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Assessment of the Early Development Work for Kuyucak Geothermal Field, Turkey

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ABSTRACT

There are a number of geothermal fields that are developed or currently under development for power generation in the Buyuk Menderes Graben and recent exploration field works and drilling operations indicate that this number is bound to increase in the near future. An example for a newly discovered region is located at the northern flank of the Buyuk Menderes Graben, within a small-scale graben structure perpendicular to the main graben. The study area covers the geothermal operation license owned by SDS Enerji. This area is mainly characterized by EW- trending high-angle normal faults of the Buyuk Menderes Graben. This study entails the correlation of the exploration work including geological and geophysical field studies and the deep drilling works conducted in the study area.

Menderes Massif is unconformably overlain by the Neogene sediments which are further overlain by the Quaternary deposits in the study area. The Menderes Massif mainly consists of highly jointed, thick bedded-massive marble, quartzite and intensely folded various schists and gneisses. This unit is highly deformed and fractured due to metamorphism and the tectonic activity in the region. The reservoir formation generally consists of the marble units of this massif as it is the case for the entire Buyuk Menderes geothermal system. According to the geological field works, the Menderes Massif acting as the bedrock formation for the entire Buyuk Menderes Graben could be encountered at shallow depths towards the north of the study area in line with the topography.

A magnetotelluric (MT) survey was conducted at 83 points within the study area. MT (~10 km penetration depth) data were employed to identify the deep seated geothermal system of the study area located at depths below 2500 m. At these depths, a low resistivity zone was observed in the MT sections. The observed decrease in resistivity accompanied with a slight increase in the geothermal gradient was mainly tied to the permeable fracture zones filled with saline hydrothermal fluids. The results of the MT analysis (Schlumberger, 2015) were consistent with the geological studies and further allowed the determination of the geometry of the reservoir. Two wells, KS-1 and KS-2 were drilled by considering the results of the geological and geophysical studies and the accessibility of the drilling sites at the study area. The correlation of the lithological logs, the depth of loss of circulation, and the temperature measurements of the two wells with the 3D MT results indicated that the MT measurements were able to identify the approximate depth of the reservoir. However, the well logs indicated the presence of two reservoir sections, which was not visible on the MT cross-sections due to the low resolution of MT at great depths.

Further, the results of the PT and flow rate measurements taken from the wells showed that the area was suitable for geothermal power generation. Thus, results of this study indicate that for the further development of the field, starting with the currently proven areas around the KS-1 and KS-2 wells, new wells could be drilled towards the northern part of the license area where the reservoir could be encountered even at shallower depths.

1. INTRODUCTION

Geothermal energy development in Turkey has started in the mid 1960s. The discovery of new fields over the last decade has led to a considerable growth in the geothermal industry. Owing to the complex geological structure of Western Anatolia identification of high enthalpy areas suitable for power generation requires extensive geological, geophysical, geochemical, drilling works etc. Geothermal energy industry, from service providers to investors, gained considerable amount of experience through these extensive exploration works. However, geothermal industry, considering the vast development potential and the abundance of geothermal resources, has yet to meet its true potential. Discovery of new sites not only will increase power generation capacity from a renewable resource but also will increase the demand and allow for the further development of the industry.

This study encloses the late stage exploration works conducted in a newly discovered geothermal field, located north of Buyuk Menderes Graben (BMK), in Aydın, Kuyucak. Extensive geological, geophysical, geochemical and drilling works have been performed in the study area. The geothermal reservoir of the systems is identified through correlation of 3D MT analysis with the lithological and temperature logs collected from deep drillings. In this paper, the highlights of the early stage exploration work regarding the general geology and structural geology, relevant to the current study, are also presented.

The Paleozoic-Mesozoic Menderes Metamorphics are the basement rock of the study area. The marble layers in the Menderes Metamorphic serves as the reservoir rock and the schistic levels serve as the cap rock for the system. They are unconformably overlain by the Neogene deposits and in turn overlain by the Quaternary graben fills. The 3D MT model shows a sharp resistivity decrease after around 2500 meters at the location of the deep drillings (KS-1 and KS-2). These depths match with the depths where the loss in circulation is experienced along with a slight increase in the geothermal gradient.

The low resistivity anomalies observed on the MT cross sections were interpreted as the marble units of Menderes Massif that serve as the reservoir rock for the geothermal system. The extensive tectonic activity in the region caused the Menderes Massif units to be highly deformed and fractured. Thus, a highly permeable and porous environment, ideal for the circulation of geothermal fluids, is created causing the observed resistivity anomalies.

2. STUDY AREA

The study area is located about 2 km north of Kuyucak Village, on the northern flank of Buyuk Menderes Graben in Aydın, Turkey. East of the study area, lies the well known Pamukoren geothermal field where several geothermal power plants are in place. The elevation varies between 55 m to 1580 m asl increasing mainly from south to north. The location map of the study area can be seen in Figure 1 where the drill works conducted in the study area (KS-1 and KS-2) and in the vicinity of the study area are indicated.

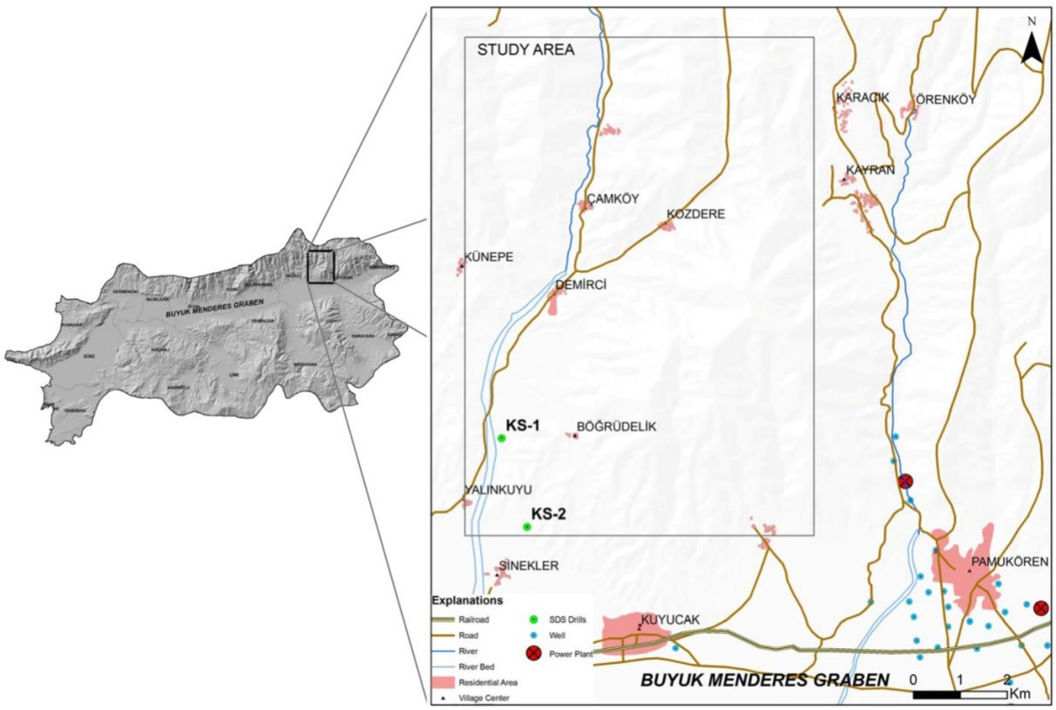

Figure 1: Location map of the study area.

2.1 Geological and Structural Settings

South Western Turkey has been undergoing a N-S extensional neotectonic regime characterized by a series of grabens-horsts and active normal faults. BMG is bordered by a low angle E-W trending normal detachment fault. The study area is located on the hanging wall fault block (Neogene cover sediments) juxtaposed to the northern boundary fault of the BMG.

The Paleozoic-Mesozoic Menderes Metamorphics are the basement of the study area. They are unconformably overlain by the Neogene deposits and in turn overlain by the Quaternary graben fills. The Menderes Massif is composed of "core" and "cover" rock assemblages. Core assemblage is composed of augen gneiss, metagranite, schist and metagabbro whereas the cover assemblage is composed of metapelites, amphibolite with dolomitic marble intercalations and marble dominated re-crystallized sedimentary sequence. In the Menderes Massif the highly fractured augen gneisses, quartzites and marbles present high porosity due to the multiphase brittle deformation and underground dissolution openings form the geothermal reservoir while the schists, such as the mica and chloriteschists, represent the cap rocks of the geothermal system at places (Koçyiğit, 2015). The graben fill units (Neogene) are the Middle Miocene conglomerate and sandstone units at its bottom followed by coal bearing sandstone, claystone, siltstone and marl. Upper Miocene units, comprised of red gravelstone, sandstone, claystone deposits conformably overlie the Middle Miocene units. These units are further overlain by the Quaternary alluvial and Pleistocene continental deposits. The fine grained sedimentary sequence of the graben fills have low permeability allowing them to serve as the cap rock of the geothermal system. The simplified geological map of the study area can be in Figure 2. The main heat sources of the system as described by Koçyiğit (2015) are "zone of shallow curie points, the asthenospheric upwelling up to shallower depths, the natural radioactivity and the shallow seated magma chambers of felsic intrusions".

The structural setting in BMG is characterized by a 130 km long zone of deformation with fault zones consisting mostly of N-E- and less commonly of E-W-, N-S- and W-NW- trending fault sets. The E-W- normal faults have been obliquely offset by NE-SW to NNE-SSW left lateral strike slip faults (Koçyiğit,1984). The detachment faults are crossed and displaced by high angle active normal faults. This active tensional tectonics and related normal faults allow for deep circulation of meteoric water (Faulds et al., 2010).

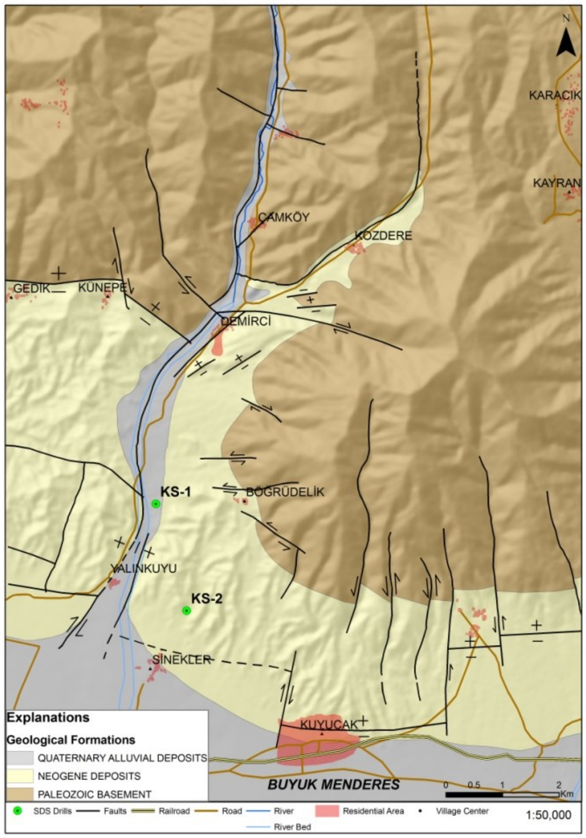

Figure 2: Simplified geological map of the study area

3. BACKGROUND MATERIAL

The geothermal fluids and clay alteration along with high temperatures associated with geothermal activity commonly result in lower resistivity values (Ussher, 2000). Thus, hydrothermal systems cause strong variations in the electrical resistivity of the subsurface, making them ideal targets for electromagnetic methods (Spichak and Zakharova, 2015). The development in MT analysis over the years, especially on 3-D inversion methods, allowed MT surveys to become an invaluable resource for geothermal exploration for the identification of best locations for future drillings.

The main factors affecting the electrical resistivity in a geothermal system are; temperature, rock porosity and permeability, alteration mineralogy, fluid chemistry and saturation. However, the interpretations solely based on the parameters independently, causes misinterpretations. Each parameter and their correlations relevant with the system under investigation should be observed thoroughly. Also, the order of significance of these properties varies significantly in geothermal systems with different overall structure (low-high enthalpy systems, tectonic history, etc.).

Resistivity-temperature dependency is investigated by Llera et al. (1990). They observed almost an order of magnitude decrease in resistivity when the temperature is increased from 25 to 250°C. Ussher (2000) explained this inverse relation between resistivity and temperature with the ionic processes that are responsible for the conduction processes in hydrothermal systems.

A relationship between electrical conductivity of rocks and their porosities is found by Archie (1942) which is later improved by Waxmann and Smith (1968) incorporating the surface conductivity. The relationship suggests that the electrical conductivity is proportional to porosity and permeability (Zhang et al., 1994). Roberts et al. (2001), compared the resistivity values of intact and fractured rocks and observed a decrease in resistivity of 25-50% from intact rock to fractured rock (fluid-filled). Duba et al. (1978) also observed a resistivity decrease of 8 orders of magnitude on rock samples after saturation with distilled water.

There is an inverse relation between salinity and resistivity. Conductivity is controlled by the presence of ions in a solution where the dissolved ions act as conductors. Consequently, the more ions that are present, the higher the conduction. The dominant conductive species in geothermal systems are Na-Cl. Ussher et al. (2000), compared resistivity values of the samples of unaltered rocks with different salinities where they found that, more saline sample results in lower resistivity values. However, in the presence of clay minerals, an interface between clay surface and the water forms, called the electrical double layer, which creates an extra conduction pathway (Ward, 1990; Spichak and Manzella, 2009) referred to as surface conductance. The high positive ion concentration in the double layer causes the increased or excess double-layer conductivity in the argillaceous reservoir material. The thickness of this layer increases as brine salinity decreases which results in an inverse relation between salinity and conductivity. The high positive ion concentration in the double layer could be explained by the saturation of the porous media with an electrolyte solution, which causes abnormally low resistivity factors (resistivity of the rock when completely saturated with an electrolyte divided by the resistivity of the electrolyte itself) in altered rocks (Winsauer and McCardell, 1953).

Hydrothermal alteration is a general term embracing the mineralogical, textural, and chemical response of rocks to a changing thermal and chemical environment in the presence of hot water, steam, or gas (Henley and Ellis, 1983). Primary minerals are converted to secondary minerals as a result of changes in in-situ conditions. The alteration products could be clay minerals and clay alteration causes lower resistivity values due to surface conductance. Flovenz et al. (2005) investigated the dependence of bulk conductivity to the interface conduction and pore fluid conduction at unaltered and altered zones. Resistivity of the unaltered samples showed sole dependency on pore fluid conduction whereas the samples from the altered zone showed that the conduction is dominated by interface conductance.

Low resistivity anomolies are matched with the clay cap rocks of the geothermal systems in high temperature and supercritical fields by many researchers (Muñoz, 2014; Gasperikova et al, 2015). The common hydrothermal minerals at the zone between 70 - 200˚C are commonly represented by the abundance of conductive clays (e.g. smectites). The conductivities of clay rich rocks are inversely proportional to the Cation Exchange Capacity (CEC). High temperature alteration minerals such as illite and chlorite have lower CEC values. Smectites have much higher CEC values than illites and chlorites which in turn results in lower resistivity values. Clay alteration at lower temperatures causes a decrease in the resistivity values, and when we get to a zone with higher temperature, resistivity values will tend to increase due to the change in alteration mineralogy. However, at a reservoir with temperatures below 200˚C, such change in alteration minerology, that could cause a significant resistivity change, is not expected. Accordingly, an anomaly observed in the resistivity sections could be bound to pore fluid conductance even in the existence of altered zones. Pore fluid conductance is controlled by permeability, porosity, and the fluid chemistry and saturation of the circulating fluids. However, it should also be noted that the temperature dependence of surface conduction is higher than the temperature dependence of pore fluid conduction.

4. DATA

The 3D MT analysis of the study area was performed. The survey area is about 11x7 km where MT data were acquired at 83 station with an average spacing of 250 m on an irregular grid. Two well locations were identified by incorporating the results of the geophysical measurements and information regarding the structural and geological configuration of the study area. 2 successful production wells, KS-1 and KS-2, , with depths of 3232 m and 3614 m were drilled respectively and artesian flow was observed for both wells. Further, lithological and temperature logs were collected from these wells.

At both wells the transition between Neogene and Paleozoic units of the Menderes Massif were observed at around 700-800 meters. At KS-1 well, based on the lithological log, loss in circulation depths and results of temperature logs, two reservoir sections were identified divided by a layer of graphite-schist. The upper reservoir section was encountered between 2558-2942 m. depth with a thickness of 384 m and the lower reservoir section has been encountered at 3029 m following a 90 m graphite-schist unit. A similar situation was observed at the KS-2 well as well. The upper reservoir and lower reservoir sections were encountered between 2530-2897 m (thickness of 367m) and after 3150 m (thickness > 464 m) respectively with graphite-schist layer in between. Drilling was terminated before penetrating the entire reservoir in both wells.

5. INTERPRETATION AND RESULTS

The 3D MT model and a cross-section intersecting the KS-1 and KS-2 wells can be seen in Figure 3. The resistivity sections show a clear zone of low resistivity at the southern and central part of the survey area, consistent with the Quaternary cover. Owing to the topographical complexity at the northern parts of the study area, higher resistivity values were observed. On the 3D MT model, a general trend of high resistivity until around 2.5 km is followed by a sharp decrease in resistivity. The depth of this resistivity anomaly increases with the topography as we go north of the study area. After an approximate 750 meters of Neogene cover, the hydrothermally altered Menderes Metamorphics were encountered for the remaining depths for both wells. Neither the encountered temperatures (around 160˚C) nor the geological formations encountered through the course of the drillings suggest any significant alteration change (such as smectite-illite etc.), thus the observed resistivity anomaly cannot be linked to the surface conductance at the encountered temperatures.

With regards to the geology of the area, flow is mainly controlled by the fracture porosity. The fracture system causes lower resistivity values which is studied by many researchers over the years (e.g. Ushijima et al., 1986; Manzella et al., 2002; Del Rasario et al., 2005; Bromley, 1993; Romo et al, 2000). The marble sections identified by the lithological logs are highly fractured creating a deep circulation environment for meteoric waters. Thus, the observed decrease in resistivity accompanied with a slight increase in the geothermal gradient could be tied to the permeable fracture zones filled with saline hydrothermal fluids. Thus, the low resistivity values are associated primarily with the pore fluid conductance, coupled with the surface conductance (at the altered zones) amplified by the circulating Na-Cl dominated geothermal fluids.

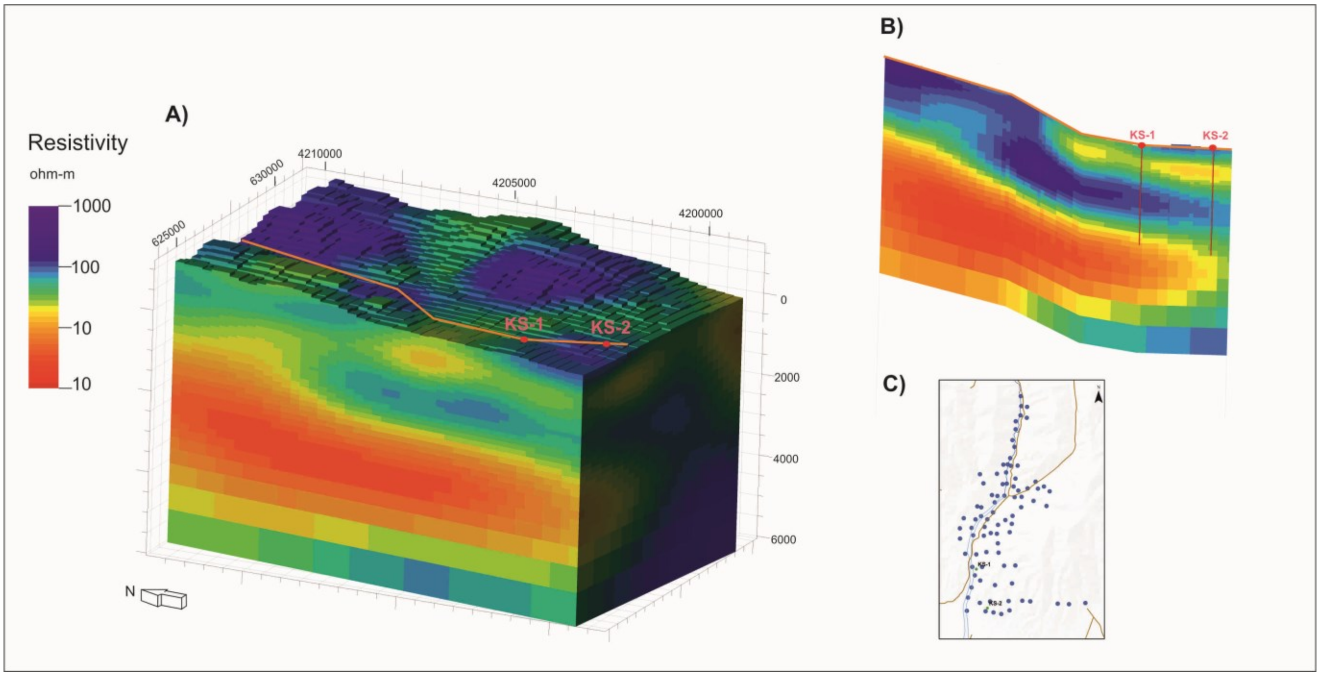

Figure 3: A) 3D-MT model of the study area, B) Cross-section intersecting KS-1 and KS-2 wells C) MT measurement locations

6. CONCLUSIONS

The geological and structural framework, MT anomalies and the drill logs are correlated to identify the geothermal system in the study area. The reservoir rocks of the geothermal system are mainly the marble units of the Menderes Metamorphic Core Rock Assemblage, where the cap rock of the system is composed of the schists of the Menderes Metamorphic Cap Rock Assemblage and the Neogene Graben fills. A 3D MT survey and 2 successful deep drillings were conducted in the study area. Initially the MT analysis revealed the existence of a conductive zone at depths below 2500 meters which is further verified by the drilling works where reservoir material and the loss in circulation along with a slight increase in the geothermal gradient was observed at approximately the same depths. This low resistivity anomaly is explained by the presence of Na-Cl dominated meteoric fluids circulating in a highly deformed and fractured medium.

MT survey and drilling works conducted in the study area revealed that the Kuyucak field has high potential and needs to be further developed for power production. It was observed that the depth of the resistivity anomaly regarded as the geothermal reservoir increases with topography towards the north of the study area. Thus, for the further development of the field, starting with the currently proven areas around the KS-1 and KS-2 wells, new wells could be drilled towards the northern part of the license area where the reservoir could be encountered even at shallower depths.

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