that are predominantly made of ash and lesser lapilli.

10.4.6 Block-and-Ash Flows

Relatively very small-volume avalanches produced by disintegrative collapse of growing andesitic to rhyolitic domes or thick flows on composite volcanoes produce **block-and-ash** flows (Figure 10.24c). Dome disintegration can be driven by exsolution of volatiles in the dome, causing explosive fragmentation; by magma-external water interactions in a water-filled crater, causing steam explosions; and by collapse of a gravitationally unstable dome. In any case, dislodged blocks cascade downslope, pulverizing one another in transit. Downslope flow is closely confined to topographic lows and canyons, diverging and turning according to slope configuration, resembling snow avalanches in mountain canyons. The accompanying upward-expanding, dilute ash-steam coignimbrite plume is less deflected by topographic features and lags behind the faster-moving flow. Block-and-ash flow runouts are less than a few kilometers and speeds are a few tens of m/s. Deposits are commonly tonguelike, levée-bounded, and a few meters thick or less and have volumes that are generally $<0.1\ \text{km}^3$ to as small as $0.001\ \text{km}^3$. Deposits are unsorted, unwelded aggregates of ash and weakly vesicular blocks that are as much as a few meters in diameter; some blocks have radially arrayed or breadcrust cooling (Figure 7.30) cracks testifying to their emplacement at high *T* and cooling within the flow. All clasts have the same composition.

At Unzen volcano, Japan, in 1990–1995, tens to hundreds of very small block-and-ash flows occurred daily as an emerging dome episodically collapsed. Forty-three people, including three volcanologists, were killed in one flow.

10.4.7 Ignimbrite-Forming Ash Flows

Ash flows are made predominantly of ash and form mostly by collapsing pyroclastic columns (Figure 10.24b), although other mechanisms have been observed. If the proportion of lapilli (and possibly blocks) of pumice exceeds 50% in a matrix of ash, they are called **pumice flows.** Smaller flows, generally $<1\ \mathrm{km}^3$, but some measuring in tens of cubic kilometers, are created by eruptions at composite volcanoes, commonly in subduction zones.

The largest ash-flow deposits, all prehistoric, are presumed to have been generated by collapse of eruptive columns formed by high rates of magma discharge. No preexisting conical volcanic edifice is associated with these eruptions in continental interiors which have been referred to as "erupted granitic batholiths." The volume of a single ignimbrite can be hundreds to thousands of cubic kilometers, equaling or exceeding the vast floods of plateau-forming basalt lava described in Section 10.2.3. Outflow sheets of ignimbrite can be tens to hundreds of meters thick, cover areas of tens of thousands of square kilometers, and reach more than 100 km from the source on negligible slopes. Topographical features are smoothed by the flows which flood depressions and thin over hills.

Flow Mobility: Fluidization.

The mobility of ash flows is unquestioned; flows tens of meters thick and tens of kilometers from their source can surmount hills hundreds of meters high. The cause of their mobility, however, remains uncertain.

One mobilizing factor is the kinetic energy imparted at the vent. As a pyroclastic column collapses, gravitational potential energy of the fountain is transformed into kinetic energy that drives a horizontally moving flow. Higher, more massive collapsing columns would impart more kinetic energy and promote farther runout. The "energy line" concept of Sheridan (1979) indicates any topography can be surmounted if a straight line drawn from the top of the gas-thrust regime of the eruptive plume to the distal toe of the pyroclastic flow lies above the topographic feature.

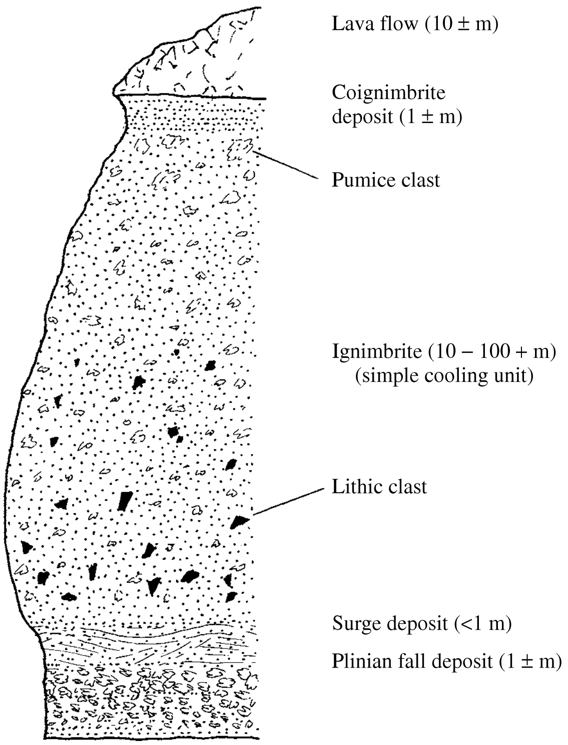
The fact that pyroclasts in ash-flows are dispersed in a gas phase may enhance flow mobility by providing a "cushion" between the solids, reducing frictional and collisional particle interactions that would otherwise impede flow.

Gas-particle flows may be mobilized by the phenomenon called **fluidization,** a process used in industry for transport of solid particles without recourse to conveyors or vehicles. Upward-flowing gas passing through a mass of cohesionless (loose) particles lifts them apart at some critical velocity so the mass behaves as a frictionless fluid whose angle of repose is zero and whose overall density is less than that of individual particles. However, in the typically unsorted ash flows that contain a size range of ash and lapilli and perhaps blocks, overall fluidization is less effective because the gas permeability is less than in a mass of uniform-size particles; smaller particles clog spaces between larger. Additionally, larger or denser clasts cannot be lifted, but smaller ones can be fluidized, and the smallest ones, whose terminal velocity is exceeded by the streaming gas, are entrained into it. This entrainment, or **elutriation,** of fine ash accounts for the universal dilute ash-steam clouds (coignimbrite plumes) observed over all pyroclastic flows, block-and-ash as well as ash flows (Figures 10.24b, c, and 10.36).

Nonetheless, this *partial* fluidization probably enhances ash-flow mobility and may produce local, subtle sorting of clasts (Figure 10.37). Fall deposits covering up to millions of square kilometers from coignimbrite plumes are enriched in fine vitric ash (glass shards) relative to the main ash flow. Thin ash flows possibly lose half their volume to winnowing (elutriation) of fine particles into the coignimbrite plume, whereas thicker flows probably lose a much smaller fraction.

Depositional and Cooling Units.

Small volatile-rich silicic magma systems lodged in composite volcanoes explode for days to months during a particular eruptive episode, which can be separated by hundreds of years from other episodes. Large, caldera-forming eruptions



10.37 A common pyroclastic sequence that might form in a single eruptive episode. A basal plinian fall deposit of sorted ash and pumice is overlain by thinner surge deposits. The overlying simple ignimbrite **cooling unit** can be 1 m to more than 100 m thick. Note slight downward concentration of denser lithic clasts and upward concentration of less dense pumice fragments. The pyroclastic flow deposit is overlain by sorted fine ash deposited from the coignimbrite plume. Near the vent, a lava flow formed from largely degassed magma might be extruded over the pyroclastic sequence.

have repose times between eruptive episodes of as much as 10^5–10^6 y. Thus, ignimbrite sequences are built of multiple **depositional flow units;** each unit represents one explosive event. These ignimbrites may be separated by surge and fall deposits (Figures 10.29 and 10.37).

A **cooling unit** is a pyroclastic flow deposit nearly instantaneously laid down that cools as a thermal entity. A **simple cooling unit** can comprise one depositional unit, or it can be made of two or more that are emplaced nearly simultaneously so that there are no internal cooling breaks, such as intervening less welded tuff (discussed later). Discerning boundaries between depositional units within a simple cooling unit can be challenging; compositional discontinuities and intervening surge and fall deposits can be helpful. A **compound cooling unit** consists of a succession of flows emplaced closely in time so that only partial cooling breaks occur between depositional units.

Composition of Deposits. Most ignimbrites are rhyolite; fewer are dacite, trachyte, and phonolite; andesite is uncommon. Juvenile pyroclasts are predominantly ash-size vitroclasts and lesser crystals. Larger cognate pumice lapilli are typical, whereas lithic lapilli can be conspicuous in some deposits. Crystals include euhedral to subhedral intact phenocrysts formed in the preeruption magma chamber and phenoclasts of the same ancestory but broken during eruption. These primary crystals may be very sparse, <1% of the deposit, but can range to as much as about 50%. Some lithic clasts are cognate crystalline fragments related to the erupted magma, such as from the crystallized wall of the magma chamber. Accidental lithic fragments (xenoliths) can be chunks of rock torn from the enlarging conduit during explosive eruption, wallrock from the preeruption magma chamber, and loose rock fragments on the ground picked up and incorporated into a turbulent flow. The proportion of lithic fragments, pumice clasts, and phenocrysts in the deposit can vary widely, each from 0% to as much as 50% or so, whereas juvenile vitric ash particles are always in abundance.

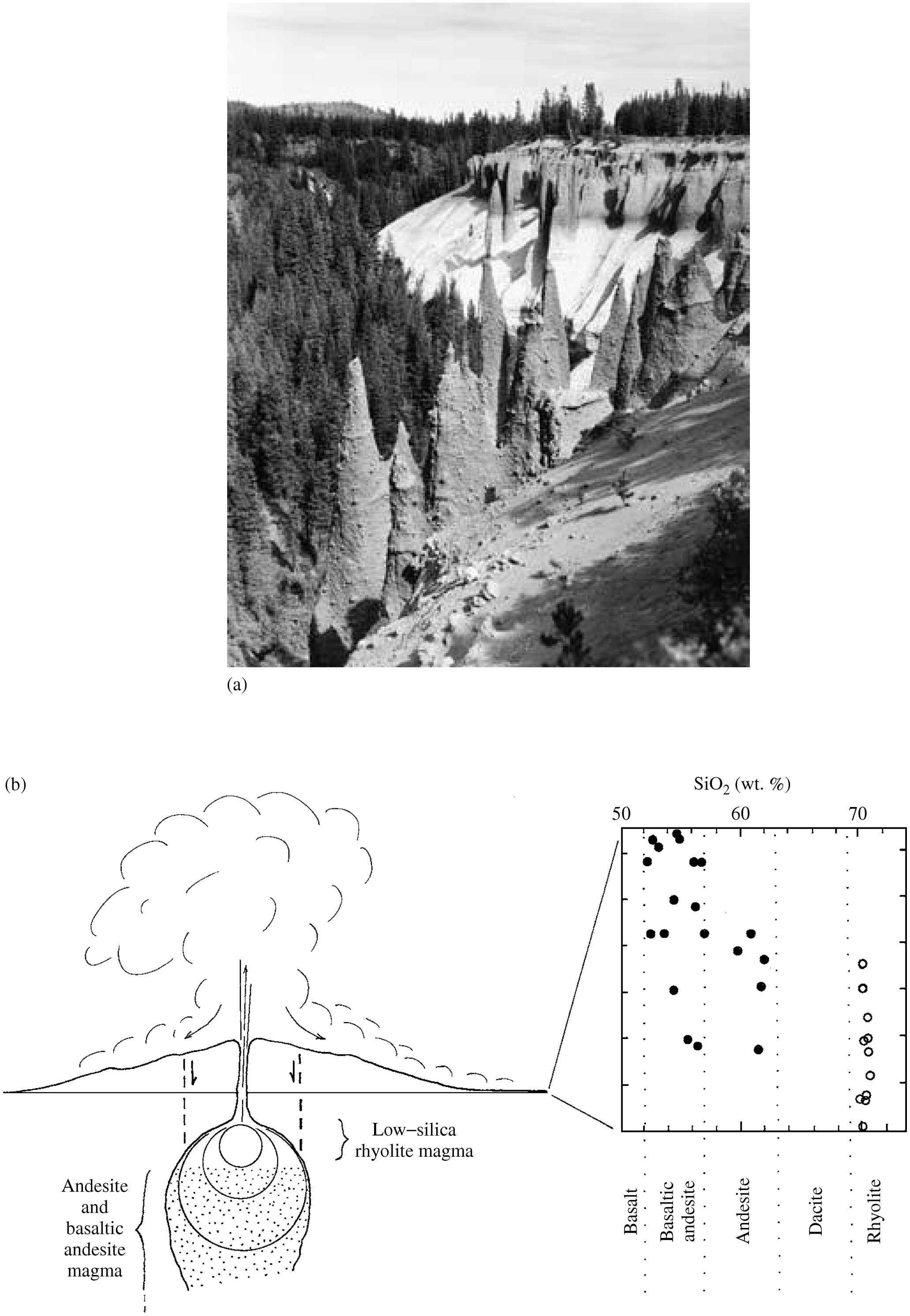
Compositionally zoned ignimbrites were first well documented by Lipman et al. (1966; see also Hildreth, 1981). In some of these ash-flow deposits zonation is cryptic and can only be discerned by laboratory analyses, whereas in others it is quite conspicuous in the field (Figure 10.38a). Normally, the proportion of phenocrysts in the rock, as well as their sizes, increase stratigraphically upward in the sheet, as do FeO, MgO, and CaO, whereas the lower part of the ignimbrite sheet has a more evolved composition. A common zonation is a basal, high-silica rhyolite overlain by low-silica rhyolite, by dacite, or, in instances of strong zoning, by andesite. In some deposits, lateral zonation is also evident from proximal parts near the source to distal parts tens of kilometers distant. Strong vertical and horizontal zonation in an ash-flow deposit may make it difficult to correlate isolated exposures of one depositional unit. Other useful correlation tools include precise isotopic dating and paleomagnetic analyses (Best et al., 1995).

Zoned ignimbrite deposits are derived by more or less systematic withdrawal from preeruption magma chambers that have compositional gradients (Figure 10.38b). The more evolved top of the chamber is erupted first; then successively deeper parts are erupted, producing, in the deposit, an *inverted* zonation of that in the chamber. It is obvious that a sample of bulk tuff in most instances does not accurately represent any of the preeruption magma; the tuff sample is an explosive mixture of pyroclasts derived from different compositional zones in the chamber. Moreover, the tuff has likely suffered some differential loss of fine vitric ash by elutriation from the ash flow. Unaltered pumice lumps hosted in the tuff, on the other hand, represent unmodified samples of the preeruption magma. Therefore, analyses of pumice best portray compositional variations in the preeruption magma body. Likewise, analyses of single glass shards, usually by electron microprobe, accurately reflect the melt composition.

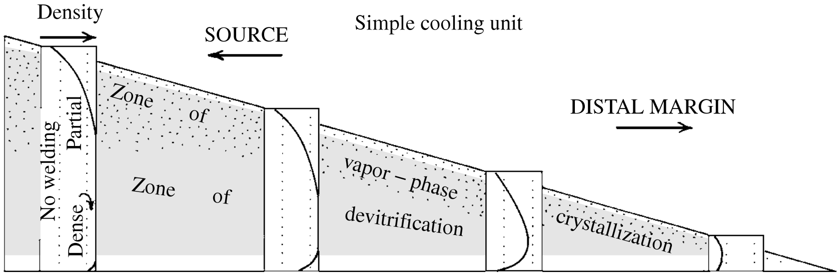
Secondary Zonation after Deposition. Ash-flow deposits commonly have other zonal features that are superimposed on any primary compositional zonation just described. Secondary processes formed during cooling of the hot mass of pyroclasts and entrapped gas include (Figure 10.39):

1. Welding and compaction
2. Vapor-phase crystallization of minerals from the entrapped gas
3. Devitrification (delayed crystallization) of the glassy material

Welding is the bonding of hot glass particles. Because of the weight of overlying pyroclasts on these soft sticky particles, they are compacted together and trapped gas is squeezed out, collapsing pore spaces and vesicles within pumice fragments and reducing the bulk porosity of the tuff. In some deposits, interstitial gas that is largely steam may be partially resorbed into vitroclasts, reducing their viscosity and, hence, promoting welding more or less independently of compaction (Sparks et al., 1999). But generally the most intense welding and compaction occur in the lower portion of the flow, though not at the base, where faster cooling prevents much welding (Figure 10.39). Welding and compaction operate simultaneously to create the typical eutaxitic fabric of welded ash-flow tuffs, in which pumice lapilli and glass shards are flattened into



10.38 Compositionally zoned, poorly sorted Mazama ignimbrite, Crater Lake National Park, Oregon. (a) The upper, slightly more welded and erosionally resistant part of deposit is crystal-rich hornblende andesite; the underlying lighter-colored part into which it grades without a sharp cooling break is a crystal-poor, low-silica rhyolite. Altogether, the deposit is an inverted representation of the compositional zonation in the source magma chamber. (Photograph by Oregon State Highway Department along Wheeler Creek.) (b) Explanation of compositional zonation. On the right, silica concentrations in *pumice* clasts in the ignimbrite, plotted against height in the deposit, correspond to bulk magma compositions in the zoned preeruption magma chamber, but upside down. On the left, cartoon illustrates how successive, increasingly larger "spheres" of magma withdrawal from the zoned chamber beneath ancestral Mount Mazama first tapped only uniform low-silica rhyolite magma, followed by deeper withdrawal of more variable mafic magma. After caldera collapse along ring faults (dashed lines), the depression filled with water to form Crater Lake. (From Bacon and Druitt, 1988.)



10.39 Idealized secondary zonation in a **simple ignimbrite cooling unit.** Vertical scale is exaggerated for clarity. Four upright rectangular panels show variation in density with respect to height in the unit and three degrees of related **welding and compaction**—dense, partial, and no welding and compaction. Dense welding occurs in lower two-thirds to half of unit near source. Zone of **vapor-phase crystallization** (stippled) is in upper part, and zone of **devitrification** (light shade) occupies most of cooling unit. All zonal boundaries and extents are highly variable in different deposits.

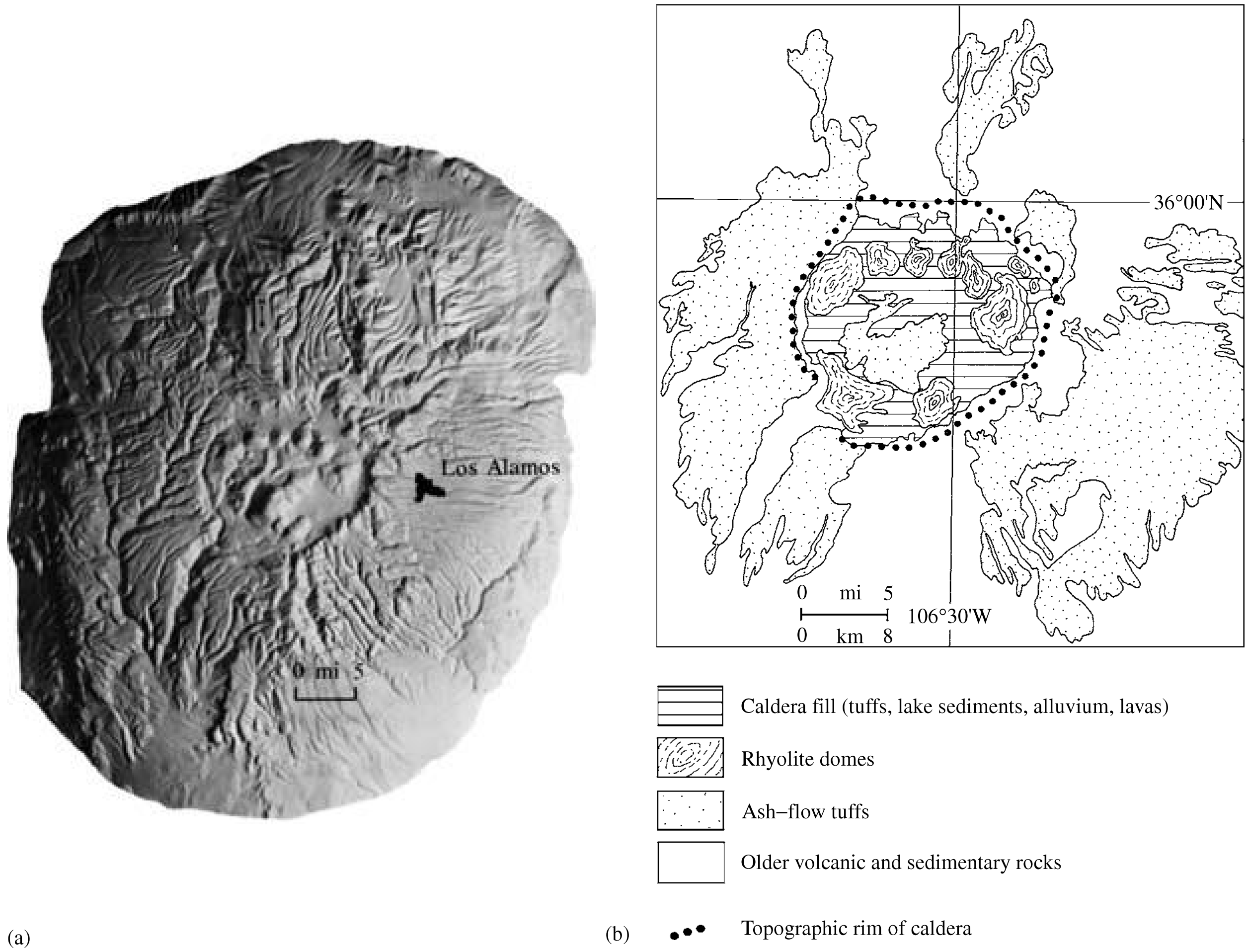
discoidal shapes more or less parallel to the depositional plane (Figure 7.34). The **compaction foliation** so expressed is enhanced by rigid inequant mineral grains, such as biotites and feldspars, that rotate in the soft glassy matrix during compaction and also become aligned in similar orientation to the flattened vitroclasts. Some densely welded tuffs with abundant lapilli and crystals, especially biotite, resemble foliated schists because of this well-developed planar fabric. Secondary **rheomorphic flowage** may occur where crystal-poor, high-*T* pyroclastic flows were deposited on slopes. Pumice lumps become extremely attenuated and lineated, even folded, particularly in alkaline, low-silica flows in which the glass is not highly viscous. Such **rheomorphic ignimbrites** may be difficult to distinguish from lava flows if the characterizing vitroclastic fabric is obliterated during flow.

Two types of secondary crystallization can occur simultaneously with welding and compaction in the hot ash-flow deposit. Trapped gas, which contains significant amounts of dissolved silica, alkalies, and other mobile chemical entities, migrates up through the permeable deposit and escapes into the atmosphere. Some gas collects into subvertical channels and vents at fumaroles (Figure 10.40). But **vapor-phase crystallization** takes place throughout the upper part of the deposit (Figure 10.39), where migrating gases cool and precipitate dissolved minerals in open pore spaces in the less compacted tuff. Minerals are mainly alkali feldspar, quartz, tridymite, and cristobalite. The other secondary crystallization that occurs in ash-flow deposits is **devitrification** of glass shards and pumice (Figures 7.35). Devitrification chiefly affects the middle to upper parts of the deposit; the lower boundary of devitrification against vitric tuff can be abrupt and sharp. In outcrop where this contact occurs within the welded zone, the devitrified tuff is red, pink, brown, or purple and the rock looks stony, in contrast to the black, glassy, underlying nondevitrified tuff (vitrophyre). In devitrified tuffs, aphanitic quartz-feldspar intergrowths, locally spherulitic or lithophysal, replace glass, but delicate pumiceous and vitroclastic textures are faithfully preserved, even though the rock may be entirely crystalline. In other instances, devitrification completely erases fragment outlines; vitroclastic and eutaxitic fabrics are obliterated and the tuff assumes a massive, featureless aphanitic fabric similar to that of many lava flows. The presence of phenoclasts, however, can reveal its pyroclastic origin.

10.4.8 Calderas

The distinction between a **caldera** (Figure 10.41; sometimes called a *cauldron*) and a **crater** is succinctly expressed by Williams and McBirney (1979, p. 207): "A caldera is a large volcanic collapse depression, more or less circular or cirquelike in form, the diameter of

10.40 Fossil **fumaroles** in a 150-m-thick section of the densely welded Bishop tuff in Owens River Gorge, California, east of its Long Valley caldera source (Figure 10.26a). Normally subvertical columnar joints in ignimbrite sheet (left) curve and converge into fumarole conduit (partly in shadow, right). Remnant fumerole mound on top of sheet can be seen in left background.



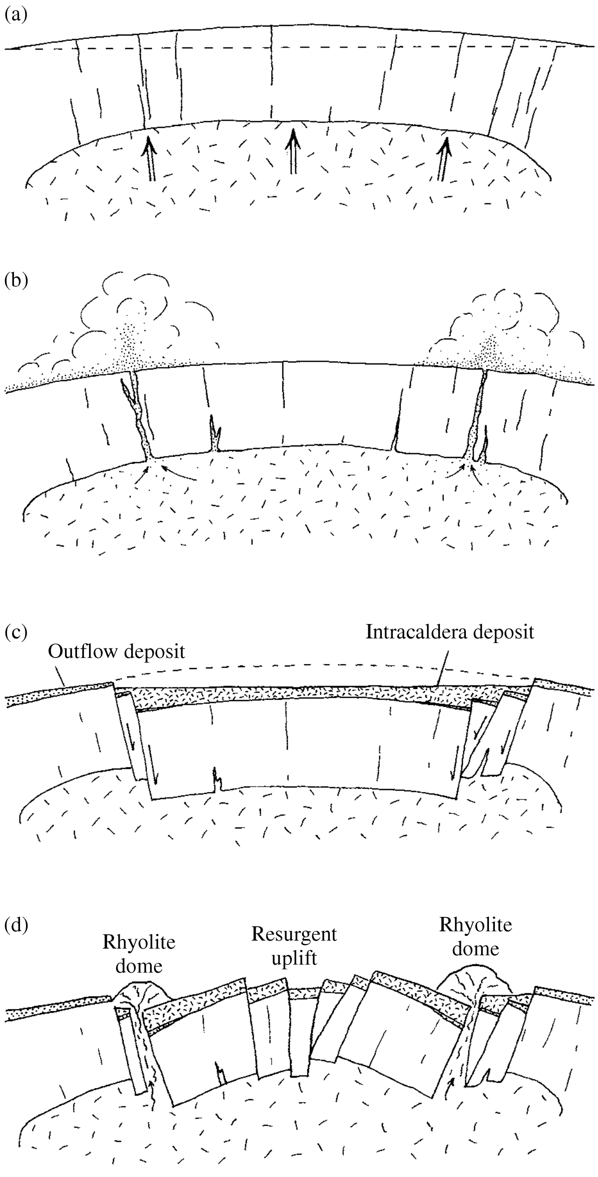
10.41 Plio-Pleistocene Valles **caldera** and related outflow ignimbrite sheet, New Mexico (Figure 10.35). (a) Relief model made by Stephen H. Leedom from U.S. Geological Survey relief maps. (b) Generalized geologic map. Faults have been omitted for clarity. The patchy distribution of the ignimbrite outside caldera is due to the uneven topographic features onto which it was deposited as well as to subsequent erosion. (Redrawn from Smith and Bailey, 1968.)

which is many times greater than that of any included vent. A crater may resemble a caldera in form but is almost invariably much smaller and differs genetically in being a constructional form rather than a product of destruction."

Contrary to widespread lay belief, calderas, such as the one that holds so-called Crater Lake, Oregon, did not form when the volcano "blew off its top," as Williams (1941) astutely observed. Had it done that, there would be a volume of accidental rock fragments in the pyroclastic deposit matching the volume of the caldera. This is definitely not the case, for the deposit is almost entirely juvenile vitric pyroclasts (Figure 10.38a).

Calderas form where a substantial volume of magma is withdrawn from a subterranean magma chamber in a geologically short time and the unsupported rock roof over the evacuating chamber collapses into the growing void (Figure 10.42). Calderas related to ash-flow eruptions are thought to begin where overpressured magma fractures the roof, forming one or more extrusive conduits, possibly along arcuate ring fractures. Initial eruptions create an extracaldera outflow sheet. After some critical volume of magma has been vented, the unsupported roof subsides into the chamber. The sinking, denser roof rock possibly adds a driving force for continued expulsion of less dense magma that can accumulate to thicknesses of kilometers inside the caldera, depending on the amount of draw-down, forming an intracaldera tuff deposit.

The exact manner of caldera collapse (Lipman, 1997) is commonly difficult to establish because of incomplete exposures and erosion. Some roofs subside as more or less intact plates, or pistons, inside a circumscribing ring fault. Others fracture into blocks that subside in piecemeal fashion; still others, only partially circumscribed by a fault, subside in a hinged, or trapdoor, manner. Yet other roofs flex or downsag rather than subside along faults; these might form over deeper evacuating magma chambers.



10.42 Schematic cross sections illustrating the generalized evolution of a **caldera** of the Valles type (Figure 10.41). (a) Doming of the roof over the intruding magma and formation of ring fracture system. Dashed line is original ground surface. (b) Initial eruption of ash flows from ring fracture(s) forms ignimbrite outflow sheet; partial evacuation of magma chamber. (c) Continued ash-flow eruption causes caldera collapse guided by existing ring fractures in roof and partially fills depression with intracaldera ignimbrite deposit. Collapse of steep caldera wall that forms intracaldera landslide breccias is omitted here for clarity. Additional postcaldera deposits in depression may consist of lake sediments and volcanic deposits from nearby sources. (d) **Resurgent uplift,** doming, and fracturing of central block due to renewed magmatic activity. Effusion of viscous rhyolite lava along ring fracture peripheral to central block forms an arcuate group of domes. (Redrawn from Smith and Bailey, 1968.)

During subsidence of fault-bounded calderas, high, steep, unstable walls along the caldera margin collapse in landslides to form lenses of breccia intercalated within the accumulating intracaldera tephra. Breccia is commonly made of house-size blocks. Such wall-collapse breccias of older rock are definitive evidence that subsidence accompanied eruption of the tephra. A thick pyroclastic deposit with no interlayered breccia within a caldera could be subsequent filling from a later nearby eruption.

Sometime after collapse, a caldera floor may be uplifted, creating a **resurgent uplift** (Figure 10.42d). The amount of time involved and the mechanism of resurgence vary.

10.4.9 Subaqueous Pyroclastic Flows

Because pyroclastic eruptions most commonly occur in subduction zones along continental margins and island arcs it is inevitable that some ash flows either enter bodies of water from subaerial sources or have a subaqueous vent. Several questions follow from this inference. Given that ash flows have a density slightly more or less than that of water, what happens when they contact lakes or the sea from subaerial sources? To what extent do ash flows maintain their high eruptive T (as high as 600°C) in bodies of water? What water depth would suppress pyroclastic flow generation if eruption were subaqueous? Are there unique properties of subaqueous ash-flow deposits in the rock record that set them apart from strictly subaerial ones? Does deposition of a flow that consists of low-density pumice clasts, denser but smaller glass shards, and still denser crystals in water produce sorting not evident in subaerial deposits?

Subaerially generated ash flows from the August 1883 eruption of Krakatau in the Indonesian archipelago entered the sea around the island and created submarine deposits as much as several tens of meters thick that are virtually identical to corresponding subaerial ones on the island (Sigurdsson et al., 1991). Paleomagnetic studies indicate emplacement temperatures in cored samples of the submarine deposit to be 350–550°C. Historical observations of other subaerially generated ash flows indicate a denser basal flow traveled beneath sea level and a more dilute and buoyant upper part swept across the ocean for tens of kilometers. Mesozoic ignimbrite hundreds of meters thick filling a partially preserved submarine caldera in a roof pendant in the Sierra Nevada batholith, California, was deposited in water 150 m or less in depth (Kokelaar and Busby, 1992). Beneath a carapace of bedded and sorted ash-fall tuff, massive unsorted tuff is densely welded and eutaxitic, indicating emplacement temperatures of possibly >500°C.

Other submarine pyroclastic deposits are bedded and sorted and have been depleted in fine ash carried away in suspension. See Fisher and Schmincke (1984) and Cas and Wright (1987) for further discussion of subaqueous pyroclastic flows.

❊10.5 OTHER VOLCANICLASTIC DEPOSITS

Locally extensive subaerial deposits of fragmental volcanic rock owe their origin not to explosive processes but to the mobilizing effects of water and the downhill driving force of gravity. Some of these volcaniclastic phenomena and their related deposits are a direct consequence of volcanic activity that destabilizes rock material on a slope. Others are only indirectly related to volcanism, and still others are epiclastic in nature and involve weathering, transport, and deposition of rock and sediment, especially through the agency of running water.

10.5.1 Epiclastic Processes and Deposits

During repose intervals between extrusions of magma, volcanic material on slopes is subject to epiclastic processes. The building up of a volcanic edifice is counteracted by erosion wearing it down toward base level. Locally, some of this eroded material accumulates as an epiclastic, or sedimentary, deposit.

All of the explosive volcanic processes described so far in this chapter create deposits of loosely consolidated material susceptible to subsequent transport and deposition by wind and running water. Additionally, coarse autoclasts on margins of lava flows are amenable to transport by water on steep slopes. **Reworked volcanic deposits** display features typical of most fluvial epiclastic deposits, such as abrasion of clasts, cross-bedding, and lenticular beds. Because of these similarities, it is commonly difficult to distinguish between reworked deposits formed from pyroclastic material that was never consolidated and epiclastic deposits formed from fragments produced by weathering and disintegration of consolidated volcanic rocks. Deposits consisting chiefly of volcanic fragments, regardless of origin, can be simply classified on the basis of grain size and referred to, for example, as *volcanic sandstone*.

10.5.2 Volcanic Debris Flows: Lahars

Currently, the Indonesian word **lahar** has a dual usage, applied to

1. A mass of intimately mixed water and rock material moving under the influence of gravity down the slopes of a volcano, also referred to as a **volcanic debris flow**
2. The resulting deposit (Figures 7.27 and 10.43).

These lahars or volcanic debris flows generally consist of a wide range of unsorted blocks and lapilli suspended in a water-saturated mud (ash) matrix that imparts mobility to the body. Their viscoplastic rheology resembles that of lava flows. Thus, lahars move in plug manner (Figure 8.13b) with lateral levees and fairly steep margins; their yield strength enables large blocks to be transported. An important component of lahars is clay, most typically derived from hydrothermally altered rock exposed on the volcano. Clay-rich rock at the lahar source promotes generation by slope failure because clays can hold large amounts of water, adding to the weight of the mass. Wet clay also facilitates transformation of rock avalanches into debris flows as water is released from the clay into the flow.

10.43 Lahars or **volcanic debris flows** on the flank of Mount Rainier, Washington (Fiske et al., 1963). The steep dips, to as much as 30°, are primary dips in this 50-m-high cliff face. Note crude vertical erosional columns and lenses of partly brecciated lava alternating with debris flows. Compare Figure 7.27. (Photograph courtesy of C. A. Hopson.)

Lahars can be generated in many different ways, and transformations in rheology and flow regime during downhill movement are typical (Smith and Lowe, 1991). Two end-member origins are dilution, whereby water is added to rock fragments, destabilizing and mobilizing the mass, and bulking, whereby fragments are added to water from the eroding bed. Hot lahars can be created as pyroclastic flows merge with external water. For example, about 4500 y ago a rhyolite pyroclastic flow was produced by catastrophic sector collapse on the side of Cotopaxi volcano, Ecuador (Mothes et al., 1998). The combination of the hot pyroclastic flow, high elevation (5890 m above sea level), covering thick ice cap, and 3 km of relief produced a 3.8-km^3 lahar that descended river systems 326 km to the Pacific Ocean and >130 km to the Amazon basin. Lava flows and domes can also generate hot lahars as the lava contacts snowfields and glaciers typically found on slopes of lofty composite volcanoes (discussed later). Alternatively, rivers can be bulked with hot pyroclasts to create hot lahars. Autoclastic envelopes around the lava as well as fractured, rigid lava in the massive core can be swept up and move downslope in a bulking stream. Sectors of cold domes may also collapse, forming rockfall avalanches of dry rock blocks (e.g., Chaos Jumbles in Figure 10.18). If avalanches ingest sufficient water they may transform, by dilution, into lahars. Pyroclastic fall deposits on volcano slopes can be diluted and mobilized by heavy rainfall during eruption as eruptive steam cools and condenses, or by chance concurrent torrential tropical storms (as at Pinatubo in June 1991), or at some time after eruption. Crater lakes at volcano summits can be breached and the flood waters bulked by picked-up loose rock debris. At the distal end of the lahar runout, commonly in confined downslope channels, water and fine particles may drain from the coarser flow mass to create hyperconcentrated flows, or mudflows, and these, in turn, can transform into more or less normal streams of sediment-laden water.

Unquestionably, the largest lahars originate from catastrophic collapse of unstable domes (Cotopaxi) or summit sectors of high composite volcanoes, such as occurred at Mount Saint Helens on May 18, 1980 (Figures 10.1 and 10.20). Unstable sector collapse also occurs on more gently sloping flanks of oceanic island shield volcanoes, as shown in Figure 10.11b, c.

Lahars are generally confined to existing topographic depressions (Figure 10.20). Lahars can be *monolithologic,* as clasts were derived from a single source, such as a lava flow that broke up as it entered a snowfield, or *heterolithologic,* where multiple sources fed the lahar. Near-source lahars are made of chaotic, extremely poorly sorted angular clasts. Farther traveled lahars tend to be better sorted and to be locally stratified deposits; clasts tend to show better rounding, either as a result of abrasion during transport or of accumulation of previously more rounded erosional rock debris. Farther transported clasts have a smaller mean fragment size. Nonetheless, huge blocks tens to hundreds of meters across can be rafted tens of kilometers from the source, forming the hummocky ground surface that is typical of lahars as well as rock avalanches.

Discriminating between a lahar and other volcaniclastic and epiclastic deposits (e.g., glacially deposited diamictite) can be challenging. Hot lahars can be identified by the presence of blocks in which radial cracks have formed by cooling and contraction during flow after incorporation from a hot source. Paleomagnetic analysis may disclose a common magnetization direction acquired in the geomagnetic field during cooling of clasts; had the clasts cooled and magnetized prior to incorporation into the flow their magnetization directions would be random.

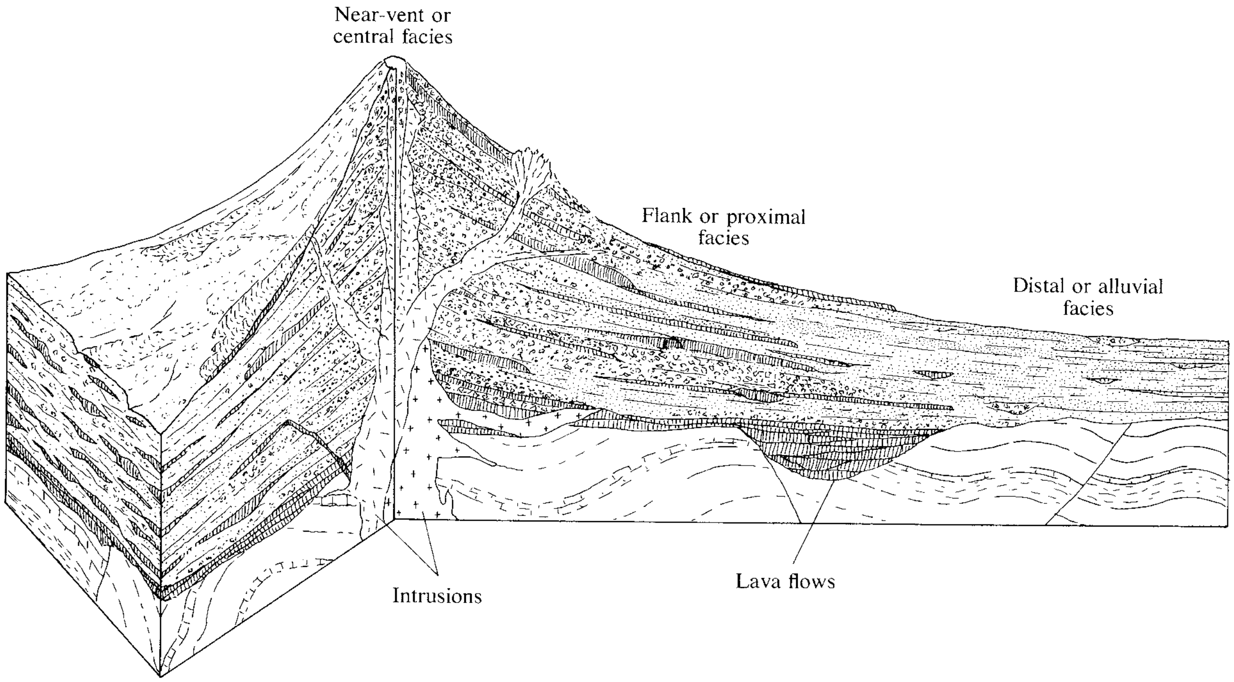
10.5.3 Composite Volcanoes

Composite volcanoes are the lofty, more or less symmetric conical photogenic landmarks that most people consider to be volcanoes. Most active or recently active volcanoes in subduction zones around the margin of the Pacific Ocean, in the Caribbean, and in the Mediterranean are of this type, including famous ones such as Fujiyama in Japan, Vesuvius in Italy, Mayon in the Philippines, and Mount Saint Helens (Figure 10.1), Shasta (Figure 10.2), and Lassen Peak (Figure 10.18) in the Cascade Range of the Pacific Northwest of the United States. Many composite volcanoes reach great heights because they rise a few kilometers above an already elevated platform of older volcanic deposits and deformed basement rocks in the orogenic belt. Although it is imposing topographically, any one composite volcano (Figure 10.6) has a total volume that is less than might be anticipated. Fujiyama, one of the largest, has a volume of approximately 870 km^3.

A **composite volcano,** also called a **stratovolcano,** is built mostly of andesitic and dacitic magmas extruded from a central vent and consists of, as the names imply, innumerable alternating tongues of lava and volcaniclastic deposits, especially lahars (Figure 10.44). Until removed by erosion, a small crater lies at the summit. Locally, magma may be extruded from flanking central vents, forming **parasitic cones** (Figure 10.2). Magma solidified within feeder conduits and minor fissures as plugs, dikes, and sills forms a reinforcing skeleton for the edifice. The steep slope of composite volcanoes reflects the following compound factors:

1. Relatively small volume and low rates of extrusion of viscous magma that does not move far from the central vent summit
2. Near-vent ballistic ejecta resting at its angle of repose of about 30–35°
3. Viscoplastic rheology of debris flows, which are a major component of any composite volcano

The effusive and volcaniclastic deposits that composite volcanoes comprise can be divided into central, proximal, and distal facies (Figure 10.44; see also Williams and McBirney, 1979, pp. 312–313). The central or near-vent facies (within about 2 km of the central vent) is a bewildering array of structures and both intrusive and extrusive rock that are commonly hydrothermally altered. Thin lava flows are subordinate to coarse, poorly sorted volcaniclastic deposits with steep initial dips. The proximal or flank facies (up to roughly 5 to 15 km from the central vent) comprises thick lava flows; lahars with subangular, coarse clasts; and some reworked clastic deposits. Zones of weathering and soil development may occur between layers of lava and volcaniclastic deposits. The distal facies comprises layers of rock with considerable lateral continuity formed of well-sorted and fairly well-bedded lahars and epiclastic deposits of rounded clasts; interstratified lake deposits may occur, and lava flows are restricted to less viscous types that flowed down valleys.



10.44 Idealized cross section through a **composite volcano** showing alternating layers of lava and volcaniclastic material cut by dikes, sills, and plugs, some of which feed surface lava extrusions. The platform on which the volcano rests is a hypothetical mass of folded and faulted sedimentary rocks capped by a sequence of basalt and andesite flows. Different facies of the composite volcano are discussed in the text. (Redrawn from Williams and McBirney, 1979.)

SUMMARY

The manner of magma extrusion is recorded in the field relations of layered volcanic deposits (stratigraphy) and their fabric. Whether extrusion is by explosive dispersal of pyroclasts or effusive flow of coherent lava depends on the dissolved volatile concentration in the melt, how the volatiles exsolve, possible interactions between external water and the magma, and the apparent viscosity of the magma. Volatile-poor magmas generally extrude as lavas. Low-viscosity lava flows, the most common of which are basaltic, are small-aspect-ratio (thickness/horizontal extent) sheets or streams of pahoehoe, aa, or subaqueous pillow lava that can travel tens or even hundreds of kilometers from their vent source on gentle slopes. Large apparent viscosities with a significant plastic yield strength, such as in high-silica and/or highly crystalline magmas, create large-aspect-ratio lava domes that pile high over the vent. High rates of discharge from the volcanic vent can decrease the aspect ratio.

Explosive eruptions, generally of volatile-rich silicic magmas, disperse pyroclasts mixed with hot gas in volcanic plumes. Plumes can be convecting plinian, or collapsing columns, or a combination of these two. Large concentrations of exsolving and expanding volatiles create high magma discharge velocities, especially where vent diameters are small, promoting high gas thrust that drives plinian plumes tens of kilometers above the vent. As upward momentum provided by expanding gas diminishes above the vent, convective heating of entrained air gives buoyant lift to the plume. Larger vent diameters and lower gas contents favor collapsing columns in which pyroclasts fall immediately around the vent for lack of upward momentum and/or lack of convective transfer to entrained air into massive columns. A common scenario is initial plinian activity that degrades into a collapsing column as the vent is reamed out, enlarging its diameter, and less volatile-rich magma is erupted. However, many possible combinations of plinian and collapsing fountain are possible during a particular eruptive episode, even concurrent play of both from a particular vent system.

Dispersed pyroclasts in plumes are transported to their site of deposition by three processes—fall, surge, and flow. Largest clasts follow ballistic trajectories and generally fall near the vent. Smaller clasts, generally of lapilli and ash size, fall vertically from plumes and are transported horizontally in surges and flows. Transport distance and depositional characteristics depend on many factors, including particle size, density, shape, trajectory (horizontal versus vertical), and concentration, which can fluctuate through the time of activity of the surge, flow, or fall process. Pyroclastic fall deposits are mantle-bedded, and are generally finer and increasingly better sorted with respect to particle size away from the vent. Beds may be normally-graded or reverse-graded.

In pyroclastic surge and flow horizontal transport occurs from the base of a collapsing column as a mixture of pyroclasts and hot gas. Surges have dilute particle concentrations and their moderately sorted deposits lie within 1 km or so of the vent. Plane-parallel surge beds are widespread, but other bedforms that can indicate direction of transport include wavy beds, low-angle cross beds, climbing dunes, and ballistic-clast sags. Near-vent accumulations of basaltic tephra built by pyroclastic surges and ballistic ejecta form tuff cones, tuff rings, and, if a below-ground-level crater is explosively excavated, maars and diatremes. Pyroclastic flows have high particle concentrations and produce massive unsorted deposits. Small block-and-ash flows, whose volume is generally <0.01 km^3, are generated by collapse of a lava dome at the summit of a volcano and happen dozens to hundreds of times in an episode of activity at a subduction-sited composite volcano. Larger ash-flow, or ignimbrite, eruptions occur less frequently at a particular locale; deposits of ash and lapilli can be hundreds of meters thick (a few km in caldera depressions), extend over a hundred kilometers from source, and have volumes as much as thousands of cubic kilometers. The considerable mobility of hot pyroclastic flows results from their potential energy inherited from the collapsing massive column and their endowment of gas that produces partial fluidization. As some of the fluidizing gas escapes from the avalanche it carries with it the finer, mostly vitric ash and creates an overlying coignimbrite plume that produces downwind beds of fine ash. Escaping gas in deposits promotes vapor-phase crystallization in pore spaces, which accompanies devitrification and welding and compaction of the ignimbrite after deposition.

A wide spectrum of explosive style is dictated by the range in magma composition and volatile content. Least explosive are Hawaiian eruptions, in which basaltic lava fountains build near-vent spatter deposits and streams of lava, some formed as rootless flows of molten spatter, and flow away from the vent. Strombolian eruptions of a boiling top of the basaltic or andesitic magma column exposed in the vent throw out ballistic ejecta, forming a cinder (scoria) cone; lava flows away from the vent area. Vulcanian eruptions commonly begin with steam blast ejection of accidental clasts and then proceed to ejection of juvenile clasts as the ascending column of magma is exposed. At the most explosive end of the spectrum are plinian and ash-flow eruptions. Plinian eruptions create lofty plumes of ash and pumice lapilli, fallout from which creates bedded and sorted pyroclastic fall deposits.

Explosiveness and magma viscosity govern the character of volcanic edifices, or landforms. Steep, conical composite volcanoes are created by countless central eruptions over a million years or so of relatively viscous andesitic-dacitic lava and exploded ballistic ejecta accumulating near vent and pyroclastic flows and debris flows (lahars) sweeping farther downslope. Enormous floods of basaltic magma create oceanic plateaus on the seafloor. Fissure-fed floods create continental plateaus in just a few million years. Gently sloping, fissure- and central-vent-fed basaltic shield volcanoes grow in a half-million years or less. In contrast to these long-lived, focused extrusions, monogenetic extrusions of basaltic lava build strombolian cinder (scoria) cones and isolated lava flows in less than a few years, forming small basaltic lava fields.

CRITICAL THINKING QUESTIONS

10.1 Characterize conditions that allow explosive versus effusive extrusions of magma.

10.2 Describe and account for the contrasts in effusions of basaltic and silicic lavas.

10.3 Discuss the nature of explosive volcanic plumes and controlling factors in their development.

10.4 Summarize styles of explosive eruption in terms of explosiveness, associated volcanic plumes, and pyroclastic deposits that are produced.

10.5 Discuss the origin of volcanic edifices, explaining the contrasts in their shape and how they are built up above ground level or extend below.

PROBLEMS

10.1 Devils Tower in the northeastern corner of Wyoming is a mass of rock that rises 260 m above the surrounding plain and has spectacular subvertical columnar joints. It is often said to represent a volcanic neck, the feeder conduit of now-eroded overlying lava flows. Make a sketch of the tower and critique this explanation.

10.2 Make a sketch of Figure 10.10b showing how the radial arrays of joint columns in the entablature could have been produced by isotherms perturbed by water entering in widely spaced fractures.

10.3 Describe, or diagram, the transformations and transfers of conserved energy in a volatile-rich magma that take place from its generation by thermally induced partial melting in the deep crust, through explosive venting into a plinian plume, and final deposition in ash-fall beds.

10.4 In Figure 10.38b, why are there both rhyolite and mafic pumices in the Mazama ignimbrite deposit from heights of about 15 to 35 m, whereas there are only mafic above and rhyolite below?

10.5 Draw topographic profiles of hilly terrain on which you characterize and distinguish between the field relations and fabric of pyroclastic fall, surge, and flow deposits.