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Combination of geophysical prospecting techniques into areas of high protection value: Identification of shallow volcanic structures

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ABSTRACT

Timanfaya National Park is a volcanic area located in the southwest of Lanzarote Island (Canary Islands, Spain). Several lava tubes have been found in the lava flows but many others remain unknown. Its location and identification are important to mitigate collapse hazards in this touristic area. We present a new study about the location of recent lava tubes by the analysis and joint interpretation of ground penetrating radar (GPR), microgravity and electromagnetic induction (EMI) data along the same profile over an area not previously surveyed. GPR data display a complex pattern of reflections up to ~10 m depth. The strongest hyperbolic reflections can be grouped in four different areas. Visual inspections carried out in the field allow confirming the occurrence of lava tubes at two of them. These reflections have been interpreted as the effect of the roof and bottom interfaces of several lava tubes. The microgravity survey defines a wide gravity low with several over-imposed minor highs and lows. Using the GPR data, a 2.5D gravity model has been obtained revealing four lava tubes. EMI data have been used to obtain an inverted resistivity model that displays four high resistivity areas that closely match the locations of the lava tubes derived from the previous methods. This resistivity model exhibits the lower resolution although reaches a deeper investigation depth (~20 m). The comparison of the results has revealed that joint interpretation of GPR, microgravity and EMI methods provides reliable models useful for the detection of unknown shallow lava tubes.

1. Introduction

Timanfaya National Park is a volcanic area which occupies a surface of about 51.07 km^2 in the southwest of Lanzarote Island (Canarian Archipelago, Spain). The 1730–1736 eruption gave rise to this volcanic landscape with more than 30 volcanic cones formed in different phases of basaltic type eruptions with tholeiitic composition covering 23% of the island (Carracedo et al., 1992). It was one of the most important volcanic events which occurred in the Canarian Archipelago over the last 500 years (Fig. 1). The last eruption at Lanzarote occurred during 1824 at Tinguaton, Tao and Chinero volcanoes (Carracedo et al., 2003).

The perimeter of the main eruption area is made up by extensive surfaces of rugged “aa” lava flows (malpaises) and “Pahoe-hoe” or rope lava flows, which have had minimal human alteration (Carracedo et al., 1992). In addition, the unique climate of the island has allowed the original volcanic landscape to remain virtually unaltered with a high concentration of geologic and geomorphologic formations, such as volcanic chimneys, caves, lava tubes and malpaises. Several canyons are crossing this landscape in all directions, being created while the surface of the lava cooled off, and broke into pieces, falling down into the several tubes (“jameos”) which had been formed by the lava (Carracedo et al., 2003). When flows are very fluid, lavas continue to circulate beneath the already cooled outside crust to form so-called lava tubes. This process ends with the material cooling down and subsequent formation of retraction fractures, which sometimes lead to the collapse of the tube roofs.

The presence of cavities in lava type volcanic materials is relatively frequent. The size of these cavities ranges from a few dm^3 to several m^3, forming caves from hundred to thousand meters in length. Their presence can give rise to geotechnical instability problems related to loads on foundations (Serrano et al., 2007). The recognition of these lava feeder networks in modern systems plays an important role in unraveling the emplacement and propagation of flow sequences and

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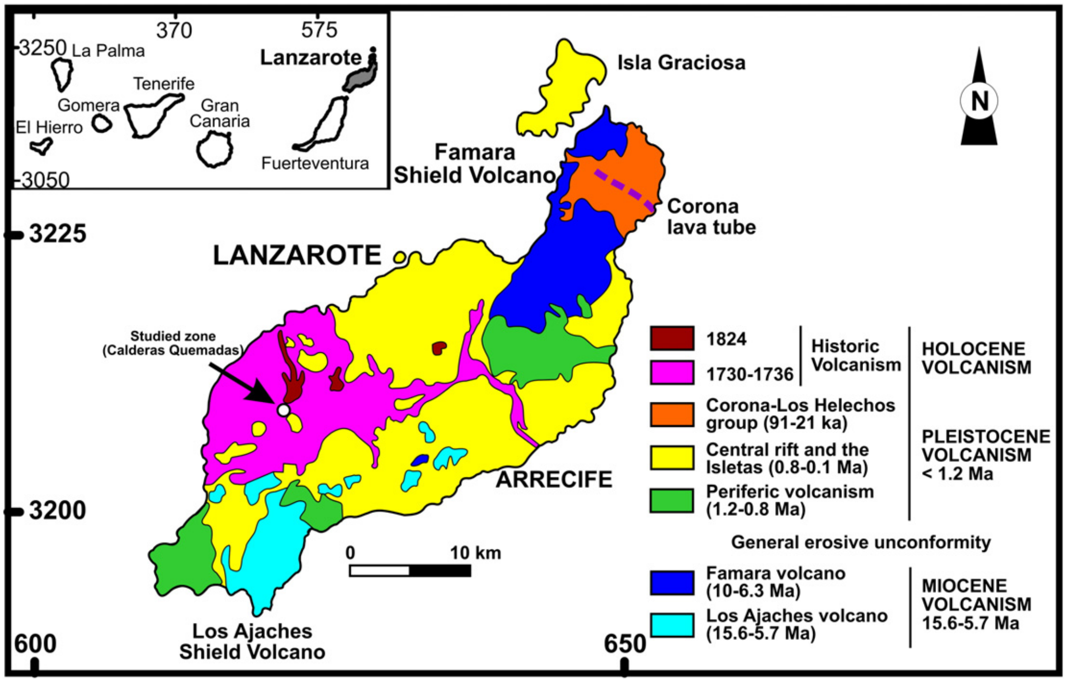

Fig. 1. Simplified geological map of Lanzarote island (Canary Islands, Spain) showing the main volcanic episodes. Coordinates UTM Zone 28 N (km). Modified from Hernández et al. (2012).

the evolution of the volcanic process (e.g. Calvari and Pinkerton, 1998). Moreover, its location and identification is important to prevent hazards or to achieve a good exploitation from a visitor view point in a touristic area as the Timanfaya National Park. The Timanfaya National Park is a restricted area and only a small portion of the park can be visited. Therefore, the use of prospective techniques which helps to know the near subsurface structure of the park is very complicated and, in this way, only some regional study through gravity, magnetism and seismic has been undertaken to attempt to model the deeper crustal structure of Lanzarote Island (e.g. Blanco et al., 2005; Camacho et al., 2001; Vonlanthen et al., 2006).

Site investigation techniques in volcanic islands usually require larger number of boreholes and specific geophysical methods appropriated for volcanic materials. Although different previous works about the geophysical investigation of shallow volcanic structures can be found in the literature, mainly from GPR (e.g. Cagnoli and Ulrych, 2001; Courtland et al., 2013; Gomez et al., 2008; Grimm et al., 2006; Heggy et al., 2006; Rust and Russell, 2000), manuscripts about the location of hidden lava tubes are scarce (e.g. Al-Oufi et al., 2008; Deroussi et al., 2009; Gómez-Ortiz et al., 2006; Miyamoto et al., 2003, 2005), as well as with the combination of different shallow prospection techniques (e.g. Gómez-Ortiz et al., 2007; Kruger et al., 2002).

Usually, the detection of cavities by GPR techniques, using a central frequency of 200 MHz, is limited to 10 m depth (Annan, 2003); electric tomography is also limited to 50 m depth (e.g. Bernard, 2003) and gravimetric methods cannot be appropriate to identify very small size cavities (whose gravity effect can be similar to the accuracy of the gravity survey) (e.g. Deroussi et al., 2009). So, the search of cavities or tubes must be rather complemented using several geophysical methods being each technique overcoming the drawbacks of the other ones. In relation to this, it is important to mention that the use of Electromagnetic Induction equipments with a low depth of investigation but a high resolution, such as DUALEM 4 or EM31 meters, could be useful when only small shallow cavities are of interest. However, the reason to use geophysical methods with higher depths of investigations (up to ~50–60 m) is that, although shallow lava tubes are the most dangerous, the occurrence of several overimposed levels of lava tubes has also been described in the area, and so it was important to detect if different lava tubes at different depths are present.

This work presents a new study about the near subsurface structures of the volcanic area of Timanfaya National Park by the analysis and interpretation of high-resolution gravity, GPR, and electromagnetic data obtained over areas which had not been surveyed up to date.

2. Geological setting

The Canary Archipelago is located in the eastern Central Atlantic off the Moroccan coast, and consists of seven major islands and several islets extending about 450 km from east to west. There is a recognized east-to-west age progression of the oldest subaerial volcanism, from about 20 Ma for the eastern islands of Lanzarote and Fuerteventura to about 15 Ma for Gran Canaria, 8 Ma for Tenerife, and 2 Ma for the westernmost islands of La Palma and El Hierro (Ancochea et al., 1994; Dañobeitia and Canales, 2000; Guillou et al., 1996).

Lanzarote is the easternmost island of the archipelago, located about 140 km off the African continent. The island has an elongated shape (55 km in length and 20 km in width) and is situated at the northeast side of the archipelago. Together with the island of Fuerteventura, Lanzarote presents the emergent part of the East Canary Ridge (ECR), a NNE–SSW linear volcanic structure of about 400 km in length and 65 km in width (Marinoni and Pasquare, 1994). The ECR consists of a number of uplifted blocks of oceanic basement covered by a thick sedimentary sequence (10 km) mantled by 5 km of volcanic rocks, with an intrusive complex between the two layers (Banda et al., 1981). The emergent part of Lanzarote is essentially formed by volcanic rocks, mainly basaltic in composition (Marinoni and Pasquare, 1994). Its subaerial volcanic activity dates back to the mid-Miocene (Coello et al., 1992) and can be divided into: (1) a shield-building stage, mainly Miocene in age (14.5–8.7 Ma), followed by sporadic volcanic activity (Serie I) interrupted by long-lasting erosive periods up to the early Pliocene (3.8 Ma), and (2) a post-shield stage, Plio-Quaternary in age (2.7 Ma–Recent), characterized by the formation of small NE–NNE aligned volcanoes with associated lava fields (Series II, III and IV). From 1730 to 1736 Lanzarote suffered the longest eruption in historical times in the Canary