MAGNETOTELLURICS APPLIED TO HOT DRY ROCK GEOTHERMAL EXPLORATION IN ARIZONA AND NEW MEXICO

Mark E. Ander
Earth and Space Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

SUMMARY

Magnetotellurics (MT) is an electrical geophysical prospecting technique first developed in 1952 and used primarily in minerals, geothermal, and oil exploration. The technique has also been used to a much more limited extent in solid earth geophysical investigations of the crust and upper mantle. Traditionally, the MT technique has been plagued with many difficult technical problems in all aspects of the technique: experiment design, field procedures, data acquisition, data reduction and analysis, and data interpretation. Recently the MT technique has undergone a revolution in which most of the major difficulties have been overcome. This revolution is still going on, and today we are capable of collecting excellent quality MT earth response functions. The thrust of MT research now lies in the realm of data interpretation.

During the past three years, Los Alamos National Laboratory has conducted a regional MT survey of Arizona and New Mexico for the Hot Dry Rock (HDR) Geothermal Program. The survey consists of over 200 deep MT soundings along several long profiles with sounding spacings of 15 to 20 km (Fig. A-7). The MT lines are located in areas where other geophysical and geologic studies indicate local and regional areas of tectonic and geothermal interest, hot dry rock in particular, such as tectonic province boundaries or late Cenozoic volcanic regions. The MT study is aimed at mapping the depth to the pervasive deep electrical conductor within the crust and/or upper mantle over a large region and then attempting to correlate this depth with terrestrial heat flow, depth-to-Curie point measurements, regional tectonics and local geology. To date, all data have been collected and processed and are in the modeling and interpretation stage. With the exception of the first 56 sites, data from all the remaining sites have been collected using the remote reference MT noise reduction technique.

The locations of the MT profiles for this study (Fig. A-7) and some of the more important preliminary observations of the data are as follows:

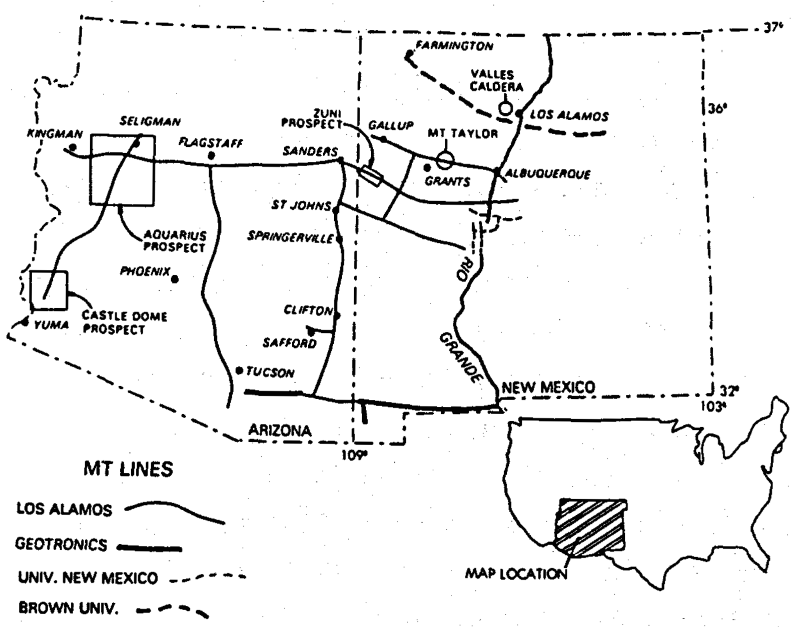

Fig. A-7.
Map showing locations of magnetotelluric profiles in Arizona and New Mexico.

1. A north-south line with 17 sites runs from Yuma in southwest Arizona to Seligman, Arizona, concentrating on the Aquarius and Castle Dome HDR geothermal prospects and traversing the Colorado Plateau/Basin and Range Province boundary. The Castle Dome area coincides with a large amplitude gravity low and with a 70°C/km temperature gradient measured in the center. A caldera, not indicated on the published geologic maps, occurs in the same area. Analysis of the MT data suggests the presence of magma at shallow depths. The Aquarius area is associated with high heat flow, shallow Curie depth, a gravity low, and is associated with a shallow depth to the crustal electrical conductive zone. The Date Creek basin, just south of the Aquarius area, is also associated with a shallow crustal conductor, not as shallow or as conductive as the Aquarius anomaly. The observations are very exciting because they appear to correlate with a very recent migration of the Colorado Plateau boundary from the Date Creek basin to the Aquarius region suggested in a study being conducted by the U.S. Geological Survey (USGS).

2. There are 25 sites along a north-south profile in central Arizona from Tucson northward through Phoenix to Flagstaff, traversing the Colorado Plateau/Basin and Range boundary. The area around Tucson has high heat flow, greater than 104 mW/m^2. Chemical geothermometry measurements also indicate

heat flow greater than 104 mW/m^2 to the northeast of Phoenix. There are geothermal gradients greater than 36°C/km to the southeast of Phoenix. Preliminary observations of the MT data indicate that alternately conductive and resistive layers exist within the crust between Phoenix and Tucson. This observation is intriguing because extensive geophysical surveys performed by oil companies at about the same time as our data were collected show that the western Laramide overthrust passes through this region. Further analysis of the data has proven difficult because of large three-dimensional effects and the large MT site spacing. North of Phoenix, a very shallow, very conductive crustal anomaly is associated with the rim of the Colorado Plateau. This observation, coupled with the MT observation in the Aquarius area and geophysical interpretations across the Colorado Plateau boundary in Utah, provide important constraints on the genesis of the Colorado Plateau. These data sets suggest that the Colorado Plateau boundary is associated with a passive rift system that would impede the propagation of stress across the boundary. Such a passive rift system was hypothesized by Eaton. If the rift system exists, it will provide an important constraint on our models for formation of the Colorado Plateau and Rio Grande rift.

3. Twenty-five sites are along a north-south line starting in the Chiracahua Mountains in southeast Arizona passing through the thermally anomalous Safford-Clifton region, through the Datil-Mogollon volcanics, over the Colorado Plateau boundary, across the northeast-trending Jemez volcanic zone at Springerville, and then to Sanders, Arizona. The Jemez volcanic zone is interpreted to pass through Springerville, Mount Taylor, and the Valles Caldera. These data have not yet been studied.

4. An east-west line consisting of 10 sites runs from St. Johns, Arizona, crossing the Jemez zone and the Plains of San Augustin to Magdalena, New Mexico, where it connects with an MT study of the Rio Grande rift conducted by Jiracek and others. Analysis indicates that the Jemez zone is associated with a shallow conductor suggesting magma at depth and that the Plains of San Augustin may also be associated with magma in the mid-crust. Unlike other conductive anomalies observed in this study, the anomaly beneath the Plains of San Augustin does not correlate with surface heat flow measurements. Elston suggests that the San Augustin basin is a bifurcation of the Rio Grande rift. If this is the case, the existence of a recently developed

magma chamber similar to the one recently discovered in the Albuquerque-Belen basin could account for the discrepancy in the two data sets.

5. The longest MT profile consists of 36 sites from Torreon, New Mexico, to Kingman in western Arizona, traversing the Rio Grande rift and the Jemez zone, passing through Flagstaff, Arizona, and the Aquarius region. This profile passes through the Zuni HDR prospect where a detailed MT/AMT survey consisting of 119 AMT stations and 25 MT stations has been completed. Results indicate that the Jemez zone is a structural flaw associated with magma conduits that penetrate the entire thickness of the lithosphere. Observations of the data from the long profile indicate (a) that the MT soundings have sensed a magma body beneath the San Francisco Peaks area near Flagstaff, and (b) that the depth to the deep electrical conductor along the profile correlates with surface heat flow, the thickness of the lithosphere, and an inverse correlation has been noted with Bouguer gravity.

6. There are 15 sites along an east-west profile from Gallup to Albuquerque, New Mexico, that passes over Mount Taylor, a volcanic field of the Jemez zone. Again, the data strongly indicate that the Jemez zone is associated with a shallow electrical conductor, probably caused by magma at depth. The observation from all MT profiles across the Jemez zone that the zone is associated with a crustal flaw penetrating the lithosphere correlates with (a) preliminary results of a teleseismic P-wave delay study that indicates the zone is associated with a low seismic velocity zone from 15 to 140-km depth; (b) elevated heat flow along the zone; and (c) the observation by numerous workers that the zone is associated with a Precambrian age boundary. Based on the MT data and extensive integration of other geophysical and geologic data, I suggested that the Colorado Plateau southeastern boundary is presently coincident with the Jemez volcanic zone and that a recent migration of the Colorado Plateau boundary to the northwest has occurred. Other workers have since found structural evidence to support these findings.

7. Five sites have been occupied in southeast Arizona connecting two nonproprietary MT surveys consisting of 40 sites occupied by Geotronics Corp., resulting in a station distribution that is a continuous east-west profile from El Paso, Texas, to Tucson, Arizona, along the 32°N latitude. These MT data have not been studied yet.

8. This MT study integrates with a telluric-magnetotelluric survey in the Jemez Mountains of northern New Mexico to characterize the geothermal

system of the Valles Caldera and with a regional northwest-trending MT survey. These surveys were conducted by Hermance for the USGS and Los Alamos National Laboratory.

Based on the results obtained so far, several general conclusions can be made. No single geophysical technique is a panacea for geothermal exploration, hot dry rock in particular. But, because MT is sensitive to the crustal state, it is an excellent exploration tool when used in combination with geologic and other geophysical techniques. The depth of the deep electrical conductor obtained by the MT method in general correlates with the expected crustal thermal regime as predicted by terrestrial heat flow, depth to Curie, regional tectonics, and/or local geology. In this study, mapped crustal electrical conductivity upwellings in otherwise resistive crustal rock correspond with known or suspected thermally anomalous areas. These conductivity upwellings fall into two basic categories. The first contains a resistive cap rock ($\geq$1000 Ωm) and appears to be associated with local thermal features, e.g., Castle Dome anomaly. Because the cap rock is resistive, suggesting impermeable upper crust, local ground-water percolation is not a likely mechanism for creating the high conductivity anomaly. Such regions, when coincident with other thermal indicators (e.g., late volcanic activity and high heat flow), may be good hot dry rock targets. The second type contains a moderately conductive cap rock ($<$100 Ωm) and appears to be associated with zones of tectonic extension, e.g., Colorado Plateau boundary. These regions are probably associated with deeply circulating ground water that causes increased conductivity. Because these regimes are usually associated with elevated thermal regions, the anomalously high electrical conductivity beneath the more resistive cap may be due to free water in the presence of elevated temperature and/or partial melt. These regions may also be important hot dry rock resource areas, but more care must be taken to evaluate the cause of the conductive anomalies.