Geophysical Techniques for Geothermal Exploration of Rico, CO

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I. Introduction

The use of renewable energies is shot down in many situations because of the relatively high start-up costs and long-term commitment it requires to actually become profitable. Therefore, in order to induce a sense of confidence in the community one must have reproducible data as evidence that proves an energy's overall availability and benefit. For geothermal energy, it is often quite difficult to accurately characterize a reservoir's quality with just one measurement. Therefore, it is necessary to correlate different geophysical techniques collecting different signals in order to accurately identify what is the noise and what are the anomalies in a specific data set. This paper will discuss many different geophysical techniques, comparing their pros and cons, to demonstrate which would be the best to explore and monitor the hot and highly faulted geothermal reservoir of Rico, CO. It will then look at the geophysical exploration that has already been done in Rico, CO, and will suggest future useful study in the area.

II. Different Geophysical Techniques

II-A. Gravity Surveys

The purpose of a relative gravity survey is to directly map the structure of the subsurface. Gravity is the attractive force between two or more bodies of mass. The force is proportional to the mass of the object, and decreases with distance as seen in the $1/R^2$ term of Equation 1. In the case of the Rico, CO described below, we are seeing the direct effect of the dense basement rock that makes up the deep subsurface basement floor. Due to its high density, the basement rock that is being extended and faulted stands out as the body that the gravimeter detects. [CSM GP FC 2008]

$$g = -\frac{GM}{R^2} \qquad \text{Equation (1)}$$

A small mass on a highly sensitive spring inside the gravimeter is being attracted by the dense basement rock and indicates very small scale changes in gravity as the survey moves East to West along the gravity profile. Based upon variations in gravity, subsurface geometries can be predicted showing the basement rock's distance from the surface at different points along the profile. As the basement rock dives deeper from the surface, the gravity reading decreases, whereas when the basement rock rises close to the surface the gravity reading increases. Where sharp changes in gravity are present, forward modeling can be used to detect possible faulting in the subsurface. Gravity can work well to identify the main flow paths of heat in the Rico region along its faults. Coupled with a seismic survey, which will be explained next, forward modeling can be done to study the effect of these faults on the data and actually invert the data so that energy is focused by the faults instead of being dispersed as in the data.

II-B. Seismic Surveys

Seismic surveys record acoustic echoes from sedimentary rock layers beneath the surface. A seismic measurement involves injecting sound into the ground and recording the energy that reflects back at different times and locations on the surface. Processed seismic data can give information about subsurface geology, including rock types and fault structures (our primary intended target). It can also be correlated with gravity surveys to define more accurate velocity models which provide more accurate depth estimates, which drill teams can be very picky about.

II-B-1. Deep Seismic Surveys

The source of energy for a deep seismic profile consists of two thirty-ton Vibroseis trucks provided by geophysical contractors such as CGG Veritas or Western GeCO. The trucks are moved to different known locations along a line, their weight is raised onto large, square, metal plates, and the trucks are vibrated at a series of frequencies (5-80 Hz) over a period of 5 seconds. This process is repeated ten times at each location and the results added together to improve the reliability of the measurements. The vibrations travel downward, reflect and refract off of major geologic structure changes, and return to the surface. The returning vibrations are very weak, and are picked up by receivers called geophones, which send the signal to a control center. The signal from each geophone is a wavelet that is altered either by the geology it traveled through, or by noise from a variety of external sources, including traffic, people walking, bad connections, and even weather. At the control center, the signal is processed in a special computer that carries out a calculation called “correlation.” Correlation converts the signals obtained over a long period of time (5 seconds) into the signal that would have been recorded if an explosive source was used. After correlation, the external noise is suppressed, resulting in much cleaner recordings. [CSM GP FC 2008]

Due to this intensive processing and expensive equipment, deep seismic can usually exceed the budget of most local communities and does not always provide the best results. In highly mountainous regions, data is often further smeared by effects from mountain slopes, deep large glacial tilled boulders and fluvial patterns which aren’t always as horizontally continuous as anticipated.

II-B-2. Near Surface Seismic Surveys

The source for many of the near-surface seismic data acquisition techniques is a large metal weight (approximately 120 lbs) that is dropped onto a metal plate. Although much weaker than the 60,000 pound vibrator trucks, the weight produces excellent high frequency waves which travel near the surface and give relatively good resolution. This approach is used for imaging anything above about 500m depth. Unfortunately, the high frequency wavelets, which can show small structures very clearly, cannot travel very deep.

II-C. Electrical Surveys

II-C-1. DC Resistivity

DC resistivity is a time-domain survey where a direct current is sent into the ground through electrodes. The electrodes then record signals (in the form of voltage differences between two electrodes) for an extended time period. It takes time for certain conductive structures to respond to the current and for a signal to be recorded. There is a variety of electrode setups that image varying depths and provide different information. Knowing the input current and measured voltage difference, one can get information about subsurface resistivity/conductivity and create an inverted model.

At the 2008 CSM Geophysics Field Camp, DC resistivity data was acquired and in Figure III-C-1 below, it clearly shows groundwater level near Chalk Creek, on the easternmost survey grid. It also possibly shows the fault structure that was also seen with the self potential method. The data from DC resistivity was combined with information from the self-potential survey, well logs, and ground penetrating radar to show where groundwater is located and how it is moving.

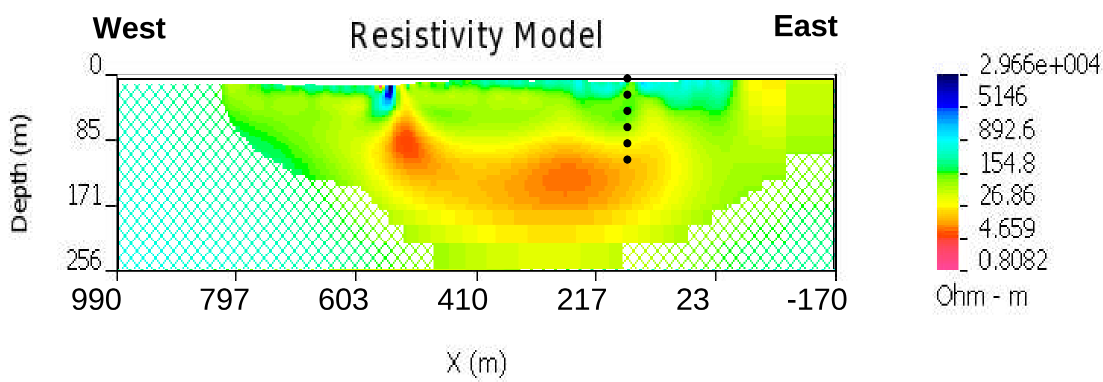

Figure II-C-1 Resistivity Inversion of survey line at Mt. Princeton. The vertical dots represent a suggested drill site for geothermal direct use based on this data and on the self-potential data in the following section.

II-C-2. Self-Potential Surveys

Self-potential occurs on the earth surface naturally without inducing current into the subsurface. The DC resistivity and Self-potential (SP) methods share the same concepts. In both methods we measure the potential difference along two electrodes. However, in the DC resistivity method we have to induce current in the subsurface, which makes it different from the SP method. In the EM method we also induce current in the subsurface. As a result, the measured values for the potential difference would be increased in the DC resistivity method. Thus, the naturally occurring potentials would be considered as noise in the DC resistivity method.

The SP method has several applications. In our case we are trying to locate the flow of geothermal fluids. When water flows in the subsurface it creates a current along the interface between the water and the sediments and this current is our source for anomalies. Below is the equation that explains the relationship between the current and the electrical potential.

$$\nabla.(\sigma \times \nabla\Psi) = \nabla.Js \qquad \text{Equation (2)}$$

Where

σ = Conductivity
Ψ = Electrical potential
Js = Current density

Self potential is a passive electrical method, meaning that there is no signal put into the ground. Two non-polarizing electrodes, such as a lead/copper combination, are put into tubes with permeable surfaces so that they are coupled with the ground. The tubes are partially filled with a salt solution to improve conductivity and get a stronger signal. One electrode is kept at the same location and the other is moved relative to it. A voltmeter is then used to measure the voltage difference between the two electrodes. Whether the voltage is positive or negative indicates the direction of subsurface water flow. A strong positive anomaly can show the location of a fault where water is upwelling towards the surface. Below in Diagram 1, a simple model of the spontaneous potential generated in a geothermal reservoir is depicted.

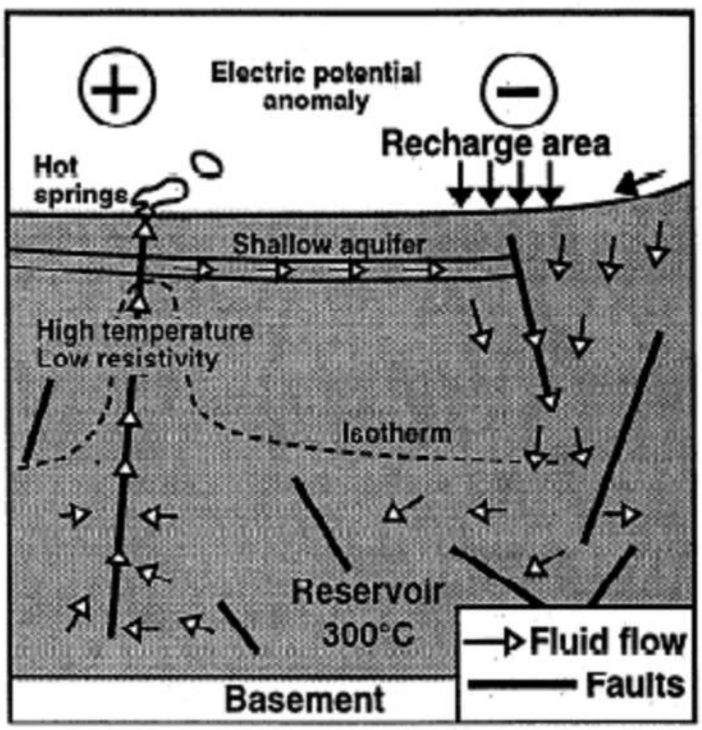

Diagram 1. Simple depiction of spontaneous potential generated in geothermal reservoir comparable to Rico, CO.

Two superb advantages to using the SP method are its instant results and "system" portability. The instant results played a large factor in proceeding with the SP surveying. At CSM's 2008 Field Camp, an initial self-potential survey was performed in the west high-resolution field (see Figure II-C-2A) which was also surveyed using the DC method from before. When an anomaly was seen during the survey, the SP lead (Dr. André Revil) ran the P2 profile survey to the east, and subsequently determined a new high-resolution survey field should be created to the east in an open field (see Figure II-C-2A).

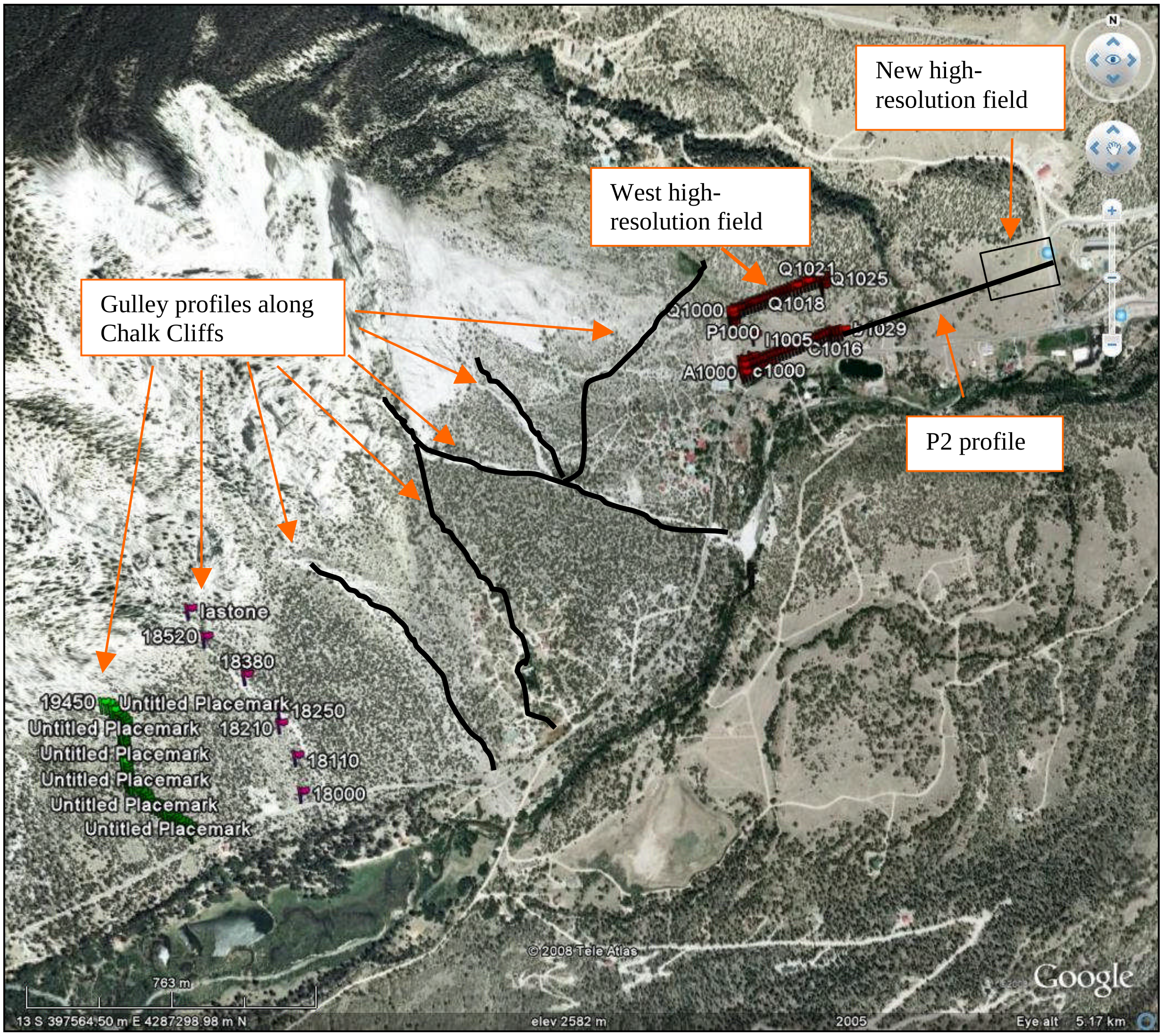

Figure II-C-2A. Geophysics valley view with partial SP survey included

These profiles were then processed by correcting for the difference in measurements at intersection points of different profile lines. This allows the processing team to view all of the electrical data as if it were acquired simultaneously because all of the effects from daily and weekly variations have been corrected out by referencing all profiles to one base electrode location. Below in Figure III-C-2B, is the culmination of all of the profiles over the Mt. Princeton valley after the corrections had been applied.

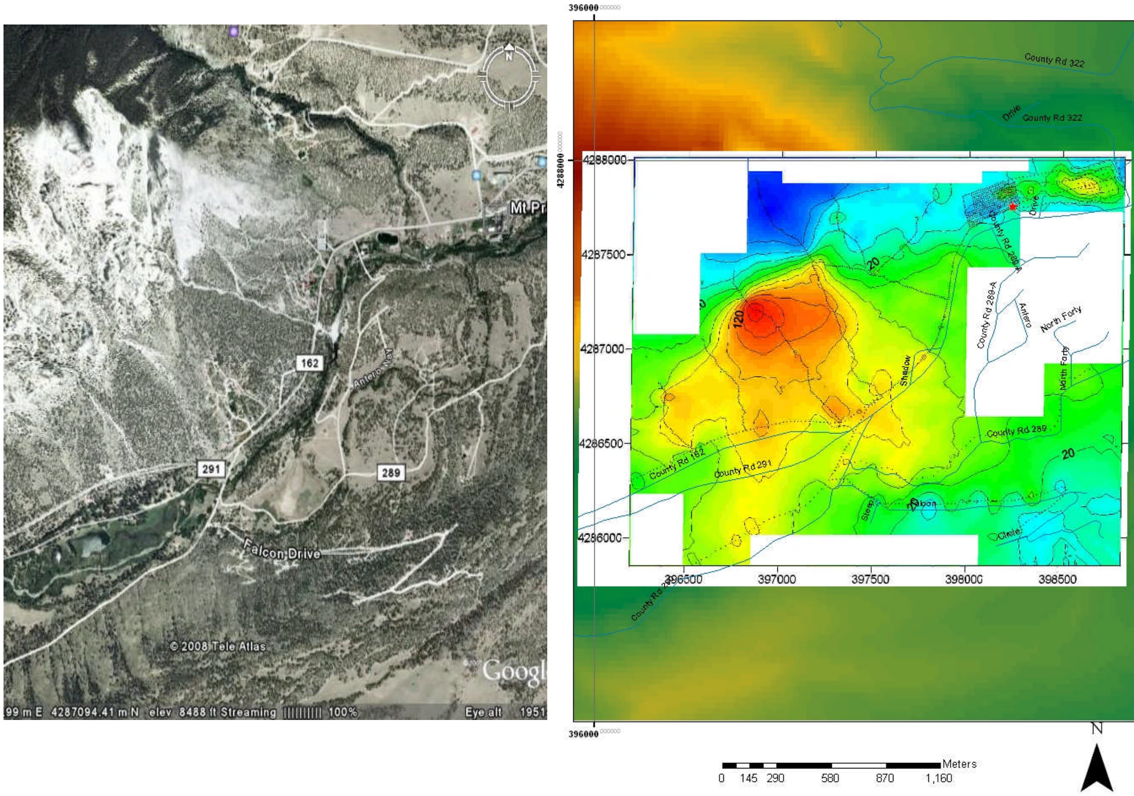

Figure II-C-2B. SP data overlaid with roads as lines in order to place anomalies in their correct surface acquisition locations. Notice how the large SP anomaly in the center correlates excellently with the Chalk Cliffs which have been hydrothermally altered from granite to kaolinite, not chalk.

This SP data shows good promising signs of a generic and inexpensive way of exploring for large geothermal anomalies. However, due to the highly forested and high topographic change rates of the Chalk Cliffs, only a few lines were able to be completed as opposed to a high resolution characterization as in the NE grids. Below in Figure III-C-2C is a closer look at the high resolution grid as well as an inversion attempt which matched up well with the DC resistivity model results.

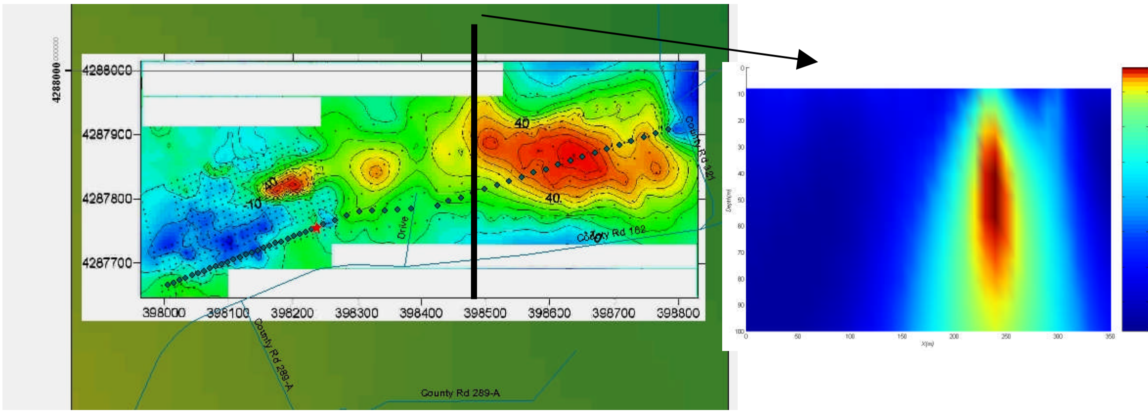

Figure II-C-2C. The image on the left is a closer look at the high resolution grid area as well as the DC resistivity survey line highlighted as bold dots going approximately through the middle of the survey grid. The image on the right is an inversion result from just analyzing the decay of the potential field measured by the SP survey, not from a DC survey data set because only a DC line was completed in the area and not a grid. The approximate depth from the inversion is 45-55m which is approximately what the DC inversion line results concluded.

II-D. Electromagnetic Surveys

Electromagnetic methods (EM) utilize the different conductivities of different rocks and materials in order to characterize their structural and spatial locations. For instance, sulphides and water have much higher conductivities than sandstones. EM surveys utilize the relationships between electric and magnetic fields and use current to generate these fields. Buried conductors will change the generated fields and the measured signal will reflect this change. [CSM FC 2008]

The EM-34 is one EM method that consists of two large coils, one that uses current to generate a magnetic field and one that records the secondary field at a set distance away. Spreading the coils further apart results in the transmitted field traveling deeper. The deepest point of investigation is located at the midpoint between the two coils. After attempting to interpret Mt. Princeton field camp data, it does not appear that the EM-34 penetrated great enough depths to view the top of groundwater. After correlating it to DC resistivity data, it only reaches to a depth of about 60m. This is not a method which should be used where depths of investigation are very large, unless borehole induction devices are used to accurately acquire data by getting closer to the zone of interest.

II-E. Well Logging

Well logging involves extending tools down boreholes or wells to determine information about the water or rocks. Flow direction, temperature, rock porosity, and rock type are all important pieces of information when trying to characterize groundwater flow and geothermal activity. Gamma ray logs send rays into the walls of the well and collect information about relative rock types. This is important for differentiating between sandstones, which are good sources of fluids, and shale, which has low porosity and permeability and can surround other rock layers and trap fluids. [CSM FC 2008]

III. Rico, CO Research

With the breadth of available geophysical exploration techniques described above the geothermal resource in Rico, CO could be better understood and better defined by using a suite of these methods. A USGS geologic map is available (Pratt et al , 1969) and detailed geology has been published for small areas near Rico, but there is still some level of uncertainty in the subsurface structure. All the accessible mines have been mapped and the structural regime of the area is described as being controlled by small and large scale continuous and discontinuous faults and intrusive bodies. Some fault zones are up to 3 meters thick and others are very narrow. Four mineral exploration holes were drilled in the 1970's on the crest of the Rico dome and the trace of a normal fault. These holes had water flows up to 800 liters/minute, water temperatures up to 114 C, contained CO2 and H2S gas and exhibited signs of massive sulfide mineralization (Medlin, 1983). The water and gases appear to be fault controlled since they were encountered at discrete zones in each hole.

Most of what has been done as far as geophysical exploration of the geothermal resource in the Rico area was for a master's thesis project by Eric Medlin at the University of Wyoming in 1983. This study looked at the heat flow and the gravity anomalies of the area to model the local thermal anomalies.

Heat flow is useful data in delineating regions that are favorable for the development of geothermal systems. In Medlin's 1983 study new data was taken including temperature and thermal conductivity for several drill holes, and new data of gradient, heat flow calculations, and a regional heat flow determination was generated. Four holes that had previously been drilled were used in the study. The interval thermal gradients were calculated for each hole and plotted against depth and thermal conductivity measured in the laboratory from available core samples (see example plot below, Figure III - A). The interval method was used to calculate the observed heat flow. The thermal regime of the drill holes was found to be disturbed only miniscule amounts by the surrounding mine workings. Looking at the data for the four holes Medlin concluded that the regional heat flow for the Rico area is 1.8 – 2.2 HFU (75-92 mW/m^2). Rico was concluded to be the site of a heat flow anomaly and near a negative gravity anomaly.

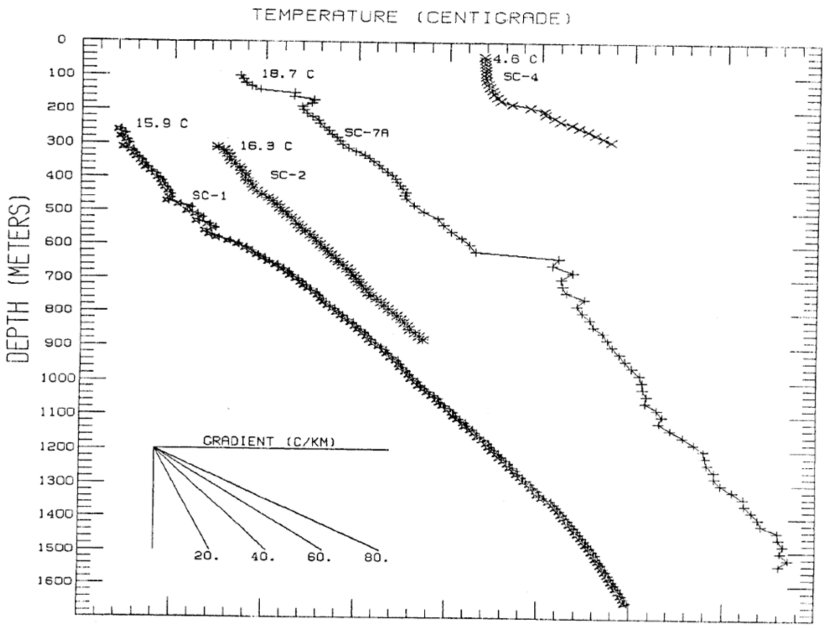

Figure III –A: Temperature-depth profiles for 4 drill holes. Temperatures are relative values. The number printed at the top of each plot is the temperature of the first point (from Medlin, 1983)

Gravity measurements in the Rico area consist of a terrain corrected Bouger gravity map contoured at 5 mgal intervals for the San Juan Volcanic area (Plouff and Pakisen, 1972). Based on gravity modeling, with an assumed density contrast of 0.1 g/cm^3, Plouff and Pakisen concluded the gravity low over most of the San Juans is caused by a low density batholithic complex and accompanying calderas and intrusive structures (Figure III -B).

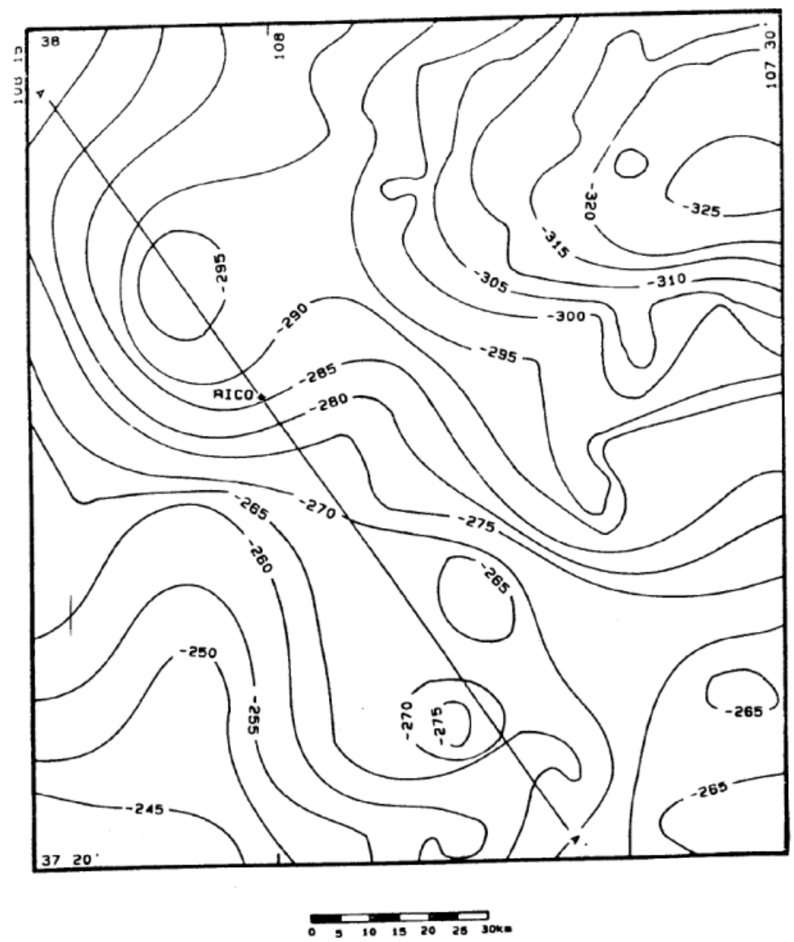

Figure III-B: Terrain corrected Bouger anomaly map contoured at 5 mgal intervals. (From Plouff and Pakiser 1972).

There is not a recognizable residual Bouger anomaly at Rico although there are several in the region. A large anomaly is centered approximately 13 km northwest of Rico near Dolores peak. This area is a gravity low with a terrain corrected value of -300 mgal. It is assumed that the Dolores peak gravity low is related to a buried granitic body, as most large negative gravity anomalies are associated with granite plutons which are less dense then the surrounding country rock. In Medlin's thesis paper multiple gravity models were constructed using a variety of shapes, sizes and densities of the subsurface materials to most closely match the actual values. It was concluded that buried spheres best matched the anomaly and provided the greatest simplicity. Using this data the heat flow anomalies at Rico resulting from a large body near Dolores Peak were calculated. The obvious gravity-thermal model of a granite body cantered about 13 km northwest of the town failed to account for the heat flow anomaly at Rico. The preferred model that

Medlin came up with was a more recent 'cupola' type intrusion very close to the Rico heat flow site, similar to areas of Molybdenum deposits extensively studied in other similar geologic settings (Figure III – C).

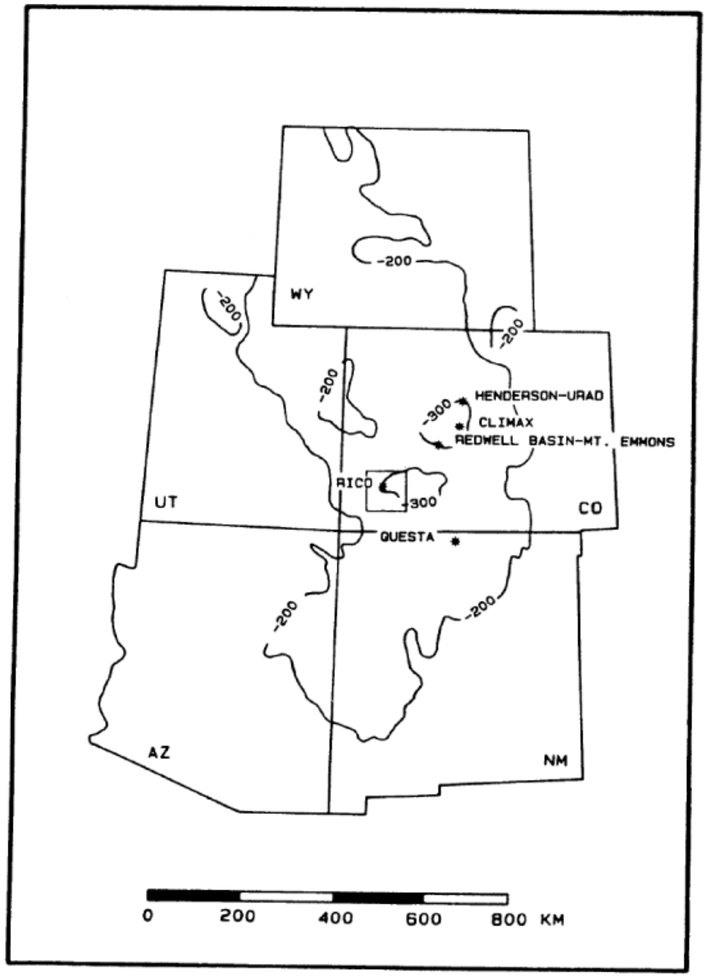

Figure III_C: Map showing relation of major climax type deposits to -300 mgal Bouger anomaly contour. These are thought to be related to a 'cupola' type intrusion

Although helpful in some respects in defining the geothermal character of Rico, Medlins exploration of the Rico geothermal area is not an adequate study of the geophysical characteristics of the area. He only measured temperatures in 4 drill holes, and of those 4 he only had core samples from 3 to lab test the thermal conductivity. His heat flow models are based on a cross-section done by Anaconda Minerals which was based on just two drill holes. The gravity models are based on regional data rather than data that obtained locally for the Rico area.

In the 1970's and 80's, various geophysical techniques were employed by RAMCO and Anaconda to identify or better define sulfide deposits at Rico. Current records indicate that the following surveys were conducted: VLF_EM, IP-resistivity, and magnetometer survey. Unfortunately, only the 1980 resistivity profiles have been recovered, but without the survey location information. It is possible that some of these geophysical records are still located within Anaconda's files (MegaMoly, 2009). With some investment the geophysical study could be vastly improved for this area and this will help better define the resource. MegaMoly has written a current and more advanced geophysical investigation into their geothermal power production business plan.

The MegaMoly plan includes analyzing in the field the structural and stratigraphic controls on the "hot springs" in the vicinity of Rico, performing geophysical surveys (resistivity and magnetotellurics), drilling and performing temperature logging in up to ten geothermal gradient wells, as well as analyzing remote sensing data, including hyper-spectral and thermal infrared satellite imagery to identify geologic structures, "hot spots" and hydrothermally altered deposits. There is also a plan for DC resistivity and/or MT. MT may include related techniques of TDEM, CSAMT, AMT. Seismic surveys are also being considered for their ability to image stratigraphy and faulting.

Conclusions

Geophysical data has been proven to have the capability of accurately characterizing geothermal reservoirs (Meidav, T., 1970, Harthill, N., 1978, McEuen, R.B., 1970, Fuis, et al 1984) and exploring for new ones, as long as more than one method is being considered for interpretation. Different data provides different levels of accuracy of the signal, from heat anomalies, structural elements or just plain noise. By correlating different data sets, it is possible to decipher which ones are showing geothermal anomalies, or if that method is just not effective in measuring anything but noise in a specific area. Rico, CO should implement the electrical methods as cost effective ways of exploring for reservoirs. The structural information can be deciphered afterwards by seismic and gravity techniques once the anomaly has been located. This allows us to more accurately predict the economics of the project based on the area and structural characteristics of the reservoir zone.

References

CSM/BSU Geophysics Field Camp 2008. “Characterization of the Upper Arkansas River Basin, Chaffee County Colorado.” Colorado School of Mines. June 5, 2008.

Fuis, G.S., Mooney, W.D., Healy, J.H., McMechan, G.A., and Lutter, W.J., 1984, A seismic refraction survey of the Imperial Valley Region, California. Journal of Geophysical Research, Vol. 89, B2, p.1165-1190.

Harthill, N. (1978). A quadripole resistivity survey of the Imperial Valley, California. *Geophysics, 43*(7), 1485-1500. doi:10.1190/1.1440910

McEuen, R. B. (1971). Delineation of geothermal deposits by means of long-spacing resistivity and airborne magnetics; united nations symposium on the development and utilization of geothermal resources, proc., vol. 2, part 1. *Geothermics, 2*(2), 295-302. Retrieved from www.csa.com

Medlin, Eric. “Modeling Local Thermal Anomalies: Constraints from Conductivity, Gravity, and Heat Flow.” Master’s Thesis, University of Wyoming, Laramie, WY, December 1983.

MegaMoly business plan for geothermal power production near Rico, Colorado, 2009.

Meidav, T. (1971). Application of electrical resistivity and gravimetry in deep geothermal exploration; united nations symposium on the development and utilization of geothermal resources, proc., vol. 2, part 1. *Geothermics, 2*(2), 303-310. Retrieved from www.csa.com

Plouff, D. and Pakiser, L.C., 1972, Gravity study of the San Juan Mountains, Colorado: United Statea Geol. Surv. Professional Paper 800B, p. B183-B190.

Pratt, W.P., McKnight, E.T. and Dehon, R.A., 1969, Geologic map of the Rico quadrangle, Dolores and Montezuma counties, Colorado: U.S. Geological Survey Map GQ-797.