Unrest at large calderas: the control of sill emplacement

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Summary*. As many as 20 large calderas show signs of unrest each year through ground uplift or elevated seismicity. Recent examples include emergencies in 1969-72 and 1982-84 at Campi Flegrei, in southern Italy, and in 1983-85 at Rabaul, in Papua New Guinea. Most emergencies do not end in eruption. Here we propose that the unrest coincides with the emplacement of sills at shallow depths and that these will lead to eruption only when either a sill exceeds a critical radius or the crust has been extended by a critical amount. Long-term geodetic monitoring of large calderas is essential for identifying the preferred critical condition before eruptions.*

1. Unrest at Rabaul and Campi Flegrei

Historical unrest at the large calderas of Rabaul and Campi Flegrei has been characteristed by (Figs 1 & 2): caldera-wide uplift across diameters of c. 6-10 km; unrest that has continued for decades, with episodes of rapid uplift (~1 m yr^{-1}) over years between longer intervals of slower movement (~0.1 m yr^{-1} or less); elevated rates of seismicity during episodes of rapid uplift; and eruptions from locations at least 2.5 km away from the centre of caldera-wide uplift [*1-4*].

At Campi Flegrei, unrest has continued since 1969, for the first time since its last eruption in 1538, which itself was preceded by a century of net uplift across the caldera [*4*]. At Rabaul, unrest began in 1972 and culminated in an eruption in 1994, after a repose interval of 57 years [*5*]. These features strongly indicate that the episodes of rapid, caldera-wide uplift have been triggered by the transport of magma into the shallow crust.

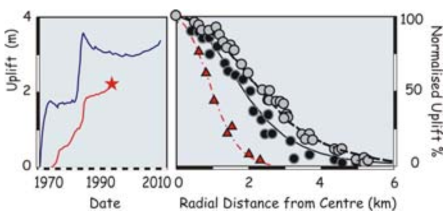

Figure 1. *Left*. Uplift near centre of caldera at Campi Flegrei (*blue*; corrected for secular subsidence) and Rabaul (*red*). *Star* shows 1994 eruption at Rabaul. *Right*. Using the penny-shaped sill model [*10*], sills at depths of 2.0 (*triangles*), 2.5 (*black circles*) and 2.75 km (*grey circles*) account for normalised vertical movements during the 1985-85 uplift at Rabaul and the 1972-74 and 1982-83 uplifts at Campi Flegrei.

2. The control of sill emplacement on unrest

Ground deformation during the non-eruptive crises at Campi Flegrei and Rabaul are consistent with the emplacement of sills with radii of 2-2.5 km at depths of 2-3 km (Fig. 1). Although alternative source geometries have been proposed [*6*], only a sill can produce the observed deformation at over-pressures low enough to avoid bulk failure of the upper crust and the triggering of an eruption.

A sill induces tensile stresses in the crust around its periphery [*7*]. We thus expect that the epicentres of accompanying volcano-tectonic seismicity will occur preferentially above the peripheries of sills, especially where these have entered zones of faulting produced by caldera collapse. The expectation agrees well with observation (Fig. 2).

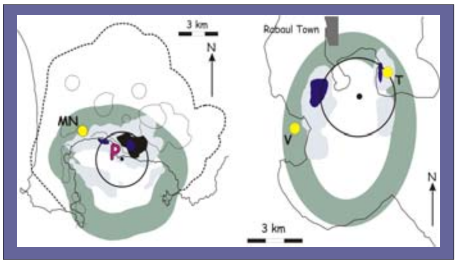

Figure 2. The epicentres of VT events during crises coincide with the overlap between the locations of ring fault zones (*green*) and the periphery of pressurised sills (*circles, heavy outline*). *Left*. The 1982-1984 crisis at Campi Flegrei. *MN*: Monte Nuovo. *P*: Pozzuoli. *Right*: The 1983-1985 crisis at Rabaul. *T*: Tavurvur. *V*: Vulcan. *Pale blue, left*: More than 20 VT events km^{-2}. *Pale blue, right*: More than 80 VT events km^{-2}. *Dark blue, both*: More than 200 events km^{-2}. (Seismic and structural data from [*2*] & [*11*].)

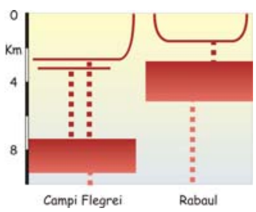

Figure 3. Components of the magmatic systems beneath Campi Flegrei and Rabaul. The shallow sills are not to scale.

3. The magmatic system

Seismic-tomographic studies have identified caldera-wide magma bodies with tops at depths of c. 3-4 km beneath Rabaul [*8*] and 7-8 km beneath Campi Flegrei [*9*]. We therefore suggest that long-term unrest is governed by pressure increases in the major magma reservoirs, with short-term episodes of rapid uplift being triggered by the escape of batches of magms to feed the shallow intrusion of sills (Fig. 3).

4. Pre-eruptive scenarios

When a sill has extended its radius to distances greater than its depth, the induced stress field generates an upward-curving path for propagating a magma-filled fracture. Such a path will define an annulus for preferred locations of eruptions away from the centre of uplift - a tendency that may be enhanced by interaction with sub-vertical faults within the zone of caldera collapse.

Most episodes of rapid unrest do not lead immediately to an eruption. A threshold condition must therefore be exceeded before an eruption occurs. Extension of a sill into a ring-fault zone is not a sufficient condition, because this appears to have occurred during non-eruptive crises (Fig. 2). Two potential threshold conditions are that:

- a sill must achieve a critical radius.
- the accumulated strain in the crust must exceed a critical value.

In the first case, each episode of elevated unrest has the potential to lead to eruption if a sufficiently large sill can be produced. In the second, an eruption is expected only after all episodes of unrest have raised the total strain to a critical value. Long-term geodetic monitoring of large calderas is thus essential for identifying the nature of the threshold condition and so improving short-term forecasts of eruption.

References.

1. Saunders SJ, 2001. Bull Volcanol, 63: 406-420. **2. De Natale G et al., 2006.** Geol Soc London Spec Pub 269: 25-45. **3. Woo JYL, Kilburn CRJ, 2010.** J Geophys Res, 115: 10.1029/2009JB006913. **4. Bellucci F et al., 2006.** Geol Soc London Spec Pub, 269: 141-157. **5. Johnson RW et al., 2010.** Rabaul Volcano Workshop Report, Australian Govt-AusAID, pp. 84. **6. Gottsmann J et al., 2006.** J Volcanol Geotherm Res, 150: 132-145. **7. Gudmundsson A, 1998.** Developments in Volcanology 10. Elsevier, Amsterdam, pp. 313-349. **8. Finlayson DM et al., 2003.** J Volcanol Geotherm Res, 124: 153-171. **9. Zollo A et al., 2008.** Geophys Res Lett, 35: 10.1029/2008GL034242. **10. Fialko Y et al., 2001.** Geophys J Int, 146: 181-190. **11. Mori J et al., 1989.** IAVCEI Proc Volcanol, 1: 429-462.

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