Δελτίο Ελληνικής Γεωλογικής Εταιρίας τομ. XXX/5 15-26, 1994
Πρακτικά 7ου Επιστημονικού Συνεδρίου, Θεσσαλονίκη, Μάιος 1994

Bulletin of the Geological Society of Greece vol. XXX/5, 15-26, 1994
Proceedings of the 7th Congress, Thessaloniki, May 1994

MAGNETOTELLURIC RECONNAISSANCE IN THE VOLCANIC COMPLEX OF METHANA PENINSULA, (WEST SARONIKOS GULF, GREECE)

A. Tzanis* and E. Lagios*

ABSTRACT

A wide band (128-0.04Hz) magnetotelluric survey comprising 14 stations was conducted in order to investigate the deep structure, tectonic framework and geothermal potential of Methana volcanic complex. Good data quality combined with the extensive ranges of depths penetrated, (~200m-12km), allow the delineation of shallow and deep conductive structures interpreted as signatures of normal faults associated with the presence of fluids. All the regional faulting features have been identified, but very significant appears to be a N-20°-W fault possibly associated with transportation of geothermal fluids through permeable links between the hot springs of Methana and Palaia Loutra. This intersects conductive enclosures at depths 1500-2500m beneath the centre of the peninsula, possibly comprising zones of fluid concentration.

ΣΥΝΟΨΗ

Μαγνητοτελλουρική διασκόπηση ευρέος φάσματος (128-0.04Hz) διενεργήθηκε προκειμένου να ερευνήσει την βαθιά δομή, τεκτονικό ιστό και γεωθερμικό δυναμικό του ηφαιστειακού χώρου χερσονήσου Μεθάνων. Δεδομένα καλής ποιότητας σε συνδυασμό με το μεγάλο βάθος διασκόπησης, (~200m-12km), επέτρεψαν την ανίχνευση ρηχών και βαθέων αγωγών που ερμηνεύονται ως ίχνη ρηξιγενών δομών συνδεομένων με παρουσία ρευστών. Όλες οι περιφερειακές ρηξιγενείς δομές αναγνωρίσθηκαν στην περιοχή μελέτης, αλλά αξιοσημείωτη φαίνεται να είναι ρήγμα παράταξης N-20°-W, πιθανόν σχετιζόμενο με μεταφορά γεωθερμικών ρευστών μέσω διαπερατών οδών συνδεουσών τις περιοχές θερμών πηγών Μεθάνων και Παλαιών Λουτρών. Το ρήγμα αυτό διατέμνει αγώγιμους θύλακες σε βάθη 1500-2500m υπό το μέσο της χερσονήσου, οι οποίοι ερμηνεύονται ως ζώνες συγκέντρωσης ρευστών.

INTRODUCTION

Methana peninsula is a small Quaternary volcanic complex, erected by extrusion of basaltic-andesitic to dacitic material forming domes or lava flows and lava beds. It is considered to comprise the westernmost surface expression of the Hellenic Volcanic Arc and it has been active in historical times. For an informative account of its volcanological characteristics refer to Fytikas et al, (1987).

The geologic and tectonic environment of the peninsula is illustrated in Figure 1, drawn on the basis of information from Papanikolaou et al, (1989) and Fytikas et al (1984). Emphasis is given in presenting the details of the regional tectonic framework, while the illustration of lithological formations

---

* Both at Department of Geophysics and Geothermy, University of Athens. Panepistimioupolis, Ilisia, 157 84 Athens, Greece.

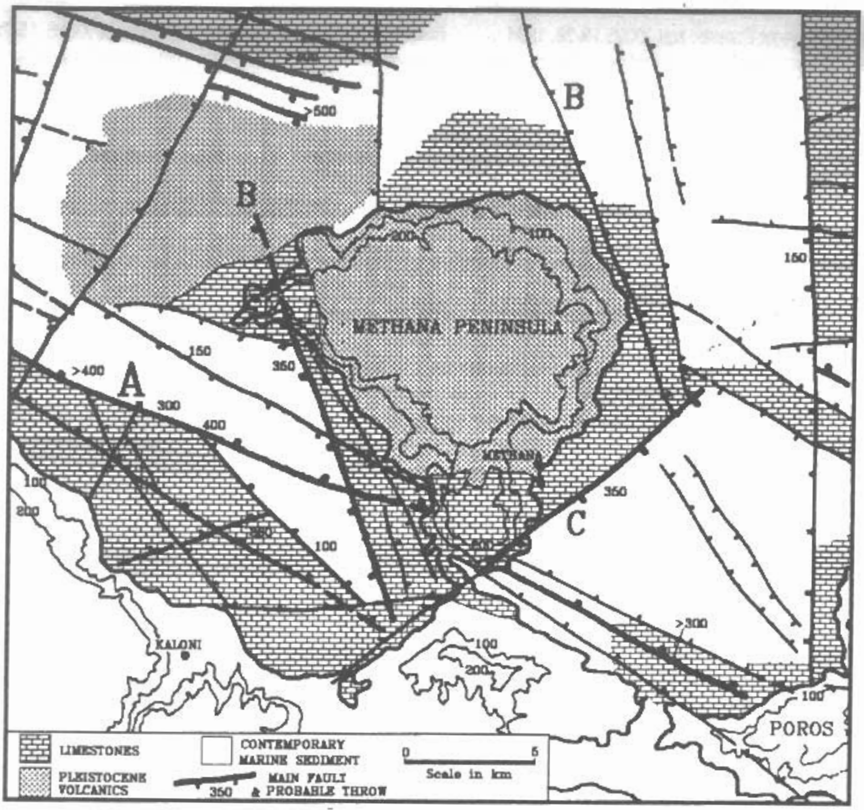

Fig.1: Tectonic and simplified geological map of Methana peninsula, after Papanikolaou et al, (1989) and Fytikas et al, 1984). A,B and C are the major regional normal faulting zones (with throws also indicated where measured.

Σχ. 1: Τεκτονικός και απλοποιημένος γεωλογικός χαρτης της χερσονησου Μεθάνων, από Παπανικολάου κ.ά, (1989) και Φυτίκα κ.ά (1984). Α, Β και C οι μεγάλες ρηξιγενείς ζώνες της περιοχής, με σημειωμένα άλματα ρηγμάτων, όπου αυτά έχουν μετρηθεί.

is simplified, intending only to show the mode of emergence of the volcanic rocks through the sedimentary carbonate rock formations (Triassic-Eocene limestones).

The regional neotectonic structure is controlled by three major normal faulting zones of direction N-70°-W (zone A), N-20°-W (zone B) and N-50°-E (zone C), which also appear to bound the lateral development (expansion)of the volcanic complex. In the immediate vicinity of the peninsula, the three faulting zones appear with throws of the order of 350m. The apparently most significant of the three zone A, frequently exhibits throws in excess of 400m-500m and contributes fundamentally in the neotectonic evolution of the broader area of Methana peninsula.

At first sight, the probability of abundant geothermal energy accumulating underneath Methana peninsula appears to be rather remote. According to *Geotermica Italiana*, (1984), the geochemical and petrological characteristics of the volcanic rocks indicate that magmatic differentiation processes leading to their formation have taken place at great depths and not near the surface (specifically, near the base of the lower crust or at the crust- mantle boundary). Thus, the possibility of a shallow magma chamber feeding a convective geothermal system appears rather remote. According to the same source nevertheless, the young age of the volcanic activity, (even at historic times), does not preclude the existence of some significant geothermal anomaly at accessible depths beneath the surface of the peninsula. The quest for the discovery of this anomaly however, presents considerable problems.

The interpretation of the geochemical analysis of fluids from the hot springs of Methana town is rmade difficult, and is even sometimes misguided by the extensive mixing of geothermal fluids with sea water (Geotermica Italiana, 1984). Some results however, do indicate that these fluids might have had an initial temperature of 100-120°C, provided that before discharging, they circulated in a substratum comprising carbonate rocks, or were stored in a reservoir within carbonate rocks (Geotermica Italiana, 1984). The same source questions the existence of a geothermal reservoir but it does not preclude the concentration of hot fluids within faulting structures at great depths.

Besides the above problems, Methana peninsula is geographically restricted and the topography of the volcanic edifice disaccessible (or inaccessible at some points), inhibiting the realisation of multi-disciplinary geophysical investigations. There are no indications for the existence of structural features (depressions, grabens) that might store fluids and be detectable with gravity or magnetic methods. Seismic (refraction or reflection) methods cannot be applied and the passive (seismological) investigations may not yield results due to the absence of seismic noise and/or microearthquakes generated by the geothermal system; it is possible however that some seismological techniques (e.g. tomography), may be able to exploit signals from nearby earthquakes, if and when they occur. The applicability of DC geoelectric methods in deep exploration is drastically constrained, either due to rough topography (Schumberger and Wenner), or geographical restrictions (e.g. dipole-dipole or roving dipole). Thus, it is not peculiar that only geological and geochemical studies have been conducted in the area, the geophysics being limited to some applications of the Self Potential method only.

In this paper we present results from a Magnetotelluric (MT) survey conducted in order to overcome some of the above problems by exploiting the deep penetration capability of the MT method and its faculty to distinguish the spatial characteristics of the geoelectric structure. Specifically, given the deep origin of thermal fluids, the purpose of the survey was to explore the intermediate/deep structure and determine the configuration and depth extent of the most important fluid transportation conduits, as well as the tectonic framework accommodating them.

The fieldwork was conducted in cooperation with the Department of Geology and Geophysics of the University of Edinburgh (Mr G.J.K. Dawes), using the Short Period Automatic Magnetotelluric system (S.P.A.M. model MkIIb), designed and constructed in Edinburgh by Mr G.J.K. Dawes. The survey comprised a total of 23 soundings in the nominal frequency bandwidth 128Hz-40s. Only 14 soundings are used in this presentation, the locations of which are shown in Figure 2. Of the remaining 9,

- Four (128B,R and 129B,R) are located outside the peninsula and are not included herein.
- One (126R) is redundant, being a test site positioned in the immediate vicinity of 126B.
- Three (121B,R and 132) can be considered lost to exceptionally intense anthropogenic noise.

(specifically, near the base of the lower crust or at the crust- mantle boundary). Thus, the possibility of a shallow magma chamber feeding a convective geothermal system appears rather remote. According to the same source nevertheless, the young age of the volcanic activity, (even at historic times), does not preclude the existence of some significant geothermal anomaly at accessible depths beneath the surface of the peninsula. The quest for the discovery of this anomaly however, presents considerable problems.

The interpretation of the geochemical analysis of fluids from the hot springs of Methana town is rmade difficult, and is even sometimes misguided by the extensive mixing of geothermal fluids with sea water (Geotermica Italiana, 1984). Some results however, do indicate that these fluids might have had an initial temperature of 100-120°C, provided that before discharging, they circulated in a substratum comprising carbonate rocks, or were stored in a reservoir within carbonate rocks (Geotermica Italiana, 1984). The same source questions the existence of a geothermal reservoir but it does not preclude the concentration of hot fluids within faulting structures at great depths.

Besides the above problems, Methana peninsula is geographically restricted and the topography of the volcanic edifice disaccessible (or inaccessible at some points), inhibiting the realisation of multi-disciplinary geophysical investigations. There are no indications for the existence of structural features (depressions, grabens) that might store fluids and be detectable with gravity or magnetic methods. Seismic (refraction or reflection) methods cannot be applied and the passive (seismological) investigations may not yield results due to the absence of seismic noise and/or microearthquakes generated by the geothermal system; it is possible however that some seismological techniques (e.g. tomography), may be able to exploit signals from nearby earthquakes, if and when they occur. The applicability of DC geoelectric methods in deep exploration is drastically constrained, either due to rough topography (Schumberger and Wenner), or geographical restrictions (e.g. dipole-dipole or roving dipole). Thus, it is not peculiar that only geological and geochemical studies have been conducted in the area, the geophysics being limited to some applications of the Self Potential method only.

In this paper we present results from a Magnetotelluric (MT) survey conducted in order to overcome some of the above problems by exploiting the deep penetration capability of the MT method and its faculty to distinguish the spatial characteristics of the geoelectric structure. Specifically, given the deep origin of thermal fluids, the purpose of the survey was to explore the intermediate/deep structure and determine the configuration and depth extent of the most important fluid transportation conduits, as well as the tectonic framework accommodating them.

The fieldwork was conducted in cooperation with the Department of Geology and Geophysics of the University of Edinburgh (Mr G.J.K. Dawes), using the Short Period Automatic Magnetotelluric system (S.P.A.M. model MkIIb), designed and constructed in Edinburgh by Mr G.J.K. Dawes. The survey comprised a total of 23 soundings in the nominal frequency bandwidth 128Hz-40s. Only 14 soundings are used in this presentation, the locations of which are shown in Figure 2. Of the remaining 9,

- Four (128B,R and 129B,R) are located outside the peninsula and are not included herein.
- One (126R) is redundant, being a test site positioned in the immediate vicinity of 126B.
- Three (121B,R and 132) can be considered lost to exceptionally intense anthropogenic noise.

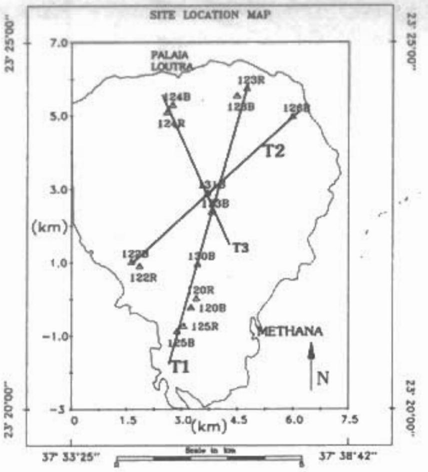

Fig 2: The distribution of MT soundings on Methana peninsula. T1, T2, T3 are the resistivity pseudosections of Figures 4,5 and 6a,b respectively.

Σχ 2: Κατανομη των MT βαθοσκοπήσεων στην χερσόνησο Μεθάνων. T1, T2 και T3 είναι οι ψευδοτομές ειδ. αντίστασης των σχημάτων 4,5 και 6a,b αντιστοίχως.

· One (127), located at the far west of the peninsula exhibits peculiar physics and is not included in the presentation.

DATA ANALYSIS AND RESULTS

The Magnetotelluric (MT) method is based on the phenomenon of natural (passive) electromagnetic induction, in which horizontal, plane polarised (sub)vertically propagating source magnetic fields generated by magnetospheric or ionospheric processes, enter and induce electric (telluric) currents in a conducting Earth, free of sources or sinks of electromagnetic energy. The total horizontal magnetic and electric fields are obtained in the form of mutually orthogonal components in an orthonormal (cartesian) experimental frame of reference. In the frequency domain, they are linearly related as $E(\omega)=Z(\omega)H(\omega)$, where $Z(\omega)$ is a cartesian tensor of rank 2, representing the (input) impedance of the Earth and conveying information about the quantitative and spatial characteristics of the geoelectric structure in the vicinity of the recording station.

Because the source field is plane and horizontal, any vertical magnetic component that may appear will have to have been generated within the Earth and will owe its existence to secondary inductive phenomena at the interfaces of laterally inhomogeneous geoelectric structures. The single site vertical field transfer function or Magnetic Transfer Function (MTF) consists of two complex quantities $A(\omega)$, $B(\omega)$, mapping the horizontal components of the magnetic field on to the vertical, according to the relationship $H_z(\omega)=A(\omega)\cdot H_x(\omega)+B(\omega)\cdot H_y(\omega)$. The MTF conveys information about the configuration of laterally inhomogeneous structures in the vicinity of the measurements.

Detailed accounts on the MT methods can be found in Rokityansky (1982) and Vozoff (1985), as well as in Karmis et al (1994).

The estimation of the experimental MT tensor impedance (MTTI) and the MTF was based on fairly standard, least squares, frequency domain procedures, (Sims et al., 1971), supplemented with the robust methods of Tzanis and Beamish (1989) and Tzanis (1988) in order to suppress the effects of anthropogenic noise and reduce the biasing effects of random and anthropogenic noise.

1. Spatial Analysis - The Tectonic Framework

The spatial analysis of the MT tensor impedance (MTTI) attempts to decode information pertaining to the configuration of EM inductive processes in space. These, in turn, depend uniquely on the geometry and configuration of lateral inhomogeneities in the geoelectric structure. In this case, spatial analysis was performed using the generalised theory of Tzanis (1988, 1992), which provides as a fuction of frequency, the magnitude, phase, azimuth and inclination of the maximum and minimum characteristic states of the MTTI,

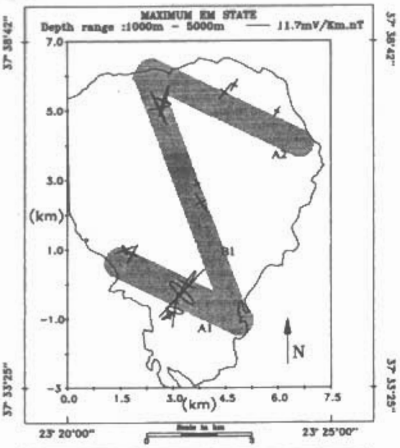

Fig. 3a: Spatial analysis of the MT tensor impedance. The Maximum Characteristic State is illustrated. Thick gray lines indicate the detected elongate conductive zones interpretated as fault structures.

Σχ. 3α: Χωρική ανάλυση των ΜΤ τανυστών εμπέδησης. Απεικονίζονται μόνον οι Μέγιστες Χαρακτηριστικές Καταστάσεις. Οι παχείες ανοικτότεφρες γραμμές καταδεικνύουν τις ανιχνευθείσες επιμήκεις αγώγιμες ζώνες που ερμηνεύονται ως ρηξιγενείς δομές.

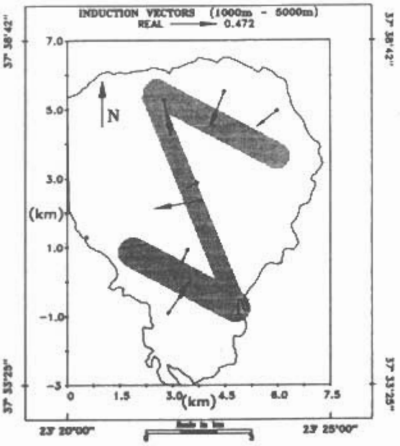

Fig. 3b: Spatial analysis of the real induction vectors. The thick gray lines are interpreted as per Fig. 3a.

Σχ. 3β: Χωρική ανάλυση των πραγματικών επαγωγικών ανυσμάτων. Οι παχείες ανοικτότεφρες γραμμές ερμηνεύονται όπως και στο Σχ. 3α.

respectively described by the relationships:

$E(\omega,\Theta_E,\Phi_E)=\mu_{1(\omega)}H(\omega,\Theta_H,\Phi_H+\pi/2)$, and $E(\omega,\Theta_E,\Phi_E+\pi/2)=\mu_{2(\omega)}H(\omega,\Theta_H,\Phi_H)$

where:

· $E(\omega,\Theta_E,\Phi_E)$ and $E(\omega,\Theta_E,\Phi_E+\pi/2)$ represent the maximum and minimum electric field at the angular frequency ω, along the directions (Θ_E,Φ_E) and $(\Theta_E,\Phi_E+\pi/2)$ respectively.

· $\mu_1(\omega) > \mu_2(\omega)$ are the complex maximum and minimum impedances along the directions (Θ_E,Φ_E) and $(\Theta_E,\Phi_E+\pi/2)$ respectively, and comprise a quantitative measure of the attenuation of the natural EM field at the angular frequency ù, as it propagates through the Earth.

· $H(\omega,\Theta_H,\Phi_H)$ and $H(\omega,\Theta_H,\Phi_H+\pi/2)$ respectively represent the maximum and *minimum magnetic field at the angular frequency ω, along the directions* (Θ_H,Φ_H) and $(\Theta_H,\Phi_H+\pi/2)$.

· Φ represents the azimuthal direction of the electric/magnetic fields and is associated with the local strike of the geoelectric structure.

· Θ is the inclination of the electric/magnetic fields, also admitting an equivalent representation as the ellipticity of elliptically polarised EM

field components in the horizontal plane (=tanΘ).

· It can easily be verified tnat in the case of 1D and 2D geoelectric structures $\Phi_E=\Phi_H$ and $\Theta_E=\Theta_H=0$. In 3D structures however, one should rather observe $\Phi_E \neq \Phi_H$ and $\Theta_E \neq \Theta \neq H0$.

The spatial properties of the geoelectric structure as derived from the analysis of the MTTI are summarised in Figure 3a, presenting the Maximum Characteristic States (MCS) in the form of averages over the skin depth interval 1-5km. The skin depths have been calculated from the average, azimuthally invariant impedance function $Z_a(\omega)=(Z_{yx}(\omega)-Z_{xy}(\omega))/2$, which comprises the half-trace of the impedance tensor and has the physical meaning of a spatially smoothed variation of resistivity with depth. The results indicate that *the geometry and dimensionality of the geoelectric structure cannot be higher than 2D*, since the ellipticities Θ_E, Θ_H are very small and $\Phi_E \approx \Phi_H$.

Consider now that by definition, the maximum electric field $E(\Theta_E, \Phi_E)$ is *parallel* to the local strike of maximum resistivity. Then, given the constraints arising from Maxwell's equations, the spatial analysis of the MTTI is based on the following simple rules (see also Swift, 1971):

· On the conductive side of a lateral 2D interface, the maximum electric field will be parallel to the strike of the interface and will represent the Transverse Electric (TE) mode of EM field propagation.

· On the resistive side of a lateral 2D interface, the maximum electric field will be normal to the strike of the interface and will represent the Transverse Magnetic (TM) mode of EM field propagation.

Using these rules alone, one can define the correct configuration of a 2D interface only if the lateral resistivity contrast is very high, so that the TE and TM modes can be unequivocally distinguished. In the case of low resistivity contrasts, such as Figure 3a indicates to be the case in a large part of Methana, one can define the spatial properties of the interface uniquely, only by using the information contained in the MTF.

The spatial analysis of the MTF is based on the common method of induction vector (IV) representation. The IV comprises a magnitude and an azimuth that defines the normal to the strike of a local geoelectric lateral gradient, producing an anomalous concentration of current. Two such vectors are defined for vertical fields responding in-phase *(real)* and out-phase *(imaginary)* with the horizontal component with which the vertical field exhibits maximum correlation. The IV representation of the MTF admits a simple interpretation when the structure is 2D; in such circumstances the real and imaginary IV will be parallel or anti-parallel and perpendicular to the lateral conductivity inhomogeneity (e.g. Rokityansky, 1982). In the case of 3D structures, the IV define the normal to the local strike of the anomalous concentration of current which produces the anomalous magnetic field and are oblique to each other. In this paper, and since the spatial characteristics of the MTTI *do not* indicate the presence of appreciable 3D induction effects, we only make use of the real IV for simplicity and brevity. The vector is drawn in the Parkinson convention, so that it will be normal to the 2D interface and point towards current concentrations (i.e. towards the conductive side of the inhomogeneous structure).

The spatial properties of the geoelectric structure as derived from the analysis of the MTF are summarised in Figure 3b, presenting the real IV in the form of averages over the skin depth interval 1-5km. The skin depths have been calculated as per Figure 3a, from the invariant impedance function $Z_a(\omega)$. An element of caution should be applied when interpreting the IV of soundings 123, 124 and 126, because they contain indication that they may be influenced by the curvature of the peninsula and/or distorted by induction processes in the marine area to the N and NE of the peninsula.

In a final step and following the above discussion, the properties of the MTTI and the MTF can be combined, leading to the following simple rules for the spatial analysis of 2D structures:

- When the maximum electric field and the real IV are tangential, the MT sounding site is located on the resistive side of a 2D interface.
- When the maximum electric field and the real IV are normal, the MT sounding site is located on the conductive side of a 2D interface

Implementation of these rules facilitates the unique determination of the location and strike of linear conductive zones, which in Figures 3a,b are illustrated with light grey shading. In a geotectonic environment and geothermal system controlled by extensional tectonics, (such as the one of Methana is believed to be), deep elongate conductors usually represent faulting structures associated with the presence (or circulation) of fluids - see Tzanis and Lagios, (1993) and Tzanis et al, (1994) for detailed explanations.

It is apparent that all the linear conductors detected by the survey are aligned parallel to the regional normal faulting zones A and B and, therefore, can be attributed to them. Note however that the somewhat inadequate horizontal distribution of MT soundings (resulting from insurmountable topographic obstacles), only the southernmost zone A is constrained bilaterally, and again only by the IV. B1 can located with certainty, but only from unilateral observations, so that its width cannot be defined. Due to the aforementioned reservations about the IV of sites 123,124 and 126, the existence and strike of A2 is determined by the MCS, with the IV serving only as auxiliary indicators of its relative position. Faulting zone C does not appear on the peninsula, at least in the immediate vicinity of the sounding sites.

Particular attention should probably be paid to the N-20°-W trending conductor designated as B1 in Figures 3. This feature can be positioned with fair precision, because it is known to:

- appear underneath sites 131B and 133B,
- pass *between* sites 124B and 124R, as is clearly demonstrated by the marked difference in the configuration of the Maximum Characteristic States of the MTTI.

Thus constrained, the southward extension of B1 will have to pass through Methana town and its northward extension nearby the area of Palaia Loutra, both of which are associated with the occurrence of thermal springs. An obvious connotation is that B1 comprises a faulting structure associated with circulation of geothermal fluids.

2. Quantitative Analysis - The Resistivity Structure

The quantitative interpretation of MT data requires an adequate understanding of the geoelectric dimensionality of the structure, so as to implement techniques compatible with the physical constraints arising from the different modes of EM induction in media of different geoelectric structural dimensionality. The necessary information is conveyed in Z.

The spatial analysis clearly demonstrated the absence of discernible 3D geoelectric structures. The Kao and Orr (1982) normalised dimensional indices demonstrated a dominant 1D geoelectric structural component, (typically over 80% contribution in the composition of the MTTI). At frequencies f>1Hz, the 1D structural component exceeds 85-90% and only at f<1Hz, it drops to the level of 80% or lower. The 2D structural component varies in the range 10-20%, with the higher values appearing at the southernmost soundings 125B,R and 120B,R. In a final step, the application of the fully analytic, non-linear inverse

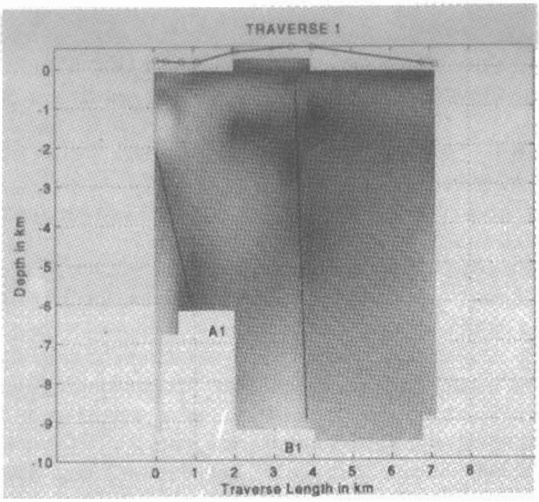

Fig. 4: True resistivity pseudosection along Traverse 1 (see Fig. 2). The resistivity grey scale *(white-black)→(most resistive-most conductive)* is common in all Figures 4,5 and 6 and is presented in Figure 5.

Σχ. 4: Ψευδοτομή πραγματικής ειδ. αντίστασης κατά μήκος της Τομής 1 (Σχ. 2). Η κλίμακα ειδικής αντίστασης, *(λευκό-μαύρο)→(πλέον υψηλή - πλέον χαμηλή)*, είναι κοινή σε όλα τα Σχήματα 4,5 και 6, παρουσιάζεται δε στο Σχήμα 5

theory of Parker (1980) has certified the ubiquitous existence of analytic solutions to the inverse problem in D^+ and, therefore, provided the necessary and sufficient conditions for the existence of geoelectric structure sufficiently interpretable with 1D analysis tools. The details of the dimensionality analysis can be studied in Lagios (1992).

In the present study, we implement 1D analytic inversions of the invariant impedance Z_a, carried out with the fully analytic and non-linear method of Parker (1980) and Parker and Whaler (1981), referred to as C^{2+}. The method is generically related to D^+ and yields continuous conductivity versus depth profiles. The detailed results are also included in Lagios (1992). Herein, they are presented in the form of four true resistivity pseudosections constructed by collation of 1D C^{2+} inverse solutions (see Figure 2). A natural (1:1) horizontal and vertical scale is used throughout.

Turning first our attention to the longest and most complete pseudosection T1, (Figure 4), we note that its southern half (from km 0-4.4), is covered with a satisfactory density of soundings and can be easily interpreted. One can easily distinguish the major faulting features A1 and B1 detected by the spatial analysis, as sub-vertical conductive (<20Ωm) zones descending to depths of 9km at least, with apparent dip angles compatible with those expected for normal faults. It is also noteworthy that the two faulting zones appear to communicate at depths >7km. Particular attention should be paid to the conductive enclosure located approximately underneath the centre of the peninsula, at depths 1000-2000m. It is very probable that it comprises zone(s) where fluids concentrate and/or circulate laterally and vertically; such a zone could well function as a geothermal reservoir. In the northern half of T1, from km 4,5 to 7.3, the spacing of MT soundings is inadequate due to the inaccessible terrain. There exist results only for the two northernmost soundings 123B and 123R, and as a consequence the interpretation of the geoelectric structure is rather difficult (if at all possible) in the interval 4.5-6.5 km, and quite problematic in the remaining part, up to the end of T1.

The resistivity structure along traverse T2 can be studied in Figure 5. As is apparent, the spacing of MT soundings is rather wide, (only 3 over a distance of 6km) and therefore, only the very gross geoelectric structural characteristics may be seen. At depths <3000m the electrical structure is stratified, with good, laterally coherent conductors appearing at sea level (invasion by sea water) and at depth 1500-2000m. Still, the interpretation of the latter feature will remain dubious due to the inadequate spacing of the soundings and therefore none shall be elaborated herein. The traverse is presented mainly for the purpose of showing the differences between the NE and the SW-Central part of the peninsula. The most apparent feature at depth is a transversal change in resistivity from conductive (<15Ωm) to resistive (>100Ωm), occurring at depths >3000m, between kilometres 3 and 6 along the traverse (between sites 131 and 126B at its NE end). As a matter of fact, this kind of lateral resistivity transition was expected from the spatial analysis of the MTTI and the MTF at site 126B. The deep structure at the SW end of the traverse is very conductive (2-12Ωm) and may be attributed to the abundant presence of fluids. There is no indication that the origin of these fluids is geothermal, although the very low resistivities indicate that they certainly are saline. One plausible hypothesis is that they comprise sea water infiltrating to great depths through the major faulting zone A and possibly mixing with other saline fluids of geothermal origin.

Traverse T3 has been designed to show the differences in the geoelectric structure between sites 124B and 124R. Figure 6a illustrates the vertical resistivity distribution along the line joining sites 131B-133B-124B, which is designated as Traverse 3.1. Figure 6b is the same for the line 131B-133B-124R and is designated as Traverse 3.2. It is immediately apparent that the geoelectric structure underneath site 124B is considerably more resistive than the structure underneath 124R, especially at depths >2500m. This is more or less the resistivity distribution expected from the spatial analysis of the MTTI and confirms that a conductive zone crosses the area between sites

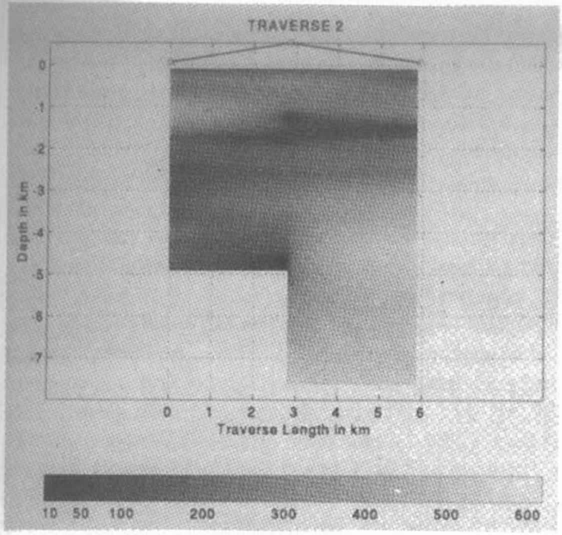

Fig.5: True resistivity pseudosection along Traverse 2 (see Fig. 2)

Σχ. 5: Ψευδοτομή πραγματικής ειδ. αντιστασης κατα μήκος της Τομης 2 (Σχ. 2).

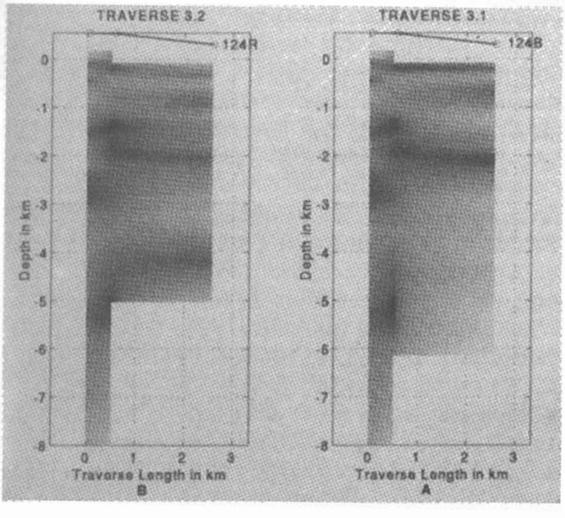

Fig.6: True resistivity pseudosection(A) along Traverse 3.1 and (B) along Traverse 3.2 The resistivity grey scale is common in all Figures 4,5 and 6 and presented in Figure 5.

Σχ. 6: Ψευδοτομή πραγματικής ειδ. αντίστασης (A) κατά μήκος της Τομής 3.1 και (B) κατα μήκος της Τομής 3.2. Η κλίμακα ειδικής αντίστασης είναι κοινή σε όλα τα Σχήματα 4,5 και 6, παρουσιάζεται δε στο Σχήμα 5

124B and 124R. Note however that the magnitude of resistivity contrast between the two sites should be interpreted with caution, inasmuch as C^{2+} tends to exaggerate vertical resistivity gradients. At nay rate, the resistivity contrast is expected to be somewhat low, since the necessary and sufficient conditions for the existence of 1D solutions are upheld in both sites.

DISCUSSION - CONCLUSIONS

The MT reconnaissance of Methana peninsula achieved deep penetration and provided new information and insight into the deep structure of the volcanic complex and its associated geothermal system.

The shallow geoelectric structure (<1000m) has not been discussed in the foregoing. In all figures 4,5 and 6 however, it may be seen to comprise a complex and sometimes laterally incoherent sequence of alternating resistors and conductors. A low conductivity layer definitely exists at sea level. We interpret these observations as resulting from laterally discontinuous stacks of resistive lava beds, lava flows and pyroclastic formations, wrapped around by anastomosing, water-soaked, electrically conducting zones which have been formed by their alteration from sea and meteoric water infiltrating *latteraly* between the bedding surfaces and interfaces. It may also be noted that the geoelectric structure is only beginning to be explored from a depth of ~200-300m downwards, due to the very high resistivity of the near-surface volcanic formations rendering them transparent to high frequency EM fields.

The survey confirmed the existence and approximate location of major faulting zones with particular reference to areas covered by young volcanic rocks, where neither the surface geological reconnaissance, nor the remote sensing techniques could distinguish any. In the MT data, these appear as elongate or linear conductors because by spreading apart, normal faults facilitate the infiltration of surface or near-surface waters and the circulation of subterranean fluids. These faulting zones can be identified with the regional, normal faulting systems trending N-70°-W (zone A) and N-20°-W (zone B).

From a geothermal point of view, the survey confirmed Geotermica Italiana, (1984), which anticipated the circulation of fluids through faulting structures at great depths. From this perspective, the most important zone appears to be a N-20°-W striking structure designated as B1 in figures 3, which brings in (direct) permeable communication the localities of Methana town and Palaia Loutra, both known for the surface thermal spring activity occurring in their vicinity.

It is reasonable to suggest that B1 may be in direct permeable link with the sea, since it bisects the peninsula from coast to coast. Moreover, the deep resistivity data indicate that faulting zones B1 and A1 (in Figure 3), may communicate at great depths. Thus, it is also reasonable to suggest that sea water infiltrates through these faulting structures to considerable depths, possibly mixing with ascending geothermal fluids. These findings are consonant with the geochemical analyses of surface thermal waters reported in Geotermica Italiana (1984), which determined that prior to discharging, the geothermal fluids have undergone extensive mixing with cold sea water.

B1 also appears to intersect an extensive conductor located approximately under the centre of the peninsula, at depths 1200-2500m. This is interpreted to comprise a domain of active fluid circulation and concentration, functioning as a geothermal reservoir.

The capacity of this reservoir can be estimated to a fair approximation.

Based on the geochemical analyses, (it is safe to) assume a liquid fraction with salinity at least equal to that of sea water, having a temperature dependence of $\rho_w=(3+T^\circ C/10)^{-1}$ (Lee et al, 1983). Considering that the bulk resistivity $\tilde{n}_r$ of the 'reservoir' formations is, 3-5 Ωm, the *formation factor* $F=\rho_r/\rho_w$, varies in the interval 10.5-62 by assuming temperatures in the interval 50°C-120°C. This ensures effective porosities of the order 25%-12% according to Archie's law (see also Keller and Rapolla, 1974, for more details).

These results indicate that the rock formations hosting the 'reservoir' exhibit high hydraulic permeability. Note however that the higher the temperature at depth, the lower the capacity of the 'reservoir' appears to be. The same geochemical analyses have determined that the surface thermal fluids might have had initial temperatures of 100-120°C, provided that before discharging, they remained in a carbonate rock environment. The EM fields cannot, of course, distinguish lithological variations at great depths and therefore, no answer to such questions can be given at present.

ACKNOWLEDGEMENTS

The reported work was financed by the Government of Greece through project 90ΠΣ5 of the General Secretariat for Research and Technology (Ministry of Industry Research and Technology) and the Public Power Corporation of Greece. We greatly appreciate the assistance of Ms Theodora Volti, Mr Dimitrios Kosmatos and Mr Ioannis Giannopoulos during the field campaign.

REFERENCES

FYTIKAS, M., INNOCENTI, F., and MAZZUOLI, R. (1984). Geological map of Greece 1:50.000, Methana Sheet, I.G.M.E., Athens.

FYTIKAS, M., INNOCENTI, F., KOLIOS, N., MANETTI, P. and MAZZUOLI, R. (1987). The Plio-quaternary volcanism of Saronicos area (western part of the active Aegean volcanic arc) *Ann. Geol. Pays Hellen.*, 23-44.

GEOTERMICA ITALIANA, SLR. (1984). IGME: Methana-Poros, Loutraki-Sousaki, Platystomon, Aedipsos Geothermal Projects, Final Report, IGME, Athens.

KAO, D. and ORR, D. (1982). Magnetotelluric studies in the Market Weighton area of eastern England. *Geophys. J. R. astr. Soc.*, 70, 323-337.

KARMIS, P., TZANIS, A. and LAGIOS, E. (1994). Electromagnetic methods of geophysical investigation: A review and their applications in Greece. *Proceedings, 2nd Congress of the Hellenic Geophys. Union*, Florina, Greece, 5-7 May 1993 (in press; in Greek with English abstract).

KELLER, G.V. and RAPOLLA, A. (1974). Electrical prospecting methods in volcanic and geothermal environments. *In L. CIVETTA, P. GASPARINI, G. LUONGO and A. RAPOLLA (ed.), Physical Volcanology,* 133-166, Elsevier,

LAGIOS, E. (1992). Magnetotelluric investigations in the geothermally prospective areas of Sousaki and Methana, Volume II, Methana. Final technical report submitted to General Secretatiat for Research and Technology, programme 90ĐÓ5 (in Greek).

LEE, C.D., VINE, F.J. and ROSS, R.G. (1983). Electrical conductivity models for the continental crust based on laboratory measurements of high grade metamorphic rocks, *Geophys. J. R. astr. Soc.*, 72, 353-371.

PAPANIKOLAOU, D., CHRONIS, G., LYKOUSIS, B. and PAVLAKIS, P. (1989). Undersea neotectonic map of Saronikos gulf. Published by Org. of Earthquake Planning and Protection (ΟΑΣΠ), National Centre of Oceanographic Research (ΕΚΘΕ) and Department of Dynamic, Structural and Applied Geology, University of Athens, (in Greek).

PARKER, R.L. (1980). The inverse problem of electromagnetic induction: Existence and construction of solutions based on incomplete data. *J. Geophys. Res.*, 85, 4421-4428.

PARKER, R.L. and WHALER, K.A. (1981). Numerical methods for establishing solutions to the inverse problem of electromagnetic induction, *J. Geophys. Res.*, 86, 9754- 9784.

ROKITYANSKY, I.I. (1982). Geoelectromagnetic investigations of the Earth's Crust and Mantle. Springer Verlag.

SIMS, W.S., BOSTICK, F.X. JR and SMITH, H.W. (1971). The estimation of magnetotelluric impedance tensor elements from measured data. *Geophysics*, 36, 938- 942.

SWIFT, C.M. (1971). Theoretical magnetotelluric and Turam response from two-dimensional inhomogeneities. *Geophysics*, 36, 32-52.

TZANIS, A. (1988). Investigations on the properties and estimation of Earth-response operators from EM sounding data. PhD Thesis, University of Edinburgh.

TZANIS, A. and BEAMISH, D. (1989). A high resolution spectral study of audiomagnetotelluric data and noise interactions. *Geophys. J. Int.*, 97, 557-572.

TZANIS, A. (1992). Generalised rotation analysis of the magnetotelluric tensors in three dimensions: A group theoretical approach, XVII EGS Gen. Assembly, Edinburgh, 6-10 April 1992.

TZANIS, A. and LAGIOS, E. (1993). On the relationship between active tectonics and fluid circulation in the geothermal system of Nissyros caldera, *Bull. Hell. Geol. Soc.*, XXVIII, No2, 587-603 (in Greek with abstract in English).

TZANIS, A., MAKROPOULOS, K.C., MARTIN, J-L., CORMY, G. and DRAKOPOULOS, I. (1994). Contribution to the study of tectonic deformation in south-east Thessaly, Greece: Geomagnetic Deep Sounding and Seismotectonic observations. *Proceedings, 2nd Congress of Hell. Geophysical Union*, 5-7 May, Florina, Greece (in press).

VOZOFF, K. (1985). Magnetotelluric methods. *SEG, Geophysics reprint series* No 5.