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# Hydrothermal system of Central Tenerife Volcanic Complex, Canary Islands (Spain), inferred from self-potential measurements

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## ABSTRACT

An extensive self-potential survey was carried out in the central volcanic complex of Tenerife Island (Canary Islands, Spain). A total amount of ~237 km of profiles with 20 m spacing between measurements was completed, including radial profiles extending from the summits of Teide and Pico Viejo, and circular profiles inside and around Las Cañadas caldera and the northern slopes of Teide and Pico Viejo. One of the main results of this mapping is the detection of well-developed hydrothermal systems within the edifices of Teide and Pico Viejo, and also associated with the flank satellite M. Blanca and M. Rajada volcanoes. A strong structural control of the surface manifestation of these hydrothermal systems is deduced from the data, pointing to the subdivision of Teide and Pico Viejo hydrothermal systems in three zones: summit crater, upper and lower hydrothermal systems. Self-potential maxima related to hydrothermal activity are absent from the proximal parts of the NE and NW rift zones as well as from at least two of the mafic historical eruptions (Chinyero and Siete Fuentes), indicating that long-lived hydrothermal systems have developed exclusively over relatively shallow felsic magma reservoirs. Towards Las Cañadas caldera floor and walls, the influence of the central hydrothermal systems disappears and the self-potential signal is controlled by the topography, the distance to the water table of Las Cañadas aquifer and its geometry. Nevertheless, fossil or remanent hydrothermal activity at some points along the Caldera wall, especially around the Roques de García area, is also suggested by the data. Self-potential data indicate the existence of independent groundwater systems in the three calderas of Ucanca, Guajara and Diego Hernández, with a funnel shaped negative anomaly in the Diego Hernández caldera floor related to the subsurface topography of the caldera bottom. Two other important self-potential features are detected: positive values towards the northwestern Santiago rift, possibly due to the relatively high altitude of the water-table in this area; and a linear set of minima to the west of Pico Viejo, aligned with the northwestern rift and related to meteoric water infiltration along its fracture system.

## 1. Introduction

Persistent active subaerial volcanism is usually accompanied by hydrothermal activity, which develops an energy transfer between the deep magmatic reservoirs and the surface layers of a volcanic system. The heat exchange between these two distinct parts of a volcanic system is performed mainly by convection of subsurface fluids, both by groundwater circulation supplied by meteoric water recharge and also by the ascension of hot volcanic gasses liberated from deep magma cooling and gas exsolution during magma migration toward the surface (Giggenbach, 1996; Ingebritsen et al., 2006, 2010; Pirajno, 2009).

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Hydrothermal activity greatly enhances alteration and argillization of volcanic rocks and therefore constitutes one of the major agents in mechanical alteration of volcanic edifices (Siebert et al., 1987; Lopez and Williams, 1993; Wyk et al., 1997; Kerle et al., 2001; Reid et al., 2001; Wyk et al., 2001; Cecchi et al., 2005). Because of this, hydrothermal alteration is considered a major factor affecting volcano flank stability (Aizawa, 2008; Aizawa et al., 2009) and it is usually invoked to explain volcanic landslides and gravitational flank collapses, which are widely observed in volcanic oceanic islands (Le Friant et al., 2003, 2004; Merle and Lénat, 2003; Merle et al., 2006; Barde-Cabusson and Merle, 2007; Romagnoli et al., 2009a, 2009b). Hydrothermal systems can develop a strong coupling with the eruptive activity of their parent magmatic systems and sometimes the state of the hydrothermal system, its spatial dimensions and the intensity of the heat transfer can be used as a volcano monitoring tool (Aubert et al., 2008; Gaudin et al., 2013). The lateral extension and the geometry of a hydrothermal system are highly variable, depending on diverse factors, both internal to the volcanic system, like structural boundaries (caldera, craters, regional faults, weakness areas) and also external, like the pattern and magnitude of meteoric groundwater recharge by rain and snow (Finizola et al., 2004; Tort and Finizola, 2005; Barde-Cabusson et al., 2012; Peltier et al., 2012).

In the present work we have focused on the central area of Tenerife Island (Canary Islands, Spain), dominated by Teide and Pico Viejo stratovolcanoes and Las Cañadas caldera, in which active hydrothermal activity is evidenced by fumaroles, thermal anomalies and $CO_2$ diffuse emission in Teide summit and upper-cone flanks. Several geophysical studies (gravimetric, magnetic, seismic and magnetotelluric) have been devoted to this area (Ablay and Keary, 2000; Araña et al., 2000; Canales et al., 2000; Pous et al., 2002; Coppo et al., 2008, 2009, 2010; Gottsmann et al., 2008; Blanco-Montenegro et al., 2011; Camacho et al., 2011) but only a few have focused on its hydrothermal system (García de la Noceda et al., 1989; Aubert and Kieffer, 1996; Ohno et al., 2004). The surface expression of Teide summit hydrothermal system has been recently studied by Del Potro et al. (2009), who analyzed also the mechanical properties of the clay-rich materials resulting from the hydrothermal alteration (alunite and kaolinite, Del Potro and Hürlimann, 2009). Although these two works provide a useful general cartography of upper-Teide hydrothermal field, no information is available about the subsurface extension and magnitude of the corresponding hydrothermal system.

Knowledge about Teide–Pico Viejo hydrothermal system can be very useful at least in two different ways. Firstly, any realistic investigation on the mechanical properties and inner strength of Teide–Pico Viejo edifices must take into account the extension, geometry and degree of hydrothermal alteration experienced by their subsurface materials, with obvious implications about the potential for future lateral collapses and about the possibility of any deformation having affected these volcanic edifices (for example volcano spreading, see Márquez et al., 2008). Secondly, it can serve to further develop volcano monitoring tools based on the observation of the state and intensity of the hydrothermal system associated to this volcanic area, either by periodic repetition of geophysical measurements in selected areas or by the installation of continuous monitoring.

The objective of our work has been to study (1) the extension, geometry and structure of the hydrothermal systems and (2) some hydrogeological main features of the Teide–Pico Viejo complex of Tenerife summit. We have chosen the self-potential method due to its sensitivity to subsurface fluid movement, which makes it an ideal tool to investigate hydrothermal activity and its interaction with structural boundaries in volcanic edifices (Corwin and Hoover, 1979; Revil and Pezard, 1998; Revil et al., 1999a,b, 2004, 2008; Finizola et al., 2002, 2003, 2004, 2006; Zlotnicki and Nishida, 2003; Ishido, 2004). Our results will be compared with other complementary geophysical studies already performed in the summit part of Tenerife Island.

## 2. Geological setting

The bulk of Tenerife Island consists of basaltic materials accumulated over the seafloor since at least the middle Miocene, forming a basaltic shield whose oldest subaerial exposures are probably older than 11.9 Ma (Abdel-Monem and Watkins, 1972; Ancochea et al., 1990; Thirwall et al., 2000; Guillou et al., 2004). The eroded remnants of this shield-building phase make up the Anaga, Teno and Roque del Conde massifs (see Fig. 1). Later, the emission of more evolved magmas (mainly basalts, trachytes and phonolites) constructed the Las Cañadas edifice in the centre of the island, which has experienced several constructive–destructive cycles between <4 Ma and ~0.17 Ma ago (Ancochea et al., 1990; Martí et al., 1994; Bryan et al., 1998; Ancochea et al., 1999; Martí and Gudmundsson, 2000; Edgar et al., 2007). This central activity has been coetaneous with basaltic emissions along two clear rift systems (the Dorsal and Santiago rift systems, the “NE rift zone” and the “NW rift zone” respectively in Fig. 1) and in a more diffuse southern basaltic field called “S volcanic zone” in Fig. 1 (Ancochea et al., 1990; Carracedo et al., 2007).

The constructive–destructive cycles affecting Las Cañadas edifice are responsible for the formation of Las Cañadas caldera, a NE–SW elliptical structure ~16 km-wide in the centre of the island whose origin is still controversial. The caldera is subdivided in three smaller calderas separated in two different parts (Ucanca in the west, and Guajara and Diego Hernández in the centre-east) by the Roques de García spur, which is made of remnant material from Las Cañadas edifice (Fig. 2). The hypothesis about a vertical collapse origin for Las Cañadas caldera proposed by some authors (Araña, 1971; Ridley, 1971) was confronted by the proponents of a lateral landslide origin (Bravo, 1962; Coello, 1973; Navarro and Coello, 1989; Carracedo, 1994; Watts and Mason, 1995; Masson et al., 2002; Teide Group, 1997; Ancochea et al., 1999), who interpreted the caldera walls along its southern and eastern rims as the eroded remnants of the headwall of the Icod landslide-valley detachment fault; the clay-rich volcanic breccia known as “mortalón”, encountered in the water-supply galleries that perforate the Icod Valley, is viewed by those authors as delineating the failure surface of this landslide (see also Márquez et al., 2008), although the existing data do not allow to retrieve an univocal and complete picture of its geometry and specifically of its headwall location. In addition to Icod, La Orotava and Güímar valleys are also recognized as having a landslide origin (Watts and Masson, 1995; Ablay and Hürlimann, 2000; Hürlimann et al., 2004), as well as three other minor valleys (Anaga, East Dorsal and Teno, see Hürlimann et al., 2004 and Figs. 1 and 2).

Other authors have further developed the vertical collapse hypothesis for Las Cañadas caldera, associating the voluminous ignimbrite deposits in the southern part of Tenerife (Bandas del Sur Formation) to the explosive products of different major caldera-forming events in Las Cañadas edifice (Martí et al., 1994; Bryan et al., 1998, 2000; Edgar et al., 2002, 2007). According to Martí et al. (1997) and Hürlimann et al. (1999), both vertical and lateral collapses have interplayed to produce the present structure of the caldera, with some erosion affecting also the relief of the remaining walls. In this view, three different caldera-forming events dated at 1.02, 0.57 and 0.18 Ma produced the overlapping Ucanca, Guajara and Diego Hernández calderas, respectively, delineating an eastward migration of the corresponding magma chambers (see Fig. 2; Martí and Gudmundsson, 2000). These authors propose also a possible trigger of major lateral landslides by caldera collapses and suggest a link between the formation of Guajara and Diego Hernández calderas with La Orotava and Icod valleys, respectively. In this scheme, the headwall of the last major landslide (Icod Valley, ~180 ka), which is supposed to have eliminated the northern rim of Las Cañadas caldera, is tentatively placed somewhere beneath Teide–Pico Viejo edifices (this is the proposed location shown in Figs. 1 and 2; Hürlimann et al., 2004). Ancochea et al. (1999) presented a different geochronological and conceptual scheme for the constructive–destructive cycles of Las Cañadas Edifice, in which at least two main