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Constraints on the source of resurgent doming inferred from analogue and numerical modeling — Implications on the current feeding system of the Yenkahe dome–Yasur volcano complex (Vanuatu)

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ABSTRACT

Resurgence, defined as the post-collapse long-term uplift of a caldera floor, is commonly attributed to a renewed rise of magma. The Yenkahe dome (Vanuatu) exhibits a common morphology – elongated with a graben on top – among resurgent domes, and is also one of the most active structures of the kind. In this study, we performed a joint analysis based on analogue and finite element numerical models to (1) constrain the width and depth of the long-term deformation intrusive source of the Yenkahe dome and (2) discuss the close association between the Yenkahe dome and the active Yasur cone. We consider the resurgent deformation at the surface to be driven by the uplift of a magma reservoir roof in depth. As the edifice deformation response depends on the medium and the source properties, the mechanical behavior of the upper crust and the nature of the source are modeled using two very different sets of hypotheses. Analogue modeling uses silicone putty, an analogue for a large viscous magma body, intruding a sand–plaster mixture reproducing a Mohr–Coulomb behavior for the crust. Numerical models consider the vertical displacement of a rigid indenter, allowing the conservation of a flat-shaped roof, into an elastoplastic material. Numerical and analogue models show different resurgent dome structures at depth but similar dome and graben morphologies in the surface. Inverse faults – or equivalent shearing zones – delimiting the dome provide an explanation for the confined nature of resurgent doming and the persistent volcanic activity on the dome border represented by the Yasur volcano. Analogue and numerical models together provide an estimation range of 1–1.8 km for the intrusive deformation source depth, and 1.3–2 km for its width. The proposed association between the Yenkahe dome and the Yasur volcano is compatible with such a shallow depth of the magma reservoir, and argues for a discontinuous resurgence process.

1. Introduction

Given their explosivity, ash flow calderas are considered to be among the most dangerous volcanoes in the world. Indeed, the link between these collapse calderas and large pyroclastic eruptions has been recognized and widely illustrated for more than seventy years (e.g. Williams, 1941; Matumoto, 1943; Bond and Sparks, 1976; Lipman, 1984; Wilson, 1985; Orsi et al., 1996). The recurrence of the phenomenon in well-studied regions (e.g. Valles caldera, Smith and Bailey, 1966; San Juan volcanic field, Steven and Lipman, 1976) led Lipman (1984) to propose the idea of a general caldera cycle composed of pre-collapse volcanism, followed by large ash flow eruptions and concurrent caldera collapse, and then, post-collapse activity. The latter commonly includes post-caldera volcanism, tectonic resurgence, sedimentation within the caldera basin and hydrothermal activity. Geophysical signatures of persistent magmatic and hydrothermal activities, such as seismicity and ground deformation, have been monitored in a few currently active calderas over the last decades (e.g. Long Valley, Hill, 2006; Campi Flegrei, De Natale et al., 2006; Yellowstone, Chang et al., 2007). Yet, mechanisms and potential hazards related to this unrest remain poorly appraised, as we probably lack sufficient hindsight on the matter.

Resurgence is defined as the long-term uplift of a caldera floor following its collapse. Several studies agree on the idea that resurgence is a relatively early process in the post-collapse history of calderas, with a peak of uplift occurring typically a few tens to a few hundred thousand years after the caldera formation (Smith and Bailey, 1968; Lipman, 1984; Phillips et al., 2007). A few constraints are available on the

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average speed of uplift processes, which generally range from a few cm/year (e.g. Tibaldi and Vezzoli, 1998; Phillips et al., 2007) to a few tens of cm/year (Chen et al., 1995; Ukawa et al., 2006). Eroded analogues of resurgent calderas (e.g. Grizzly Peak caldera, Fridrich et al, 1991; Chegem caldera, Gazis et al., 1995; Turkey Creek, Du Bray and Pallister, 1999; Ishizuchi, Yoshida, 1984; Okueyama, Takahashi, 1986) tend to show that resurgence is associated with the emplacement of shallow magmatic intrusions. In several cases of active calderas, the presence of an intrusion under resurgent structures is strongly suspected on the basis of geophysical prospects (e.g. Ischia, Paoletti et al., 2013; Toba, Masturyono et al., 2001). This renewed rise of magma within the caldera is supported by additional evidence, such as thermal modeling of heat flow around young calderas, requiring stages of replenishment by additional hot magma (Lipman, 2000), or the common association between post-collapse volcanism and resurgence (Smith and Bailey, 1968). Post-collapse volcanic products are typically less silicic than the associated ash flow, reflecting the injection of a more primitive magma (Morán-Zenteno et al., 2004; Kennedy et al., 2012).

Among the great diversity of resurgence shapes, the doming of a caldera floor portion remains one of the best documented (e.g. Valles, Creede, Timber Mountain, Yellowstone, Long valley, La Pacana, Turkey Creek, Cerro Galan, Bennett Lake, Campi Flegrei, Toba). Like calderas, resurgent domes commonly deviate from circular shapes, under the influence of regional structures or tectonics. As illustrated in Fig. 1, many of these elongated domes exhibit a longitudinal graben on top (e.g. in Valles, Yellowstone, Timber Mountain and Creede calderas). Variations of this morphology, notably the presence of multiple longitudinal grabens, are observed in the case of Toba (Fig. 1e) and Long Valley. It is also interesting to note that this type of dome with an associated graben may also form at a larger scale, as it is observed in San Juan volcanic field (U.S.A.) or in the Rotorua region (New-Zealand), probably in response to the emplacement of very large intrusions (Fig. 1f; Smith and Bailey, 1968). The Yenkahe tectonic dome (Tanna Island, Vanuatu) can be considered as one of the most relevant examples of that resurgence morphological type, with an elongated shape and a clear longitudinal graben on top (Fig. 2c). Located in the very active Siwi caldera, the dome is affected by a very high average uplift rate of 15 cm/year over the last 1000 years (Chen et al., 1995). As a recent fast-growing resurgent structure, the morphology of the Yenkahe is probably well preserved and may be studied by resurgence modeling.

Numerous models have been developed to understand and locate the source of observed short-term deformation in active calderas, pointing out a variety of sources such as sill/dike opening, hydrothermal system pressurization, magma reservoir pressurization or magma degassing, often acting together (e.g. Amelung et al., 2000; Hill, 2006; Hurwitz et al., 2007; Aly and Cochran, 2011). However, measured deformation patterns are highly dependent on the considered timescale (Wicks et al, 1998; Troise et al., 2007; Vezzoli et al., 2009), and therefore the current observed deformation does not necessarily reflect the processes at stake in long-term deformation. Surface deformation associated with the resurgence has been analyzed by a more limited number of authors. Acocella et al. (2001) presented models of vertical intrusions of a circular-shaped viscous source into a sand-pack. The results of their experiments highlighted the importance of the ratio of the overburden thickness to the diameter of the intrusive source, as a determining factor of the resurgent structure morphology. For thick overburdens in comparison to the intrusion diameter (i.e. for ratios around 1), resurgence is expressed by the uplift of an almost undeformed block. For relatively

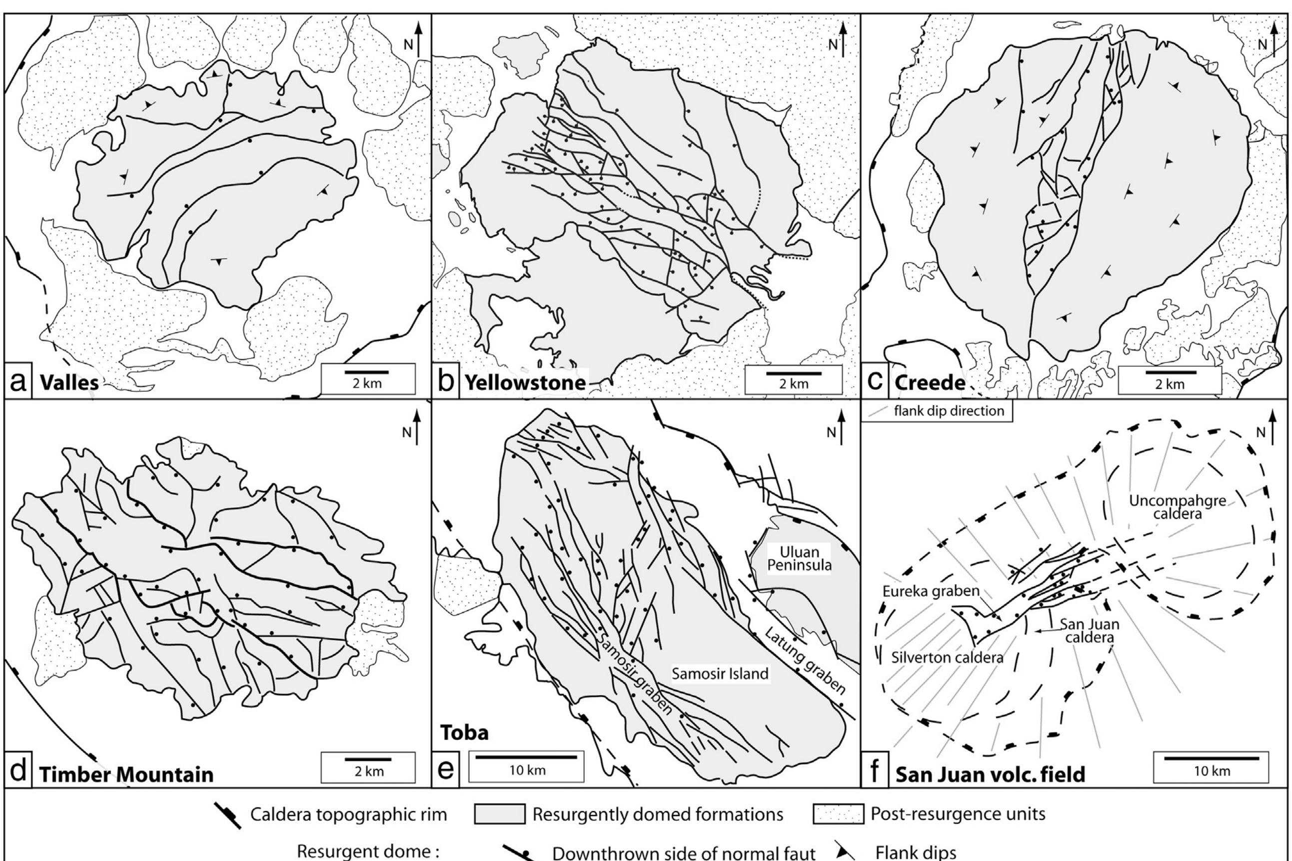

Fig. 1. Structural sketch map of resurgent domes showing longitudinal grabens. (a) Redondo dome, Valles caldera (after Smith and Bailey, 1968); (b) Mallard Lake dome, Yellowstone (after Christinansen, 2001); (c) Snowshoe Mountain, Creede caldera (after Lipman, 2006); (d) resurgent dome, Timber Mountain caldera (after Christiansen et al., 1977); (e) Samosir Island and Uluan Peninsula, Toba caldera (after Aldiss and Ghazali, 1984); (f) resurgent dome representing the joint resurgence of San Juan and Uncompahgre calderas, Western San Juan caldera field (after Steven and Lipman, 1976).

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