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Influence of the regional topography on the remote emplacement of hydrothermal systems with examples of Ticsani and Ubinas volcanoes, Southern Peru

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ABSTRACT

Present work studies the influence of the regional topography on the hydrothermal fluid flow pattern in the subsurface of a volcanic complex. We discuss how the advective transfer of heat from a magmatic source is controlled by the regional topography for different values of the averaged permeability. For this purpose, we use a 2-D numerical model of coupled mass and heat transport and new data sets acquired at Ticsani and Ubinas, two andesitic volcanoes in Southern Peru which have typical topography, justifying this approach. A remarkable feature of these hydrothermal systems is their remote position not centered on the top of the edifice. It is evidenced by numerous hot springs located in more than 10 km distance from the top of each edifice. Upwelling of thermal water is also inferred from a positive self-potential anomaly at the summit of the both volcanoes, and by ground temperatures up to 37 °C observed at Ticsani. Our model results suggest that the regional topographic gradient is able to significantly divert the thermal water flow and can lead to an asymmetric emplacement of the hydrothermal system even considering a homogeneous permeability of the edifice. Inside the thermal flow, the hydraulic conductivity increases with the decrease of temperature-related viscosity, focusing the flow towards the surface and creating a hydrothermal zone at a large lateral distance from the heat source. The location and temperature of the hot springs together with the water table position given by self-potential data can be used to constrain the average permeability of the edifice, a key parameter influencing fluid flow and associated advective heat transfer in the direction opposite to the regional topographic gradient. Our study allows to explain the emplacement of the hydrothermal systems at volcanoes with asymmetric edifices or even the absence of a shallow hydrothermal system. These results can be generalized to the study of non-volcanic hydrothermal systems.

1. Introduction

Most active volcanoes are associated with hydrothermal systems, which can be sometimes recognized by fumarolic activity and hot springs on the flanks of the edifice, high electric conductivity at depth, and self-potential anomalies on the surface (e.g., Aizawa et al., 2005; Bedrosian et al., 2007; Aizawa et al., 2009a,b; Revil et al., 2011). Variations in hydrothermal circulation may reflect the temporal evolution of the volcanic activity (Granieri et al., 2003; Chiodini et al., 2009; Carapezza et al., 2009); in some cases the hydrothermal system interacts with magma ascent leading to hydromagmatic eruptions (e.g., Wohletz, 1986); long term hydrothermal circulation can also contribute to destabilization of the edifice by weakening the stiffness of the rocks (e.g., Reid, 2004; Reid et al., 2010).

Mapping the self-potential (SP) at the surface gives insights into the geometry of the thermal fluid flow inside the edifice.

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A classical W-shape SP anomaly observed at strato-volcanoes is centered on the summit area and limited by the size of the edifice: as one climbs the slopes of the volcano, the self-potential first decreases several hundred millivolts to several volts. As the summit crater is approached, the self-potential rapidly recovers to the initial level measured on the base of the volcano (e.g., Ishido et al., 1997; Ishido, 2004; Aizawa et al., 2009a). The self-potential method is sensitive to the movement of the water phase: usually, upwelling thermal waters are associated with a positive self-potential anomaly, and infiltration of cold meteoric water is associated with a negative anomaly, anti-correlating with the topography at the lower part of the edifice. Field data on hydrothermal systems sometimes agree with this simple model but in general show more variable behavior.

For example, at the basaltic shield volcano Piton de la Fournaise in Reunion island, the main hydrothermal system seems to be located within the central Dolomieu crater (Lénat et al., 2000, 2011). Despite of high precipitation, there is no clear correlation between the topography of its flanks and the self-potential, and no clear manifestation of hydrothermal activity on the flanks or on the base of the volcano. To understand the ground water flow at Piton de la Fournaise, Violette et al. (1997) proposed a system of interconnected perched aquifers channelizing the ground flow to a continuous basal aquifer with an outlet to the ocean.

On strato-volcanoes with steep topography the hydrothermal activity at the summit is often limited to few fumaroles; a water dominated hydrothermal system is found on the lower part of its flanks. Again, the existence of a preferential pathway for thermal water flow is often required to understand the emplacement of the hot springs (e.g., Ingebritsen and Sorey, 1988). Some hydrothermal systems extend beyond the edifice (Aizawa, 2008; Aizawa et al., 2009b; Onizawa et al., 2009). For example, the hydrothermal system of Iwate volcano (2038 m) is displaced by several kilometers with respect to the summit and to the magmatic source inferred by seismicity and geodetic data (Aizawa et al., 2009a).

The goal of the present paper is to discuss the influence of the regional topography and permeability of the edifice on the geometry of the hydrothermal body defined by the presence of thermal waters. We build our study on field data of self-potential, soil and spring temperature at the surface, and on the results of direct numerical simulation coupling mass and heat transfer inside the volcanic edifice. The basic idea is that there is a control by the topography of the ground water flow, which in turn controls the advective heat transfer from a magmatic source and the associated self-potential distribution. Decrease of viscosity of hydrothermal fluids with temperature leads to increase of the hydraulic conductivity which might explain the existence of the preferential pathways evidenced by the field results. This idea is tested with a new set of data collected at Ticsani and Ubinas volcanoes, major dacitic–andesitic volcanoes in Southern Peru. Both volcanoes are characterized by extended hydrothermal systems and are good targets for this study because of the differences in elevation on different sides of the edifice reaching almost 2500 m at Ticsani and about 2000 m at Ubinas.

2. Ticsani volcanic complex

Ticsani volcano is a 5408-m-high dacitic lava dome complex located behind the Central Volcanic Zone in Southern Peru (see position in Fig. 1). Ticsani and its two neighbor volcanoes, Ubinas and Huaynaputina, are often named as a single volcanic group because of the particular location outside the main arc, in the more complex environment of major regional fault-systems: NW–SE strike-slip fault system, associated with the main arc, and N–S normal faults related to the Graben of Rio Tambo (Lavallé et al., 2009). The predominant fault orientations around Ticsani volcano are shown in Fig. 2b. Geochemical isotope characteristics suggest that the magmas of Ubinas, Huaynaputina and Ticsani evolved from a common reservoir localized at a depth between 20 and 30 km.

Lavallé et al. (2009) distinguish two main phases of volcanic activity at Ticsani. The first phase consisted of constructing the edifice of the ancient cone of Ticsani by numerous lava flows and volcaniclastic deposits. This ancient cone collapsed westward leaving a 3 km large ridge in NW–SE direction (Fig. 1). In the following phase of volcanic activity, three andesitic to dacitic lava domes (D1–D3 in Fig. 1) were emplaced at Ticsani accompanied by explosive eruptions dated to middle Holocene. A sub-Plinian and phreatomagmatic eruption occurred afterwards overlaying these middle Holocene deposits with brown pumice and bombs. Finally, the emplacement of the youngest, Ticsani dome, followed, and the 1600 eruption of Huaynaputina (Mariño and Thouret, 2003; Lavallé et al., 2009). This complex history is responsible for the highly asymmetric edifice of Ticsani volcano with its domes sitting in an area marked by a distinct topographic gradient in the NW direction and intersected by a system of active faults.

In 2005, a seismic swarm occurred near Ticsani volcano with a normal fault main shock having a magnitude $Mw=5.8$, an epicenter close to summit of Ticsani volcano, and an inferred depth of 4 km below the sea level (Holtkamp et al., 2011). Ticsani is located quite far from the megathrust system and therefore the authors suggested the regional fault system as a source of the ground deformation (Holtkamp et al., 2011). On the other hand, the location of the seismic events below the edifice of the Ticsani complex and reactivation of the fault on its western slope close to the Putina hot springs (see Fig. 1) might indicate its possible relation to the activity of the hydrothermal system.

3. Field surveys

Over 4000 self-potential measurements were performed around the edifice of Ticsani volcano along six profiles, connecting the base of the volcano with one of the domes, with a spacing between the measurements of 25 m. The profiles were also connected by one closed circular profile with 50 m spacing, at the base of the volcano, in order to create self-potential loops. This approach is traditionally used to avoid the accumulation of errors along unconnected profiles. We used non-polarizable second generation Petiau Pb/$PbCl_2$–NaCl electrodes (Petiau, 2000) and a voltmeter with a sensitivity of 0.1 mV and an input impedance of 10 MΩ. The soil was sufficiently wet to ensure good electrical contacts. The stability of the pairs of electrodes used for mapping was regularly checked by measuring their potential difference which was always smaller than 1.5 mV. The self-potential data were combined to provide a map, which represents the distribution of the electrical potential with respect to the potential of a reference taken as zero. These data were krigged with Surfer Software and the resulting map is shown in Fig. 2, the zero reference point was chosen at Toro Bravo lake. The self-potential distribution displays a classical dipolar anomaly with a peaked positive lobe (250 mV) around the youngest dome (Ti), and extended negative lobes on the upper part of the flanks and on the older domes D1–D3. The negative anomalies reach −3400 mV south of the dome. A more variable behavior is observed in the area of the ancient collapse of the old Ticsani dome, on the NW flank of the present volcano. On this side of the volcano, the mean self-potential values are typically 1000 mV higher than on the SW side.