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Magnetotelluric study of the Las Cañadas caldera (Tenerife, Canary Islands): structural and hydrogeological implications

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Abstract

The Las Cañadas caldera in Tenerife (Canary Islands) is a well-exposed caldera depression in which the active Teide–Pico Viejo complex stands. In addition to its volcanological interest, the Las Cañadas caldera also holds the main groundwater reservoir of Tenerife. An audiomagnetotelluric and magnetotelluric survey was carried out in order to image the interior of the caldera depression. The field campaign consisted of 33 audiomagnetotelluric sites in the period range from 0.001 to 0.3 s and 11 magnetotelluric sites from 0.004 to 200 s. A detailed mapping of the electrical conductivity of the subsurface was obtained. For the long periods a three-dimensional modelling of the island – including the bathymetry – was carried out to study the effect of the ocean. This effect starts to be important at periods longer than 10 s. Accordingly, the sites were arranged into six profiles and a two-dimensional joint inversion of all data until 10 s was performed for each profile. The geometry of the high conductive zones found indicates that the caldera includes two closed depressions in the western (Ucanca) and central (Guajara) sectors, whereas in the eastern sector (Diego Hernández) the top of the main conductive zone shows a gentle inclination towards the northeast (La Orotava valley). A narrow and marked high conductive anomaly, probably caused by the presence of highly fractured rocks and fossil hydrothermal alteration along a fracture zone, runs parallel and close to the present caldera wall, suggesting the position of the structural border of the caldera. The results indicate that there are two main aquifer zones separated by the Roques de García spur, coinciding with the western and central depressions. The eastern depression could be hydrologically disconnected from the central depression by another structural limit not visible at the surface. The saturation zones would have a thickness of more than 700 m starting at a few hundred metres below the present caldera floor. The data are consistent with a multiple vertical collapse origin for the caldera depression rather than a sector collapse origin.

Keywords: magnetotelluric surveys; hydrogeology; volcanology; Tenerife; Las Cañadas caldera

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1. Introduction

The Las Cañadas caldera, in Tenerife (Canary Islands, Fig. 1), like many other caldera structures around the World, is a complex volcanic depression in which post-caldera activity has caused burial of the caldera floor by thick piles of volcanic deposits (the Teide–Pico Viejo complex), which hide most of its internal structure. The presence of flank sector collapse scars on Tenerife, plus the complex nature of the Las Cañadas, has generated much debate over its origin. Most of the geological evidence (isopach maps, proximal pyroclastic deposit facies, timing of subsidence and major pyroclastic units, occurrence of shallow plutonic blocks and dike orientations: see [1–5]) points to the periodic existence of shallow phonolitic magma chambers, of up to 50 km^3, beneath the central region of Tenerife for much of the last 1.6 Ma. At the same time, it is clear that large volumes of rocks (> tens of km^3) from the north flank of Tenerife have been moved in submarine debris flows over the sea floor for distances exceeding 100 km [6,7]. Based on this evidence two main hypotheses have been proposed to explain the origin of the Las Cañadas caldera. Geological and volcanological evidence has been used to support this origin by multiple vertical collapses [1,3,5]. However, the absence of the northern caldera walls and the adjacent sector collapse scars suggest that the caldera was originated by giant, northward-directed landslides [8–12]. Recently, it has also been proposed that there may be a link between true caldera collapse episodes and flank collapses [4].

The internal structure of the Las Cañadas caldera is still largely unknown. Gravity [13–16] and magnetism studies [17] carried out in the Las Cañadas caldera both suggest several depressions, filled in with relatively thick piles of light, non-magnetic volcanic material in addition to the post-caldera lavas from Teide. This indicates the presence of phonolitic pre-caldera rocks inside the depression. These studies also provide evidence of the role of Roques de García (Fig. 2), a large spur of old pre-caldera rocks abutting the south wall, which morphologically divides the caldera into two unequal sectors, as a true structural limit that separates a western depression from a central one.

In addition to its volcanological interest, the Las Cañadas caldera is also important as the main groundwater reservoir of Tenerife. Its geometry seems to be closely related to the internal structure of the caldera. In fact, some of the previous geophysical results suggest the presence of thick bodies of fresh water in the interior of the Las Cañadas caldera [18]. Moreover, the presence of thermal anomalies and fumaroles at Teide suggests an active geothermal system in the central part of the island. The presence of hot, hydrothermal fluids has also been proposed to explain some geophysical anomalies found in the Las Cañadas caldera [19,20]. However, little is known of the nature and structure of the aquifer rocks and present and past geothermal systems.

A combined audiomagnetotelluric (AMT) and magnetotelluric (MT) survey was carried out in the Las Cañadas caldera in September 2000 with the aim of obtaining new constraints on both the internal structure of the Las Cañadas caldera and the distribution of potential water-wearing zones. This paper describes the results of these AMT and MT studies. Magnetotelluric surveys in islands are not frequent probably because of the screening effect of the sea. Here, we performed a study of the effect of the ocean by three-dimensional (3D) modelling of the bathymetry in order to assess its influence over the data. In particular, we found the shortest period range without influence of the sea and, therefore, containing only information on the internal structure of the caldera.

2. Geological setting

Tenerife is the largest of the Canary Islands and, after Hawaii, the largest intraplate volcanic island on the planet. The basal subaerial portion of the island, the Old Basaltic Series (OBS), is a composite mafic alkaline formation constructed by fissure eruptions of ankaramites, basanites, and alkali basalts between 12 and 3.3 Ma [10,21]. The OBS is now exposed at the three corners of the island: the Anaga peninsula (NE), the

Teno massif (NW) and the Roque del Conde complex (S) (Fig. 1). Toward the end of this period, volcanic activity concentrated in the central part of Tenerife, where shallow, phonolitic magma chambers developed and the Las Cañadas central volcanic complex was constructed [1,3, 10]. The Las Cañadas caldera developed at the summit of the Las Cañadas edifice (Fig. 1). It has been partially filled in by the products of the active Teide–Pico Viejo volcanic complex, which has a summit elevation of 3718 m. Basaltic activity along two main rift zones running NE (the Dorsal Ridge) and NW (the Santiago del Teide Ridge) from the caldera complex (Fig. 1) has been nearly continuous since the construction of the Las Cañadas edifice till present, producing mafic lavas and scoria cones. Large scale, lateral collapses from the sides of the island edifice, involving rapid mass movements of hundreds of cubic kilometres of rock, are responsible for the formation of the Icod, La Orotava and Guimar valleys during the construction of the Las Cañadas edifice [6,8].

The Las Cañadas caldera (Fig. 2) is one of the most important geological structures in Tenerife, and its internal structure and origin are still a matter of debate. It is an elliptical depression measuring 16×9 km, with a maximum depth of 600 m below the top of the caldera wall at Guajara (2717 m.a.s.l.). Its morphological boundary comprises several scalloped walls (Fig. 2). A large spur (Roques de García) divides the caldera into two parts, the western depression being 150 m deeper than the eastern one. The caldera wall is visible for 27 km and is open towards the north and bounded to the west, south and east by high walls (Fig. 2). The northern wall is absent except for an isolated segment, La Fortaleza, which forms part of the Tigaiga massif [22]. Tigaiga separates the Icod and Oratava valleys, which are deep scars deriving from major flank collapses [4,7–9,23]. Two drillholes penetrated a sequence of more than 500 m of mafic and intermediate lavas from the post-caldera Teide–Pico Viejo complex in the central-eastern part of the caldera, but did not reach the underlying pre-caldera rocks [24]. Therefore, the minimum depth of the original caldera is ∼1100 m.

3. MT data

The data consist of 33 AMT sites in the period range from 0.001 to 0.3 s and 11 MT sites from 0.004 to 200 s (Figs. 3 and 4). Because of the circular shape of the Las Cañadas caldera some similarity with the behaviour of the resistivity structure was expected. Accordingly, the sites were arranged in six profiles distributed approximately radially to the caldera: Fortaleza, Risco Verde, Medio, Teide, Parador and Ucanca (upper panel of Fig. 8). The four horizontal components were measured in the NS and EW direction (x and y axes, respectively) as well as the vertical magnetic component for the 11 MT sites. The time series were processed by using a robust processing algorithm [25]. Due to the practical absence of noise the data were of a very high quality and a very good estimation of the transfer functions was obtained.

At short periods (less than 1 s) the data have a uniform behaviour close to one-dimensional (1D) in the whole area (Figs. 3 and 4). The shape of the apparent resistivity and phase curves (e.g. minimum at about 1 s in the apparent resistivities) revealed a conductive layer at shallow depth, underlying a more resistive cover. In contrast, at longer periods the MT data show a splitting of the curves, indicating a more complex structure. Furthermore, at the longest periods a particular

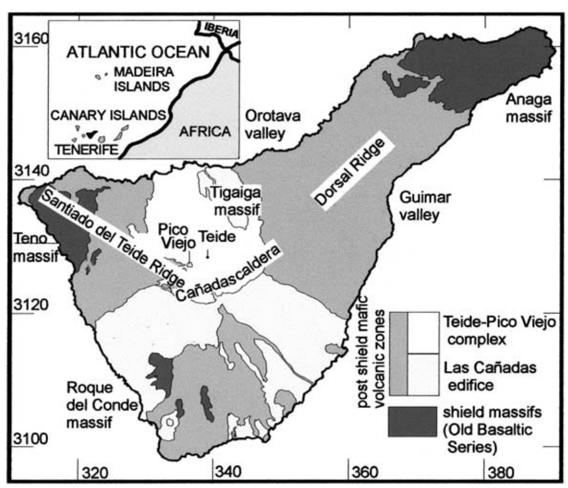

Fig. 1. Geological map of Tenerife island.

behaviour appeared at all the sites: a steep ascending branch of the phases reaching, in some cases, 90°. At sites located to the west, in Ucanca, this behaviour occurs for one mode (Fig. 3) while in the sites located in the centre and eastern caldera it occurs for both modes (*xy* and *yx*). We rule out the possibility that this effect was produced by the topography. The interior of Las Cañadas caldera is relatively flat and almost all the sites were located at a distance from Teide. Moreover, simple two-dimensional (2D) modelling of the topography indicates that its effect consists mainly in a decrease of the TM phases at short periods, which is not consistent with our data. As will be discussed below, this particular behaviour of the longest periods can be modelled by a combination of the sea and some sort of current channelling around the island.

3.1. Ocean effect

MT surveys in islands are strongly influenced by the ocean effect. Therefore, before modelling the structure of the caldera, a study of the ocean effect was performed in order to determine the period range in which the ocean did not influence the data. A 3D model of the island including the bathymetry was considered. The island was simulated (Fig. 5) by a square of 40 km side length with a resistivity of 300 Ωm containing a conductive layer of 10 Ωm surrounded by a sea of 0.3 Ωm. This layer was inferred from the 2D modelling of the short periods (see below). The 3D modelling was performed using the staggered grid finite difference code of Mackie et al. [26]. The mesh used was of $80 \times 80 \times 50$ with a variable size of the cells, the minimum being 400 m in the

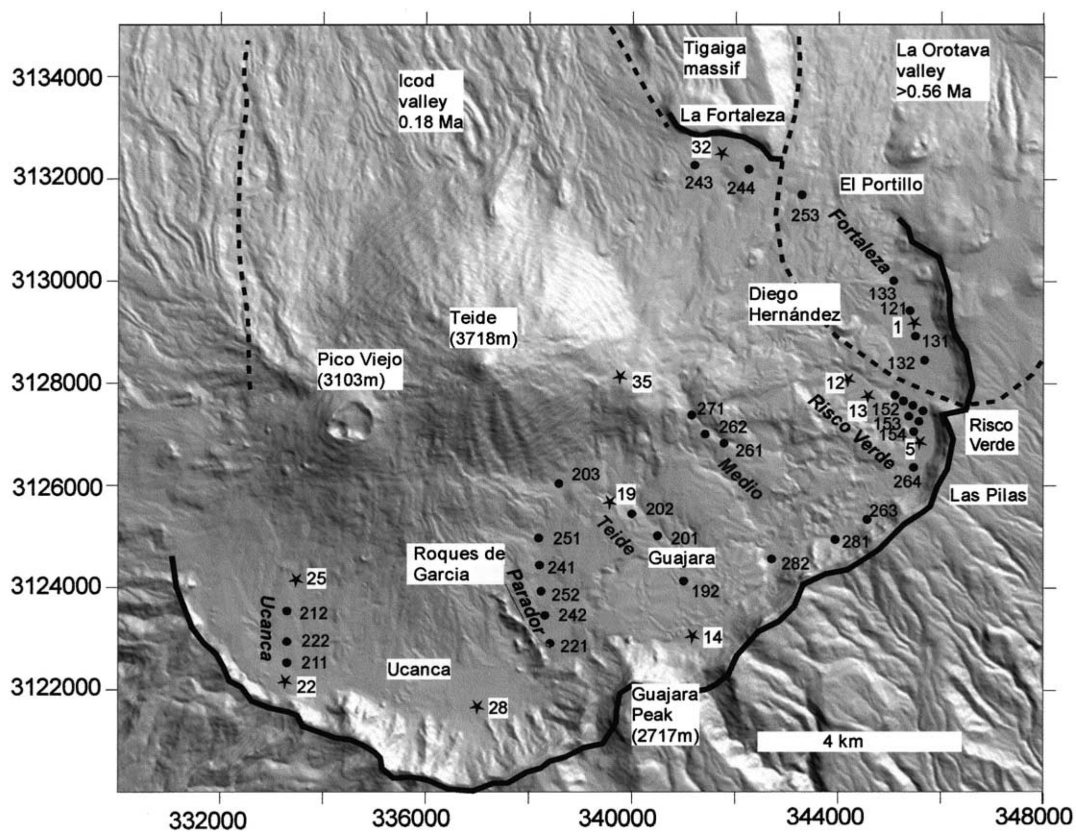

Fig. 2. Shaded relief map of the Las Cañadas caldera with indication of AMT (circles) and MT (stars) sites; profile names are given in italics. The thick line indicates the caldera wall. Dashed lines indicate the visible limits of the La Orotava and Icod valleys.

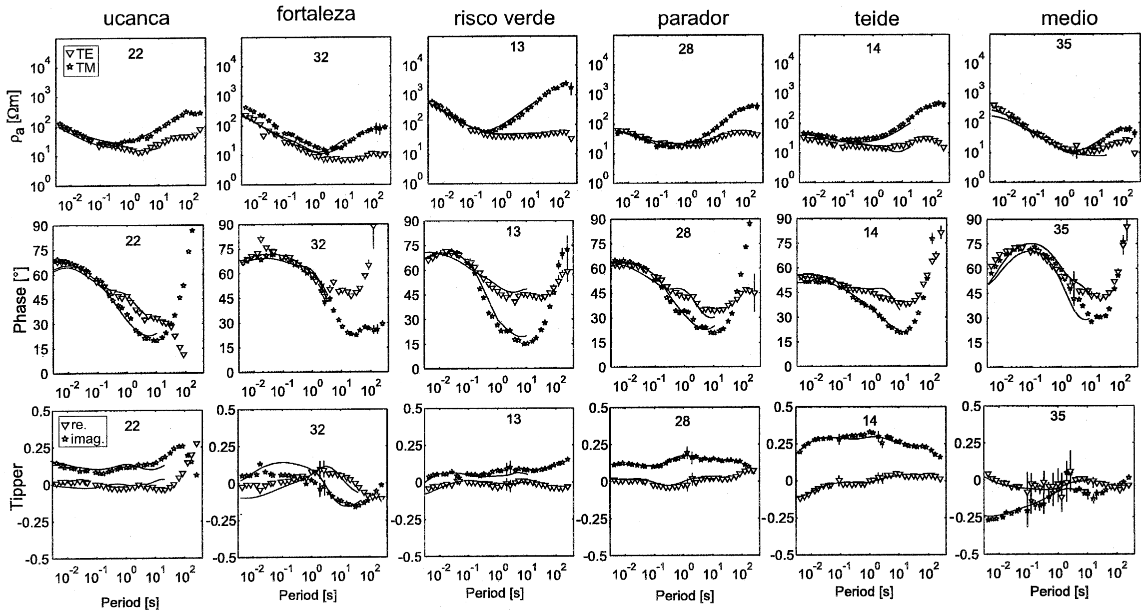

Fig. 3. Apparent resistivity (ρ_a), phase and tipper curves for one MT site of each profile (see Fig. 8 for identification). The data are rotated to 60°, except for the Ucanca site, where it is rotated to 100°. The solid lines are the responses of the REBOCC inversion until 10 s.

horizontal direction and 25 m in the vertical direction. The results are summarised in Fig. 5c, where the responses of a site located at 11 km from the coast is shown together with the 1D model response. Note that all the sites inside the caldera are at more than 12 km from both adjacent coasts. The comparison with the 1D responses reveals that the effect of the ocean starts at about 4–6 s for the phases and 20 s for the apparent resistivities. Of course this period depends on the model chosen. Note, however, that we used the conductive layer found later in the 2D modelling of short periods. Therefore, we assume that our data reflect the structure of the caldera without influence of the sea in the interval of periods from 0.001 s to 4–20 s.

It should be pointed out that the effect of the sea on the apparent resistivities and phases is the

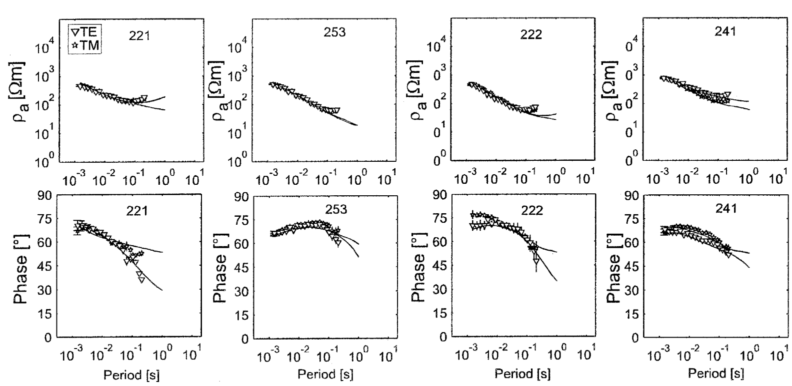

Fig. 4. Apparent resistivity and phase curves for four representative AMT sites. The data are rotated to 60° with the exception of site 221 (in profile Ucanca, 100°). The solid lines show the responses of the REBOCC inversion until 1 s.

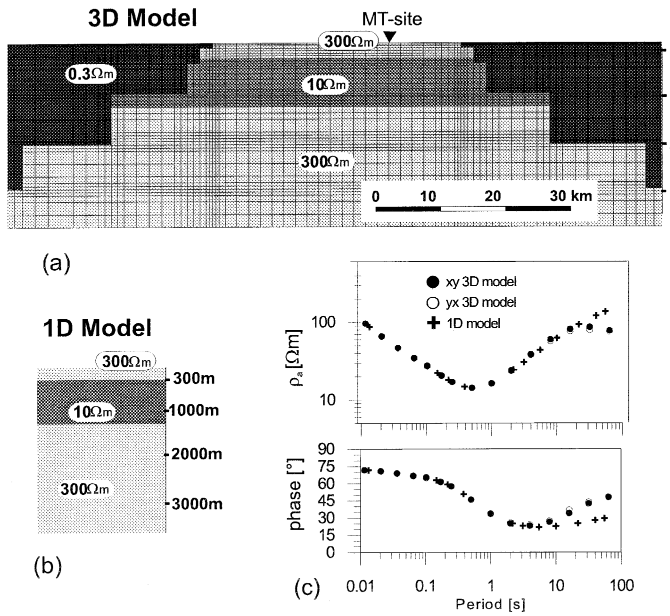

Fig. 5. (a) Simplified 3D model of the island (a square of 40 km×40 km) including the bathymetry (ocean effect) and the shallow conductor found by the 2D inversion (see Fig. 6). (b) 1D model inside the island. (c) Responses of the 3D and 1D models at the site indicated in panel a.

same as for a deep conductive layer (maximum on the apparent resistivities at 20 s and minimum on the phases at 4 s).

3.2. Dimensionality, static shift, 2D inversion

In accordance with the above result the dimensionality analysis was made for periods less than 10 s. The multi-site–multi-period analysis [27] based on the Groom–Bailey decomposition [28] was applied to each profile. The data behaviour for the shortest periods is clearly 1D and only at periods between 0.2 and 10 s was a 2D structure

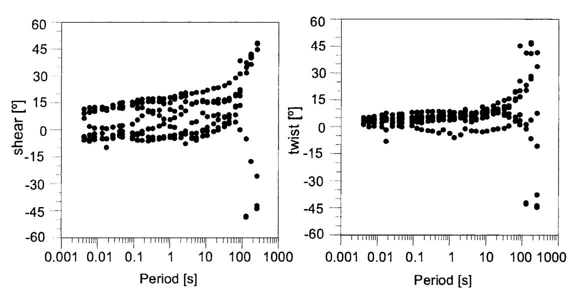

Fig. 6. Twist and shear of the Groom–Bailey decomposition for a strike of 60° at sites located in the central caldera.

with a predominant strike of 60° found for all profiles except for the westernmost one at Ucanca, where the strike was 100°. In Fig. 6 we show the twist and shear for a strike of 60° for the central and eastern caldera MT sites. Note the frequency-independent twist and shear for periods lower than 10 s. At longer periods the frequency dependence reveals the 3D character induced by

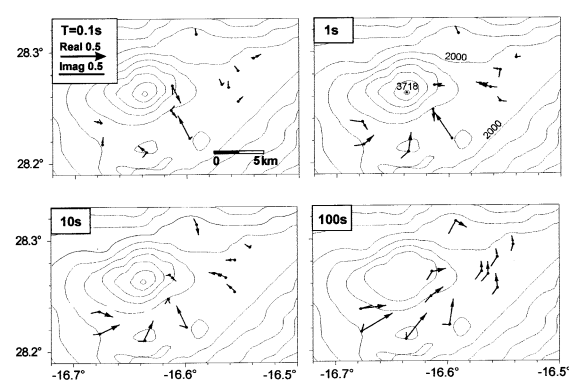

Fig. 7. Induction arrows (Schmucker convention) of the MT sites at periods of 0.1 s, 1 s, 10 s and 100 s. The long period arrows are influenced by the ocean while the induction arrows at short periods point away from the caldera wall.

the sea. The induction arrows (Fig. 7) for periods less than 10 s are small and do not contradict the above result. At 100 s they reflect the shape of the coastline.

The sites were projected into several profiles and the data rotated into the strike directions. A 2D joint inversion of all the data until 10 s (both polarisations of the apparent resistivities and phases and the projected geomagnetic transfer functions) was performed for each profile using the REBOCC code [29].

The scattering in the apparent resistivities due to static shift was not significant. The only exceptions were found in the sites located near the wall of the caldera where – evidenced by the short period data – superficial conductive units outcrop and the apparent resistivities appeared half a decade lower than the rest of the sites. As this occurred at all sites near the caldera wall the lower resistivity level was maintained for those sites. The rest of the sites were shifted to the same level, but only very small corrections were necessary. However, at sites where the data fit caused problems, we used the option of the REBOCC code to correct the static shift. The maximum global RMS was 3. Figs. 3 and 4 show data and responses of a representative selection of sites.

The joint inversion of all the data (including the geomagnetic transfer functions) constrains the models strongly. The bottoms of the conductive zones are resolved by the long period MT sites and in particular by the period in which TM mode presents the minimum in the apparent resistivities (maximum on the TM phases) (Figs. 3 and 4), but given the limited number of sites for which the long periods were acquired (MT) we carried out a resolving test with a 2D forward modelling using the code of Wannamaker et al. [30]. Conductive zones at the bottom of the models were subsequently removed beneath the AMT sites until reaching the minimum depth of these conductive structures required by the data.

4. 2D models

Fig. 8 shows the final resistivity models for each profile. The models show for almost the entire caldera the presence of a high conductive layer (between 5 and 40 Ωm) underlying a high resistive unit (500–1000 Ωm) at the surface. This conductor is interrupted by the Roques de García spur (profile Parador), which divides it into two parts corresponding to the western (Ucanca) and central (Guajara) sectors of the caldera. Note that site 28 is in fact in Ucanca (Fig. 2), at a distance from the profile, and therefore the conductive zone beneath site 28 corresponds to the Ucanca sector.

Within the conductive layer we distinguish two zones with maximum conductivity: (1) a clearly marked high conductive (less than 10 Ωm) zone close to and parallel to the caldera wall in all the profiles, and (2) a second high conductive and thicker zone in the interior of the caldera near Montaña Blanca (beneath sites 35, 271) and in the Fortaleza (sites 32, 244), which disappears to the SW in the Parador profile and appears in the Ucanca profile (beneath site 25).

In the Medio profile the top of this conductive layer is at an altitude of 1900 m a.s.l., which is higher than in the two closest profiles, about 1600 m a.s.l. (Fortaleza profile) and 1800 m.a.s.l. (Teide profile). This fact suggests two separated depressions in the central and eastern sectors of the Las Cañadas caldera (see Section 9). The thickness of the conductive layer in the whole caldera has a mean of 700 m whereas in the Montaña Blanca and Fortaleza sectors it is thicker than 1.5 km (Fig. 8).

Beneath the conductive layers there is a thick resistive unit (more than 200 Ωm), beneath which there is another conductive layer (not shown in Fig. 8) at more than 20 km depth. This deeper conductive layer is required by the minimum of the phases. However, as stated above it is the same effect as produced by the seacoast and, therefore, we cannot be sure of the presence of such a deep conductive layer. Later we will come back to this point with a 3D modelling of the coast and a deep conductive layer.

5. 3D model of the two main shallow conductors

The thicknesses of the conductors are con-

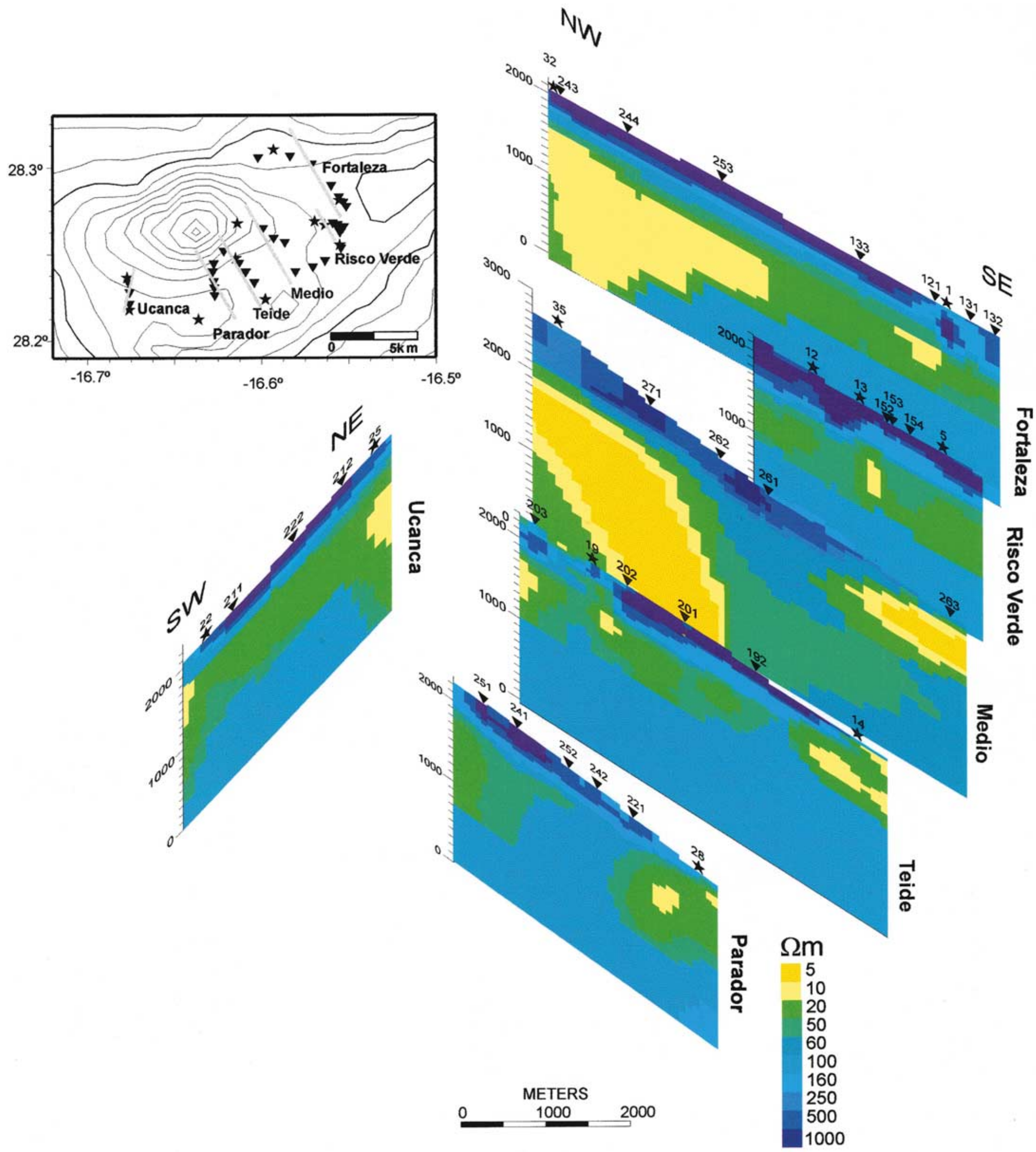

Fig. 8. The 2D inversion (REBOCC) models for the six profiles. Strike direction of the models is 60° except for the Ucanca profile, where the strike is 100°. The data fit of some MT and AMT sites is shown in Figs. 3 and 4.

strained by the long period sites whereas the divergence between both polarisations (the TE apparent resistivity is lower than the TM) reveals lateral thickness variations of these conductors, their position being well defined by the geomagnetic transfer functions. In the 2D inversion their projection perpendicular to the strike is taken. Although the induction vectors are not very scattered from the directions of the profiles, the geometry of the conductive zones was checked by a 3D modelling of the caldera using the Mackie and Booker code [26]. A simplified 3D model was constructed from the geometry of the 2D inversion models. Only few changes in the resistivities had to be considered to fit the induction vectors. Fig. 9 shows a plan view of the conductors, the data

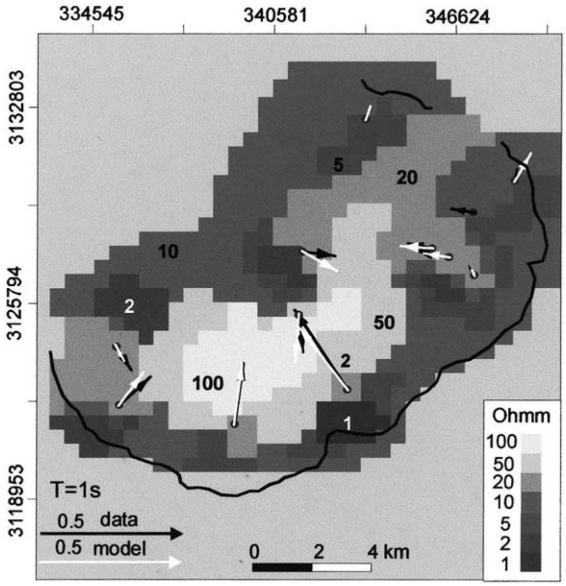

Fig. 9. Plan view of a 3D model of the two main conductors at a depth of 600 m and the fit of the real induction arrows at 1 s.

and the model responses of real induction vectors at 1 s. In this figure the continuity of the two main conductors can be seen more clearly: a narrow one running close and parallel to the caldera wall and another one towards the interior of the caldera depression.

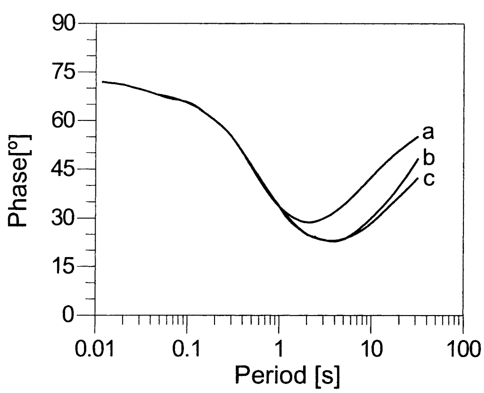

Fig. 10. Phase responses of the 3D model of the island of Fig. 5, but containing a deep conductive layer (1 Ωm and 5 km thickness). Curve a, conductive layer at 10 km depth; curve b, conductive layer at 25 km depth; curve c, without conductive layer.

6. Is a deep conductor detectable beneath the island?

In order to ascertain whether a deeper conductor beneath the deep resistive unit may be detected we performed a 3D modelling including the sea effect. Thus, we included a conductive layer in the 3D model of Fig. 5. Fig. 10 shows the phase responses for three different depths of this conductive layer: 10 km, 25 km and without a deep conductive layer. A comparison between curve a (ocean effect and deep conductive layer at 10 km) and curve c (ocean effect without deep conductive layer) shows that the deep conductor is well detected. Note the different positions of the minima in the phase responses. For a conductor at 25 km depth (curve b) this minimum occurs at the same period as the minimum produced by the ocean effect (curve c without a deep conductive layer). Both models have similar phase curves and, therefore, they cannot be distinguished clearly. The only difference is the higher slope in the ascending branch in the case of the 25-km conductive layer (curve b). We conclude that there is no deep conductor at a depth of less than about 25 km. Otherwise the minimum in the data phases should appear before 10 s. On the other hand, if the conductor is deeper than 25 km we cannot detect it since the ocean effect dominates the curves. The deep conductor could be distinguished from the sea only by using very long periods and a very accurate modelling of the coastline.

The period at which the ocean starts its effect depends on the distance of the ocean from the sites and on the model inside the island, mainly of the shallow conductor (skin depth). In the case of a 3D model with a shallow conductor thicker than the one used in the model (Fig. 5), both the ocean effect and the deep conductor effect shift at longer periods and the minimum depth for a deep conductive layer does not change significantly.

7. Is there a shallow magma chamber?

The above study refers to a deep conductive layer and does not contradict the possible presence of a shallow magma chamber or remnants of it beneath the active Teide–Pico Viejo complex. In fact, the phonolitic eruptions of Montaña Blanca, at 2000 b.p. [31] or Lavas Negras, at 500–600 b.p. [32], indicate that a shallow magma chamber existed below Teide in relatively recent times. Because of the abrupt topography and logistic problems it was not possible in this survey to collect data over this complex. However, the deepest part of the shallow conductor in the interior of Las Cañadas caldera located near the Teide–Pico Viejo Complex, in Fortaleza (beneath sites 32–244), Montaña Blanca (beneath sites 35–271) and beneath the northern sector of Ucanca depression (beneath site 25), could be due to the presence of hot hydrothermal fluids related to a possible magma intrusion located in the centre of the caldera beneath the Teide–Pico Viejo complex. This is supported by the presence of fumaroles in the summit of the Teide, although the low temperature (16°C) of water found in two boreholes in the Las Cañadas caldera [24] suggests a hydraulic disconnection between the two water systems or a rapid circulation of the water in the aquifer thus dissipating the heating effect of the hydrothermal system. New AMT–MT sites located on the northern and western flanks of the Teide–Pico Viejo volcanoes should be carried out in order to examine whether a shallow magma chamber is still present beneath the active central system.

8. Current channelling

The steep ascending branches in the phases reaching values of 90° at long periods represent an additional effect which cannot be explained only by the ocean. Phases higher than 90° are not frequent in the literature. This behaviour, when observed at individual sites, is often attributed to local, near-surface distortions [33]. Current channelling [34] has also been invoked to produce such an effect. Jones et al. [35] reported a survey with phases higher than 90°, which were attributed to a 3D regional effect caused by a large batholith. However, they could not model such a structure. Recently, current channelling has been modelled by 3D structures including strong conductors [36,37]. Since this behaviour is common to all the MT sites in the Las Cañadas caldera, it should correspond to a regional effect in the island. However, a simple model considering the island in an infinite ocean does not produce phases over 90° (Fig. 5c).

After many attempts we found this effect in current channelling models. A large number of 3D models were calculated with different sizes and geometries of the channels. Typical local dyke type conductors only explain the phases at sites nearby. However, given that all the sites show this similar behaviour, we sought a larger (regional) structure. Finally, we found that a steep increase in the phases could also be achieved by a finite conductive channel around the island. Owing to insufficient site coverage, the width and thickness of the channel were not well constrained. One of these models is shown in Fig. 11. It consists of a conductive channel of 20 km width, 3 km thick around the island and a resistivity of 0.3 Ωm, and a conductive layer of 0.3 Ωm at 25 km depth (Fig. 11). Without this deep layer the slope of the modelled phases was not

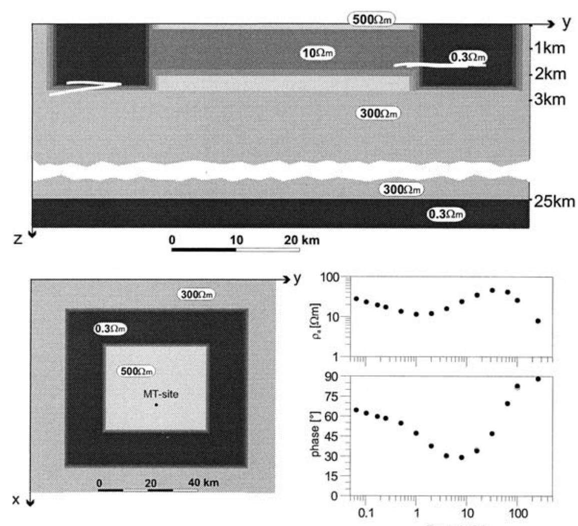

Fig. 11. The combination of a conducting channel and a deep conductive layer reproducing the steep slope of the phase curves reaching values of 90°. Responses correspond to a site located at the same distance from the seacoast as the sites in the caldera Las Cañadas. The two modes deliver practically the same values.

large enough to fit the data. Fig. 11 also shows the apparent resistivities and phases for a site located at a distance of 15 km from the coast, approximately the same distance as the sites in the Las Cañadas caldera are from the sea. This regional model roughly explains the observed slope of phase curves at long periods. More complicated and additional local structures (local close dyke-like conductors) would have to be incorporated to account for their rolling out of quadrant but this requires a much finer discretisation and surmounts the available computing facilities at present.

This model may be explained by the presence of the other Canary Islands (Gomera is at a distance of 20 km, Gran Canaria at 40 km, and Africa is at a distance of 200 km) although the strong ocean currents in the narrow channels between the islands [38] could also induce an additional effect which cannot be reproduced by a 3D model. The deep conductive layer could be related to the underplating in the Canary Islands predicted by Dañobeitia and Canales [39].

9. Discussion

The results obtained in this study offer new insights into the use of the MT method in volcanic areas and, in particular, into the internal structure and groundwater distribution of the Las Cañadas caldera. These three aspects are discussed separately below.

9.1. On the use of the MT method in volcanic areas

Most of the theoretical aspects and new findings concerning the use of magnetotellurics and audiomagnetotellurics in the Las Cañadas caldera have already been discussed above. However, it is worth noting a number of consequences of this study that refer to the application of such a geophysical method in volcanic areas. In caldera depressions filled with porous rocks containing fluids (water), such as the Las Cañadas caldera, a high resistivity contrast between an impermeable, resistive basement (pre-caldera?) and post-caldera units (conductive) is expected. This makes the combined AMT and MT surveys especially interesting to image the internal structure of the caldera in terms of the electrical resistivity distribution.

In volcanic islands a 3D modelling of the coast effect is necessary in order to check the period interval not influenced by the sea. In the case of a volcanic island such as Tenerife high conductivities at few kilometres depths related to shallow magma chambers or hydrothermal alteration are expected. In Tenerife the 3D modelling performed indicates that a conductive layer cannot be present at depths of less than 25 km, but a shallow small magma chamber or a remnant of this beneath Teide is possible. In fact, this is compatible with the thicker conductor appearing in almost all the profiles towards the Teide, as well as with the induction arrows (Fig. 7). Only a new MT survey in the northern sector of the Teide volcano could confirm the existence of a shallow magma chamber beneath the central edifice.

9.2. On the structure and origin of the Las Cañadas caldera

The well defined boundary between the conductive layer and the underlying resistive unit suggests that such a limit defines a major contact between geological units inside the caldera, or alternatively, it corresponds to a relative sharp change in hydrothermal alteration with depth. Note that, as stated above, this boundary can be at a higher depth given that the conductive layer of the models in Fig. 8 is the minimum thickness required by the data. The contrast in physical properties (density, porosity, permeability, etc.) and composition (basalts, tephrites, phonolites, etc.) between the two main rock sequences observed at the surface, the Las Cañadas edifice pre-caldera rocks (mainly phonolitic, welded rocks capping sequences of non-welded pumice deposits) and post-caldera rocks (highly permeable Teide–Pico Viejo basaltic lavas and scoria), suggests that in some sectors of the caldera this limit could correspond to the top of the pre-caldera sequence. But, the existence of strong vertical contrasts of hydrothermal alteration along the intracaldera sequences cannot be discarded in the light of the results obtained. Although there are some variations between profiles and along them, the geometry of the lower boundary between the conductive and non-conductive sequences is rather flat, showing an average depth of 1000 m in most of the caldera depression, and thickens close to the caldera wall and near Teide where a strong high conductive anomaly is present. Given that the conductive layer thickens approximately radially towards the Teide–Pico Viejo complex we cannot discard that the deepest parts of the bottom of the conductor may also be due to hydrothermal fluids and associated hydrothermal alteration affecting the pre-caldera rocks. In fact, the presence of thermal anomalies and fumaroles at Teide volcano and the existence of recent eruptions in the area reveal a geothermal system in the Las Cañadas caldera associated with a relative shallow heat source (residual phonolitic magma chambers?) or with a deeper one. The presence of hot water at temperatures and pore pressures close to those at water-stream transition in a fractured environment has been proposed as an explanation of the low V_p/V_s ratios obtained in the Las Cañadas area [20]. If so, the depth of the caldera floor would be shallower than the bottom of the conductive layer.

The geometry of the conductive zones suggests two closed depressions in the western (Ucanca) and central (Guajara) sectors of the caldera, as predicted by the structural models [3–5], which support a multiple vertical collapse origin for the Cañadas caldera. A structural barrier, the Roques de García Formation, separates these two depressions. The Roques de García Formation is composed of a relatively old (2.5–1.5 Ma) sequence of pre-caldera rocks intruded by numerous phonolitic dykes [3]. From the magnetotelluric models we can establish that this formation is a true vertical structural limit which goes deep into the caldera depression. This disagrees with the idea recently proposed [12] that the Roques de García Formation represents the proximal facies of one of the sector collapse deposits that formed the Las Cañadas caldera. This also rules out the formation of the caldera by a single landslide event [9], as it should have produced a continuous listric plane even below the Roques de García Formation.

As seen before, in the central zone of the caldera, in the Medio profile, the top of the conductor is at a higher altitude than the two closest profiles. This also suggests two separate depressions in the central (Guajara) and eastern sectors (Diego Hernández) of the Las Cañadas caldera, which is in agreement with the self-potential data [18]. However, the separation between these two depressions does not crop out at the surface. It may be attributed either to the intersection of two collapse calderas, following the structural model [3], or to the barrier effect of a radial dike (or group of dikes). In this case the existence of two true caldera depressions in that sector of Las Cañadas would be doubtful. This second option would favour the existence of independent groundwater bodies in the caldera resulting from the presence of abundant dikes intruded preferentially in the direction of the main rift systems (NE and NW), but also radially [40]. A higher density of MT sites would be necessary in order to resolve this ambiguity and detect possible dikes.

In the eastern sector of the Las Cañadas caldera the top of the conductor shows a continuous gentle inclination towards the NE, coinciding with the results shown by Aubert and Kieffer [18] who suggested that the caldera is open in that direction. They also proposed that this is clear evidence for a sector collapse originating that part (Diego Hernández), the youngest part, of the Las Cañadas caldera. This interpretation, however, is not supported by the age relationships deduced for the landslide of the La Orotava valley which is clearly older than the Diego Hernández edifice [4,10]. Therefore, the geometry of the conductor observed in the eastern sector of the Las Cañadas caldera cannot be used as evidence for a landslide origin of the caldera. Anyway, this raises the question of why the effect of the eastern caldera wall is not observed in the MT data. More MT sites at the La Orotava head wall zone would be necessary to resolve this problem.

The narrow and continuous conductor observed close to the caldera wall is a characteristic of the models of Fig. 8. This conductive zone along the caldera wall reaches very shallow depths at some points and it descends (about 1000 m a.s.l.) in all the profiles. The geometry of this anomaly can be explained by the presence of a relatively deep fracture zone. This zone would coincide with the structural border of the caldera, in which a high fracture permeability and existence of an intense fossil hydrothermal alteration, visible in some sectors of the caldera wall, may combine to produce such a marked anomaly. Such a fracture zone would be consistent with the existence of near vertical concentric normal faults limiting the caldera depressions and connecting with extinct shallow magma chambers.

9.3. On the groundwater and geothermal zones in the Las Cañadas caldera

The results obtained in the present work have also significant implications for the distribution of groundwater in the Las Cañadas caldera. The high conductive zones observed are mainly attributed to discontinuous groundwater bodies corresponding to different structural sectors of the caldera. The calculated depth of the top of these groundwater bodies at the central and eastern sectors coincides with the data available on the depth of the water table obtained from continuous borehole measurements [24]. However, the thickness of the potential groundwater bodies could be overestimated due to the effect of hot hydrothermal fluids below Teide and fossil hydrothermal alteration near the caldera wall. Temperatures from water samples collected from the Las Cañadas boreholes are rather low (16°C) whereas the temperature of Teide fumaroles coincides with the boiling temperature of water at that altitude. This suggests either that geothermal circulation is isolated from the Las Cañadas aquifers or that the associated anomalous heat flow is mainly absorbed by the groundwater circulation.

The distribution of the groundwater bodies inside Las Cañadas leads us to identify true hydrological barriers, which coincide with structural elements of the caldera depression. This is the case of the Roques de García spur or, to a lesser extent, the intersection between the Guajara and Diego Hernández depressions. The existence of dikes acting as hydrological barriers has also been noted by hydrogeological studies carried out in Tenerife [40], but the probably narrow widths require a higher density of MT sites.

10. Conclusions

The use of MT and AMT methods in the Las Cañadas caldera provides important data to improve our understanding of its internal structure and of the distribution of groundwater resources. Despite the limitations imposed by the logistic difficulties, that significantly restricted the number of sites, the results obtained allow us to establish a coherent picture of the interior of the caldera. A marked electrical resistivity contrast appeared between the porous, water-saturated sequence of post-caldera rocks, and pre-caldera sequence, which allowed us to obtain an image of the interior of the caldera. However, the seacoast effect, which produces the same behaviour on the data as a deep conductor, disturbs the investigation of the deeper structure. Therefore, it was necessary to perform a 3D modelling of sea around the island in order to find the period range free of the sea effect. The main conductors in the caldera are related to cold water and a possible influence of hydrothermal alteration. From the distribution of the conductive zones and the morphology of its top and bottom surfaces, two caldera depressions are clearly distinguishable in the western (Ucanca) and central sectors (Guajara). The Roques de García Formation, a large spur of pre-caldera rocks, forms a deep structural limit dividing these two caldera depressions. The eastern sector (Diego Hernández) appears to be opened to the northeast, to the La Orotava landslide valley. However, this does not necessarily support a landslide origin of the caldera as the La Orotava valley is clearly older than the eastern sector of the Las Cañadas depression.

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