CALDERAS

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GLOSSARY

ash, volcanic Fine pyroclastic material, down to dust size, that is formed by explosive volcanic eruptions.

ash-flow tuff Rock formed by the deposits of pyroclastic flows. Synonymous with ignimbrite; common usage in North American literature.

crater A bowl- or funnel-shaped depression, generally in the top of a volcanic cone, often the major vent for eruptions.

ignimbrite Pyroclastic-flow deposit. Synonymous with ash-flow tuff.

intrusion A subsurface igneous rock body formed when molten igneous rock forces its way into surrounding host rocks and then cools.

magma Molten rock material with dissolved gases that forms igneous rocks on cooling; magma that reaches the surface erupts as lava or pyroclasts.

magma chamber An underground reservoir in the Earth's crust filled with magma, from which volcanic materials are erupted.

pyroclastic flow Laterally transported, fluidized mass of hot dry rock fragments mixed with hot gases. Moves away from a volcano at high speeds.

welded tuff A hard pyroclastic rock compacted by internal heat and the pressure of overlying deposits. Forms the interiors of thick ash-flow (ignimbrite) sheets.

CALDERAS ARE LARGE volcanic depressions, more or less circular in form, the diameter of which is many times greater than that of included vents. Formation of calderas, by some form of roof collapse over an underlying shallow magma reservoir, is now widely recognized as accompanying most eruptions that involve magmatic volumes greater than a few cubic kilometers. Small calderas (<5 km in diameter) associated with lava eruptions are common at crests of basaltic and andesitic volcanoes; calderas as much as 75 km in largest dimension have formed during large ignimbrite (ash flow) eruptions. In general, caldera diameter increases in proportion to volume of the associated eruption. Diverse subsidence geometries and collapse processes for ash-flow calderas are inferred to reflect varying sizes, roof geometries, and depths of the source magma chambers, in combination with preexisting volcanic and regional tectonic influences.

I. INTRODUCTION: CALDERAS AND ERUPTIVE PROCESSES

Calderas have been much studied during the past half century, stimulated by recognition of their association with large ash-flow sheets and by several landmark reviews (see Further Reading), yet the processes of caldera formation remain incompletely understood and controversial. Origin dominantly by subsidence has been overwhelmingly recognized, with only minor proportions of the caldera volume being generated by explosive ejection and removal of older rocks. In their origin by subsidence, even small calderas are thus distinct from large volcanic craters that form by constructional accumulation of cinders and spatter or by explosive ejection of wall rocks adjacent to a volcanic vent. Varied processes have been inferred as important or dominant: piecemeal or chaotic subsidence, plate (piston) subsidence of a relatively coherent floor bounded by ring faults, funnel-shaped subsidence into an areally restricted central vent, and hinged downsag of a central area with little or no boundary faulting. Many calderas are geometrically complex, containing elements of more than a single structural type and subsidence process. Most caldera subsidences have been attributed to collapse accompanying or following large-volume eruptions, but inception of subsidence at some calderas has been attributed to subsurface movement of magma, which in turn may have triggered an eruption. The term caldera, as used here, includes features previously described as "cauldrons," which are considered to represent deeper erosional levels of the same fundamental structures and igneous processes. In many volcanic areas, successive large eruptions and associated overlapping subsidence events have produced caldera clusters that have complex resulting geometries and structures.

In addition to real diversity among caldera structures, the divergent interpretations of dominant subsidence processes reflect ambiguities resulting from the large dimensions of many calderas, gross slumping of caldera walls, incomplete cross-sectional exposures, overprinting by postsubsidence structures, and resulting uncertainties about subsidence geometries. Little-eroded young calderas with well-preserved eruptive morphology generally provide minimal direct information on underlying structures, depth of subsidence, or relation to the source magma reservoir. In contrast, where erosion has proceeded sufficiently to expose subvolcanic structures and granitic rocks of the solidified magma reservoir, the relations of such structures and intrusions to individual eruptions and to surface volcanic morphology commonly have been largely obscured. Complete sections from surface volcanic rocks to deep features of ash-flow calderas are preserved and exposed only rarely—in regions of exceptional topographic relief or sites of rapid tectonic rotation of the upper crust. Geophysical studies and drill-hole information can provide important additional information on caldera geometry and structure, although geophysical models are commonly ambiguous due to uncertain physical properties at depth. Few drill holes penetrate deeply through the fill of large calderas.

On Earth, calderas have been recognized throughout the documented geologic record, back into Archean time, and likely were part of faintly preserved earlier processes of crust formation, as suggested by evidence from other planetary bodies. Calderas of varying sizes are associated with virtually every type of volcanic activity, including summit calderas on basaltic shields of oceanic islands and andesitic stratocones of volcanic arcs. Larger calderas are commonly associated with regions of crustal extension, both within volcanic arcs and in continental rift zones; the largest calderas have formed in regions of thick continental crust. Even larger calderas have been imaged on other planetary bodies, such as Olympus Mons on Mars. Some representative terrestrial calderas, cited in this review, are listed in Table I. Especially informative are many recent studies of the numerous Tertiary calderas in the western United States and in Japan, although only a few of the latter are readily accessible in the international literature.

A. Historical Development of Geologic Concepts

Early 19th century interpretations that large volcanic depressions represent the collapsed crests of structural uplifts ("craters of elevation") or explosive excavation were gradually abandoned later in the century, largely in response to careful observations at La Palma in the Canary Islands (probably the type locality for the term caldera) by Lyell, at Kilauea in Hawaii by Dutton, and at Santorini in the Aegean by Fouqué, and especially by the evidence developed by Verbeek for the great 1883 Krakatau eruption in Indonesia.

Early in the 20th century, arcuate intrusions and ring faults bounding subsided blocks were described as cauldron structures in Scotland by Clough, Bailey, and others; similar structures were recognized in the San Juan Mountains in the United States by Cross and Burbank.

TABLE I Some Well-Documented Caldera Eruptions

Date	*Caldera name*	*Location*	*Edifice; structure*	*Topographic caldera diameter (km)*	*Eruption volume [km^3 (DRE)*	*Reported collapse geometry*
1991	Pinatubo	Philippines	Stratocone	2.5	4–5	Funnel?
1968	Fernandina	Galapagos	Basaltic shield	5 × 6	0.1	Trapdoor; composite
1912	Katmai	United States	Stratocone	2.5 × 4	12	Funnel?
1883	Krakatau	Indonesia	Clustered stratocones	8	10	Funnel?
1750–1790?	Kilauea	Hawaii	Basaltic shield	3 × 5	??	Plate
1.4 ka	Rabaul	Papau, New Guinea	Volcano cluster	10 × 15	11	Plate
1.8 ka	Taupo	New Zealand	Rift/caldera cluster	35	35	Downsag?[a]; composite
3.6 ka	Santorini	Mediterranean	Volcano cluster	7 × 10	25	Composite
7.7 ka	Crater Lake	United States	Volcano cluster	8 × 10	55	Plate
22 ka	Aira	Japan	Caldera cluster	18 × 22	300	Funnel?[a]
35 ka	Campi Flegrei	Italy	Volcano cluster	13	80	Plate
75 ka	Toba	Indonesia	Dacitic arc; fault zone	30 × 80	1500	Plate (R)[b]
95 ka	La Primavera	Mexico	Volcano cluster	11	20	Plate
600 ka	Yellowstone	United States	Caldera cluster	60	1000–2000	Plate (R)
760	Long Valley	United States	Older volcanoes	15 × 30	600	Plate (R)
1.1 Ma	Valles	United States	Volcano cluster	20 × 22	300	Plate (R)
2.2 Ma	Cerro Galán	Argentina	Volcano cluster	25 × 35	2000	Plate (R)
2.8 Ma	Chegem	Russia	Collision zone	15 × 20	>300	Plate?
5.6–3.8 Ma	Dorobu	Japan	Caldera cluster	6 × 13	??	Piecemeal, composite
25.9 Ma	Lake City	United States	Caldera cluster	15 × 20	200–500	Plate (R)
26.6 Ma	Creede	United States	Caldera cluster	24	>500	Plate (R)
27.6 Ma	Silverton	United States	Caldera cluster	15 × 20	50–100	Trapdoor
27.8 Ma	La Garita	United States	Volcano cluster	35 × 75	5000	Multiple plates? (R)
73 Ma	Tucson	United States	Andean arc	25	>500?	Trapdoor
Ordovician	Scafell	England	Volcanic arc	>15	??	Piecemeal (composite?)

[a] Alternatively interpretable as plate subsidence.
[b] (R), resurgent postcollapse uplift of caldera floor.

By the mid-20th century, the subsidence origin of many volcanic calderas was emphasized by Williams in his study of Crater Lake in Oregon (Fig. 1) and his comprehensive 1941 review "Calderas and Their Origin," by Matumoto's concurrent identification of large clustered calderas in southern Japan, and by later recognition of the Valles resurgent caldera type by Smith and Bailey. More recent studies have built on these concepts to decipher stratigraphy and structure of caldera-related volcanic deposits, constrain timing of eruption and collapse, determine compositional and temporal relations between volcanism and solidification of subcaldera magma chambers, and document unrest and precursors to large caldera-forming events for hazards evaluation. Volcanic studies of calderas have also been applied to societal needs to utilize volcano-generated ore deposits, generate electrical power from geothermal heat, and evaluate potential effects of large caldera eruptions on global climate.

B. Notable Historical Eruptions

Much has been learned about caldera-forming processes from historical eruptions, although none have been on the scale of the largest older caldera-forming eruptions evident in the geologic record. Well-documented historical and near-historical caldera-related eruptions include Pinatubo (1991), Fernandina (1968), Katmai (1912), Krakatau (1883), Kilauea (1750–1790?), Taupo (1.8 ka), and Santorini (3.6 ka). Such young volcanoes

FIGURE 1 Crater Lake caldera, United States, as viewed from its south rim. The caldera formed 7700 years ago by collapse of the volcano known as Mount Mazama. The prominent cliff on the north caldera rim, Llao Rock, is a rhyodacite lava flow erupted within a few hundred years before the caldera-forming eruption. The cinder cones and lava flows of Wizard Island are the top of a 1- to 2-km^3 andesitic cone, erupted soon after caldera collapse. [Photograph by C. R. Bacon, U.S. Geological Survey.]

provide only limited information on the internal structure of magmatic systems, however, in comparison with exposed features of deeply eroded older volcanic edifices. Complementary study of both young and ancient volcanic systems (Table I) are needed to understand caldera-forming processes.

The 1991 eruption of Mount Pinatubo in the Philippines, during which a small caldera (2-km diameter) formed during eruption of 4–5 km^3 (DRE, dense-rock equivalent) of ignimbrite and tephra-fall deposits, has been the best monitored caldera-forming event thus far. This eruption demonstrated that caldera collapse can accompany even relatively small-volume pyroclastic eruptions. The timing of the recurrent subsidence events can be inferred from several peaks in seismic energy release during the eruption.

In 1968, subsidence of 300 m within the summit caldera of the Fernandina basaltic shield in the Galapagos was preceded by a subaerial eruption that was an order of magnitude smaller than the volume of caldera collapse. This event confirmed previous inferences that basaltic calderas can subside recurrently in response to subsurface magma withdrawal, in response to intrusion or perhaps to flank eruptions low on the edifice (underwater at Fernandina?).

The 1912 eruption from the funnel-shaped Novarupta crater in Alaska, the largest eruption of the 20th century (about 12 km^3, DRE), triggered 1200 m of subsidence at the summit of Mount Katmai (at least 5-km^3 subsidence volume), 10 km from the eruptive vent. Katmai thus documents an unusual spatial divergence between eruptive and subsidence processes where the magmatic plumbing system is complex. Stratigraphic relations between dust layers generated by subsidence at Katmai and tephra erupted from Novarupta demonstrate that the caldera subsided incrementally during this eruption.

The 1883 eruption of about 10 km^3 (DRE) of pyroclastic materials from Krakatau in Indonesia played a pivotal role in focusing attention on the relations between highly explosive pyroclastic eruption and formation of large calderas. Some key observations from this eruption include demonstration that erupted lithic debris was inadequate to account for the volume of the caldera (thus disproving prior hypotheses of explosive evacuation of caldera basins), recognition that caldera eruptions could generate destructive tsunamis capable of causing coastal damage far beyond the region directly impacted by eruptive deposits, and the effect of globally distributed volcanic ash dispersed in the atmosphere for several years after the eruption.

The summit caldera of Kilauea volcano in Hawaii, much visited while occupied by a lava lake during much of the later 19th century, was recognized early as having resulted from collapse, probably in connection with eruptions along the long flanking rift zones. The most recent deep subsidence of Kilauea caldera occurred in conjunction with, or just preceding, major explosive activity in 1790; during the 19th century, the caldera was filled to overflow by lavas. Recent work has documented that such large basaltic shields undergo repeated cycles of caldera subsidence and filling throughout their shield-building stage. In addition, short-term inflation–deflation cycles preceding and accompanying eruptions have been documented in great detail by geodetic measurements.

The 1.8-ka Taupo eruption of 35 km^3 (DRE) of magma on the North Island of New Zealand, probably the world's most violent and largest in the past 2000 years, would have been even more renowned than the roughly contemporaneous A.D. 79 eruption of Vesuvius if it had occurred in a populated region where historical records were preserved. The Taupo caldera has been interpreted by Walker to constitute a representative example of subsidence by downsagging, although determination of caldera processes and even caldera size is impeded by poor exposures as a result of location within the extensional trough of the Taupo Volcanic Zone. Recent geophysical studies suggest the subsurface presence of a fault-bounded caldera complex nested within graben structures.

No true historical records exist for the 3.6-ka Bronze Age eruption of Santorini in the Aegean arc (about 25 km^3 DRE), but this eruption is prominent in European archeological and volcanologic studies for its well-preserved caldera and proximal eruptive deposits and also for the Minoan cultural sites preserved beneath proximal deposits. In addition, recent studies by Druitt and associates have documented that the Bronze Age caldera is the youngest of at least four successive caldera cycles involving nearly confocal composite subsidence since 100 ka or earlier.

II. CALDERA-FORMING ERUPTION CYCLES

Many large calderas form at sites of preceding volcanism that record shallow accumulation of caldera-related magma (Fig. 2). Large eruptions (>50–100 km^3 of erupted magma) typically cause caldera collapse concurrently with eruption, as indicated by thick intracaldera ash-flow fill, interleaved collapse slide breccias, and structural features. Postcollapse volcanism may occur from vents within or on the margins of ash-flow calderas; eruptions from the bounding-fault zone are most common in resurgent calderas, reflecting renewed magmatic pressure. In addition to resurgence within single calderas, broader magmatic uplift occurs widely within silicic volcanic fields, reflecting isostatic adjustment to emplacement of associated subvolcanic batholiths. Large intrusions related to resurgence are exposed centrally or along the margins of some deeply eroded calderas.

A. Precollapse Volcanism

Volcanism prior to a major caldera-forming event may provide the only record of the rise to shallow crustal levels and early chemical evolution of the growing magmatic system that culminates in large-volume eruptions and caldera formation. Buoyant rise of the magma body may cause broad uplift and generation of incipient ring and radial fractures. Volcanic "leaks" from the evolving magma body commonly produce clusters of vents over the magma chamber, at times in linear or arcuate patterns controlled by nascent radial and ring faults, at others controlled by regional tectonic structures. Virtually all well-documented young calderas have formed at sites of immediately preceding volcanism, although the volume and composition of such premonitory activity may vary substantially. Many small calderas have formed at the summits of basaltic shield volcanoes (Hawaii, Galapagos) or within single stratovolcanoes, but large ash-flow calderas typically have subsided within clusters of preexisting cones and domes. At many caldera sites, the caldera-forming event has covered or caved away much of the near-source record of precollapse volcanism.

B. Morphologic and Structural Geometry

Major structural and morphologic elements of calderas (Fig. 3) include topographic rim, inner topographic wall, bounding faults (if present), structural caldera floor, intracaldera fill (mainly ponded ignimbrite and landslide debris from caldera walls), and the underlying magma chamber or solidified pluton. Although highly generalized and not intended to accurately depict relations at any actual caldera, such a model provides a basis for discussing caldera structural elements and subsidence processes, computing approximate volumetric proportions between subsidence geometry and caldera-filling deposits, and inferring relations between eruption and subsidence processes.

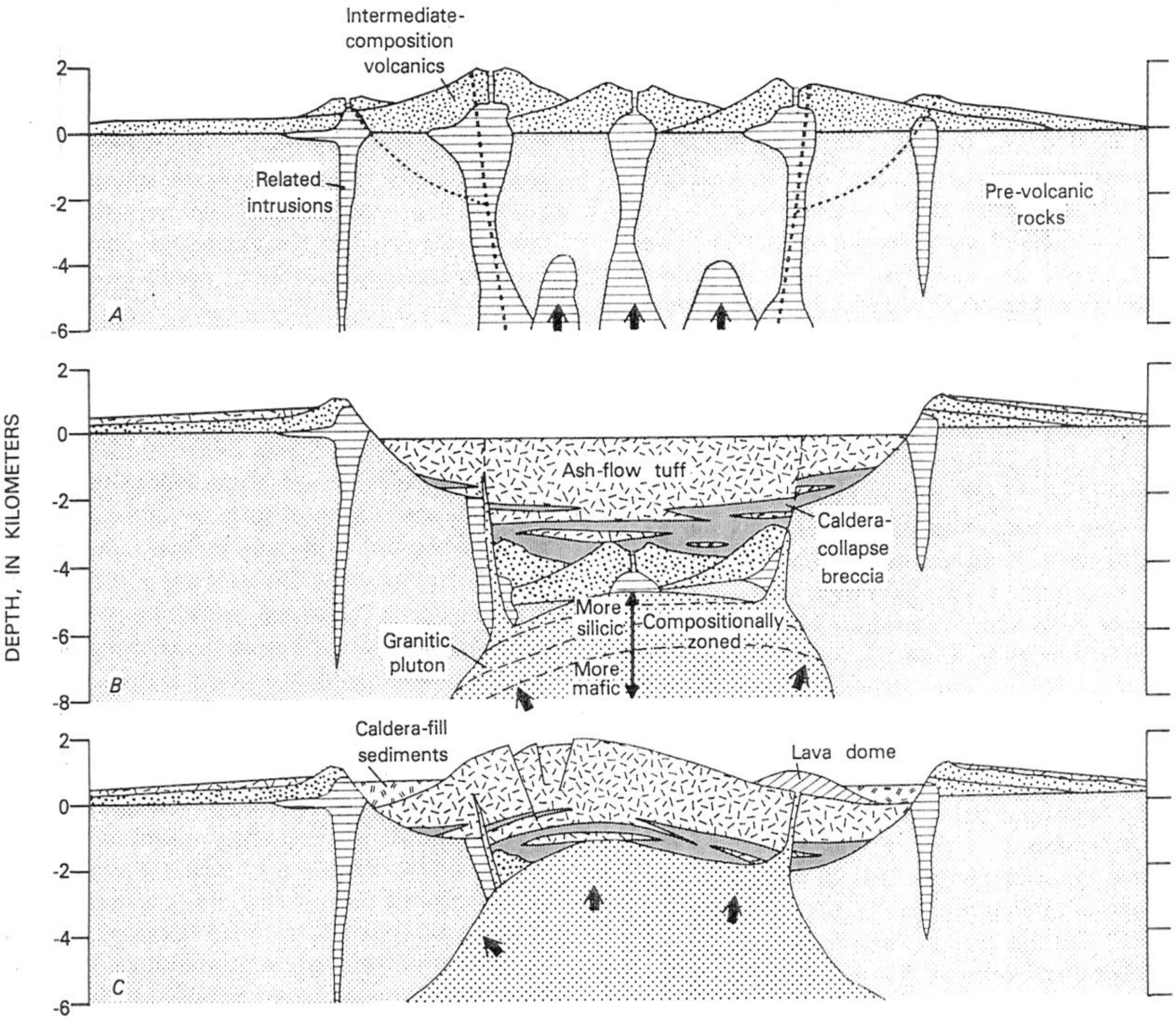

FIGURE 2 Generalized evolution of ignimbrite calderas (based largely on studies of Cenozoic calderas in the western United States). (A) Precollapse volcanism. Clustered intermediate-composition stratovolcanoes grow over isolated small high-level plutons that mark the beginning of accumulation of batholithic-size silicic magma body that will feed ignimbrite eruptions. Broad uplift related to emplacement of plutons may lead to development of arcuate ring fractures. The site of subsequent caldera collapse is indicated by dotted lines; heavy arrows indicate upward movement of magma. (B) Caldera geometry just after ash-flow eruptions and concurrent caldera collapse. Central area of clustered earlier volcanoes caves into collapsed area. Intracaldera tuff ponds during subsidence and is an order of magnitude thicker than cogenetic outflow ignimbrite sheet. Initial collapse along bounding faults is followed by slumping of oversteepened caldera walls and accumulation of voluminous collapse breccias that interfinger with ignimbrite in the caldera fill. Caldera floor subsides asymmetrically and is tilted to the left side of diagram. Main magma body underlies entire caldera area and is compositionally zoned or layered (or was, prior to eruptions), becoming more mafic downward. (C) Resurgence and postcaldera deposition. Resurgence is asymmetrical, with greatest uplift in area of greatest prior collapse. Extensional graben faults from over crest of dome. Some resurgent uplift is accommodated by movement along ring faults in sense opposite that during caldera subsidence. Magma body has risen into volcanic pile and intruded cogenetic intracaldera ignimbrite. Original caldera floor has been almost entirely obliterated by rise of magma chamber to near level of prevolcanic land surface. Caldera moat is partly filled by lava domes and volcaniclastic sediments. Hydrothermal activity and mineralization are prevalent late in cycle. [From Lipman, 1984].

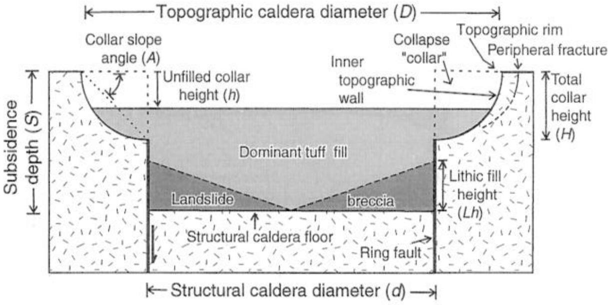

FIGURE 3 Generalized structural model of plate (piston) caldera subsidence, showing simplified geometric relations. Ring faults, which typically dip steeply, are arbitrarily shown as vertical. The landslide breccia is shown schematically at the base of caldera fill, in order to permit geometrically simplified calculation of overall volume relations, rather than the more actualistic complex interfingering that occurs in many calderas. Presence of subcaldera magma chamber, any resurgent structures, and postcollapse volcanic constructs are omitted. [From Lipman, 1997].

1. *Topographic Rim*

The topographic rim is simply the top of the escarpment that bounds the caldera, beyond which lie largely undisturbed outer volcanic slopes. The rim encloses both the subsided area and also the area of scarp retreat due to rock falls and mass wasting. For young calderas, the topographic rim defines the overall areal extent of subsidence, although outlying circumferential fractures at some calderas (e.g., Kilauea in Hawaii and Chegem in Russia) accompany modest additional sagging toward the main subsided area. For old calderas, erosional mass wasting first tends to enlarge the original topographic rim, but later erosion of outer slopes of the upper caldera edifice can also reduce the apparent topographic diameter.

2. *Inner Topographic Wall*

The topographic wall is typically steepest in its upper parts, commonly as precipitous cliffs at young calderas, but tends to have a concave profile that flattens downslope. Upper slopes of the inner topographic wall virtually never represent an unmodified subsidence fault scarp; rather, they develop in response to landslide enlargement and rock falls from oversteepened slopes during and after caldera collapse. At the base of the topographically enlarged caldera wall, intracaldera fill may deposit directly against caldera-boundary faults that have been unmodified by gravitational slumping (Glen Coe, Scotland; Lake City, United States; calderas of the Olso graben in Norway). Such contacts are rarely preserved, because continued caldera subsidence causes further faulting.

In plan view, the topographic walls of most large ash-flow calderas are scalloped by scarps of landslides and rock falls. Suggestions that topographic enlargement and scalloped embayments along some caldera walls result from irregular peripheral subsidence of overhangs along satellitic bounding faults may be valid for irregular walls of basaltic pit craters and other small collapse structures (e.g., pit craters of Kilauea's east rift zone) but are inconsistent with the structurally coherent bedrock stratigraphy that has been mapped and documented by drilling along the footwall embayments in many large calderas (Creede, La Garita, Timber Mountain, and Valles in the United States; Aso in Japan; Campi Flegrei in Italy; Chegem in Russia), some projecting 5 km or more back from the main caldera wall. Such shallowly rooted embayments can only have formed by surficial collapse and insliding along oversteepened caldera walls, an inference that is confirmed by the provenance and large volume of slide material in adjacent caldera fill. Large scallops in walls of some multicyclic ash-flow calderas may be related to successive eccentrically overlapping subsidences associated with recurrent eruptions (Toba, Santorini). At other multicyclic calderas, late large eruptions have caused subsidence of the entire prior caldera area, and earlier subsidence structures lie within the late caldera (e.g., Valles and Platoro in the United States and Taupo in New Zealand).

3. *Collapse Collar*

Material removed by mass wasting and scarp retreat defines a collapse collar (Fig. 3): the volume of rock lying between the topographic caldera wall and the structural caldera boundary. Average overall slopes of inner topographic walls (collar slope angle) are moderate: 25° is typical, and 45° a probable upper limit. Lower slopes along the collapse collar, dipping as gently as 10–15°, are the only parts preserved in many eroded calderas, where the inner wall is expressed as an irregular unconformity between precaldera and caldera-filling rocks. Gentle dips on lower slopes of the collapse collar permit exposure, by erosion or drilling, of precaldera rocks at shallow depths well inboard from the topographic rim. Such geometric relations had been inferred to demonstrate funnel geometry for large calderas such as Aso, Japan, where geophysical and drilling data now document the presence of concealed bounding faults.

4. *Bounding Faults*

Arcuate bounding faults (ring faults) are exposed at some deeply eroded volcanic areas (mainly 5 km and greater in diameter), unambiguously defining plate (piston) subsidence at calderas, as well as at many volcanic "cauldrons" and plutonic ring complexes in older terranes. The presence of bounding ring faults in some less eroded calderas can be inferred from the distribution of caldera-forming or postcollapse vents and symmetrical resurgent uplift of caldera-filling volcanic rocks. Ring faults can accommodate uplift, as well as subsidence: e.g., domical magmatic resurgence at Lake City caldera, United States, occurred along the same faults as earlier had accommodated caldera collapse, and magma was injected as partial ring dikes. Similarly, trapdoor uplift within the 45-ka Cinque Denti caldera in Pantelleria was accommodated by reversed movement along old ring fractures.

Most observed ring faults are near-vertical or dip steeply inward. Ring faults that dip steeply inward at shallow crustal levels may steepen with depth and dip outward at levels just above the magma chamber into which the caldera subsided. Such a geometry may reflect sequential change, from an early stress field related to magma withdrawal (Fig. 4A) to later stresses related to slumping along caldera walls, as the thickness of precaldera rocks in the subsiding region is reduced by stoping during continued upward rise of magma (Fig. 4C). Because of such complexities and uncertainties, all ring faults are shown arbitrarily as vertical in Figs. 3 and 6. Some sizable young calderas lack clear evidence for the presence of arcuate bounding faults, but limited erosion depths typically preclude unambiguous interpretation. At many calderas, regional tectonic trends have influenced the geometry of collapse to varying degrees, but deeply eroded calderas bounded by strongly polygonal faults appear to be much less common than those with arcuate fault boundaries.

Circumferential extensional fractures peripheral to the topographic rims of young calderas are commonly associated with recurrent gravitational slumping of the free face of the inner caldera wall. Such peripheral fractures at Kilauea caldera have opened and closed repeatedly during major historical earthquakes, independently of caldera eruptive or subsidence events.

5. *Intracaldera Fill*

Intracaldera fill provides key evidence of caldera processes because most or all large calderas collapsed during the associated eruptions, and ignimbrites and interleaved caldera-wall slide breccias accumulated to multikilometer thickness within the subsided area. Distributions and volumes of slide breccia vs intracaldera tuff provide critical evidence on timing and geometry of subsidence.

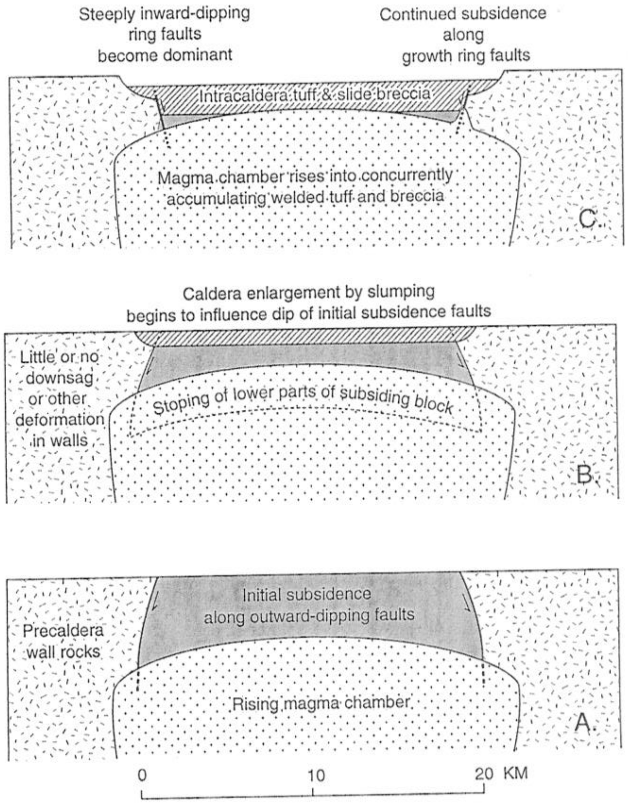

FIGURE 4 Possible evolution of ring-fault geometry, in which initial outward-dipping ring faults are replaced by inward dips, as progressive subsidence destabilizes the caldera walls and continued upward rise of magma reduces the thickness of the subsiding plate or piston.

In addition to ignimbrites and slide breccia that accumulated synchronously with caldera subsidence, most pre-Holocene calderas are partly to completely filled by younger lavas and tuffs erupted from postcollapse caldera-related vents, sedimentary debris eroded from adjacent volcanic highlands, and volcanic deposits derived from other volcanic centers. Such postcaldera deposits tend to conceal the primary volcanic structures, especially at nonresurgent calderas, impeding interpretation of subsidence processes or even the presence of some large calderas.

6. *Caldera Floor*

The geometries of caldera floors have been well documented at only a few large ash-flow calderas (e.g., Scafell in England; Tucson, Organ Mountain, Stillwater Range in the United States; Kumano in Japan), and the typical degree of disruption during subsidence remains uncertain. The structural floor is the subsided precaldera land surface, in contrast to the topographic caldera floor exposed at the surface within a young caldera. Few calderas that provide a clear record of volcanic evolution are eroded to depths sufficient to expose their structural floors, and in many, cogenetic magma has risen to such shallow depth that much of the floor has been destroyed. Structures at many deeply eroded calderas are further complicated or obscured by multiple subsidence events associated with successive ignimbrite eruptions or by later regional tectonism.

For some calderas (Chegem, Cerro Galan, Lake City), exposures of structurally coherent fill that accumulated within the caldera concurrently with subsidence provide strong evidence of, at most, limited disruption of the caldera interior. Even where the fill consists of massive ignimbrite, partial cooling breaks, flow-unit partings, compositional boundaries, and interlayered landslide breccia sheets commonly provide stratigraphic markers to evaluate fault disruption within calderas. Most faulting of intracaldera fill that has been documented so far by such stratigraphic features occurred not during subsidence but during later resurgent doming or other uplift of the caldera floor, as indicated by displacement of all caldera-fill units (e.g., Valles, Bachelor, and Campi Flegrei). Intracaldera deposits are less well exposed in most nonresurgent calderas than those on resurgent domes, but erosionally inverted topography at some nonresurgent calderas, such as Chegem in Russia and Superstition in the United States, provides exceptional exposures of widely continuous flow units and cooling breaks within thick exposed intracaldera tuff without significant fault disruption. Complex disruption of caldera floors may accompany overlapping subsidence during successive caldera-forming eruptions, but available evidence suggests that most large calderas subside fairly coherently during individual eruptions.

Growth faults, with upward decreasing displacement, should be present within syncollapse fill if the caldera floor were significantly disrupted during subsidence, but documented examples are rare. Because synsubsidence faulting would disrupt high-temperature ignimbrites as they welded, growth faults should be marked by conspicuous local rheomorphic zones, even where offset of lithologic markers was obscure. Widespread growth faulting has been well documented at the Ordovician Scafell caldera, but these faults variably displace multiple separate eruptive units, and relations to individual collapse events are less clear.

Small calderas (less than a few kilometers in diameter) merge in geometry with diatremes and likely lack a coherent floor. Rather, the inner walls converge downward into the eruptive conduit in a funnel-shaped geometry, as discussed later.

7. *Subcaldera Magma Chamber*

Magma chambers, preserved as solidified plutons or batholiths, are exposed in many deeply eroded ash-flow calderas, as indicated by petrologic and age correlations with erupted volcanics (Chegem in Russia; Lake City, Questa, and Turkey Creek in the United States; Kumano in Japan). Such plutons have commonly been emplaced within a few kilometers of the regional volcanic surface, some roof zones protruding into the syneruptive fill of the associated caldera. Accumulation of low-density silicic magma in a large shallow chamber, which can generate uplift and tensile stresses at the surface, could be important in initiating ring faulting and permitting caldera collapse. Tumescence associated with growth of a subvolcanic magma chamber has been recorded instrumentally during many monitored eruptions and episodes of volcanic unrest, but the magnitude of uplift has typically been too small to generate geologic structures that would be detectable in the prehistoric record.

Shallow depths to incompletely solidified caldera-related magma chambers are documented for a few active calderas by seismic-attenuation studies, magnetic curie-temperature depths, and other geophysical data. Such studies indicate the presence of magma at depths as shallow as 4–7 km at the 0.76-Ma Long Valley caldera in the United States. At the historically active Rabaul caldera in Papua, New Guinea, seismic hypocentral locations define an elliptical area 5 × 10 km, interpreted as bounded by ring faults, that overlies a central region of low seismicity at depths below 2–4 km that is inferred to represent the present-day magma chamber. For some older systems, the petrology of eruptive products also requires shallow depths of magmatic crystallization (e.g., presence of clinopyroxene rather than hornblende phenocrysts in H_2O-rich magma).

Although only small intrusions are exposed at present erosional levels in eroded Tertiary calderas, geophysical data commonly document the subsurface presence of large magma bodies or solidified granitic rocks. For example, the clustered Tertiary calderas of the San Juan volcanic field, United States, lie within a large negative Bouguer gravity anomaly (−50 mgal), characterized by steep marginal gradients, that has been interpreted to delimit a shallow batholith about 75 × 150 km across with its roof at an average depth of about 5 km. Upper crustal accumulation and fractionation of magma in the subvolcanic batholith is interpreted to have been recorded by the regional volcanic succession in the San Juan field, involving eruption of intermediate-composition lavas from scattered volcanoes, followed by large ash-flow eruptions associated with caldera collapse (Fig. 2). Individual calderas of the central cluster, as well as the overall caldera cluster, have only minor gravity expression, indicating that the density of caldera-filling rocks is only a minor component of the overall anomaly.

Detailed inferences about shapes of exposed intrusions and collapse geometry commonly remain ambiguous at eroded calderas, because subvolcanic magma bodies likely continue to evolve in composition, shape, and depth after cessation of the caldera-forming volcanism. Despite such uncertainties, some consistent relations have emerged between collapse geometry and pluton shape. For example, some trapdoor calderas expose high-level plutons along the most subsided side of an asymmetrical caldera (Silverton, Tucson), suggesting that maximum subsidence was influenced by the shallowest portion of the magma chamber. At several calderas, high-resolution dating has documented cooling of subcaldera plutons within brief time intervals after caldera subsidence. For example, at Chegem in Russia the intracaldera tuff and central granitic intrusion yield $^{40}Ar/^{39}Ar$ ages that are indistinguishable at 2.82 ± 0.02 Ma.

Several recent studies have inferred important roles for sills or shallow domical laccoliths of fine-grained hypabyssal rocks during caldera collapse and resurgence (Turkey Creek and several "laccocalderas" in the United States). Floors of such intrusions are generally not exposed, however, and their overall geometry remains uncertain. Other deeply eroded calderas expose large steep-sided subcaldera plutons containing granitic textures transitional to typical mesozonal batholithic bodies (e.g., Questa, United States). Perhaps resurgent intrusions initially spread as sill-like bodies near the base of the caldera fill, developing into stocklike plutons as continued emplacement of intrusive material gravitationally loads caldera floor rocks and encourages block stoping.

Any large caldera (>20-km diameter) must necessarily have been underlain by a large-scale magma chamber of broadly tabular aspect ratio in order for the intrusion to reside in the middle and upper crust, but to describe such large granitic bodies as laccoliths seems misleading. The concept of a laccolith, as used by most geologists, implies making space by doming the roof rocks; no such evidence exists for most large plutons, including sizable upper crustal bodies with associated volcanism. Few if any large subvolcanic batholiths can be demonstrated to have strongly domed their roofs, and many are composite aggregates of multiple plutons with smaller map dimensions and steep intrusive contacts. Many subcaldera plutons have steep margins, cut across gently dipping wall rocks, and intrude associated volcanic sequences (Glen Coe, Peruvian Andes, Olso Graben). The most feasible mechanism for generating the space needed for a batholith to rise into the upper crust in places like the San Juan Mountains, where regional tectonic faulting is nonexistent, is by large-scale stoping, and caldera formation can be considered a near-surface component of such stoping. Crustal rocks have negligible strength to support regional loads, as long recognized from isostatic adjustments to loading by glaciers or even manmade reservoirs. Much additional space for growing upper crustal batholiths likely results from subsidence of crustal rocks of the magma-chamber floor.

C. Postcollapse Magmatism and Resurgence

Volcanic activity within and around margins of calderas after collapse can include eruptions from vents randomly scattered within the caldera, eruptions localized along regional structural trends, and eruptions along the caldera margins. Such events may begin shortly after initial collapse and continue intermittently for millions of years. Such postcollapse volcanism can closely constrain the timing and nature of differentiation in the subcaldera magma chamber. Thermal modeling of heat flow around young calderas suggests that heat loss by hydrothermal convection is so great that shallow caldera-related magmatic systems cannot survive more than a few hundred thousand years without replenishment by additional magma. Long histories of postcollapse volcanism at many calderas suggest that such replenishment is common.

Renewed rise of magma after collapse has resurgently uplifted many calderas (Fig. 5). Such uplift varies from doming or block uplift of the cores of individual calderas to broad regional uplift of one or more calderas and adjacent portions of the volcanic field. Best known, although relatively uncommon, is symmetrical resurgent doming of the caldera floor, as in the Valles, Creede, Timber Mountain, and Turkey Creek calderas in the United States. Resurgent calderas appear to be more numerous within continental crust, as along the Cordilleran margin of the Americas than in young volcanic arcs within ocean basins. The first identified resurgent caldera was Toba in Sumatra, however, and although only a few of the numerous Tertiary calderas in Japan have been described in the international literature, several are reported to contain resurgently uplifted blocks

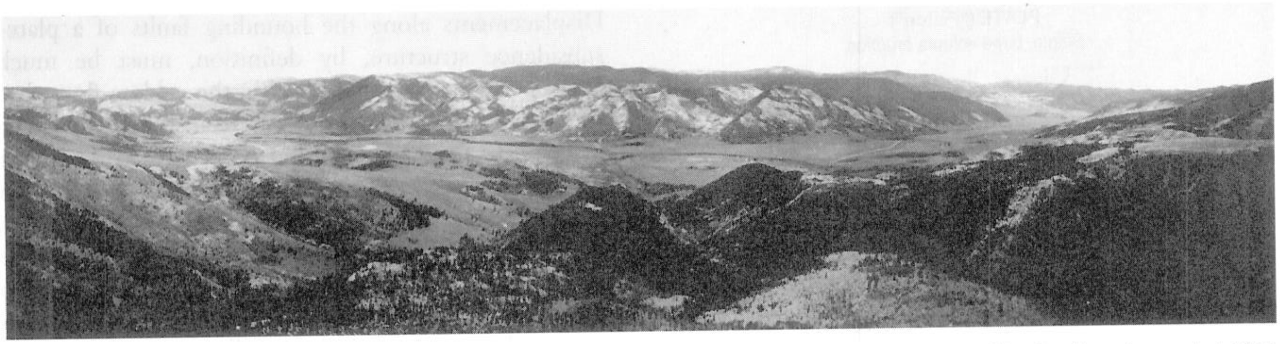

FIGURE 5 The resurgent Creede caldera, Colorado, as viewed from near its northwest topographic rim. Broad rounded hill in middle distance is the postcollapse resurgent dome. Arcuate valley marks topographic moat, now followed by the Rio Grande (see Fig. 7), which is underlain by Oligocene caldera lake sediments. Despite formation at 26.5 Ma, primary volcanic morphology is well preserved due to infilling of the caldera moat by sediments that have only been erosionally excavated in geologically recent time. [Photograph by J. C. Ratté, U.S. Geological Survey.]

or high standing intrusions (e.g., Onikobe, Hiwada, and Okueyama).

In addition to resurgent structures that are specific to individual calderas, some silicic volcanic fields containing clusters of calderas show weak regional uplift centrally within the volcanic field that is interpreted as indicating broad late resurgence over an underlying batholithic magma body larger than any individual caldera. Such broad uplift can be reflected in young volcanic fields by regionally high topography, mild tilting of volcanic strata away from central parts of the field, and extensional structures trending between individual calderas.

D. Hydrothermal Activity and Mineralization

Hydrothermal activity and mineralization can accompany all stages of ash-flow magmatism, becoming dominant late during caldera evolution. Caldera-forming ignimbrite eruptions are probably unlikely to directly produce major ore deposits, because such explosive activity would tend to disperse any concentrations of metals that accumulated in upper parts of precaldera magma chambers, but the resulting caldera structures can be important loci for subsequent magmatic and hydrothermal ore-forming events. Much rich mineralization is millions of years younger than caldera collapse, where the caldera served primarily as a structural control for late intrusions and associated hydrothermal systems. Some calderas show little or no evidence of associated hydrothermal activity.

III. CALDERA-SUBSIDENCE PROCESSES

Prior approaches to subdividing and classifying calderas have tended to distinguish caldera types based on eruption style and magma composition at representative volcanoes: for example, Krakatoan type, Valles type, Katmai type, etc. Size of the eruption and geometry of the cogenetic magma chamber also bear on subsidence processes. For example, stated distinctions between "Krakatoan" and "Valles" caldera types (foundering of the top of a composite volcano versus subsidence independent of preexisting volcanoes) are mainly functions of reservoir area and eruption volume, which influence resulting caldera size without any necessary difference in subsidence processes.

Alternatively, the broad diversity of well-documented ash-flow calderas can be considered in terms of a continuum of features and processes. Many calderas have such varied transitional geometries and structures that subclassification into discrete types seems less useful than relating subsidence geometry and resulting structures to a few geometrically simplified end members (Fig. 6). Many larger calderas dominantly involve *plate (piston) collapse* of a coherent floor, bounded by steeply dipping faults. *Trapdoor subsidence*, bounded by an incomplete arcuate fault and by a hinged segment, reflects early downsagging and incipient plate collapse. Simple *downsag subsidence* seems rare, although many plate-subsidence calderas contain inward-tilted blocks along their margins. A component of *piecemeal-fault disruption* of caldera floors is fairly common, although such structures do not seem to accommodate the bulk of subsidence in

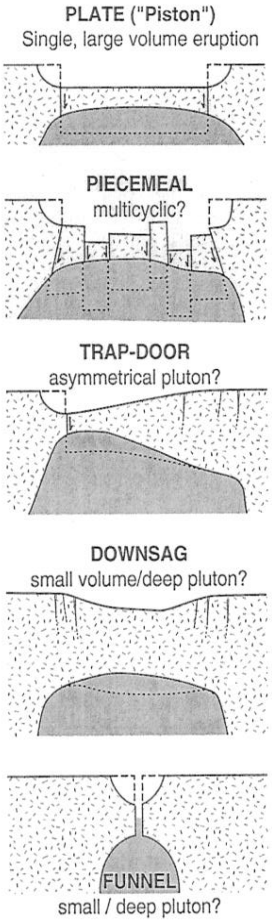

FIGURE 6 Schematic models of alternative subsidence geometries in relation to depth and roof geometry of underlying magma chamber. Dashed lines indicate postsubsidence depths of downdropped caldera floor blocks, which are inferred to have been partly removed by stoping into magma chamber during and immediately after caldera collapse. [From Lipman, 1997].

most large calderas. Pervasively brecciated *chaotic disruption* of subsiding caldera floors is rare, at least at calderas more than a few kilometers across. Small calderas (<3–5 km in diameter) commonly have a *funnel geometry* because of dominant enlargement by slumping into an areally restricted vent.

A. Plate Subsidence

Many large calderas have long been recognized to involve plate (piston) subsidence of a relatively coherent floor, bounded by steeply dipping bounding faults with kilometer-scale displacements ("Valles type"). Ring and arcuate intrusions have long been recognized as deeply eroded analogs of large plate-subsidence calderas. Displacements along the bounding faults of a plate-subsidence structure, by definition, must be much greater than on any faults within the caldera floor, but some calderas contain structures transitional toward a piecemeal-subsidence geometry. At a few calderas that are well exposed and adequately studied (Glen Coe in Scotland; Grizzly Peak, Bachelor, Stillwater Range in the United States), the subsided lid over the source magma chamber was variably faulted (offsets of tens to hundreds of meters) due to differential movement during ash-flow eruptions and postcollapse magmatism, but the scale of internal disruption is typically an order of magnitude less than displacements on bounding faults. At the type Valles caldera, drilling and geophysical data show that the caldera floor was locally disrupted by faulting that occurred largely or entirely during postcollapse domical resurgent uplift. In some places, such as Glen Coe, current interpretations diverge as to whether subsidence was dominantly along the bounding ring faults or by internal disruption. Subsidence by highly chaotic disruption of the floor has not been clearly documented for any large caldera.

Many plate-subsidence calderas, 10 km or more in diameter and bounded by ring faults, have been recognized recently in Japan, as Tertiary volcanic areas have been mapped geologically and explored by drilling (e.g., work by Yamamoto and associates in the Inawashiro and Aizu districts of northern Honshu). Some calderas as small as 4–5 km in topographic diameter appear to have fault-bounded floors, based on evidence for ring faults and structurally coherent caldera fill. Examples in the United States include the 8 × 10 km Crater Lake and 4.5 × 8 km Kulshan calderas in the Cascade Range.

B. Downsag Subsidence

Large-scale downsag subsidence has been inferred by some researchers to be common, based on inward-sloping topography, inward-tilted wall rocks, and apparent absence of large-displacement bounding faults at some major calderas. Many large plate-subsidence calderas involve subordinate downsag, but no deeply subsided calderas appear to have been well documented where downdropping is accommodated dominantly by inward tilting without major bounding faults.

Components of downsag, in conjunction with dominant subsidence along bounding faults, appear to be common and include (1) mild flexuring and fracturing during initial subsidence prior to establishment of a well-defined fault boundary, processes that accompany inception of all faulting of brittle upper crustal rocks; (2)

incomplete ring-fault subsidence, transitional between downsag and plate subsidence, that produces a hinged or trapdoor caldera; (3) subordinate sagging of the structural caldera floor within bounding ring faults; and (4) gravitationally induced inward late tilting and fracturing of oversteepened unstable caldera walls, in conjunction with slumping and landsliding. Monoclinal flexures and extensional fractures probably accompany inception of all bounding faulting, as in regional tectonic faulting of brittle upper crustal rocks. The appearance of downsag on the flanks of multicyclic caldera depressions can also be generated by volcanic units draped over a preexisting caldera or structural basin.

Because most calderas resulting from large ignimbrite eruptions subside several kilometers or more and are topographically enlarged by late slumping, clear evidence for initial flexuring and fracturing is rarely preserved. Subordinate downsagging is common within caldera floors bounded by well-developed ring faults that accommodate the bulk of total subsidence (e.g., Glen Coe in Scotland, Sabaloka in Sudan, Grizzly Peak in the United States). Saucer-like geometry of an otherwise coherent caldera floor may result from inward dips along the bounding faults, inheritance from broader downsagging during initial subsidence prior to full development of the bounding faults, or generally from localized subsidence of the thermally weakened thin lid over a large shallow magma chamber as a result of focused magma drawdown during rapid eruption. Some large coherently rotated inward-dipping blocks along caldera walls are incipient slide blocks, related to second-order enlargement of the topographic caldera wall by landsliding, rather than primary collapse structures bounded by steeply dipping faults or fractures.

Inward-dipping foliations of intracaldera welded tuff that decrease in dip upsection have been cited as evidence of downsag during eruption and subsidence at several calderas (Chegem, Lake City). Alternatively, such geometries can also readily be interpreted as due to differential primary depositional compaction of intracaldera tuff against caldera walls and caldera-margin slide breccias without need for any downsagging. Compaction dips typically are highly varied near caldera walls (locally approaching vertical), and tuff foliations commonly correlate closely with adjacent buried slopes. Older volcanic strata in walls of many calderas dip horizontally or gently outward, and most prevolcanic strata are in continuity with regional structural attitudes—geometries incompatible with downsag as a dominant subsidence process.

Many basaltic lava-flow calderas (Hawaii, Galapagos, Olympus Mons, etc.) that have subsided repeatedly in small increments have an overall inward downstepping geometry that has also been described as downsagged or downwarped. Such a geometry of nested sequential collapses within a single caldera during recurrent lava eruptions or intrusions along rift zones, although differing in scale from catastrophic caldera collapse during individual large explosive eruptions, may involve similar processes and be transitional to the multicyclic collapse histories that characterize many ash-flow calderas. In addition to small-scale incremental caldera collapse at basaltic volcanoes, at least some of these (e.g., Kilauea and Mauna Loa) also preserve evidence of longer term cycles of caldera filling and recurrent collapse. Nested recurrent collapse events, although cumulatively generating an inward-sloping composite subsidence profile, need not involve major downsag during individual eruptions and caldera-subsidence events.

C. Trapdoor Subsidence

Trapdoor subsidence, bounded by a partial ring fault and by a hinged segment, constitutes incomplete or incipient plate collapse, intermediate between plate and downsag subsidence processes. Such partial subsidence may be related to smaller eruptions, an asymmetrical magma chamber, or regional structural influences. Geometrically well-defined examples of trapdoor subsidence in the western United States include Silverton, Organ Mountains, Eagle Mountain, Big John, Whitehorse, and Tucson Mountains calderas. Well-described hinged or trapdoor calderas elsewhere include Snowdon caldera in Wales, Bolsena in central Italy, and Sakugi in southwest Japan.

D. Piecemeal Disruption

Small-displacement piecemeal faulting of subsiding caldera floors is probably common. Fracturing during subsidence has been demonstrated for a few calderas by growth-fault deformation of an intracaldera ignimbrite concurrently with welding. Complex piecemeal subsidence of caldera floors on a coarse scale, involving arrays of arcuate or rectilinear growth faults without large-scale bounding structures, has been interpreted as the dominant subsidence process for a few calderas. Such features could result from interaction with the prevolcanic structural grain or from intricate fracturing of the caldera floor during a single eruption, but without clear evidence of large-scale growth faulting during a single eruption, piecemeal fracturing of a caldera floor can be open to alternative interpretations.

Geometrically complex fracturing should be expected at sites of multiple nested or overlapping collapses that cause incremental subsidence during successive ash-flow eruptions, as is likely present in floors of overlapping caldera complexes that subsided recurrently at intervals of tens to hundreds of thousand years (documented by drilling data for Dorobu caldera in Japan, Bolsena and Latera calderas in Italy, and clustered calderas in the southwest Nevada volcanic field). Other multicyclic calderas, probably comparably geometrically complex but lacking caldera-floor structural data, include Santorini in the Aegean, the Kagoshima Bay area of southern Japan, and the central San Juan caldera complex in the United States). Such complexities in caldera-floor geometry may also be indicated by scattered or transverse distributions of postcaldera postcollapse vents within recurrently subsided calderas, as at Campi Flegrei, Aso, or Santorini. Analogous complexities in subsidence geometry appear likely for the historically active Rabaul caldera in Papua, New Guinea, where geologic relations document successive overlapping caldera subsidences during the past few hundred thousand years, even though present-day seismicity defines a geometrically simple ring structure for the active caldera.

The well-exposed Ordovician Scafell caldera in the English Lake District has been interpreted by Branney as a piecemeal subsidence structure, involving dispersed subsidence along growth faults during a single eruption, but the multiple intracaldera depositional units that have been mapped there appear to record diverse eruption and emplacement processes during accumulation of intracaldera fill. The stratigraphically complex fill at Scafell thus differs from the thick ignimbrite accumulations during single eruptive cycles at many younger calderas and suggests, alternatively, that subsidence could have been incremental during successive eruptions over a sustained time interval.

At the widely known Glen Coe caldera in Scotland, recurrent block faulting, with displacements of tens to a few hundred meters, accompanied successive early eruptions of relatively small-volume pyroclastic deposits. Much deeper subsidence along bounding ring faults at Glen Coe appears to have been associated with more voluminous later ignimbrites. The cauldron block subsided at least 1 km, as recorded by the thickness of preserved volcanic sequence, but this amount is a minimum because correlative volcanic rocks are not preserved outside the subsided block. Despite emphasis of recent work on the role of piecemeal faulting at Glen Coe, its overall structure seems reasonably interpreted as dominated by subsidence along the bounding ring faults, with smaller scale breakup of the floor largely preceding development of the ring-fault subsidence.

E. Chaotic Subsidence

Chaotic subsidence, marked by intense wholesale disruption and brecciation of caldera-floor rocks, has been inferred to be an important caldera-forming process in some reviews, but such processes have not been documented for any well-exposed large ash-flow calderas. Chaotic subsidence has been proposed as a process (1) to generate low-density material within calderas that can account for the observed negative gravity anomalies and (2) to generate lithic breccias by collapse of the roof over a depressurizing magma chamber. However, observed gravity anomalies in calderas can be modeled successfully with alternative assumptions, and voluminous lithic breccias within many calderas are demonstrably formed by gravitational failure and landsliding of oversteepened walls adjacent to bounding faults. Thick megabreccias exposed in deeply eroded calderas typically are interleaved conformably with ash-flow tuff, indicating that such breccias are depositional units of the caldera fill, rather than drastically disrupted floor. Large landslides from the inner caldera walls (collapse collar volume of Fig. 3) are also a potential source of voluminous extracaldera lithic material, in addition to direct vent erosion, that could be entrained in the eruption column and emplaced as lithic lag breccia; chaotic disruption of floor or vent material need not be the sole or even dominant source. The volumes of lithic lag breccia in proximal outflow deposits are typically small in comparison to the slide breccias that accumulate within the subsided area.

F. Funnel Calderas

The term "funnel shaped" is potentially ambiguous for caldera structures. Virtually all calderas are funnel shaped in overall geometry in the sense that their topographic walls flare outward from the structural boundaries due to gravitational slumping (Fig. 3). A funnel-shaped structural boundary could also result from severe downsag or piecemeal subsidence or, probably more commonly, from recurrent subsidence during successive eruptions.

Small calderas (<2–4 km in diameter at topographic rim) commonly have a simple funnel geometry, because enlargement by slumping of the inner wall into an areally restricted vent is the dominant process in establishing the overall size of the subsided area (Fig. 6). Such calderas are associated with explosive eruptions from a central vent, lack a bounding ring fault or a coherent subsided block, and probably overlie relatively small (or deep?) magma chambers. Well-documented funnel calderas, associated with relatively small ash-flow eruptions, include Nigorikawa and Sunagohara calderas in Japan, which are well constrained in three dimensions by geothermal drilling, and Red Hills in the United States. Such funnel calderas appear to merge in geometry and structural type with diatremes associated with explosive eruption of more mafic magma to form tuff rings and maars.

Based mainly on modeling of gravity anomalies, some large young calderas, especially in Japan (Aira, Aso, Kuttyaro), have been inferred to have a funnel structure attributed to broad upward flaring of the primary eruption conduit. Such funnel structures have been inferred to develop in relatively weak crusts of young island arcs, in contrast to ring fault and plate subsidence of calderas in cratonic environments. However, no large funnel structures have been clearly documented for eroded calderas in Japan, even though many ring-fault calderas and plate-subsidence structures have recently been recognized in eroded Tertiary volcanic fields.

A further complexity for large calderas inferred to have funnel geometry is the ambiguity of interpretations based on gravity data. A plate-subsidence structure with lithic debris concentrated near structural margins, as is commonly observed in eroded calderas, could generate a gravity profile indistinguishable from a funnel structure. Geometrically simplistic gravity modeling of some Japanese calderas as funnel shaped (e.g., Aso) is complicated by recurrent eruption of multiple large ash-flow sheets and multistage incremental subsidence. Recent detailed processing of gravity data and results from deep drilling at Aso suggest multiple flat-bottomed gravity lows and an overall "piston–cylinder type structure rather than a funnel-shaped structure." Elsewhere, deep erosional exposure and/or exploration drilling has documented that an overall stepped funnel-like geometry can result at large ash-flow calderas from multistage subsidence along nested ring fractures (e.g., Campi Flegrei, Grizzly Peak, and several San Juan caldera complexes).

G. Ignimbrite "Shields"

While caldera sources have been identified worldwide for most well-preserved large ash-flow sheets, among the late Tertiary volcanoes spectacularly exposed on the altiplano of the central Andes are silicic centers where a large-volume tuff sheet dips gently outward from a central lava dome complex. Initially interpreted mainly from satellite images for this difficult-of-access high-altitude region, these have been described as "ignimbrite shields" that erupted without significant caldera collapse or resurgence. Ignimbrite shields have been proposed as an important but little recognized class of explosive silicic centers that reflect eruption from relatively deep magma chambers.

Because Andean volcanologists have also described many plate-subsidence and resurgent calderas similar to ash-flow centers elsewhere, the apparent absence of comparable ignimbrite shields in North America and elsewhere suggests possible interpretive problems with the Andean ignimbrite "shields" resulting from their lack of dissection, inaccessibility, and resulting limited field study. At least some ignimbrite "shields" seem alternatively interpretable as conventional (structurally bounded) nonresurgent calderas, surrounded by their ignimbrite aprons, that were then filled to overflowing by younger intracaldera lavas and tuffs.

Potentially analogous nonresurgent large calderas that were once completely buried by later lava flows and other volcanic deposits have been variably exposed by erosion in many volcanic areas (Black Mountain and Kane Springs Wash calderas in southwest Nevada and several calderas of the San Juan field in the United States; Cappadocia field in Turkey). Some intracaldera and caldera-margin constructs in the San Juan region were stratovolcanoes originally rising well above the regional terrain; others were clusters of smaller lava domes that interleave with pyroclastic-flow and volcaniclastic sedimentary deposits. The primary pre-erosion morphology of these filled calderas would have looked strikingly like the described "ignimbrite shields" of the Andes. In comparison with the altiplano region, and its superb exposures of near-pristine unvegetated volcanic features, the southern Rocky Mountains provide the advantage of exposing a third dimension in glacial canyons a kilometer or more deep (along with disadvantages such as heavy vegetation).

H. Volcano-Tectonic Depressions

Inferred sources for some large ash-flow eruptions, which have been interpreted during reconnaissance studies as having vented directly from regional graben without developing localized calderas, have been described as volcano-tectonic depressions. While ash-flow eruptions and associated calderas have long been recognized as associated with extensional tectonics, no large pyroclastic eruptions have been shown unambiguously to be accompanied mainly by subsidence along regional fault troughs. Many typical calderas are known within and adjacent to major graben and rift zones. While the margins of subsequant calderas can be influenced by regional structures, some developing polygonal fault boundaries, drastic elongation of individual ash-flow subsidence structures along regional structural trends seems rare. To the contrary, some calderas along regional fault troughs are elongate perpendicular to their graben setting (Long Valley, Questa in the United States).

Association of ash-flow eruptions and caldera formation with regional extension leads to subsidence and burial of calderas along axes of graben, obscuring relations between volcanism and tectonic setting. Increasingly, detailed geologic, geophysical, and deep-drilling data have demonstrated that several regions commonly cited as volcano-tectonic depressions contain clusters of subequant calderas along the graben axis. Examples include the Taupo Volcanic Zone in New Zealand, where at least eight major ignimbrite calderas that have formed since 1.6 Ma are variably concealed beneath volcanic and sedimentary fill; the Toba depression in Indonesia, where four discrete ignimbrite eruptions were accompanied by caldera collapses from varying locations between 1.2 Ma and 75 ka; and Kagoshima Bay in Japan, where at least five calderas have erupted in the past million years. Even where bounding caldera faults consist of linear segments, the surface expression of caldera subsidence typically assumes a more nearly circular geometry as unsupported oversteepened walls slump into the central depression. On a smaller scale, even the strongest linear extensional structures can host circular volcanic subsidences, as exemplified by the development of equant pit craters along rift zones of Hawaiian volcanoes.

I. Discussion

Many well-studied calderas involve subsidence processes intermediate between idealized end members: ring-fault calderas can have complex boundaries involving more than a single arcuate bounding fault, both hinged downsag boundaries and ring faults are involved in trapdoor caldera subsidence, and floors within some ring-fault calderas have sagged or faulted at loci where magma erupted rapidly. Many calderas have such transitional attributes that subclassification can be inherently ambiguous and subjective. For example, the exceptionally exposed Grizzly Peak caldera in the United States, originally described as a nested ring-fault plate-subsidence structure, has impressed others as involving significant downsag and piecemeal subsidence. Interpreting caldera structures in terms of a continuum of subsidence styles, rather than as end-member types, can clarify relations between eruptive and structural processes in comparison to size of the eruption and the location and geometry of the cogenetic magma chamber.

The flaring of inner caldera walls as a result of landsliding during subsidence is a major process in generating caldera morphology and caldera fill. Lithic material, derived from vent enlargement and slumping of caldera walls, is more voluminous in caldera fills than commonly recognized from study of young, little-eroded calderas. In funnel calderas and small ring-fault subsidences, such lithic material is the dominant component of the caldera fill; model calculations suggest that some funnel calderas generate as great a volume of lithic debris as can be contained within the caldera (to the level of the unfilled collar height; Fig. 3). In larger calderas, wall-rock lithics are roughly equal in volume to the juvenile syncollapse volcanic ejecta that accumulate within the caldera. For the largest calderas, the proportion of intracaldera slide debris is lower, and only minor slide material would reach central parts of the caldera fill.

Caldera enlargement by landsliding and changes during postvolcanic erosion complicate comparisons of caldera geometries and structures. Postcollapse erosion of the inner caldera wall first enlarges the area of the topographic caldera basin, but continued erosional dissection down to structural boundaries of calderas will reduce the apparent caldera size. For example, the resurgent Creede caldera in the Oligocene San Juan volcanic field is presently best defined by the unconformity between caldera-filling and caldera-wall rocks (Fig. 7). This boundary is intermediate between the inferred initial topographic rim, parts of which are discontinuously preserved in the modern landscape, and the concealed structural boundary that is approximately defined by arcuate alignment of resurgent structures, postcaldera vents, and hot-spring upwelling loci. The structurally bounded subsided block has only about one-third the area of the original topographic caldera, demonstrating how heavily apparent caldera size is influenced by erosional depth. Despite such uncertainties, calderas associated with explosive eruptive activity worldwide have fairly similar ranges of dimensions, as approximated by plots of maximum diameter (Fig. 8). The largest calderas occur within continental crust, and many of these are composite, are multicyclic, or provide evidence of sequential subsidence into geometrically complex magma chambers.

IV. SOCIETAL IMPLICATIONS

Caldera-forming eruptions, like most volcanic activity, can have both positive and adverse impacts on the envi-

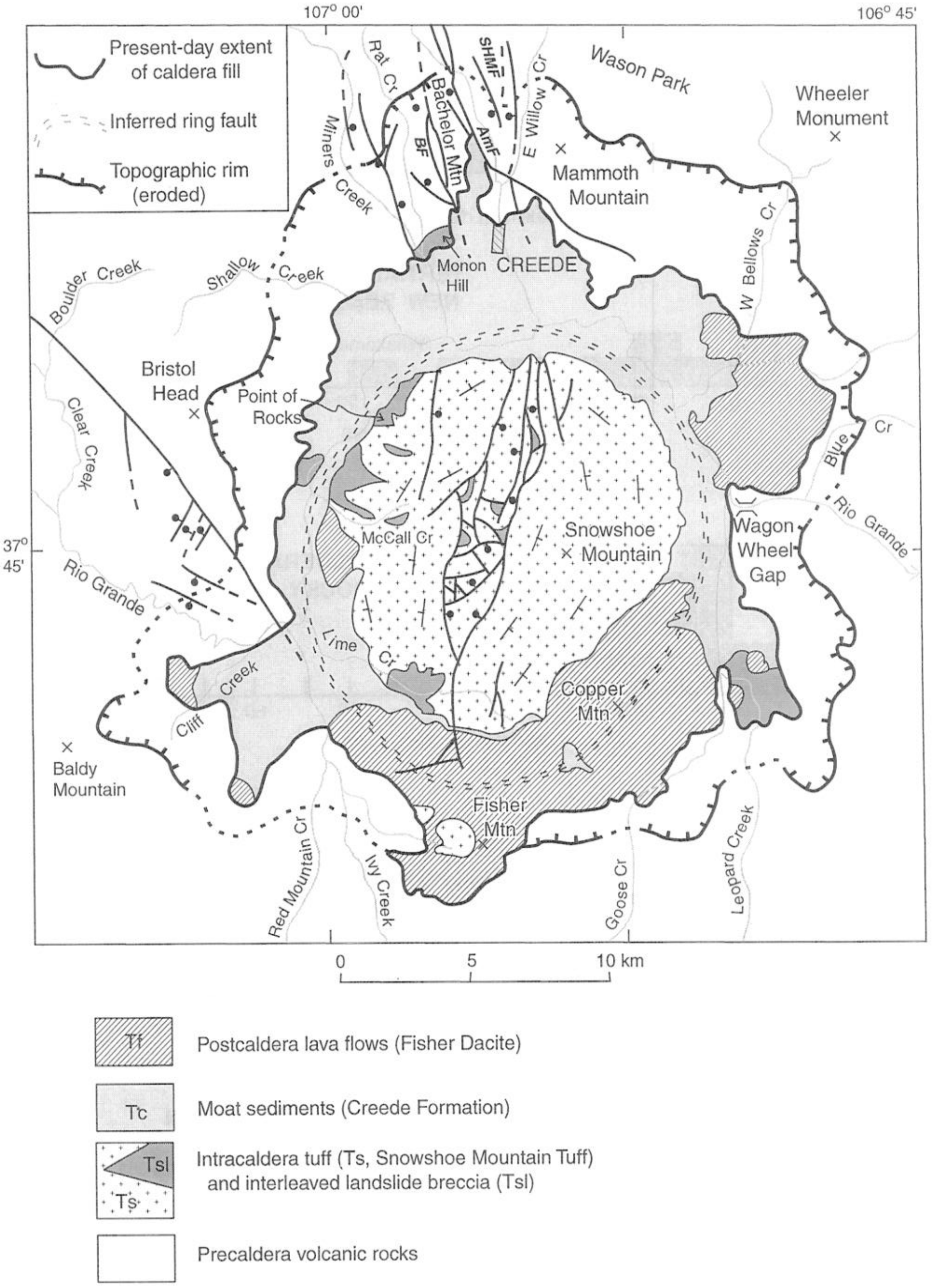

FIGURE 7 Generalized geologic map of the Creede caldera, United States, showing approximate location of eroded topographic caldera rim, present-day extent of moat-fill deposits, inferred buried ring fault, and late normal faults formed during resurgent doming and mineralization.

ronment and human society. Large explosive eruptions involve obvious hazards to people and property, while the volcanic ash generated by such events generates some of the world's most fertile soils and agricultural areas (cf. "Volcanic Soils"). Volcanic ash and aerosols generated on vast scales during caldera-forming events can adversely modify global climate. Caldera structures are important loci for valuable metallic ore deposits (cf. "Mineral Deposits Associated with Volcanism") as well as for hydrothermal heat that can become valuable energy resources (cf. "Exploitation of Geothermal Resources").

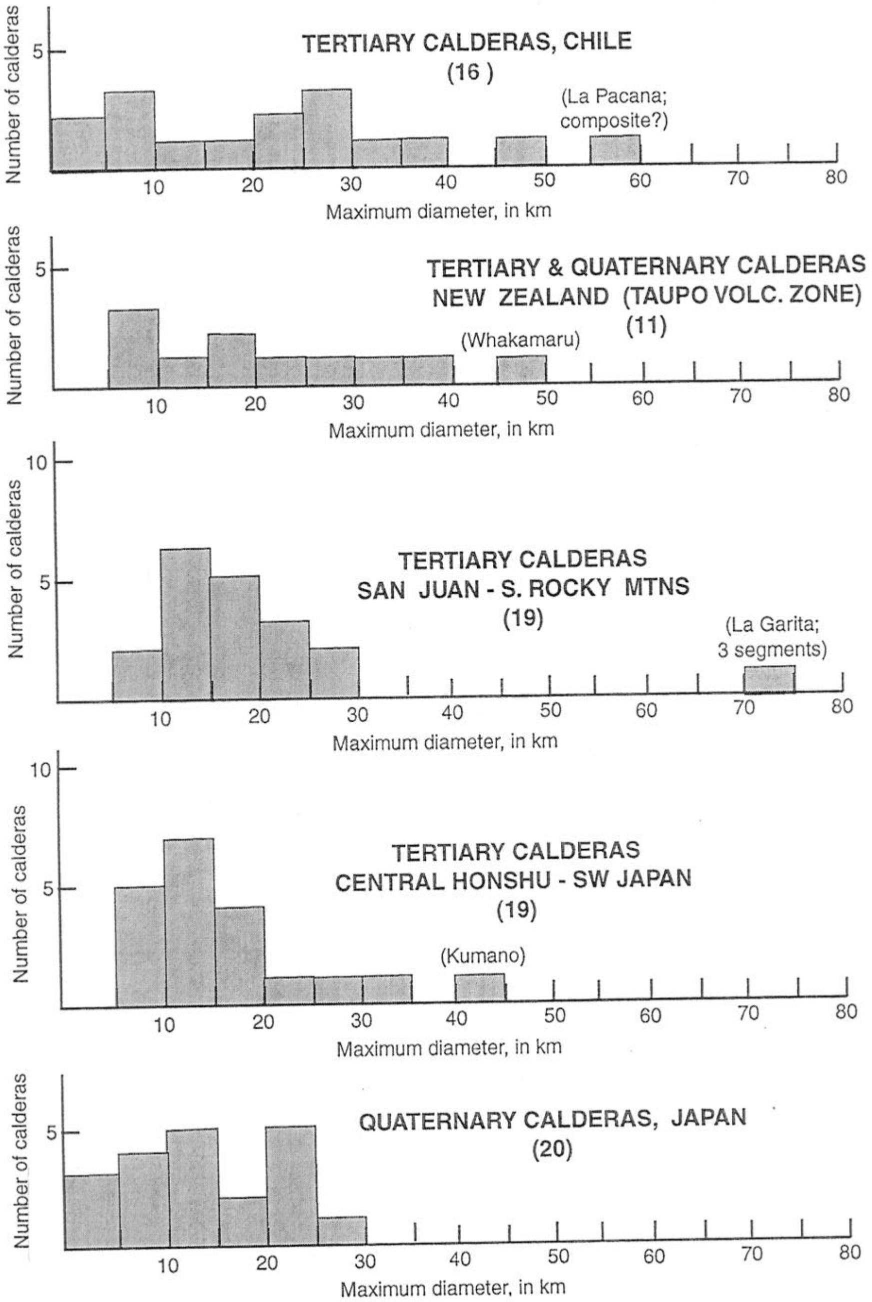

FIGURE 8 Diameters (maximum dimension) of calderas in diverse tectonic settings. Calderas in most regions have similar ranges of diameters. Smaller young calderas, as recorded in the Quaternary of Japan, probably tend to be obscured by erosion and cover by younger volcanic rocks in the older (Tertiary) volcanic fields. The largest calderas tend to be composite (multiple eruptions at La Pacana in Chile) or geometrically complex (successive subsidence of multiple segments during a single eruption at La Garita in the San Juan Mountains).

A. Calderas and Volcanic Hazards

Large caldera-forming explosive eruptions probably represent the most catastrophic geologic events that affect the Earth's surface, other than rare large meteorite impacts. Krakatau in 1883 caused 30,000 deaths, mainly from tsunamis associated with the caldera eruption. The much smaller 1991 Pinatubo eruption in the Philippines could have been comparably deadly because of the high population density on its lower flanks had the onset of this eruption not been accurately forecast and large areas evacuated successfully. The potential societal impact of a future eruption comparable in size to large prehistoric events, should it involve a heavily populated area such as Napoli in Italy or Kagoshima Bay in Japan, are so enormous as to defy comprehension.

In recent years, relatively intense unrest has occurred at Long Valley in the United States (1980 to present), Campi Flegrei in Italy (1983 to present), and Rabaul in Papua, New Guinea (1971–1994). The unrest at Rabaul culminated in 1994, when two volcanoes erupted simultaneously along opposite sides of the ring-fracture system defined by current seismicity, but no large ignimbrite eruptions or caldera-wide subsidence were involved. Both Campi Flegrei and Rabaul have already experienced multiple caldera-subsidence events associated with large eruptions, so additional caldera-forming events are a significant long-term hazard for any existing restless caldera. One of the most important future tasks for volcanologists will be to recognize precursors for potentially devastating caldera-forming eruptions, as contrasted with the more frequent small eruptions at previously active volcanoes. Most future caldera-forming eruptions can be expected to occur at sites of existing calderas, but any cluster of active volcanoes should be evaluated as a potential site of a growing upper crustal magma chamber that could fuel a future caldera eruption. Because calderas form so infrequently, present understanding is woefully inadequate concerning the variety of potential precursors, the proportion of precursor events that lead to major eruptions, and especially the characteristic time intervals between precursors and eruption.

B. Caldera-Forming Eruptions and Global Climate

Large pyroclastic eruptions that generate caldera collapse carry fine-grained ash and sulfur aerosols into the upper atmosphere. Historical caldera-forming eruptions such as Tambora in 1815, Krakatau in 1883, and Pinatubo in 1991, although several orders of magnitude smaller in eruptive volume than the largest prehistoric eruptions, appear to have modified global climate, including visible atmospheric effects such as strange colors and halos on the sun and moon, vivid sunsets and sunrises, and anomalously cold weather. The dominant influence is believed to be injection of sulfur aerosols into the stratosphere, a process whose efficiency varies in relation to magmatic sulfur content and height of the eruption column. As a consequence, some exceptionally large silicic eruptions such as the 0.6-Ma Yellowstone event, characterized by relatively low sulfur contents, may have affected global climate less than smaller eruptions of more mafic sulfur-rich magma. The overall impact of explosive volcanic eruptions on global climate, in comparison to other influences such as polar ice cap volumes and deep ocean currents, remains uncertain.

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