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Satellite observations of fumarole activity at Aluto volcano, Ethiopia: Implications for geothermal monitoring and volcanic hazard

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ABSTRACT

Fumaroles are the surface manifestation of hydrothermal circulation and can be influenced by magmatic, hydrothermal, hydrological and tectonic processes. This study investigates the temporal changes in fumarole temperatures and spatial extent on Aluto, a restless volcano in the Main Ethiopian Rift (MER), in order to better understand the controls on fluid circulation and the interaction between the magmatic and hydrothermal systems. Thermal infrared (TIR) satellite images, acquired by the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) over the period of 2004 to 2016, are used to generate time series of the fumarole temperatures and areas. The thermal anomalies identified in the ASTER images coincide with known fumaroles with temperatures >80 °C and are located on or close to fault structures, which provide a pathway for the rising fluids. Most of the fumaroles, including those along the major zone of hydrothermal upwelling, the Artu Jawe Fault Zone, have pixel-integrated temperature variations of only ~2 ± 1.5 °C. The exception are the Bobesa fumaroles located on a hypothesised caldera ring fault which show pixel-integrated temperature changes of up to 9 °C consistent with a delayed response of the hydrothermal system to precipitation. We conclude that fumaroles along major faults are strongly coupled to the magmatic-hydrothermal system and are relatively stable with time, whereas those along shallower structures close to the rift flank are more strongly influenced by seasonal variations in groundwater flow. The use of remote sensing data to monitor the thermal activity of Aluto provides an important contribution towards understanding the behaviour of this actively deforming volcano. This method could be used at other volcanoes around the world for monitoring and geothermal exploration.

1. Introduction

Volcanoes show signs of unrest in a variety of ways, such as deformation, seismicity or hydrothermal activity. In many cases, unrest does not precede an eruption and it is essential to distinguish baseline levels of activity from the signals that might be precursory to an eruption (e.g. Fournier et al., 2010; Parks et al., 2015; Biggs et al., 2016; Coco et al., 2016). The interaction between magmatic and hydrothermal systems creates complex signals, particularly in terms of the deformation, which make it difficult to interpret the cause of the unrest (e.g. Gottsmann et al., 2006; Lowenstern and Hurwitz, 2008; Coco et al., 2016; Hemmings et al., 2016). Fumaroles offer an important window into the processes at work beneath the surface of a volcano and some studies have suggested that monitoring changes in the composition and temperature of the gases they emit might aid in the prediction of changes in volcanic activity (Madonia and Fiordilino, 2013; Laiolo et al., 2017). The fluids released at the fumaroles have undergone a long journey: escaping from the magma, travelling up through the rocks and the shallow hydrothermal and groundwater systems to reach the surface. As a result, the fumarolic fluids provide information that with careful interpretation can yield to insights into the interaction between the magmatic and hydrothermal systems (Fournier, 1999; Ingebritsen et al., 2010; Laiolo et al., 2017).

Fluid flow in hydrothermal systems is controlled by many overlapping processes, which are unique to each system: the thermal gradient, the anisotropy of the permeability (Arnórsson, 1995), the precipitation of secondary minerals (Lowell et al., 1993), the availability of groundwater for recharge, the local topography (Hurwitz et al., 2003), and the phases present in the system (Ingebritsen and Sorey, 1988). In some cases, both precipitation and groundwater flow are known to have an influence on the temperature of fumaroles (Richter et al., 2004), but not in others (Connor et al., 1993; Di Liberto, 2011). These examples demonstrate the highly individual behaviour of the

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hydrothermal systems at volcanoes and emphasize the necessity for a careful understanding of the subsurface structures and the parameters that control groundwater flow in each individual scenario.

Aluto, a typical caldera volcano of the Main Ethiopian Rift (MER), is currently showing signs of unrest, including seismicity (Wilks et al., 2017) and ground deformation (Biggs et al., 2011; Hutchison et al., 2016a). In this study, we use satellite remote sensing to analyse the changes in behaviour of the fumaroles on Aluto in an attempt to further understand the causes of the unrest. When considering how interactions between the magmatic and hydrothermal systems might be observed at the surface from changes in the behaviour of the fumaroles, two end-member scenarios may be proposed, depending on whether changes in the hydrothermal system are driven by hydrological factors ("top-down") or magmatic processes ("bottom-up"):

1) "top-down" scenario: the fumaroles are only connected to the shallow hydrothermal system and the changes they display are linked solely to hydrological processes such as precipitation and groundwater flow. The hydrothermal system is heated by the deeper magmatic system, but the changes in the magmatic system are not reflected in the behaviour of the fumaroles. From observations at other volcanoes, the temperatures are expected to decrease during the rainy season due to the addition of cold rain water to the groundwater flow (Richter et al., 2004; Di Liberto, 2011);

2) "bottom-up" scenario: the magmatic and hydrothermal systems are linked and an increase in fumarole temperature is expected in periods of increased magmatic activity (unrest episodes), whereas a decrease will accompany a deflating trend caused by a cooling and crystallisation of the underlying magma body (Chiodini et al., 2011; D'Auria et al., 2011).

Satellite remote sensing is ideal for looking at hazardous and remote areas of the planet such as volcanoes (Pyle et al., 2013). The Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) onboard NASA's Terra satellite has been used to investigate eruptive and thermal activity at volcanoes around the world (Pieri and Abrams, 2004), such as in South America (Jay et al., 2013) and in the Northern Pacific (Dehn et al., 2000, 2002; Pieri and Abrams, 2005; Carter & Ramsey, 2009). The detection of thermal anomalies at volcanoes is strongly dependent on the intensity and size of the anomaly, as well as its duration relative to the frequency of observation (Pieri and Abrams, 2005). Although the detection of low-temperature fumaroles (<100 °C) can be done (e.g. Jay et al., 2013), the lower limit of detection of the ASTER instrument has yet to be determined (Pieri and Abrams, 2005).

In this study, ASTER thermal infrared (TIR) images are used: 1) to detect the low-temperature fumarole activity on an active volcano and quantify the spatio-temporal limits of our current sensors in relation to monitoring and geothermal exploration; 2) to observe changes in temperature and spatial extent of the fumaroles on Aluto, understand how these relate to the other signs of unrest and evaluate the interaction between the hydrothermal and magmatic systems; 3) to quantify the subpixel temperature and spatial variations necessary to cause the changes in pixel-integrated temperatures observed.

2. Background

2.1. Regional setting

The Main Ethiopian Rift (MER)extends over 500 km and forms the northernmost segment of the East African Rift system, from the Afar depression in the North to the Turkana basin in the South (Corti, 2009) (Fig. 1). Two major sets of faults are present in the MER: (i) the boundary faults, which are long and characterised by large vertical offsets, and (ii) smaller internal faults that cut obliquely through the centre of the rift valley; these fault systems are well expressed in the northern MER (NMER), where they are characterised by a NE-SW and NNE-SSW directions, respectively. (Corti, 2009; Agostini et al., 2011a, Fig. 1). The latter are collectively called the Wonji Fault Belt (WFB) and accommodate the majority of the current tectonic extension in the MER (Chorowicz, 2005; Agostini et al., 2011b). The MER is tectonically active, extending in an E-W direction at a rate of 4–6 mm/yr (Stamps et al., 2008; Kogan et al., 2012; Saria et al., 2014).

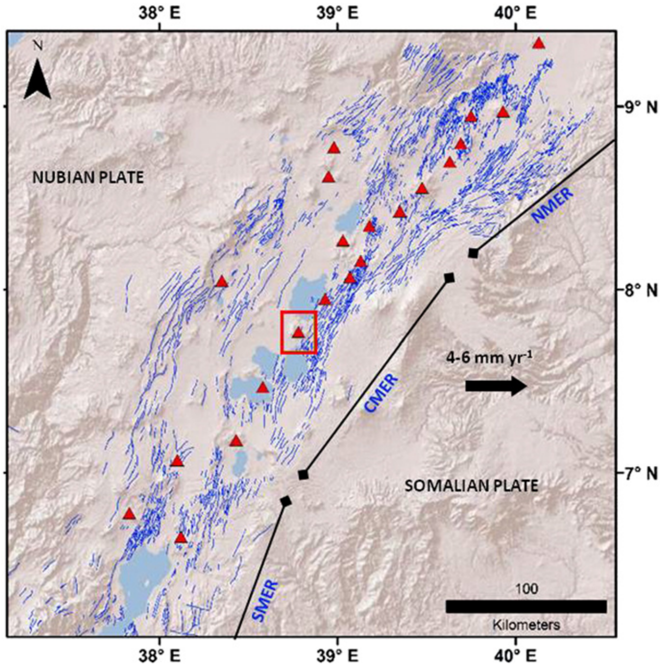

Fig. 1. – Map of the tectonic and volcanic features in the Main Ethiopian Rift (MER), divided into the northern MER (NMER), Central MER (CMER) and the southern MER (SMER). The surface faults are shown in blue (mapped by Agostini et al., 2011b, and available at ethiopianrift.igg.cnr.it/utilities_MER.html). The extension rate is 4–6 mm yr^{-1} relative to a fixed Nubian plate (Saria et al., 2014). The red triangles are the Holocene volcanoes listed in Ethiopia (Global Volcanism Program). Aluto is located in the red box in the centre.

The MER is lined by silicic volcanoes (Fig. 1) and although several of these are showing InSAR evidence for unrest (Biggs et al., 2011; Hutchison et al., 2016a), very little is known about their recent eruptive histories (Aspinall et al., 2011; Hutchison et al., 2016b; Vye-Brown et al., 2016; Wadge et al., 2016). Although unrest has been observed at several MER volcanoes, no confirmed historical eruptions have occurred since 1810–30, which took place at Fantale and Kone volcanoes (Gibson, 1974; Rampey et al., 2010; Biggs et al., 2011; Wadge et al., 2016).

2.2. Aluto volcano

Aluto is silicic peralkaline volcano located in the Central Main Ethiopian Rift (CMER) (Fig. 1).Aluto has been in a phase of post-caldera volcanism since 55 ± 19 ka (Hutchison et al., 2016b) and its youngest volcanic deposits are a series of obsidian coulees and pumice domes, the most recent of which were likely erupted ~400 years ago (Hutchison et al., 2016b, 2016c). Aluto has been showing many signs of unrest in the form of surface hydrothermal activity, episodic ground deformation (Biggs et al., 2011; Hutchison et al., 2016a) and seismic activity (Wilks et al., 2017).

Interferometric Synthetic Aperture Radar (InSAR) studies have shown that over the last 12 years, Aluto has undergone two phases of rapid uplift in 2004 and 2008 interspersed with episodes of slow subsidence (Biggs et al., 2011) (Fig. 2) and since 2009, Aluto has been slowly subsiding (Hutchison et al., 2016a). The deformation pattern has an elliptical shape centred on the volcano, extending beyond the inferred caldera ring faults. The source has been modelled as a point source located at 5.1 ± 0.3 km depth (Hutchison et al., 2016a), supported by a