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Electrical tomography of La Soufrière of Guadeloupe Volcano: Field experiments, 1D inversion and qualitative interpretation

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Abstract

The Soufrière of Guadeloupe lava dome consists of several 3D domains of relatively unaltered massive andesite separated by major radial fractures that reach at least up to about half of the dome's height. More than 20,000 geo-electrical measurements made on the top and the flanks of the lava dome are used to construct the first geophysical image of the internal structure of this active volcano. The main features of the apparent conductivity structure of the lava dome are high-conductivity regions associated with the strongly altered material of present and fossil hydrothermal zones. Local 1D inversions of data subsets belonging to regions where the geological structure is supposed laterally invariant confirm the structures observed in the pseudo-sections. The relatively stable units lie above a basal inclined layer of highly conductive geological materials interpreted to be more altered and thus characterised by reduced internal friction and probably increased pore pressure. Past and current hydrothermal fluid circulation through these fractures has promoted rock alteration and particularly along the base of the dome that likely contributes to the instability of parts of the edifice.
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1. Introduction

La Grande Découverte – La Soufrière composite volcano located on the Basse – Terre Island of Guadeloupe is one of the active volcanoes of the recent inner arc in the Lesser Antilles. The IPGP (Observatoire Volcanologique et Sismologique de Guadeloupe) maintains an extensive integrated monitoring network on this volcano located within 5 to 9 km North of the towns of Saint-Claude and Basse-Terre (population of 25,000). The Soufrière lava dome (1467 m, highest point of the Lesser Antilles) was formed during the last magmatic eruption of this volcano dated around 1440 AD [1–3]. The lava dome is cut by several radial fractures that opened during the successive six historical phreatic explosive eruptions of 1690, 1797–98, 1812, 1836–37, 1956, 1976–77 AD.

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The most substantial eruptions occurred in 1797–98, 1956, and 1976–77. Different fractures or portions of fractures have been newly opened or reactivated during these eruptions, sometimes repeatedly (Fig. 1). Only the central phreatic crater (the Tarissan crater) was active in all eruptions. During the last 1976–1977 crisis, the so-called July 8th and August 30th fractures opened in the eastern and south-eastern part of the lava dome, partly reactivating a fracture formed to east during the 1956 eruption.

The intense hydrothermal activity associated with acidic fumaroles and hot springs that has developed in the last 10,000 yrs at the periphery and base of the lava dome, below the lava dome, and within the fractures on the lava dome has led to extensive argilization of geological formations enhanced by the about 10 m of rainfall per year. Historical observations show that the nature, distribution, and intensity of these geothermal manifestations has fluctuated considerably over time [2,4–6].

Phases of fumarolic reactivation were reported in 1737–1766, 1809–1812, 1879, 1890, 1896, 1899 and 1902–1903. Between the end of the 1976–77 eruption and 1984 there was a phase of progressive decline in fumarolic activity in all areas on the summit (Tarissan, Cratère Sud, Fente du Nord, Cratère 1956), on the flanks (disappearance of the Lacroix fumaroles in 1984) and at the base of the lava dome (disappearance of the Carbet fumaroles in 1979, of the Collardeau fumaroles in 1982, and of the Col de l'échelle fumaroles in 1984). A phase of minimum fumarolic activity occurred between 1984 and 1992, with no fumaroles at the summit and only minor degassing along the SW regional La Ty fracture that intersects the base of the lava dome (fumaroles of the Route de la Citerne and of the Morne Mitan) [5,7].

A phase of systematic progressive increase in fumarolic degassing with reactivation of summit fumaroles began in 1992 at Cratère Sud [5,7], continued in 1996–97 at Napoléon Fracture/Crater, and finally involved Tarissan crater in 1997 with an increase since 1999 [6–8]. Since 1992, the volcano observatory has recorded a systematic and progressive increase in shallow low-energy seismicity, significant development of three acid-sulfate thermal springs at the SW base of the volcano with a slow rise of temperatures [9], and most noticeably, a significant increase in summit fumarolic activity associated with HCl-rich and H_2S acid gas emanations [6,7]. Currently there is no significant fumarolic activity at the base of the dome except weak non-pressurized emanations from the stable areas of Morne Mitan and Route de la Citerne.

Numerous geological works were carried on the volcano [2,6–8] and a good knowledge of its history is now obtained. During its construction, La Grande Découverte – La Soufrière volcano has experienced a series of flank-collapse events [2,3,6,10,11], particularly during its recent stage, making this volcano one of the most unstable of the world. The last one occurred probably at the beginning of the 1440 AD eruption and the lava dome is built inside a small horseshoe-shaped crater opened to the South as the precedent ones. Evidence from the geological record indicates that in the last 15,000 yrs the frequency of partial edifice collapse has increased although the volume of the collapses has decreased. Several factors suggest that the Soufrière lava dome is locally mechanically weak and thus pre-disposed to flank instability: 1) numerous fractures formed and reactivated during phreatic eruptions, 2) faults, 3) morphological constraints (steep slope), 4) the pervasive extensive hydrothermal alteration of parts of the Soufrière dome, 5) the reactivation of the hydrothermal system involving acid fluids, 6) a ring of thermal springs at the base of the lava dome with a discharge rate that can reach several kilogrammes per second. These springs promote the development of head-ward erosion in concave embayments.

Detailed geophysical imaging of the upper part of volcano edifices is of primary importance for the interpretation of data provided by the permanent sensors networks influenced by the heterogeneous character of the medium [12]. Self-potential measurements are among the most widely used geophysical observables to monitor the activity of volcanoes [13–17], and a correct interpretation of these data needs the knowledge of the electrical conductivity distribution [18,19].

Mechanical and dynamic modelling of the stability of the lava dome and its potential partial collapse requires a better knowledge of its past activity but also of its internal structure. Moreover, obtaining volumetric estimates of the mechanically weak areas susceptible to collapse within the lava dome as well as of the hydrothermal active cells susceptible to participate to a phreatic explosion remain key objectives for any improved hazard and risk analysis concerning the future evolution of the lava dome.

In this study, a geophysical imaging of the lava dome is made by electrical tomography. Direct current electrical profiles are achieved using a multielectrode data acquisition system connected to cables with 64 electrode plugs. 5 or 15 m electrode spacing provides a total layout of more than 300 or 900 m long, and the depth of investigation may reach a few hundred meters. Profiles made of several hundreds of measurements cross the lava dome, on the top, the flanks and around the base. The data are integrated in pseudo-sections of apparent

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