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Fluid circulation pattern inside La Soufrière volcano (Guadeloupe) inferred from combined electrical resistivity tomography, self-potential, soil temperature and diffuse degassing measurements

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After a drastic decline in 1983, hydrothermal activity at La Soufrière lava dome (Guadeloupe, Lesser Antilles) has been progressively increasing in the summit area since 1992, raising the threat of a renewed eruptive activity. To better constrain the geometry of the hydrothermal system, an extensive high-resolution self-potential survey was performed on the dome and three multi-method profiles combining electrical resistivity tomography, self-potential, ground thermometry and soil CO_2 diffuse degassing measurements were carried out to cover its southern periphery in January 2011. Results indicate that hydrothermal ascending flows are currently restricted to a proximal area including the dome and its very vicinity. The extension of hydrothermal alteration inferred from electrical resistivity tomography reflects the presence of a heat source just below the dome. A first-order correction of topography-related self-potential variations allows the identification of major hydrothermal fluid circulations pathways, as well as significant meteoric infiltration zones. Local shifting of hydrothermal fluids towards the dome periphery is favored by the presence of major axes. The regional La Ty fault appears as the major axis draining large volumes of hydrothermal and magmatic fluids. However hydrothermal activity remains confined inside a collapse structure surrounding the dome, that formed in the last 9000 years as a result of recurrent edifice collapses, the latest occurring at the onset of the 1530 AD eruption. The combination of these qualitative results with structural analysis leads to a synthetic model of magmatic and hydrothermal fluids circulation inside the dome, which may be useful for the assessment of potential hazards associated with a renewal of fluid pressurization, and a possibly associated partial flank-failure.

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1. Introduction

The presence of well-developed hydrothermal systems on active volcanoes has been recognized as a major hazard factor for several reasons. Hydrothermal circulation usually alters and weakens the internal parts of volcanic edifices, increasing the risks of instability (López and Williams, 1993; Vallance and Scott, 1997; Reid et al., 2001; Komorowski, 2008). Hydrothermal systems are unstable energy transfer systems, therefore, modifications of heat fluxes within the edifice can result in pressurization triggering phreatic explosions (e.g. Lube et al., 2014–in press) or favoring partial edifice collapse along low strength layers with higher fluid pore pressure and associated reduced friction (Reid et al., 2001; Komorowski, 2008). Additionally, hydrothermal systems can interact with magma, giving rise to highly explosive phreato-magmatic dynamisms. From these different perspectives, the hydrothermal system geometry and evolution appear as key parameters to better constrain volcanoes potential behavior and associated hazards. At La Soufrière volcano (Guadeloupe), flank collapse has been recognized as a repetitive phenomenon along the history of the volcano (Komorowski et al., 2002, 2005; Boudon et al., 2007; Komorowski, 2008; Legendre, 2012) and the major role of extended hydrothermal alteration in these events has been evidenced by recent works on the

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associated debris avalanche deposits (Salaün et al., 2011). The implication of the hydrothermal system has been proven in many eruptions, from phreatic crises to cataclysmic phreato-magmatic events (11 500 BP, 3 100 BP; Boudon et al., 1992). Since the first descriptions in 1635 AD, this hydrothermal system has undergone many fluctuations, alternating between resting periods characterized by residual hydrothermal activity, fumarolic reactivations, and phreatic eruptions sometimes rather violent (Komorowski et al., 2005; David, 1998, and references therein). The last phreatic crisis, in 1976–77, resulted in the evacuation of 70,000 inhabitants of the island and a large scientific controversy on the presence of an eventual magmatic component, pointing out the lack of data available for hazard assessment and forecasting (Feuillard et al., 1983; Komorowski et al., 2005; Hincks et al., 2014).

La Soufrière is located just 5 km north to the town of Saint-Claude (10 000 inhabitants). Currently active, the volcano has been monitored through seismic, deformation (tiltmeters, GPS, extensometers, distancemeters) and geochemical (gas, fluid, spring, flux, and temperature analyses) networks since 1950 (Observatoire Volcanologique et Sismologique de Guadeloupe; OVSG managed by Institut de Physique Globe de Paris). After a drastic decline in 1983, hydrothermal activity has been slowly and progressively increasing in the summit area since 1992, raising the threat of a new eruption. In the last decade, the Guadeloupe Volcanological and Seismological Observatory (OVSG-IPGP) has recorded a systematic progressive increase in shallow low-energy seismicity, a slow rise of temperatures of some acid-sulfate thermal springs (Villemant et al., 2005) close to the dome, and, most noticeably, a significant increase in the summit fumarolic activity associated with HCl-rich and H_2S acid gas emanations (OVSG, 1999–2014; Komorowski et al., 2001, 2005). The permanent acid degassing from two summit high-pressure fumaroles has caused vegetation damage on the downwind flanks of the dome and required the establishment by the authorities of a no-public access zone since 1999 that concerns the most active areas of the summit (Komorowski et al., 2005). At present time, a magmatic origin to this prolonged unrest cannot be excluded.

In the recent years, significant efforts have been made to characterize the geophysical structure of the dome (Nicollin et al., 2006; Coutant et al., 2012; Lesparre et al., 2012; Lesparre et al., accepted for publication). Yet, better constraints on the hydrothermal system geometry, and its relations with the main structural features of the edifice are still needed (Komorowski, 2008). Within this scope, we present here a combination of multi-electrodes high-resolution electric resistivity tomography (ERT), self-potential (SP), sub-surface temperature, and soil CO_2 diffuse degassing to derive information on the location of the hydrothermal system over the volcano.

2. Geological setting

Basse-Terre Island (Guadeloupe archipelago) belongs to the northern part of the recent inner arc of the Lesser Antilles. La Grande Découverte-Soufrière (GDS) is an andesite-type explosive volcanic complex, representing the latest, and the only active, of six volcanic complexes composing the island. The construction of this volcanic complex started most likely 445 to 435 ka ago with the formation of La Grande Découverte. This edifice consists of thick lava flow sequences alternating with deposits from several major explosive eruptions (Boudon et al., 1988; Carlut et al., 2000; Komorowski et al., 2005; Samper et al., 2007, 2009) dated at about 140 ka, 108 ka, and finally about 42 ka ago during the Pintade eruption that produced the La Grande Decouverte caldera (Boudon et al., 1988; Komorowski et al., 2005). The second phase, from 42 ka to 11.5 ka, corresponds to the construction of the Carmichaël edifice inside the La Grande Decouverte caldera. This phase ended with at least two major collapses (13.500 and 11.500 yrs BP) affecting the western flank of the edifice and forming the Carmichaël crater (Fig. 1). Following a non-magmatic partial collapse of the S-SE flanks of the remaining part of the Carmichael edifice at about 8200 yrs B.P. which formed the Amic crater, new effusive activity marked the onset of the third phase, called La Soufrière (Komorowski et al., 2005; Boudon et al., 2007; Legendre, 2012). Alternating effusive and explosive activity developed within the Amic structure which was widened by the occurrence of at least 8 distinct edifice collapse events, with the most recent event dated at 1530 AD (Komorowski et al., 2002, 2005; Boudon et al., 2007; Komorowski, 2008; Komorowski et al., 2008a; Legendre, 2012). One of the main effusive phases led to the formation of the Amic dome that preceded the formation of two scoria cones (L'Echelle and La Citerne) around 1700 BP. La Soufrière lava dome, culminating at 1467 m and representing the highest point of the Lesser Antilles, was formed during the last major magmatic eruption dated around 1530 AD by radiocarbon dating (Boudon et al., 2008; Legendre, 2012; Komorowski et al., 2008b). The dome is surrounded by a collapse structure affecting the Amic dome and L'Echelle cone, formed or reactivated for the last time at the onset of the magmatic eruption (Boudon et al., 2008), and named after the event (Figs. 1, 2). Many fumaroles, temperature anomalies and thermal sources on the dome and its surroundings highlight the presence of a well-developed hydrothermal system, as a result of an enormous rainfall rate (7–10 $m.y^{-1}$ on the summit area; OVSG-IPGP, 1999–2013; Villemant et al., 2005) combined with the existence of permanent heat sources at depth. The dome is cut by numerous fractures (Fig. 2; Nicollin et al., 2006; Lesparre et al., 2012) mainly radial to the summit. Most of the main fractures opened during historic phreatic eruptions (1690, 1797–98, 1809–12, 1836–37, 1956 and 1976–77; Boudon et al., 1988; Komorowski, 2008). The north–south fractures, Fente du Nord to the north and La Ty fault to the south-east of the dome, correspond to a system of regional active tectonic faults crossing the dome (Fig. 1; Feuillet, 2000; Feuillet et al., 2002; Mathieu et al., 2013). La Ty fault intersects the base of the dome and can be followed in the landscape up to Ravine la Ty and the south-western flank of La Citerne cone (Figs. 1, 2). Five major explosion craters are present at the summit of the dome: Tarissan, Dupuy, Napoleon, Cratère Sud, and Cratère 1956 (Fig. 2). During the latest eruptions, explosive phreatic activity mostly affected the south-eastern part of the dome, but some of the northern structures were also active albeit to a lesser extent (Fig. 2). During the last phreatic eruption in 1976–1977, explosive activity, which started on the eastern flank by reactivating the pre-existing 1956 fractures, led to the opening of two new large fractures on July 8th to the east and on August 30th to the south-east of the dome (Fig. 2). Activity then migrated to the summit area where it was concentrated at the central Tarissan crater. Throughout the eruption, water vapor and acid gases mixed with non-juvenile blocks and ash were emitted at a high flux from the Tarissan crater (Feuillard et al., 1983; Komorowski et al., 2005). The 1976–1977 eruption has been interpreted as a stillborn magmatic or failed magmatic eruption by Feuillard et al. (1983) with the data available at the time. On the basis of new data and analytical techniques, Villemant et al. (2005), Boichu et al. (2008, 2011), and Ruzié et al. (2012) have confirmed this hypothesis.

After the 1976–1977 eruption, a decline of fumarolic activity was observed both on the summit and at the base of the lava dome (notably by the disappearance in 1984 of the Col de l'Echelle fumaroles along the eastern end of July 8th fracture). Only minor degassing still remained along the La Ty fault (Zlotnicki et al., 1992). Since 1992, a slow and progressive increase of fumarolic degassing has been observed. The reactivation of the summit fumaroles began at Cratère Sud in 1992 (Zlotnicki et al., 1992), at Napoléon crater in 1996–1997 and then at Tarissan crater in 1997 (OVSG-IPGP, 1999–2014; Komorowski et al., 2001, 2005). More recently, fumarolic activity resumed at Cratère 1956 in 2007 and two new fumaroles appeared in the summit area in December 2011 and October 2013 (Figs. 1, 2). The renewal of fumarolic activity is associated with HCl-rich and H_2S acid gas emanations (volcano observatory reports) and, at the SW base of the volcano, with a slow rise of temperatures at three acid-sulfate thermal springs (Villemant et al., 2005). In parallel, the volcano observatory has recorded since 1992 a progressive increase of shallow low-energy volcano-tectonic earthquakes (OVSG-

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