Land and Marine Magnetotelluric Exploration at the Salton Sea Geothermal Field

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ABSTRACT

The Salton Sea geothermal field is one of the largest geothermal resources in the world. It was discovered in the 1950s but has only been developed on the southeastern lake shore and the actual field boundaries are not well known. In this paper we describe a combined offshore/onshore Magnetotelluric (MT) survey made over the known geothermal field and surrounding region to determine the formation resistivity signature of the geothermal field and to use this signature to map the external field boundaries and internal structure.

The survey was made with land, marine and hybrid MT field systems. These instruments use a portable, low-power digital data acquisition system with sensors deployed on land, and on the shallow sea bed. The survey consisted of 70 sites arranged in 4 profile lines; 3 of these profiles cross the northeast trending geothermal field in a NW-SE direction and the 4^{th} profile crosses in a NE-SW direction. The data from the sites were processed to provide apparent resistivity and phase as functions of frequency for each site. The sites were then grouped into profiles, and a 2D inversion code was applied to provide a resistivity versus depth section along each profile.

The MT profiles show that the geothermal reservoir has a lower resistivity than the background. This difference is largely due to the higher temperatures and higher formation water salinity. Based on the low resistivity signature, we estimate that the field encompasses more than 200 km^2, over half of which lies offshore. Within the field, the MT profiles match the known geology and borehole induction resistivity logs well. The general stratigraphic section can be divided into three vertical horizons: a shallow mud and silt cap rock, an upper reservoir zone consisting of high temperature sand and clays and a deeper, more continuous reservoir zone of consolidated sand and silt.

Introduction

The Salton Sea geothermal field lies at the southern shore of the Salton Sea in Imperial County, California. The field was first discovered in the 1950s but only the southeaster shore has been developed. Researchers have concluded that the bulk of the resource lies offshore (Hulen *et al.*, 2003).

In this paper we describe a combined offshore/onshore MT survey. The survey was conducted to map the resistivity structure within the known geothermal resource and to map the field boundaries, both onshore and offshore.

With the MT method, natural electrical and magnetic fields were simultaneously collected at the earth's surface to provide an estimate of the earth's electrical resistivity structure from the surface to great depths. The fields originate from solar wind and distant thunderstorm activity and were measured over a range of frequencies, corresponding to a range of investigation depths. Data were processed to provide a model of resistivity versus depth, often in a 2D profile or a 3D volume.

MT provided formation resistivity to great depths on a large scale, using both surface- and seabed-deployed instrumentation. We expected that the high temperature and high salinity of the formation brines would produce an anomalously low resistivity that would allow us to differentiate the geothermal resource from the surrounding formation. The method has long been a geothermal industry staple because of its great depth of penetration but until recently its use has been hampered by uneven data quality and low resolution.

The California Energy Commission, the CalEnergy Corporation and Schlumberger jointly initiated the project. The project consisted of three phases:

- In the first phase, we extensively designed the field system, the survey, and did a short field test to set data acquisition parameters and the processing scheme.
- In the second phase, we used MT to survey the land and marine areas.
- The third, and most important phase of the project, was to interpret the data and integrate it with the existing field model.

Below we provide a preliminary model based primarily on the MT results. However, we expect that this model will be updated as these data are combined with existing and future geophysical and well data in this field.

Geological Setting and Background

The Salton Sea geothermal field lies within the Salton trough physiographic province in southern California and northern Baja California, Mexico (Elders and Sass, 1988). The Salton trough is a landward extension of the Gulf of California and marks the beginning of the San Andreas Fault system (Figure 1). It is a rapidly sinking Pleistocene pull-apart basin mainly filled with sands and muds deposited by the flood plain and channel deposits of the Colorado River system with periodic shallow water marine sequences.

The Salton Sea Geothermal field is thought to lie along a transform fault that connects active fault segments of the San Andreas system (Elders and Sass, 1988). Five small volcanic domes along the southeastern lakeshore mark the field, but no other surface manifestations appear. The stratigraphic sequence consists largely of flood plain and channel Quaternary sands, silts, and clays deposited by the Colorado River system with minor sequences of marine sediments from periods when the Salton trough was part of the Gulf of California. In addition, a number of exploration wells have encountered locally thick intrusive volcanic materials, chiefly rhyolites, but these are not continuous across the field (Hulen *et al.,* 2003).

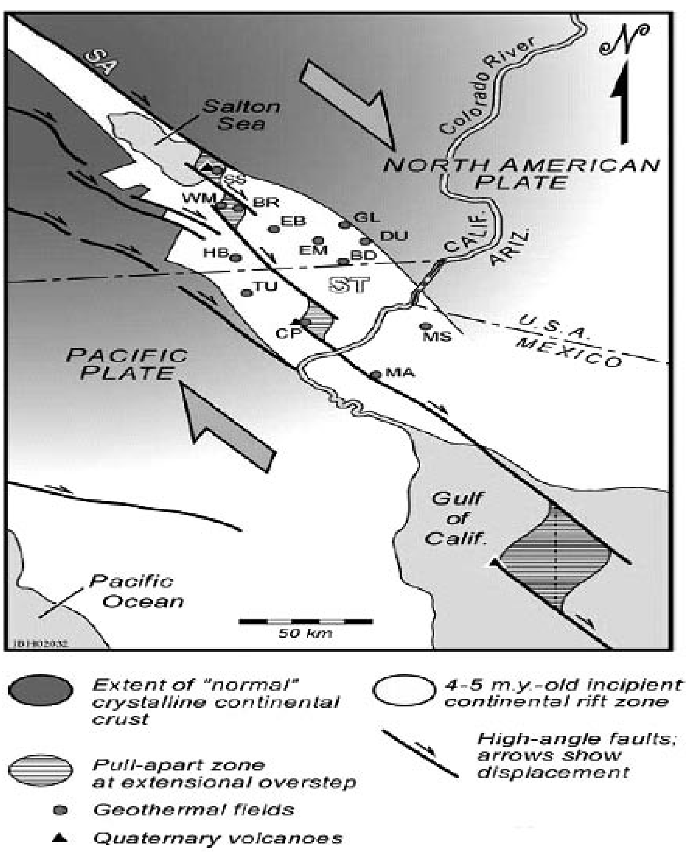

Figure 1. The Salton Trough physiographic province (Hulen *et al.,* 2003).

Geothermal field development at the Salton Sea field began in the mid-1970s but it was not aggressively developed until the mid-1990s when problems associated with the production of high-salinity, mineral-saturated brines were solved. Currently, the field produces 360 MW of electrical power from approximately 25 wells, but estimates of the field capacity range from 8 to more than 50 times this level (Hulen *et al.,* 2003). The operator (CalEnergy) has immediate plans for a 40% field expansion and more development is envisioned over the next few years as the demand for electric power in southern California continues to rise.

MT Survey Design Phase

Although a series of reconnaissance MT surveys were made at the Salton Sea geothermal field over the past 30 years these surveys provided sparse coverage and did not extend into the sea or the shallow water transition zone (Jensen *et. al.,* 1990).

Instrumentation Design

Modern MT instrumentation is significantly easier to use than systems applied in earlier surveys (Jensen *et.al.,* 1990). The instruments are lightweight, portable, and battery-powered and can record all necessary field components for several days while left unattended. The land-based instruments we used consisted of a five-sensor package connected to a 24-bit broadband data acquisition system. We normally deployed two 100-200m long electric field dipoles in an orthogonal array, along with a 2 or 3-component orthogonal magnetic sensor package. The battery-powered 6-channel data acquisition system consisted of front-end analog electronics linked to a 24-bit Analog-to-Digital with a flash card memory. The timing and station positioning was controlled through global positioning satellite (GPS) and internal high-stability clocks. The system could record data over a frequency range from 0.001 – 500 Hz continuously for more than a week on a single 12-V car battery.

With the marine MT (MMT) system the data acquisition and sensors were combined into a single waterproof package. The electric field dipoles were 8 m long and attached to stiff arms, which provided the electrode positioning on the seafloor. The total system with the anchor weighed more than 225 kg, requiring a crane for deployment and recovery. For the shallow Salton Sea environment, the flotation, acoustic positioning and flotation packages were removed so the system could be unloaded into the sea by a 2 to 3-person crew operating from a 28-ft pontoon boat. For recovery, a floating buoy was attached

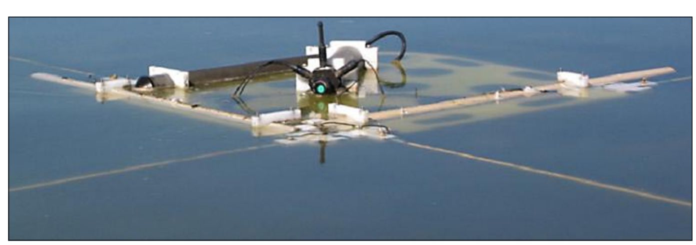

Figure 2. MMT instrumentation for shallow water (hybrid).

to a small anchor tied to the system. Recovery was managed by simply pulling up the anchor. We also designed a hybrid platform system for very shallow water deployment. In this case, the acquisition system, battery case and sensors were mounted on a polyethylene sheet and four orthogonally mounted arms holding the electrode hinged to the sheet as shown in (Figure 2).

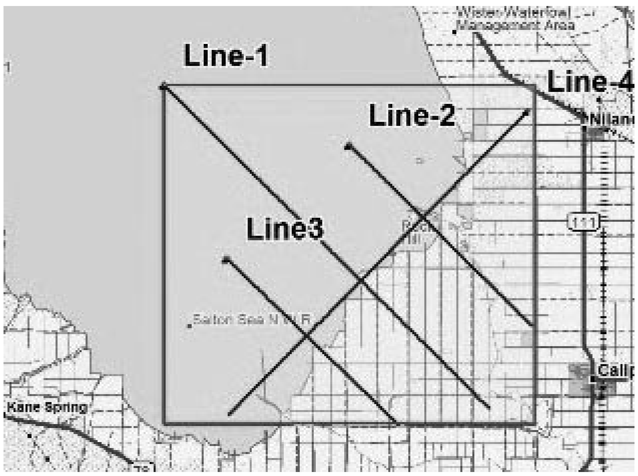

Figure 3. Survey location map.

MMT Survey Design

We designed the field survey to obtain 4 profiles (Figure 3). Three of these profiles cross the NE-trending geothermal field in parallel along a NW-SE direction, thereby crossing the field at 3 offsets approximately 4 km apart. In the fourth profile, we measured directly across the field in a NE-SW direction to both establish the lateral boundaries and also to map the basin structure. Stations were spaced roughly 1 km apart along each of the field profiles.

In this phase, we did an extensive survey design and short land- and marine-based test survey. This survey specified noise levels and recording times and developed techniques to mitigate electrical noise originating from the geothermal plant and mechanical noise originating from wave activity in the sea.

Because of low formation resistivity, we found that a wide-band system was required to obtain the resistivity to depths exceeding 3 km. The field data was collected over the frequency band from 0.001 – 500 Hz; each sounding requiring 1–3 days of continuous field recording. We also discovered that large and pervasive electrical noise originating from the existing geothermal power plants required a distant field reference site to mathematically separate natural field noise from local noise. Finally, our pre-survey modeling suggested that stations be spaced approximately 500m to 2 km apart along the 4 lines, to adequately cover the entire geothermal field within the 1-month time frame allotted for the survey.

MT Data Acquisition Phase

In the second phase, we deployed our land-based systems in a 3-week survey. We normally installed 6–8 stations and measured the fields simultaneously for 1–3 days. These systems were then redeployed in new locations, and the process was repeated until all stations were measured.

The marine surveys were much more difficult. The majority of the deployments were made using a 28-ft pontoon boat. This craft could carry three or four systems at a time out to the deployment area. For very shallow water, access was only possible using airboats.

The major difficulties were the local noise from the geothermal plant and road traffic and the sometimes severe motion noise from wind and waves. Often the best quality data was obtained during nighttime hours when winds were lowest and local noise was minimal. In the end, we collected data from 75 stations; data from 65 of these were used in the final data interpretation. More than 40% of the stations recorded were offshore and we extended coverage to more than 10 km past the known field boundaries, encompassing an area of more than 400 km^2.

MT Data Processing and Inversions Phase

The MT method is a passive technique, whereby naturally occurring electrical and magnetic fields over a broad frequency range are recorded simultaneously over an extended time period. The signals being looked for are typically low-level signals that can be swamped by local electrical or motion noise. Good-quality data can be acquired by recording the fields over several days and establishing a remote site on a quiet location, and then using data from the external fields to reduce station noise using cross-correlation techniques. The techniques for MT data reduction are a customized application of well-known time series processing developed and refined over the past 20 years (Egbert, 1997).

The first step in data reduction is to select quiet periods, where the time series have the best signal-to-noise ratio. From the data acquired thus, impedances are formed by taking the ratio of electrical-to-magnetic field components (Egbert, 1997). From the impedances, one can then calculate an apparent resistivity versus frequency curve by applying a simple transformation. The field data are collected in two orthogonal directions and it is often desirable to mathematically rotate the fields into those parallel to and perpendicular to the geological strike.

An example of a sounding we processed is provided in Figure 4, overleaf. This sounding presents the two orthogonal apparent resistivity curves as a function of frequency. Note that the curves are coincident at higher frequencies, indicating that they are sensing a vertically varying but laterally uniform shallow section, but they diverge at lower frequencies, indicating a 2D response for the deeper part of the section. For this data set, the two curves typically correspond to fields oriented parallel with the Salton basin Transverse Electric (TE) and those oriented perpendicular to the basin Transverse Magnetic (TM).

Once all of the data were reduced, then we carried out 2D inversions using a numerical code. We have applied a code developed at the University of Utah and routinely used within the geophysical community (Rodi and Mackie, 2001).

The code calculates the MT response for a 2D model and compares calculated and observed data. It then adjusts the model parameters until the observed and calculated data fit within a given tolerance, as determined by the 5–10% data measurement error.

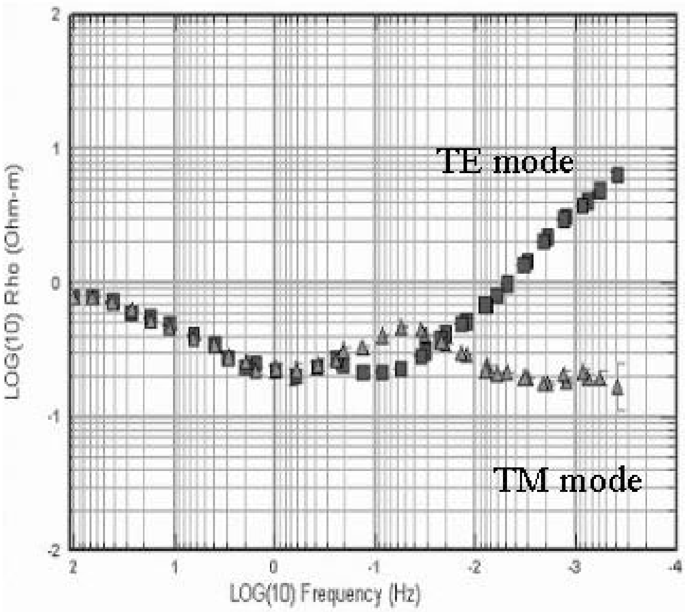

Figure 4. Sample land-based MT sounding from line 2.

In Figure 5 we show an example of an interpreted 2D resistivity section that crosses the Salton Sea field in a NW-SE direction (see Line 2 in Figure 3). The profiles indicate a very low average resistivity both for the background and the section within the producing field. The low resistivity is primarily a function of the high-porosity sedimentary section and the high-salinity brines in the pores. Within the geothermal field the resistivity is even lower because of the high temperature and higher-salinity brines. The plot also shows a complex section where the resistivity is increasing with depth, with a semi continuous marker within the field at a depth of approximately 1km.

In examining Figure 5, we observed that the producing field has a resistivity of only 10–30% of the background field, although the lithology is much the same. The difference is primarily due to the elevated temperatures and pore water salinity within the geothermal reservoir. For example, laboratory measurements suggest a temperature-induced resistivity decline of up to a factor of 10 at a temperature of 200 degC (Ucok, Ershaghi and Olheeft; 1979). Similarly, the resistivity of high salinity brines is reduced with increasing brine salinity (Ucok et al. 1979). We note that this effect is partially mitigated by the effect of reduced porosity in the field as a result of mineral precipitation.

The plot in Figure 5 indicates that the low-resistivity anomaly associated with the field extends for approximately 10 km along this line. We note that a similar depression occurs on all of the other profiles thereby allowing us to estimate the margins of the field as indicated by the resistivity low. Our rough calculations, as indicated in Figure 3, suggested that the encompassed area of the resource is possibly more than 200 km^2.

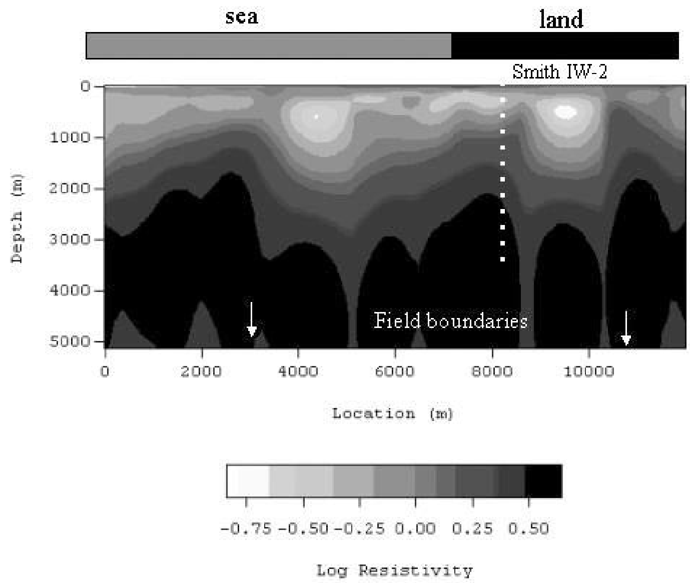

Figure 5. 2D resistivity cross-section from inverted Line 2 MT data.

Figure 6 compares the vertical resistivity distribution derived from the cross-section to a borehole resistivity log from a production well, Smith IW-2, which is located within 1 km from the section studied. The plot indicates a fairly close correspondence between the log and the MT resistivity section, which may allow us to assign lithological or thermal markers to particular resistivity horizons.

The upper 200m (approximately) are mostly silts and mud. Below 150m, this formation is hot, with temperatures ranging from 100–200 degC. The high temperatures can be correlated to the lowest resistivity (0.2 ohm.m). With increasing depth, the resistivity gradually increases, showing an abrupt increase at 0.5–1.0 km deep. This horizon correlates to a stiffer formation and it actually marks the upper reaches of the producing reservoir. The resistivity increase is a largely a function of reduced porosity due to mineral precipitation by the hot brines. Below this horizon, the resistivity continues to increase primarily because of depth-induced porosity reduction but it is also caused by a rhyolite intrusion encountered between 1600–1800 m deep in the well.

The thermal and flow variations within the field are substantial- as measured by the variable flow rates of production wells, and these variations are largely governed by geologic structure. For example it is widely accepted that a series of en-echelon, NE-SW trending faults passes through the center of the producing fields and provides much of the vertical permeability structure for the most productive wells. These combined faults constitute a transform zone that connects the active branches of the San Andreas Fault system (Hulen *et al.,* 2003). The possibility that local lateral resistivity variations observed in the cross field profiles correlate with these high productivity zones is not as yet established but it is presently under study.

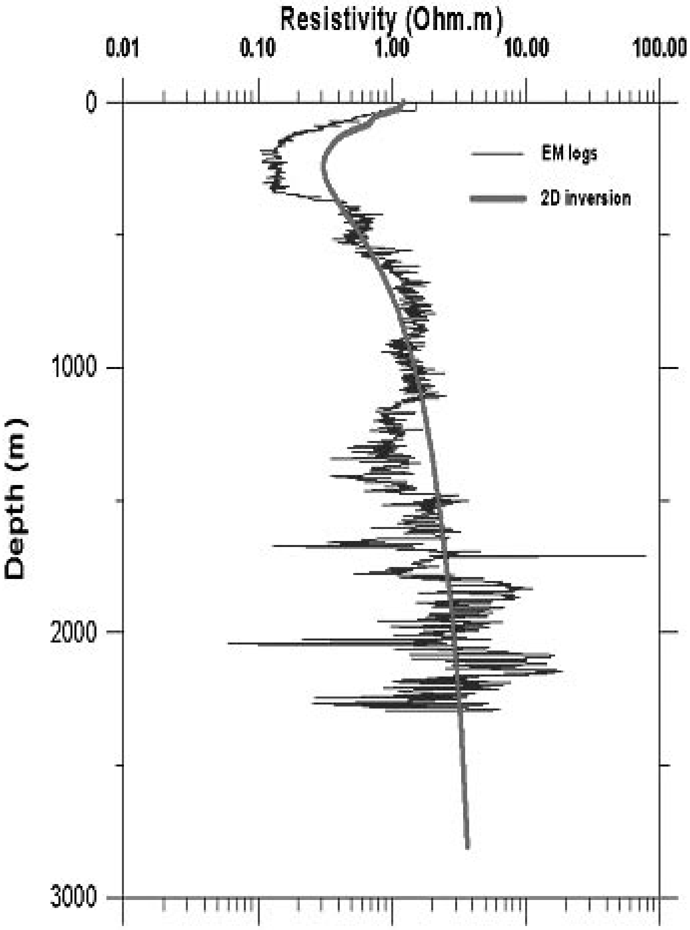

Figure 6. Comparison of Smith IW-2 well log and MT-based resistivity results from Line 2 of Figure 3.

Summary and Conclusions

This paper describes a combined land and sea deployed MT survey of the Salton Sea geothermal field for the purpose of identifying field boundaries and mapping internal structure. The high temperature and high salinity environment in the geothermal field allowed us to discriminate the geothermal reservoir from the surrounding region based on the formation electrical resistivity. MT was selected for the field survey because of its great depth of penetration and ability to determine the electrical resistivity structure from natural fields.

The field survey was accomplished on land, in the sea and in the shallow water transition zone using custom-designed instrumentation and novel deployment schemes that utilized pontoon and airboat system deployment. Data were collected in 4 profiles that crossed the known geothermal field in NW-SE and NE-SW directions. Data reduction was accomplished using remote reference sites for noise cancellation to mitigate the effect of the operating geothermal power plant. The data were interpreted by employing a 2D inversion algorithm that fit the collected data to a 2D resistivity model.

The 2D resistivity sections made it possible for us to clearly define the field boundaries. The margins of the field were typically related to zones of rapidly changing resistivity where interior regions had a resistivity of less than half the value of the exterior at the same depths. We also found an excellent correlation of the MT resistivity with borehole induction logs within the well field, which adds to the credence of the interpretation.

This study was notable for several reasons. It was the first combined land/sea MT survey known. We used this unique capability to create the first map of the offshore portion of the Salton Sea geothermal field. The survey also proved that by using modern instrumentation and sophisticated processing it is possible to collect good quality data in the vicinity of an operating power plant, which constitutes a huge noise source. Finally the survey demonstrated that MT has sensitivity to internal field structure, such as the sealing cap rock and local volcanic deposits. This can be important in future surveys.

The next step for this field is to improve the resolution of the inter field structure. This could be accomplished by completing additional soundings and combining the MT results with an upcoming seismic reflection survey.

Acknowledgments

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