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Structure and evolution of an active resurgent dome evidenced by geophysical investigations: The Yenkahe dome-Yasur volcano system (Siwi caldera, Vanuatu)

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ABSTRACT

In this contribution, we focus on one of the most active resurgences on Earth, that of the Yenkahe dome in the Siwi caldera (Tanna Island, Vanuatu), which is associated with the persistently active Yasur volcano. Gravity and magnetic surveys have been carried out over the past few years in the area, as well as electrical methods including electrical resistivity tomography (ERT), time domain electro-magnetics (TDEM) and self-potential (SP). These investigations were completed by thermometry, CO_2 soil gas measurements, field observations and sampling. This multi-method approach allows geological structures within the caldera to be identified, as well as associated hydrothermal features. The global structure of the caldera is deduced from gravity data, which shows the caldera rim as a high density structure. Large lava fields, emplaced before and after the onset of resurgence, are evidenced by combined gravity, magnetic and resistivity signals. In the middle of the caldera, the Yenkahe dome apparently results from a combination of volcanic and tectonic events, showing that lava extrusion and resurgence have been operating simultaneously or alternately during the Siwi caldera post-collapse history. There is a clear distinction between the western and eastern parts of the dome. The western part is older and records the growth of an initial volcanic cone and the formation of a small caldera. This small caldera (paleo-Yasur caldera), partially filled with lava flows, is the present-day focus of volcanic activity and associated fluid circulation and alteration. The eastern part of the dome is presumably younger, and is characterized by intense, extensive hydrothermal alteration and activity. Its northern part is covered by lava flow piles and exhibits a shallow hydrothermal zone in ERT. The southern part has hydrothermal alteration and activity extending at least down to the base of the resurgent dome. This part of the dome is built up of low cohesion rock and is thus potentially prone to gravitational landslides. Lastly, while self-potential and temperature data suggest that widespread hydrothermal circulation occurs throughout almost all of the caldera, and possibly beyond, the most active parts of this hydrothermal system are associated with the dome. The presence of this active hydrothermal system is the clearest indicator that these methods can provide of a potential shallow magmatic body underneath the dome.

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1. Introduction

Resurgence is a common process corresponding to the post-collapse uplift of the caldera floor observed in many calderas (Smith and Bailey, 1968; Lipman, 1984; Newhall and Dzurisin, 1988). The phenomenon has been recognized in active or recent calderas as well as in old, sometimes deeply eroded ones (e.g. Yoshida, 1984; Fridrich et al., 1991; Du Bray and Pallister, 1999). Resurgence has traditionally been associated with large calderas of more than 10 km in diameter (Smith and Bailey, 1968; Steven and Lipman, 1976; Francis, 1983), though examples of smaller size exist (e.g. Cinque Denti, Panteleria; Mahood and Hildreth, 1986). Emplacement and dismantling processes of resurgent structures remain poorly constrained in most calderas. Different mechanisms have been identified as potential triggers for resurgence (Marsh, 1984 and references therein): relaxation of the crust following caldera collapse, emplacement of new intrusions, and pressurization of confined aquifers. Several approaches may be used to infer the dominant resurgence mechanisms at a given volcano. For old, eroded volcanoes, the geological approach is the most appropriate. For young and active volcanoes, various approaches contribute to our understanding of the mechanisms: analysis of the nature of young eruption products, geological and geophysical studies of the structures involved in (or created by) resurgence, and monitoring of geophysical and degassing signals.

We focus here on one of the most active resurgences on Earth, that of the Yenkahe dome in the Siwi caldera (Tanna Island, Vanuatu), which is associated with a permanently active volcano (Yasur). Apart from a few pioneering works (Carney and Macfarlane, 1979; Nairn et al., 1988; Chen et al., 1995), little is known about the post-collapse history of the caldera and the hazards associated with such a fast resurgence. Better constraining resurgence processes at Yenkahe involves unraveling the dome history (emplacement by intrusive and/or eruptive processes) as well as identifying main structures, fluid circulations and potential hydrothermal or magmatic sources of deformation. In this perspective, several recent studies have been led. In this contribution, we study the internal structure of the system and its hydrothermal activity coupling several geophysical methods. In terms of hazards, the geophysical data of this contribution allows identifying low-cohesion material, highlighting the probability of a future flank instability supported by external features. This study is complementary to two others led by our team, which allowed to better understand the global functioning and evolution of the Siwi–Yenkahe–Yasur complex. The first one concerns the structural aspect in terms of external tectonic features using the results of a newly-computed high-resolution photogrammetric digital surface model (DSM; Brothelande et al., in this issue). The second one uses internal and external features to constrain deformation models of magmatic intrusions in the upper crust (Brothelande et al., submitted for publication).

For this study, three geophysical campaigns have been carried out within the Siwi caldera, in 2004, 2008 and 2012, including gravimetry, magnetics, time-domain electromagnetics (TDEM), electrical resistivity tomography (ERT), self-potential (SP), ground temperature and CO_2 soil concentration measurements. Rock sampling and thermal infrared data were used to complete this data set. Given the large amount of data, the results of each method are first described separately, before proposing a combined interpretation in terms of the inner structure of the Siwi–Yenkahe–Yasur complex and the associated fluid circulation pattern. The implications of these geophysical results are then discussed in terms of dome history and evolution.

2. General context

2.1. The Vanuatu arc and Tanna Island

Volcanism of the Vanuatu oceanic arc (formerly known as the New Hebrides) results from the subduction of the Indo-Australian plate beneath the Pacific plate (Pelletier et al., 1998; Calmant et al., 2003). Tanna Island, located on the southern segment of the arc, is a large structure, 60–80 km wide on the sea floor, and about 2 km high (Robin et al., 1994). The geology of Tanna Island (40 × 16 km; Fig. 1a), described in a few pioneering works (Carney and Macfarlane, 1979; Robin et al., 1994; Chen et al., 1995; Neef et al., 2003; Allen, 2004), is not known in detail. The island was built by volcanic activity and coral reef growth. Three volcanic complexes were recognized by Carney and Macfarlane (1979): the Upper Pliocene to Pleistocene Green Hill to the north, the Pleistocene Tukosmeru volcano to the south and the Siwi Group Volcanic Centre (Upper Pleistocene to present) to the east. In addition, Robin et al. (1994) proposed the existence of a Pliocene–Pleistocene volcano, named Eastern Tanna volcano; the center of this volcano would be located offshore of the north-east coast of the northern part of the island.

2.2. Structure and activity of the Siwi caldera

The Siwi caldera is located at the base of a huge amphitheater-like depression on the eastern flank of the Tukosmeru volcano (Fig. 1a), and is a more or less rectangular structure (9 × 4 km for the inland part; Fig. 1b). The caldera is bounded by faults a few tens of meters to nearly 100-m high, and its eastern extent is unknown as the caldera is open to the sea. The Siwi caldera formation has been associated with an ignimbrite eruption of rather small-volume (1–2 km^3; Allen, 2004; Nairn et al., 1988; Robin et al., 1994). The caldera collapse is still undated, but the freshness of the deposits and the morphology suggest a relatively young age to some authors (less than 20,000 years for Nairn et al., 1988). The Yenkahe dome, ~5 km long by ~3 km wide and ~200–300 m high, in the middle of the Siwi caldera, is elongated in the same direction as the caldera (Fig. 1b). Its origin is attributed to a resurgent doming process, well illustrated by the presence of emerged corals and waterlain tuffs at its surface (Carney and Macfarlane, 1979; Nairn et al., 1988; Chen et al., 1995; Neef et al., 2003). Chen et al. (1995) performed $^{230}Th/^{234}U$ dating on coral samples from terraces on the eastern part of the Yenkahe dome, at mean altitudes of 155 m and 15 m above sea level. Respective ages of AD 1002 ± 10 and AD 1868 ± 4 imply a mean uplift of 156 mm/year for the eastern part of the Yenkahe dome in recent times. Resurgence has been attributed to magma intrusion at depth (Carney and Macfarlane, 1979; Nairn et al., 1988; Chen et al., 1995; Metrich et al., 2011), and the study of Chen et al. (1995) suggests that resurgence occurred mostly during discrete uplift events. This is well illustrated by the co-seismic uplift events of 6 and 4 m in 1878 (Chen et al., 1995 and references therein). Hydrothermally altered and warm ground spots are frequent at the surface of the Yenkahe dome (Peltier et al., 2012).

The Yenkahe dome is associated with two strombolian cones. The Ombus cone, located at the southern foot of the dome (Fig. 1b), is extinct and now heavily covered by vegetation. The Yasur cone is the present-day focus of volcanic activity, located at the north-western edge of the Yenkahe dome (Fig. 1b). The three presently active vents inside the Yasur crater have frequent (every few minutes) strombolian explosions that expel ashes, scoriae, Pele's hair and centimeter-to-meter-sized bombs of basaltic–trachyandesitic composition (Metrich et al., 2011). The cone is built up of the accumulation of these products, and is located on a former volcanic center, of which the remnants of a pyroclastite cone and a caldera-like structure can be observed (Carney and Macfarlane, 1979; Merle et al., 2013). Nairn et al. (1988) have proposed, on the base of the analysis and dating of two ash sequences to the northwest of Yasur that the paleo-Yasur could have been active from 1,400 to 800 years ago, before the young Yasur started its activity. More recently, Firth et al. (2014), by analyzing two other ash sequences, proposed that the Strombolian-style activity at Yasur has persisted in its current form for the last 630–850 years and was preceded by ~600 years of higher-magnitude, lower-frequency eruptions during which less evolved compositions were erupted.