MAGNETOTELLURIC EXPLORATION OF SOUSAKI GEOTHERMAL PROSPECT, CORINTH PREFECTURE, GREECE: THE FIRST RESULTS

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ABSTRACT

A high resolution, wide-band (128-0.04Hz) magnetotelluric survey comprising 22 soundings, was conducted to investigate the deep structure of the highly prospective Theiokhoma area, in Sousaki geothermal field. High data quality, in combination with the extensive range of investigated depths (50m-20km), allow detailed delineation of shallow structures as well as deep seated features related to the geothermal fluid transportation system and apparently well correlated with contemporary regional tectonics. Emphasis is given in the findings pertinent to the deep structure (D>1km), which comprises a complex, three-dimensional geoelectric domain of intersecting conductive zones (faults=fluid circulation conduits) and resistive domains which may include igneous intrusions. No evidence of a deep geothermal reservoir was found. The primary deep normal fault zones align with the tectonic direction N-50°-W, consistently with the regional tectonics of the area as known from previous investigations.

ΜΑΓΝΗΤΟΤΕΛΛΟΥΡΙΚΗ ΔΙΕΡΕΥΝΗΣΗ ΤΟΥ ΓΕΩΘΕΡΜΙΚΟΥ ΠΕΔΙΟΥ ΣΟΥΣΑΚΙΟΥ ΚΟΡΙΝΘΙΑΣ: ΤΑ ΠΡΩΤΑ ΑΠΟΤΕΛΕΣΜΑΤΑ

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ΠΕΡΙΛΗΨΗ

Μαγνητοτελλουρική διασκόπηση ευρέος φάσματος (128-0.04Hz) από 22 πυκνά διατεταγμένους σταθμούς, διενεργήθη προς λεπτομερή διερεύνηση της περιοχής μεγίστου γεωθερμικού ενδιαφέροντος του πεδίου Σουσακίου (έμπροσθεν θέσης Θειόχωμα). Η υψηλή ποιότητα των δεδομένων και το μεγάλο εύρος διασκοπηθέντων βαθών (50m-20km), επιτρέπει την αξιόπιστη και λεπτομερή διερεύνηση της αβαθούς δομής, αλλά και την ανίχνευση βαθέων χαρακτήρων, πιθανότατα συνδεομένων με το σύστημα κυκλοφορίας ρευστών και εμφανώς συσχετιζομένων με την περιφερειακή ενεργό τεκτονική. Εμφαση δίδεται στα περί την βαθειά δομή (D>1km) ευρήματα, τα οποία αποκαλύπτουν τριδιάστατο γεωηλεκτρικό περιβάλλον εκ συμπλέγματος διατεμνομένων αγωγίμων ζωνών (ρηγμάτων=ζωνών κυκλοφορίας ρευστών) και αντιστατικών περιοχών πιθανώς περιλαμβανουσών και εκρηξιγενείς διεισδύσεις. Δεν υπάρχουν ενδείξεις υπάρξεως βαθέως γεωθερμικού ταμιευτήρα. Οι πρωτεύουσες ζώνες κανονικών διαρρήξεων παρατάσσονται κατά την διεύθυνση Β-50°-Δ, σε αρμονία με τα υπάρχοντα στοιχεία περί του τεκτονικού καθεστώτος της ευρύτερης περιοχής.

INTRODUCTION

The area of Sousaki is located at the western end of the Hellenic Volcanic Arc (Figure 1) and comprises one of the most interesting geothermal prospects in Greece (fourth in terms of significance according to Marinelli, (1971). As such, it attracted considerable attention and has been subject to systematic and intensive exploration.

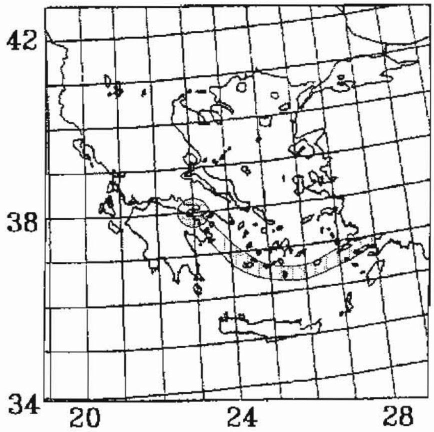

Fig.1. The area of Sousaki is located at the centre of the shaded circle in the western end of the Hellenic Volcanic arc.

The geological environment of Sousaki can be seen in Figure 2,reproduced and simplified from Mettos et al (1982). The surface geology comprises a Mesozoic "basement" consisting of limestones and ophiolites, which is overlain by sediments of the Pliocene (terrestrial lacustrine or brackish water deposits) and Pleistocene (marls, sands, continental conglomerates etc). Igneous extrusives and pyroclastic deposits of dacitic composition can be observed at places, representing lava outflows and explosive magmatic processes contemporaneous with the formation of the Pliocene basins (2.2-8 Ma, Fytikas et al., 1976; Fytikas et al., 1987).

Sousaki is located between Korinthiakos and Saronikos gulfs which comprise a very complex region of active tectonism. Its tectonic environment is characterized by two major normal faults systems striking E-W and NW-SE, which are responsible for the formation and evolution of Korithiakos gulf (e.g. Jackson et al., 1982; King et al, 1985; McKenzie and Jackson, 1986). The E-W system appeared before the deposition of the Plio-Pleistocene sediments and was reactivated in the Holocene affecting younger sediments. It appears that the Pliocene extrusive magmatism is related to these major faulting features (Kavouridis and Fytikas, 1988). The NW-SE system of faults is relatively younger, affecting the Plio- Pleistocene formations and being continuously active until the present era; it appears to comprise the most important active tectonic feature of the Korinthiakos Gulf area (e.g. McKenzie and Jackson, 1986).

The area of Sousaki has experienced intense and extensive hydrothermal activity which, according to Kavouridis and Fytikas (1988) may have been related to the Pliocene dacitic magmas. At present, hydrothermal activity is confined in the location Theiokhoma (at the middle north side of the rectangle in Figure 2), with appearance of low temperature fumaroles (mofettes) and thermal waters with temperatures of 73°C measured inside

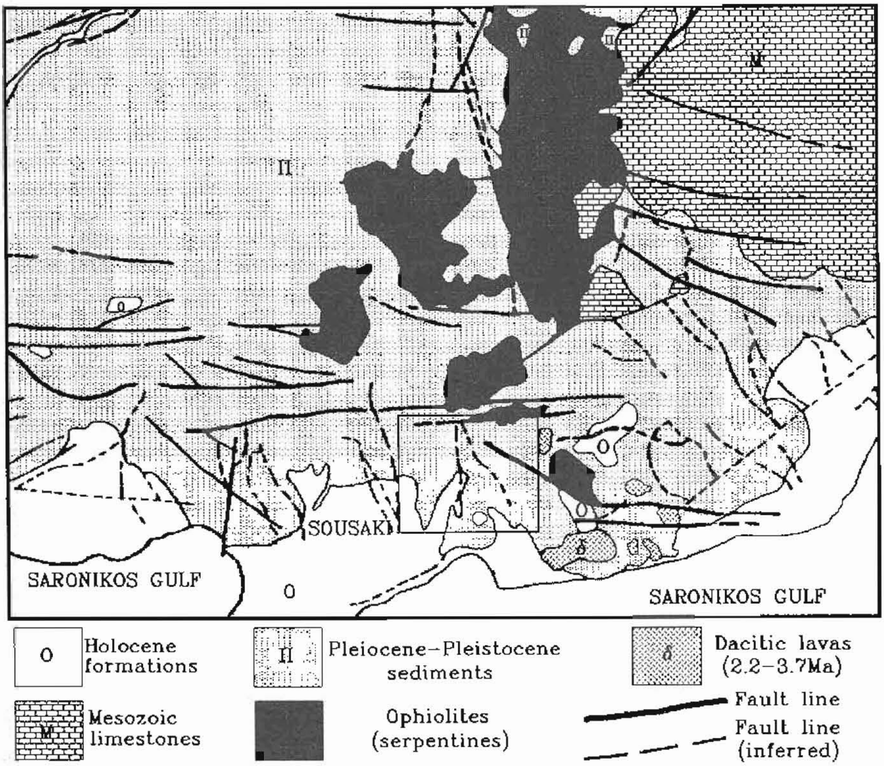

Fig.2. Geological map of the region of Sousaki geothermal field. Reproduced and simplified from Mettos et al. (1982). The rectangle outlines the MT survey area.

boreholes (Kavouridis and Fytikas, 1988). As also pointed out by Geotermica Italiana (1984), the absence of intense contemporary thermal phenomena and the relatively old age and deep crustal origin of the dacitic magmatic processes preclude the existence of an igneous heat source at shallow crustal depths; the heat source rather appears to be located quite deep in the crust. Detailed geochemical analysis (Papastamataki and Leonis, 1982; Kavouridis and Fytikas, 1988), indicates that the thermal waters may originate in a deep reservoir, possibly within the Mesozoic limestones, with initial temperature of 130-150°C. According to Kavouridis and Fytikas (1988), they ascend towards the surface along the open conduits prepared by active faults, until they encounter permeable formations and spread laterally mixing with cold sea water and near surface sweet water aquifers. The gasses exhaled at Theiokhoma appear to have the same deep origin but follow different paths and are allowed to escape only in that limited area.

Geophysical investigations in Sousaki included DC resistivity, aeromagnetic and gravity surveys (Rocca, 1985 and references therein). The aeromagnetic and gravity surveys could not detect any kind of deep features related to a geothermal reservoir, nevertheless, they confirm the existence of large scale faults and structures striking NW-SE, SW-NE and E-W. The extensive DC resistivity (Schlumberger) survey was performed with current electrode spacing AB=6000m and a large number of soundings distributed between Sousaki and Loutraki near Corinth, covering an area of approximately 130km^2. As it turned out, the effective penetration did not exceed 1500m in most cases. The results contain strong evidence of NW-SE and NE- SW trending faults and geoelectric structures. No evidence of a geothermal reservoir was found whatsoever. Near Sousaki however, there could be observed a concentration of abnormally low resistivities at very shallow crustal depths (<500m). This observation was also made by Thanassoulas (1982), who explored the vicinity of Sousaki and Theiokhoma with additional Schlumberger soundings; his reported results are confined to the first 500-600m and confirm the existence of abnormally low resistivities (2-5Ωm). Kavouridis and Fytikas (1988) assess that this not a geothermal reservoir, but nevertheless may be related to the circulation of hot fluids.

From the above becomes apparent that several important deep structural characteristics of the geothermal system of Sousaki are poorly understood or unknown. In the most prospective area of the field (Theiokhoma), the structure deeper than 500m is practically unexplored, including the characteristics of the principal fluid circulation conduits. Moreover, a deep hot water reservoir may be assumed from geochemical analysis, but its existence and location has not as yet been confirmed.

In this paper we present the first results of a Magnetotelluric (MT) survey conducted in order to resolve some of the above problems, by exploiting the deep penetration capability of the MT method and its capability to discriminate 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 in the vicinity of Theiokhoma, which comprises the most prospective area of Sousaki geothermal field.

The target area is indicated by the rectangle in Figure 2. 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 22 soundings in the nominal frequency bandwidth 128-0.04Hz. The sounding locations are illustrated in Figure 3.

DATA ANALYSIS

The Magnetotelluric (MT) method is based on the phenomenon of natural (passive) electromagnetic induction, in which horizontal, plane polarized (sub)vertically propagating source magnetic fields generated by magnetospheric or ionospheric processes, enter the Earth 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 electrical impedance of the subsurface and conveying information about the geoelectric structure in the vicinity of the recording station (details about the MT methodologies can be found in Rokityansky, 1982).

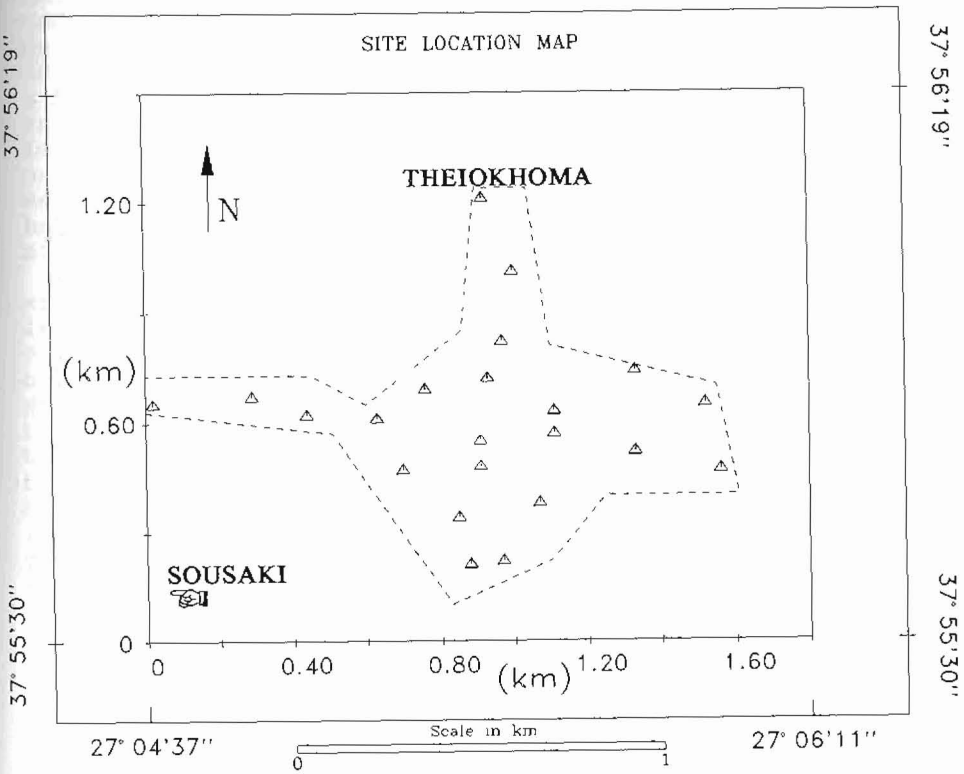

Fig.3. MT sounding locations in the survey area (enclosed in the rectangle of Fig.2).

The estimation of the experimental impedance tensor Z did not present particular problems and could be performed with standard rocedures, although the area of Sousaki is industrially developed. In three cases only, when the soundings had to be performed in the immediate vicinity of high voltage power transmission lines, specialized estimation techniques had to be implemented in order to suppress the effects of intense anthropogenic noise; the robust methodologies of Tzanis and Beamish (1989) and Tzanis (1988) were applied with success.

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 induction processes particular to the dimensionality of the geoelectric structure under consideration. The necessary information is conveyed in Z. For small penetration depths (f>1Hz, D<600-800m), Kao and Orr's (1982) analysis indicated a dominant one-dimensional (1D) geoelectric structural component with typical contribution in excess of 80% in the structure of the experimental impedance tensors; for high penetration depths (f<1Hz, D>600- 800m), the same analysis indicates multidimensional structures with typical contribution 10- 20% and up to 30% at places, while the 1D component drops to approximately 70%.

At the outset, the geoelectric structure exhibits certain multidimensional characteristics which render its formal interpretation difficult, inasmuch as 3D inversion methods do not exist and 3D modelling of complex structures is cumbersome and time consuming. Note however, that given MT responses with multi-dimensional characteristics, it is still considered acceptable to implement 1-D interpretation algorithms, provided that certain limitations and constraints arising from theory and forward models are acknowledged. For instance, in a thorough and as yet unsurpassed study, Berdichefsky and Dmitriev, (1976), suggest that 1D inversion of invariant impedance functions may yield representative images of the gross geoelectric structural features in the vicinity of the measuring station. In the present study, we implement 1D analytic inversions of the invariant impedance $Z=0.5(Z_{yx}-Z_{xy})$, which comprises the half- trace of the impedance tensor and has the physical meaning of a spatially smoothed variation of resistivity with depth. The inversion was carried out with the algorithm of Constable et al., (1987), which yields multiple layered models and is constructed to obey the principle of least complexity and maximum parsimony *(Occam's razor)*; this algorithm guarantees that the real geoelectric structure must be at least as rich in structure as the model found by the inversion, but never less complex. Although it may be acknowledged that the results will not be punctually accurate, the high 1D geoelectric structural component indicated by Kao & Orr's dimensionality analysis ensures that they will yield a gross albeit representative image of the subsurface distribution of resistivity.

The resistivity structure

The results are shown in Figures 4 and 5. The adopted method of presentation comprises stacks of orthographic projections of horizontal resistivity sections at selected depths below mean sea level, all viewed from the SE corner of the survey area.

Figure 4 illustrates the resistivity distribution of the first 1000m and appears to confirm the findings of Thanassoulas

(1982). The uniformly and highly conductive shallow structure of the first 500m indicates the abundant presence of electrolytes and/or clay minerals. Kavouridis and Fytikas (1988) interpreted this zone of shallow conductors as a result of (possibly hot) lateral fluid circulation and not as signature of a shallow reservoir. The electrical structure begins to change sharply for depths >500m, with appearance of a resistor which expands laterally with increasing depth. The top of this resistor was definitely detected by Thanasoulas (1982), who attributed it to the 'limestone basement' of the area. The eastern part of the survey area remains relatively conductive at the depth of 1km.

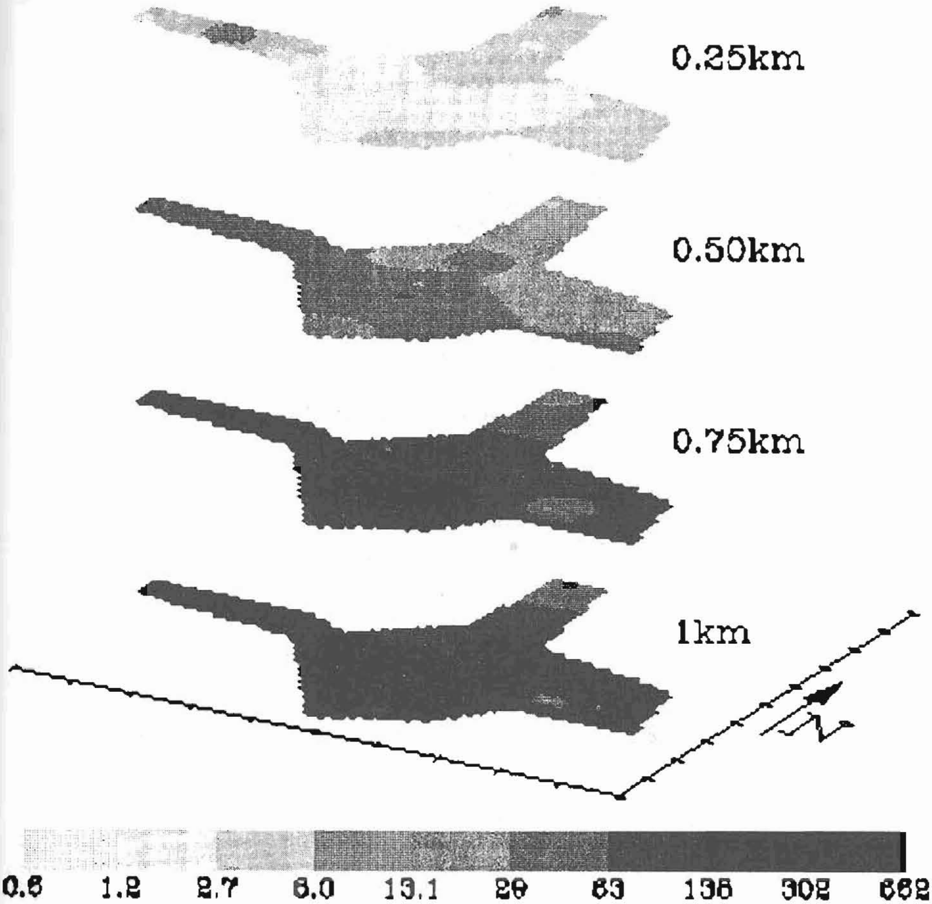

Fig.4. Resistivity distribution for the depth interval 0km-1km. (Occam inversion results).

In the vicinity of Theiokhoma the structure is highly conductive at shallow depths, but as the resistor expands northwards, it is squeezed to a limited space at the northernmost part of the survey area; its resistivity rises from less than one, to more than 30Ωm at the depth of 1km, signalling the diminishing presence of fluids with increasing depth in the vicinity of that location.

Figure 5 illustrates the resistivity distribution for the depth interval 1-12km, which is characterized by very sharp lateral contrasts. The resistor of Figure 4 can here be traced to depths exceeding 12km. It comprises a uniform single body down to the depth of 4-5km and begins to split up at approximately 8km, probably as a result of faulting. Its maximum resistivity according to Occam's inversion is nearly 10kΩm and is most likely overestimated. A value of 2-3kΩm established from the MT data by other means, appears to be closer to reality. At any rate, the body appears to be very compact and impermeable. Its nature is

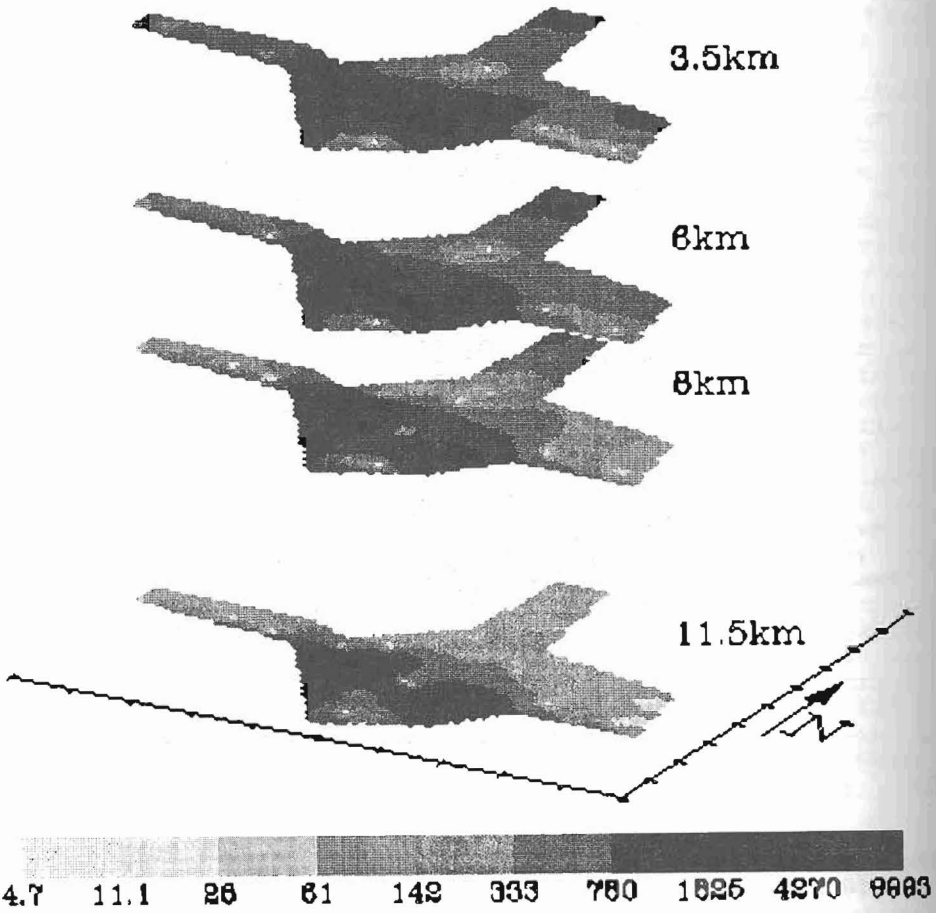

Fig.5. Resistivity structure for the depth interval 3km-12km (Occam inversion results).

not known, however the very narrow shape, great depth extent and very high resistivity point against interpreting it as a limestone block; if it was, it should be more conductive due to high secondary permeability from extensive fracturing and karstification, which are known to affect the carbonatic rocks of the area. These characteristics together with the acknowledged existence of numerous dacitic extrusives nearby, appear to favour its interpretation as of magmatic origin.

The structure underneath the fumaroles of Theiokhoma exhibits high resistivity (>700Ωm) for 2km<D<8km, which indicates a practically complete absence of fluids and implies that the fumarolic activity at Theiokhoma should be attributed to (intersection of) faults, which transport fluids and gases from elsewhere and allow them to escape at Theiokhoma only.

Within the same depth interval (2km<D<8km), conductive zones can also be detected, with very low resistivity, (less than 10Ωm at places), which alternate with resistive formations; this indicates the abundant presence of electrolytes at depth. However, the distribution of these zones is such, that the existence of an extensive reservoir underneath the survey area can be ruled out. Scrutiny reveals that the highly conducting formations ($\rho<20\Omega m$) which possess the highest liquid fraction, have limited lateral extent. This in turn suggests that they probably represent the electrical signatures of open fluid circulation conduits (=faults). With the 3D graphical presentation adopted here, it is not easy to distinguish the exact location, strike and width of these conductive fault zones; their configuration will be investigated shortly, in detail.

One important observation is that at great depths, (D>10km), the resistivity decreases considerably relative to the resistivity in the depth interval 1-8km. The change is more apparent at the northern and western flanks of the survey area; underneath the fumaroles of Theiokhoma the resistivity drops to below 220Ωm. The phenomenon can be traced at even greater depths, unfolding over the whole survey area. Owing to the very nature of electromagnetic induction processes, this depth of occurrence ascertains that it not a local effect, but extends underneath the broader area of Sousaki.

The resistivity of these deep quasi-conducting formations remains high enough, so as to preclude the existence of a very deep reservoir. In general, rocks at great depths cannot have high porosity. An estimate for the effective porosity can be afforded however, on the basis of Archie's law, $\rho=\rho_w a\varphi^{-m}$, with ρ being the bulk resistivity of the formation, ρ_w the resistivity, of the pore fluids and φ the effective porosity. Based on the geochemical analysis, we presume temperatures >150°C at depths greater than a few km and we can safely assume pore fluids with salinity at least equal to that of sea water, the temperature dependence of which is $\rho_w=(3+T^oC/10)^{-1}$ (Lee et al, 1993). With resistivities ranging in the interval 50-300Ωm, the formation factor $F=\rho/\rho_w$ assumes values in excess of 1000, which is indicative of crystalline rocks (e.g. Keller and Rapolla, 1974). Thus, at D>10km we can safely assume the existence of brine-saturated crystalline rocks with low, either intergranular or joint porosity; under these conditions a reasonable choice of the constants is a=1 and m=2 (also see Brace and Orange, 1968).

Then, for T=150-300°C and ρ=50-300Ωm we obtain φ=1-3%. If the resistivity had been overestimated by as much as 100%, the effective porosity would not exceed 6%. Furthermore, if we assume a petrology comprising low porosity sedimentary rocks, the results do not change by any significant proportion. It becomes clear that such rock properties do not facilitate the formation of fluid reservoirs. Thus, it appears possible that the decrease in resistivity is an effect of a limited liquid fraction combined with high temperatures at depth. Note however, that even with such low porosity there exists a large net volume of hot fluids which find, eventually, their way upwards through the open active faults and generate the limited thermal phenomena at the surface.

Spatial analysis of the impedance tensor

Let (x,y,z) denote the cartesian experimental coordinate system and let (x,y,z) denote a coordinate system intrinsic to the geoelectric structure. Although the experimental **Z** is determined in (x,y,z), it incorporates all the information of the geoelectric structure in (x,y,z) intact, since any cartesian coordinate system can be mapped onto another by isometric transformations. This information can be recovered from Z by inverse isometric transformations (namely rotations about the axes of (x,y,z). In this paper we implement the 3D rotation analysis method of Tzanis (1988, 1992), which utilizes the symmetries of the 3D pure rotation group SU(2), of 2x2 unitary matrices and provides a theoretical framework for the treatment of MT data obtained over multi-dimensional geoelectric structures. The 3D rotation, results in the decomposition $\mathbf{Z}=E(\Theta_E,\Phi_E)\mathbf{M}H^{+}(\Theta_H,\Phi_H)$ which transforms the experimental system into two cartesian (intrinsic) coordinate systems carrying the output electric and the input magnetic fields and are espectively defined by the rotation angles Θ_E,Φ_E and Θ_H,Φ_H; $E(\Theta_E,\Phi_E)$ and $H(\Theta_H,\Phi_H)$ are SU(2) operators involving rotations about the vertical and one of the horizontal axes; + denotes the transposed complex conjugate. Φ represents an azimuthal direction and Θ an inclination, also admitting an equivalent representation as the ellipticity of components in the horizontal plane (=tanΘ). **M** is an antidiagonal matrix containing the characteristic (extremal) impedances μ_1 and μ_2 ($\mu_1>\mu_2$). The electric and magnetic components in the intrinsic systems are related as $E(\Theta_E,\Phi_E)=\mu_1 H(\Theta_H,\Phi_H+\pi/2)$, and $E(\Theta_E,\Phi_E+\pi/2)=\mu_2 H(\Theta_H,\Phi_H)$ and form the two characteristic states (3D modes of propagation) of the EM field within the Earth. The term spatial analysis is used to define the process of rotation and mapping of the results. The configuration of the principal components of the observed impedance tensors can, then, be used to find the corresponding configuration of the geoelectric structure(s) producing them and to delineate geoelectric structural blocks and lateral conductivity interfaces.

It can easily be verified that in the case of 1D and 2D geoelectric structures $\Phi_E=\Phi_H$ and $\Theta_E=\Theta_H=0$. In 3D structures however, one may observe $\Phi_E\neq\Phi_H$. For instance, the accumulation of surface charges on the walls of conductors, flow around or channelling effects etc., may deflect the electric fields away from the true local strike of the geoelectric structure. This phenomenon, albeit of small magnitude, has been observed in the reported survey affecting the soundings over the most conductive parts of the structure; the results will not be analyzed here for lack of space. The magnetic field cannot be deflected by static or quasi-static charges and may well be used for the spatial analysis of MT data in place of the electric field. The technique presented here utilizes the admittance tensor $\mathbf{A}=\mathbf{Z}^{-1} = H(\Theta_H,\Phi_H)\mathbf{M}^{+} \mathbf{E}^{+}(\Theta_E,\Phi_E)$ and specifically, the maximum admittance and the magnetic field component of the maximum state of **A**, defined as $H(\Theta_H,\Phi_H)=(\mu_2)^{-1}E(\Theta_E,\Phi_E+\pi/2)$.

The maximum admittances from all sites are presented in Figure 6, in the form of averages over the (skin) depth interval 1km-8km. As can be seen immediately, the ellipticities (Θ angles) are very small, confirming that the three-dimensionality of the structure is weak; the area rather appears to respond in the 2-D mode.

Without entering into details, we note that the *maximum admittance function indicates the downhill direction of local geoelectric gradient*, i.e. points towards the most conductive local structure. Moreover, the magnitude of the maximum

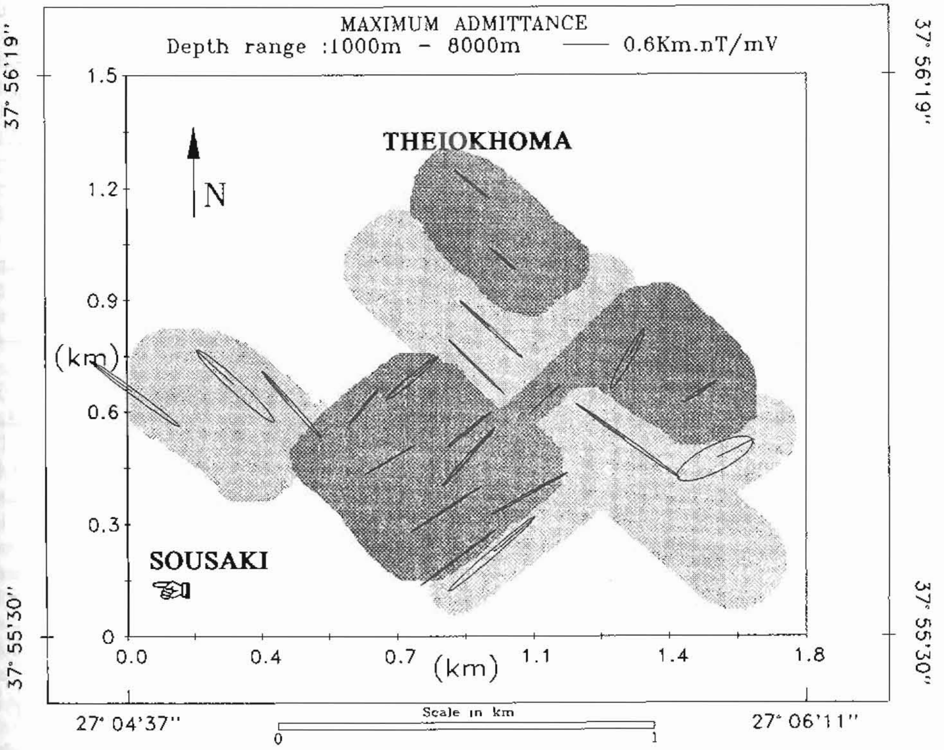

Fig.6. Spatial analysis of the MT data based on the maximum state of the admittance tensor and the maximum admittance. The lightly shaded areas represent the conductive domains. The heavily shaded areas represent the resistive domains.

admittance is proportional to the conductivity of the geoelectric structure in the vicinity of the recording station. Thus, small admittances indicate a resistive domain and large admittances a conductive one. There exists a well defined lateral succession of intersecting conductive (lightly shaded) and resistive (heavily shaded) zones, striking at N-50°-W and N-50°-60°-E respectively; these are the principal directions of the geoelectric structure, responsible for its weak three-dimensionality.

The primary (most significant) conductors strike at N-50°-W and can be directly identified from the apparent perpendicularity of maximum admittances located over the resistive and conductive parts of the survey area. They are also independently identified by the analysis of magnetic variations recorded simultaneously with the MT data (e.g. Lagios, 1992).

The secondary conductors strike at N-50°-60°-E. In reality, only one such zone can be directly identified; it is defined by the large magnitude of maximum admittances in the south and south-east extremes of the survey area and their perpendicularity to the primary conductors. This zone is also definitely and independently confirmed by the analysis of magnetic variations, (e.g. Lagios, 1992).

The two conductive zones represent the principal fluid convection paths of the Sousaki geothermal system, at least as identified within the survey area. In the geological and geotectonic setting of Sousaki, the convection paths are generated by active normal faulting which allows fluids to circulate between the surface and the heat source.

CONCLUSIONS

The reported MT survey of the highly prospective Theiokhoma area achieved deep penetration and provided new insight into the nature of the geothermal field and system of Sousaki. It was shown that the system comprises a shallow (D<600-700m) and a deep part.

The shallow structure is characterized by abnormally low resistivities which can be interpreted as result of abundant water (brine), and/or clay minerals. Very shallow (100-200m) hot water (73°C) aquifers have been identified from exploration drilling (e.g. Kavouridis and Fytikas, 1988). The clay minerals may have formed from the alteration of the ophiolites which are known to underlie the surface of a large part of the survey area, with thicknesses as much as 400m. The existence of clay minerals renders difficult, if not impossible, the estimation of the liquid fraction in the shallow conductive formations. At any rate, the liquid fraction must be rather large as is also attested by the exploration drilling data. The warm water from the may easily be used for intermediate and low enthalpy applications of geothermal energy.

Although a deep hot water reservoir within the limestones was anticipated from the geochemical data, it was definitely not found underneath the surveyed area and may even not exist in its vicinity. Likewise, we could not observe any characteristic traces of contemporary deep igneous processes (e.g. a magma chamber), the existence of which is anyhow doubtful for a variety of reasons (e.g. Geotermica Italiana, 1984). Instead we found strong evidence for the existence of wet hot rock at great depths (D>10km), as well as clear traces of open (active) faults which facilitate the direct communication of the deep hot rock with the surface. The faults are clearly discernible from their very conductive signatures, which can be attributed to the abundant presence of saline fluids (geothermal fluids). Thus, the geothermal system of Sousaki rather appears to function by convective transfer of excess heat from great depth to the surface, via the highly permeable paths prepared by active extensional faulting. The heat source itself could not be studied because of the limited area covered with MT soundings. It may be a residual of past (Pliocene ?) magmatic processes; this interpretation has, in one way or another, been favoured by many previous workers. Additional MT measurements in the broader area of Sousaki may provide some more definite answers in the future.

From the above discussion, it appears that the best way to exploit the geothermal potential of Sousaki, is to tap the geothermal fluids directly from the faults at some sufficient depth such, that they do not rise very close to the surface and lose much of their original high temperature.

The results of the MT survey also provide useful information about the contemporary tectonic regime and deformation processes affecting the broader area of Sousaki. The basis for such an assertion derives from the very nature of macroscopic EM induction processes. A distinctive characteristic of deep MT sounding is its capability to penetrate and explore deep into the Earth's crust from point observations on the surface. In this survey we achieved penetration in excess of 15km for most soundings. It is apparent (and can be demonstrated in a variety of ways), that features discernible at such great depths below the point of measurement, must have one horizontal dimension of, at least a few times the depth of detection; such features necessarily belong to structures with regional extent. In a tectonically controlled geothermal system such as is Sousaki, the conductive zones are generated by active normal faulting which allows fluids to ascent from great depths. The primary tectonic direction defined by the MT data is N-50°-W; the secondary is N-50°-60°-E. No traces of important E-W faults were found within the survey area.

The existence of tectonic lineaments parallel to N-50°-W and N-50°-60°-E has been independently identified by other geophysical methods possessing the capability to register signals from very deep structures (gravity and aeromagnetic, e.g. Rocca, 1985). In fact, the NW-SE and NE-SW trending lineaments revealed from analysis of gravity data, (and interpreted by Rocca as 'faults'), are almost identical with the directions derived from the MT data.

Tectonic lineaments with similar directions are confirmed over the broader area of southern Korinthiakos gulf from morphotectonic and seismotectonic observations (e.g. Jackson et al., 1982; King et al., 1985). Moreover, the faults which reactivated with co-seismic dislocations during the Korinthos earthquakes of 24-25 February 1981, exhibit general strikes of N-60°-W and N-60°-70°-E. The MT results indicate that these contemporary active tectonic directions and their causative stress field persist in Sousaki, approximately 20km to the SE of the 1981 earthquake zone.

The tectonic directions detected at Sousaki are not identical with those observed in the faults of Korinthos earthquakes. The small differences of 10°-15° can be attributed, either to local structural effects registered in the MT data, or, to minor differentiation in the stress field; the answer cannot be given until additional MT measurements are performed in the broader area of southern Korinthiakos and northern Saronikos gulfs.

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REFERENCES

Berdishefsky,M.N. and Dmitriev,V.I., (1976). Basic principles of interpretation of magnetotelluric curves, in Adam, A. (ed), Geoelectric and Geothermal Studies, Akademiai Kiado, 165-221.

Brace,W.F. and Orange,A.S., (1968). Further studies of the effects of pressure on electrical conductivity of rocks, J. Geophys. Res., 94,9429-9438.

Constable,S.C., Parker,R.L. and Constable,C.G., (1987). Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data, Geophysics, 52, 289-300.

Fytikas,M., Giuliani,O., Innocenti,F., Marinelli,G. and Mazzuoli,R., (1976). Geochronological data on recent magmatism of the Aegean sea, Tectonophysics, 31, 29-34.

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.

Jackson,J.A., Gagnepain,J., Houseman,G., King,G.C.P., Papadimitriou,P., Soufleris,C. and Virieux,J., (1982). Seismicity, normal faulting and the geomorphological evolution of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981, Earth and Planetary Science Letters, 57, 377-397.

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

Kavouridis,Th. and Fytikas,M., (1988). Geothermal investigations in the area of Sousaki. Report, IGME, Athens, Greece (in Greek).

Keller,G.V. and Rapolla,A., (1974). Electrical prospecting methods is volcanic and geothermal environments; in Civetta, L., Gasparini, P., Luongo, G. & Rapolla, A. (eds), "Physical Volcanology", Elsevier, 133-166

King,G.C.P., Ouyang,Z.X., Papadimitriou,P., Deschamps,A., Gagnepain, J., Houseman, G., Jackson, J.A., Soufleris, C. and Virieux, J., (1985). The evolution of the Gulf of Corinth (Greece): an aftershock study of the 1981 earthquake, Geophys. J. R.astr. Soc., 80, 667-693.

Lagios,E., (1992). Magnetotelluric surveys in the geothermal prospects of Sousaki and Methana, Volume 1 (Sousaki). Final report, project 90ΠΣ5. Submitted to General Secretariat for Research and Technology, Ministry of Industry Research and Technology, Athens, Greece, 272pp (in Greek).

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

Marinelli,G., (1971). Possibility of developing geothermal resources in Greece. O.E.C.D. Techn. Coop. Serv., Consultant Report CT/7191, 1-28.

McKenzie,D. and Jackson,J., (1986). A block model of distributed deformation by faulting, J. Geol.Soc. London, 143, 349-353.

Mettos,A., Gaitanakis,P., Rondoyanni,Th., Bavay,Ph., Ioakeim, M. and Koutsouveli,A., (1982). Geological investigation of the Loutraki-Sousaki area. Report, IGME, Athens, Directorate of General Geology and Mapping, I, 65pp (in Greek).

Papastamataki,A. and Leonis,K., (1982). Geochemical investigation of the geothermal potential in the area of Loutraki-Sousaki. Report, IGME, Athens Greece (in Greek).

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

Rocca, A., (1985). Geophysical studies of the Loutraki-Sousaki area, Doctorate Thesis, Department of Geology, University of Thessaloniki (in Greek with extended English abstract).

Thanasoulas,K., (1982). Geoelectric measurements in the area of Loutraki-Sousaki, report, IGME, Athens, Greece (in Greek).

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). Generalized rotation analysis of the magnetotelluric tensors in three dimensions: A group theoretical approach, Proc. XVII EGS Gen. Assembly, Edinbutgh, 6-10 April 1992.