Geothermal exploration using geoelectric methods in Kestanbol, Turkey

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Abstract

A self-potential survey was carried out in the Kestanbol area in order to investigate the fault zones that might be associated with geothermal activity. Two fault zones, which could be interpreted as planes electrically polarized by geothermal activity, have been detected by compilation of a self-potential map. A resistivity survey, using the Wenner configuration, was able to identify the geoelectrical structures that are caused by different rocks with variable degrees of fracturation and also affected by geothermal activity. The resistivity maps and two-dimensional geoelectric models indicated a good conductive region (<10 ohm-m) in the southwest part of Kestanbol. On the basis of the results of both methods, a new location is proposed for drilling in this conductive zone. © 1999 CNR. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Geothermal energy has been harnessed by using the steam or hot water stored underground at high temperatures and pressures for the generation of electric power in conventional steam turbines, and by the direct use of the heat content of the resources in heat exchangers in industrial or domestic utilizations.

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Turkey is located within an important geothermal area, and has an estimated 31,500 MW geothermal heat potential (Mertoğlu et al., 1995). In north-western Anatolia, the region around the Biga Peninsula (Fig. 1), is characterized by high heat flow anomalies, in the range 141–185 mWm\(^{-2}\) (Ilkışık, 1995; Tezcan, 1995), which are associated with the Kazdağ and Menderes massifs in the south. Several geothermal fields, such as Gönen, Kestanbol, Tuzla, Edremit and Dikili, are located in this region.

Temperature and the circulation of subsurface hydrothermal fluids, both of which are characteristic features of geothermal systems, are capable of generating a surficial electrical potential field. Such electric fields are the result of streaming
Fig. 2. (a) Geology of the study area. (1) Quaternary; (2) Neogene. Permian units are (3) syenite; (4) granite-syenite-quartzite; (5) granite. Paleozoic units are (6) gneiss; (7) schists. (8) Fault; (9) hot spring; (10) spring; (11) well; (12) village; (13) geological section (geology after Şamilgil, 1983). (b) Location of self-potential measurement points (●) and resistivity sounding sites (○). R = reference point. X and Y axes are indicated by two perpendicular arrows at site L1-P18, to place the fault models from self-potential modelling.
potential, caused by the movement of hydrothermal fluids around the subsurface heat source (Fitterman and Corwin, 1982). This event produces an electrokinetic phenomenon that can be measured by the self-potential method.

The compact and dry geological rocks may be characterized by an electrical resistivity step up to 10,000 ohm-m (Telford et al., 1976). Temperature in the geothermal systems strongly influences the electrical resistivity of geological materials. Resistivity is controlled by ionic conduction through fluids in pore spaces of the fractured rocks. The resistivity of fractured rocks, depending on hydrothermal fluid-saturation, thus decreases to a very low value. 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 electrical resistivity method. Both the self-potential and the resistivity method, therefore, seem to be suitable tools for investigating geothermal fields.

The main purpose of the research described in this paper was to identify a potentially valuable new region in the Kestanbol area and to determine whether any fault zones in the area are geothermally active, using the self-potential and resistivity methods. The results of both methods are used to plan new drillholes.

2. Geological setting and thermal data

The study area is located in the north-western part of Anatolia on the Biga Peninsula, not far from other geothermal sites (Gönen, Tuzla and Edremit). The Biga Peninsula is situated in the western part of Sakarya zone, which consists of a Paleozoic continental basement of metamorphic rocks and granitoids (Fig. 1). The area of Kestanbol was known in historical times as the Alexandria Troas. The city Alexandria Troas was built in the year 310 B.C., during the Hellenistic period. With the help of Hadrian, Emperor of Rome, public baths known as Kestanbol spa were constructed in the city. Today a modern building with baths can be found near the ruins of the ancient spa.

The study area and its surroundings are tectonically active and influenced by the recent seismic events of 1955–1956. A north–south trending tectonic fault, the Gülpinar fault zone (GFZ in Fig. 1), has been hypothesized in the region, extending over 30 km from the Gulf of Edremit in the south to the western part of Ezine further north (Fig. 1) (Siyako et al., 1989). The area dealt with in this paper is enclosed within the rectangle of Fig. 1 and is represented in greater detail in Fig. 2. Two main thermal spring sites, Kestanbol and Akçakeçili, occur in this area, about 20–30 m above sea level. Springs of slightly mineralized fresh water at lower temperatures can be found at the same level or at slightly higher altitudes. The geology is shown in Fig. 2a. The thermal springs represent the outflow of a local groundwater that has been recharged and circulates in the fissured rocks of the intrusion of Permian rocks. The Paleozoic metamorphic schists are the oldest rocks of the study area and are unconformably overlain by Permian geological units. The younger rocks, consisting of granite, syenite and quartzite, are from the...
upper Permian. These units are overlain by Neogenic limestone, sand and marn. Neogene formations cover the north-west part of the area and dip north-west by about 25–28°. The western part of the area, near the Aegean Sea, is commonly covered by Quaternary alluvial units that represent the youngest sedimentary sequence, consisting of sand-clay-gravel and blocks carried by the Ilica and Değirmen rivers. The faults observed around Kestanbol and Akçağecili springs, branches of the Gülpinar fault zone, have basically developed in the granite-syenite and gneiss-schist, respectively.

The maximum temperatures of the geothermal fluid discharged from hot springs at Kestanbol and Akçağecili were 76 and 40°C, respectively. Surface flow-rate from these springs is fairly low, the total discharge in Kestanbol and Akçağecili being 5 and 0.1 L/s, respectively. The spring waters of the Kestanbol spa are of therapeutic value, and many people use them for bathing. In Kestanbol, the observed chemical and isotopic compositions of the water (Table 1), suggest that it is a mixture between a deep, lightly mineralized groundwater and meteoric water (Balderer, 1994). The thermal waters of Tuzla, further south (Fig. 1) and Kestanbol, probably have the same origin, since a similar chemical composition is observed in both geothermal systems (Şamilgil, 1983). Three main hot springs and about ten leakages are observed around the Kestanbol site.

A borehole drilled to 290 m depth in the vicinity of Kestanbol spring (Fig. 2a) encountered an alternation of altered syenite and granite to a depth of 60 m from the surface. The partly fractured gneiss in the depth interval of 60–180 m was

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bath spring</th>
<th>Main spring</th>
<th>Second spring</th>
<th>Sample from Well-S1</th>
<th>Akçağecili</th>
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<tr>
<td>Temperature (°C)</td>
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<td>76</td>
<td>72</td>
<td>74</td>
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<td>NO₃</td>
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<tr>
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<td>68.7</td>
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<td>CO₂</td>
<td>403</td>
<td>507</td>
<td>234</td>
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Table 1
Geochemical analyses of Kestanbol and Akçağecili hot springs (after Yenal et al., 1975)
found to be the first reservoir of the Kestanbol springs. Effectively fractured syenite between 240 and 290 m formed the second reservoir (Ölmez, 1976). Hydrothermal water flows upward by artesian effect from these pressured aquifers.

Information on the chemical analysis of water samples from these springs is given in Table 1 (Yenal et al., 1975). Based on the silica geothermometer, the reservoir temperatures are calculated at 83 and 140°C for Akçakeçili and Kestanbol sites, respectively.

3. Geoelectric studies

3.1. General

We applied the self-potential method to the Kestanbol area to obtain the geometries of the possible hot water-bearing fault zones or fracture zones (electrically polarized fault planes). The self-potential method has a long history of successful exploration for geothermal regions. Self-potential measurements in geothermal areas have revealed anomalous regions associated with near-surface thermal zones and faults that are thought to be fluid conduits (Anderson and Johnson, 1976; Corwin and Hoover, 1979; Thanassoulas and Lazou, 1990; Zohdy et al., 1973). Anomalous surface potentials with high amplitudes are commonly measured near upflows of thermal fluid. These potentials are measured, in millivolts, relative to a survey reference, where the potential is arbitrarily taken to be zero.

Case histories from several investigated geothermal fields around the world have also demonstrated that the electrical resistivity method is a valid geophysical exploration technique for geothermal exploration. The use of electrical resistivity methods in geothermal exploration is based on the fact that the resistivity of thermal ground water in the rocks decreases significantly at high temperatures and that geothermal activity can produce conductive alteration minerals.

Considering Eq. (1) (adapted for the resistivity parameter; Archie, 1942),

$$\rho_b = \rho_f \phi^{-\eta}$$

(1)

it is known that the low resistivity of pore fluid ($\rho_f$) in the rock with porosity ($\phi$) has an active role in decreasing the bulk resistivity of the rock, $\rho_b$, in geothermal areas ($\eta$ is an experimental constant with values between 1.8 and 2.2). The specific resistivities of hot waters in the Kestanbol and Akçakeçili springs, according to laboratory measurements at a temperature of 19°C, are 0.35 ohm-m and 0.44 ohm-m, respectively. The role of these low values in decreasing rock resistivity will be considered in our interpretation of the geoelectric data.

3.2. Data acquisition and corrections

Fig. 2b shows the locations of the self-potential and resistivity measurement
sites. Self-potential measurements were made along ten parallel lines. The basic equipment consisted of a pair of electrodes connected by wire to a Goldstar-type digital multimeter with a high input impedance (larger than 10 Mohm) capable of a reading accuracy of \( \pm 0.00001 \) volts. Sometimes the digital multimeter was used to measure resistance in order to control the contact quality between electrodes and ground. The total field configuration, which utilizes two electrodes and a connecting wire between measurement stations, was used during the field studies. After the potential difference had been measured between the two electrodes, one electrode was moved forward along the survey line while the other remained fixed. Pb–PbCl₂-type electrodes (Petiau and Dupis, 1980) were used, and selected randomly each time in order to avoid self-bias of the electrodes, which could add linear trends to the measurements.

The resistance between the two electrodes is measured with a digital multimeter, to read the exact natural potential of the ground. Where the resistance was not below 50 kohm, the electrodes were relocated to another more conductive hole. The voltage between the electrodes is measured with normal polarity and sometimes controlled by assuming reverse polarity (Corry et al., 1983). After the voltage reading, the electrodes were cleaned with a stiff bristled brush to minimize electrochemical reactions between different soil types at each point. The electrodes were placed in a good hole and isolated from sunlight since this may cause changes in the electrode content. Drift correction and reference-tie corrections

![Typical vertical resistivity sounding data.](image)

Fig. 3. Typical vertical resistivity sounding data.
Fig. 4. The self-potential map (10 mV contour interval). Lines K (Kestanbol) and A (Akçakeçili) represent the geothermal fluid circulation zones (faults) modelled by the self-potential anomalies. Origin of the $X-Y$ plane is taken at point L1-P18 to show these zones. $R$ = Reference point.
were made for all data taken over each line, before drawing the anomaly contour map. The measured lines were smoothed with a five-point moving average filter to avoid edge effects, so that high frequencies were eliminated and low frequencies were preserved. A self-potential anomaly contour map was produced, relative to a reference point (R) north-east of the area.

The resistivity method was used primarily to locate anomalous regions of low resistivity associated with geothermal activity, and to define the resistivity distribution at different depths beneath the survey area. The procedure adopted in this method includes conventional vertical electrical soundings, which provide the resistivity distribution at depth. Because of the heavy terrain in the area, the rough topography and the poor accessibility of the survey sites, we decided to use the Wenner electrode configuration since it can be easily applied. Sounding data acquisitions were performed at 108 points along the lines (Fig. 2b) with a maximum electrode spacing (a) of 2500 m.

The density of the resistivity soundings was increased around Kestanbol spa and Akçakeçili hot spring. The electrode spreadings of the soundings were normally run almost parallel to the Gülpinar fault zone, in order to minimize the distortions on the apparent resistivity sounding curves caused by lateral resistivity variations. The typical sounding data of some sites are represented in Fig. 3. For an electrode spacing (a) equal to 70 m, the apparent resistivity generally becomes minimal (<10 ohm-m) in soundings L4-P13, L4-P5 and L5-P9. The specific (true) resistivities of various rocks that are helpful in interpreting geoelectrical structure were measured in outcrops of these rocks using a short electrode spacing (a = 10 m). They were grouped according to their lithologies as 200–500 ohm-m for limestone, 50–300 ohm-m for schists, and 100–950 ohm-m for granite.

4. Interpretation of results

4.1. Self-potential results

The self-potential anomaly contour map drawn from corrected and reference-tied data (to point R; Fig. 2b) is shown in Fig. 4. Short and long wavelength anomalies can be seen in the map. Short wavelength anomalies are due to very local conditions, while long wavelength anomalies are attributed to deep polarized planes (fractured zones). Anomaly groups with high amplitudes in the range of about -65 to +45 mV and -50 to +40 mV are observed in the areas surrounding Kestanbol and Akçakeçili hot springs, respectively. They have a general SW–NE direction. Another two groups with negative and positive high amplitudes cover the north of Kestanbol and around Değirmen river, respectively.

The detected anomalies have appreciable amplitudes and wavelengths that can be interpreted by following the patterns of theoretical anomaly contour maps calculated for various models of a geothermal fluid circulation zone (Fitterman, 1979). The theoretical anomaly contours produced by the electrically polarized planes tend to be anti-symmetric in the direction perpendicular to the strike.
A general view of the anomaly contour map (Fig. 4) suggests that the investigated area may be qualitatively interpreted to consist of several faults or fracture zones with an approximately SW–NE trend. These zones are essentially the branches of the Gülpinar fault zone that formed in the neo-tectonic period (Siyako et al., 1989).

The anomalies around Kestanbol and Akçakeçili springs have an elongated circular pattern on each side of zero voltage contours, with the sign of the anomaly changing from one side of the polarized plane to the other. At first glance, these anomaly contours closely resemble a dipole-like anomaly, and are therefore suitable for further analytical modelling attempts. A computer program (Noutsis and Skianis, 1987) was used, with an inversion scheme proposed by Marquardt (1963), to model the self-potential anomaly values. This quantitative interpretation, based on Fitterman’s method (1984), provides estimates of the geometries of dipping sheets (Fig. 5), which represent geothermal zones. The parameters of the models were iteratively changed by the program until a good agreement was reached between the calculated contours and the field map. The parameters of two fault models (geothermal zones) obtained from a three-dimensional interpretation based on the values of the self-potential map (Fig. 4) are summarized in Table 2. The position of the fault models detected by the self-potential anomaly values, which most probably represent or are caused by geothermal fluid circulation zones, are also shown in the anomaly contour map in Fig. 4.

Fig. 5. Representation of the parameters of a fault model (geothermally active) or a geothermal fluid circulation zone suggested by Fitterman (1984). Model parameters are: $F_0 =$ source polarization charge of fault or zone; $L =$ strike length; $T =$ dip extent; $X_0, Y_0 =$ Cartesian coordinates of the center of the strike length; $Z_0 =$ depth of burial; $\alpha =$ strike angle; $\varphi =$ dip angle.
4.2. Resistivity results

The resistivity maps were used to make a qualitative interpretation of resistivity distributions at various depths, depending on electrode spacing. These maps (Figs. 6–8) are constructed from apparent resistivity values corresponding to the 60, 200 and 500 m electrode spacing (a) of each sounding. Preliminary interpretations of these maps show that the apparent resistivity contours closely follow the north–south trend. Apparent resistivity values in Figs. 6 and 8 are mostly influenced by shallow and deep inhomogeneities, respectively. The map in Fig. 6 indicates a conductive zone formed by resistivity contours of 10 ohm-m. It is narrower in Fig. 7 (at moderate depth, \( a = 200 \) m). The apparent resistivities are less than 10 ohm-m within this zone and at their lowest (<5 ohm-m) near Ilica river (Figs. 6 and 7). The low resistivity in this zone is comparable to the resistivity of Quaternary and altered syenite and limestone (fractured). The resistivity decreases to a very low level due to the circulation of conductive (0.35–0.44 ohm-m) hydrothermal fluids. This zone covers a smaller area in Fig. 8, which represents greater exploration depths (Roy and Elliot, 1981). The apparent resistivity values increase towards the east in all maps. This high resistivity, in the range of 50–300 ohm-m, is an indication of more compact metamorphic and magmatic rocks. The high resistivity region, with a resistivity of 250–800 ohm-m, extends towards the village K. Alemșah and probably reflects unfractured granite and schist.

4.3. Geoelectrical structures

We used the resistivity pseudo-sections plotted using the apparent (observed) resistivity values of lines AA’ and BB’ (Fig. 2b) as input data in a two-dimensional inversion algorithm (Loke and Barker, 1995) to obtain geoelectric structures. In this algorithm, the computations of the true geoelectric model were iterated until a good match was achieved between the calculated pseudo-section (synthetic data) of the geoelectric model and the observed pseudo-section (field data). The root mean square (RMS) error was always below 10% in each inversion.

The calculated geoelectrical models are given in Figs. 9a and 9b, where different shadings correspond to different resistivities. The geological cross-sections of lines AA’ and BB’ are given above these models. The results are interpreted in view of

<table>
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<tr>
<th>Zone (fault)</th>
<th>( X_0 ) (m)</th>
<th>( Y_0 ) (m)</th>
<th>( Z_0 ) (m)</th>
<th>( T ) (m)</th>
<th>( L ) (m)</th>
<th>( D ) ((^\circ))</th>
<th>( A ) ((^\circ))</th>
<th>( F_0 ) (mV)</th>
</tr>
</thead>
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<tr>
<td>K</td>
<td>1090</td>
<td>3907</td>
<td>577</td>
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<td>A</td>
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<td>897</td>
<td>502</td>
<td>409</td>
<td>1393</td>
<td>103</td>
<td>33</td>
<td>631</td>
</tr>
</tbody>
</table>

Table 2

Parameters of the geothermal zones (site: A=Alkâkeçili, K=Kestanbol). \( X_0, Y_0 \) cartesian coordinates of the centre of the strike length; \( Z_0 \) depth of burial; \( T \) dip extent; \( L \) strike length; \( D \) dip angle; \( A \) strike angle; \( F_0 \) source polarization charge.
the two-dimensional geoelectric models, with true resistivity values, by comparing geological sections. This geophysical interpretation has often been used profitably to distinguish geological units on the basis of their different resistivities. Basically, geoelectric models reflect both vertical and horizontal resistivity variations. From the geoelectric models, it can be seen that there are many regions in the section where subsurface geology is far from a horizontally layered earth model. They are characterized by strong lateral resistivity changes. There is a remarkably different
resistivity pattern between the mid-sector, towards the Ilica river, and the southeastern region (Fig. 9a). Apart from the effect of the alluvial series, which can decrease resistivity, the region beneath the sites L4-P7 and L5-P8, which have lower resistivities (4–6 ohm-m) than the surrounding rocks, could indicate a permeable zone, probably caused by a high degree of alteration. Thermal fluids may be transferred upwards into the surface springs of Kestanbol spa along this
zone. The high resistivity (>250 ohm-m) observed between points L6-P9 and L10-P13, towards Uluköy, could be ascribed to the existence of compact Permian rocks (Fig. 9a). Here the low resistivity regions in the geoelectric model (i.e. geoelectrical structure) represent poorly altered or fractured rocks. Indeed, the Akçakeçili fault at site L8-P11, also determined by self-potential modelling (A in Fig. 4), and the surrounding region have a lower resistivity due to the circulation of thermal groundwater. High resistivity in this part of the geoelectrical structure represents more compact rocks. The increase in resistivity towards Dalyanoba
could indicate marly and sandy limestone with a lower degree of fracturation (Fig. 9a).

Based on the geoelectric structure along Line-7 (BB direction; Fig. 9b), the southern part of the area, towards K. Alemşah, clearly shows high resistivity. Here the resistivity range, 250–800 ohm-m, could be caused by schist, granite and syenite units. The rapid changes of resistivity from north to south, around the region between P13 and P15 (near Akça keçili), indicate a fault. The boundary between gneiss and granite around K. Alemşah, could have developed along a fault (no evidence of geothermal activity). The resistivity in two regions, between
P2 and P5 and P9 and P11, is very low (2–6 ohm-m). These regions, extending to deeper levels of about 200 m, are the geothermal circulation zones and dip to the north and south from point P7. A more resistive and dike-type zone can be observed beneath point P7.

5. Discussion and conclusion

Geoelectric methods can be applied with success in geothermal areas. Based on the modelling of the self-potential map, which provides useful evidence of geothermal activity, the fault around Kestanbol (K in Fig. 4) has a large potential as a geothermally active zone and extends east and west of the area, although it can not be immediately identified from surface geological observations. The geoelectrical models (Figs. 9a and 9b) provide an electrical image of the subsurface along lines AA’ and BB’ (Fig. 2), and reveal the existence of two good conductive regions around this zone (Figs. 9a and 9b). These conductive regions are highly permeable due to alteration, and, considering Eq. (1), their remarkably good conductivity is caused by geothermal fluid, with a low resistivity of 0.35 ohm-m, and alteration minerals in the rocks. The high values of Fe and NaCl observed in the waters of the hot springs (Table 1) coincidentally explain the presence of limonite and kaolin, which are only produced by this alteration. It seems that the geothermal activity is more important towards the west. Within the region of lowest resistivity (<5 ohm-m), cut by the active zone of Kestanbol (from self-potential modelling), we have proposed a new drill site, denoted by S in Fig. 7, down to 100–150 m depth, in order to produce hot water with a higher flow-rate (>5 L/s) than at Kestanbol. Several wells could be drilled around this location to obtain much hot water. No new drilling site has been suggested around the Akçakeçili site, since the geoelectrical structures have not indicated very low resistivity values. Here, the fault zone obtained from self-potential modelling (A in Fig. 4) only indicates the circulation of the thermal water of Akçakeçili spring.

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