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Insights into the evolution of the Yenkahe resurgent dome (Siwi caldera, Tanna Island, Vanuatu) inferred from aerial high-resolution photogrammetry

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ABSTRACT

The Yenkahe dome (Tanna Island, Vanuatu) is one of the most spectacular examples of presently active post-caldera resurgence, exhibiting a very high uplift rate over the past 1000 years (156 mm/year on average). Although numerous inhabited areas are scattered around the dome, the dynamics of this structure and associated hazards remain poorly studied because of its remote location and dense vegetation cover. A high-resolution photogrammetric campaign was carried out in November 2011 over the dome. Georeferenced photographs were treated by "Structure from Motion" and "Multiple-view Stereophotogrammetry" methods to produce a 3D-digital surface model (DSM) of the area and its associated orthophotograph. This DSM is much more accurate than previously available SRTM and Aster digital elevation models (DEMs), particularly at minimal (coastline) and maximal altitudes (Yasur culmination point, ~390 m). While previous mapping relied mostly on low resolution DEMs and satellite images, the high precision of the DSM allows for a detailed structural analysis of the Yenkahe dome, notably based on the quantification of fault displacements. The new structural map, inferred from the 3D reconstruction and morphological analysis of the dome, reveals a complex pattern of faults and destabilization scars reflecting a succession of constructive and destructive events. Numerous landslide scars directed toward the sea highlight the probable occurrence of a tsunami event affecting the south-eastern coast of Tanna. Simulations of landslide-triggered tsunamis show the short time propagation of such a wave (1–2 min), which could affect coastal localities even following relatively small destabilized volumes (a few million cubic meters).

1. Introduction

Vanuatu is a 1200 km-long volcanic arc located in the south-west Pacific, resulting from the eastward subduction of the Australian plate beneath the Pacific plate. In the southern segment of the arc, at the latitude of Tanna, the convergence rate reaches ~12 cm/year (direction N69) and the associated back-arc extension rate of the North-Fiji basin, to the east, is ~4 cm/year (Pelletier et al., 1998; Calmant et al., 2003). Tanna Island is approximately 2.5 Ma old (oldest rocks are from late Pliocene; Carney and Macfarlane, 1979) and was constructed by successive phases of volcanism and reef limestone growth. The Siwi Group, to the southeast of the island (Fig. 1A), dated from upper Pleistocene to present, is composed of pyroclastic deposits and associated lavas, mainly andesites to basaltic andesites. A moderate volume eruption (1–2 km^3), still undated but estimated to be as young as a few tens of ka, formed the Siwi caldera and the associated ignimbrite (Nairn et al., 1988; Allen, 2005). The Siwi caldera (>24 km^2) is defined on land by a more or less rectangular ring fracture (Carney and Macfarlane, 1979) and extends offshore between Ipikel (also named Sulphur Bay) and Port Resolution (Fig. 1B).

The Siwi caldera is a remarkable example of caldera unrest as it hosts the rare association between one of the most active volcanoes of the archipelago, Mount Yasur, and the impressive Yenkahe resurgent

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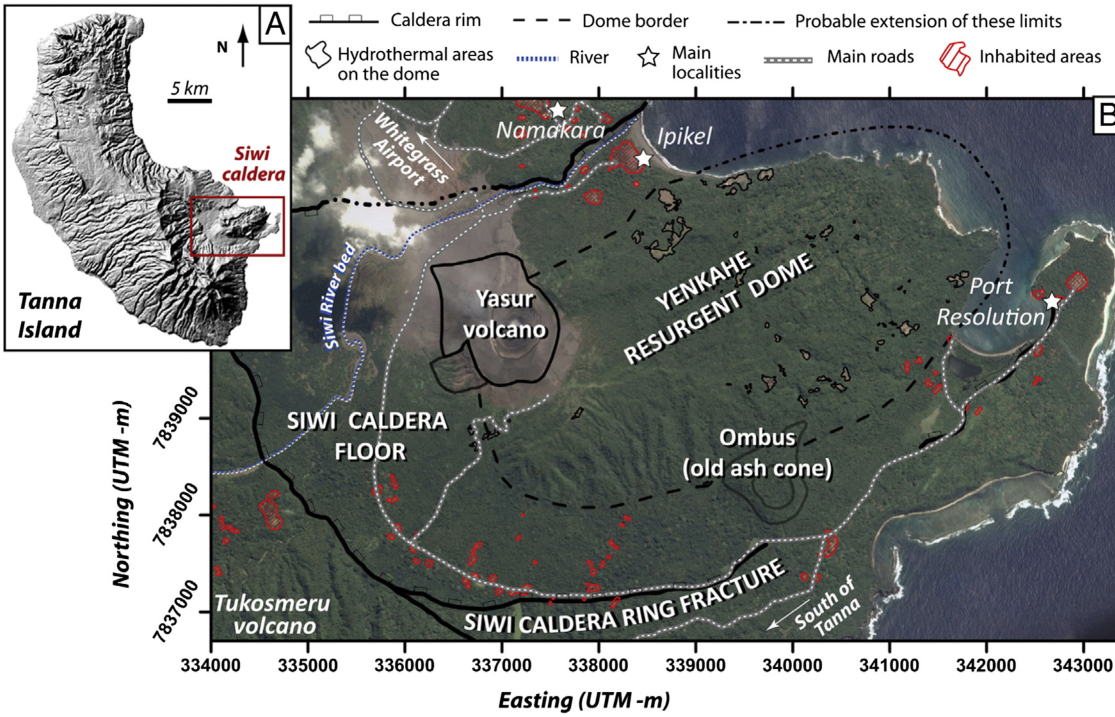

Fig. 1. (A) The volcanic island of Tanna and the location of the active Siwi caldera (SRTM DEM). (B) Map of the Siwi caldera, on a Google Earth Pro orthoimage, showing the caldera rim, the volcanic edifices, the Yenkahe dome and notable visible features. Structural limits are inferred from the SRTM DEM. Coordinates: UTM 59S–WGS84.

dome. Given the small amount of lava emitted by the Yasur volcano, Metrich et al. (2011) proposed that the high SO_2 degassing rates (630 t/day on average over the past 5 years, Bani et al., 2012) could be associated with an intrusion rate of 5.10^7 m^3/year of basaltic magma in the Siwi area. Located in the middle of the caldera, and elongated in the same direction (~N67), the Yenkahe dome is about 5 km long, 3 km wide, and 200–300 m high (Fig. 1B). The Yenkahe dome represents one of the most spectacular examples of presently active post-caldera resurgence. The last uplift occurred during two strong local earthquakes in 1878 (not felt 20 km away, Paton and Paton, 1894), resulting in a 10-meter elevation of the bay of Port Resolution. $^{230}Th/^{234}U$ dating performed on coral samples from terraces on the eastern part of the Yenkahe dome revealed a mean uplift of 156 mm/year over the last 1000 years (Chen et al., 1995). Like other examples of resurgent domes (e.g. Long Valley, Battaglia et al., 2003; Yellowstone, Miller and Smith, 1999; Husen et al., 2004), Yenkahe is probably related to shallow magma intrusion processes generating rapid surface deformation and possible destabilization of the edifice, as observed for instance at Ischia (Tibaldi and Vezzoli, 2004).

The latest structural analysis of the Yenkahe dome was carried out by Merle et al. (2013). Their study principally relied on field observations, relatively limited by the dense vegetation, satellite images, and existing low-resolution digital elevation models (DEMs) such as SRTM (90-m resolution) and Aster 2nd generation (30-m resolution). They made a clear distinction between the western and eastern parts of the dome. The western dome (Fig. 2A) exhibits a 1-km wide graben delimited by 40 to 60 m-high normal faults in the field (the Yenkahe North Fault, YNF, and the Yenkahe South Fault, YSF). The graben position is asymmetrical, with the northern flank of the dome being shorter and steeper than its southern counterpart. The graben is interrupted to the west by the semi-circular ring faults of a small caldera (Paleo-Yasur caldera, ~4 km in diameter; Fig. 2A) in which the Yasur cone is now established. Finally, in this western part of the dome, the graben is affected by a few westward-dipping transverse normal faults (T_1, T_2 and T_3). The vertical displacement of these faults, probably posterior to the graben, is not mentioned. The eastern part of the dome, to the east of T_3, exhibits a different pattern. The graben is replaced by a network of perpendicular longitudinal and transverse normal faults on a relatively flat dome roof (Fig. 2B). Transverse faults are still dipping westward. These differences between the eastern and western fault patterns and the geometry of transverse normal faults led Merle et al. (2013) to propose a recent uplift of the eastern dome relative to the western dome. Such a process may be explained by the eastward migration of a magmatic body at depth. Finally, the presence of landslide scars is mentioned by these authors above Ipikel and coarsely defined on the eastern side of the dome (Fig. 2B).

Recent advances in publicly available high-resolution Google imagery allow the mapping of interesting visible features within the caldera (Fig. 1B). Unvegetated areas on the Yenkahe dome itself may be mapped as hydrothermal areas; most of them were visited during a field campaign in 2012 and correspond to hydrothermally altered ground affected by high temperatures (40–100 °C). The density of these areas on the eastern side of the dome reflects a higher hydrothermal activity level in comparison to the western side.

Other features, such as populated areas in and around the caldera were also mapped, based on the identification of individual and collective buildings (churches, schools). These populated areas (and tourist lodges) are scattered around the dome and along the coast, which makes them vulnerable to direct and indirect consequences of potential landslides. Roads between the airport and the volcano or the south of the island, used by both locals and a great number of tourists each day may also be affected by this type of event. In spite of its relevance in terms of resurgence processes and associated hazards, the Yenkahe dome remains poorly studied because of its remote location and difficult field work conditions (lack of infrastructures, density of vegetation). Unfortunately, further structural research in the area has been limited by currently available digital elevation models (DEMs).

Photogrammetry is a method based on image processing that produces 2D and 3D reconstructions, digital terrain models (DTM), digital surface models (DSM), orthoimages and classification of objects, at relatively low cost in comparison to other methods (Terrestrial Laser Scanner, LIDAR, etc.). This technique is used in a great variety of