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Article abstract

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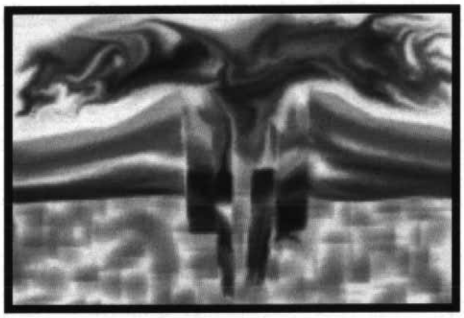

Igneous Rock Associations 1. Styles and Mechanisms of Caldera Collapse

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SUMMARY
In this article, we summarize some of the most influential papers and concepts regarding caldera collapse. We also present a synopsis of the different types of calderas, their characteristics and field examples and provide a glossary of related nomenclature. We discuss piston, downsag, trapdoor, concentric step-down, chaotic, rifted and piecemeal calderas. Some calderas appear to be combinations of different types. We examine the complex interactions of variables that control the structure and morphology of calderas and result in a particular collapse style.

SOMMAIRE
Le présent article fait état des concepts et des publications les plus importantes en matiPre d'effondrement des caldeiras. On y présente également une vue d'ensemble des différents types de caldeira, leurs caractéristiques illustrées d'exemples concrets, ainsi qu'un glossaire de la nomenclature afférente. Nous traiterons des concepts de piston, d'affaissement, d'effondrement concentrique par paliers, ainsi que de caldeiras de style chaotique, de fossé tectonique et fragmentaire. Il semblent que certaines caldeiras soient le résultat d'une combinaison de style. Nous considérons les interactions complexes de variables qui déterminent la structure et la morphologie des caldeiras et en conditionnent le style.

INTRODUCTION
Volcanic eruptions associated with the formation of calderas are among the most dramatic phenomena in the history of our planet. Hundreds of calderas have been identified on Earth and other planets that range from two to more than a hundred kilometres in diameter. Williams (1941) described a caldera as "a large volcanic depression, more or less circular or cirque-like in form". However, calderas vary widely in surface morphology, structure and mode of formation.

Volcanologists and geophysicists study the formation of calderas by interpreting maps and cross-sections from field mapping, borehole, remote sensing, gravity and seismic data. Scientists also use mathematical, finite element, and scaled analogue models to study the nature of the collapse process (Druitt and Sparks, 1984; Burov and Guillou-Frottier, 1999; Roche et al., 2000). It is often difficult to map young calderas (i.e., < 2 Ma), as the internal structure of the caldera is commonly buried beneath significant accumulations of intracaldera ignimbrite and postcaldera deposits. For this reason, the internal structure of the caldera is inferred in other ways. Lava domes emplaced within the caldera after collapse in some cases define a specific pattern. In the case of Valles caldera, New Mexico, the circular spatial pattern of domes was used to infer a single cylindrical fault bounding a coherent central piston (Smith and Bailey, 1968) (Fig. 1). Subsequently, geothermal drilling data at Valles revealed a caldera floor that was broken up by many faults (Heiken et al., 1990) (Fig. 2). Thus, a lack of subsurface data may result in an oversimplified model of the caldera's collapse history and the incorrect classification of many young calderas as piston types.

At deeply eroded ancient calderas, such as Scafell, Snowdon and Glencoe calderas in the British Isles (Kokelaar, 1992; Branney and Kokelaar, 1994; Moore and Kokelaar, 1998), intracaldera deposits and structures are well exposed. These calderas reveal multiple fault blocks within the caldera and collapse and intrusion histories that are complex and specific to the individual caldera. Such histories include several collapse episodes and magmatic intrusions before and after individual collapse events. These seminal studies also revealed the importance of regional structural systems on the structural history of the caldera. For example, at Glencoe, pre-existing tectonic faults trending northwest and northeast controlled the collapse structure and the magmatic plumbing (Moore and Kokelaar, 1998). Calderas may form from a single relatively short-lived episode of collapse occurring over a period of hours, days or weeks; e.g., Krakatau in 1883 (Simkin and Fiske, 1983) and Katmai in 1912 (Hildreth and Fierstein, 2000), or calderas may be composite structures formed from a series of separate collapse and intrusion events that take place over a large time interval (> 0.5 Ma); e.g., Scafell (Moore and Kokelaar, 1998).

A major problem in understanding caldera formation is that the process has never been observed directly. Relatively few caldera-forming eruptions have occurred in historic times, and many of these events are far too violent to observe directly. Geophysical data recorded during subsidence events at Katmai caldera, Alaska (1912), Fernandina caldera, Galapagos Islands (1968), Mt. Pinatubo, Philippines (1991), and Miyakejima caldera, Japan (2000), have provided useful information on fault orientations and collapse mechanisms of these relatively small events (Simkin and Howard, 1970; Munro and Rowland, 1995; Mori et al., 1996; Hildreth and Fierstein, 2000; Geshi et al., 2002). This paper focuses mainly on the collapse mechanisms of large subsidence events associated with explosive silicic eruptions.

There are numerous variables that control caldera type and morphology. These include both internal and external parameters. Internal properties include the shear strength of the country rock, the dimensions, depth and internal pressure of the associated magma chamber, and structures produced by magmatic intrusion during tumescence and resurgence. External parameters include topographic features that exert a lithostatic pressure on the magma chamber and regional structures such as tectonic faults and basement grain. These external parameters are largely controlled by the regional stress regime. An extensional stress regime, as manifested by rift and pull-apart basins, is frequently associated with caldera formation (Chesner and Rose, 1991; Rowland et al., 2000). These variables can interact in a variety of ways, giving rise to a wide range of caldera types.

The goal of this paper is to summarize our current understanding of the processes and mechanisms that produce calderas. We first provide a brief summary of the most influential papers on the nature of caldera collapse, and then group calderas into different types, presenting a classification scheme based on caldera structure. Within this scheme, we also define some of the parameters responsible for each caldera type.

A BRIEF REVIEW OF THE LITERATURE

Calderas and cauldrons have been recognized in the geological record since the work of Fouqué (1879) on the origin of Santorini, Greece, and the studies by Clough et al. (1909) on Glencoe cauldron, Scotland. The nature of the caldera-forming process has remained the subject of heated debate since this time.

The work of Williams (1941) initiated modern studies of caldera formation by showing that rapid evacuation of a large, shallow, magma chamber can cause subsidence of the chamber roof and produce a caldera. Smith and Bailey (1968) furthered this model after spending many years mapping Valles caldera, New Mexico. They developed a six-stage caldera cycle model (Fig. 1). The first stage was regional tumescence associated with magma chamber intrusion. The second stage was the partial evacuation of the magma chamber by caldera-forming eruptions. The third stage was piston-like collapse of the caldera floor along inward dipping ring fractures, which formed the structural boundary of the caldera. The fourth stage was renewal of volcanism and formation of a caldera lake. The fifth stage was resurgent doming from renewed magmatic pressure. The sixth stage was post-caldera volcanism and dome extrusion along the ring fault. A circular pattern of these post-collapse lava domes was used as evidence for the presence of a circular ring fault.

Lipman (1984, 1997) provided significant improvements on the Smith and Bailey model after spending many years mapping calderas in the western United States. His mapping revealed that the topographic margin of the caldera is significantly larger than the diameter of the ring fault. This work also revealed that the intracaldera ignimbrite deposits were interleaved with kilometre-sized blocks and landslide breccias derived from the caldera margins, which he termed megabreccias and mesobreccias, respectively. He proposed that widening of the caldera walls occurred by massive landslips and debris avalanches synchronous with collapse and eruption (Fig. 3), as opposed to a distinct eruption stage followed by collapse as suggested by Smith and Bailey (1968).

Walker (1984) showed that ignimbrite deposits dip at varying angles

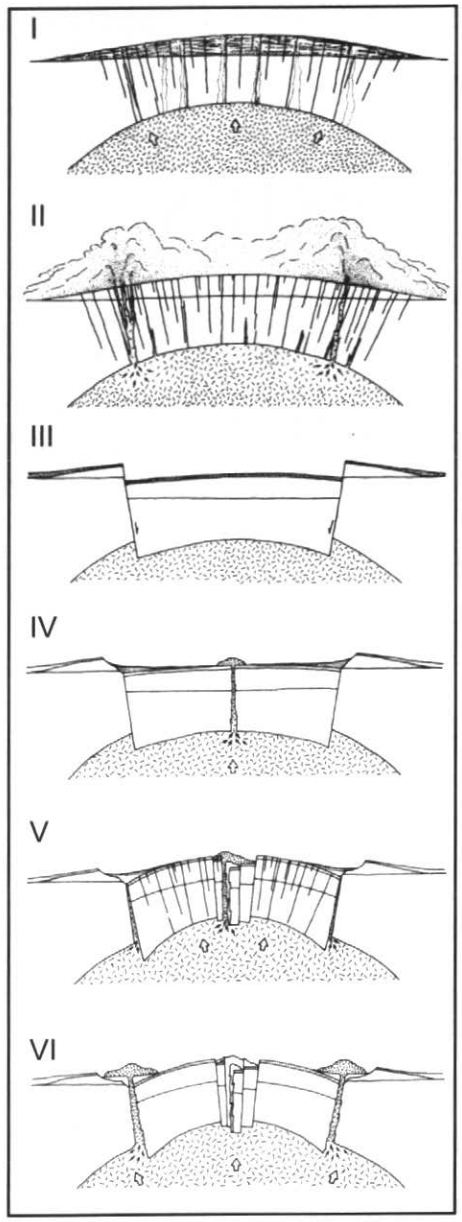

Figure 1. Caldera evolution according to Smith and Bailey (1968). During Stage I, ring fractures are formed by regional tumescence. Caldera-forming eruptions are initiated during Stage II, followed by caldera collapse during Stage III. A lull in activity occurs during Stage IV, with sedimentation in the caldera accompanied by minor volcanism. During Stage V, resurgent doming occurs, which fractures the crustal block. The cycle is terminated by ring-fracture volcanism during Stage VI (from Smith, R.L. and Bailey, R.A., 1968, reprinted by permission of the Geological Society of America).

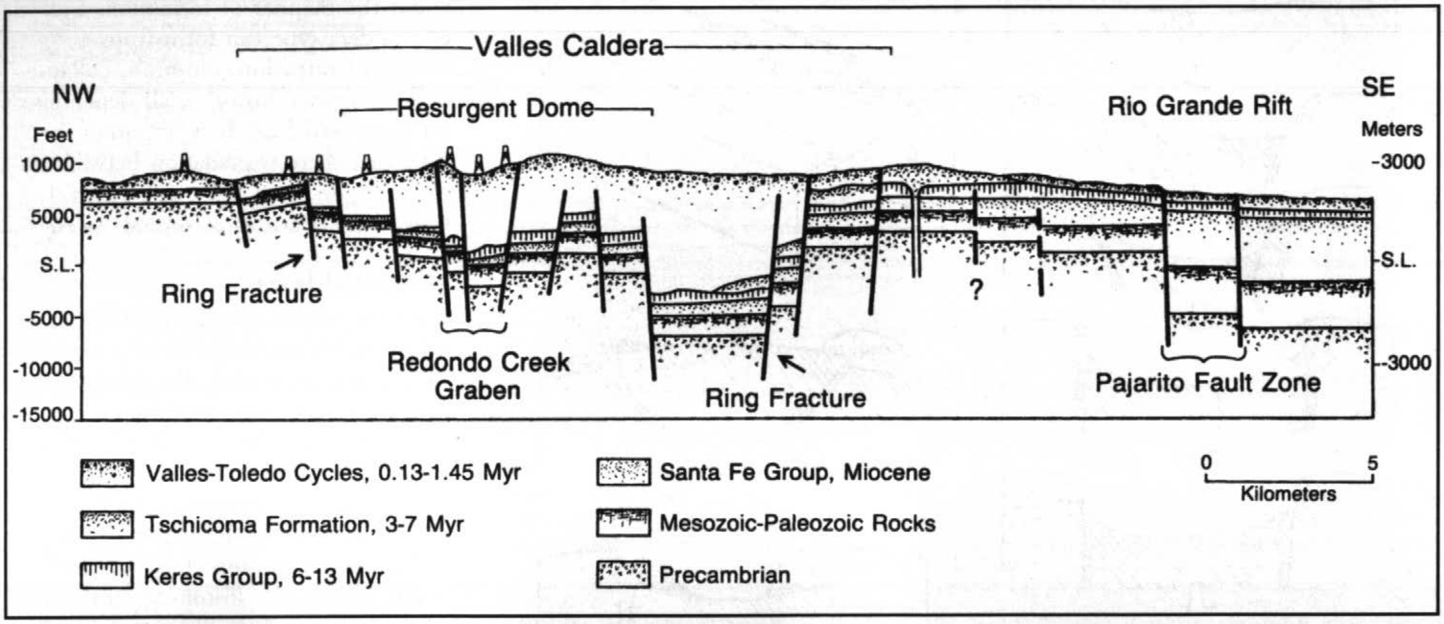

Figure 2. A conceptual NW-SE cross-section across Valles caldera, as interpreted by Heiken et al. (1990) based on data from geothermal drill holes and gravity surveys. The caldera resembles a complexly faulted trapdoor structure, with significant accumulations of intracaldera ignimbrite in the southeast sector. The resurgent dome consists of several up-faulted blocks (from Heiken et al., 1990, reprinted by permission of Annual Reviews of Earth and Planetary Sciences).

towards the center of some calderas, an observation that is not necessarily consistent with a piston style of subsidence. He coined the term downsagging to describe the tilting or bending of horizontally deposited beds toward the center of the caldera. He also noted that spatial vent patterns at many calderas are not always circular, suggesting that the vent distribution is frequently influenced by factors other than a ring fault. Based on these and other observations, he proposed seven different styles of caldera collapse (Fig. 4).

Branney (1995) used data from detailed field mapping at Scafell caldera, England, other calderas, mining subsidence structures, and ice-melt collapse pits to interpret caldera structures. He observed steep inward dips, crevasses, and arcuate normal faults around the margins of these subsidence structures. He also observed outward-dipping faults with large displacements well inside the topographic boundary of these subsidence structures. He proposed that the majority of subsidence occurred on outward dipping faults, with this subsidence producing a zone of extension at the caldera margins as manifested by normal faults, inward tilted blocks and crevasses forming at the surface (Fig. 5).

During the last twenty years numerical and experimental models have become an important part of caldera research. Druitt and Sparks (1984) proposed a two-stage mathematical model in which a central vent eruption was followed by collapse and eruption along a ring fault. They

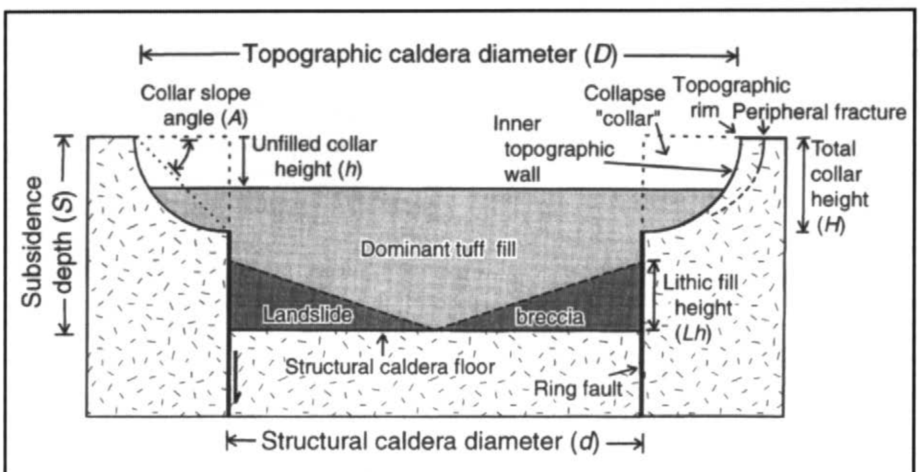

Figure 3. Subsidence of a piston-type caldera along vertical faults according to Lipman (1997). The landslide breccia at the bottom of the caldera results from slumping of the unstable caldera walls during collapse. The collapse collar represents the volume of material lost from the caldera walls by slumping. The slumping of the walls serves to enlarge the caldera; as a result, the topographic diameter of the caldera is larger than its structural diameter as defined by the vertical faults (from Lipman, 1997, Fig. 1; copyright Springer-Verlag, reprinted by permission of Springer-Verlag).

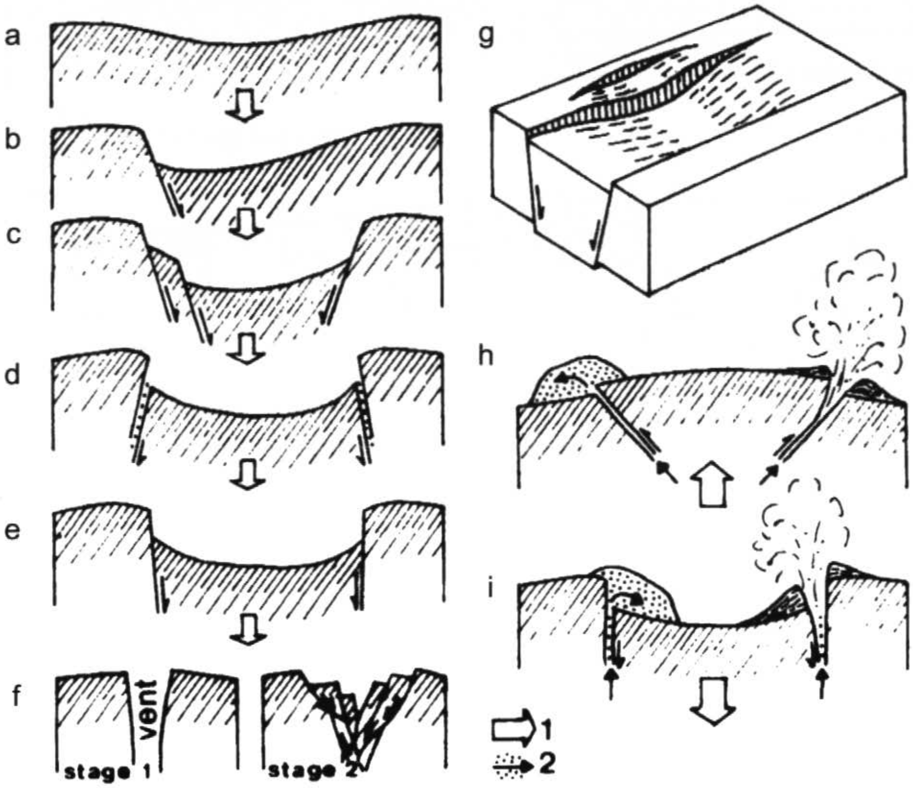

Figure 4. Styles of caldera subsidence as viewed by Walker (1984). a. Simple downsagging. b. Downsagging accompanied by normal faulting. c. Subsidence along multiple inward-dipping ring faults. d. Subsidence along a steeply outward-dipping ring fault. e. Subsidence along a steeply inward-dipping ring fault. f. Collapse of a widened vent along inward-dipping faults. g. Graben structure exhibiting subsidence by normal faulting and downsagging. h. Magma ascent and eruptions through an inward-dipping cone sheet formed by upward-directed pressure. Note that the central block is uplifted. i. Magma ascent and eruptions through a ring fracture formed by subsidence. Arrow 1 indicates downward movement of the crustal block, while arrow 2 shows upward movement of magma (from Walker, 1984).

used relationships between chamber pressure, lithostatic pressure and the strength of the rock to calculate eruption volumes and the initiation of collapse. Burov and Guillou-Frottier (1999) used finite element computer models to calculate the thermo-mechanical behavior of calderas during collapse and eruption. Recent scaled analogue models of caldera formation using sandbox experiments have produced structures that generally support the observations of Branney. These models illustrate a strong dependence of caldera structure on the depth of the chamber (aspect ratio of the subsiding block) (Marti et al., 1994; Roche et al., 2000; Kennedy, 2000; Acocella et al., 2001).

A DESCRIPTIVE OUTLINE OF CALDERA TYPES

The caldera types proposed by Walker (1984) and Lipman (1997) provide a good starting point for categorization. However, a combination of descriptive and interpretive definitions has been applied in some cases, causing some confusion. Authors have used different words for the same type of caldera, as well as the same word to describe different calderas. Lipman (2000) pointed out the confusion that has arisen over funnel-type calderas and piecemeal-type calderas. Therefore, this section of the paper attempts to set out straightforward, applicable definitions of different caldera types. These definitions consist of a simple structural description and do not imply anything about the manner of formation. Indeed, one caldera type can form from a variety of intrusion, eruption, collapse and resurgence histories, all dependent on many variables. It is important to note that there is gradation between caldera types, and most calderas will show some features of several types.

Piston Calderas

A piston caldera consists of a coherent subsiding block, bounded by a circular ring fault that controls the subsidence. The caldera appears roughly symmetrical in plan view and in cross-section. The topographic boundary of the caldera is an expression of the ring fault scarp that has been enlarged by slumping and erosion (Lipman, 1997; 2000) (Fig. 3, 6). Piston-type calderas with a more or less coherent piston have been identified, including Lake City caldera, Colorado, U.S. (Fig. 6b) (Lipman, 2000), and many calderas in northern Honshu, Japan, for example, Ishizuchi (Yoshida, 1984). The dip direction of the ring fault has been a subject of heated debate, and it appears that the ring fault is generally steep (Lipman, 1997). However, piston-type calderas with an inward- or outward-dipping ring fault also exist (Branney, 1995).

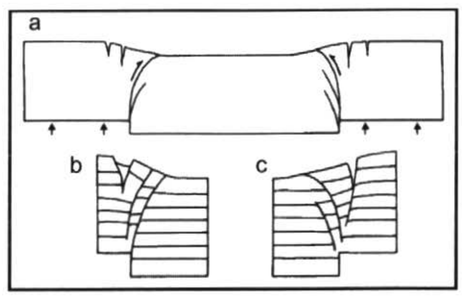

Figure 5. Experimental results of Sanford (1959) from a subsided block, as interpreted by Branney (1995). Experimental materials consisted of 85% sand and 15% clay. i. Subsidence is characterized both by outward dipping faults and by downsagging. ii. Development of a peripheral graben structure as a result of the subsidence. iii. Development of a peripheral normal fault and a crevasse as a result of the subsidence (from Branney, 1995; copyright Springer-Verlag, reprinted by permission of Springer-Verlag).

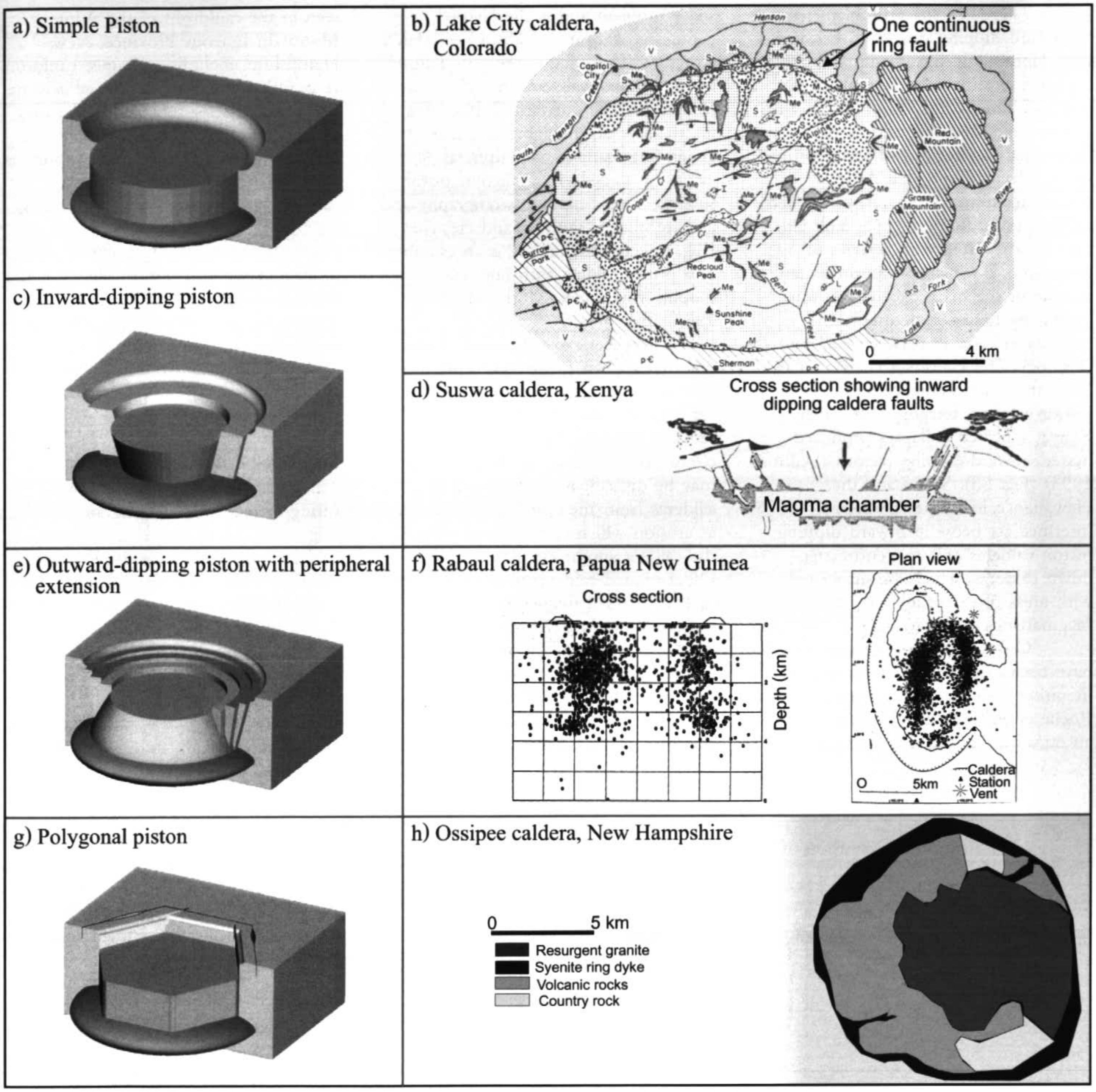

Figure 6. a. Three-dimensional block diagram of piston collapse along vertical ring faults, with a back-eroded topographic margin. b. Geological map of Lake City caldera, showing a single vertical ring fault. This caldera has formed from piston style collapse (from Lipman, 1984). c. Three-dimensional block diagram of piston collapse along inward dipping faults; two concentric ring faults can be seen. d. Suswa volcano, Gregory rift valley, Kenya; this caldera formed from piston collapse along nested inward-dipping faults (from Skilling, 1993; reprinted by permission of the Geological Society Publishing). e. Three-dimensional block diagram of outward-dipping piston collapse with a peripheral area of normal faulting. f. Rabaul caldera, Papua New Guinea; the locations of earthquakes (1983–1985) depict an outward-dipping ring fault (reprinted with permission from Mori and McKee, 1987; copyright [1987] American Association for the Advancement of Science. g. Three-dimensional block diagram of polygonal piston collapse, with linear subsidence-controlling faults. h. Ossipee cauldron, New Hampshire, showing polygonal ring faults, redrawn from Kingsley (1931).

There is a space problem with an inward dipping ring fault, because subsidence along inward dipping fractures requires a horizontal length increase. This is not a problem in areas of extension, and this caldera type may be common in regions of active rifting such as Iceland and East Africa (Gudmundsson, 1998). Piston calderas with an inward-dipping ring fault also may be associated with a series of concentric, downstepping normal faults outside of the main coherent piston, producing nested structures with benches or terraces between ring faults (Fig. 6c). The Hawaiian calderas may be of this type (Francis, 1993). At Suswa volcano, Gregory Rift Valley, Kenya, repeated collapses produced nested, inward-dipping pistons (Skilling, 1993) (Fig. 6d). Suswa and the Hawaiian calderas are perhaps intermediate between inward dipping piston calderas and concentric step-down calderas, which are associated with areas of extension and basaltic magmatism (see below).

Outward-dipping pistons also have been discussed at length in the literature (Walker, 1984; Branney, 1995; Roche et al., 2000). Subsidence along an outward-dipping ring fault has no space problem and is the favored geometry of a purely subsidence-related structure. These faults promote failure of the caldera walls and megabreccia formation. The outward-dipping ring fault causes downsagging to occur, generating features of peripheral extension outside the coherent piston, such as inward-dipping stratigraphy and arcuate normal faulting and crevasses (Fig. 6e). Rabaul caldera is an example of a piston caldera with outward-dipping ring faults (Mori and McKee, 1987) (Fig. 6f).

Another type of piston caldera is one that appears polygonal in plan view instead of circular. The caldera still subsides as a coherent block, but the block is bounded by a series of connected near-linear faults (Fig. 6g). It may be difficult to recognize these calderas from their surface morphology, as erosion will round corners, making the caldera appear circular in plan. Older eroded calderas where the ring fault is exposed frequently exhibit polygonal outlines (Kennedy et al., 2000). Cone sheets or ring dikes are exposed at many intrusions; although previously described as circular, they also show a clear polygonal shape. Excellent examples of this feature are seen in the cauldrons of the White Mountain Igneous Province, New Hampshire, including Ossipee cauldron (Fig. 6h). Calderas that use pre-existing regional faults for subsidence also may show polygonal outlines; examples include Tengger caldera, Java, Indonesia (Rowland et al., 2000) and Ischia caldera, Italy (Acocella and Funiciello, 1999).

Ishizuchi cauldron shows aspects of all four types of piston caldera: it has two concentric faults in the north dipping inward, while in the south, a single ring fault dips outward with evidence for inward-tilted stratigraphy (downsagging). The ring fault even shows a polygonal form (Fig. 7).

Downsag Calderas

This type of caldera exhibits inward tilting of pre-caldera stratigraphy (Fig. 4, 8). There also is an absence of caldera faults with large displacements (Walker, 1984). A downsag caldera will allow ignimbrite sheets to pond in a depression that is not bounded by significant tangential faults. Previously-erupted ignimbrite sheets will be tilted toward the caldera center by the subsidence. Examples of this type of caldera are Rotorua and Taupo, New

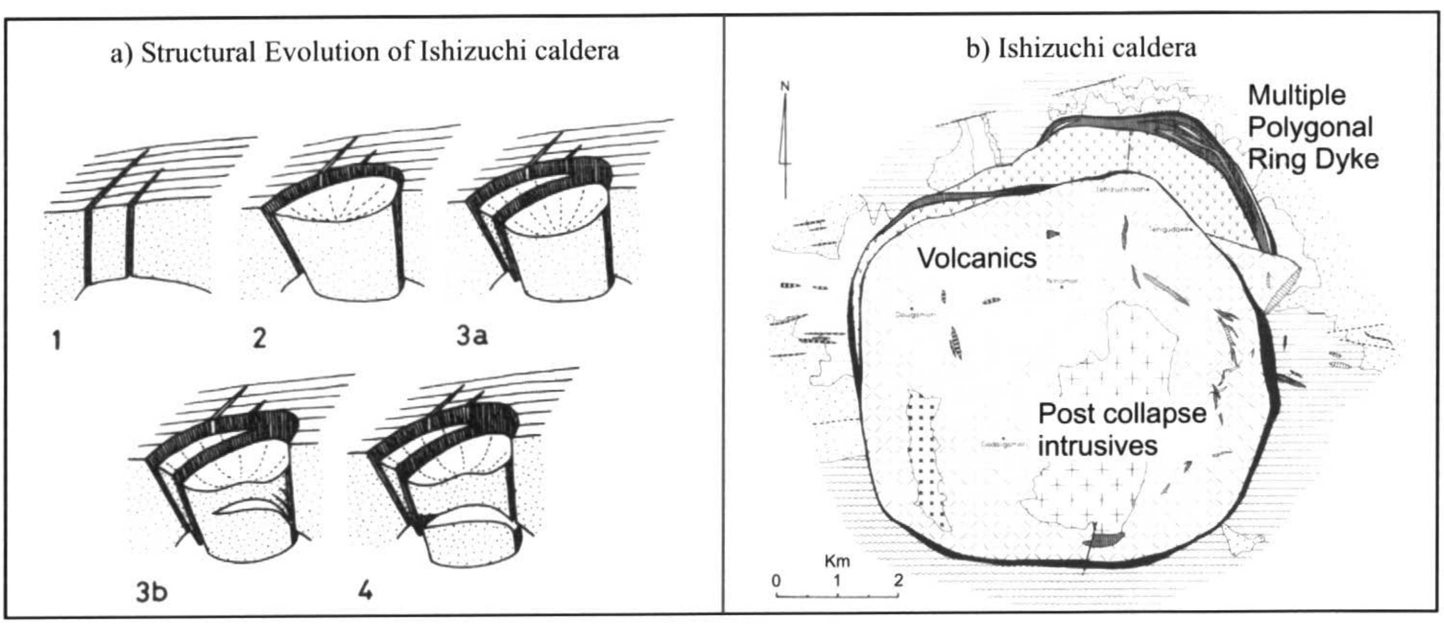

Figure 7. a. The temporal evolution of Ishizuchi cauldron, Japan (Yoshida, 1984). b. Geological map of Ishizuchi cauldron. This structure shows a combination of different styles of piston collapse, including subsidence along both inward- and outward-dipping faults and a polygonal-shaped subsiding block (from Yoshida, 1984).

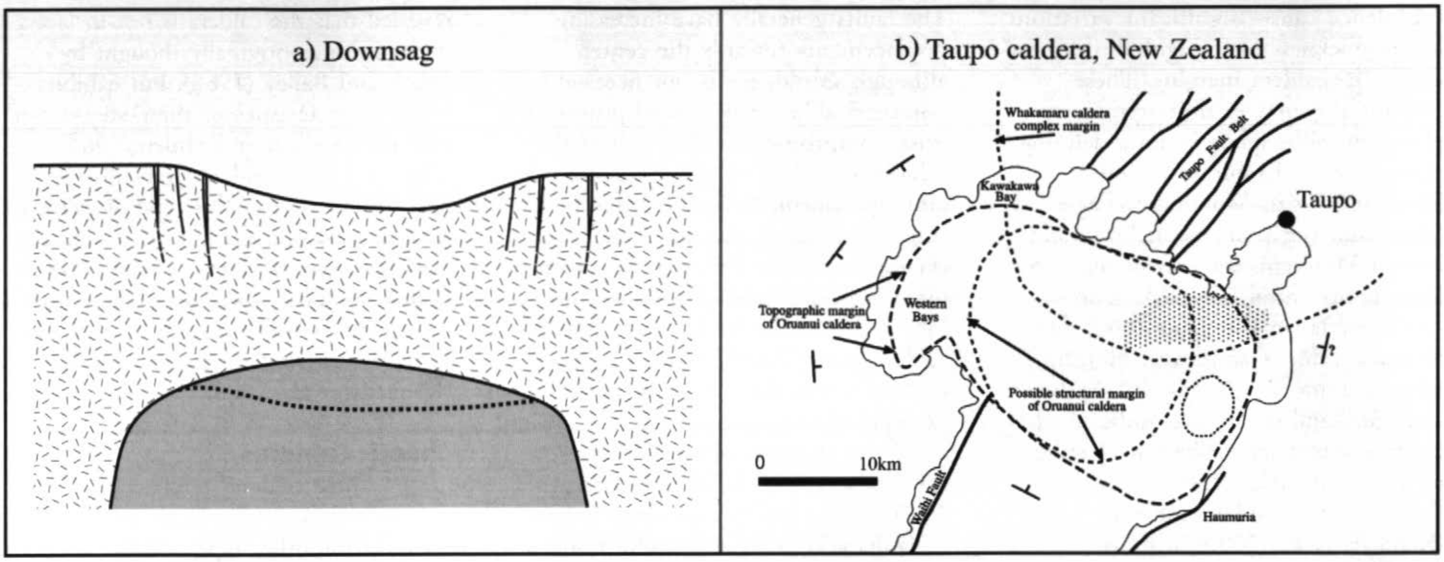

Figure 8. a. A model of a caldera formed by downsag (from Lipman, 1997, Fig. 2, copyright Springer-Verlag, reprinted by permission of Springer-Verlag.) b. An example of downsag from Taupo caldera, New Zealand, in which deposits dip toward the center of the caldera (from Walker, 1984).

Zealand (Walker, 1984) (Fig. 8). Downsag calderas may have faults, but they are not concentric to the depression and are usually tectonic in origin, without large displacements across them. In fact, it may be rare to find purely downsag calderas, as most calderas do appear to have an element of arcuate concentric faulting. However, downsag is an important element of many caldera types, as most calderas show inward tilting of stratigraphy in peripheral regions (Branney, 1995). Scaled sandbox models show that small-volume eruptions from large shallow chambers favor downsag calderas (Roche et al., 2000; Kennedy et al., 1999; 2000).

Trapdoor Calderas

This type of caldera is produced when subsidence is highly asymmetrical. A subsidence-controlling fault with large displacement may exist on only one side of the caldera (Fig. 9). The subsidence on the other side of the caldera is controlled largely by downsag (Walker, 1984). The down-sagged side of the caldera acts as a flexural hinge and may be associated with small-scale arcuate normal faults, graben and crevasse formation (Branney, 1995; Kennedy et al., in press). Such asymmetrical

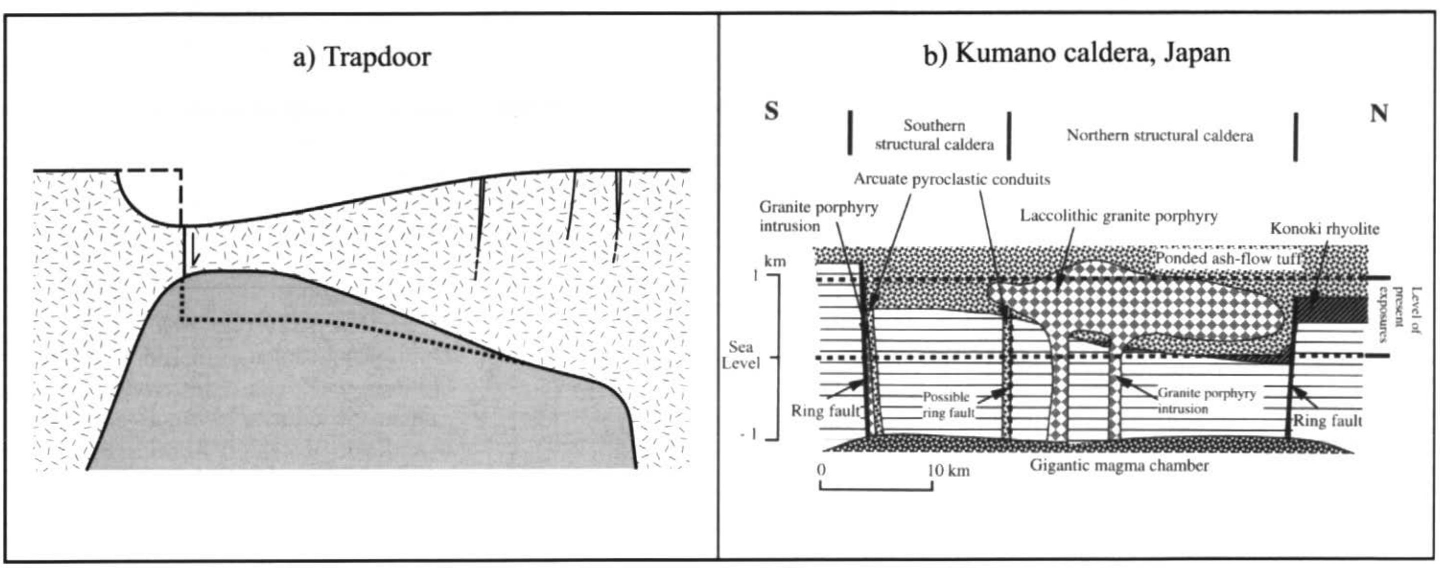

Figure 9. a. A model of a trapdoor-style caldera (from Lipman, 1997, Fig. 2, copyright Springer-Verlag, reprinted by permission of Springer-Verlag.). b. An example from Kumano caldera, southwest Honshu, Japan (from Miura, 1999; copyright 1999, reprinted with permission from Elsevier).

subsidence causes significant variations in the thickness of the ignimbrite sheet inside the caldera margins. These calderas also may exhibit asymmetry in plan view, although it is not a defining characteristic. Examples include Silverton, Organ Mountains, Eagle Mountain, Big John, Whitehorse and Tuscan Mountain calderas in the U.S., Bolsena in central Italy, Sakugi in southwest Japan (Lipman, 2000) and Kumano caldera, southwest Honshu, Japan (Miura, 1999) (Fig 9b). Scaled analogue sandbox models indicate that collapse into a large, shallow chamber or an asymmetrical chamber favors formation of trapdoor calderas (Kennedy et al., 2000; in press).

Concentric Step-down Calderas

These calderas consist of a series of concentric rings and arcuate faults. Collapse occurs along these faults, each with comparatively small displacement. The faults generally have increasing displacements towards the center, although subsidence is not necessarily symmetrical. A small central piston may exist, comprising less than half of the caldera area (Fig. 10). The caldera may grow incrementally outward during subsidence, increasing its overall area (Hallinan, 1993). This type of caldera is often associated with a V-shaped or funnel-shaped gravity anomaly, but the caldera is not a true funnel. Guayabo caldera, Costa Rica, is an excellent example of this type of caldera, showing all of the above-mentioned features (Hallinan, 1993; Hallinan and Brown, 1995) (Fig. 10b). A concentric pattern of faults also exists at Dorobu caldera, northeastern Honshu, Japan, interpreted as representing a series of collapse events moving sequentially toward the caldera center (Miura and Tamai, 1997), opposite to the case of Guayabo. Drilling at Valles caldera has revealed that the caldera is not in fact a pure piston as originally thought by Smith and Bailey (1968), but exhibits some characteristics of these step-down calderas (Nielson and Hulen, 1984) (Fig. 2). Latera caldera, Italy, also has been interpreted as this type of caldera, with its development linked to multiple collapse episodes (Barberi et al., 1984). Scaled sandbox experiments show that concentric step-down calderas also can form from a single collapse episode (Kennedy et al., 2000).

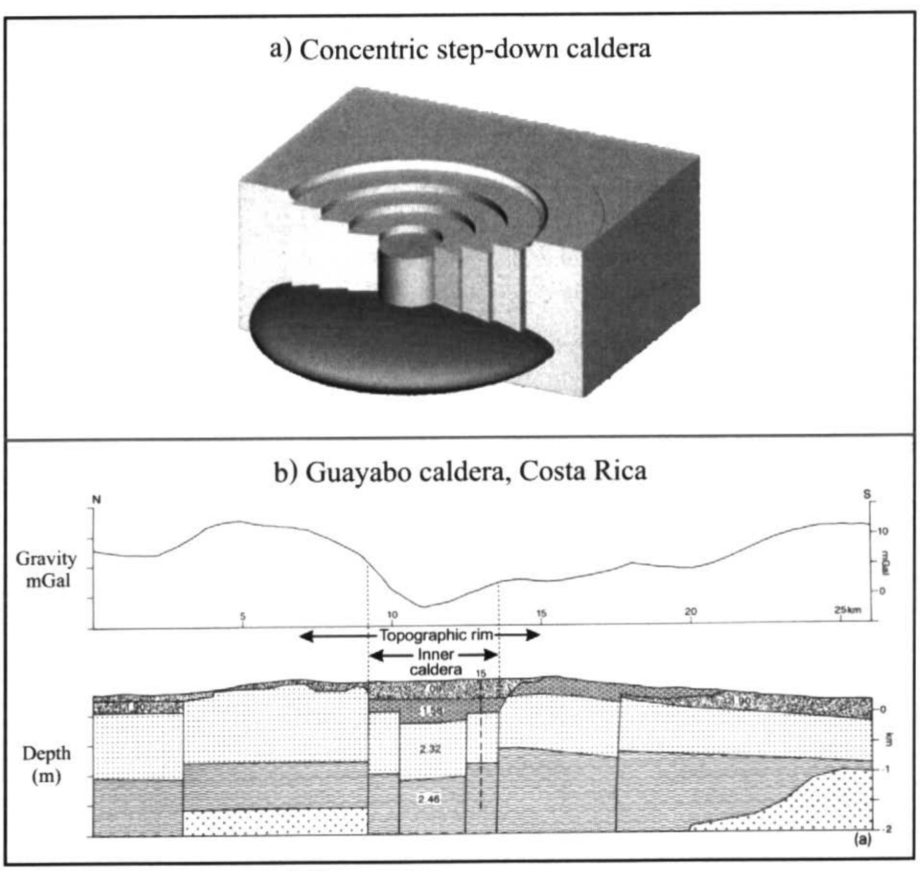

Figure 10. a. Three-dimensional block diagram of step-down concentric collapse, showing a small central piston and concentric nested faults. b. A cross-section through Guayabo caldera, Costa Rica showing multiple nested faults and a funnel-shaped gravity anomaly (from Hallinan and Brown, 1995; copyright 1995, reprinted with permission from Elsevier).

Chaotic Calderas

These calderas tend to be of smaller scale (<10 km diameter) than many of the other types. At the surface, the caldera floor is disrupted but without clear subsidence-controlling faults, while in the lower parts of the subsiding block, nested-outward dipping faults form (Fig. 11a). If these outward-dipping faults intersect beneath the surface, a cone structure may form (Roche et al., 2000). The topographic wall of the caldera does not represent a ring fault but instead the surfaces of slide blocks that contribute to the chaotic nature of the caldera floor.

This type of collapse is commonly associated with the foundering of a hydrothermally weakened pre-caldera volcanic edifice. The alteration reduces the tensile strength of the rock, promoting chaotic collapse of the edifice. The caldera floor consists of low-density brecciated material and generates a V-shaped negative gravity anomaly in cross-section. These calderas have been termed funnel calderas in some reviews, but such terminology can lead to confusion, since calderas of many types exhibit a funnel-shaped gravity profile (Lipman, 2000).

The 1883 caldera-forming eruption of Krakatau in Indonesia could be interpreted as a chaotic type of caldera (Scandone, 1990). It is possible that the 1991 caldera-forming eruption of Mount Pinatubo, Philippines, also formed this type of structure. The volcano had been previously affected by large amounts of hydrothermal alteration, and no evidence of ring structures was observed in fissures or vents before the eruption. Post-climactic eruption seismicity revealed the beginnings of an outward-dipping ring fault up to 14 km deep beneath the volcano (Mori et al., 1996) (Fig. 11b); however, this structure was never used and was of a much larger scale than the caldera that formed during the climactic eruption. The chamber roof appears to be about 14 km deep and 10 km in diameter, with a high aspect ratio value of 1.4 (Mori et al., 1996). Outward-dipping faults appear to intersect at 0–4 km, creating a cone structure (Fig. 11b). By contrast, the ring structure at Rabaul caldera depicts a coherent piston with a roof aspect ratio of 0.67, underlain by a chamber 4 km deep and 6 km in diameter (Mori and McKee, 1987) (Fig. 2f). These data and scaled experimental studies (Roche et al., 2000; Kennedy et al., 2000; in press) suggest that high aspect ratios of the chamber roof may promote chaotic collapse.

Chaotic collapse has been proposed to explain some of the Japanese "funnel" calderas that exhibit V-shaped gravity anomalies. For example, Aira caldera, southern Kyushu, Japan, was interpreted to have a central chaotic area of subsidence and a more coherent margin (Aramaki, 1984) (Fig. 11c). This interpretation is a combination of a concentric step-down type caldera and a chaotic collapse-type caldera.

Rifted Calderas

This type of caldera has not been discussed previously in the literature as an individual type. Such calderas have a significant amount of subsidence controlled by a linear graben. The rest of the caldera subsidence is controlled either by arcuate faulting or by downsagging (Fig. 12a). An example is Toba caldera, Northern Sumatra, Indonesia, which parallels the Latung Graben, normal faults related to this graben were reactivated during subsidence and resurgence (Chesner and Rose, 1991) (Fig. 12b). Submarine calderas that form on the sea floor associated with spreading ridges of the East Pacific Rise also are being recognized and interpreted as this type of caldera (Lagabrielle et al., 2000). Snowdon caldera is a rifted-type caldera

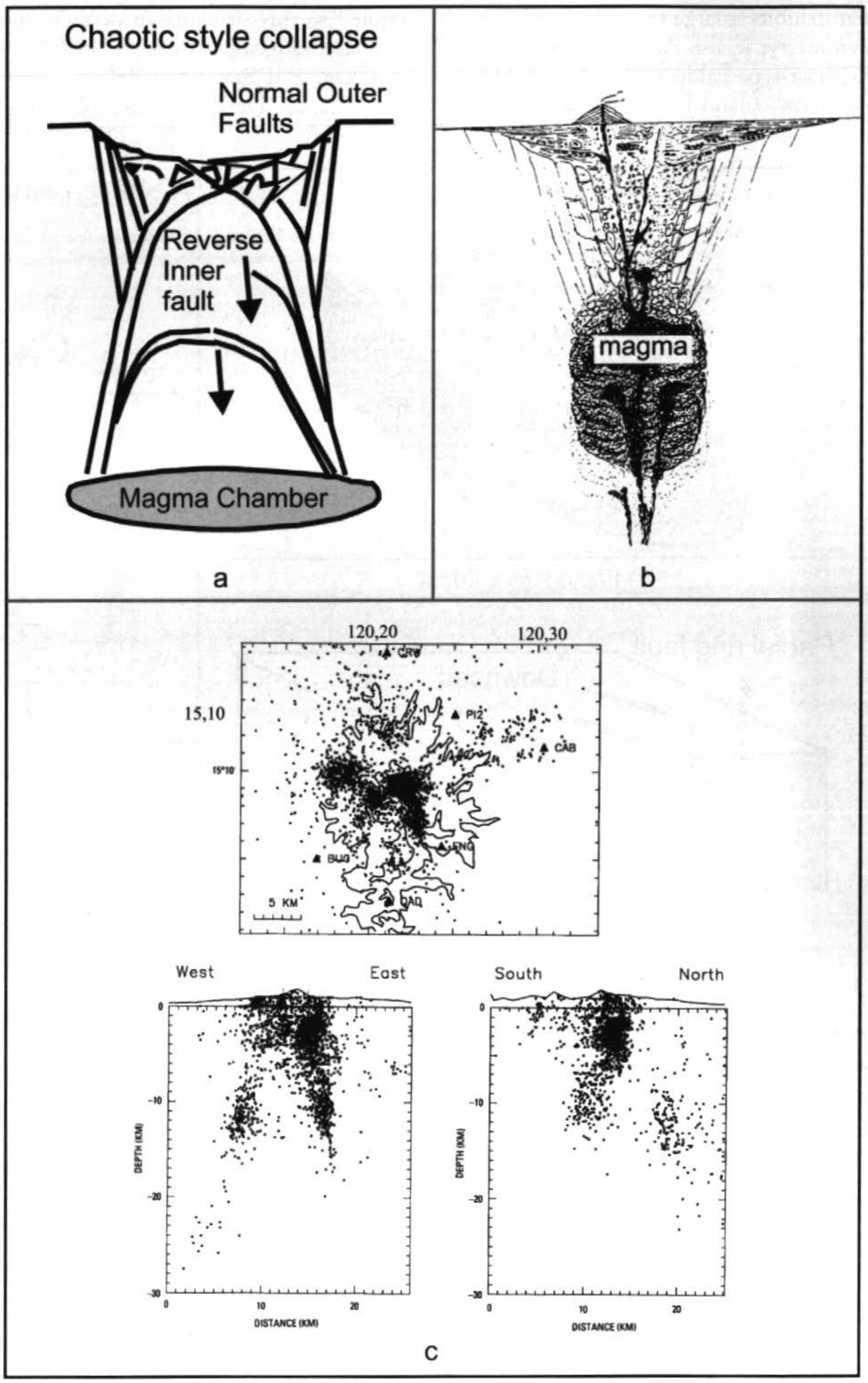

Figure 11. a. Cross-sectional diagram of chaotic collapse, showing no clear ring faults at the surface and a disrupted caldera floor; at depth outward-dipping faults are seen. b. An example from a hypothetical cross-section through Aira caldera, southern Kyushu, Japan. The internal structure of this caldera is poorly constrained; a funnel-shaped gravity anomaly was interpreted as an inward-dipping ring fault. However, an alternative explanation is a funnel-shaped subsurface structure controlled by outward-dipping faults (from Aramaki, 1984). c. Post-climactic eruption seismicity at Mount Pinatubo, Philippines, 29 June–16 August 1991. The earthquake locations depict outward dipping structures in cross-section with no clear ring fault at the surface (from Mori et al., 1996; reprinted by permission of the University of Washington Press).

that exhibits a large component of asymmetry; it also can be considered a trapdoor-type caldera (Kokelaar, 1992). The term "piano key" caldera has been applied to this structure to describe the parallel arrangement of fault blocks (Kokelaar and Branney, 1999) (Fig. 12c, d). The occurrence of rifting also can contribute to significant subsidence in some piecemeal calderas (see below).

Another type of rifted caldera is

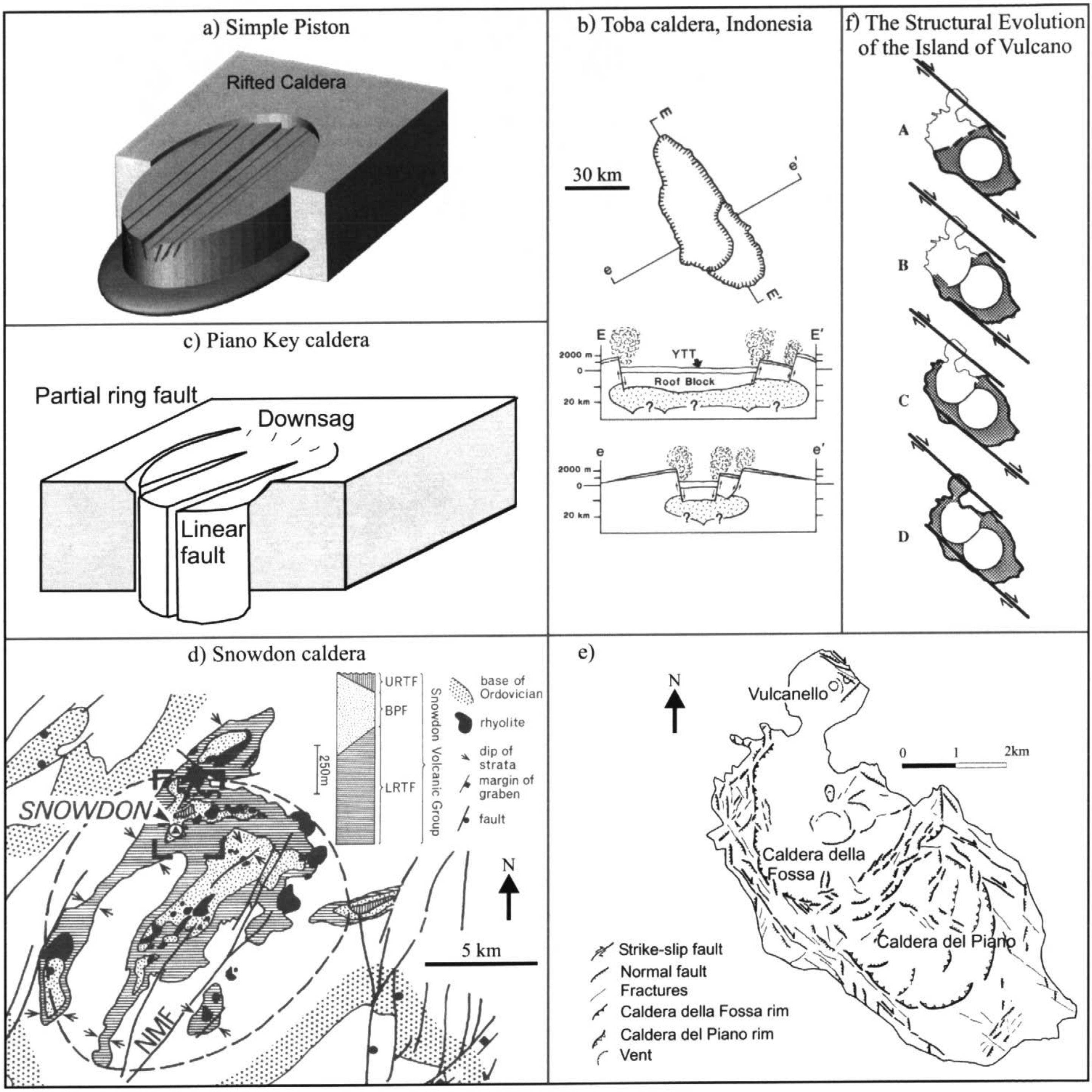

Figure 12. a. Three-dimensional block diagram of a rifted caldera. b. Toba caldera, northern Sumatra, showing an elongate caldera whose collapse was partially controlled by a rift system (from Chesner and Rose, 1991, Fig. 6e; copyright Springer-Verlag, reprinted by permission of Springer-Verlag). c. Three-dimensional block diagram of a piano-key caldera. d. Snowdon caldera, Wales, showing an elongate caldera broken up by linear faults with a partially developed ring fault (from Kokelaar, 1992; reprinted by permission of the Geological Society of America). e. Geological map of Vulcano Island, showing typical morphological features of a pull-apart basin (from Ventura, 1994; copyright 1994, reprinted with permission from Elsevier).

related to pull-apart basins; these calderas appear asymmetrical in plan view and are associated with strike-slip-induced extension. The calderas are commonly elongate parallel to the regional strike-slip faults. Caldera faults that parallel the regional strike-slip system should be near vertical, while normal faults will control subsidence on the adjacent sides of the caldera (Fig. 12f). A central rifted area also may be present. An example of this type is seen on Vulcano Island, Italy, which shows clear pull-apart basin morphology (Ventura, 1994) (Fig. 12f). Indeed, calderas commonly form in transtensional tectonic regimes. The morphology of many calderas in circum-Pacific volcanic arcs is controlled by asymmetrical structures and influenced by strike-slip tectonics (Tereda and Ida, 2000). The Negra Muerta caldera, northwest Argentina, shows evidence of strike-slip-controlled collapse (Riller et al., 2001). The role of transtensional tectonics upon caldera development is probably underappreciated and remains poorly documented for many calderas. Transtensional tectonics may be particularly important in the development of magma chambers. The morphology of the magma chamber will be reflected by the morphology of the caldera. Transtensional structures are used to explain the elliptic calderas in the Wonji Fault Belt of the Ethiopian rift, which are obliquely orientated relative to the rift (Acocella et al., 2002).

Piecemeal/Regional Fault-controlled Calderas

Piecemeal calderas consist of a series of blocks that subside independently. This type of caldera may show aspects of all caldera types mentioned above. However, there is no large single piston that controls the subsidence (Fig. 13a). Some areas of the caldera may subside along pre-existing linear graben structures, strike-slip faults or even thrust faults. Other subsidence-related faults may form during collapse and will be curved and either inward or outward dipping. Steeply inward-dipping beds found at piecemeal calderas indicate that downsagging likely controls significant amounts of subsidence (Moore and Kokelaar, 1998). Different blocks may subside at different times, associated with separate eruptions, causing significant variation in stratigraphic thicknesses from one block to the next, particularly in ponded ignimbrite sheets. The irregular patterns of faulting indicate that there is significant asymmetry in both cross-sectional and plan views. These calderas also may be polygonal in plan view. Scafell caldera is well exposed in three dimensions and can be seen to be of this type (Branney and Kokelaar, 1994). Glencoe caldera in Scotland was previously thought to be a classic piston-type caldera (Clough et al., 1909), but further study has revealed a piecemeal-type morphology and collapse history (Moore and Kokelaar, 1998) (Fig. 13b). Campi Flegrei caldera, Italy, is a complexly nested structure (Orsi et al., 1996) that also could be described as a piecemeal style caldera.

CONCLUDING REMARKS

Extensive fieldwork on hundreds of calderas worldwide has given volcanologists a better understanding of the process of caldera formation. The complexity of the process results in a large variability in both the eruption history and the morphology of individual calderas. The different types of calderas are largely defined by the style in which they collapse, since subsidence style strongly influences the eventual morphology of the caldera. Numerical and experimental models of caldera formation have helped us to understand collapse mechanisms and internal structures of natural calderas, despite certain limitations of the

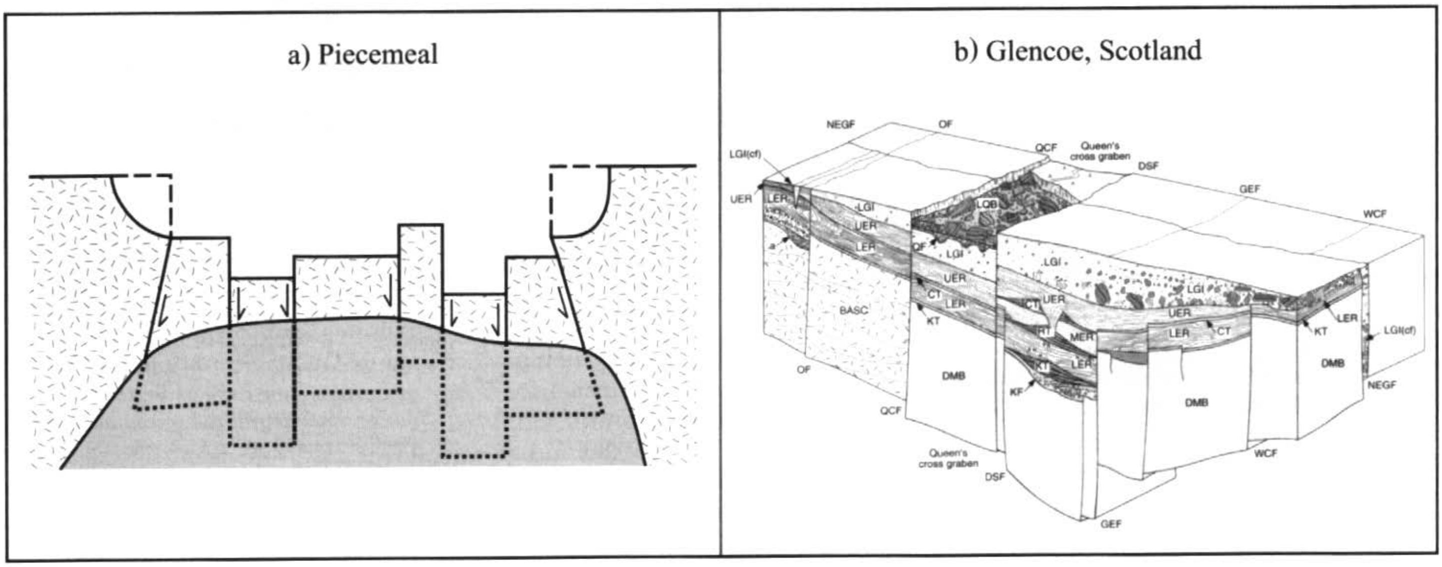

Figure 13. a. A model of a piecemeal-style caldera (from Lipman, 1997, Fig. 2; copyright Springer-Verlag, reprinted by permission of Springer-Verlag). b. A three-dimensional view of Glencoe, Scotland, showing caldera subsidence as a series of separate blocks (from Moore and Kokelaar, 1998, reprinted by permission of the Geological Society of America.).

models. Proper classification of calderas should be based upon detailed fieldwork, drilling data and geophysical surveys that reveal the internal structure and collapse history of the caldera.

Caldera environments are also interesting from an economic viewpoint. Epithermal gold and copper deposits are commonly associated with subaerial calderas (Lipman and Sawyer, 1985), and volcanogenic massive sulphide mineral deposits are often found in submarine calderas (Stix et al., 2003). To a large extent, the subsurface structure of the caldera controls the hydrothermal systems responsible for these ore deposits. Although often modified by resurgence, the caldera structure is dominated by its collapse history. A clear understanding of this structure permits us to understand the structural environments in which caldera-related ore deposits form, thereby providing a useful guide for exploration geologists. As a final point, a better understanding of the subsurface structure of calderas can help us to improve our hazard assessments at currently restless calderas, such as Yellowstone, Long Valley, Campi Flegrei and Rabaul. The deformation, gravity changes and seismic activity that have been occurring at these calderas are not fully understood. By improving our comprehension of the subsurface fault system, we can gain insight into the mechanisms responsible for this unrest.

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GLOSSARY

Aspect ratio of subsiding block - The ratio of the distance from the top of the magma chamber to the surface, divided by the maximum diameter of the chamber.

Caldera - Collapse structure that is approximately circular and formed by magma evacuation from a subsurface reservoir. Recently, this definition has been broadened to include ancient volcanic subsidence structures whose surface expression has been modified by erosion (Kokelaar and Branney, 1999).

Cauldron - This term was commonly employed in the older literature (Kingsley, 1931; Smith and Bailey, 1968) and used to describe "the exhumed internal structure of an inferred former caldera following erosion" (Kokelaar and Branney, 1999).

Cone sheet - A dike, roughly circular in plan view, that dips inward and is associated with upward magmatic pressure.

Degassing - The process of volatile loss from a magma.

Downsag - Layered rocks that dip toward the center of the caldera; the dips are the result of tilting or bending during subsidence.

Extracaldera - Rocks deposited outside a caldera.

Ignimbrite - A pumice-rich deposit from a density current of pyroclastic fragments and hot gas generated from an explosive eruption (also referred to as pyroclastic flow deposit, ash flow deposit).

Intracaldera - Rocks deposited within a caldera.

Megabreccia - A breccia containing large blocks, reaching 1 km or more in diameter, which originate from a caldera's walls and have slid into the caldera.

Mesobreccia - A breccia formed in a way similar to that of a megabreccia except containing smaller blocks up to 1 m.

Overpressure - Excess pressure in a magma chamber that exceeds the lithostatic pressure.

Peripheral extension - Extensional structures, such as normal faults and crevasses, around the margins of a caldera (Branney, 1995).

Plinian fall - The accumulation of tephra as it falls from the sky during a sustained powerful explosive eruption (eruption column exceeding 30 km in height); the tephra comprises mainly pumice clasts.

Resurgence - Intrusion of magma after caldera collapse that results in structural doming and faulting of the intracaldera deposits. The resurgence may be accompanied by volcanism at the surface.

Ring dike - A dike, roughly circular in plan view, which is related to subsidence of a magma chamber roof. Ring dikes also may intrude faults in post-caldera time after caldera subsidence.

Ring fault - A fault, roughly circular in plan view, which is commonly believed to control subsidence at a caldera.

Space problem - A situation in which a subsiding block cannot subside along inward-dipping faults, since the orientation of the faults impedes the collapse process.

Trapdoor collapse - A caldera which subsides asymmetrically in cross-section; large fault displacements occur on one side of the caldera but not on the other side.

Tumescence - The structural doming that occurs during the intrusion of a large, shallow magma chamber before a caldera forms. Hence tumescence may be caused by thermal expansion, faulting or bending of the rock caused by magma pressure.

REFERENCES

Acocella, V. and Funiciello, R., 1999, The interaction between regional and local tectonics during resurgent doming: the case of the island Ischia, Italy: Journal of Volcanology and Geothermal Research, v. 88, p. 109-123.

Acocella, V., Cifelli, F. and Funiciello, R., 2001, Analogue models of collapse calderas and resurgent domes: Journal of Volcanology and Geothermal Research, v. 104, p. 81-96.

Acocella V., Korme, T., Salvini, F., and Funicello R., 2002, Elliptic calderas in the Ethiopian Rift: control of pre-existing structures: Journal of Volcanology and Geothermal Research, v. 119, p. 189-203.

Aramaki, S., 1984, Formation of the Aira caldera, southern Kyushu, ~22000 years ago: Journal of Geophysical Research, v. 89, p. 8485-8501.

Barberi, F., Innocenti, F., Landi, P., Rossi, U., Saita, M., Santacroce, R. and Villa I.M., 1984, The evolution of Latera caldera (Central Italy) in the light of subsurface data: Bulletin of Volcanology, v. 47, p. 125-141.

Branney, M.J., 1995, Downsag and extension at calderas: new perspectives on collapse geometries from ice melt, mining and volcanic subsidence: Bulletin of Volcanology, v. 57, p. 303-318.

Branney, M.J. and Kokelaar, P., 1994, Volcanotectonic faulting, soft state deformation, and rheomorphism of tuffs during development of a piecemeal caldera, English Lake District: Geological Society of America, Bulletin, v. 106, p. 507-530.

Burov, E.B. and Guillou-Frottier, L., 1999, Thermomechanical behaviour of large ash flow calderas: Journal of Geophysical Research, v. 104, p. 23081- 23109.

Chesner, C.A. and Rose W.I., 1991, Stratigraphy of the Toba Tuffs and the evolution of the Toba Caldera Complex, Sumatra, Indonesia: Bulletin of Volcanology, v. 53, p. 343-356.

Clough, C.T., Maufe, H.B. and Bailey, E.R., 1909, The cauldron subsidence of Glencoe and the associated igneous phenomena: Journal of the Geological Society of London, v. 65, p. 611-678.

Druitt, T. and Sparks, R.S.J., 1984, On the formation of calderas during ignimbrite eruptions: Nature, v. 310, p. 679-681.

Fouqué, F., 1879, Santorini et Ses Eruptions: Masson, Paris, France, 440 p.

Francis, P., 1993, Volcanoes, a Planetary Perspective: Clarendon Press, Oxford, UK, 443 p.

Geshi, N., Shimano, T., Chiba, T. and Nakada, S., 2002, Caldera collapse during the 2000 eruption of Miyakejima Volcano, Japan: Bulletin of Volcanology, v. 64, p. 55-68.

Gudmundsson, A., 1998, Formation and development of normal fault calderas and the initiation of large explosive eruptions: Bulletin of Volcanology, v. 60, p. 160-170.

Hallinan, S., 1993, Non-chaotic collapse at funnel calderas: Gravity study of the ring fractures of the Guayabo caldera, Costa Rica: Geology, v. 21, p. 367-370.

Hallinan, S. and Brown, G., 1995, Incremental collapse and stratocone growth within a funnel-shaped caldera, Guayabo, Costa Rica: Journal of Volcanology and Geothermal Research, v. 67, p. 101-122.

Heiken G., Goff, F., Gardner, J. N., Baldridge, W. S., Hulen, J. B., Nielson, D. L. and Vaniman, D., 1990, The Valles/Toledo caldera complex, Jemez Volcanic field, New Mexico: Annual Reviews of Earth and Planetary Sciences, v. 18, p. 27-53.

Hildreth, W. and Fierstein, J., 2000, Katmai volcanic cluster and the great eruption of 1912: Geological Society of America, Bulletin, v. 112, p. 1594-1620.

Kennedy, B., 2000, The nature and origin of caldera structure and morphology, using results from analogue modeling: M.Sc. Thesis, McGill University, Montreal, Quebec, 131 p.

Kennedy, B., Stix, J, Lavallée, Y. and Vallance, J., 1999, Controls on caldera structure and morphology: results from experimental simulations [abstract]: EOS, Transactions of the American Geophysical Union, v. 80, no. 46, p. F1121.

Kennedy, B., Stix, J., Vallance, J. and Lavallée, Y., 2000, Caldera asymmetry: observations and causes from field examples and experimental simulations [abstract]: IAVCEI General Assembly, Bali, Indonesia, 18-22 July 2000, Abstract volume, p. 256.

Kennedy, B., Stix, J., Vallance, J., Lavallée, Y., and Longpré M-A., Controls on caldera structure: Results from analogue sandbox modeling, Geological Society of America, Bulletin, in press.

Kingsley, L., 1931, Cauldron subsidence of the Ossipee Mountains: American Journal of Science, v. 22, p. 139-168.

Kokelaar, P., 1992, Ordovician marine volcanic and sedimentary record of rifting and volcanotectonism: Snowdon, Wales, United Kingdom: Geological Society of America, Bulletin, v. 104, p. 1433-1455.

Kokelaar, P. and Branney, M.J., 1999, Inside silicic calderas, interactions of caldera development, tectonism and hydrovolcanism: Field Guidebook of the IAVCEI Commission on Explosive Volcanism Field Workshop, 7-18 July 1999, 152 p.

Lagabrielle, Y., Garel, E., Dauteuil, O. and Cormier, M.-H., 2000, Extensional faulting and caldera collapse in the axial region of fast spreading ridges: analogue modelling: Journal of Geophysical Research, v. 106, p. 2005-2015.

Lipman, P.W., 1984, The roots of ash flow calderas in western North America: windows into the tops of granitic batholiths: Journal of Geophysical Research, v. 89, p. 8801-8841.

Lipman, P.W., 1997, Subsidence of ash flow calderas: relation to caldera size and magma chamber geometry: Bulletin of Volcanology, v. 59, p. 198-218.

Lipman, P.W., 2000, Calderas, *in* Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., and Stix, J., eds., Encyclopedia of Volcanoes: Academic Press, San Diego, USA, p. 643-662.

Lipman, P.W. and Sawyer, D.A., 1985, Mesozoic ashflow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits: Geology, v. 13, p. 652-656.

Martí, J., Albay, G.J., Redshaw, L.T. and Sparks, R.S.J., 1994, Experimental study of collapse calderas: Journal of the Geological Society of London, v. 151, p. 919-929.

Miura, D., 1999, Arcuate pyroclastic conduits, ring faults, and coherent floor at Kumano caldera, southwest Honshu, Japan: Journal of Volcanology and Geothermal Research, v. 92, p. 271-294.

Miura, D. and Tamai, M., 1997, Intracaldera structure and megabreccias at Dorobu caldera, northwestern Honshu, Japan: Journal of Volcanology and Geothermal Research v. 80, p. 195-215.

Moore, I. and Kokelaar, P., 1998, Tectonically controlled piecemeal caldera collapse at Glencoe volcano, Scotland: Geological Society of America, Bulletin, v. 110, p. 1448-1466.

Mori, J. and McKee, C., 1987, Outward-dipping ring-fault structure at Rabaul caldera as shown by earthquake locations: Science, v. 235, p. 193-194.

Mori, J., White, R. A., Harlow, D. H., Okubo, P., Power, J. A., Hoblitt, R. P., Laguerta, E. P., Lanuza, A. and Bautista, B. C., 1996, Volcanic earthquakes following the 1991 climactic eruption of Mt. Pinatubo: Strong seismicity during a waning eruption, *in* Newhall, C. G. and Punongbayan, S., eds., Fire and Mud: Eruptions and Lahars of Mt. Pinatubo, Philippines: Philippine Institute of Volcanology and Seismology and University of Washington Press, Quezon City, Philippines, and Seattle, USA, p. 339-350.

Munro, D.C. and Rowland, S.K., 1995, Caldera morphology in the western Galápagos and implications for volcano eruptive behavior and mechanism of caldera formation: Journal of Volcanology and Geothermal Research, v. 72, p. 85-100.

Nielson, D.L. and Hulen, J.B., 1984, Internal geology and evolution of the Redondo dome, Valles caldera, New Mexico: Journal of Geophysical Research, v. 89, p. 8695-8711.

Orsi, G., De Vita, S. and De Vito, M., 1996, The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration: Journal of Volcanology and Geothermal Research, v. 74, p. 179-214.

Riller, U., Petrinovic, I., Ramelow, J., Strecker M. and Oncken, O., 2001, Late Cenozoic tectonism, collapse caldera and plateau formation in the Central Andes: Earth and Planetary Science Letters, v. 188, p. 299-311.

Roche, O., Druitt, T.H. and Merle, O., 2000, Experimental caldera formation: Journal of Geophysical Research, v. 105, p. 395-416.

Rowland, S.K., Mouginis-Mark, P.J. and Garbeil, H., 2000, Interferometric topography studies of caldera structure and formation at Tengger/Bromo volcano, E. Java, Indonesia [abstract]: EOS, Transactions of the American Geophysical Union, p. F1332.

Sandford, A.L., 1959, Analytical and experimental study of simple geologic structures: Geological Society of America, Bulletin, v. 70, p. 19-52.

Scandone, R., 1990, Chaotic collapse of calderas: Journal of Volcanological and Geothermal Research, v. 42, p. 285-302.

Simkin, T. and Howard, K.A., 1970, Caldera collapse in the Galapagos Islands, 1968: Science, v. 169, p. 429-437.

Simkin, T. and Fiske, R.S., 1983, Krakatau 1883, The Volcanic Eruption and Its Effects: Smithsonian Institution Press, Washington, D.C., USA, 470 p.

Skilling, I.P., 1993, Incremental caldera collapse of Suswa volcano, Gregory Rift Valley, Kenya: Journal of the Geological Society of London, v. 150, p. 885-896.

Smith, R.L. and Bailey, R.A., 1968, Resurgent cauldrons, *in* Coats, R.R., Hay, R.L. and Anderson, C.A., eds., Studies in Volcanology, Geological Society of America Memoir, v. 116, p. 613-662.

Stix J., Kennedy B., Hannington M., Fiske R., Mueller W., Franklin J., and Gibson H., 2003, Caldera-forming processes and the origin of massive sulphide mineralisation, Geology, v. 31, p 375-378.

Terada, A., and Ida, Y., 2000, Quantative analysis of geometric features of caldera's outlines: Implication for the effect of tectonic stress conditions on the caldera formation [abstract]: IAVCEI General Assembly, Bali, Indonesia, 18-22 July 2000, p. 224.

Ventura, G., 1994, Tectonics, structural evolution and caldera formation on Vulcano Island (Aeolian Archipelago, southern Tyrrhenian Sea): Journal of Volcanology and Geothermal Research, v. 60, p. 207-224.

Walker, G.P.L., 1984, Downsag calderas, ring faults, caldera sizes and incremental caldera growth: Journal of Geophysical Research, v. 89, p. 8407-8416.

Williams, H., 1941, Calderas and their origin: Bulletin of the Department of Geological Sciences, University of California, v. 25, p. 239-346.

Yoshida, T., 1984, Tertiary Ishizuki cauldron, southwestern Japan arc: formation by ring fracture subsidence: Journal of Geophysical Research, v. 89, p. 8502-8510.

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