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EXPRESS LETTER

On the detectability of Teide volcano magma chambers (Tenerife, Canary Islands) with magnetotelluric data

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Abstract

Tenerife has been the subject of numerous studies covering a wide range of fields. Many studies have been focused on characterising the magmatic plumbing system. Even so, a controversy still exists regarding the location and size of the current magma chambers. Several magnetotelluric (MT) surveys have been carried out in the island, but no conductivity anomalies associated with the chambers have been detected. We report the results of a set of tests conducted against the 3-D resistivity model of the island, to determine the characteristics of the detectable chambers with the MT data. The most remarkable results indicate that the MT dataset is incompatible with a large-scale mafic reservoir located at shallower depths than 8 km b.s.l. However, shallower phonolitic chambers smaller than $3 \times 3 \times 1$ km^3 could be undetected by the existing MT sites and new data should be acquired to confirm or not their existence. This new information is essential in volcanic islands like Tenerife, since many volcanic hazards are related to the size and depth of the sources of magma. Additionally, a joint interpretation of the obtained results together with other information is summarised in a hypothetical model, allowing us to better understand the internal structure of the island.

Keywords: 3-D magnetotellurics, Tenerife internal structure, Magma chambers characterisation

Introduction

One of the most important aspects to understand the internal structure of a volcano is to characterise its magmatic system. Some volcanic hazards, for instance, are strongly related to the size and depth of the magma source. The presence of an active magma chamber generates strong resistivity contrasts with the hosting units, since magmas contain dissolved water in their composition that reduces its resistivity (e.g. Lebedev and Khitarov 1964; Gaillard 2004). This contrast between the magma and the hosting geological units represents an appropriate framework for the application of electromagnetic methods, such as magnetotellurics (MT) (e.g. Newman et al. 1985; Moroz et al. 1988; Park and Torres-Verdin 1988; Spichak 2001, 2012).

In this work we analyse the capability of the MT dataset presented by Piña-Varas et al. (2015) to detect the magma chambers below Teide volcano. To do this analysis, the 3-D resistivity model obtained in Tenerife by Piña-Varas et al. (2015) has been modified by introducing low-resistivity bodies performing the role of potential magma chambers, according to geological, geophysical and petrological information. The variations in the data fit between the original 3-D inversion model (Piña-Varas et al. 2015) and the models with these conductive bodies (modified models) will provide us information about the characteristics (e.g. size, location, depth) of the potential magma chambers compatible with the available MT data.

Furthermore, the findings reached are interpreted jointly with other geological, geophysical and hydrogeological information (e.g. Martí 2004; Marrero 2010; Piña-Varas et al. 2014; García-Yeguas et al. 2017) to obtain a

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more comprehensive scheme of the Tenerife internal structure. This scheme includes not only information about the internal structure but also information related to the extension and location of the magma chambers, the hydrogeology and the hydrothermal alteration products derived from the geothermal system. The model here presented can be considered one step forward to integrate all these information.

Geological setting

Tenerife is the largest island of the Canarian archipelago. The oldest units on the island, Old Basaltic Series, are visible in three eroded edifices located in the extremes of the island, the Anaga (NE), Teno (NW) and Rocas del Conde (S) massifs. Together with the Santiago del Teide ridge and the Dorsal ridge, these massifs form the basaltic shield complex. The younger volcanic sequences of Tenerife are the Las Cañadas Edifice and Teide–Pico Viejo twin stratovolcanoes. These edifices were developed in the centre of the island and constitute the Las Cañadas–Teide–Pico Viejo Complex (CTPVC) (Fig. 1).

A large caldera, Las Cañadas Caldera, was formed in the centre of Tenerife as result of multiple vertical collapse episodes (Martí et al. 1994; Ablay et al. 1998; Marti and Gudmundsson 2000; Carracedo et al. 2007) and was filled by later emissions of Teide–Pico Viejo.

Magma chambers

Two kinds of volcanism are present on the island: fissure basaltic and explosive volcanisms. The fissure basaltic volcanism is still active along the ridges and is associated with different source regions at different depths (Fig. 2a). The explosive eruptions, however, involve shallow phonolitic magma chambers developed in the centre of the island (Mitjavila and Villa 1993; Martí et al. 1994; Bryan et al. 1998; Marti and Gudmundsson 2000; Wolff et al. 2000; Edgar 2003).

Petrological evidence suggests that the region where the phonolitic magmas are stored would not be constitute of a single chamber but rather, several coexisting isolated reservoirs (Ablay et al. 1998; Martí and Geyer 2009; Andújar and Scaillet 2012; Andújar et al. 2013) (Fig. 2b-ii). The location of these phonolitic chambers has varied significantly during the evolution of the CTPVC (Andújar 2007). Thus, Teide–Pico Viejo phonolites were stored at depths of about 1–2 km below sea level (b.s.l) (Ablay

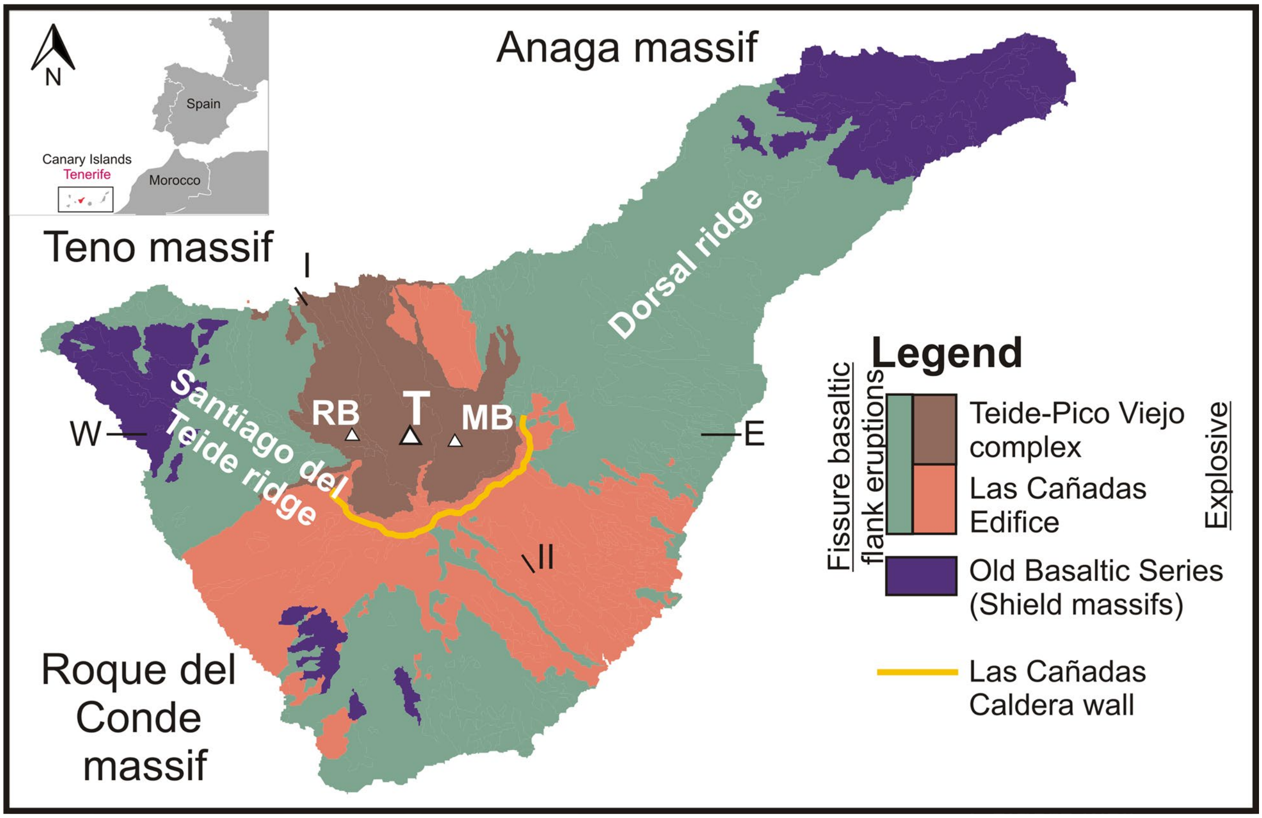

Fig. 1 Simplified geological map of Tenerife Island. *T* Teide; *MB* Montaña Blanca; *RB* Roques Blancos; I–II: section shown in Fig. 5; E–W: section shown in Fig. 2. (Modified from Piña-Varas et al. 2014)

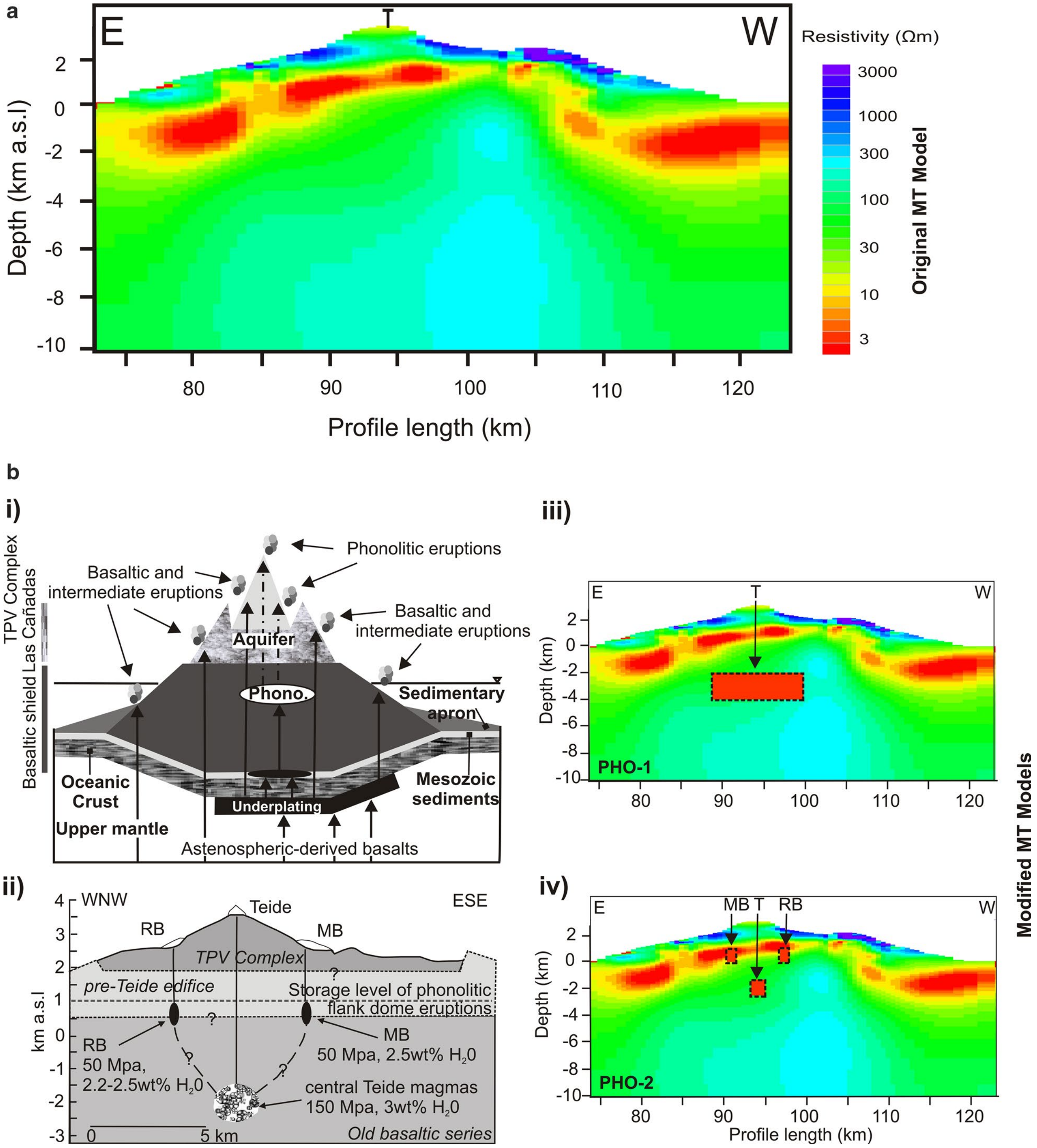

Fig. 2 Upper panel: vertical cross section of the 3-D resistivity model (*original model*) used as a reference (Piña-Varas et al. 2015). Lower panel: Schematic models of Tenerife magmatic system and *modified resistivity models* used for the phonolitic magma chambers study. **a** Tenerife magmatic system proposed by Martí (2008) (modified from Martí 2008); **b** volcanic system of Teide volcano composed of three phonolitic chambers (modified from Andújar et al. 2013); **c** resistivity model PHO-1, equivalent to the volcanic system proposed by De Barros et al. (2012); **d** resistivity model PHO-2, equivalent to the volcanic system proposed by Andújar et al. (2013)

and Martí 2000; Andújar 2007; Andújar et al. 2010), while the storage depth for Montaña Blanca and Roques Blancos would be shallower, around 1 km above sea level (a.s.l) (Fig. 2b-ii; Andújar and Scaillet 2012; Andújar et al. 2013).

Nevertheless, based on geophysical information the locations of both magma storage sites, phonolitic chambers and mafic reservoir are not well constrained. Magnetic studies (e.g. Araña et al. 2000; Blanco-Montenegro 2011) revealed the presence of anomalies at depths exceeding 5 km b.s.l. Gravimetric surveys indicated the presence of anomalous bodies with densities which may be interpreted as magmatic complexes located at different depths (Ablay and Kearey, 2000; Gottsmann et al. 2008; Camacho et al. 2011). De Barros et al. (2012) detected using seismic tomography data two main structures associated with potential magma chambers: one at 2–4 km b.s.l, interpreted as the phonolitic chambers associated with the CTPVC; and a second structure at 6–10 km b.s.l interpreted as the mafic reservoir associated with basaltic eruptions.

Magma chambers detectability using magnetotellurics

The MT method uses naturally occurring electromagnetic field variations as a source for imaging the electrical resistivity structure of the earth (Vozoff 1991), resolving conductivity gradients rather than sharp boundaries or thin layers because electromagnetic energy propagates diffusely. Thus, MT data involve simultaneous measurements of temporal variations in the electric and magnetic fields at the earth's surface (Chave and Jones 2012).

The measured fields are transformed into the frequency domain, to obtain the transfer function which relates the orthogonal electric (**E**) and magnetic (**H**) fields:

$$[\mathbf{E}] = [\mathbf{Z}][\mathbf{H}]$$

where **Z** is the impedance, a frequency-dependent 2×2 complex tensor, which contains information about the electrical conductivity of the subsurface, as well as about the dimensionality and direction of the geoelectrical structures.

Previous works

Several MT and AMT studies have been carried out on Tenerife to study the Las Cañadas Caldera structure and aquifer (Pous et al. 2002; Coppo et al. 2008, 2009, 2010). In the last few years, two works using 3-D approach have been carried out on Tenerife Island. On the one hand, Piña-Varas et al. (2014) focused on understanding the effect of topography and conductive ocean on the MT responses. The model in this work was interpreted in a high-temperature geothermal system context, where the most striking feature is a low-resistivity unit interpreted as the hydrothermal alteration products (clay cap) typically generated in the conventional geothermal systems. On the other hand, Piña-Varas et al. (2015) studied the origin of the Las Cañadas Caldera by analysing and further interoperating the MT model. Here, we consider the model presented in Piña-Varas et al. (2015) (Additional file 1: Fig. S1 in SM) in order to better understand the information that the resistivity model can provide us regarding the location of the potential magma chambers.

The quality of the MT dataset used in these studies is good for high frequencies, but becomes lower at long periods. Therefore, the resistivity models were performed by using a frequency range from 1000 to 0.1 Hz during the inversion process.

It is important to keep in mind that Tenerife is characterised by a very steep topography, which together with the surrounding ocean, has an impact on the observed MT responses. This issue was addressed by Piña-Varas et al. (2014), concluding that the MT responses are strongly distorted by the effect of topography and sea at frequencies lower than 0.1 Hz.

Note that the quality of the data becomes low at the same frequency than the effect of the topography and ocean is distorting the MT responses (0.1 Hz), which is a coincidence. The 3-D inversion models performed included both ocean and topography/bathymetry, so lower frequencies could be modelled and inverted if the data quality was good enough. Therefore, the limitation in the frequency range used to undertake the inversions is only due to the lower quality of the data, which is not related to the effect of topography and sea. Consequently, the test performed in this study and presented herein is also limited to the lower frequency used to perform the 3-D resistivity models.

Magma chambers detectability

Most of the geological, petrological and geophysical studies agree to place the mafic reservoir at depths between 5 and 14 km b.s.l, while the phonolitic chambers are located between 1 km a.s.l and 4 km b.s.l. To determine the resolution of the MT data against these intrusive bodies, several non-linear-sensitivity tests (e.g. Ledo and Jones 2005) were performed. For this purpose, high-conductivity structures (constant resistivity of 4 Ωm; e.g. Newman et al. 1985) associated with the potential magma chambers were introduced into the original 3-D resistivity model (e.g. Fig. 2c, d). The presence of these high-conductivity bodies has an impact on the data fit.

By comparing the MT responses of the original 3-D model (Fig. 2a) and modified models (Fig. 2b-iii, iv and Additional file 2: Fig. S2), we can determine the effect of the high-conductivity magma chambers on the data fit and therefore their compatibility with the available MT data. The tests have been performed taking into account the error floor imposed during the inversion (5% for the impedance tensor, meaning 2.68 degrees for the phases and 10% for the apparent resistivities). Therefore, differences larger than the error floor imposed are related to those structures potentially detectable by the current MT dataset (Fig. 3).

Shallow phonolitic magma chambers: explosive volcanisms

The studies conducted by De Barros et al. (2012) and Andújar et al. (2013) suggest the presence of several phonolitic chambers located in the centre of the island.

According to the scheme proposed by Andújar et al. (2013), the current volcanic system under the Teide is comprised of three phonolitic chambers associated with Roques Blancos, Montaña Blanca and the Teide (Fig. 2b). The Montaña Blanca and Roques Blancos' magma chambers are similar in size and depth and are located between 1 and 2 km a.s.l. In addition, the Teide's magma chamber has larger dimensions and it is located at greater depths, between 1 and 2 km b.s.l (Fig. 2b).

On the other hand, the seismic tomography study carried out by De Barros et al. (2012) highlights the presence of one structure interpreted as a possible phonolitic chamber (Fig. 2a). The structure is 10 km wide and is located at 2–4 km b.s.l (Fig. 2c).

In order to analyse each case separately, we modified the resistivity model of Piña-Varas et al. (2015) by adding new structures taking into account the magma chambers proposed on these studies. Consequently, we obtain two new models: (1) PHO-1, similar to that proposed by De Barros et al. (2012), consisting of a single magma chamber under the Teide (Fig. 2c); and (2) PHO-2, similar to the scheme proposed by Andújar et al. (2013), with three small chambers associated with the Teide, Roques Blancos and Montaña Blanca (Fig. 2d).

Figure 3 summarises the main tests performed. Figure 3b shows the pseudosection of the differences between the responses of the 3-D original model and PHO-1 model (see Fig. 3a for location of the profile). The difference between these models is greater than the error floor imposed in the MT data for the inversion, indicating that most of the MT sites are sensitive to the structure introduced. Thus, the available MT data do not support the presence of these chambers.

In the case of the model PHO-2, the result indicates that the existing MT data do not have sufficient resolution to detect the chambers introduced (not shown here). The lack of resolution may be due to several factors. Firstly, the magma chambers corresponding to Montaña Blanca and Roques Blancos are located in a very conductive area (resistivity < 10 Ωm); thus, the resistivity contrast between the original and PHO-2 models is too small to be perceptible. Secondly, the location of the phonolitic chambers in relation to the distribution of the MT sites recorded in the area, since there is only one MT site located in the area of influence of these structures (site TEN044b, Fig. 3a). A more detailed analysis of the MT response of the site TEN044b for both models (PHO-1 and PHO-2) is shown in Additional file 3: Figure S3-B. Model PHO-1, the only one sensitive to the phonolitic chambers included, does not fit the observed data better than the original model response.

However, the lack of resolution in the vicinity of the phonolitic chambers could be consequence of the low coverage of MT sites in this area. In order to determine whether a denser MT dataset could provide a higher resolution, 13 synthetic MT sites were added to the model PHO-2 (Additional file 3: Fig. S3-A). The result shows that most of the synthetic sites are sensitive to the potential magma chambers included in the model PHO-2 (Additional file 3: Fig. S3-C).

From these tests we conclude that similar structures to those considered in model PHO-1 lead to a considerable increase in the data misfit (Fig. 3b). Consequently, MT data are not compatible with such magma chambers. Regarding the model PHO-2, with three small shallow chambers, the results reveal that chambers larger than $3 \times 3 \times 1$ km^3 are incompatible with the current MT dataset. The absence of MT sites near those chambers makes it unfeasible to provide more information about their characteristics and possible location. However, the test carried out by adding synthetic MT sites shows that this question could be addressed by adding more MT sites in Las Cañadas caldera area.

Deep mafic reservoir: fissure basaltic volcanism

Most studies agree on locating the reservoir associated with mafic basaltic in the northern part of the island, at depths between 5 and 14 km b.s.l (Araña et al. 2000; Almendros et al. 2007; Blanco-Montenegro 2011). The seismic tomography study mentioned above (De Barros et al. 2012) also detected a second structure probably associated with a mafic reservoir. This structure is about 25 km wide, and it is located at 6–10 km b.s.l depth.

Following the same methodology used for the phonolitic chambers, we obtain a different model by adding the magma chamber proposed on this last study: Model MAF-1 (Additional file 2: Fig. S2). The result indicates that most of the MT sites are highly sensitive to this structure (Fig. 3c).

In view of these results and since some studies point towards deeper mafic reservoir (e.g. Almendros et al. 2007; Martí 2008; Fig. 1a), deeper magma chambers were considered. The model that marks the limit of resolution

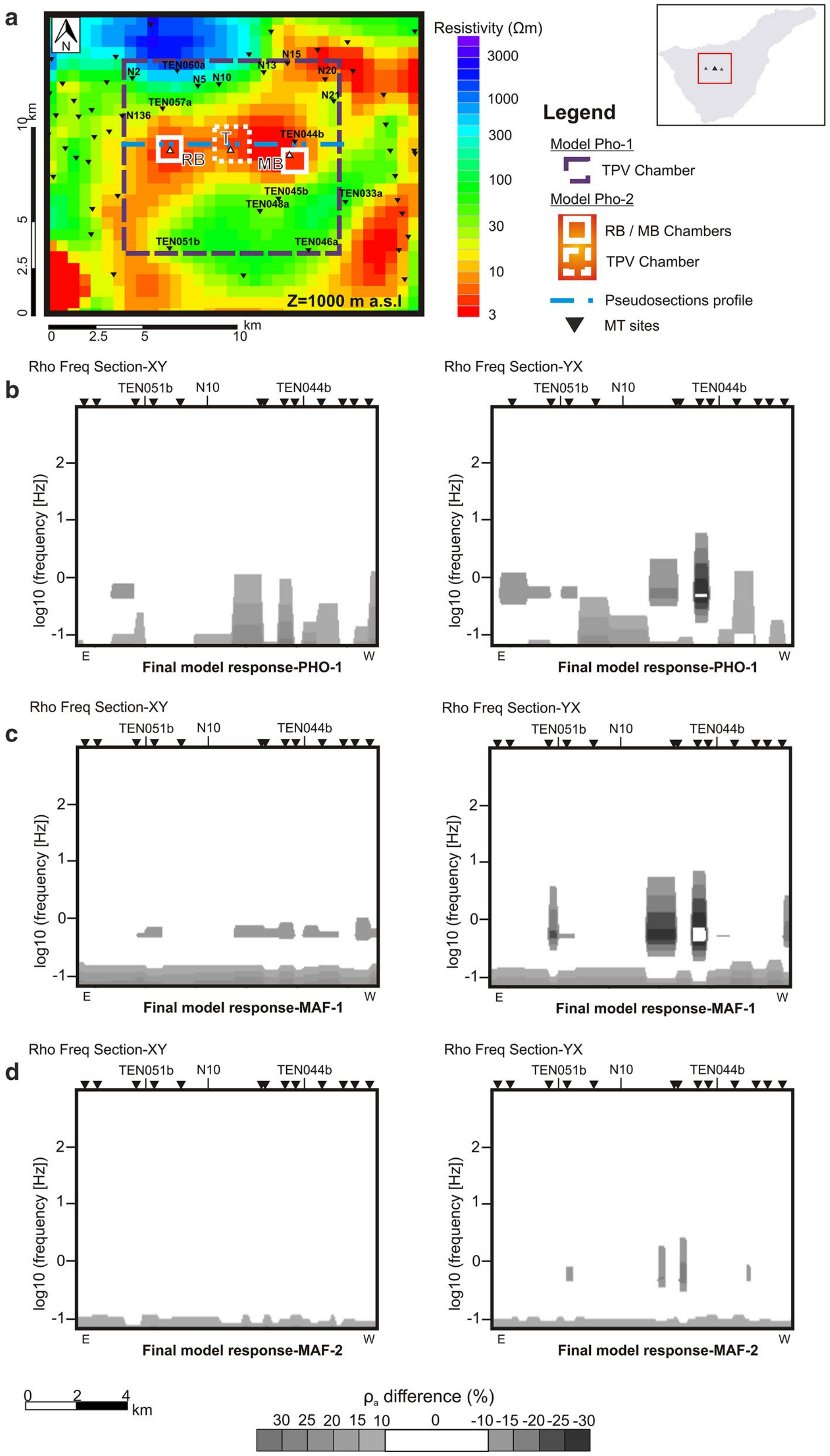

Fig. 3 Pseudosection plots of the apparent resistivity difference between original and modified models. **a** Plan view of the 3-D resistivity model at 1 km a.s.l. Black triangles: MT sites recorded; white squares: potential magma chambers; blue line: EW profile used to plot the results. **b** Difference between original and PHO-1 models. **c** Difference between original and MAF-1 models. **d** Difference between original and MAF-2 models

in depth for this structure has been called MAF-2 (Additional file 2: Fig. S2 in SM and 3D).

The sensitivity tests carried out showed a significant increase in the data misfit for those models with a mafic reservoir at shallower depths than 8 km b.s.l. Therefore, such a large mafic reservoir would be located at greater depths; otherwise, it should be substantially smaller than considered here.

Discussion and conclusions

Potential magma chambers

Numerous geophysical and geological studies have been carried out on Tenerife Island to investigate its internal structure (e.g. Martí et al. 1994; Ablay and Martí 2000; Araña et al. 2000), revealing the presence of two types of magma chambers: (1) shallow phonolitic chambers associated with the CTPVC, and (2) a deep mafic reservoir related with the fissure volcanism (Fig. 2b-i, ii).

The differences between phonolitic eruptions suggest that Teide–Pico Viejo is currently in the initial phase of magmatic evolution, introducing less evolved magmas. This degree of evolution involves less explosive magmas stored in small chambers (Martí et al. 2008).

Regarding the basaltic magmas in Tenerife, some geological and geophysical data (Canales 1997; Watts et al. 1997; Ablay et al. 1998; Neumann et al. 1999; Ablay and Kearey 2000; Dañobeitia and Canales 2000) point to the periodical accumulation of the basaltic magmas into large bodies located in three major discontinuities (Fig. 2a): the base of the elastic lithosphere (30 km depth), in the MOHO discontinuity (14–16 km depth) and the contact ocean basement base of the Teide volcano (7–8 km depth; Martí and Gudmundsson 2000).

In this respect, the 3-D MT model provides relevant information to constrain the size and location of the potential magma reservoirs, even though no chambers have been detectable with the current MT dataset. Nevertheless, the results obtained help us to constrain the debate regarding the characteristics of the magma chambers.

Shallow phonolitic magma chambers

The location of these reservoirs is well constrained by geological and petrological information, between 1 km a.s.l and 2 km b.s.l. Thus, the sensitivity tests were focused on characterise the dimensions of these chambers. The different tests performed reveal that, for these shallow depths, magma chambers larger than $3 \times 3 \times 1$ km^3 are incompatible with the current MT dataset.

These small and shallow chambers are located in the centre of the island, beneath Teide, Montaña Blanca or Roques Blancos, where a limited number of MT sites have been recorded at date. This lack of data leads to a lack of resolution, making it difficult to validate the compatibility of these chambers with the original MT resistivity model. Thus, the acquisition of new MT data in Las Cañadas caldera area is needed for the proper detection of small magma chambers beneath Teide, Montaña Blanca or Roques Blancos. Understanding the location and size of these shallow magma chambers is very important in order to assess the volcanic hazards factors in Tenerife Island.

Deep mafic reservoir

MT data provide information about the depth of this reservoir. The geological and geophysical data discussed above suggest that the magma is stored in a large-scale deep mafic reservoir. According to our study, a reservoir with such characteristics should be located at depths greater than 8 km b.s.l.

Joint interpretation and hypothetical internal structure model

Interpreting all the information supplied by the 3-D MT studies jointly with other evidence (e.g. geological, geophysical, hydrogeological) leads us to a more widespread understanding of the internal structure of the island.

From some of the geophysical studies conducted on Tenerife (Fig. 4), it is deduced that the centre of the island is characterised by medium–high electrical resistivity (Piña-Varas et al. 2014), high P wave velocities (García-Yeguas 2012) and high density (Gottsmann et al. 2008). This indicates that the centre of the island is formed by dense and low permeability materials that might be associated with the Old Basaltic Series. Similarly, the correlating low P wave velocities, low density and low resistivity may be associated with the presence of hydrothermal alteration products (Piña-Varas et al. 2014).

In addition, the MT data support the vertical collapse hypothesis proposed by Martí (2004) and Martí et al. (1997) to explain the origin of Las Cañadas caldera (Piña-Varas et al. 2015). This study is based on the good agreement between the geological cross section proposed by Martí (2004) and the corresponding vertical cross section extracted from the 3-D resistivity model along a NW–SE profile (Fig. 1). The same profile was used by Marrero (2010) and Marrero-Diaz et al. (2015) to summarise the findings of the hydrogeochemical studies conducted on the island, which show a hydrothermal alteration core below Teide and Montaña Blanca.

According to the hypothesis testing carried out in this work, we propose a model for the internal structure of Tenerife (Fig. 5), resulting from merging and comparing all the information derived from geological, geophysical and hydrogeochemical studies along the same NW–SE profile. As a novelty, this could be considered one of the unusual attempts conducted in Tenerife to integrate information

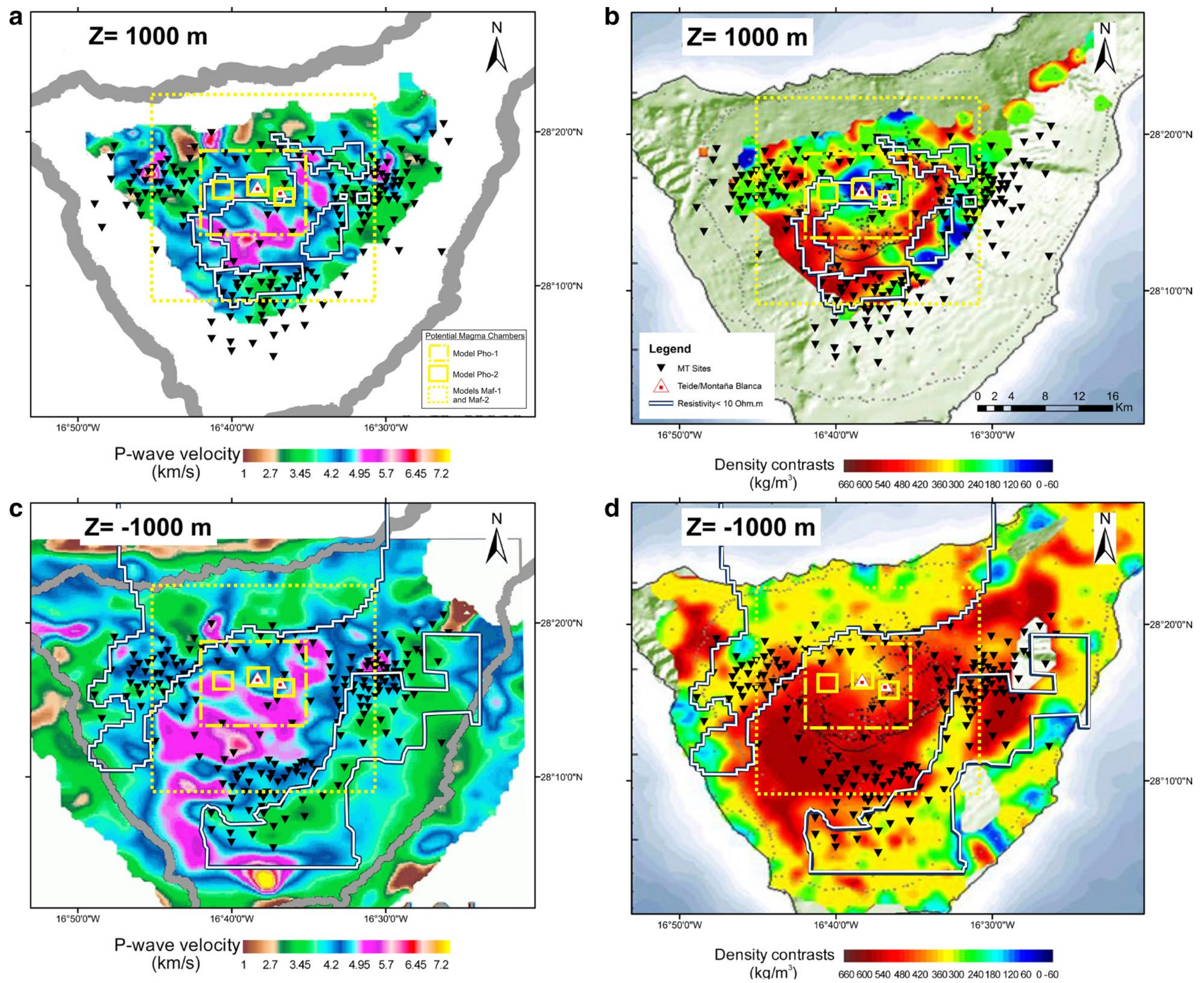

Fig. 4 Different geophysical models. Comparison between the 3-D P wave velocity model derived by García-Yeguas et al. (2012) and the original 3-D resistivity model at: **a** 1 km a.s.l; **c** 1 km b.s.l. Comparison between the density contrast model derived by Gottsmann et al. (2008) and the original 3-D resistivity model at: **b** 1 km a.s.l; **d**1 km b.s.l. White line corresponds to resistivity values < 10 Ωm, which has been interpreted as the hydrothermal alteration clay cap. Grey triangles correspond to the MT sites. White triangles correspond to Teide (left) and Montaña Blanca (right). Yellow lines correspond to the potential magma chambers considered on the different test performed

concerning the structure, the magma chambers location, the hydrogeology and the hydrothermal alteration products.

According to this scheme, Las Cañadas aquifer is surrounded by the hydrothermal alteration products (clay cap), which is part of its basement, together with the landslides deposits in the northern area. This interpretation agrees with the results exposed by Marrero-Diaz et al. (2015) and Marrero (2010). Even so, the 3-D MT model provides a more accurate characterisation of the hydrothermal alteration products. Our main findings regarding the characteristics of the magma chambers have been also included, as well as a characterisation of the hypothetical geothermal system in relation to the resistivity values.

To conclude, it is important to take into account that the clay cap characterised by the MT data could not represent the extension of the current geothermal system. This low-resistivity structure probably corresponds to the superposition of all the clay caps developed for the different geothermal systems associated to the multiple volcanic cycles (Araña 1971; Ancochea et al. 1990, 1998, 1999; Martí et al. 1994) involved in the construction of the Las Cañadas Edifice. Therefore, this low-resistivity body represents both the current clay cap and the fossil clay caps developed on the island, making it impossible to determine the extension of the present clay cap only from its geoelectrical signature.

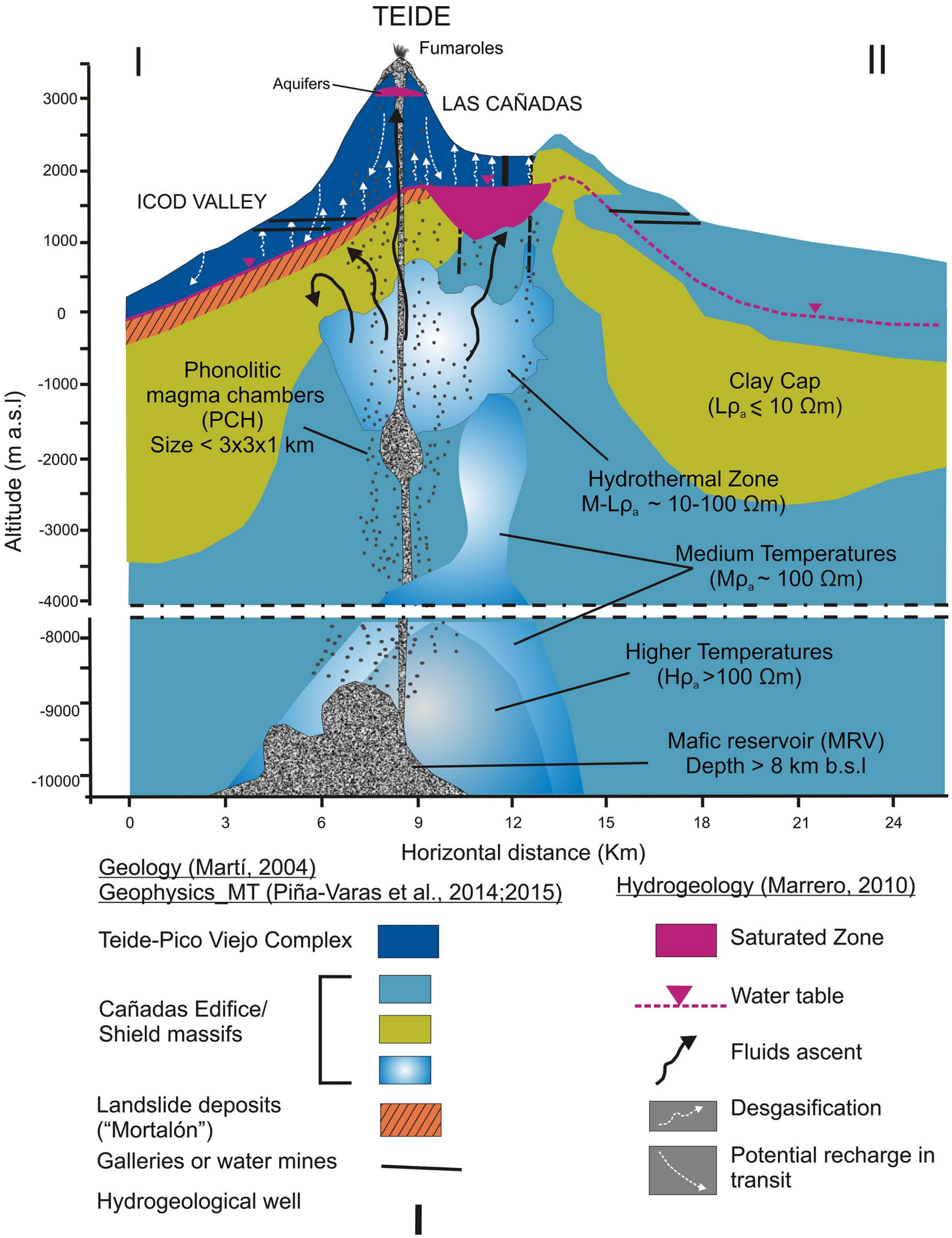

Fig. 5 Hypothetical model of Tenerife volcanic system. The background model corresponds to the geological scheme proposed by Martí (2004) to explain the origin of Las Cañadas Caldera by vertical collapse (see Fig. 1 for location of the profile I–II). The resistivity values (in Ωm) are overlapping the geological scheme providing valuable information about the hydrothermal alteration products (clay cap). The location of the phonolitic chambers beneath the Teide is based on the petrological studies (Andújar et al. 2013), while its size is constrained by the results obtained in this work. The depth of the mafic reservoir is determined from the results obtained in this study, for a large-scale magma chamber as that proposed by De Barros et al. (2012)

Additional files

Additional file 1: Figure S1. Horizontal slice through the 3-D resistivity model at different depths above sea level (From Piña-Varas et al., 2015). Black solid line corresponds to the location of the Las Cañadas caldera wall, and white triangles correspond to Teide (left) and Montaña Blanca (right).

Additional file 2: Figure S2. 3-D resistivity models used to perform the sensitivity tests. All models have been built by adding conductive magma chambers to the resistivity model presented by Piña-Varas et al. (2015).

Additional file 3: Figure S3. A) Plan view at 1 km a.s.l of the center of the island. T: Teide; white squares: phonolitic chambers used in model PHO-2; black triangles: Recorded MT sites; white triangles: synthetic MT sites. B) Comparison of apparent resistivity of observed data, original model and calculated data for models PHO-1 and PHO-2 for site TEN044b. C) Pseudosection plots of apparent resistivity difference between original and PHO-2 model after adding synthetic site in the center of the island.

Authors' contributions

PPV and JL helped in modelling, interpretation and writing. PQ, AM and NP contributed to interpretation.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Requests for more information about the results and the data should be addressed to P. Piña-Varas (e-mail: ppinavaras@gmail.com).

Ethics approval and consent to participate

Not applicable.

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