Characterization of volcanic structures using ground penetrating radar and additional inverse modelling

Multidisciplinary geophysical investigation in the Timanfaya National Park (Spain)

M. Solla
Defense University Center (CUD-ENM)
Marín, Spain
merchisolla@cud.uvigo.es

D. Gómez-Ortiz, T. Martín-Crespo
ESCET, University Rey Juan Carlos
Madrid, Spain

F.G. Montesinos
Facultad de Matemáticas (UCM)
Madrid, Spain

J. Arnoso, E. Vélez
Instituto de Geociencias (CSIC, UCM)
Madrid, Spain

***Abstract*—A ground penetrating radar survey is presented over a recent lava flow at the volcanic area of Timanfaya National Park (Canary Island, Spain). The purpose was to locate lava tubes into the lava flow through the combination of field and simulated data. Different modelling strategies were used for the analysis and knowledge of the signal behaviour. Finite-difference time-domain algorithm was considered for simulations, and the pattern of reflections generated from previously known volcanic structures were characterized. After the characterization of the radar-wave response, the interpretation achieved was applied over the field data acquired at other non-studied area in which different lava tubes were recognized.**

***Keywords*—lava tubes; GPR; FDTD modelling; geophysics**

I. Introduction

Timanfaya National Park is a volcanic area, located in the southwest of Lanzarote Island (Canary Islands, Spain), which occupies a surface of about 51 km^2 with more than 30 volcanic cones formed in different phases of basaltic type eruptions. The area is made up by extensive surfaces of rugged "aa" lava flows and "Pahoe-hoe" or rope lava flows that have suffered minimal human alteration. 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 leads to the collapse of the lava roof and provokes geotechnical instability problems regarding loads on foundations [1]. Therefore, its location is important to mitigate collapse hazards.

The use of non-destructive geophysical techniques has demonstrated its capabilities to recognize the near subsurface structure of the park [2]-[3]. In such context, the ground penetrating radar (GPR) has been extendedly in the investigation of shallow volcanic structures [4]-[7]. However, there are not many published contributions in the literature about the location of hidden lava tubes [8]-[10].

This work presents a study about the location of recent lava tubes by the analysis and interpretation of GPR data. Additionally, numerical modelling was used to simulate the propagation of the electromagnetic GPR signal. The irregular geometry that characterizes the lava tubes results in complex reflections patterns, which makes the resulting radargram difficult to interpret. In heterogeneous environments, the use of numerical finite-difference time-domain (FDTD) modelling allows for the understanding of the propagation of the signal in order to assist the interpretation of field data [11]. Moreover, some authors [12] have recommended the joint inversion of different geophysical data, which provided better results than basic modelling when estimating dielectric properties of media. Then, taking these recommendations into account, the simulations in this work were built using both basic and more sophisticated modelling. The FDTD data produced was directly compared to the processed field GPR data.

The purpose was to characterize the response of the radar-wave over a previously known lava tube structure and, then, the interpretation achieved was applied over an area not previously surveyed up to date in order to detect probable structures. Thus, the method was calibrated over lava flows located at the Calderas Quemadas zone formed during the 3rd eruptive phase of the 1730-36 eruption, in which underground cavities can be visually identified. Field GPR, microgravity and electromagnetic induction (EMI) data was collected along the same profile to create a joint model for simulation to analyse the pattern of reflections produced by GPR. After characterization, such assumptions were applied to the field GPR data acquired over lava flows located at the Chinero zone. This zone was formed during the 4th eruptive phase in 1824, a century after the phase of the 1730-36 eruption originating the Timanfaya area and the lava tubes at the Calderas Quemadas zone.

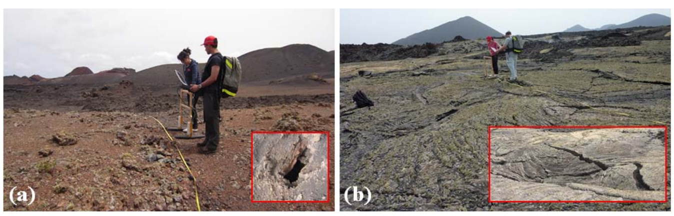

Fig. 1. GPR data acquisition at the Calderas Quemadas (a) and Chinero (b) zones.

978-1-4799-6495-6/15/$31.00 ©2015 IEEE

II. MATERIALS AND METHODS

A. *Ground Penetrating Radar*

The GPR data were collected using a RAMAC/GPR system from Malå Geoscience. A central frequency of 200 MHz was selected as the most optimum to produce reflections from the bottom of the lava tubes.

The GPR survey was carried out with the antenna polarization perpendicular to the data collection direction (Fig. 1). The offset between transmitter and receiver antennas was 0.6 m. Common-offset point-to-point data were acquired with 0.2 m trace intervals (in-line spacing), within a total time window of 190 ns and composed by 405 samples per trace.

B. *FDTD Modelling*

Different modelling strategies were used to achieve a better understanding of the radar-wave propagation. First, basic geometries were simulated to analyse the pattern of reflections produced when the signal encounters a lava tube structures. After this pattern recognition, more advanced modelling was developed through the combination of additional geophysical methods and inversion.

The synthetic radargrams were created using GprMax v.2.0 software, which is an electromagnetic wave simulator for GPR based on the FDTD algorithm.

1) Basic modelling

Several models were built (Fig. 2) based on the different typologies of tube structure compile from the literature [13]. The purpose was to analyse the geometry of the reflections produced in such sceneries.

The synthetic model was built using the MATLAB© software. The model was created with a small spatial-step (grid cell size in the x and y directions) equal to 16 mm, and the excitation pulse was a Gaussian of 200 MHz frequency. The trace-interval and the total time window were 0.1 m and 100 ns, respectively. The synthetic results produced were exported to ReflexW and filtered using a very similar processing sequence to that used for the field data.

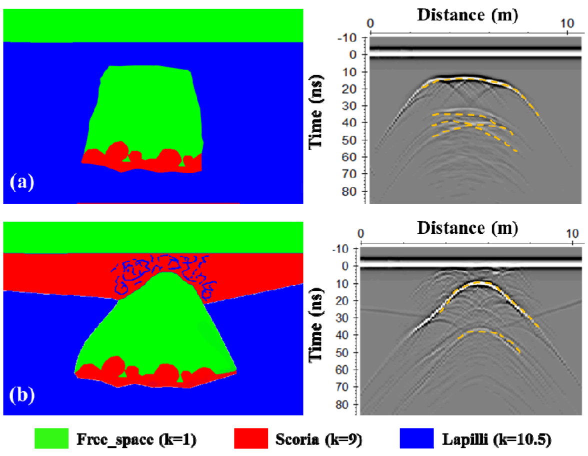

Fig. 2. FDTD simulations built to analyze the pattern of reflections produced by considering different geometries of lava tube structures.

Fig. 2 displays the models used for simulations and the dielectric constant assumed to characterize each medium. The interpretation of the reflections produced by the lava tube is also shown in the synthetic radargrams generated. For more circular structures (Fig. 2b), the reflection produced at the interface between the volcanic material and the free-space presents a hyperbolic shape in comparison with square tubes (Fig. 2a). Moreover, the heterogeneity commonly presented in such environments was simulated over the tube in the second model corroborating the confluence of more complex reflections due to the diffraction events associated. The corner reflections produced in the first case because of the perpendicular interfaces between the walls and the floor of the tube [11] also allows defining a square geometry of the tube.

2) Advanced modelling and inversion

Although the basic modelling presented in the previous subsection allowed for the understanding of the GPR response, these types of structures are more complex because of the heterogeneity and irregular shape of the volcanic materials. In such circumstances, more sophisticated simulations are required, and the best approximation of the models to reality is also proposed from the combination of data obtained from different complementary techniques.

For this particular case, the synthetic model was built through inverse strategies, and data from different geophysics techniques were combined: electromagnetic induction (EMI) and microgravity. The next steps presents a brief explanation of the approach assumed until obtaining the final model used for simulations. More information about the techniques, methodologies and processing data can be found in [14].

a) EMI data: the inverted model produced (Fig. 3a) showed five areas of highest resistivity values, which are typically associated to the presence of air-filled tubes (Areas A-D). Visual inspection conducted in the field during the data acquisition confirmed the occurrence of lava tubes at 5 and 17 m from the beginning of the profile.

b) Gravity modelling: for the interpretation of the gravity data, relative gravity lows were searched. Four interesting anomalies were identified at several positions of the profile (12, 24, 34 and 44 m), for which a density value of 2700 Kg/m^3 was considered as the density contrast between air-filled tubes and the lava flow. Thus, the final 2.5D density model (Fig. 3b) was made from the GPR interpretation and improved using a trial and error process until a reasonable fit between both observed and calculated anomaly presenting an overall RMS error of ±0.022 mGal.

c) Field GPR data: accordingly to EMI data, reflections can be grouped in the same four areas (Fig. 4). The visual inspections carried out allow confirming the occurrence of lava tubes in areas A and B, in which the strong hyperbolic reflections observed were interpreted as the effect of the roof and bottom interfaces of the tubes. On the other hand, reflections from areas C and D do not correspond to any known lava tube, but the similarities of both geometry and intensity of the reflections suggest a similar origin. The depth-scale (or elevation) was obtained based on a velocity of 0.09 m/ns for recent basaltic lava flows [9].

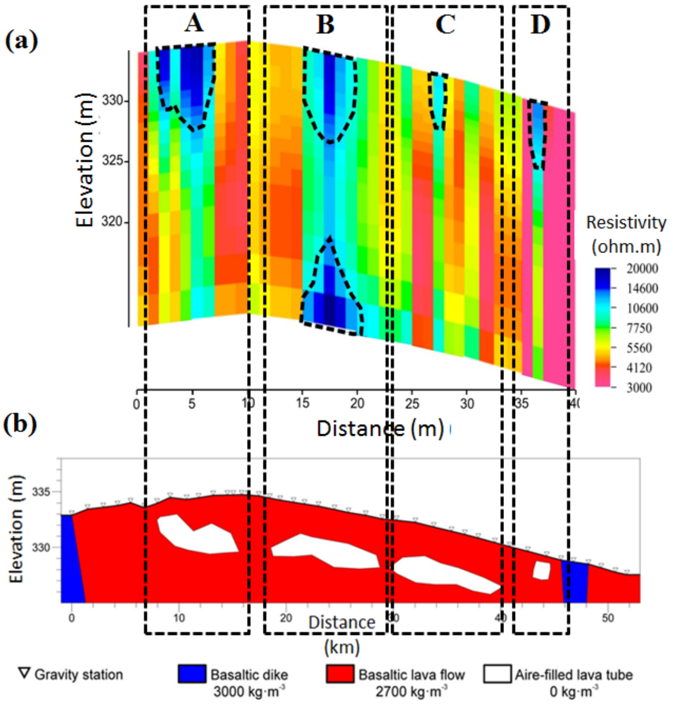

Fig. 3. (a) EMI inverted resistivity model showing five areas of high resistivity (bounded in black lines) and (b) Microgravity data: final 2.5D density model with four lava tubes identified and two basaltic dikes at the edges of the model. Modified from [14].

d) FDTD data: the input geometry for simulations corresponds to the gravity model (Fig. 3b). For media characterization, dielectric constant (k) and conductivity values of air were 1 and 0 S/m respectively, whereas estimated values for lava flows were 11 (0.09 m/ns) and 0.005 S/m.

The synthetic data produced (Fig. 5) show different reflections corresponding to the roof, bottom and edges of the lava tubes. A good agreement exists for the geometry of the reflections and their horizontal location between both synthetic and field data. However, differences exist in the time scale (20 ns) for the reflections in area A that indicates lateral variation of the radar-wave velocity. The poorest match corresponds to lava tube D in respect to horizontal location and geometry of the reflections. An explanation could be the possible heterogeneity in the internal structure of the lava flow and the occurrence of a vertical dyke at the position of the GPR reflections as suggested by the EMI and gravity data [14].

Moreover, that work presents additional simulations to determine the variation in the velocity of propagation. It was carried out by adjusting the reflections produced by the lava tube in both real and synthetic profiles, and the best approximation was achieved with velocity of 0.078 m/ns in the first 10 m (area A) and velocity of 0.09 m/ns in areas B and C.

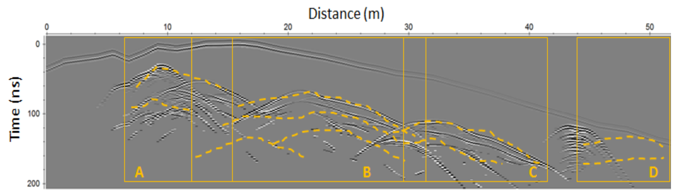

Fig. 5. Synthetic radargram (k=11) built using the geometry of the lava tubes obtained from the gravity model. Orange lines correspond to the real reflections identified (Fig. 4). Modified from [14].

The interpretation achieved from FDTD regarding the pattern of reflections produced by the presence of lava tubes was assumed to identify unknown structures in some GPR profiles acquired in the Chinero zone (Fig. 1b).

III. Results and Discussion

Different GPR profiles were additionally acquired in the Chinero zone in order to validate the interpretational acknowledge achieved from the integrated modelling strategies applied to the Calderas Quemadas zone. It is important to note that in this zone, there was not any previously known lava tube structure allowing the characterization of the pattern of reflections produced from such complex and heterogeneous structures. Therefore, to facilitate the identification of non-visible lava tubes, similar reflections than those observed for the Calderas Quemadas zone (Fig. 4) were sought in these new profiles (Fig. 6).

Observing the processed radargrams in Fig. 6, the reflections interpreted as the roof and bottom interfaces of possible lava tubes display reflections very similar in shape and size to the pattern of reflections identified in Fig. 4 – area A. The dimensions of these lava tubes detected range from 6-8 m wide and approximately 30 ns (4.5 m) in height, which is in accordance with the dimensions measured in area A at Calderas Quemadas zone with 6 m wide and ceiling height of about 4 m (Fig. 4).

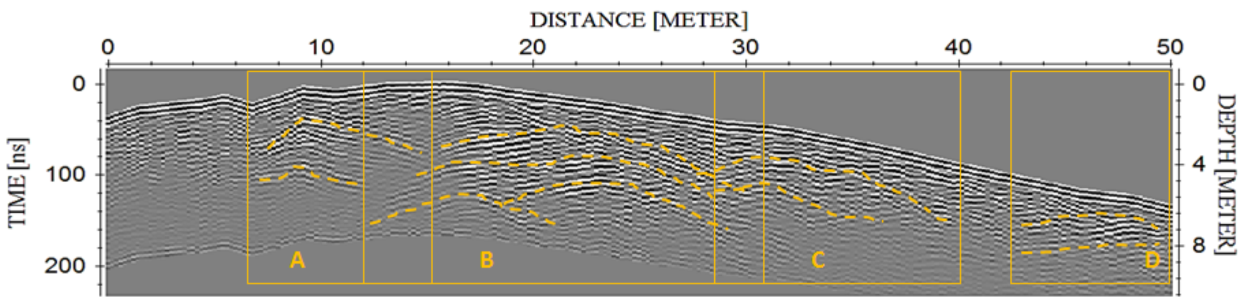

Fig. 4. Field GPR data produced and interpretation of the four areas (A to D) associated to the existence of lava tubes.

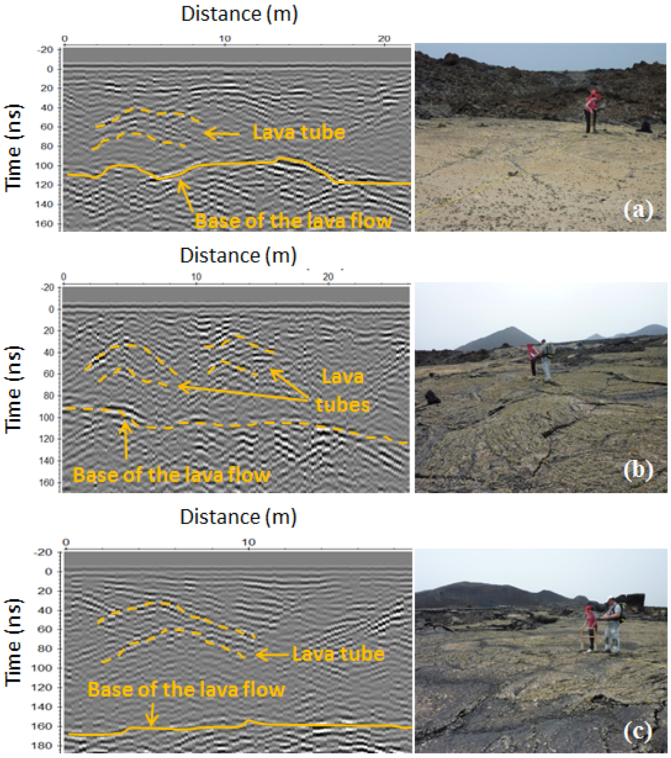

Fig. 6. 200 MHz reflection profiles obtained at different locations in the Chinero zone showing the interpretation of the lava tubes identified.

IV. Conclusions

Lava tubes, if unknown, can present a risk in such a tourist site as the Timanfaya National Park by instability problems and collapse hazards.

This paper demonstrates the capabilities of FDTD modelling strategies applied to the understanding of the radar-wave behaviour when propagating in complex environments such as volcanic areas. An integrated modelling through the combination of three shallow geophysical methods, GPR, microgravity and EMI, was developed over a recent lava flow.

Two shallow lava tubes were visible during the field data acquisition in the Calderas Quemadas zone and were used to check if the different techniques were able to detect them. The synthetic model was built from the gravity model, and the reflections thus obtained were compared to the field GPR data produced. As a result, apart from the two known cavities, two more shallow lava tubes were detected and confirmed by the three methods. The signals related to these structures were then used to locate similar hidden lava tubes pending to be identified in the Chinero zone.

Several shallow lava tubes in the Chinero zone were detected and confirmed by simulations. The patterns of reflections obtained were similar to those produced in one of the visible lava tubes in the Calderas Quemadas zone. Apart from geometric similarity, the dimensions of the structures identified were also in accordance with such known lava tube, ranging from 6-8 m wide and ceiling height of about 4-4.5 m.

Acknowledgment

Authors thanks to the financial support of the National Parks Network of the Spanish Ministry of Environment and Rural and Marine Affairs (320/2011 – project "Caracterización estructural del Parque Nacional de Timanfaya mediante uso combinado de técnicas y métodos geodésicos y geofísicos". The staff of National Park of Timanfaya is also acknowledged, as well as the Applied Geotechnologies research group from the University of Vigo for providing the RAMAC/GPR equipment. Additionally, this study is a contribution to the EU funded COST Action TU-1208.

References

[1] A. Serrano, A. Perucho, C. Olalla, and J. Estaire, "Foundations in volcanic zones," in 14th European Conference on Soils Mechanics and Geotechnical Engineering. Millpress, Rotterdam, Netherland, 2007.

[2] A.G. Camacho, F.G. Montesinos, R. Vieira, and J. Arnoso, "Modelling of crustal anomalies of Lanzarote (Canary Islands) in light of gravity data," Geophys. J. Int. 147(2), 2001, pp. 403-414.

[3] I. Blanco, F.G. Montesinos, A. García, R. Vieira, and J. Villalaín, "Paleomagnetic determination of Lanzarote from magnetic and gravity anomalies: implications for the early history of the Canary Islands," J. Geophys. Res. 110, 2005, B12102.

[4] A.C. Rust, and J.K. Russell, "Detection of welding in pyroclastic flows with ground penetrating radar: insights from field and forward modeling data," J. Volcanol. Geotherm. Res. 95, 2000, pp. 23-34.

[5] B. Cagnoli, and T.J. Ulrych, "Downflow amplitude decrease of ground penetrating radar reflections in base surge deposits," J. Volcanol. Geotherm. Res. 105, 2001, pp. 25-34.

[6] C. Gomez, F. Lavigne, N. Lespinasse, D.S. Hadmoko, and P. Wassmer, "Longitudinal structure of pyroclastic-flow deposits, revealed by GPR survey, at Merapi Volcano, Java, Indonesia," J. Volcanol. Geotherm. Res. 176, 2008, pp. 439-447.

[7] L. Courtland, S. Kruse, and C. Connor, "Violent Strombolian or not? Using ground penetrating radar to distinguish deposits of low- and high-energy scoria cone eruptions," Bull. Volcanol. 75, 2013, pp. 1-13.

[8] H. Miyamoto, J. Haruyama, S. Rokugawa, K. Onishi, T. Toshioka, and J. Koshinuma, "Acquisition of ground penetrating radar data to detect lava tubes; preliminary results on the Komoriana Cave at Fuji Volcano in Japan," Bull. Eng. Geol. Environ. 62, 2003, pp. 281-288.

[9] D. Gómez-Ortiz, S. Martín-Velázquez, T. Martín-Crespo, A. Márquez, J. Lillo, I. López, and F. Carreño, "Characterization of volcanic materials using ground penetrating radar: a case study at Teide volcano (Canary Islands, Spain)," J. Appl. Geophys. 59(1), 2006, pp. 63-78.

[10] A. Al-Oufi, H.A. Mustafa, E. Al-Tarazi, and J.A. Rajab, "Exploration of the extension of two lava tubes, faults and dikes using very low frequency-electromagnetic technique in NE Jordan," Acta Geophys. 56, 2008, pp. 466-484.

[11] M. Solla, H. Lorenzo, F.I. Rial, and A. Novo, "Ground-penetrating radar for the structural evaluation of masonry bridges: results and interpretational tools," Constr. Build. Mater. 29, 2012, pp. 458-465.

[12] N. Linde, A. Binley, A. Tryggvason, L.B. Pedersen, and A. Revil, "Improved hydrogeophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar traveltime data," Water Resources Research 42, 2006, W12404.

[13] J.C. Carracedo, B. Singer, B. Jicha, H. Guillou, E. Rodríguez Badiola, J. Meco, F.J. Pérez Torrado, D. Gimeno, S. Socorro, and A. Láinez, "La erupción y el tubo volcánico del volcán Corona (Lanzarote, Islas Canarias)," Estudios Geol., 59, 2003, pp. 277-302.

[14] D. Gómez-Ortiz, F.G. Montesinos, T. Martín-Crespo, M. Solla, J. Arnoso, and E. Vélez, "Combination of geophysical prospecting techniques into areas of high protection value: Identification of shallow volcanic structures," J. Appl. Geophys. 109, 2014, pp. 15-26.