Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Electrical Resistivity Time Evolution of Volcanic Islands: Gran Canaria, Tenerife and La Palma Islands (Spain)

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Keywords: Magnetotelluric, electrical resistivity, volcanic islands, Canary Islands

ABSTRACT

The Canary Islands are an archipelago of volcanic origin located off northwest Africa that comprises seven major islands. Among them Gran Canaria, Tenerife and La Palma. The Canary archipelago is volcanically active. The three islands display signs of Holocene volcanism and Tenerife and La Palma have had historical eruptions in the last 500 years. The last onshore eruption occurred on La Palma in 1971. The age of the islands spans from the 14.7 Ma of the older Gran Canarias islands, 11.7 Ma for Tenerife to 1.7 of La Palma. Electrical resistivity is a parameter that can be used to determine the structure and the processes that have occurred in volcanic islands. In this work we will present the 3D electrical resistivity models of the Gran Canaria, Tenerife and La Palma islands that have been obtained from the 3D inversion of magnetotelluric data acquired at the three islands in the last years. In the three islands a low resistivity structure is found at depth although the geological interpretation of this structure differs among the islands. Some of the differences of the observed electrical resistivity structures present in the three islands can be associated to the time evolution and the difference of ages among the three islands.

1. INTRODUCTION

The Canary Islands are an intraplate volcanic archipelago composed by seven main islands and four islets located in the eastern Atlantic Ocean in between the latitudes 27°N and 30°N. The islands are aligned in the E-W direction, extending for about 500 km, with the most eastern one (Fuerteventura) being about 100 km away from NW Africa. The volcanic activity of the archipelago started in Oligocene and it is still in progress at present (Staudigel and Schmincke, 1984). The Canary Islands rest on top of and old, cold, rigid and thick oceanic crust that has limited the amount of subsidence of the archipelago in comparison to the Hawaiian one. Major differences from the classical hot spot model developed for Hawaii include the long volcanic history of individual islands and the entire archipelago, multiple cycles of volcanism, the large temporal and spatial variety in the chemical composition of the volcanic deposits, and the absence of a broad topographic swell and gravity/geoid high (Hoernle & Schmincke, 1993).

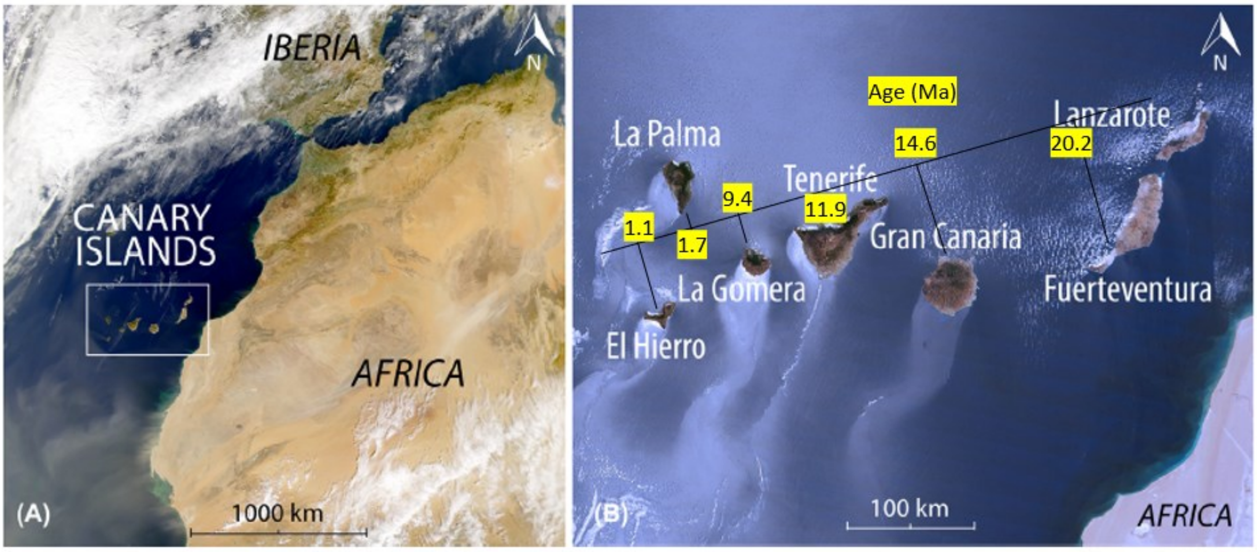

Figure 1: A) Geographic setting of the Canary islands. The eastern islands are about 100 km from Africa. B) The seven main islands of the Canary archipelago with ages in Ma (yellow squares).

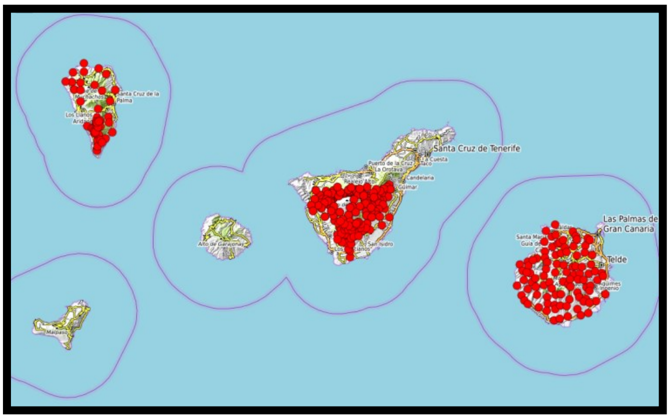

Figure 2: Location of the MT stations (rep points) in La Palma, Tenerife and Gran Canaria islands.

The magnetotelluric method (MT) has revealed an optimal tool to explore geothermal reservoirs, map the presence of fluids and image significant structural contrasts in the subsoil because the electric resistivity is a quantity sensitive to the presence of fluids/brines, salts, and, for a vast range of materials, it is also temperature-dependent. Usually, the resistivity structure in a geothermal area is characterized by a conductive clay layer associated to the presence of smectite (< 10 ohm.m) and illite-smectite (a few tens of ohm.m) overlying a more resistive zone (10-100 ohm.m) where the reservoir is located, and such a sharp contrast can be easily detected by the application of MT3. The use of MT to map the presence of conductive layers in volcanic/geothermal areas is well documented in literature, not just for the assessment of the geothermal system and the connected hydrothermal circulation but also for structural investigation and magmatic reservoir characterization. In particular, a 3D resistivity model of the subsurface of a volcanic surveyed by MT can reveal the presence and the shape of such structures. Magnetotelluric surveys have been used extensively to characterize volcanic islands (Coppo et al., 2008; A. García-Yeguas et al., 2017; Garcia & Jones, 2010; Piña-Varas et al., 2014, 2015, 2018; Pous et al., 2002) and also in combination with other geophysical and geochemical datasets (Rodríguez et al., 2015; García-Yeguas et al., 2017). The magnetotelluric method involves measuring the temporal fluctuations of the horizontal components of the natural electromagnetic field at the Earth's surface to infer the lateral and vertical variations of electrical conductivity of the Earth's interior (Chave et al., 2012, and refrences therein). In this work, a dataset of 100 magnetotelluric soundings were acquired in Gran Canaria, 40 in La Palma and more than 200 in Tenerife island in the last seven years (see figure 2). In this paper we present a review of the main results obtained from the 3D inversion and interpretation of the models for each of the islands.

2. TENERIFE ISLAND

The geological evolution of Tenerife is an alternation in both constructive and destructive episodes. Constructive episodes involve the accumulation of volcanic materials corresponding to two kinds of volcanism, fissure basaltic and explosive, while destructive episodes include gravitational landslides. As examples of hydrothermal activity in Tenerife we find an intense hydrothermal alteration effect in the southern part of the caldera, as well as important gas emissions, mainly carbon dioxide and helium, and fumaroles at Teide. These emissions suggest an active geothermal system in the central part of the island. Even so, compared with developed geothermal systems around the world, the geochemical indicators of geothermal conditions under Tenerife are weak. A total of 285 broadband MT sites (10-3-102 s) distributed around the island were available for the studies conducted in Tenerife (Figure 2). With all this information, different studies were published in the last few years. The first study (Piña-Varas et al., 2014) emphasizes the need for understanding the effect of the topography and the ocean on the MT responses. The presented 3D resistivity model was the result of the inversion of 148 MT sites using the ModEM code (Kelbert et al., 2014). It was interpreted in a high-temperature geothermal system context, where the most obvious feature is a low-resistivity layer associated with the clay cap of the reservoir (Figure 3). The second study (Rodriguez et al., 2015) combines geochemical and geophysical techniques to better characterize the existence of geothermal reservoirs in the subsurface of the southern volcanic rift zone of Tenerife. In this case, only 47 MT sites were chosen from the previous MT surveys. The results show an inverse correlation between the thickness of the clay cap and enrichments of non-reactive gases as He, suggesting the presence of permeability discontinuities in the study area. These results are used to define the areas for more detailed research, minimizing the uncertainty in locating future exploratory drilling. A detailed study about the Las Cañadas caldera (Piña-Varas et al., 2015). Thus, the 3D model of Tenerife island reveals a clear relationship between the characteristics of the main resistivity structure (low-resistivity clay cap) and the processes involved in the origin of Las Cañadas caldera. The continuity, at depth, of the clay cap in the northern part of the caldera has been interpreted as the northern wall of the Las Cañadas caldera. The presence of this wall together with the distribution and slope of the clay cap would imply that the hangingwall of the Icod Valley is not located in the current wall (south wall) of Las Cañadas caldera, but rather northernmost.

Thus, the 3-D resistivity model supports the hypothesis of the vertical collapse for the origin of Las Cañadas calderas proposed by Martí [2004] and Martí et al. [1997]. In this last study the authors suggest a coincidence in time between some of large-volume landslides and caldera collapse events, playing the vertical collapses a key role in targeting lateral collapses [Martí et al., 1997]. Even so, some considerations should be taken into account. In first place, the buried northern wall of the caldera is detected south of Teide, being the collapsed area smaller than that proposed in the vertical collapse model [Martí, 2004, Figure 2]. On the other hand, it is essential to consider the role of the clay alteration cap in the process of Las Cañadas caldera formation. In this sense this work represents a significant contribution. Is important to note that following the hypothesis proposed here, we can assume that the ring shape of the clay alteration cap is related with the successive vertical collapses, giving us information about the alteration age. Thus, the hydrothermal system was developed prior to the explosive eruptions which lead in calderas formation. The oldest vertical collapse of the multicyclic process resulted in theformation of the Ucanca caldera (western part of Las Cañadas caldera, Figure 3), around 1.02 Ma. A fuzzy cluster analysis (FCM) of the 3D seismic velocity model and the 3D electrical resistivity model (García-Yeguas et al., 2017) allowed us to interpret in more detail the complex structure of Tenerife Island. Based on cluster analysis the most relevant result is the presence of a geothermal system below Teide volcano at 600 m (b.s.l). This interpretation has already made by other authors suggesting that the heat source of the fumarolic activity is located around this depth. Moreover, the clay cap, a typical structure for geothermal systems characterize by low resistivity and medium velocity values and observed in several geothermal environments has been also observed at shallower depths. On the other hand, at deeper depths the results from cluster analysis suggests that the observed structures correspond to ancient volcanic edifices (basaltic bodies) as Roque del Conde in the south. The joint interpretation using FCM has allowed us to identify different interfaces, better constrain the position of the geothermal system and to obtain a more detailed inner structure of Tenerife Island.

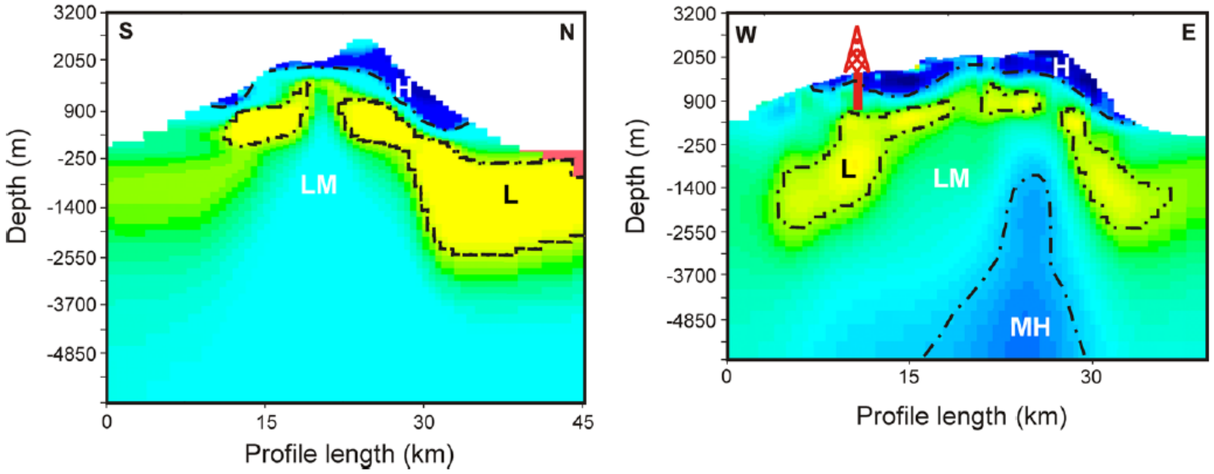

Figure 3. Left: Vertical (north–south) resistivity cross section of the 3-D final model. Right: Vertical (east–west) resistivity cross section of the 3-D final model. The dashed line corresponds to the area with a resistivity lower than 10 ohm. m, which has been interpreted as the smectite clay cap corresponds to hydrothermal alteration zone

3. GRAN CANARIA ISLAND

The geological evolution of Gran Canaria is separated into three main evolutionary stages: the Miocene shield stage, the Pliocene post erosional stage of Roque Nublo volcanism and the Pleistocene, Holocene and recent alkaline volcanic activity in the northern part pf the island. Each stage has its own distinct magma compositions and types related to discrete magmatic processes at depth, and likely related to three successive mantle "blobs" of variable chemical composition (Schmincke & Sumita, 1998). The chronostratigraphic division of Gran Canaria included three magmatic cycles separated by erosional intervals: Cycle I (from 14.5 to 8.0 Ma), an erosional interval of about 3 Ma; Cycle II (the Roque Nublo Group), an erosional interval of 5 Ma; and Cycle III (the Post-Roque Nublo Group). Therefore and due to several controversies in this classical differentiation of the volcanic stages in the Islands, it is better to consider two main phases of the subaerial construction of the island: a juvenile or shield stage (ca. 14.5-8.0 Ma) which includes a basaltic shield volcano, a vertical caldera collapse and a sialic post-caldera resurgence, and a rejuvenated or post-erosive stage (ca. 5 Ma to present), both separated by a period of volcanic inactivity of ca. 3 Ma. The subaerial Miocene phase (16 Ma) started with the rapid formation of the exposed tholeiitic to mildly alkalic shield basalts with a decrease in age from west to east, it constitutes, by large, the most abundant material on the island. The shield basalts are covered by a small layer (200 m) of ignimbrites and minor lavas of predominantly peralkaline trachytic forming the Mogan group. This was followed by a second felsic eruption phase producing thachyphonolitic ignimbrite, the Fataga group. Volcanic activity was practically absent on the islands between 9 to 5 Ma during this time the island became strongly eroded. The Pliocene phase began with minor nephelites and basanites at 5 Ma. Subsequently Pliocene Roque Nublo volcanism formed a stratocone, possibly as high as 3000 m.a.s.l. The southern and central sectors of this central stratocone collapsed at 3.5 Ma. Following a possible brief gap in volcanism, highly undersaturated mafic lavas erupted. Quaternary volcanism is restricted to the northern half of the island. Tejeda Caldera was formed synchronously to the Mogan ignimbrites and was due to the emplacement of a shallow level reservoir and the eruption of massive ignimbrite which emptied this reservoir and initiated a complex interplay of repeated inflation and deflation cycles (Troll et al., 2002) formed the Caldera de Tejeda, which is likely the most dramatic volcanic features in the volcanic evolution of the island. The gravitational and vertical collapse of the reservoir roof opened ring fractures at the caldera perimeter. This elliptical caldera (20x17 km wide) has a vertical displacement of its interior of more than 1000 m. For this island, a dataset of 100 new magnetotelluric soundings distributed around the island (Figure 2) has been acquired from July 2017 to September 2017. Instrumentation consisted of three Metronix ADU-07 and two ADU-06, along with EPF06 electrodes and MFS06/07 magnetic coils. The final 3D resistivity inversion model, obtained from the inversion of the impedance tensor components using the ModEM code (Kelbert et al., 2014), is shown in Figure 4 as six horizontal depth slices and 2 vertical cross-sections. The upper part of the model (-500 m.a.s.l.), that roughly coincides with the limits of the Tejeda caldera, is very heterogeneous and shows high resistivity contrasts that can be associated to the presence of highly porous materials and fractures with or without meteoritic water and clays that can produce the observed resistivity contrast. However, at depth, the most obvious feature is the high resistivity (> 500ohm.m) central region surrounded by a less resistive structure (20-50 ohm.m). This high resistivity structure seems to be delimited by the walls of the Tejeda Caldera up to depths of -2000 m.a.s.l. With increasing depth, the high resistivity structure elongates in SE direction and at -

5000 m.a.s.l. is cutting in two the island. In the vertical cross-sections, also the most obvious feature is the presence of a high resistivity anomaly associated with the Tejeda Caldera. It shows a near vertical contact with the surrounding materials (ring fault). Inside the Tejeda caldera the presence of an intrusive complex of cone sheet swarm surrounding a central core of hyperabisal syenite stocks (Donoghue et al., 2010) as well as the fluid-rock interaction sealing the fractures will reduce the permeability of the central part of the island drastically and produce the observed high resistivity in the 3D model. A combination of both, hydrothermal alteration for the deeper parts of the island and the presence of mixed waters with a moderate amount of salinity within medium-high porosity Miocene shield basaltic rocks in the shallow parts are considered as the most likely explanations of the observed resistivity values.

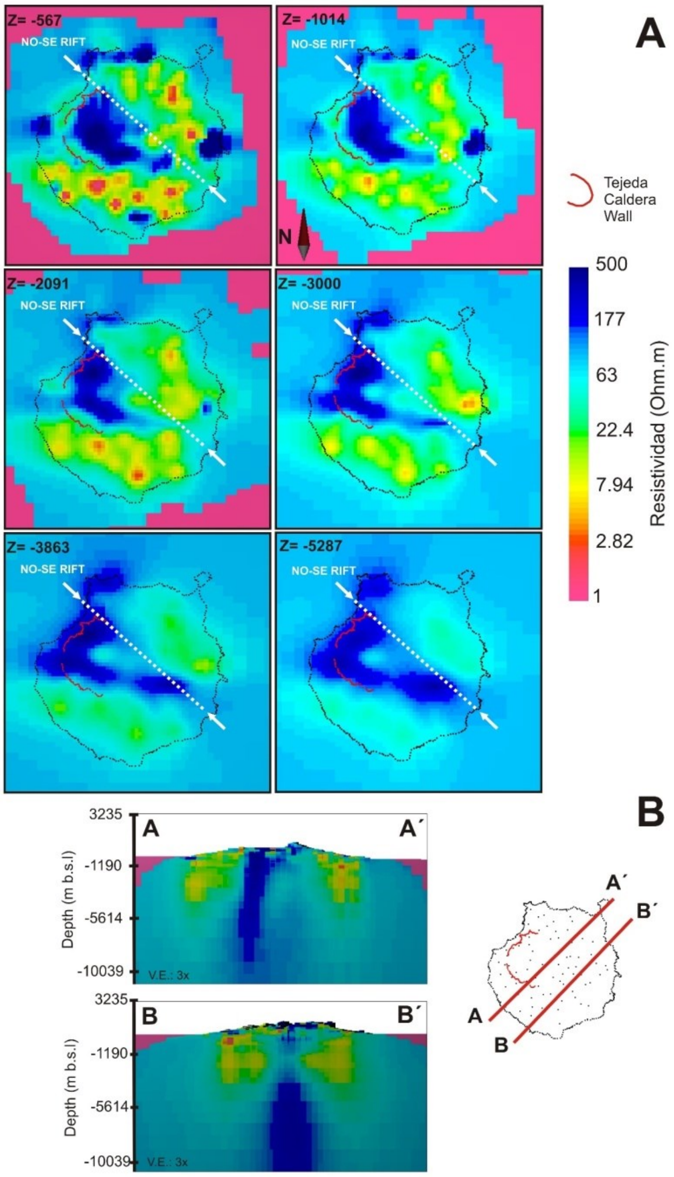

Figure 4. A: Horizontal cross-sections of the 3D electrical resistivity model. B: Vertical cross sections SW-NE across the island.

4. LA PALMA ISLAND

Located in the western part of the archipelago, La Palma is one of the youngest islands, the second in height and the fifth in area, having a surface of about 706 km2 and it is elongated in a north-south direction, with a length of about 45 km. The geological evolution of the island, connected to the most significant visible volcanic edifices, can be summarized as: i) the old basal complex (ca. 4 to 3 Ma) comprising a Pliocene seamount sequence and a plutonic complex, uplifted and tilted by subsequent intrusions, currently cropping out only inside the Taburiente caldera thanks to an extensive erosion; ii) a volcanic series (1.7 to 0.4 ka), including the Garafía volcano, the Taburiente shield volcano and Cumbre Nueva and Bejenado edifices, covering the northern part (more than a half in surface) of the island; iii) the Cumbre Vieja series (123 ka to present), a ridge system having rift, faults and volcanic vents aligned along its N-S crest and whose volcanic products cover the southern part of the island. During the last 500 years Cumbre Vieja experienced at least six eruptions (Day et al., 1999), with the last eruptive episodes occurring in 1971

(Teneguía volcano). Associated to the main rift, a system of normal faults usually parallel but occasionally oblique to the rift axis has been developed. Cumbre Vieja has been probably fed by a distinct magma reservoir/plumbing system with respect to the older Taburiente/Cumbre Nueva volcanic system; such a distinction in between the two volcanic complexes has been also pointed out by (Camacho et al., 2009) from the interpretation of gravity anomalies in the interior of the island.

Between June and August 2018, 44 broadband MT stations have been deployed on La Palma island. The instrumentation consisted of four Metronix ADU-08e equipped with EPF-06 electrodes and MFS-06e magnetic coils. At each site the horizontal components of the electromagnetic field were recorded, orienting the x-axis along the N–S direction pointing the north and y-axis in the E–W direction pointing the east. To improve the data quality two reference stations where placed at distances varying from 2 to 23 km from the measurement points, in order to remove the uncorrelated noise. The data shows a clear 3D behavior and the 3D electrical resistivity model was obtained from the inversion of the impedance tensor components using the ModEM code (Kelbert et al., 2014), using 14 periods in the range 0.001 to 1000 seconds. The model consisted of 89x121x84 mesh grid in which the topography and the surrounding bathymetry of the island have been included. The final model (Figure 5) shows a high resistivity structure that can be associated to the Taburiente caldera to the north and a structure with lower resistivity at depth to the south in the Cumbre Vieja area.

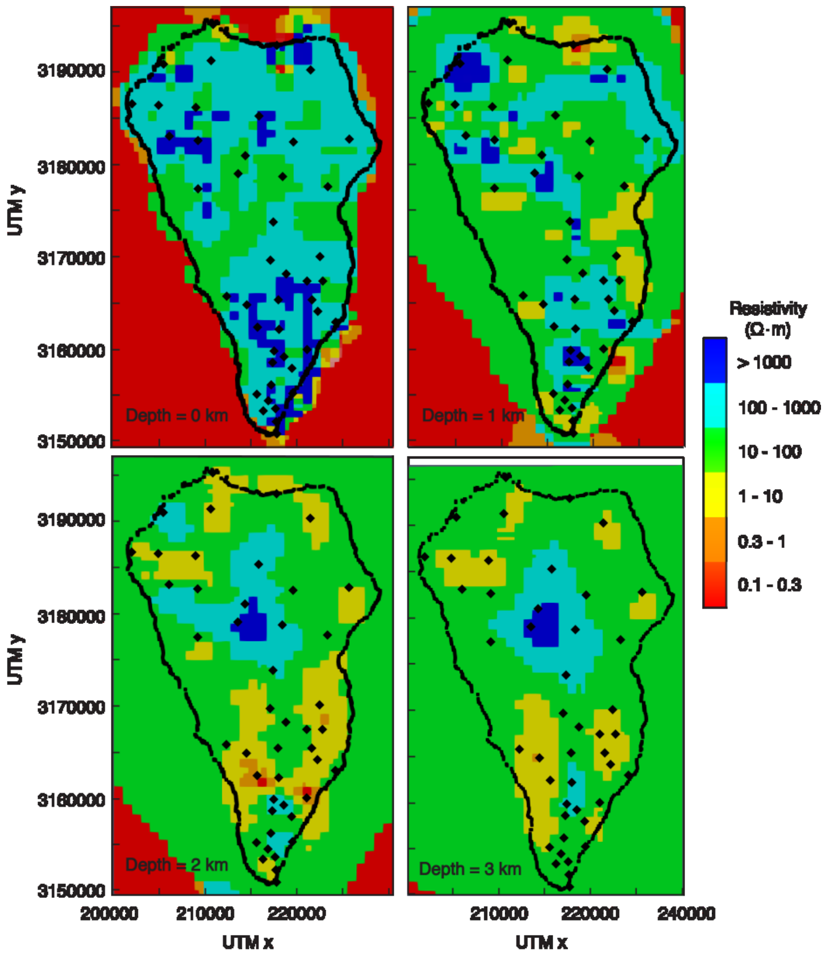

Figure 5. Horizontal cross-sections of the 3D electrical resistivity model.

5. DISCUSSION AND CONCLUSSIONS

The three islands show a high resistivity structure that can be associated to the calderas of the island (Las Cañadas, Tejeda and Taburiente). The presence of low resistivity structures around these calderas shows different patterns and resistivity values in the three islands. Figure 6 shows two horizontal cross sections of each of the islands at 0 km and -2.7 km a.s.l. The low resistivity structure with a ring shape is clearly imaged in Tenerife at z=0 km a.s.l. while at this depth the clearest features in the two other islands are the Tejeda caldera in Gran Canaria and the Cumbre Vieja one in La Palma. At -2.7 km a.s.l the three islands show clearly the high resistivity structures associated to their main calderas and in La Palma (the youngest island) a NS low electrical resistivity is imaged in the Cumbre Vieja zone.

In order to better understand the geological meaning of the observed electrical resistivity values of the three islands a comparison with other geological and geophysical models available for the islands as well as a thorough comparison between the electrical resistivity models of the islands will be done in the near future.

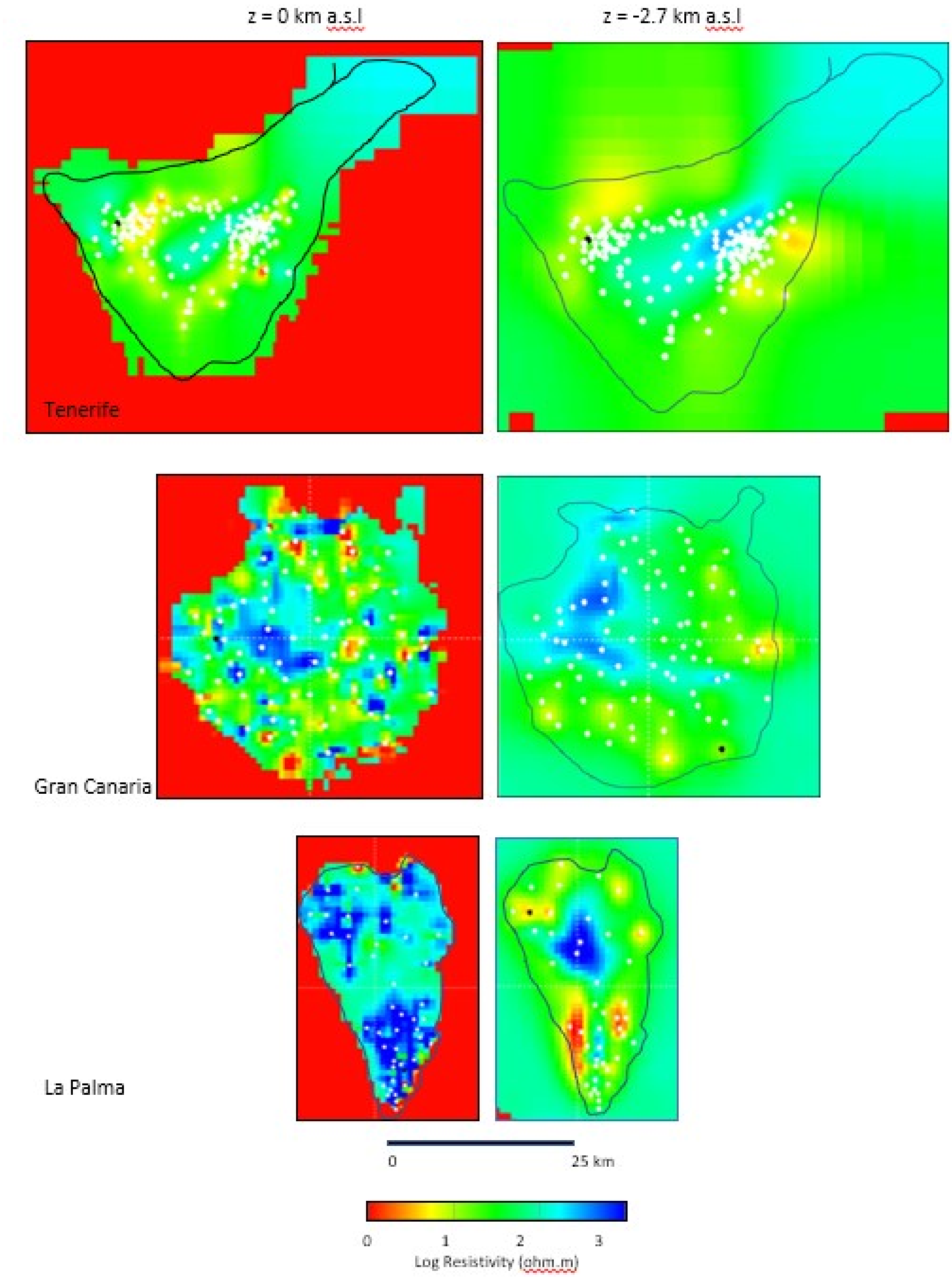

Figure 6. Horizontal cross-sections of the 3D electrical resistivity models of La Palma, Tenerife and Gran Canaria islands at 0 km and -2.7 km a.s.l

ACKNOWLEDGMENTS

This research is been supported by the projects Geothercan (IPT-2011-1186-920000), Ibergic GL2017-82169-C2-2-R, Doctorado Industrial Marta García-Merino (DI-16-08959) and Termovolcan (RTC-2017-6627-3), financed by Spanish National Plan for Scientific and Technical Research and Innovation, as well as the projects TF-GEOTERMIA_01, GC-GEOTERMIA_01 and LP-GEOTERMIA_01 financed by the Cabildos Insulares de Tenerife, Gran Canaria and La Palma, respectively. We thank also the support of the Ayuntamiento de Fuencaliente and the Dirección General de Seguridad y Emergencias del Gobierno de Canarias for their assistance and logistic support on La Palma's field work. Assistance to this meeting is supported by PIXIL Nº EFA362/19 that has been co-financed by the European Regional Development Fund INTERREG POCTEFA.

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