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Magnetotelluric Surveying and Monitoring at the Coso Geothermal Area, California, in Support of the Enhanced Geothermal Systems Concept: Survey Parameters, Initial Results

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ABSTRACT

Electrical resistivity may contribute to progress in enhanced geothermal systems (EGS) by imaging the geometry, bounds and controlling structures in existing production, and by monitoring changes in the underground resistivity properties in the vicinity of injection due to fracture porosity enhancement. To these ends, we are acquiring a dense grid of magnetotelluric (MT) stations plus contiguous bipole array profiling centered over the east flank of the Coso geothermal system. Acquiring good quality MT data in producing geothermal systems is a challenge due to production related electromagnetic (EM) noise and, in the case of Coso, due to proximity of a regional DC intertie power transmission line. To achieve good results, a remote reference completely outside the influence of the dominant source of EM noise must be established. Experimental results so far indicate that emplacing a reference a distance of 65 miles from the DC intertie in Amargosa Valley, NV, is still insufficient for noise cancellation much of the time. Even though the DC line EM fields are planar at this distance, they remain coherent with the non-planar fields in the Coso area so that remote referencing produces incorrect responses. We have successfully unwrapped and applied MT times series from the permanent observatory at Parkfield, CA, and these appear adequate to suppress the interference of the artificial EM noise. The efficacy of this observatory is confirmed by comparison to stations taken using an ultra-distant reference east of Socorro, NM. Operation of the latter reference was successful by using fast ftp internet communication between Coso Junction and the New Mexico Institute of Mining and Technology, using the University of Utah site as intermediary, and allowed referencing within a few hours of data downloading at Coso.

1. INTRODUCTION

A candidate for an Enhanced Geothermal System (EGS) possesses higher than average heat flow but has natural permeability and/or fluid content which is limited (Robertson-Tait and Lovekin, 2000). At the eastern margin of the Coso geothermal system (Figure 1), measured formation temperatures exceed 300^{o}C at depths less than 9,000 ft, but the natural permeability is disappointingly low. Preliminary studies indicate that appropriate tectonic conditions exist to create shear failure following hydraulic stimulation at the east flank of Coso, such that reservoir stimulation techniques may create sustained permeable fractures. In addition, the main Coso field is one of the largest and most productive liquid-dominated geothermal systems in the U.S., and concepts on reservoir controls are still evolving (Adams et al., 2000; Kurilovitch et al., 2003).

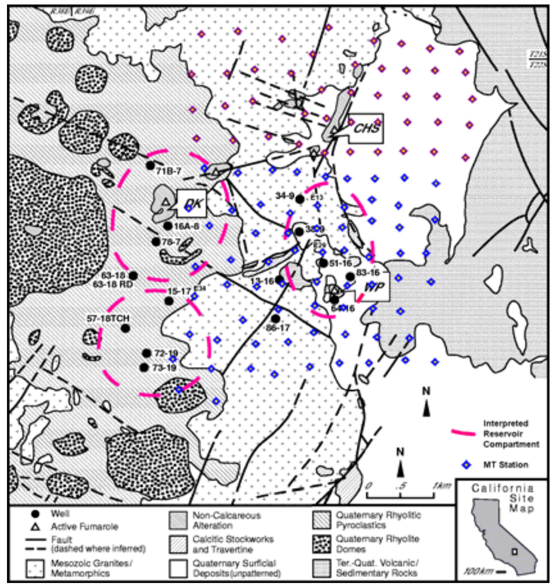

Figure 1: Simplified geological map of the Coso geothermal area including interpreted reservoir compartmentalization (after Adams et al., 2000), and MT data sites. Blue symbols are sites supported by U.S. DOE, while purple are supported by U.S. Dept. of Navy. Geology map somewhat modified from Adams et al. based on Whitmarsh (2002). Principal alteration areas Devil's Kitchen (DK), Coso Hot Springs (CHS), and Wheeler Prospect (WP) shown.

A successful approach to understanding and developing an EGS must include technology to provide images of subsurface structures which control geothermal fluid flow. Moreover, an EGS will be promoted if images can obtained of the changes in subsurface properties which may occur following hydraulic stimulation. Electrical resistivity is a primary physical property of the Earth which can be strongly affected by geothermal processes. Since an increased fluid content due to fracturing, and the development of more conductive alteration minerals (clays, etc.), can give rise to an electrical resistivity contrast, electromagnetic (EM) methods of probing have been investigated and applied for many years. Consequently, we have been acquiring a reasonably dense magnetotelluric (MT) data set over the eastern Coso field (Figure 1).

The MT technique makes use of naturally occurring EM wave fields produced by regional/global lightning activity and by solar wind/magnetospheric interactions as sources for probing underground electrical resistivity structure

(Vozoff, 1991). These signals are small in amplitude (e.g., 10's of micro-V) and thus are easily contaminated by unrelated environmental noises, principally man-made ones. Given that the Coso field currently produces in excess of 250 MW or power, artificial noises can be expected to be large. In addition, Bonneville Power Authority operates a DC intertie power transmission line extending some 800 miles from The Dalles, OR, to the north Los Angeles area, with peak power loads up to 3 GW (*Keeping Current*, BPA monthly, Oct. 2000). In principle, as described more below, high quality MT data can be recovered in such environments if a remotely located MT site which records simultaneously with the main survey is established. The broad reach of the DC intertie fields has been perhaps the principle challenge to achieving good MT results and it is the main purpose of this paper to describe our experience in establishing effective remote referencing for the Coso field.

2. COSO FIELD GEOLOGICAL SETTING

The Coso Geothermal area (Figure 1) is located in the Coso Range at the margin between the eastern flank of the Sierra Nevada and the western edge of the Basin and Range tectonic province of southeastern California, and lies within the Walker Lane/Eastern California Shear Zone (WLSZ). The Basin and Range province, an area of high heat flow and seismicity, is characterized by northerly trending fault block mountains separated by alluvial valleys that result from extensional tectonism. The Walker Lane/ Eastern California Shear Zone is a tectonically active feature and is characterized in this region as accommodating approximately 11 mm/yr of north-south trending, right-lateral strike-slip motion between "stable North America" and the Sierra Nevada (McClusky et al., 2000). To the west, the Coso Range is separated from the Sierra Nevada by Rose Valley, the southern extension of the Owens Valley. It is bounded to the North by Owens Lake, a large saline playa. On the east, the range is bounded by Darwin (Coso) Wash and the Argus Range, and on the south by Indian Wells Valley.

The Coso Range basement is dominated by fractured Mesozoic plutonic with minor metamorphic rocks, that have been intruded and partly covered by late Cenozoic volcanic rocks. The basement complex has been intruded by a large number of northwest trending, fine-grained dikes. These dikes range in composition from felsic to mafic and are believed to be part of the Independence Dike swarm with a suggested Cretaceous age. The late Cenozoic volcanic rocks consist of basalts and rhyolites. In the most recent volcanic phase, thirty-nine rhyolite domes were emplaced in the past million years in the central region of the field along with a relatively small amount of basalt on the margins. Over the past 0.6 My, the depth from which the rhyolites erupted has decreased, ranging from ~10 km depth for the ~0.6 Ma magma, to ~5.5 km for the youngest (~0.04 Ma) magma. These results are consistent with either a single rhyolitic reservoir moving upward through the crust, or a series of successively shallower reservoirs, in keeping also with recent Ar-Ar geochronology (Kurilovitch et al., 2003). As the reservoir has become closer to the surface, eruptions have become both more frequent and more voluminous (Manley and Bacon, 2000). This partially molten magma chamber is believed to be the heat source that drives the geothermal system.

Stresses that control the faulting and fracture permeability of the reservoir rocks are believed to be the result of the location of the Coso Range in the transitional zone between Basin and Range extensional tectonics to the east and strike-slip tectonics to the west (Roquemore, 1980; McClusky *et al*, 2000). Two major fault orientations have traditionally been recognized to control the geothermal system. The first set of faults strike WNW, have a vertical dip, and have strike-slip earthquake solutions, while the other strongly developed system of faults strike NNE and dip to the east. The NNE striking fault zones have been successfully targeted in development of the Coso geothermal field, in particular in the east flank area where wells drilled with a steep westerly dip have been the most productive (e.g., Sheridan et al., 2003). Permeability is high within the individual Coso reservoirs (i.e., Figure 1) but low in most of the surrounding rock. This limits recharge to the reservoir and makes reinjection important for sustained productivity. A dominantly ESE-WNW to nearly E-W extensional direction is confirmed by recent focal mechanism studies (Unruh et al., 2002). However, this extension is interpreted in the context of distributed dextral shear involving important fault zones of truly SE-NW orientation (op. cit.), some subsidiaries of which are drawn in Figure 1.

3. MAGNETOTELLURIC DATA ACQUISITION

A very simplified cartoon of an MT site deployment as used at Coso is shown in Figure 2. The electric and magnetic field components of the EM waves are measured with two types of sensors. The electric field principle is simple, with voltage differences taken over a bipole span of nominally 100 m, and the voltages divided by distance to get E-field. Contacting endpoints of the bipoles were cold-rolled steel plates in holes ~20 cm deep with ~1 liter water added to improve contact. The magnetic fields are obtained using high-sensitivity solenoids (coils) with preamplifiers built in. These are buried a similar depth for thermal and mechanical stability. Due to the remote nature of the sources and the high index of refraction of the earth relative to the air, the source fields are assumed to be planar and to propagate vertically downward. However, two axes of E and three axes of H are measured because the scattering of EM waves by subsurface structure can be arbitrary in polarization, necessitating a tensor description.

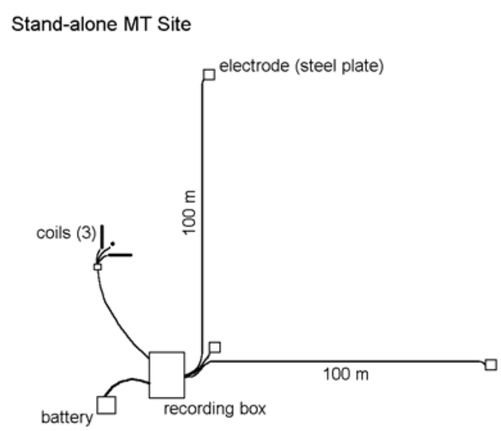

Figure 2. Simplified view of an MT station as deployed at the Coso geothermal field.

Broadband EM times series are recorded by these devices, and they are decomposed into individual frequency spectra through fourier transformation. Through band averaging and ratioing, we arrive at the fundamental MT quantity which is interpreted for geological structure, namely the tensor impedance of the earth to vertically incident, planar EM wave propagation. This is expressed as:

$$\mathbf{E} = [Z]\mathbf{H} \quad ,$$

where *Z* is a two-rank tensor. Individual elements of the impedance are subject to simple arithmetic to obtain an apparent resistivity (Rho) and impedance phase, which are more intuitive to inspect and interpret (Vozoff, 1991). The nominal frequency range recorded was 250 Hz to 0.01 Hz, which spans a depth range of several 10's of m to >10 km.

The assumption of a planar geometry to the MT fields is crucial and artificial EM sources nearby can invalidate it.

An obvious source could be the high-voltage 60 Hz production of the field, which may be so strong under transmission lines or next to generation plants as to saturate MT recording electronics. Strictly speaking, however, the loss of a very narrow band of results around 60 Hz is generally not serious since the impedances are a smoothly varying function of frequency. More problematic are broadband noises whose causes are often obscure but can include load fluctuations (either within the Coso field or from the DC intertie), rotating machinery, and vibration. These are especially onerous in the 3-0.1 Hz frequency band where the MT fields are particularly weak.

An example of MT time series taken at the Coso area ~0.5 km west of the Navy II power plant is presented in Figure 3. These are compared to series acquired simultaneously just east of Socorro, NM, some 600 miles to the east of Coso. Most obvious in the first portion of the plot at the Coso site is sinusoidal variation with a frequency of ~6 Hz which is absent at Socorro. The cause of this fluctuation is unknown. In the quieter portion of the plot, higher energy bursts of MT signal are seen at both sites (e.g., time 4:06:14 and 4:06:22; note that amplitude range of plots differs). However, the signal burst at 4:06:05 at Socorro is swamped by the noise source at Coso at the same time. During weaker signal times even with noise sources less obvious, the visible correlations between the two sites is often obscure, evidence of broad band noise of a lower level but still competitive with the signal. Note that the vertical magnetic field is completely dependent on lateral variations in resistivity structure, so that visible correlations even without noise are naturally more obscure. Numerous other noise examples could be plotted, such as very large spikes with accompanying decaying transients.

2.1 "Local" Remote Reference Processing Attempts

The remote reference method (reviewed by Vozoff, 1991) is designed to overcome environmental noise through coherent detection utilizing simultaneous, remotely recording sensors completely outside the influence of the noise sources. The reference site of course may have its own noises but as long as these are uncorrelated with the local site then the detection principle remains valid. Of course, the remote site should be of high fidelity or the final result will be degraded or a greater length of averaging time will be needed to achieve equivalent results (e.g., Egbert, 1997). In the Coso data campaign so far, reference sites were attempted at five locations of varying distance from the geothermal field (Figure 4). The nearer three sites which measured fields using the same equipment of the MT contractor (Quantec Geoscience Inc.) include the Centennial Flat area approximately 15 miles north of the Coso field, Panamint Valley about 30 miles distant, and Amargosa Valley NV about 60 miles distant. Time series from these sites were downloaded to field PC by the local Coso collection crew for processing at essentially the same time as those in the Coso field, which is normal survey procedure. For the more distant references we discuss later, more elaborate communications procedures were required. An increasingly great distance for the reference was recognized as the survey proceeded.

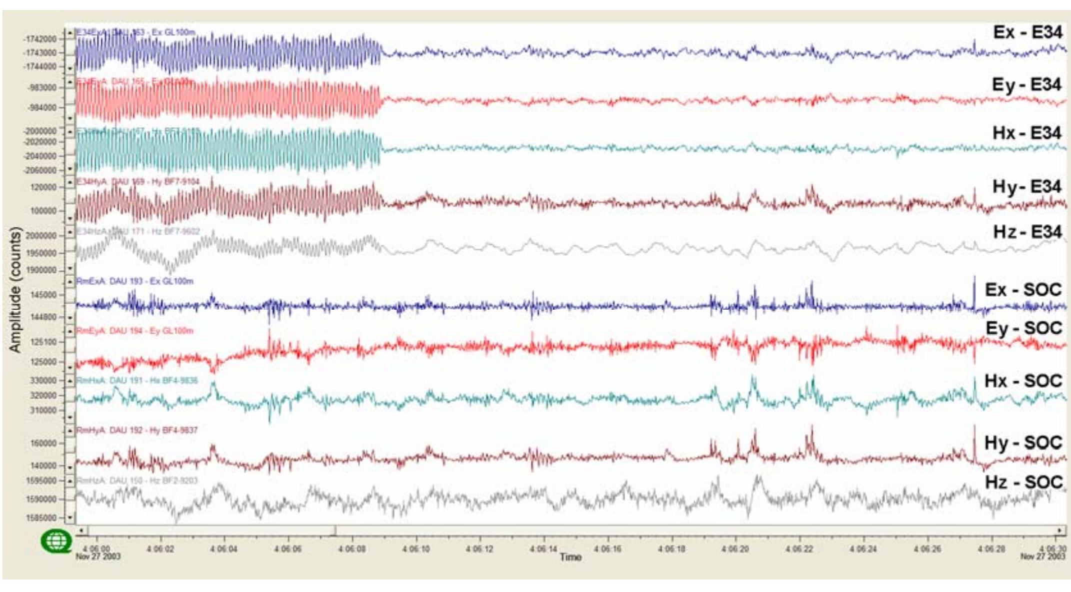

Figure 3. A 30 s segment of MT time series taken at site E34 in the Coso field (top five traces) compared to series taken near Socorro, NM. Ordinates are full-scale plots, so relative amplitude factors may differ.

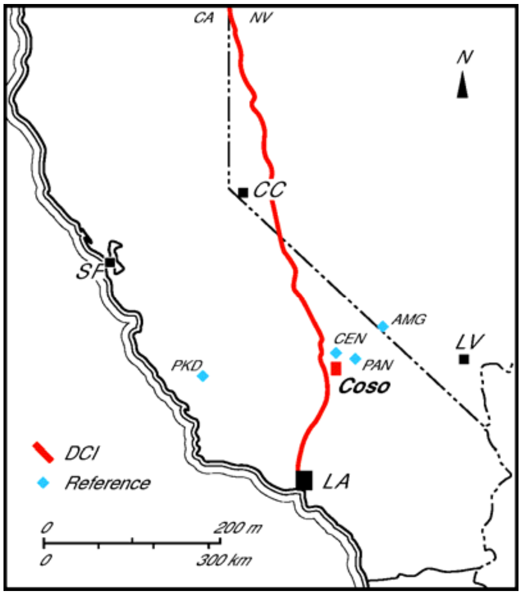

Figure 4. Location of "remote" MT references in the vicinity of the Coso geothermal field. These are Centennial Flat (CEN), Panamint Valley (PAN), Amargosa Valley (AMG) and Parkfield (PKD). Not shown is Socorro, NM, some 600 miles to the east. Also shown is trace of BPA DC intertie line (red) which passes within a few miles of the Coso field. Urban centers include San Francisco (SF), Los Angeles (LA), Las Vegas (LV), and Carson City (CC). DC intertie trace provided by Jim Lovekin.

The MT apparent resistivities corresponding to impedance elements Zxy and Zyx for the reference site at Centennial Flat and in Panamint Valley are shown in Figure 5. Characteristic of non-MT artificial effects are apparent resistivities which rise with decreasing frequency at an anomalously steep rate in the weak MT middle band, and then fall almost discontinuously around 0.1 Hz where the MT fields become quite strong again due to solar wind energy. This is apparent at the Centennial Flat site, as is the case for soundings generally in the Coso area processed using these nearer references. The effect is analogous to that seen in controlled-source (CSAMT) surveys when the transmitter is to close to the survey area (Zonge and Hughes, 1991; Wannamaker, 1997). The distortion propagates to higher frequencies to an unknown degree so that structural images in the pertinent depth range of several km may be unreliable. Essentially only the yx component is effected, which corresponds to an E-field directed N-S. This behavior implicates the Bonneville DC intertie, which runs in this direction, and which generates E-fields parallel to itself.

In an attempt to escape the influence of the DC intertie, references were tried in Panamint Valley and Amargosa Valley, about 30 and 65 miles distant from the intertie respectively. The sounding from Panamint is shown in Figure 5 also. This good-quality sounding does not show the cusp-like behavior near 0.1 Hz seen in Centennial Flat, and the site at Amargosa Valley was even more clean. Initially, we concluded from this that we were essentially free from influence of the DC intertie at these distances and that they would constitute sufficient references. However, soundings in the Coso area processed using these references still showed strong cusp-like behavior in this frequency range (Figure 6, site taken ~1/2 km east of well 34-9), although the results using the more distant Amargosa site were better. This was disappointing as 65 miles of often winding road was reaching the limit in terms of practical, on-site reference retrieval.

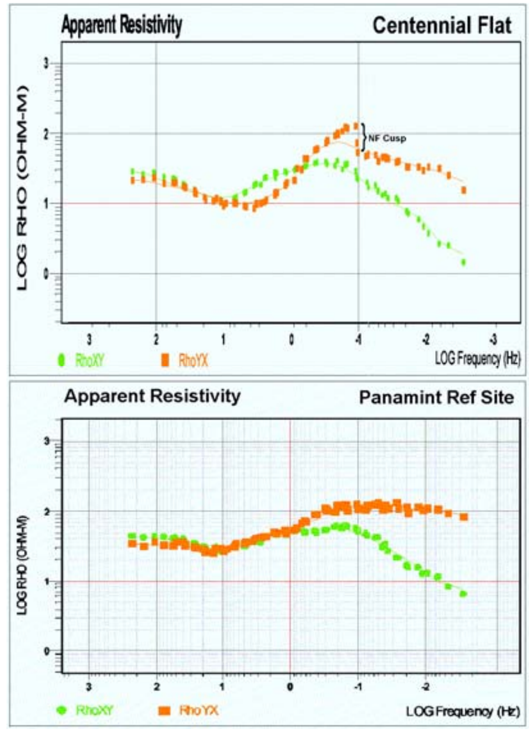

Figure 5. Apparent resistivity soundings taken at Centennial Flat about 15 miles north of Coso field, and in eastern Panamint Valley, about 30 miles northeast of the field. Note the abrupt change in RhoYX around 0.1 Hz, indicative of a near-field (NF or non-MT) effect, in the former (closer) site, but its absence in the further site.

It is evident that a site giving good quality plane-wave (MT) results does not necessarily serve as a good remote reference for soundings taken in a noisy environment. Clearly, EM fields which are correlated with the DC intertie are persisting at least as far away as the Amargosa Valley reference. This is occurring even though such fields have become planar by this point and only serve to improve the local MT responses at Panamint and Amargosa Valleys (e.g., as in Figure 5). However, the powerline fields in the Coso field area, which are quite non-planar, remain correlated with the Panamint and Amargosa sites and thus are not removed by remote reference processing. A reference must be established which is completely outside the domain of the noise source in a survey, not just put where the noise has become planar.

2.3 Distant Remote References: Parkfield California Observatory and Socorro New Mexico

By this point (May/03), >50 MT soundings had been taken at Coso, most of which showed such non-MT contamination to some degree. To obtain high quality results at these locations, we were faced with a complete reoccupation using a yet more distant reference (expensive) or else locate a reference site of opportunity which fortuitously happened to be running while the Coso survey was underway. Luckily, such a reference site exists in the way of the Parkfield, CA, permanent MT observatory, run by the University of California at Berkeley (for info, see http://quake.geo.berkeley.edu/bdsn/em.overview.html of the Berkeley seismic network) (PKD in Figure 4). Due to powerlaw falloff and dissipation of EM fields from a line-source, the DC intertie fields at PKD should be weaker than those at Amargosa by about a factor of 5, making the attempt to use PKD worthwhile. The EM times series are available at no charge essentially in real time through an ftp request. They are sampled at a rate with allows their use as a reference for frequencies up to 20 Hz, which covers the contaminated band at Coso. The contractor Quantec successfully unwrapped the native SEED format of the time series and automated their use as references in their processing software. A plot of the results for site E13 appears in Figure 7 and indicates that the near-field effect has been corrected. The principal frequency range of distinction between the Parkfield-processed and the previous results is 1-0.1 Hz. Similarly good results were obtained for reprocessing the other ~50 sites of the Coso area.

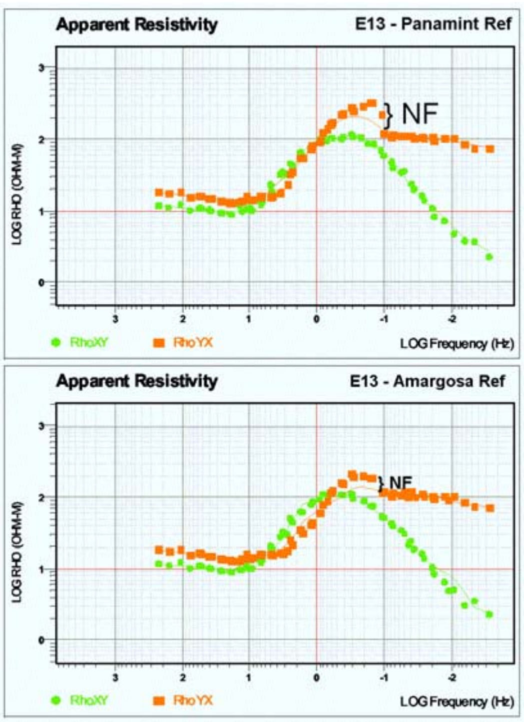

Figure 6. Apparent resistivity data from site E13 in the Coso geothermal field processed using sensors in Panamint Valley (upper) and in Amargosa Valley (lower) as remote references. Some near-field effect appears to remain near 0.1 Hz.

This outcome is very fortunate, but there is concern that Parkfield is barely adequate and that during times of exceptionally low natural MT field activity there may be some noise remaining. Hence, for the resumption of MT surveying at Coso which took place Nov.-Dec./03, a remote reference was set up near Socorro, NM (SOC), >600 miles to the east of the Coso field. Because it is important to recognize surveying problems as they may occur, the Coso and the reference time series should be brought together as quickly as possible. To achieve this, crew at Coso uploaded acquired time series to the U. Utah/EGI ftp site using the Caithness Energy high-speed computer facilities at Coso Junction. The data processor/ reference operator in Socorro down-loaded these series from Utah using the high-speed computer facilities of the New Mexico Institute of Mining and Technology. Site and reference time series thereby were combined several hours after their acquisition at Coso.

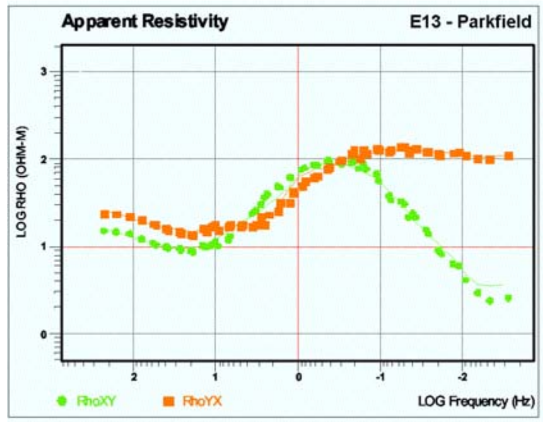

Figure 7. Apparent resistivity data from site E13 in the Coso geothermal field processed using the Parkfield MT observatory as a remote reference.

To verify that the MT time series at Socorro are well correlated with those at Coso, and Parkfield for that matter, we show in Figure 8 a 2 min segment taken simultaneously from site E29, PKD and SOC. This is an unusually quiet segment of time at E29 and excellent correlations are seen both between the impulsive, high-frequency data due to regional-scale lightning energy, and the low-frequency magneto-spheric signals, at all three sites. Site E13 was not reoccupied during the second deployment using the Socorro reference, but we can compare results from site E29 processed using PKD with those processed using SOC (Figure 9). The sounding curves are essentially identical indicating that Parkfield was an adequate reference in this case, although we view Socorro with more assurance as a quiet site outside the influence of the DC intertie.

The effort to which we have gone to establish a quiet remote reference free from both local and broadscale artificial EM interference has been completely necessary. The zones of producing fractures at Coso reside in the 1-3 km depth range (Adams et al., 2000) in plutonic rocks mantled by a variable layer of altered overburden. This situation determines the first order character of the soundings shown thus far, namely apparent resistivities in the 10-30 ohm-m range for frequencies > 3-10 Hz rising to values near 100 ohm-m at lower frequencies. It will be subtle variations in the upward slope of the apparent resistivity, plus corresponding impedance phase responses, which will provide the second-order evidence for bedrock structure of potential geothermal significance.

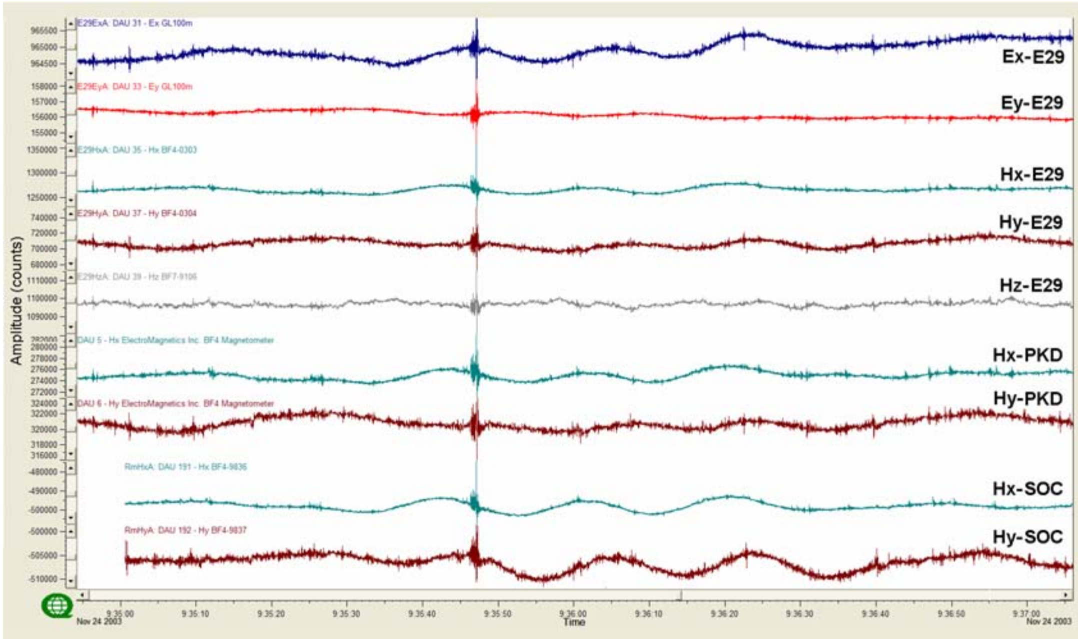

Figure 8. Comparison of all five channels of MT time series at site E29 with the two horizontal magnetic fields used as references at PKD and at SOC.

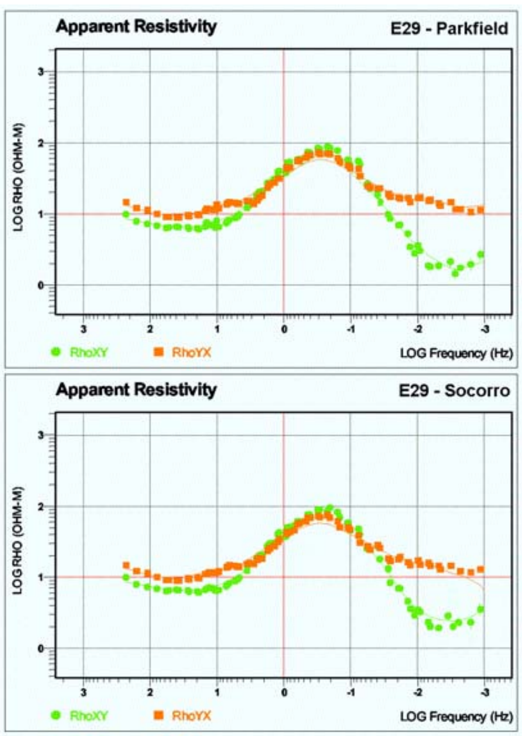

Figure 9. Sounding E29 processed using the Parkfield observatory as a reference compared to E29 processed using the Socorro site as a reference.

3. Conclusions and Plans

High quality MT data have been acquired in the Coso geothermal field following adequate efforts to establish a clean remote reference. It is not sufficient to use a reference site which appears to give good plane-wave results locally. This is because there may be EM noise fields (albeit planar) at the reference site that are correlated with those of the survey area, which are non-planar. In this survey, we found that MT time series at the permanent Parkfield observatory in California were adequate as reference fields to the sites at Coso. In the course of doing this, technology has been established by the contractor to utilize the Parkfield fields in MT surveying generally, thereby improving survey quality for other applications. Noise sources of scales as broad as that of the BPA DC intertie are rare, but this particular one may be a factor in exploration of numerous other geothermal systems in western Nevada and easternmost California due to its proximity.

At this writing, all but about 10 MT sites in the northernmost portion of the Coso area have been acquired, and this should be completed in the late winter of 2004. The need for high quality results is especially important in this field because the basement structures being sought will have a second-order influence on the data, which are dominated by the response of variable conductive overburden upon bedrock. Following basic quality control assessment of the site ensemble, principle structural trends in the basement will be estimated using modern galvanic decomposition techniques (e.g., Sodergren, 2002). This should resolve whether primarily north-south average fault trends or primarily northwest-southeast fault trends dominate the conductivity (and presumably permeability) grain of the basement. Ultimately, 3-D MT inversion will be applied to the data, which we are developing building on the work of Sasaki (1999, 2001) and Wannamaker (1991).

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