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# Electric structure of the Copahue Volcano (Neuquén Province, Argentina), from magnetotelluric soundings: 1D and 2D modellings

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## Abstract

Four magnetotelluric soundings were carried out in 1993 in the region of the Copahue active volcano located at the border between Chile and Argentina (37°45′S, 71°18′W). Three soundings were located inside the caldera of the ancient stratovolcano (east of Copahue) and the fourth outside it. The soundings inside the caldera were situated at about 6, 11, and 14 km from the volcano. Digital data were obtained covering the range of periods from 1 sec to 10,000 sec using induction coils and a flux-gate magnetometer to obtain the magnetic data and Cu-$SO_4$Cu electrodes for electric field measurements. The apparent resistivity curves corresponding to principal directions were analyzed in conjunction with the geological background in order to eliminate distortion — which is very important in this hot volcanic region. Then, 1D modellings were performed using the "normal" curves — i.e., curves without distortions. Using the apparent resistivity curves with distortions, 2D modelling was also performed along a profile perpendicular to the regional tectonic trend suggested by MT soundings into the caldera. Results show low resistivity values of about 3-15 Ωm between 9 km to 20 km depth in the crust, suggesting high temperatures, with minimum values of about 700°C with partially melted zones in the upper crust between 9 km to 20 km depth under the caldera. The presence of a possible sulphide-carbonaceous layer (SC layer) in the upper basement could play an important role in lowering the electrical resistivities because of its high electronic conductivity. © 2000 Elsevier Science Ltd. All rights reserved.

## Resumen

En 1993 se realizaron cuatro sondeos magnetotelúricos en la región del volcán activo Copahue, ubicado en el límite entre Chile y Argentina (37°45′ Lat. Sur, 71°18′ Long. Oeste). Tres sondeos fueron localizados dentro de la caldera del antiguo estratovolcán — al Este del volcán Copahue — y el cuarto, fuera de ella. Los sondeos dentro de la caldera fueron situados a aproximadamente 6, 11 y 14 Km del volcán Copahue. Los datos fueron obtenidos en forma digitalizada, cubriendo el rango de períodos desde 1 seg. a 10000 seg., usando bobinas de inducción y un magnetómetro flux-gate para obtener la información magnética. Para medir el campo eléctrico, se usaron electrodos de Cu-$SO_4$Cu. Las curvas de resistividades aparentes correspondientes a las direcciones principales fueron analizadas tomando en cuenta el contexto geológico para eliminar, en lo posible, las distorsiones presentes en las curvas — muy importantes en esta región volcánica caliente. Luego, se realizaron modelaciones 1D usando las curvas "normales" — es decir, sin distorsiones. Además, usando las curvas de resistividad aparente distorsionadas, se efectuó una modelación 2D a lo largo de un perfil perpendicular a la tectónica regional sugerida por los sondeos MT dentro de la caldera. Los resultados muestran valores bajos de resistividad de 3Ωm a 15 Ωm entre los 9 Km y 20 Km de profundidad en la Corteza, así sugiriendo altas temperaturas, con valores minimos de alrededor de 700°C, con zonas de

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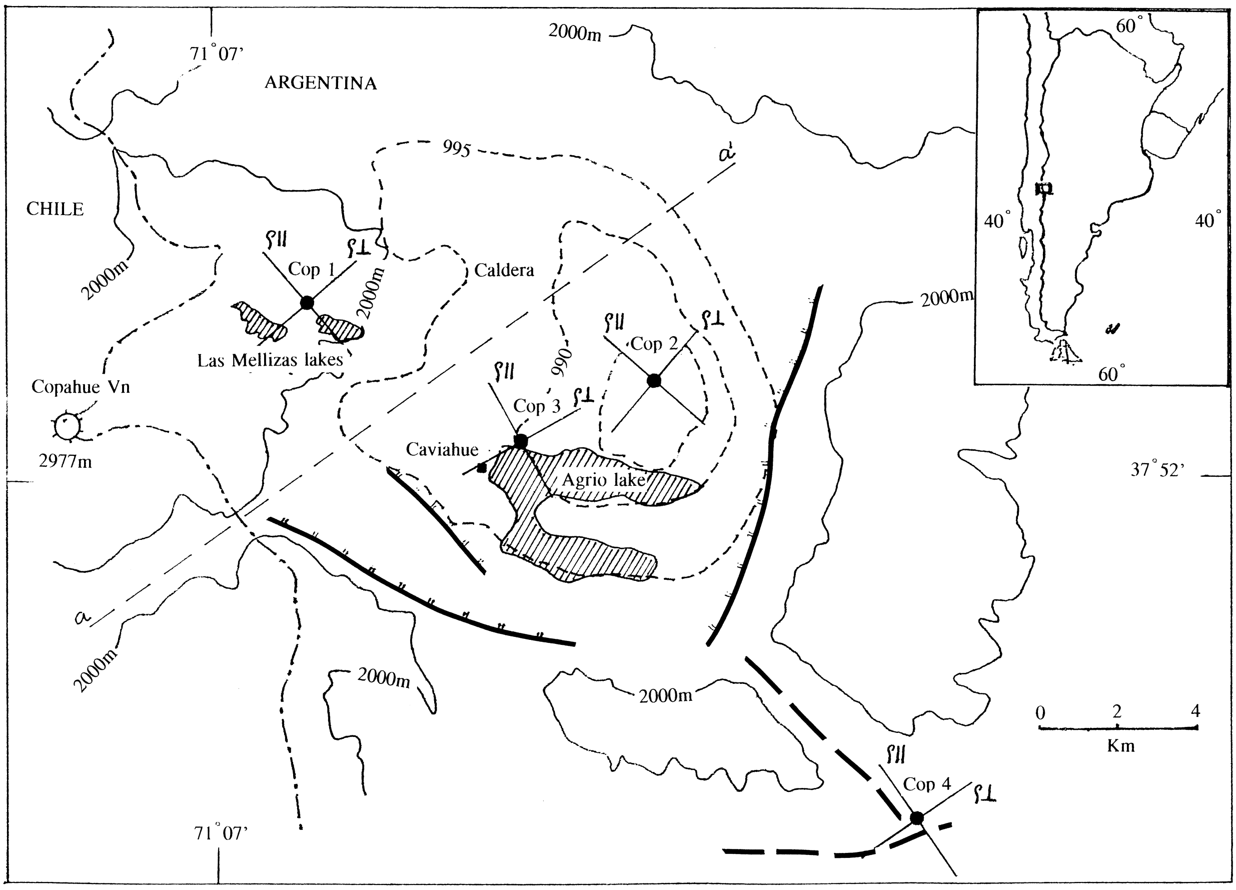



Fig. 1. Location of study zone in Argentina, next to the border of Chile and Argentina. The Copahue volcano is placed on the SW border of the "caldera" corresponding to a previous eruptive centre. The faults are the caldera's limits. Dashed lines indicate a Bouguer anomaly (into the caldera) in mgals. Solid lines indicate topographic elevations above sea level in meters. Also shown are sounding locations and principal directions corresponding to periods lower than 100 sec. See text for discussion of the selection of ρ|| and ρ⊥. Cross-section aa′ is the 2D modelling profile.

fusión parcial en la Corteza superior entre los 9 Km y los 20 Km de profundidad bajo la caldera. La presencia de una posible capa sulfuro-carbonática (capa SC) emplazada en el sector superior del basamento podría jugar un papel importante en descender las resistividades eléctricas debido a su alta conductividad electrónica. 

## 1. Introduction

The Copahue Volcanic Centre is located at 37°45′S, 71°18′W, at the border between Chile and Argentina in the Andean range. Its geological evolution began during the early Pliocene (about 4.3 million years ago), resulting in a strato-volcano. Its deposits are spread over a large region in Argentina and Chile. In Chile, these deposits are about 1700 m thick and are andesitic to basaltic in composition (Delpino and Bermúdez, 1993). Before the end of the Pliocene, the activity was relatively calm. During the late Pliocene-Pleistocene, a change in the dynamics of the Copahue volcanic arc occurred: some magmatic chambers intruded upper crustal levels and, as a consequence, the activity became explosive, forming pyroclastic flows. During that time, a caldera was developed with an elliptical shape, about 17 km in diameter and 500 m in average depth. During the Pleistocene, another strato-volcano was generated at the SW border of the caldera produced by the ancient strato-volcano (Copahue volcano with 2977 m asl), which is the centre of the present activity (Delpino and Bermúdez, 1993; see Fig. 1). Its crater is approximately 600 m in diameter, with an interior lake that is 250 m in diameter.

According to the information available, this volcano has been active from the 18th century up to the present day. The last activity period was July-August

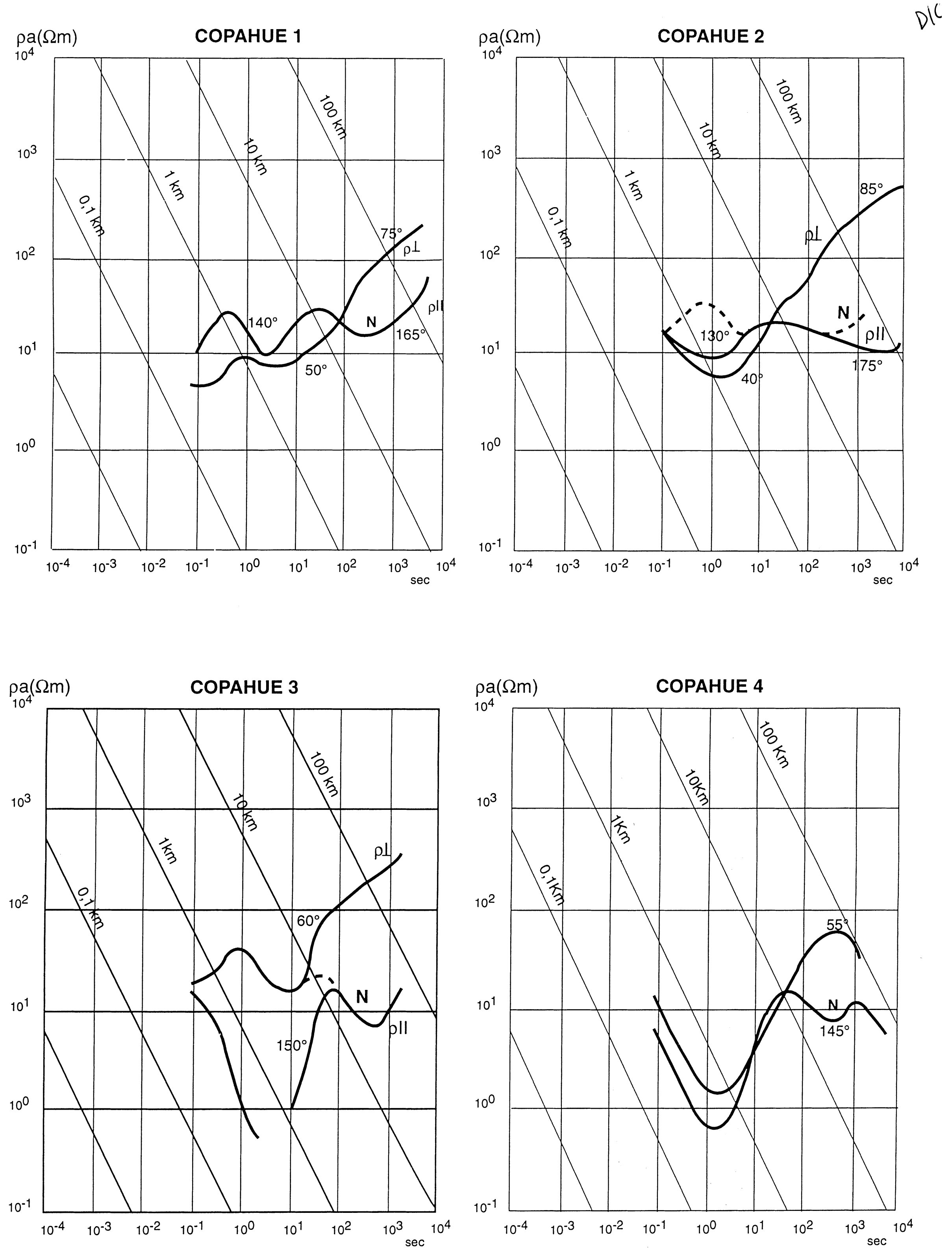



Fig. 2. Apparent resistivity curves corresponding to the principal directions in each sounding location (ρ|| and ρ⊥); curves are indicated by solid lines. Numbers next to the curves indicate strikes. N indicates the normal curve (i.e., without distortions), recovered from the field curves. Dashed lines indicate part of normal curves.

1992; at present, the region has an abundance of hot mineralized water.

According to some authors, the original magma chamber (at about 130 km depth) would not be connected at present with the volcano and its present activity would be derived from a smaller magma chamber near the surface (Pesce et al., personal communication). According to other authors (Delpino and Bermúdez, 1993), this volcano is active and the possibility of intense eruptions in the future cannot be excluded.

A gravimetric exploration was carried out inside the caldera in 1975 by YPF (Yacimientos Petrolíferos Fiscales, Argentina) covering an area of 180 km$^2$ with 285 measured points (unpublished). The Bouguer anomaly map shows a negative anomaly north of Agrio lake (see Fig. 1), which could indicate the position of a shallow magmatic chamber located in the upper crust. The present activity centre — Copahue volcano — is situated approximately 15 km west of this gravimetric anomaly.

In order to contribute to the knowledge of this volcanic area and to obtain more information about its thermal state, four magnetotelluric soundings were carried out in the area in 1993. Three were inside the caldera and the fourth outside it. The soundings in the caldera were situated at 6.5 km (Cop 1), 11 km (Cop 2), and 14 km (Cop 3) from the Copahue volcano (Fig. 1). The fourth sounding was placed next to the Hualcupen stream, outside the caldera.

The data were obtained digitally and recorded in 4 register bands with the following periods: 1 10 sec, 1 20 sec, 10 sec, and 20 10,000 sec, ensuring a good overlap of collected information. A commercial data acquisition system was used, connected to an analogic signal conditioner that applied a filtering and amplification process. The electromagnetic signals were monitored on-line to observe their quality during aquisition. Two different types of magnetic sensors were used, according to bands: induction coils for the first three frequency intervals and a flux-gate magnetometer in high periods. Cu-$SO_4$Cu electrodes, placed 100 m apart, were used for measuring the electric field.

## 2. Data processing and distortion analysis

Data collected in the field were processed using a program from Reddy and Rankin (1974), from which tensorial resistivity curves for the four locations were obtained, corresponding to the principal directions (Fig. 2). The calculated average coherences for all sites were, in general, over 0.80, and the skew values were about 0.50 for Cop 1, 1.0 for Cops 2 and 3, and 0.65 for Cop 4.

As this is a volcanic region with strong thermal manifestations, a strong variation of electrical resistivity and temperature is presumed not only vertically but also horizontally. For this reason, the natural electromagnetic field in the area is suspected to be strongly distorted by galvanic and inductive effects. In fact, in general both types of distortion seem to be present in all locations. Therefore, in this situation it is difficult to distinguish $\rho\|$ and $\rho\perp$ in principal directions. Consequently, the treatment of distortions made here — in order to eliminate previous the 1D modellings — is an approximation to the true, the one that we consider to be in best agreement with the geologic framework.

In some locations, strong inductive distortions in the field and deformations in curves are suggested in one or both principal directions in about 1 sec of period. These distortions could be produced by telluric current channelling along faults that are at the borders of the volcanic caldera (see Fig. 1). There would be also an S-effect on $\rho\perp$ curves at all sites, produced by conductance variation of the superficial conductive layers, thus suggesting a lateral temperature gradient with temperatures increasing toward a region located approximately south of the volcano. In particular, the following considerations of distortion were done for each location in order to obtain the "normal" curve in each site.

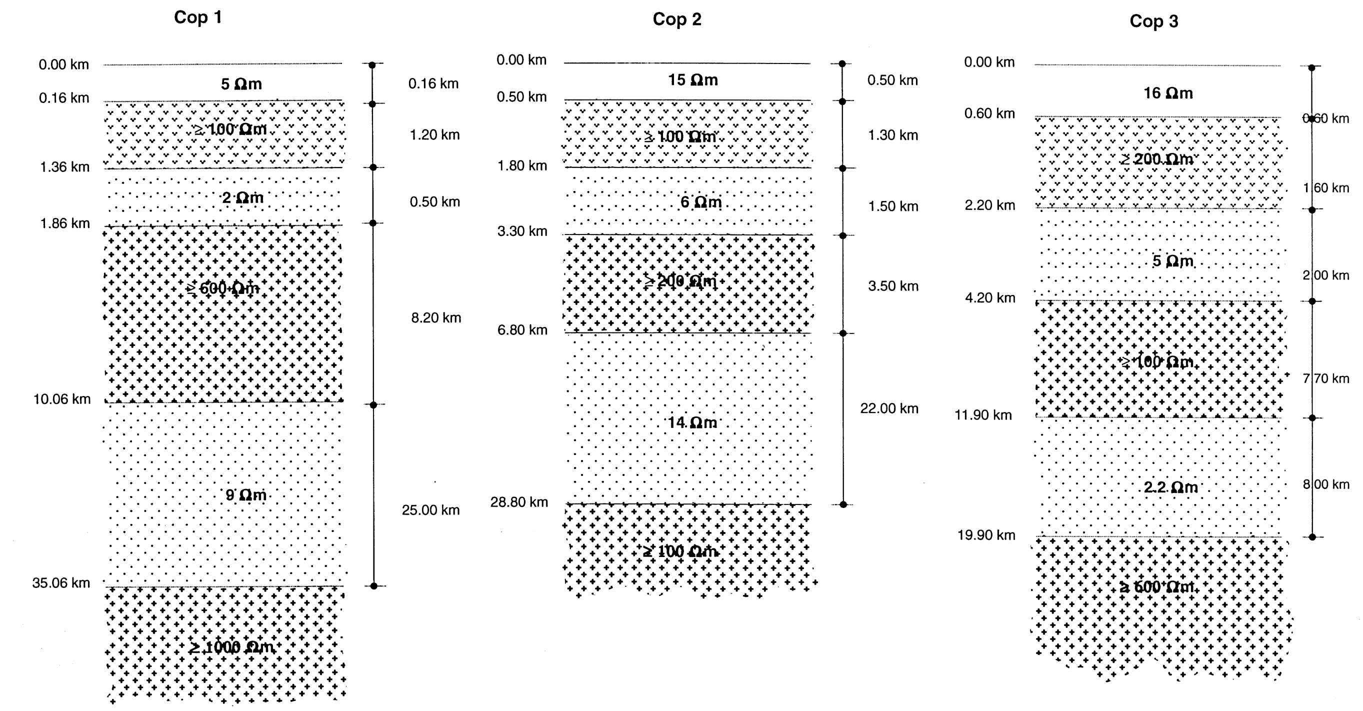
### 2.1. Copahue 1

The curve corresponding to N50°E, when compared with the other MT soundings, seems to be in a lower position by galvanic effect (Fig. 2). One explanation could be that this site shows the most intense thermal manifestation in the volcanic caldera due to the presence of a hot water reservoir located under the "Las Mellizas" lakes (Pesce et al., personal communication). Therefore, this zone would have local heating with a possible border effect at the site, thus lowering the curve. There is also on this curve a probable dispersive galvanic distortion visible from about 10 sec of period and higher. We believe it is an S-effect principally produced by the second conductive layer (see 1D modelling below). This layer would be located under a thick volcanic, resistive formation composed of lavas and pyroclastic material. This curve, which displays galvanic effects larger than the other curve for this site, was considered as $\rho\perp$. The remaining curve N140°E, when compared with the other MT sounding curves, seems to be approximately in good position on the abacus (i.e., without distortion). So this curve is considered as $\rho\|$ and as the "normal" curve for the site.

### 2.2. Copahue 2

Although this sounding displays evidence of what would be a conductive layer at depths less than 1 km

Table 1



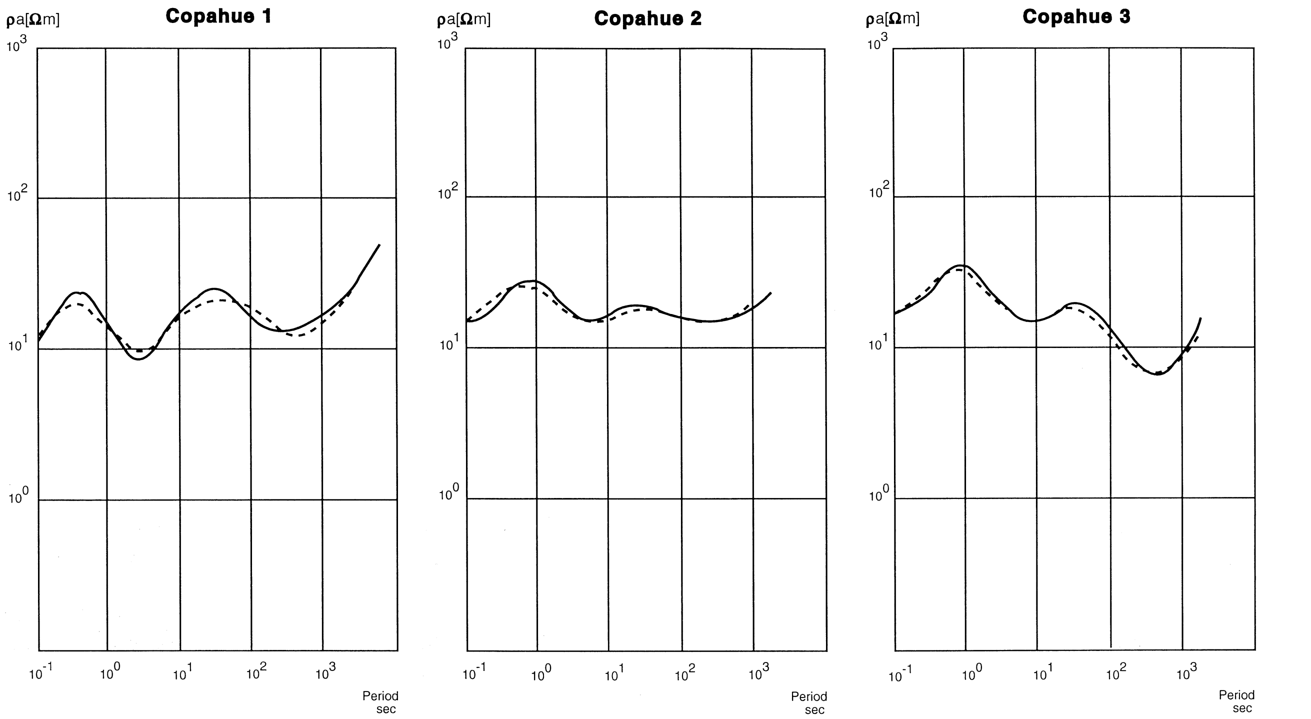




Fig. 3. Adjustment of 1D modellings corresponding to the three soundings located inside the caldera. Normal curves were used in the modellings. Solid lines indicate field data (normal curves); dashed lines indicate the results from models.

in low periods (see Fig. 2), the comparison between this site and Cops 1 and 3 and the geological background (Fig. 1) suggests the presence of an inductive distortion in both curves in the range of periods between 0.1 sec to 10 sec. The presence of two faults near the site, almost parallel to the principal directions (Fig. 1) supports this interpretation. These faults are located at the external border of the caldera. The curve corresponding to N40°E also seems to have an S-effect, like Cop 1, and was considered as $\rho\perp$. In order to obtain the "normal" curve, it was considered to be the $\rho_a$ curve N130°E (see Fig. 2), but taking the first part of $\rho\perp$ curve from Cop 3 — the site nearest to Cop 2 — in order to eliminate the suspected inductive distortion in low periods.

Some galvanic distortion is also suspected on the portion of $\rho\|$ curve corresponding to highest periods, taking into account the right portion of the other "normal" curves — Cop 1, Cop 3, and Cop 4. This deformation in the $\rho\|$ curve could very probably be produced by local heating at crustal levels. In fact, Fig. 1 shows a Bouguer anomaly for this location which could indicate the site of emplacement of an intermediate magma chamber and perhaps the location

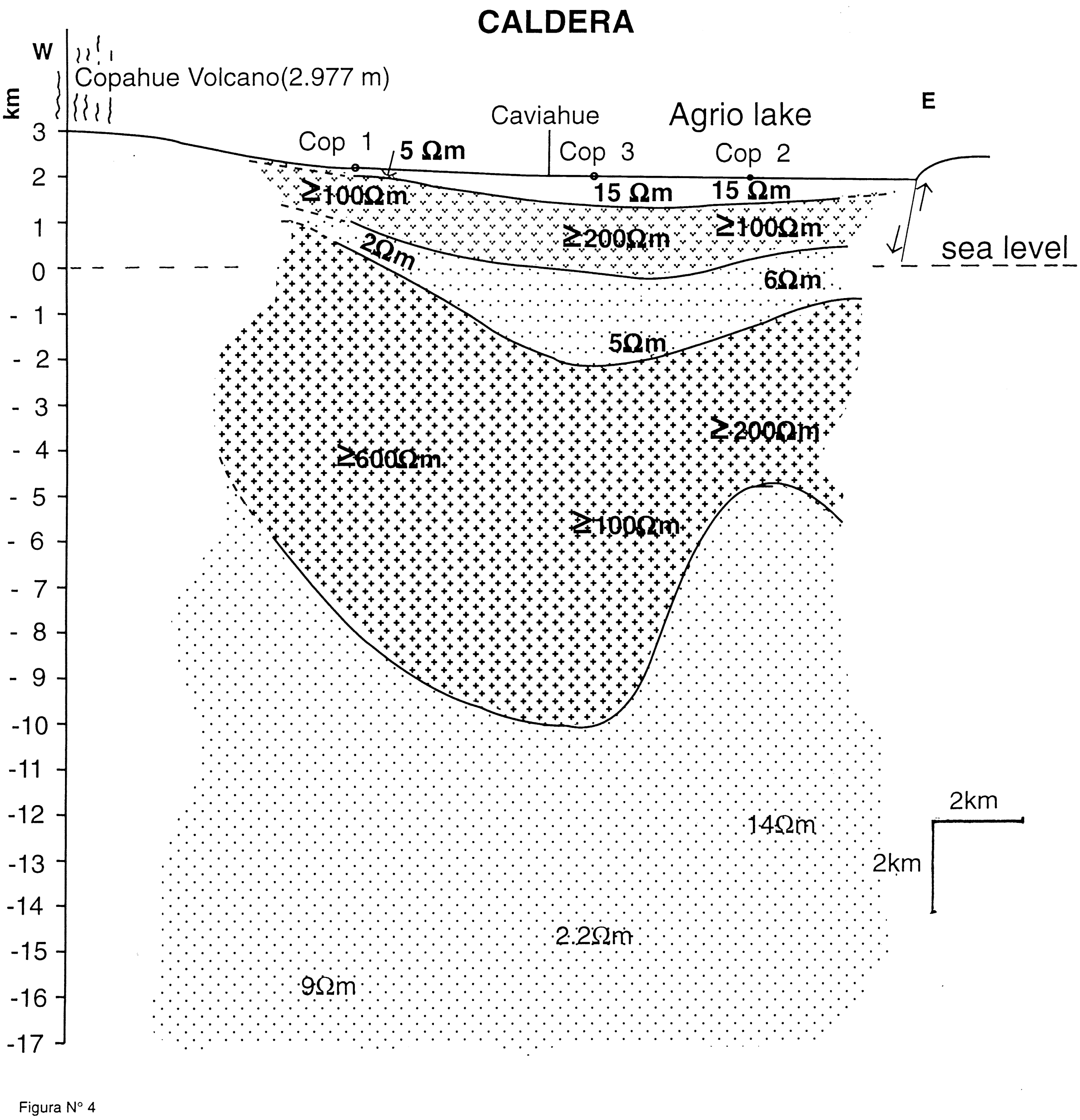



Fig. 4. West to east profile across the Copahue volcano area. The low resistivity values in the upper crust would correspond to several magmatic chambers placed under the caldera. Defined patterns: + + + + indicates basement, vvvv indicates volcanic formation.

of the crater corresponding to the ancient stratovolcano. Therefore, in highest periods, the tendency shown by the other sites was considered as normal (see Fig. 2).

### *2.3. Copahue 3*

The N60°E curve (the same as the other ρ⊥ curves from other locations), would present an S-effect in high periods so it was considered ρ⊥. The other curve seems to have a strong inductive distortion between 1 sec. to 10 sec of T (it was considered to be ρ||). The cause of this distortion on the ρ|| curve could come from some faults in the area (Fig. 1) which are almost parallel to this principal direction. Both curves were used to recover the normal curve, avoiding the distortion as shown in Fig. 2.

### *2.4. Copahue 4*

This MT sounding was performed out of the caldera, next to Hualcupen stream. The presence of two linements at this location casts doubt upon the $\rho_a$ curves at low periods. The N145°E curve in high periods is similar to the remainder MT curves; it shows a conductive layer with a top at about 10 km. Therefore, at first approximation, this curve was considered to be as normal in high periods.

## 3. 1D and 2D modellings

The obtained "normal" curves, (i.e., without distortions), for Cop 1, Cop 2, and Cop 3 were used for performing 1D modellings. An iterative program (Fournier et al., 1963) was used, which allows an adjustment process between experimental data and models using the operator's experience and the geological background. The results are given in Table 1; and Fig. 3 shows the adjustment of the models. With this information, an west-east profile was drawn which is shown in Fig. 4.

According to the principal directions obtained from processing and distortion analysis, the regional tectonic trend for periods lower than 100 sec. is NW-SE. Then, using the ρ|| and ρ⊥ curves, from processing (Fig. 2), a 2D modelling was performed along ρ⊥ directions (aa′ profile, Fig. 1). Prior to this modelling, and taking into account that both ρ|| and ρ⊥ curves present galvanic and inductive distortions, it was necessary to transform the resistivity curves to ones that would have been obtained if the geological context had been two

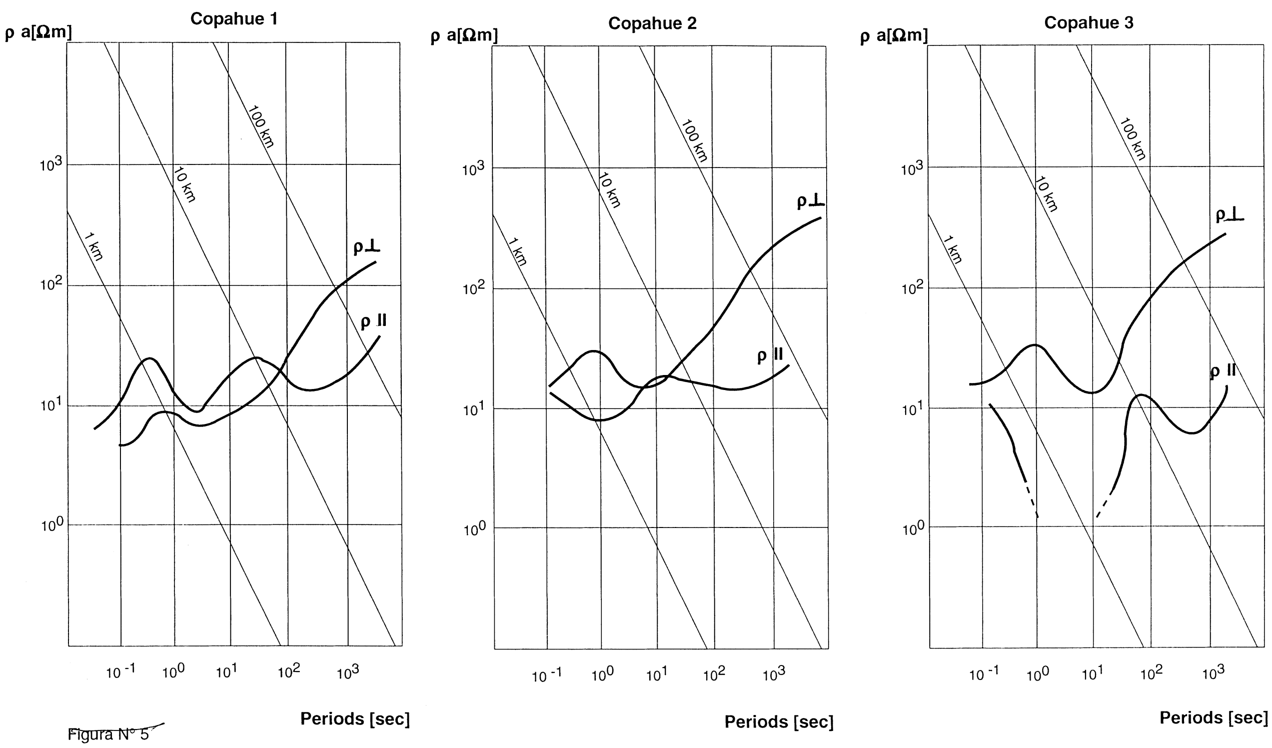



Fig. 5. Experimental curves ρ|| and ρ⊥ that would be obtained if the geological structure were 2D; probable inductive distortion the ρ⊥ curve in Copahue 2 was eliminated.

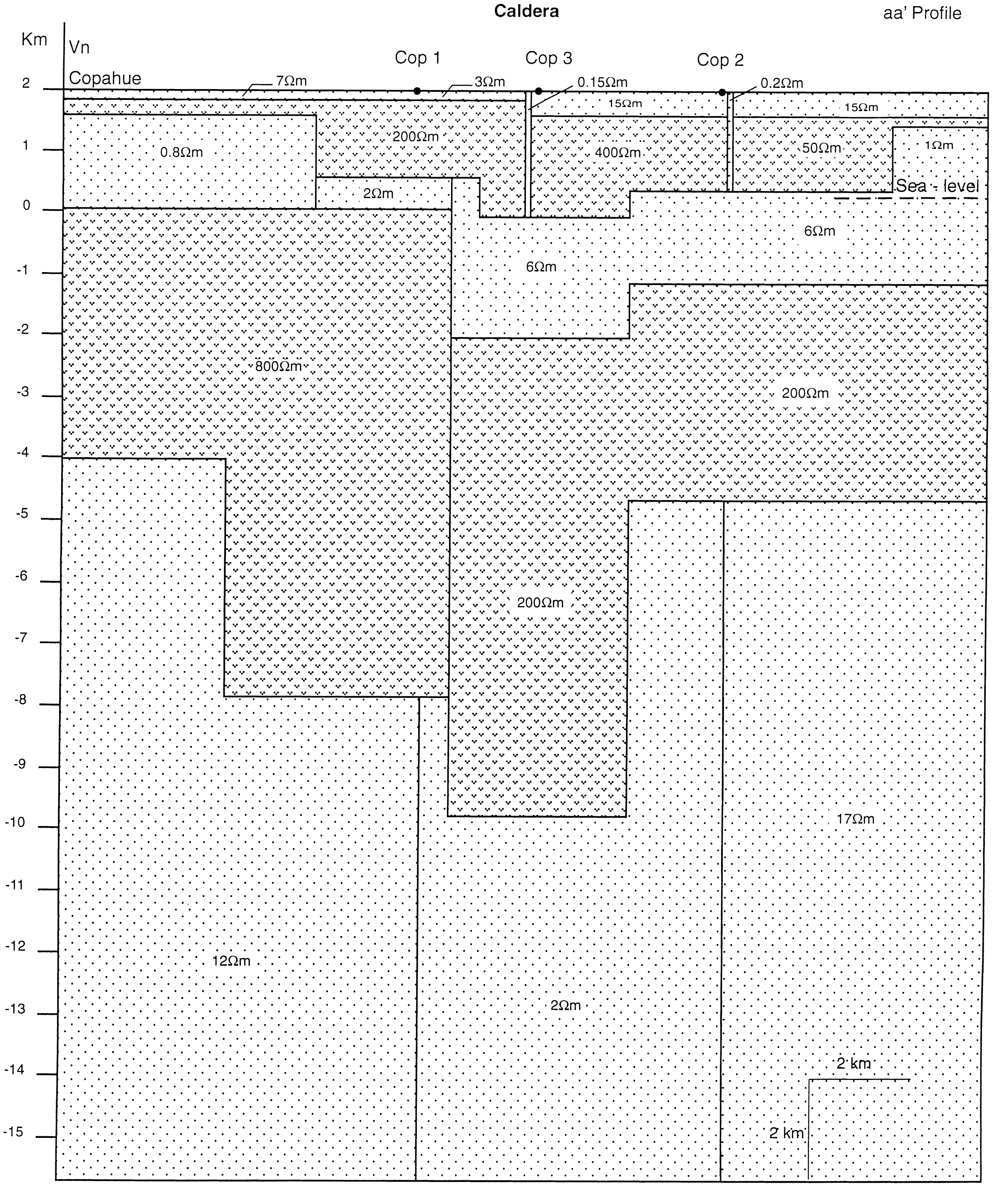



Fig. 6. 2D modelling profile. Vertical zones with high electrical conductivities suggest faults with hot mineralized water in the caldera region.

dimensional (i.e., to eliminate all possible galvanic distortions from ρ‖ and all possible inductive distortions from ρ⊥. This is because the tectonic trend is actually 3D. According to the distortion analysis made above, the 2D $\rho_a$ curves would be the ones shown in Fig. 5. A program from P. Wannamaker was used for 2D modelling and Fig. 6 shows the results. Fig. 7 shows the adjustment of model to experimental data. Observing this figure, it is clear that the fit is very good for ρ⊥ curves but not for ρ‖.

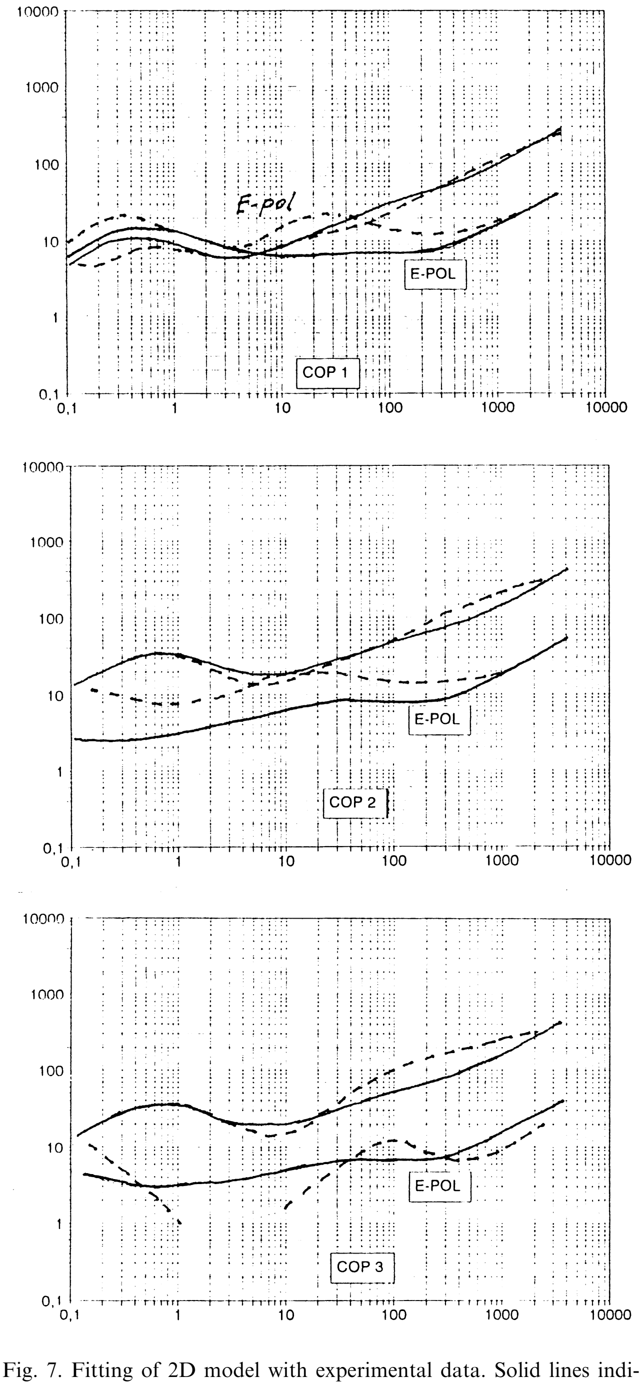



Fig. 7. Fitting of 2D model with experimental data. Solid lines indicate results from the model; dashed lines show experimental curves (ρ|| and ρ⊥).

## 4. Interpretation and conclusions

Figs. 4 and 6 show (east of Copahue volcano), under the caldera of the ancient volcano, very small resistivity values in the upper crust, even taking into account that we are studying a dynamic zone. The electrical resistivity of both nearest surface conductive layers decreases toward the Copahue volcano, on the SW border of the caldera, indicating the possible thermal nature of the low resistivity. Both layers appear to be composed of fragmented rocks saturated by hot mineralized water. The second conductive layer appears to be located on the fractured basement of the caldera, while the first — superficial — consists of "Las Mellizas" formation with pyroclastic material (Delpino and Bermúdez, 1995). Between them, there is a resistive volcanic formation apparently corresponding to the post-caldera period.

In other regions of the South Andean Cordillera, several very low resistivity values in volcanic zones have been reported. At 39°S in Chile, electrical resistivities of around 60 Ωm and even less, between 40 km and 80 km depth in the Villarrica active volcano zone, have been reported (Muñoz et al., 1990, 1992). In northern Chile and southern Bolivia, several high conductivity zones have also been detected: under "El Tatio" volcanic region; resistivities as low as 10 Ωm or less were measured by magnetotelluric soundings, between surface and about 20 km depth (Schwarz et al., 1984, 1994). These resistivity values are of an order of magnitude similar to the ones obtained in the present study in the Copahue volcano area in upper crustal depths.

In the volcanic region studied in the present work, some magmatic chambers formed at upper crustal depth during the late Pliocene-Pleistocene periods. The volcanic activity, which was relatively calm before, later became explosive. In the region of Lake Agrio, in the caldera, there is a negative Bouguer anomaly (see Fig. 1) which could indicate the location of one of these magma chambers. Geological data shows lavas with three different compositions, indicating that, under the caldera, there would be at least three separate magma chambers (Pesce et al., personal communication).

Taking into account the strong thermal manifestations in the region — especially within the caldera, in the Las Mellizas lake zone (see Fig. 1) — we favor the concept of partial melting to account for the low resistivities obtained. If so, the chambers should have at least about 40–50 vol% of melted rock, with temperatures at least of about 700°C between 9 km and 20 km depth (Schwarz, 1990), principally under Lake Agrio according to the resistivity values obtained.

Fig. 6, which is based on 2D modelling, suggests that the hottest region in the ancient caldera is under Lake Agrio. The modelling also suggests the presence of hot mineralized water rising from the upper crust to the surface through faults in the caldera.

In magmas from this volcano, the presence of $CO_2$, CO, $SO_2$, and $SH_2$ are very significant. During eruptions, pyroclastic sulfur is also produced (Delpino and Bermúdez, 1993). These products lead us to consider the role that carbon (amorphous or as graphite), carbonaceous substances, and pyrite etc. could play in reducing resistivities while still recognizing the predominant role of temperature. In fact, laboratory measurements indicate that solid carbon, either amorphous or as graphite, enhances the electrical conductivity of rocks, provided that it is abundant enough, stable, and forms an interconnected phase (Duba and Shankland, 1982). If magmas from Copahue volcano have sulphide — carbonaceous material as suggested by eruptions (perhaps produced by magma contamination from graphitic bodies), a very small quantity would be sufficient to reduce the electrical resistivity and thus contribute, along with partial melting, to produce the low values shown in Figs. 4 and 6. Similarly, the low electrical resistivities measured in the Villarrica volcano zone (about 200 km south of Copahue volcano) is suspected to be produced in part by graphitic bodies (Zhamaletdinov, personal communication). This possibility is in agreement with other current ideas: in many parts of the world the upper continental basement has a sulphide-carbonaceous formation called the "SC layer" by Zhamaletdinov and Semenov (1983), and it has electronic conductivity. The main geological features of these electronically conducting rocks are their primary-sedimentary origin, their global distribution, and their concentration in the upper supracrustal basement strata (Zhamaletdinov and Semenov 1983).

Finally, principal directions corresponding to transversal polarizations (Fig. 1) have very similar strikes, which suggests that the distortions present in these directions (S-effect) are produced principally by lateral thermal variation along directions converging south of Copahue volcano. This characteristic of $\rho\perp$ curves suggests that the hottest superficial zone is probably located around 4 km south of Copahue volcano in Chilean territory. But this is one speculation whose confirmation makes it necessary to do more MT soundings in this interesting region.

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