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A High Conductive Zone Associated with a Possible Geothermal Activity around Afyon, Northern Part of Tauride Zone, Southwest Anatolia

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ABSTRACT

A magnetotelluric line named as AG crossing Isparta Angle tectonic zone between Afyon and Antalya was taken to define geoelectrical structure. Two-dimensional (2-D) modeling of this profile was used to derive the resistivity structure and investigate its implication on possible geothermal activity within the crust.

The magnetotelluric results in the view of the 2-D geoelectric structures, with true resistivity values, obtained from transverse electric (TE), transverse magnetic (TM) data and joint TE-TM inversion was interpreted.

The 2-D models of geoelectric structures obtained from these inversions were clearly displayed the existence of an electrically conductive (<50 Ωm) zone (*ZONE-1*) beneath Sandikli Graben (around Afyon) where is the popularly known as a geothermal region. Another conductive zone (*ZONE-2* with ~5-10Ωm) was defined beneath Dinar Graben where is seismically active.

The sharp decreasing of the resistivity to very low values probably suggests that both zones *ZONE-1* and *ZONE-2* are highly permeable and saturated with geothermal fluids.

1. INTRODUCTION

Electrical resistivity of the rocks in the earth's crust depends on a wide range of petrological and physical parameters, e.g., their composition, degree of saturation with fluid, porosity and connectivity of pores, conducting minerals or enhanced temperatures.

The electrical resistivity of the fractured rocks, depending on metamorphism and fluid-saturation, can decrease to very low values of a few ohm-m, while the compact and dry geological rocks may be characterized by the high electrical resistivity up to 10,000 Ωm (Hyndman and Hyndman, 1968; Telford et al., 1990; Schwarz, 1990).

The Tauride zone within southwestern Anatolia accommodates the Isparta Angle area that is an important segment of the eastern Mediterranean region. Because of its key position within the Alpine Mediterranean belt and its complex structure a magnetotelluric line named as AG crossing Isparta Angle with north east direction was taken to define geoelectrical structure along this line in the region between Afyon and Antalya.

The region is seismically active associated with many major and moderate graben systems as presented by earthquake data (Taymaz et al., 1990; Taymaz and Price, 1992). The study area where was not far from the well-known geothermal field around Afyon and Antalya that has several potentially valuable mineral and hot springs.

The aim of this magnetotelluric survey, covering the period range 0.04-500 s, is subsequently to define the structural geometries of the Isparta Angle and surrounding geotectonic zones by their electrical response. The deep electrical resistivity data that distinguish the rocks with different nature, down to several tens of kilometers within the crust, can be obtained mainly from magnetotelluric soundings.

2. GEOLOGICAL SETTING

The major neotectonic structures shaping Turkey and adjacent areas are the right-lateral North Anatolian Fault System (NAFS) (Figure 1), the left-lateral East Anatolian and the Dead Sea fault systems and the Hellenic-Cyprus active subduction zone (Bozkurt, 2001).

In addition to these major structures, there are also some other second-order fault zones cutting across and dividing the Anatolian plate into smaller blocks. One of geologically complicated areas comprising the Anatolian plate is the Isparta Angle. This is an "acute angle towards south" shaped morphotectonic structure about 260 km long, 380 km wide outlining Antalya Bay in the Eastern Mediterranean Sea (Figure 2).

The origin of the Isparta Angle is still under debate, but it is accepted as a palaeotectonic structure resulting from the northward curvature of the originally ~E–W-trending Tauride orogenic belt due to nappe emplacements and related clockwise and anticlockwise rotations in Early Palaeocene–early Messinian times (Piper et al. 2002).

Many horst and graben systems are located within the Isparta Angle (Figures 1 and 2). The oblique-slip normal faults characterizing an extensional neotectonic regime throughout the northeast edge of the outer Isparta Angle were occurred (Koçyiğit and Özacar, 2003).

The Isparta Angle has not experienced a compressional tectonic regime after the Early Messinian phase of compression, i.e.,the nature of the neotectonic regime through the northeast edge of the outer Isparta Angle is extensional (Koçyiğit and Özacar, 2003).

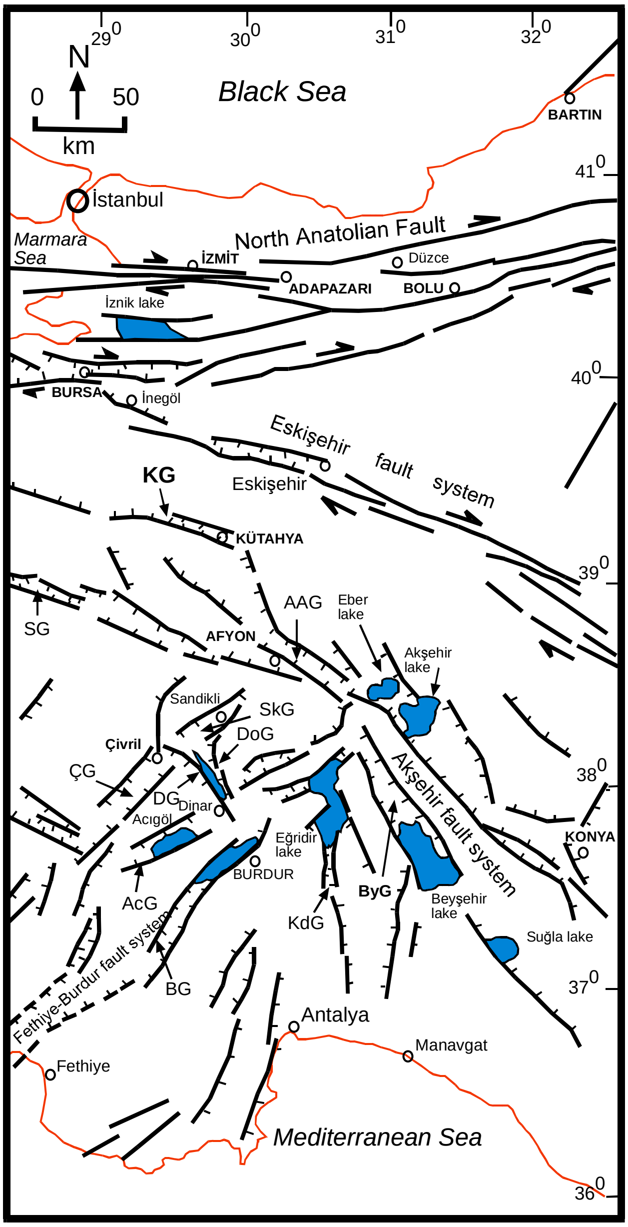

Figure 1: The faults and main grabens in the middle Anatolia and Tauride zone. Grabens: AcG: Acigöl, ÇG: Çivril, DG: Dinar, ByG: Beysehir, SkG: Sandikli, DG: Burdur, KdG: Kovada, AAG: Afyon. (redrawn from Bozkurt, 2001) .

3. MAGNETOTELLURIC DATA AND RESULTS

3.1. General

The magnetotelluric method allows the determination of an electrical resistivity structure model from measurements of natural variations of the surface electric (E) and magnetic (H) fields over a wide frequency range (Kaufmann and Keller, 1981), usually from 10^{-4}-10^{3} Hz (in our case 0.04-500 s period range). The method is based on an inductive model of electromagnetic energy penetrating vertically downward into the earth, for which the depth of penetration is both a function of frequency (inverse of period) and ground resistivity.

The amplitudes of the E and corresponding orthogonal H vectors of an electromagnetic field entering a uniform conducting half-space decrease by $1/e$ over a distance called the skin depth, $\delta \approx 503\ (\rho T)^{1/2}$ in meters, where ρ is the resistivity (inverse of conductivity σ) in Ω meters and T is the period in seconds.

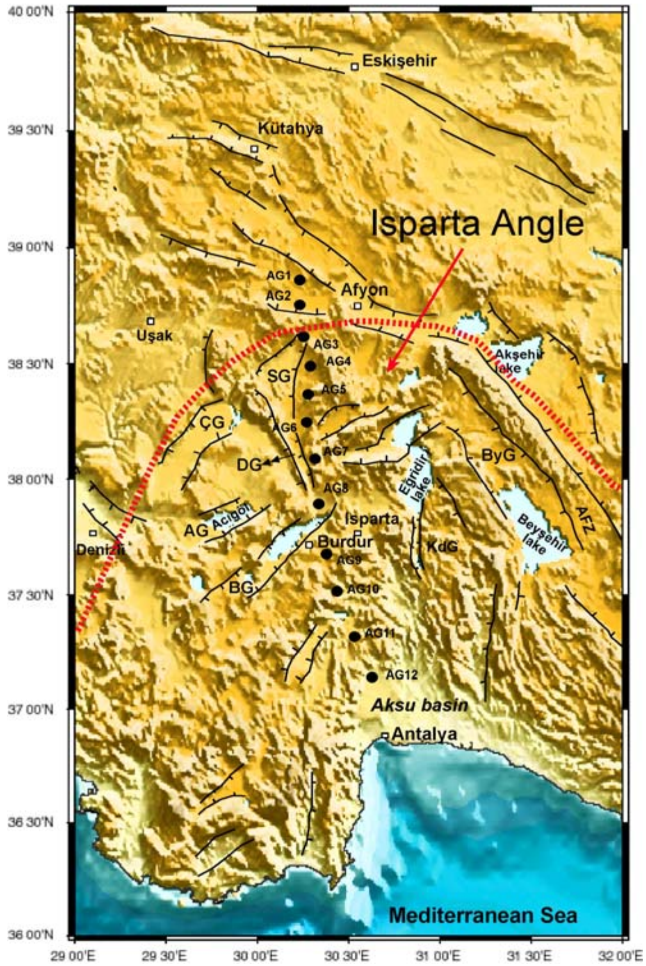

Figure 2: The topographic map of the Isparta Angle geotectonic zone and the locations of magnetotelluric sites along profile AG.

3.2. Data acquisition

The magnetotelluric soundings were performed at 12 sites along AG-line crossed the Isparta Angle zone, using Geotronics system™. Two induction coils were used to record the horizontal magnetic field components (H_x and H_y). Cu-$CuSO_4$ electrodes were used as sensors to detect the horizontal electric field (E_x and E_y). Dipole lengths are always taken about 100 m. Magnetotelluric data were obtained within the six overlapping frequency bands over the range 0.002-25 Hz (i.e. 0.04-500 s period range). Output from the electric and magnetic field sensors was fed immediately through high-gain analog amplification and band limiting, usually with custom-built electronics. The horizontal components of magnetic and electric field, E_x-H_x and E_y-H_y, were measured in the north-south and east-west directions, respectively.

The data were processed in the Department of Geophysics, Istanbul Technical University (ITÜ). All data were discrete-Fourier transformed in the frequency domain and corrected for the system response function before the application of standard processing methods.

Good quality data having high field coherences (~ 0.9) were obtained. The elements of magnetotelluric impedance that describe the conductivity structure beneath the measuring point are determined as a least square solution in desired band of frequency.

Following this, to obtain the azimuth of the maximum (Figure 4) and minimum resistivity directions we perform rotation of the impedance to minimize the diagonal elements Z_{xx} and Z_{yy} or to maximize Z_{xy} and Z_{yx} (Zang et al., 1987; Bahr, 1988) In this way two magnetotelluric apparent resistivity (Figure 5) and phase curves are obtained corresponding to the directions parallel (TE mode) and perpendicular (TM mode) to the geoelectric strike.

3.3. Magnetotelluric Two-Dimensional (2-D) modelling

The data were modelled with two-dimensional (2-D) modelling code. Transverse Magnetic (TM) and Transverse Electric (TE) modes of magnetotelluric data were inverted using the 2-D inversion code of Mackie (Mackie et al., 1993; 1997).

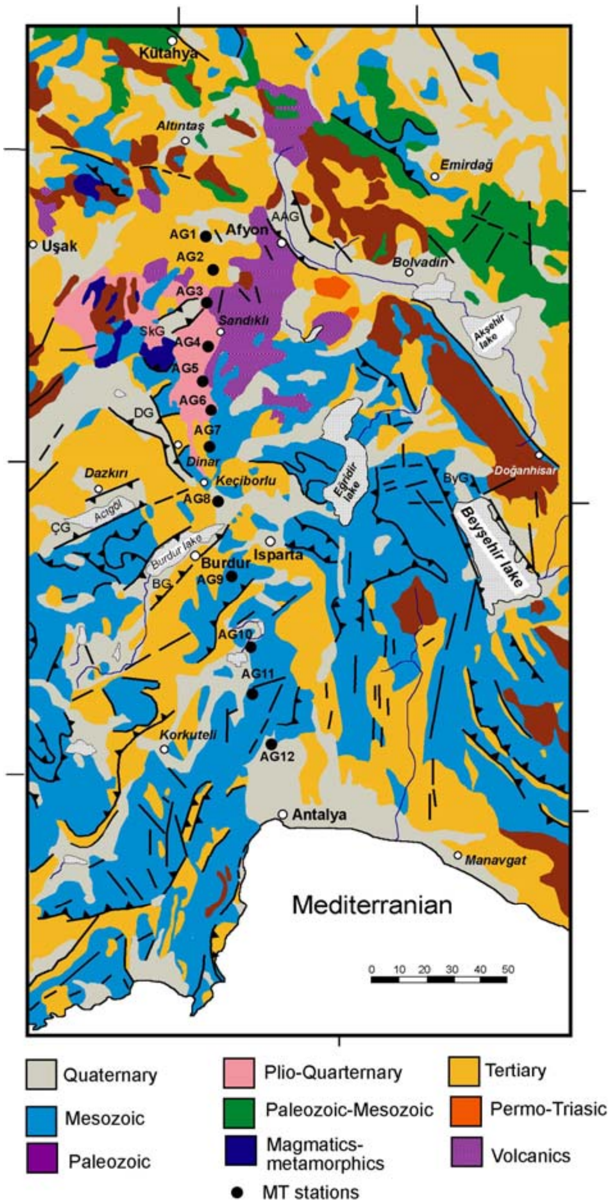

Figure 3: The general geology of the Isparta Angle geotectonic zone and surrounding region. The magnetotelluric measuring stations along the profile AG were shown in the figure.

The inversion program finds regularized solutions to the two-dimensional inverse problem for magnetotelluric data using Tikhonov method. The Tikhonov's method defines a regularized solution of the inverse problem to be a model *m* that minimizes the objective function

$$S(m) = (d - F(m))^T R_{dd}^{-1}(d - F(m)) + \tau \cdot \left\| L(m - m_0) \right\|^2$$

in which *d* is observed data vector, *F* is forward modelling operator, *m* is unknown model vector, R_{dd} is error covariance matrix, *L* is a linear operator, m_0 is apriori model and τ is regularization parameter. Each datum d_i is logarithmic amplitude or phase of TE or TM complex apparent resistivity at a particular station and frequency. The model vector is logarithmic resistivity as a function of position i.e. $m(x)=log\ \rho(x)$.

The inversion program uses the predicted impedances from the forward problem to modify the model parameters such that, over a number of iterations, the inversion will find a better set of model parameters that minimizes the objective function *S* above. The regularization parameter τ controls the trade-off between fitting the data and adhering to the model constraint. The value of τ should optimally be chosen such that the root mean square (RMS) error for the inversion is between 1.0 and 1.5.

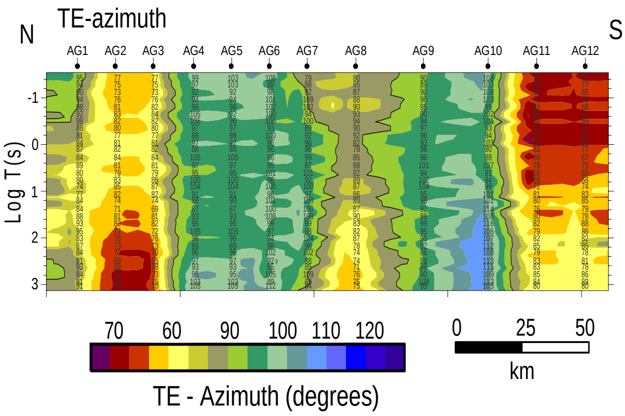

Figure 4: Computed TE Azimuth values from magnetotelluric data for AG profile

The Mackie's inversion (Mackie et al., 1997) was carried out on both TE and TM modes individually and jointly to obtain geoelectric models along the line AG. Figure 6 presents the final models obtained from TE and TM data and joint inversion using τ=20, damping factor of 0.001 and error (noise) floors of 4.0% for ρ_a and ϕ. The comparisons between the field data (Figure 5) and the synthetic response of these models are presented as calculated apparent resistivity pseudosections for all inversion (not given here). The data fit was excellent for all models. The pseudosections of the observed and calculated data were very similar. Hence we can say that the calculated two-dimensional models fit very well with the experimental (observed) data (Figure 5).

3.2. Two-Dimensional (2-D) Geoelectrical Models

3.2.1. Characterization of electrical resistivity in the rocks

It is common for altered volcanic rocks to contain antigenic minerals that have resistivities ten times lower than those of the surrounding rocks (Nelson and Anderson, 1992). Increased temperatures cause higher ionic mobility and mineral activation energy, reducing rock resistivities significantly. Unaltered, unfractured igneous are normally very resistive (typically 1000 Ωm or greater), whereas faults will show low resistivity (less than 100 Ωm) when they are comprised of rocks fractured enough to have hosted fluid transport and consequent mineralogical alteration. Carbonate rocks are moderately to highly resistive (hundreds to thousands of Ωm) dependent upon their fluid content, porosity, fracturing, and impurities. Marine shales, mudstones, and clay-rich alluvium are normally very conductive (a few Ωm to tens of Ωm). Metamorphic rocks (non-graphitic) are moderately to highly resistive (hundreds to thousands of Ωm). Tables of electrical resistivity for a variety of rocks, minerals and geological environments may be found in Palacky (1987).

3.2.2. Interpretation of 2-D geoelectrical models

Figure 5 represents electrical resistivity model calculated from the individually and jointly inversion of magnetotelluric data using TE and TM data. Between the depths about 5-13 km, the 2-D geoelectric models for TM modes basically reflect both vertical and horizontal resistivity variations. The regions under Hudai geothermal field and Sandikli graben (stations AG2-AG3) and the region under Dinar graben (*ZONE-2*; stations AG6-AG8) are characterized by relatively low resistivity values for various depths in TM model. But the near-surface regions (up to ~7 km depth) of the all geoelectrical model between AG4-AG9 generally were oppositely characterized by relatively high resistivity values. Except conductive *ZONE-1* beneath Dinar Graben, the crustal electrical resistivity about between the sites AG5 and AG10 is generally moderato to high that could be easily correlated to metamorphic basement (U. Cambrien-L. Ordovisien).

The conductive region beneath Sandikli graben (Hudai geothermal field; Tezcan, 1995) extends to the deeper levels up to 25 km in TE model probably due to strong macro-electrical anisotropy such as found in northwestern Aegean region (Caglar, 2001). At greater depths within the upper crust the main conductive zones labelled as *ZONE-1* appears in both TE and TE-TM models. This preliminary qualitative feature was taken into account during the 2-D modelling. The decreasing resistivity with depth throughout the deeper regions of Sandikli area also produces synthetic responses that are quite close to field data (Figure 5) but its extension to deeper levels than 20 km is uncertain. This region was relatively deeper in TE mode.

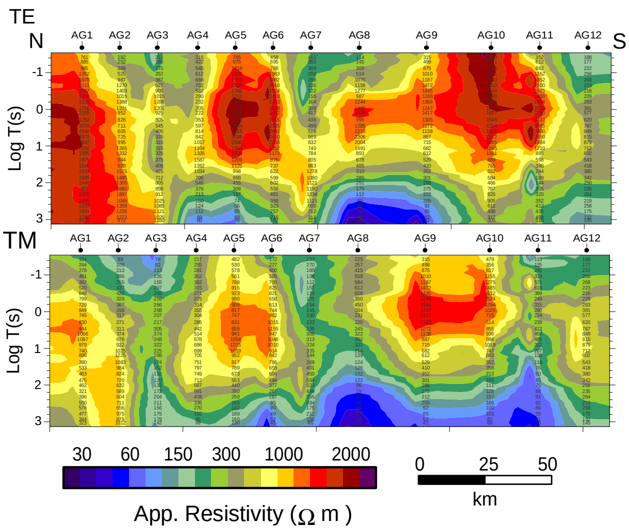

Figure 5: Apparent electrical resistivity pseudo-sections for both TE and TM mode magnetotelluric data along the profile AG.

Another conductive zone with resistivity range (5-10 Ωm) was similarly found for depths greater than about 5 km beneath AG6-AG8 (Figure 5; *ZONE-2*). This zone is wider in TM mode indicating electrical current channelling in the geoelectric structure for present depth trends mostly north south over the area.

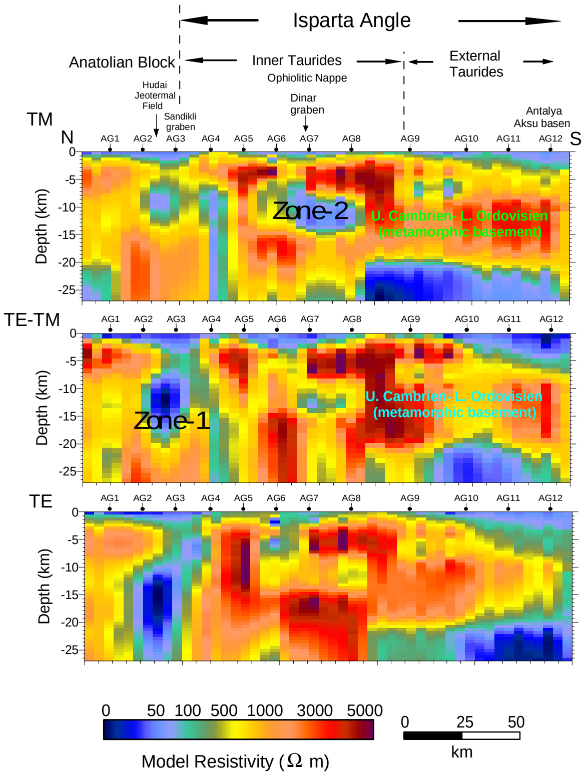

Figure 6: Two-dimensional (2-D) geoelectrical models calculated from individual and joint inversions using TE and TM data. The values are true resistivity in Ωm and red shadings show resistive rocks while blue shadings show more conductive regions. The electrically characteristic zones *ZONE-1* and *ZONE-2* are shown in the figure.

Although the TM impedance less sensitive to deep conductive structures than the TE impedance (Berdichevsky et al., 1998), both fairly conductive zones *ZONE-1* and *ZONE-2* are significantly imaged by the 2-D models. The origin of these zones needs further to explain.

4. DISCUSSIONS AND CONCLUSIONS

The magnetotelluric method is a passive surface geophysical technique, which uses the earth's natural electromagnetic fields to investigate the resistivity structure of the subsurface. The resistivity of geologic units is largely dependent upon their fluid content, porosity, fracturing, temperature, and conductive mineral content (Keller and Frischknecht, 1966). Saline fluids within the pore spaces and fracture openings can reduce resistivities in a resistive rock matrix. Also, resistivity can be lowered by the presence of conductive clay minerals, graphitic carbon, and metallic mineralization.

On the other hand, the use of geoelectrical and geo-electromagnetic (e.g. magnetotelluric) methods in geothermal exploration is based on the fact that the resistivity of hydrothermal ground water in the rocks decreases significantly at high temperatures and that geothermal activity can produce conductive alteration minerals. The resistivity of these rocks observed in geothermal areas is lower than in surrounding rocks, indicating the presence of a considerable resistivity contrast that can be investigated by the magnetotelluric method

(Garcia, 1992; Brown, 1994).

The original motivation for this work was to present the results of regional deep resistivity structure along AG-line to contribute to the understanding of some distinctive geotectonic phenomena. Although the geological complexity may affect both detect ability and resolution, nevertheless in the present circumstance, the final result (Figure 6) provides a true two-dimensional geoelectric model conforming to the geology. But uncertain points about geology in the form a depth-section could be firstly explained from the interpretation of this geoelectric model.

The electrical resistivity structures of the both external and inner parts of Isparta Angle geotectonic zone depend on petrological and physical parameters. The resistivity models (Figure 6) show a high crustal resistivity (up to 5000 Ωm) beneath the external Taurides, characteristic of igneous bodies. The basement of external Taurides trend, a high-angle, south dipping low resistivity (5-30 Ωm) zone may be interpreted as a crustal dimension fault, possibly extending to 5 to 8 km depth beneath Aksu basin (Figures 2, 3 and 6).

Moreover, the geological rocks under AG2-AG4 where well-known many hot springs of Hudai geothermal site occurred on the surface also seem as the geoelectrically characteristic place. The circulations of the hydrothermal fluids of these springs from the conducting zone *ZONE-1* to the surface probably fractured and altered rocks. These alterations principally control the bulk resistivity (Hyndman and Hyndman, 1968; Telford et al., 1990) and specific resistivity values therefore significantly decreased to lower values (here below 50 Ωm) than in the case of massive or dry rocks. This zone would have to contain hot fluids and clay or other minerals produced by the hydrothermal alteration therefore also have a role decreasing the specific resistivity. On the other hand, similar characteristic place were located in Göynük geothermal area (northwest Anatolia) by magnetotelluric (Caglar and Isseven).

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