GEOTHERMAL RESOURCE EXPLORATION, NAF EL CENTRO – SUPERSTITION MOUNTAIN AREA, IMPERIAL VALLEY, CALIFORNIA

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Abstract

The geothermal potential of West Mesa has historically been assumed to be small because it is thought to be dominated by a left-stepping transpressional regime that is generally tight and not conducive to open fluid pathways. This may not be the complete picture, however. The 85 MWe Heber geothermal project appears to be located in a right stepover from the northwest trending seismogenic extension of the Cerro Prieto fault, placing it outside the Imperial-San Andreas fault system and on a separate, sub-parallel, extensional trend to the west. A similar right stepover appears to be present at Superstition Mountain where shallow drilling in the 1980's found temperature gradients exceeding 300ºC/km (17.5ºF/100 ft.). Through the use of detailed surface mapping, electrical and potential fields geophysical methods and analysis of a relocated earthquake catalog for the region, the Navy Geothermal Program Office is beginning to define the hydrothermal history and the structural and tectonic framework of this thermal anomaly and to delineate active transtensional areas and critically stressed fractures which may serve as conduits for upwelling geothermal fluids.

Introduction and Geological Background

The Superstition Mountain geothermal prospect is located in the West Mesa area of northwestern Imperial Valley, California (Figure 1) and occurs within the Shade Tree bombing and parachute range of the Naval Air Facility, El Centro. The geothermal potential of West Mesa has historically been assumed to be small because, while the central Salton Sea trough is dominated by the Imperial fault-San Andreas fault trend, a right-stepping transtensional regime that allows for the upward circulation of heat and geothermal fluids, West Mesa has been thought to be dominated by a left-stepping transpressional regime (San Jacinto, Laguna Salida and Elsinore fault zones) that is generally tight and not conducive to open fluid pathways. Recent seismotectonic studies indicate this may not be the complete picture.

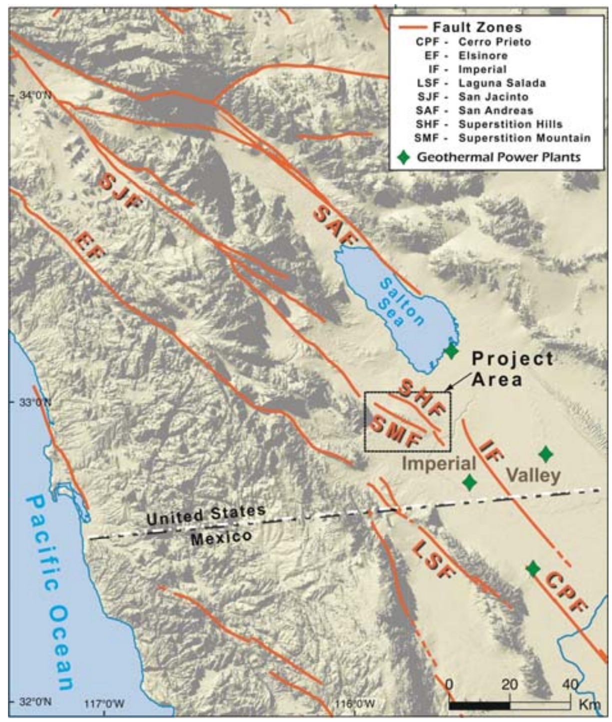

Figure 1. NAS El Centro project location and the regional structural framework.

Edmunds (1977) noted the hypothesis that current tectonic activity on the west side of Imperial Valley may be opening new heat sources there. The 85 MWe Heber geothermal project successfully operates using fluids fed from intersecting northwest trending right lateral strikeslip and northeasterly-trending normal faults (James, et al, 1987) and appears to be located in a right stepover from the northwest trending seismogenic extension of the Cerro Prieto fault (Magistrale, 2002) (Figure 2).

This evidence appears to place Heber on a structural trend outside the Imperial-San Andreas fault system and on a separate, sub-parallel, extensional trend to the west. Such a right step would be releasing, creating the critically stressed fractures found at Heber which are optimally oriented to be open pathways for upwelling geothermal fluids.

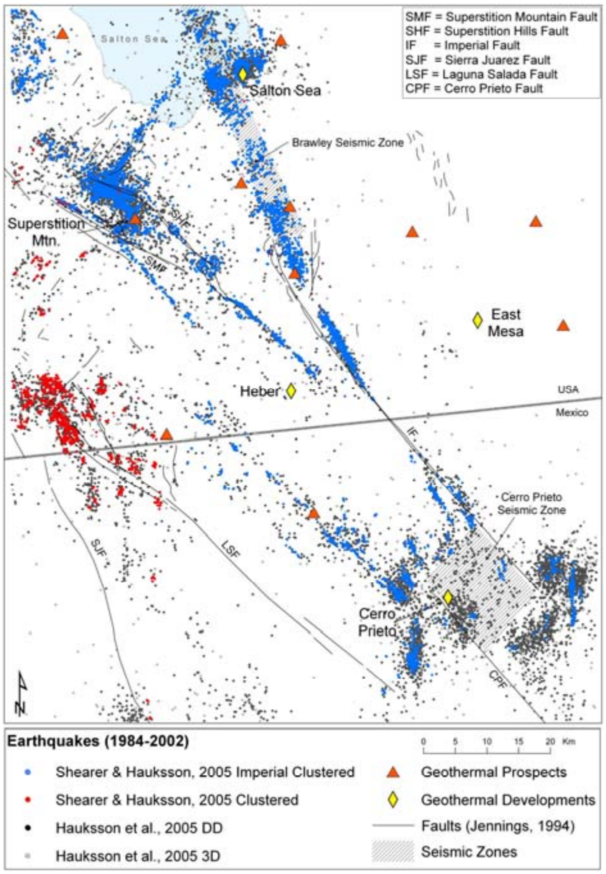

Figure 2. Plot of relocated regional earthquake catalogs relative to mapped fault zones and geothermal developments and prospects.

Further up the valley a similar, but currently more active, right step appears to be present at Superstition Mountain – one that cuts across the mapped Superstition Mountain Fault (SMF) and connects with the Superstition Hills Fault (SHF) and associated northeast trending Elmore Ranch fault. As at Heber, such a right step would allow for critically stressed fractures and upwelling of geothermal fluids. Within the Superstition Mountain prospect area shallow drilling in the 1980’s indicated temperature gradients exceeding 300ºC/km (17.5ºF/100 ft.). There are no deep thermal or fluid data available for this site, so understanding the basement structure, the current state and orientation of local tectonic stresses and how these operate together to create pathways for ascending geothermal fluids are critical keys to defining the geothermal potential - and potential drilling targets - in this area.

To test this hypothesis and identify potential targets the Navy Geothermal Program Office is conducting a multi-faceted investigation consisting of: 1) analysis of local gravity survey data; 2) surface mapping of hydrothermal alteration and active (neotectonic) late Quaternary faults; 3) kinematic analysis of the seismic events catalogs to create visualizations of the seismogenic faults, the local stress field and the potentially critically stressed faults; and 4) analysis of magnetotelluric data to further characterize the seismogenic faults. Through this work we anticipate being able to connect the shallow thermal and electrical anomalies to deeper geothermal resource targets.

The geology of the project area is dominated by a granitic knob (Superstition Mountain), a Pliocene to Recent marine/lacustrine system around the mountain, and the western Imperial Valley tectonics, specifically the Superstition Mountain and Superstition Hills faults. Superstition Mountain is a northwest-southeast trending elongate feature rising abruptly above the Imperial Valley floor to a height of 231 m (759 ft) asl. It is composed primarily of pre-Tertiary (probably Mesozoic) intrusive rocks – granite, granodiorite, quartz monzonite – and is probably closely related to the Fish Creek Mountains eight kilometers (five miles) to the west. The shallow sedimentary cover consists primarily of Pliocene to Pleistocene sediments and there appears to be no evidence for an older meta-sedimentary sequence here as is present in the central region of the valley. A small section of Tertiary rocks occur on the northeast section of the mountain including a thin section of Miocene volcanics. These flows and pyroclasitics do not play a role in the geothermal potential of the prospect, however. The depth to crystalline basement in the Superstition/West Mesa area is substantially less than the central part of the valley with the boundary between the two being very sharp. Fuis, et al (1982) estimate as little as 2.1 km to basement near the south end Superstition Hills dropping quickly to 5-6 km to the southeast.

Superstition Mountain and Hills are dominated by two sub-parallel northwest-trending dextral strike-slip faults (SMF and SHF) which are part of the San Jacinto fault system to the north and connect to the Imperial Valley and/or Cerro Prieto faults to the south. It is assumed that additional northwest-trending structures are present beneath the sedimentary cover between the two. These buried structures are indicated by the subtle northwesterly patterning of topographic contours and imply a single 3 to 5 mile wide fault zone. There is also strong evidence (both in aerial orthophotos and outcrops) for northeast-trending faults striking through the mountain in several places, creating conjugate pairing with the northwesterly faults. This orientation of dominant northwesterly dextral and subordinate northeasterly sinistral faults is well defined in the Superstition Hills. On Superstition Mountain the subordinate northeasterly structures appear to be sinistral as well.

Superstition Mountain is located in a region of significant seismicity. In 1987 a magnitude 6.2 earthquake occurred on the (previously unmapped) northeast-trending sinistral strike-slip Elmore Ranch fault, followed less than 12 hours later by a magnitude 6.6 event on the SHF resulting in significant surface rupture in the Hills, but little apparent movement on the adjacent SMF (Faneros, 2005). Shearer, et al (2005) and Hauksson and Shearer (2005) obtained precise relative locations for over 340,000 southern California earthquakes between 1984 and 2002, many of them in the Superstition area (Figure 2). Results of a kinematic analysis of these data are described below.

The presence of a thermal anomaly at Superstition Mountain has been known for many years. The USGS heat flow database lists a well (SUPR) which is located near the southeast end of Superstition Mountain and has a thermal gradient of 64°C/km, while one zone along the northeast flank of Superstition Mountain has a calculated thermal gradient exceeding 300ºC/km (17.5ºF/100 ft.) based on shallow temperature gradient drilling done by Chevron in the 1980's. California Department of Oil and Gas drilling records and information provided to the Navy by Layman Energy Associates corroborate the existence of this second anomaly (Figure 3), which is generally elongate northwesterly on the northeastern flank of the mountain and the broad valley that separates it from the Superstition Hills to the north. These areas are part of the Shade Tree bombing range, and are under Navy jurisdiction.

Geothermal Investigations

A 2003 electrical survey conducted by Innovative Technical Solutions, Inc for the Navy resulted in the identification of an 120 mV SP anomaly (ITSI, 2003) over Quaternary to Recent sediments about 450 m (1500 ft) north of granite outcrops of Superstition Mountain (Figure 3). The anomaly is elongate sub-parallel to the range front, with a half-amplitude length of about 1800 m (5900 ft) and a half-amplitude width of about 500 m (1600 ft). The considerable elongation of the anomaly suggests a SP source associated with covered faults and fractures. The data suggest a fairly shallow (~150 m (500 ft) deep) SP source area. The source of the SP anomaly may not be a geothermal system or upflow zone, however, this interpretation is very permissive given the dimensions and shape of the anomaly, the location near other geothermal systems, and spatial association with the Chevron thermal anomaly.

Through reconnaissance mapping, we have also documented the presence of a previously unmapped northwest-striking, northeast-dipping range-front fault (SMFF) along the northeastern flank of Superstition Mountain that marks the contact between the bedrock and the Quaternary to Recent sediments. This fault is associated with a moderately well-expressed northeast-facing bedrock escarpment that can be traced for about 1.25 km (0.8 mi) southeast along the mountain front. It is coincident with the thermal and SP anomalies and appears to be the extension of a previously mapped short splay from the main trace of the Superstition Mountain fault. The range-front fault shows clear evidence of hydrothermal alteration and mineralization and, as described below, also shows clear evidence of neotectonic activity.

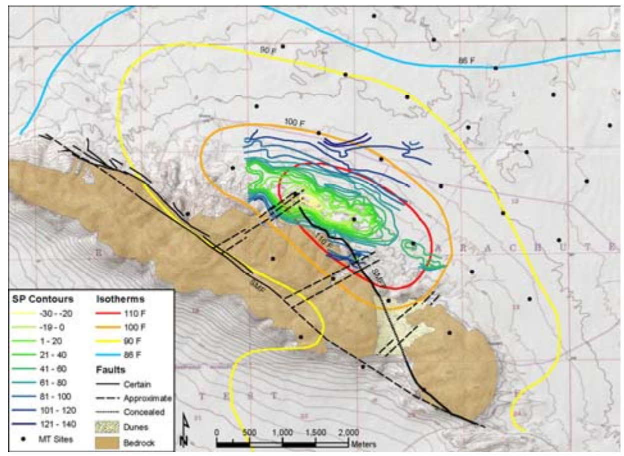

Figure 3. Superstition Mountain thermal and self-potential electrical anomalies, magnetotelluric survey stations, and the generalized geology and structure of the mountain, including the northwest-trending active range-front fault.

A gravity and magnetics survey consisting of 112 km (70 mi) of transects was conducted in December 2004. (Due to a magnetometer malfunction, the magnetic data were subsequently excluded from this analysis). The gravity survey data were processed and various corrections applied to obtain the simple Bouguer, complete Bouguer, and isostatic residual grids. The resulting gravity maps show a small, but prominent, gravity high associated with Superstition Mountain. The bulk of this high is shifted, in a parallel fashion, approximately 1100 m (3600 ft) to the northwest (Figure 4) and may be interpreted as shallow basement dipping gently away from the northeast side of the mountain contrasted by a sharp break and a significant down-dropping of the basement on the southwest side of the mountain. Additional detail on the gravity high appears to be related to prominent faults – both mapped and inferred - reflecting the broken, blocky nature of this small granitic knoll and it may, in part, be a product of localized cementing of sediments by mineralizing fluid at depth.

Three cross-sections were modeled using the gravity data and based initially on the Dibblee (1984) geologic cross-section, the refraction seismic analysis of Fuis and

Kohler (1984), including their velocity model used in the Superstition area, plus published fault maps and recent fault mapping described in this paper. The cross-sections all have a reasonable fit (~0.5 mgal error) when the sedimentary beds extend no deeper than about 3 km (10,000 ft). Section A-A' (Figure 5) is representative of the three sections and was oriented in a northeast-southwest direction in order to perpendicularly cut the apparent dominant northwest-trending fabric of the Superstition Mountain/Superstition Hills area, as well as, the previously mapped temperature and SP anomalies.

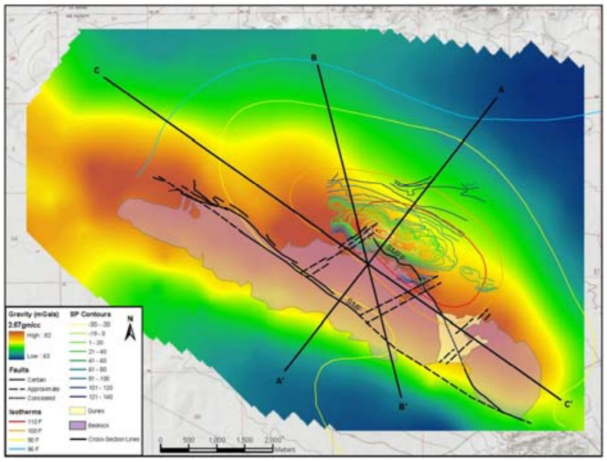

Figure 4. Superstition Mountain isostatic residual gravity map showing cross-section locations.

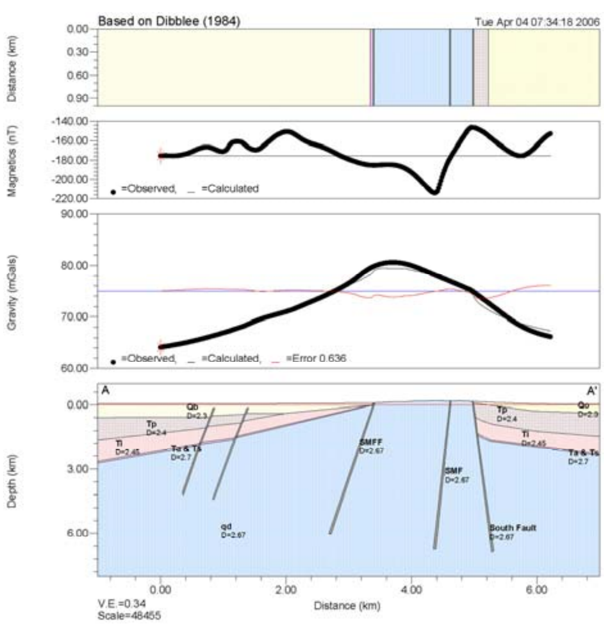

Figure 5. Gravity cross-section A-A'

At the northeastern extent of the gravity survey area, the beds in the model are extended down to about 3 km, whereas in Dibblee's model they extend no deeper than about 1.3 km. However, a large fit error (>1.50 mgals) occurred when the basement was placed above 1.3 km. A much smaller fit error (0.636 mgals) remained after increasing the thicknesses of the sedimentary units to more closely match the sedimentary section of an oil and gas drill hole (~8750 ft deep) located about four miles to the east-northeast of the project area (Loeltz, et al, 1975). Plus, the overall fit of the model is best when the sedimentary column is thickened rather than made denser.

This best-fit model is relatively simple, but it is consistent with the available geologic data. None of the subsurface geologic/geophysical data for the project area are tightly constrained, however the model is consistent with the mapped faulting, as well as, the extent of surface exposure and the generally expected regional distribution and range of thicknesses of the Tertiary to Recent sediments and the density contrast between these and the bedrock. The model is also generally consistent with the refraction seismic interpretation of Fuis and indicates that granitic basement is shallow in the area of the thermal and electrical anomalies and that both conjugate and additional *en-echelon* structures are permissive between the major northwest-trending Superstition structures.

A 3-D analysis of the relocated earthquake catalog identified several distinct seismogenic faults in the Superstition area. Planar alignments of the relocated seismicity define a number of faults in the study area, some of which clearly correspond to previously mapped faults on the surface and others which do not. For our current purposes, the most interesting are: 1) the lineament (L1 of Magistrale, 2002) SW of the mapped surface trace of the SE end of the SMF; 2) an ENE trend of seismicity crossing beneath the southeastern end of Superstition Mountain towards the broad valley NE of the mountain; and 3) a broad, NW trending cluster of seismicity underlying this valley between Superstition Mountain and the Superstition Hills. The seismicity in the lineament L1 defines a steeply dipping (80 deg to the SW) plane which strikes approximately 25 degrees more northerly than the main mapped surface trace of the SMF. The seismicity in this lineament shallows abruptly at its NW end to merge with the seismicity in the ENE trend. Its geometry in map view somewhat suggests a releasing step transferring some of the slip from the southern SMF to the Superstition Hills Fault (SHF). The seismicity underlying the valley between Superstition Mountain and the Superstition Hills seems to form a zone of subparallel, NW striking, subvertical dextral faults and on NE-striking sinistral faults. The low hills in the center of the valley may be neotectonic landforms associated with the seismogenic faults at depth.

The planar alignment clusters were combined with other, spatially distinct, clusters of earthquakes. The focal mechanisms of these events were inverted for stress and strain with the results shown in Figure 6 as the vertical stress ratio. The results show that the Imperial Valley-San Andreas trend is predominantly strike-slip faulting with the maximum compressive stress subhorizontal and striking N20E. In general, the stress and strain states in the western side of the Imperial Valley (including our study area) are similar but rotated approximately 35 degrees counter-clockwise so that the maximum compressive stress strikes N15W. However in the Superstition Mountain area itself (and to a lesser extent the area between Superstition Mountain and the Superstition Hills) there are signs of significant heterogeneity in the stress and strain states, both between small groupings of seismic events and within individual groups. Small areas of apparent crustal thickening are adjacent to areas of apparent crustal thinning implying a dynamic state of strain and a mixed transtensional and transpressional tectonic environment.

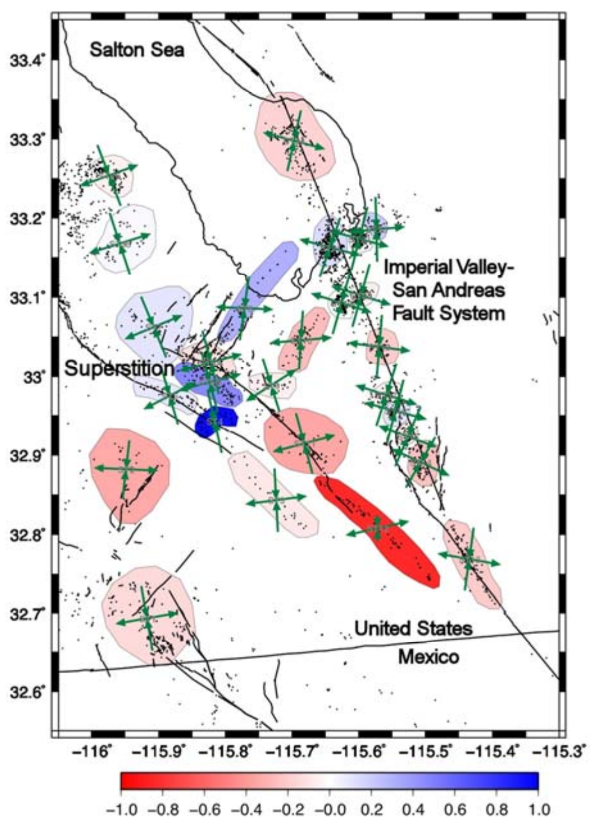

Figure 6. Earthquake clusters and vertical stress ratios. This is the ratio of the vertical stress to the maximum extensional stress. Negative (red) values indicate crustal thinning and positive (blue) values crustal thickening.

Reconnaissance neotectonic mapping along the southern portion and northeast side of Superstition Mountain and the broad valley to the north confirmed the active nature of the range-front fault (SMFF) through a series of Quaternary to Recent up-lift/erosion cycles. The rate of normal separation on this fault appears to be at least 1-2 mm/yr (Unruh, J.R., 2006).

Based on the map-scale pattern of surface faulting, the SMF through the mountain is comprised of at three geometric segments that exhibit a left-stepping *en echelon* pattern. The southern segment of the fault splays or steps north-northwest, projecting NNW and emerging along the northeastern flank of Superstition Mountain as the range-front fault (SMFF). Displacement appears to die out to the northwest and is likely transferred in a left en echelon step to the main trace of the SMF. The SMFF strikes more toward the north than the main fault, suggesting that it is kinematically distinct. Kinematic analysis of earthquake focal mechanisms from the Superstition Mountain area indicates that the style of deformation is dominantly strike slip, and that the direction of regional right-lateral shear strain is oriented approximately N60°W. The central segment of the Superstition Mountain fault strikes about N55°W, and thus is optimally oriented to accommodate strike-slip faulting, not transpression as is commonly assumed in the literature. The SMFF strikes about N26°W, nearly normal to the direction of the maximum extensional principal strain obtained from the focal mechanism inversion (i.e., N76°E), and thus is optimally oriented to accommodate extension and normal faulting in the modern seismotectonic setting. As stated above, the temperature and SP anomalies are associated with this fault.

It is not clear if transfer of slip is occurring from the SMFF to the seismogenic faults, or if the seismicity is more directly associated with the Superstition Hills fault. Any transfer of slip from the SMFF to the seismogenic faults in the valley would be right step, and thus potentially a releasing geometry relative to the direction of regional NW right-lateral shear. The SMFF has a releasing geometry relative to regional dextral shear, and thus is locally "transtensional" in the vicinity of the SP and temperature anomalies. Also, it is possible that some slip is transferred from the southern segment of the Superstition Mountain fault to the system of seismogenic faults in the valley to the east, which would be a right, releasing transfer in the regional NW dextral tectonic regime. The SMFF dips toward the temperature and SP anomalies. If the average dip of the SMFF at depth is comparable to the dip observed at the surface (about 55-60°), then the intersection of the fault and the source of the anomalies is at a depth of less than 1000 m.

Conclusions and Further Work

Through a combination of mapping, electrical and potential fields methods, and seismicity and kinematic analysis, we have begun to define the hydrothermal history and the structural and tectonic framework of the thermal anomaly at Superstition Mountain. A significant

SP anomaly has been defined within the heart of the thermal anomaly and there is clear evidence for an active range-front fault adjacent to it on the northeast side of the mountain. We interpret that the range-front fault is a segment of the Superstition Mountain fault, and that it has a more northerly strike than the main sections of the fault. While this geometry is not a true releasing stepover, the more northerly strike is a releasing geometry relative to the direction of regional NW dextral shear in the southwestern Imperial Valley. The rate of normal separation on the southern segment is at least 1-2 mm/yr, and the fault dips northeast toward the temperature and SP anomalies. Based on the observed dip of the fault at the surface, it predictably would intersect the source of the anomalies in the upper 1 km (3300 ft) of the crust.

Future work will include determining focal mechanisms for additional events in the project area in order to better characterize the stress/strain heterogeneity recognized here. A reduction of the heterogeneity will allow for a more detailed characterization the dynamics of this translational tectonic environment and a differentiation of the critically stressed faults within it. In addition, in early 2006, MT data were acquired at 31 stations on an ~1000 meter grid (Figure 3) in order to image the resistivity structure of the study areas using one-dimensional (1D) and two-dimensional (2D) inversions techniques, and to represent this structure using grids of 2D depth models. A contract is in place for the data analysis and modeling, with the work to be completed by December, 2006. It is anticipated that the MT analysis will provide sufficient detail to the resistivity structure to link surface and near-surface anomalies and the deep seismogenic structure.

References

Dibblee, T.W. Jr., 1984, Stratigraphy and Tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills and Vicinity (mapped 1954), *in* The Imperial Basin Tectonics, Sedimentation and Thermal Aspects, Rigsby, C.A., ed., Society Economic Paleontologists & Minerologists Pacific Section, Los Angeles, CA, p. 31-44.

Edmunds, S.W., 1977, Geothermal Development in Imperial County, Geothermal Resources Council Transactions, v. 1, p. 81-83.

Faneros, G., 2005, Structure and Neotectonics of the Superstition Mountain Fault, Imperial County, California, Masters Thesis, San Diego State University.

Fuis, G.S., W.D. Mooney, J.H. Healey, G.A. McMecham and W.J. Lutter, 1982, Crustal Structure of the Imperial Valley Region, *in* The Imperial Valley, California, Earthquake of October 15, 1979, United States Geological Survey Professional Paper 1254, p. 25-50.

Hauksson, E., and P. Shearer, 2005, Southern California Hypocenter Relocation with Waveform Cross-correlation, Part 1, Results using the Double-Difference Method, Bulletin of the Seismological Society of America, v. 95, n. 3, p. 896-903.

Innovative Technical Solutions, Inc., 2003, Geothermal Energy Resource Assessment on Military Lands, final technical report submitted to the US Navy Geothermal Program Office, Contract No. N68936-02-R-0236.

James, E.D., V.T. Hoang and I.J. Epperson, 1987, Structure, Permeability and Production Characteristics of the Heber, California Geothermal Field, PROCEEDINGS, 12th Workshop Geothermal Reservoir Engineering, Stanford University, SGP-TR-109, p. 267-271.

Loeltz, O.J., B. Irelan, J.H. Robinson and F.H. Olmsted, 1975, Geohydrologic Reconnaissance of the Imperial Valley, California, United States Geological Survey Professional Paper 486-K, 52p.

Magistrale, H., 2002, The Relations of the Southern San Jacinto Fault Zone to the Imperial and Cerro Prieto Faults, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 271-278.

Shearer, P., Hauksson, E., and Lin, G., 2005, Southern California Hypocenter Relocation with Waveform Cross-Correlation, Part 2: Results using Source-Specific Station Terms and Cluster Analysis, Bulletin of the Seismological Society of America, v. 95, n. 3, p. 904-915.

Treiman, J.A., 1989, Superstition Hills, Superstition Mountain, and related faults: California Division of Mines and Geology Fault Evaluation Report FER-207, 21 p.

Unruh, J.R., 2006, Results of Neotectonic Reconnaissance, Superstition Mountain, NAFEC, William Lettis & Associates, Inc. letter report to US Navy Geothermal Program Office under contract N68936-04-C-0072.