Crustal structure of the Gulf of Corinth in Central Greece, determined from magnetotelluric soundings

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Abstract
The magnetotelluric sounding method at 15 sites was employed to investigate the electrical properties of the crust and upper mantle near the epicentral region of the June 15 1995, $M_s = 6.1$, destructive earthquake in the Gulf of Corinth, Central Greece. The magnetotelluric results indicate the presence of a conductive zone in the mid-crust at a depth of 9 to 12 km near the seismogenetic region. The existence of this zone with a thickness of around 7 km can be explained by the presence of fluids in a zone of ductile shear. A second electrical discontinuity was also found at a depth of about 28 km and this may well correspond to the Moho below the Gulf of Corinth.

Key words *magnetotelluric method – electrical properties – crustal structure earthquake – Corinth Gulf*

1. Introduction

The Gulf of Corinth in Central Greece is a graben that separates the Peloponese from continental Greece. The graben has a length of 120 km, a width of 20 km and a depth of 870 m, with a NNW-SSE orientation. The uplift and north-south extension which began in this region in the middle Miocene caused the north side of the gulf to subside and to be characterised by normal faults that dip to the south while the south side of the gulf is uplifted and is characterised by larger north dipping faults. Most of the WNW trending normal faults show a curved listric geometry and in most cases the faults die out along their lengths while in other cases the normal faults terminate against NNE transfer faults (Doutsos and Poulimenos, 1992).

The gulf is presently deforming at about 1.5 cm/year NNE-SSW providing an extensional strain rate of 10^{-6}/year which is larger than the strain rate of the San Andreas fault system in California. The seismicity of this region is also intense and instrumental data indicate five earthquakes of magnitude greater than 6 in the last 30 years, as well as several catastrophic historical earthquakes with estimated magnitudes greater than 7 (Rigo, 1994).

On June 15, 1995 at 00:16 GMT a magnitude $M_s = 6.1$ earthquake devastated the city of Aigio, on the south side of the gulf, and claimed the lives of 26 people. The epicentre of the earthquake was located 15 km NE of Aigio city, in the gulf, at a depth of 10 km. Fault

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plane solutions from centroid moment tensor solutions by Harvard and GFZ Potsdam indicate a normal fault dipping 25° to the North with a E-W trending strike.

Based on the results from microseismic surveys in this region prior to the Aigio earthquake, some researchers have postulated the existence of a seismically active listric fault dipping to the north and flattening off into a mid-crustal detachment zone at a depth of 10 km. It is suggested that this detachment is due to the uncoupling of the brittle upper crust from a more ductile lower crust (Melis *et al.*, 1989; Rigo, 1994; Rigo *et al.*, 1996).

In order to investigate the crustal structure around the epicentral region of the Aigio earthquake the magnetotelluric sounding method was applied to 15 sites covering a distance of 20 km around the epicentral area. The measurements were taken in October 1995 as part of a cooperative project between the Departments of Geomagnetism and Seismology of Institute Physique du Globe, Paris and the Institute of Geodynamics of the National Observatory of Athens.

In this paper, we will present the most interesting of the magnetotelluric results and examine their relation to the seismological results with respect to the existence of the detachment zone and its association with the seismogenetic region responsible for the Aigio earthquake.

2. Method

The magnetotelluric method proposed by Cagniard (1953) is now widely employed as a powerful tool in geophysical prospecting as well as in earthquake prediction research (Kaufmann and Keller, 1981; Vozoff, 1972, 1993; Chouliaras and Rassmussen, 1988; Bernard *et al.*, 1996).

The basic advantages of the method are that it is inexpensive, because the method uses the Earth's natural electromagnetic field as a source, and that it penetrates the Earth to great depths, because the measurements cover a broad range of frequencies.

At each station, along a direction x and for each period T, one defines an apparent resistivity ρ (Ωm), which is related to the amplitude of the natural electric field E_x (mV/km) and to the amplitude of the orthogonal magnetic field H_y (nT) by the formula (Cagniard, 1953):

$$\rho = 0.27\ (E_x/H_y)^2.$$

The depth of penetration (in km) is defined as:

$$\delta = 1/2\pi\,(10\rho T)^{0.5}.$$

For most rocks, the resistivity varies between 1 and 10000 Ωm. Thus for periods varying between 10^{-3} to 10^3 s the depth of penetration varies between a few tens of meters to several tens of kilometers.

For the purpose of this investigation, the horizontal components of the Earth's electric and magnetic field in two orthogonal directions were recorded at 15 sites between October 3 and October 27, 1995. The magnetotelluric field equipment consisted of nonpolarised lead chloride electrodes as sensors for the electric field and induction coils for magnetic field sensors.

A digital data acquisition system controlled by a microcomputer was used to record the data in the field and this particular configuration gave us the possibility to monitor the recorded data quality continuously and to be able to process the data in the field.

Data analysis involved tensor processing of the recorded digital data to provide the variation of the apparent resistivity versus period along the two orthogonal measured directions for every station. In theory, Maxwell's equations imply a linear dependence between the electric (E) and magnetic field (H) at a particular frequency (Vozoff, 1972):

$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} Zxx & Zxy \\ Zyx & Zyy \end{bmatrix} \begin{bmatrix} Hx \\ Hy \end{bmatrix}$$

where Zxx, Zxy, Zyy, Zyx are the elements of the impedance tensor that describe the conductivity structure beneath the measuring point and these are determined as a least squares solution in narrow bands of frequency. Following this to obtain the azimuth of the maximum and minimum resistivity directions we perform rotation of the impedance to minimize the diagonal elements *Zxx* and *Zyy* or to maximize *Zxy* and *Zyx*. In this way two magnetotelluric curves are obtained corresponding to the directions parallel and perpendicular to the tectonic strike.

For a quantitative interpretation of the results two dimensional modelling is performed and the two dimensional structural model is obtained by the forward approach described in detail by Doucet and Pham (1984). In this procedure a starting layered model of electrical resistivity distribution versus depth is constructed and this model is updated by trial and error numerical simulation after comparison of the calculated response with the observations.

3. Results and discussion

Figure 1a shows the geographic location of the investigated region and fig. 1b shows the locations of the 15 measurement sites and their

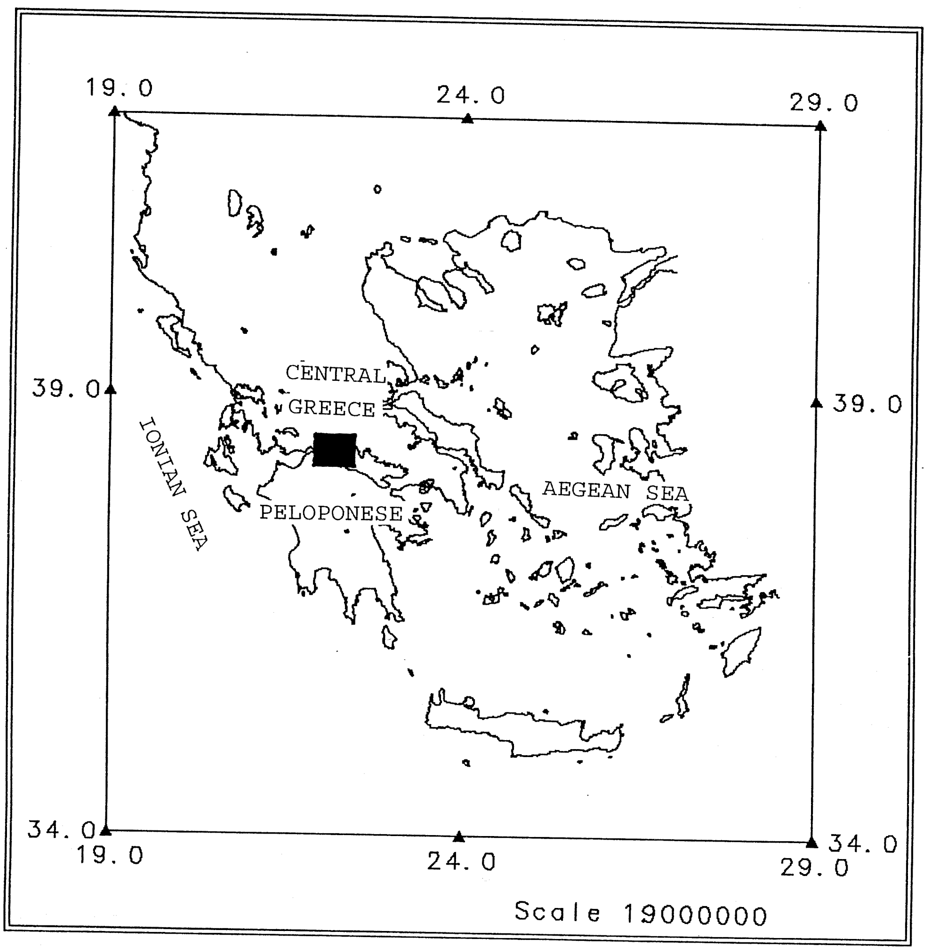

Fig. 1a. Map of Greece showing the investigated region.

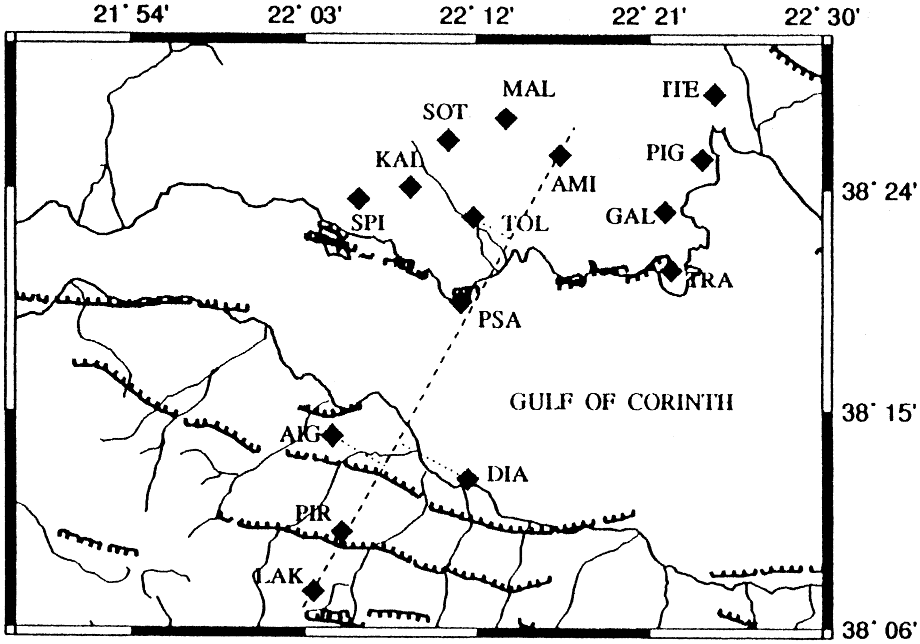

Fig. 1b. Map of the investigated region with the measurement sites.

geographic coordinates. From this distribution one notes a lack of sites covering the south side of the gulf and this is because magnetotelluric measurements could not be conducted there due to the rugged topography and the high level of electromagnetic disturbances from high power lines and mobile telephone transmitters. On the contrary, noise conditions were satisfactory on the north side of the gulf which is less inhabited.

The magnetotelluric results from the tensor analysis show that maxima and minima in resistivity for the vast majority of stations exist along two perpendicular directions. These azimuths are N110° ± 10° and N20° ± 10° respectively and these also correspond very well with the strikes of the principal seismotectonic structures in the gulf.

One exception was found for the station PSA where the directions are N55° ± 5° and N145° ± 5° and these correspond to the orientation of local active faults.

A very conductive zone in the upper crust for the SOT station with a resistivity value less than 1 Ωm in the N20° direction, is one result which aroused the interest of the researchers taking part in the field work during this experiment (fig. 2). This is because simultaneous to the Aigio earthquake the residents of the village eyewitnessed the development of a one meter diameter hole which emitted heavy smoke and a smell resembling methane gas. When the village mayor threw a burning cigarette into the hole an explosion with fire occurred.

The results from the impedance tensor analysis of the magnetotelluric data from the stations LAK, PIR, AIG, DIA, PSA, TOL, AMI (see dotted line in fig. 1b) were used to construct a two dimensional geoelectric model for this profile shown in fig. 3. For each station the resistivity versus period (depth) results were sampled vertically and also along the profile coordinate. This sampling is given by the station spacing projected onto the profile. Details of this distance versus depth interpolation using the finite element method which results in the geoelectric section of fig. 3 is given in detail by Doucet and Pham (1984).

In general, at most stations a resistive and anisotropic upper crust was observed with resistivities up to 10 kΩm. However, conductive and anisotropic superficial layers in the upper crust were observed at the stations located near the coastline of the Gulf of Corinth, DIA, PSA, TRA, GAL and PIG. This is most likely due to the intrusion of saline water in the fractured rock.

Nevertheless, the most interesting result from this investigation was the presence of a thick conductive zone in the middle of the crustal layer at a depth of 9 to 12 km, with a thickness of about 7 km. This feature is seen at all stations and the conductivity varies from 7 Ωm to a few hundred Ωm. On the south side of the gulf this layer dips to the north while on the north side of the gulf it dips to the south.

It is remarkable that the geoelectric section mapped this discontinuity at around 9 to 12 km at the depth of the proposed detachment zone and that the layer under this discontinuity has the resistivity typically attributed to ductile zones due to the presence of fluids (Pham *et al.*, 1990).

In addition, there was a great resistivity contrast at a depth around 28 km at the AMI station. This discontinuity may well mark the Moho since this result is compatible with the results of Makris (1978) regarding the depths to the Moho observed in Greece.

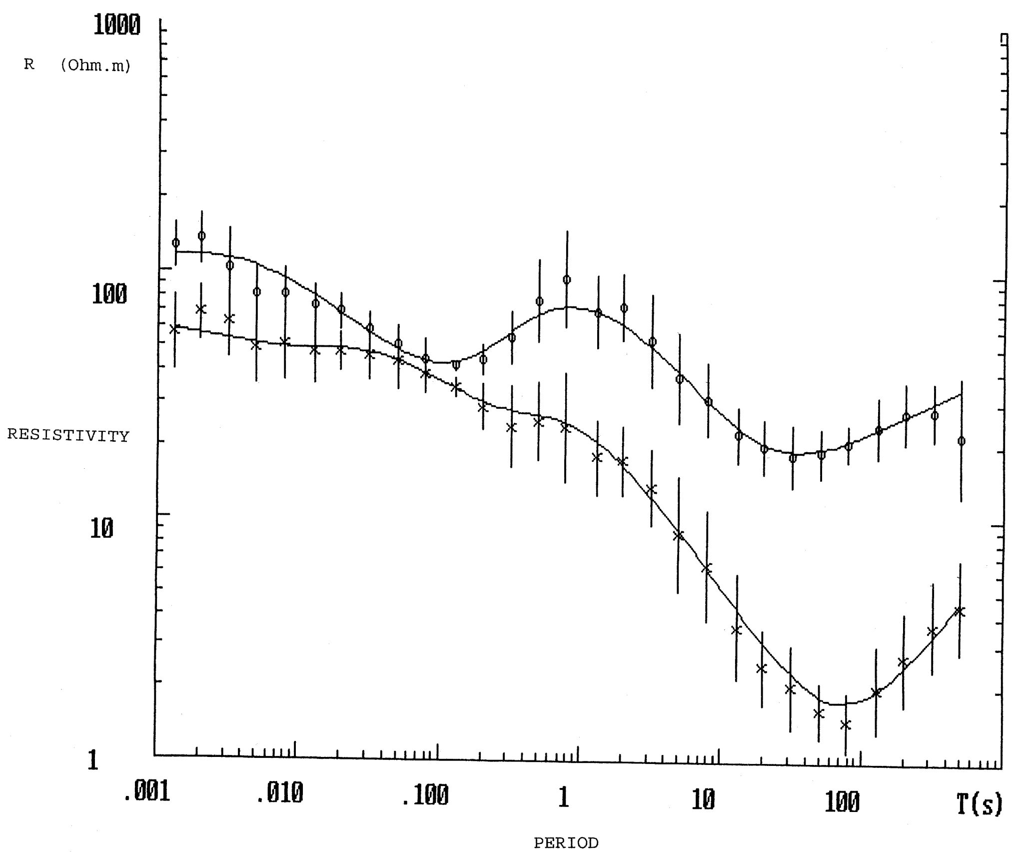

Fig. 2. Magnetotelluric sounding curve from the SOT station. Circles are representing the N110° measuring direction and stars the N20° measuring direction.

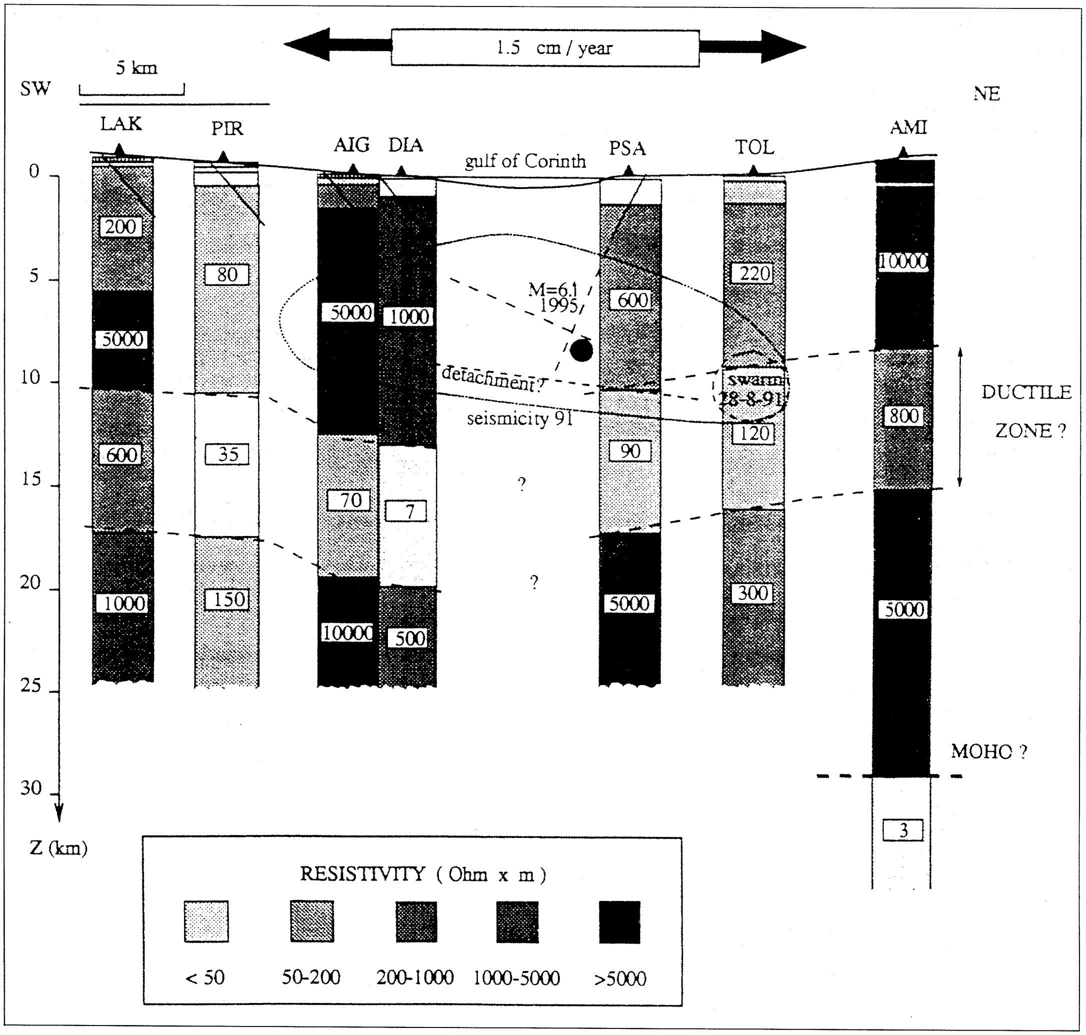

Fig. 3. Geoelectrical section along a N20° profile.

4. Conclusions

The present study investigated the geoelectric structure of a seismogenetic region in the Gulf of Corinth using the magnetotelluric method. In this investigation the number of measured sites and their spatial distribution yield only a preliminary picture of the crustal structure in the region.

The heterogeneity in the geoelectric structure in the Gulf of Corinth is attributed to the superposition of compressive forces in the Pre-Neogene with the extensional forces in the Post-Neogene, thus the older structures are trending NS and the younger ones EW. This configuration explains why seismic activity on the younger EW fault (Aigio) triggers activity on the older NS trending structures (SOT station).

The presence of a detachment zone at a depth of 9 to 12 km around the seismogenetic volume of the Aigio earthquake as proposed by many researchers was confirmed by the magnetotelluric results. This zone has a thickness of 7 km and is electrically conductive as one would expect in the presence of fluids in a shear ductile zone of the lower crust. This ductile zone is a regional phenomenon and the detachment occurs by the uncoupling of the brittle upper crust from a more ductile lower crust.

The Moho discontinuity on the north side of the Gulf of Corinth appears at a depth of 28 km which is in agreement with the results from seismological investigations.

Recently the region of the Gulf of Corinth was chosen as a test site for multiparametric earthquake prediction research by the European Council (GAIA Project). For this reason it is believed that the results of this study will be complimented with more detailed investigations in the near future and in this respect a more accurate picture of the crustal structure will be obtained.

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