Mechanisms of Activity and Unrest at Large Calderas

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Mechanisms of Activity and Unrest at Large Calderas

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Preface

Calderas are remarkable volcanic structures. They are depressions, kilometres to tens of kilometres across, formed as near-surface crust subsides into magma reservoirs during eruption. Although some of the smaller examples have developed during the effusion of lava flows, most calderas are associated with explosive volcanism, from plinian eruptions that expel 1–10 km^3 of magma to ignimbrite-forming events that erupt at least a hundred times as much. This Special Publication focuses on the evolution of large calderas, from their formation to post-collapse behaviour. It illustrates the advances that have been made during the past two decades in understanding such calderas and highlights the goals that still need to be achieved in order to mitigate the hazard from their activity.

Larger calderas are associated with larger eruptions and these, because of the greater energy required, occur less frequently than smaller events. As a result, the explosive caldera-forming eruptions in historical time represent only the smaller end of the size range. For example, the 1991 eruption of Pinatubo, in the Philippines, expelled about 5 km^3 (volumes quoted as dense rock equivalents) of magma to produce a caldera 2.5 km across; the 1912 Katmai eruption (Alaska, USA) involved 12 km^3 of magma and left a caldera 2.5 by 4 km across; and, in 1883, the eruption of 10 km^3 of magma from Krakatau (Indonesia) produced a caldera 8 km wide (Lipman 2000). Events of such magnitude occur a few times each century and rank among the largest explosive eruptions in history (Simkin & Siebert 1994). They are nevertheless modest compared with explosive caldera-forming eruptions from the geological record. Thus, the Toba caldera in Indonesia, 30 by 80 km in size, was formed 75 000 years BP after the eruption of 1500 km^3 of magma; the Cerro Galán caldera (Argentina), 25 by 35 km across, formed 2.2 Ma BP with the expulsion of 2000 km^3 of magma; and La Garita caldera (Colorado, USA), 35 by 75 km across, developed 27.8 Ma BP after 5000 km^3 of magma had been erupted (Lipman 2000).

Explosive caldera-forming eruptions that expel from hundreds to thousands of cubic kilometres of magma may occur at intervals of, respectively, about 1000 to 500 000 years or more (Simkin & Siebert 1994). Evidence for such activity has been found back to at least the Ordovician (Moore & Kokelaar 1998) and so there is every reason to expect that it will continue to recur. The impact of such an eruption will be global and catastrophic (McGuire 2006). Ground-hugging ignimbrites will obliterate thousands to tens of thousands of square kilometres immediately around the caldera, whereas buoyant eruption clouds will propel volcanic ash and gas to altitudes of tens of kilometres. The coarser ash will rain out over millions of square kilometres, leaving the finer material and gas to be carried around the world by stratospheric winds. The floating ash and gas, notably the sulphur-rich components, will create an atmospheric haze that may reduce the mean global temperature by as much as 10 °C for several months and maintain severe temperature distortions for decades thereafter (Jones *et al.* 2005). The consequent extremes in weather and disruption to agriculture would threaten a global famine. Indeed, it has been postulated that the climatic effects of the 75 000 years BP Toba eruption may have altered the course of human development by reducing the total population to just a few thousand individuals (Rampino & Ambrose 2000). Importantly, though, the eruption did not lead to total extinction. It is thus pertinent to consider strategies for optimizing survival after a future event. A cornerstone of any such strategies will be to recognize the approach to a giant caldera-forming eruption and this, in turn, requires understanding of how the underlying magmatic systems develop beforehand.

Once a large caldera has been formed, further eruptions commonly occur within the collapsed area, ranging in style from effusions of lava to plinian events. Such eruptions and related unrest have been recorded at 138 calderas larger than 5 km in historical time (Newhall & Dzurisin 1988). At any given caldera, eruptions may occur at intervals from several decades to millennia, so giving ample opportunity for humans to settle in the area, drawn especially by the fertility of volcanic soils. For example the Campi Flegrei caldera, which adjoins the western suburbs of Naples in Italy, boasts a population of some 1 500 000 people. It is not surprising, therefore, that numerous calderas are centres of high volcanic risk.

Uplift of the caldera floor is another common feature of post-collapse behaviour and some degree of unrest occurs at about 15–20 large calderas each year. Not all episodes of uplift end in eruption, but even without volcanic activity, the rate of uplift may be sufficiently rapid to damage buildings and to render them unsafe.

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Since the 1970s, for example, caldera uplift and associated seismic crises have triggered major emergencies at Campi Flegrei, Rabaul (Papua New Guinea) and Long Valley (California, USA). Two eruptions finally began, virtually simultaneously, at Rabaul in 1994 but renewed activity has yet to occur in Campi Flegrei and Long Valley. Several mechanisms may be envisaged for driving the uplift, including pressure changes in a deep magma reservoir, the intrusion of magma at shallow depths in the crust, and pressure changes in near-surface aquifers. Each mechanism is associated with a different probability of eruption. For individual calderas, however, ambiguity remains as to the relative importance of the different mechanisms and this creates uncertainty in designing the appropriate response to an episode of unrest.

From their formation to post-collapse activity, therefore, several key features of caldera behaviour have yet to be fully understood, in particular:

- the conditions that are necessary to produce and to release the large volumes of magma erupted during caldera formation;
- how magmatic feeding systems evolve before and after a caldera has formed;
- the processes that limit the behaviour of precursors to eruptions, both before caldera formation and during post-collapse unrest;
- whether pre-eruptive precursors can be distinguished from those driving unrest without an eruption; and
- given that post-collapse eruptions may occur across a wide area, what the optimum procedures for designing hazard maps and mitigation strategies would be.

Through a combination of case studies and theoretical modelling, these questions are addressed by the eleven contributions in this Special Publication. To provide a context for current issues at active calderas, the two opening chapters by **Hill** and **De Natale *et al.*** describe recent unrest at Long Valley and Campi Flegrei and the interpretations of such behaviour in terms of changes in the underlying magmatic systems. They illustrate how conceptual models of shallow magmatic feeding systems have evolved, since the 1980s, from a single large reservoir (with a volume on the order of 10^2–10^3 km^3) to collections of small reservoirs (with volumes of cubic kilometres or less), all at depths of about 3–5 km. They also introduce the importance of taking into account the behaviour of pressurized hydrothermal systems, which may produce significant ground uplift without requiring the upward movement of magma.

Da Silva *et al.*, Aizawa *et al.* and **Gudmundsson & Nilson** investigate the conditions necessary for caldera formation, based on field studies in the Central Andes, as well as on the results from analogue and numerical models. They all support a key role for regional tectonics in determining the potential for accumulating sufficiently large volumes of magma in a deep reservoir (at depths notionally greater than about 15 km) and, subsequently, for enabling the deep reservoir to feed intrusions to shallower depths before generating a system of ring faults that feed eruptions and permit caldera collapse.

Most of the remaining chapters concentrate on new models for interpreting post-collapse unrest. A recurring theme is the sensitivity of model results to initial assumptions about the sources of deformation and the structure of the enclosing crust. Their results are important for improving forecasts of eruptions and for designing appropriate strategies for mitigating eruptive hazards.

Folch & Gottsmann show how ring faults can amplify the amount of ground deformation compared with that expected from unbroken crust. When constrained by a ring fault, therefore, a given amount of deformation may be driven by a smaller source overpressure (in a magma reservoir or hydrothermal system) and so suggests a lower probability of eruption. **McGuire** relaxes the assumption of large calderas being the result only of vertical collapse along ring faults, noting that the 'type' structure after which calderas are named (Caldera Taburiente on La Palma in the Canary Islands) is in fact the product of lateral collapse. Such collapses from island volcanoes may involve very large volumes (on the order of 10^2–10^3 km^3) and have the potential to trigger damaging tsunamis across ocean basins.

The deformation history of Campi Flegrei since Roman times is re-analysed by **Bellucci *et al.*** who assume that uplifts have occurred against a background condition of constant subsidence, in contrast to the conventional view of a static background state; the results suggest that uplift for the past 2000 years has been controlled by the episodic intrusion of some 1–2 km^3 of magma, rather than by pressure changes in a hydrothermal system. Only 1% of the inferred intrusion has been erupted and, because intermittent uplifts have been continuing since 1969, Campi Flegrei may be entering a period characterized by an elevated possibility of eruption. Accordingly, **Mastrolorenzo *et al.*** have used Campi Flegrei to illustrate new statistical methods for computing probabilistic maps of the hazard from pyroclastic products. The results indicate that, in addition to Campi Flegrei itself, the metropolitan area of Naples is also vulnerable to the impact of even a modest explosive eruption.

Battaglia & Vasco re-analyse recent patterns of deformation at Long Valley caldera, discarding the usual assumptions of a single deforming source at constant overpressure. The results indicate that the observations can be explained equally well in terms of a collection of pressure sources distributed beneath the caldera at locations controlled by local tectonic structures.

Finally, **Carlino *et al.*** present a new model for the uplift of Mt Epomeo within the Green Tuff caldera on the island of Ischia, offshore from Campi Flegrei, and show that, instead of simple crustal bending over a growing intrusion at shallow depth, the pattern of deformation has also been controlled by uplift along the caldera's ring faults.

In combination, the papers in this Special Publication offer new insights into the formation and post-collapse behaviour of large calderas. They also highlight the need for a better understanding of the relative significance of magma bodies, hydrothermal systems and faulting in controlling unrest, especially that observed within populated calderas. Rather than providing all the answers, therefore, we hope that this volume will inspire a new generation of studies for unravelling some of the most challenging problems in modern volcanology.

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