Improvements in Shallow (Two-Meter) Temperature Measurements and Data Interpretation

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ABSTRACT

The Great Basin Center for Geothermal Energy has been working on improvements in shallow (two-meter) temperature surveys in two areas: overcoming limitations posed by difficult ground conditions with the use of a portable rock drill, and improvements in temperature measurements and interpretations

Previous 2-meter temperature surveys conducted by the Great Basin Center for Geothermal Energy have been limited to areas that were not excessively rocky. This limitation has been overcome by the use of a self-contained gas powered pavement breaker/rock drill capable of penetrating extremely rocky ground including bedrock. With the use of the rock drill completion of approximately 10 temperature probe holes in an 8 hour field day is possible.

Large variations in surface albedo (reflectivity of a surface to sunlight) can cause differences in the temperatures measured at a depth of 2 meters of up to several degrees centigrade. A field-based method of correcting two-meter temperatures for the effects of albedo was utilized at Columbus Marsh, Nevada. ASTER satellite imagery was used to independently estimate albedo so that solar heating effects could be filtered from the temperature data, with a resultant noticeable improvement in the definition of geothermal anomalies.

To better understand factors effecting shallow (two-meter) temperature measurements and improve the ability to predict thermal anomalies, long term monitoring of a number of sites at Desert Queen, Nevada were conducted in background and high heat flow areas to study seasonal effects on temperature at two meters. Sites were also selected to study influences on shallow temperature measurements related to geological and solar radiation factors specifically, slope orientation, ground composition and albedo. In addition to measuring a single temperature at a depth of two meters, multiple sensors were used to measure temperatures at 1, 1.5 and 2 meter depths for calculation of shallow temperature gradients. Results of the long term studies indicate that differences between thermal anomalies and background areas are smaller during the coldest part of the seasonal cycle which at a two meter depth is approximately two months after the coldest average air temperature (February-March). Nevertheless, the difference between thermal anomalies and background areas is roughly proportional throughout the year. The effects of albedo appear to be seasonally dependent and have less influence in the colder parts of the season. The slope orientation, north verses south facing slope, displays expected trends of southern exposures being warmer than northern. Measurements of shallow gradients were found to be useful in distinguishing thermal anomalies from background areas and should help remove solar radiation effects. The shallow temperature gradient in background areas is lower than in thermally anomalous areas. The gradient of background areas is also more likely to be negative (decreasing with depth) during the spring and summer as the sun heats the upper part of the soil profile. The temperature gradient profile is useful for discriminating anomalous zones from background areas when the study areas are more topographically complex and corrections for solar radiation factors such as albedo and slope orientation become important.

Introduction

This paper is divided into two sections. The first section discusses the use of a rock drill which has made it possible to conduct two-meter (2M) temperature surveys in rockier ground including areas with exposed bedrock. The second section discusses improvements in 2M temperature measurements, improvements in instrumentation, and the development of empirical methods of correcting for external, solar radiation heat inputs related to albedo and slope aspect with examples from the Columbus Marsh and Desert Queen areas of Nevada.

Rock Drill

Although 2M probes can be driven into moderately rocky soils, methods needed to be developed to allow 2M temperature surveys to be conducted in more difficult ground conditions. Review of several types of rock drills led to the selection of the Cobra Combi, a light weight gas powered pavement breaker/rock drill made by Atlas Copco.

Rock Drill Methods and Application

The rock drill equipment consists of the Cobra Combi pavement breaker/rock drill and an assortment of 2', 4' and 6' foot drill steels, fitted with bit sizes of 1 7/8", 1 1/2" and 1 3/8". Two-foot steels are fitted with 1 7/8" and 1 1/2" bits and the 4' and 6' steels are fitted with 1 1/2" and 1 3/8" bits. This allows for step drilling when conditions warrant. When loose material at the top of the hole causes excessive caving a 1 1/5" PVC pipe can be inserted in a hole drilled with the 1 7/8" bit to form a collar. A small air compressor and an air lance constructed of 1/8" pipe are used to assist in chip removal when needed. The Cobra Combi can be handled by one person, but for drilling 6' deep holes, a simple "A" frame with an electric winch was fitted to the front of the ATV. Two adjustable feet are bolted to the front bumper of the ATV to stabilize the front end. Synthetic rope is used on the winch in place of wire rope. This reduces problems with uncoiling and tangling of the wire winch rope. A switch for controlling the winch is mounted on the Cobra Combi, which allows for one-man operation of the rock drill. The rock drill equipment along with the conventional 2M probe equipment can all be carried in the ATV. Use of the rock drill is fairly straight-forward, but some practice is required, usually involving getting a few drill steels stuck, to learn which techniques work. Successful drilling requires careful monitoring of air circulation and rotation. When circulation drops off and chips are not blowing out of the hole at a good rate, or rotation starts to slow down, the drill must be worked up and down to regain good circulation and rotation. These are subjective measures and must be learned by practice. Once a hole has been drilled with the rock drill, a 2M probe is placed in the hole and hammered to a 2 meter depth if possible with the electric demolition hammer, and then backfilled. As with regular impact driven 2M probes, it is preferred to allow the temperature to equilibrate overnight before making temperature measurements.

The capabilities of both the ATV and the rock drill were initially tested in rugged terrain in Nevada (Figure 1). Unlike previous surveys, 2M measurements at this location were made in bedrock. After easy penetration of shallow (<0.5m) overburden and weathered bedrock the holes were completed in basaltic andesite. The set up and drilling time per hole averaged 50 minutes. Experience and modifications to the system have helped reduce that time to 40 minutes.

Improvements in 2M Temperature Measurements

Initial two-meter temperature studies conducted by the Great Basin Center for Geothermal Energy led to the identification of strong geothermal anomalies and it was not necessary to consider external factors that influence 2M temperatures. The topography of most of the sites where surveys have been conducted has been fairly uniform. However, when mapping more subtle anomalies and conducting surveys in more topographically complex terrain, solar radiation factors such as albedo and slope orientation become more important.

Temperatures at 2 meter depths for most of the areas where surveys have been conducted follow a predictable seasonal temperature cycle (Figure 2). Consequently, if multiple surveys are conducted in one area at different times of the year, 2M base stations can be used to measure temperatures during each survey and normalize temperatures for seasonal drift.

In order to compensate for solar radiation factors such as albedo and slope orientation, we are investigating two approaches: one involves the independent measurements of albedo and topographic slope aspect, using methods such as remote sensing, and then using those measurements to correct the temperature data; the second approach involves improvements in 2M temperature

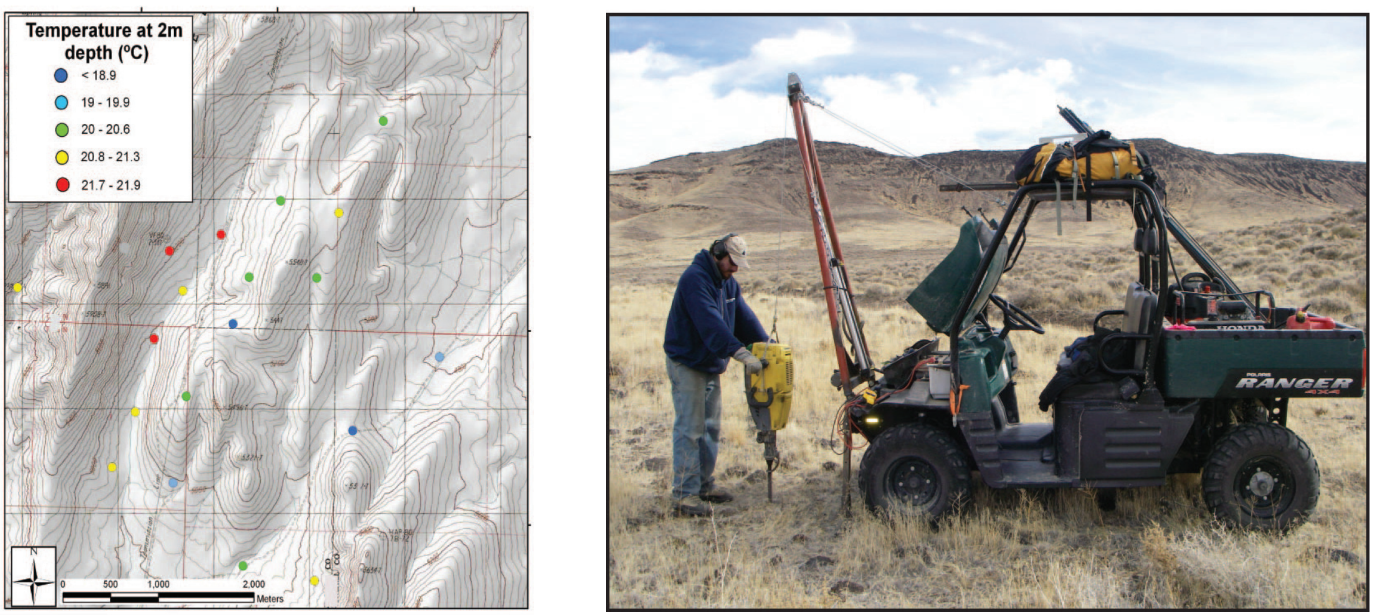

Figure 1. Map showing an example of mountainous terrain that the rock drill enables 2M temperature surveys to be conducted in, and photo of the rock drill setup with ATV. The ATV pictured is capable of carrying the 2M probe equipment, the rock drill, and up to three passengers.

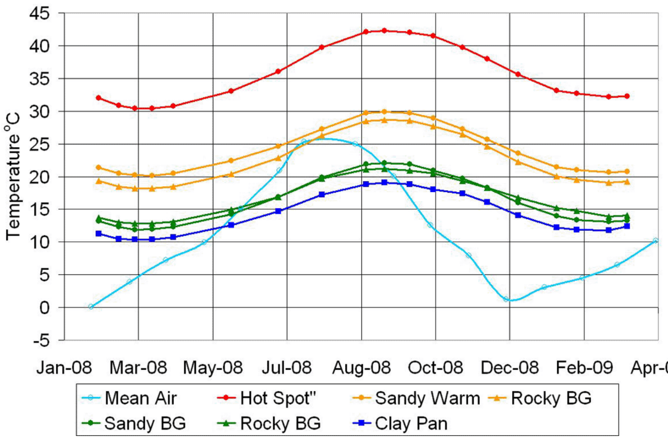

Figure 2. Annual cycle of 2M temperatures at Desert Queen and Reno mean air temperature. Both background and high heat flow areas show a lag in the 2M seasonal high temperature compared to mean air temperature of approximately 3 months and a lag in the seasonal low of approximately 4 months. The relative difference between background and high heat flow areas is consistent over the course of the annual cycle.

measurements, including the measurement of shallow temperature gradients, to produce temperature data that is less sensitive to variations in solar radiation input.

Measurement of Solar Radiation Variables

An empirical correction for variable surface heat inputs can be made by measuring 2M temperatures in a background (non-geothermal) area that contains representative ranges of albedo, slope aspect, elevation, etc. If values for albedo, slope aspect, and elevation can be measured independently (for example, using remote sensing imagery and digital elevation models) and statistically compared to the 2M temperature data, correlations can be identified which can be used to correct the 2M temperature data to remove the influence of these variable surface heat inputs. LeShack and Lewis (1983) used such an approach to correct for the effects of elevation at the Coso geothermal area, CA.

We provide an example of correcting for albedo effects in a 2M temperature survey of the Columbus Marsh area, Nevada recently completed by Kratt et al. (2009). At Columbus Marsh, surface albedo varies considerably from place to place depending on the composition of rocks and soils. Alluvial fan material down-gradient from black shale outcrops is very dark, with albedos as low at 0.05 or 5%, whereas actively precipitating evaporite minerals in the playa have albedos as high as 0.70 or 70%.

An uncorrected 2M temperature map of Columbus Marsh (Figure 3) reveals two anomalies in the southwestern portion of the valley; the larger of these anomalies, the "southwest anomaly", is believed associated with geothermal activity (Kratt et al., 2009), whereas the smaller anomaly "A" appears related to low-albedo (dark) rocks and soils that are clearly visible in an ASTER remote sensing image (Figure 3). A temperature anomaly on the north side of the playa is related to the Redlich geothermal system.

Most of the background 2M temperature variations at Columbus Marsh appear to be caused by albedo, as revealed in Figure 4 where 2M temperatures are plotted against albedo measurements obtained from an atmospherically corrected ASTER 07XT satellite image. After excluding known or suspected points influenced by

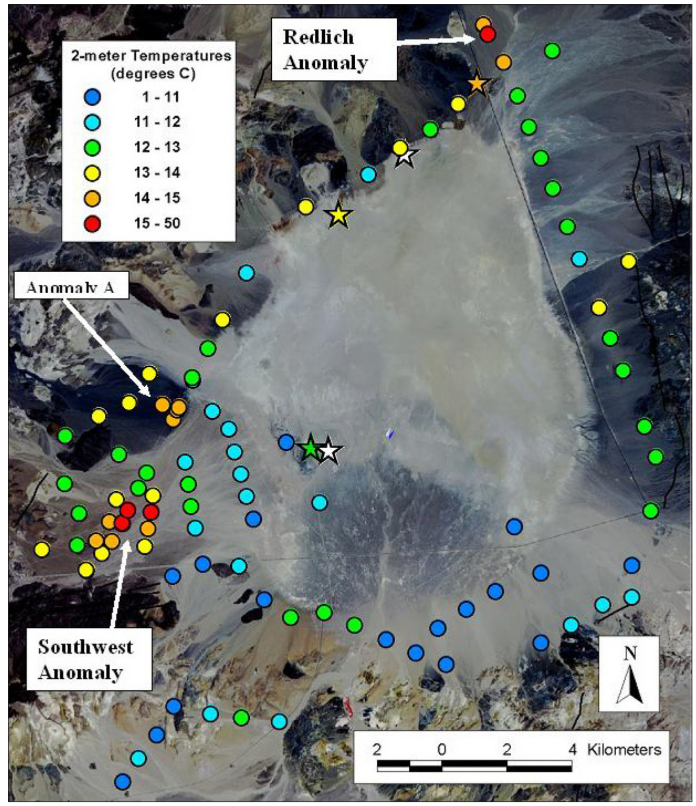

Figure 3. Two meter deep temperature measurements of Columbus Marsh playa area, Esmeralda County, Nevada, uncorrected for albedo. Data from Kratt et al. (2009). Background is band 2 of ASTER 07XT satellite imagery, illustrating areas of low (dark) and high (bright) albedo. Stars are wells and springs: orange = 30°C, yellow = 21°C, green = 14°C, white = temperature unavailable.

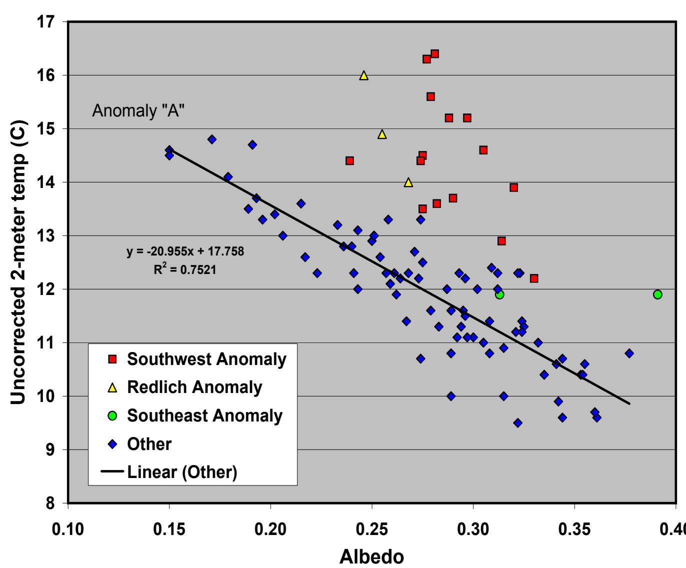

Figure 4. Two meter depth temperatures and associated albedos from the Columbus Marsh playa. Temperature data are from Kratt et al. (2009). Albedos were taken from band 2 of an atmospherically corrected ASTER 07XT satellite image. Albedos from the image at selected locations were compared to equivalent values measured in the field with a spectrometer to ensure that the image data were scaled properly to represent albedo. Topographic slope aspects were near horizontal in all parts of the survey.

geothermal activity, the remaining "other" samples were used to define a linear best-fit relationship between albedo and background temperatures which was used to correct all of the 2M temperatures. The slope of the line in Figure 4 was incorporated into an albedo correction equation: Py = -20.96 (Pa – 0.282) where Py is the albedo correction to be subtracted from an individual 2M temperature data point, "-20.96" equals the slope of the line, Pa is the albedo measured at the given point, and 0.282 is the average albedo for the Columbus Marsh two-meter temperature data set.

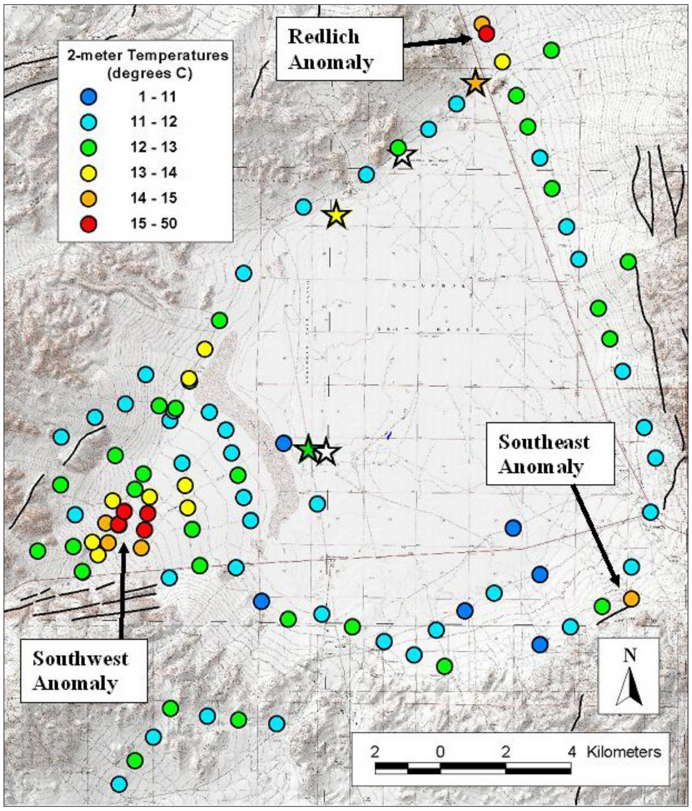

Figure 5. Two meter deep temperature measurements of Columbus Marsh playa area, Esmeralda County, Nevada, corrected for albedo. Temperature data from Kratt et al. (2009). Background is shaded topography. Stars are wells and springs: orange = 30°C, yellow = 21°C, green = 14°C, white = temperature unavailable. Black lines are Quaternary faults.

On the albedo-corrected temperature map (Figure 5), anomaly "A" has disappeared, while the southwestern anomaly has remained essentially unchanged, confirming suspicions that the "A" anomaly is caused by albedo-related solar heating and that the southwestern anomaly, as well as the Redlich anomaly on the north end of the playa, have a different origin, presumably geothermal (Kratt et al., 2009). On the corrected map, a third temperature anomaly becomes apparent in the southeastern part of the study area (see also Figure 4); this area and another small area north of area "A" may warrant follow-up investigations.

Improvements in Instrumentation and Shallow Temperature Gradients

The Great Basin Center for Geothermal Energy has been conducting long term studies at the Desert Queen area in northern Churchill County, Nevada to study seasonal influences on two-meter temperatures and to test and develop new equipment and techniques.

Resistance temperature devices (RTD) and thermocouple (TC) temperature sensors were used for temperature measurements inside 2M probes (Figure 6). RTDs were used for single measurements at a depth of 2 meters. Gradient measurements were made using TCs and RTDs placed at 1, 1.5 and 2 meters. TCs were initially used for the gradient measurements because of their lower cost, but were eventually replaced by the more accurate RTD sensors. Because TC meters are known to drift over the course of a day due to ambient temperature changes, two methods were evaluated for compensating for this drift. These methods were 1) the placement of an RTD at the 2 meter position in contact with the TC, and 2) the measurement of an isothermal block containing an RTD and TC at the same time measurements were being made in the 2M probes.

Figure 6. RTD and meter for measuring temperatures at 2 meter depth in probes (left), and gradient TC and 4 channel data logger for measuring temperatures at 1, 1.5, and 2 meters (right).

Six primary locations at the Desert Queen area were selected for initial long term monitoring to study seasonal influences on 2M temperature measurements. These sites included three background temperature locations representative of a range of soil types including an "average" soil with disseminated rocks (the "Mill Site"), a sandy area, and a low lying area near a playa that experiences seasonal saturation at the surface. Two areas of high heat flow were chosen as representative of average soils; one contains disseminated rocks and local areas of wind-winnowed lag, and the second area is sand-rich with interbedded gravels at depth. The 6th location (the "Hot Spot") corresponds to the peak 2M temperature recorded during the initial temperature survey in 2006 (Coolbaugh et al., 2007; Sladek et al., 2007). These six 2M stations were fitted with dedicated RTDs. Measurements were made at approximately 1 month intervals with shorter intervals as temperatures crossed through seasonal extremes.

After approximately 8 months of data collection, the RTDs at the Mill Site and Hot Spot were replaced with gradient TC/

RTDs to begin collection of 2M temperature gradient data. After reviewing initial 2M temperature gradient data, additional stations were added to test the effects of albedo and north-south slope orientations. Two sites approximately 100 meters apart, one with a light buff colored soil and the second mantled with dark reddish brown to black basalt gravels, were selected as albedo test sites. Albedo probes were installed using the rock drill and were emplaced to a depth of 1.7 meters, because the longest drill steel currently being used is 6'. Two areas were selected for evaluation of slope orientation. A hill approximately 25 meters high with similar north and south facing slope angles, mantled with dark reddish brown to black basalt cobbles and boulders with interstitial buff colored soil, was selected for placement of 4 probes to test the effects of slope orientation on 2M temperatures. These four probes were also implaced using the rock drill and the two north facing probes were placed to depths of 1.6-1.8 meters. The second slope orientation site was a partially vegetated sand dune of light tan sand approximately 8 meters high. One probe each was placed on the north and south facing slopes.

Temperature Sensors and Instrumentation

We found that the gradient TCs which had a RTD at the 2 meter position produced fairly accurate results when the temperatures were normalized to the RTD temperature. After conducting the survey for several months it was found that there was an additional error associated with equilibration of TC and TC meter connectors. When there was a significant difference in the temperatures of the connectors of the permanent TC and the TC meter, up to 10 minutes was sometimes required for the mated connectors to equilibrate and the temperature to stabilize. It was also found that the use of an isothermal reference did not allow for accurate correction of TC meter error and seemed to actually increase the error. Because of the non-linear characteristics of TCs, the isothermal block can only be used for temperature corrections when the TCs in the 2M probe are close to the same temperature as the isothermal block. Because of the errors associated with thermocouple measurements, the gradient TC sensors were eventually abandoned and replaced with 3-zone RTDs (Figure 7).

Figure 7. Proto type of 3 zone RTD for measuring temperatures in 2-meter probes and switch for selecting RTD at 1, 1.5, or 2 meters.

Seasonal Temperature Cycle

Measurements of the six primary Desert Queen locations collected over the course of a year show a predictable seasonal cycle (Figure 2). Background and high heat flow sites display a predictable sinusoidal pattern in which the phase of the 2M temperatures lags the seasonal mean surface temperature (Figure 2). Differences between background and high heat flow areas are relatively consistent throughout the year. The sandy warm ground averages 7.8 C° ± 0.3 std., and the sandy hot ground averages 19.4C° ± 0.7 std. The low standard deviation indicates that although there may be significant differences in measured temperatures at a station, the relative difference is consistent throughout the year and that when the conducting 2M temperature surveys over a period of time the seasonal drift can usually be compensated for by measuring base stations and normalizing temperatures to the drift of the base stations. However, one should keep in mind that differences in soil thermal conductivity and thermal inertia as well as other factors can influence the rate of seasonal drift and base stations should consist of representative soil types.

Seasonal Gradient Shift

Shallow temperature gradient measurements of the Mill Site and the Hot Spot show that these background and high heat flow areas have different patterns when viewed over a several month period (Figure 8). Between September 2008 and January 2009, the temperature gradient for 1-2 meters for the Mill Site changed from –3.4 C°/m when surface soil temperatures were high, to a +6.7 C°/m gradient in the winter. Over the same period of time, the 1-2 meter gradient at the Hot Spot remained positive but changed from 5.8 C°/m to 13.9 C°/m. The differences in character of the shallow gradients for background and anomalous zones illustrate the usefulness of 2M gradient measurements to help in the identification of thermal anomalies. Geothermal heat flux will influence the deeper portion of the gradient more than the shallower portion of the gradient, which is more susceptible to the influence of solar radiation.

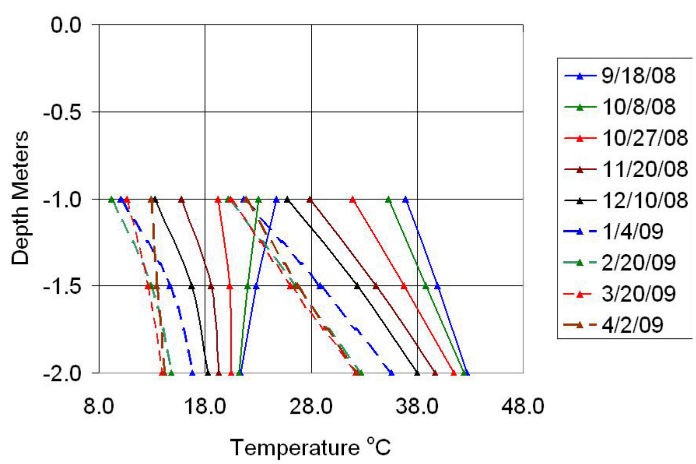

Figure 8. Graph of temperature gradients of a background (left grouping) and the highest temperature stations (right grouping) at Desert Queen. Similar color and line style represent temperatures taken on the same date.

Albedo Affects

Comparison of gradient graphs for the two albedo stations over a 5 month period from winter to spring show a significant change in patterns (Figure 9). In December both soils have a positive gradient. As the seasonal temperature cycle passes through the annual minimum, the lighter soil appears warmer and the gradients transition to negative values. Finally in spring the gradients are negative and the darker soil is again warmer. The fact that the lighter soil is warmer than the darker soil as the temperature cycle passes through its annual minimum is likely related to soil thermal conductivity. The rock drill was required for emplacement of both probes, and the darker soil area was in basalt bedrock for all but the upper few centimeters. The lighter soil was composed of rocky soil and appeared to contain thick caliche and/or tufa layers.

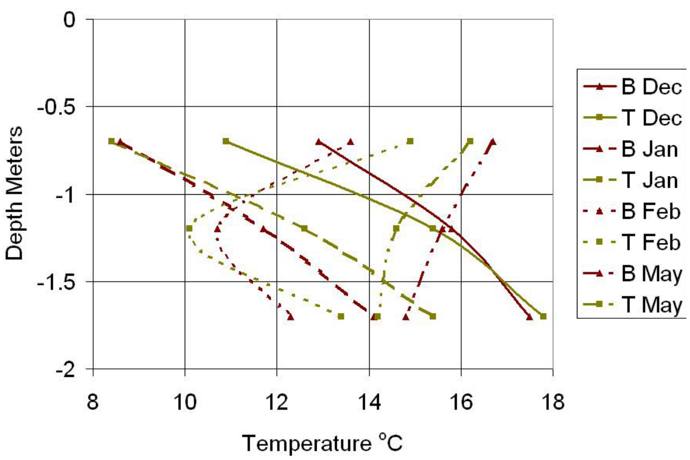

Figure 9. Temperature gradients of albedo stations over a 5 month period from winter into spring. B (brown) lines are the gradients of an area mantled with dark basalt gravel and interstitial light silt, and T (olive) lines are gradients of an adjacent area with light buff colored soil.

Correction for Slope Orientation

A pilot survey at representative sites at the Desert Queen thermal anomaly was completed to test the effectiveness of shallow temperature gradients to map thermal anomalies and filter the effects of topographic slope orientation. The standard 2M temperature anomaly defined with the deepest of the three sensors is consistent with the anomaly identified during the larger survey of Coolbaugh et al. (2007) and Sladek et al. (2007). Two pairs of north and south-facing slopes have higher temperatures on south-facing slopes, thus generating "false geothermal" anomalies. This was most evident at the slope pair "A" (Figure 10). When the temperature gradient data from 1-2 meters is plotted, the main thermal anomaly is reproduced, and the false thermal anomaly of pair "A" is compensated for and both the north-facing and south-facing slopes plot as background areas (Figure 11); however, the "B" slope pair is over-compensated for and the north-facing slope shows a false heat flux anomaly.

Conclusions

The use of the rock drill has made it possible to conduct 2M temperature surveys in more challenging areas that were not penetrable using an impact hammer. The rock drill makes it possible to not only conduct surveys where large rocks were encountered but in solid bedrock. Currently about 10 probes per day can be

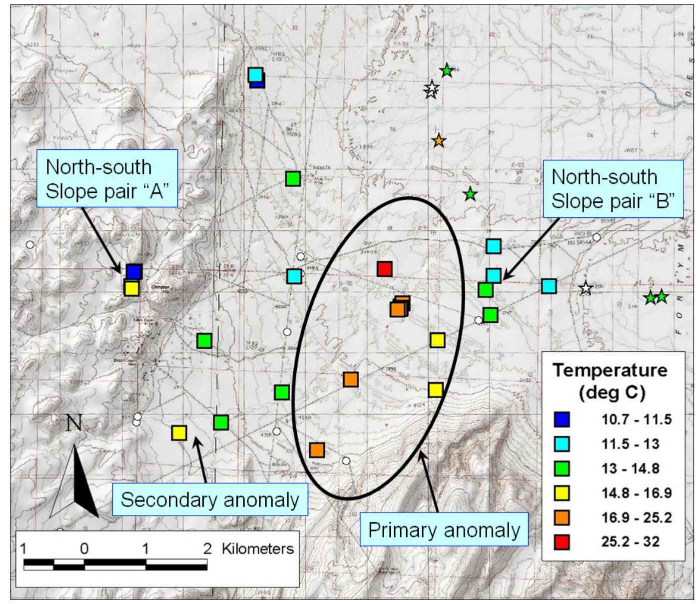

Figure 10. Temperatures at a depth of 2 meters, from a test survey of the Desert Queen area March 18, 2009. The primary and secondary temperature anomalies coincide with 2-meter temperature anomalies identified during a larger survey conducted in the fall of 2006 (Coolbaugh et al., 2007; Sladek et al., 2007). At two locations (pairs A and B above), south-facing slopes have warmer temperatures than north-facing slopes at a depth of 2 meters, thus producing "false" or "non-geothermal" anomalies.

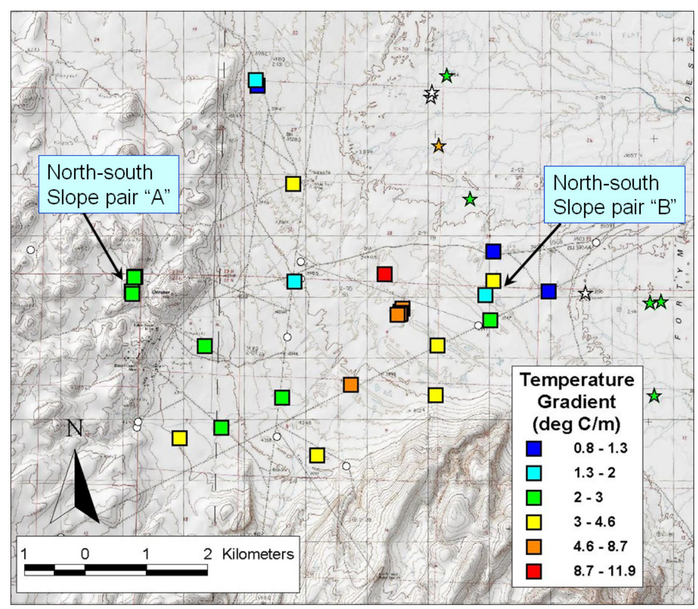

Figure 11. Temperature gradients from 1 to 2 meters, from the Desert Queen test survey of March 18, 2009. In general, higher temperature gradients in this figure match areas of higher temperatures at 2 meters (Figure 10), which correspond to areas of higher geothermal heat flux (Coolbaugh et al., 2007; Sladek et al., 2007). The "false" or "non-geothermal" anomaly caused by the south-facing slope of pair "A" (Figure 10) has been eliminated on this temperature gradient map. The "false" or "non-geothermal" anomaly on the south-facing slope of pair "B" (Figure 10) has been inverted on this temperature gradient map, such that the north-facing slope has a somewhat higher temperature gradient than the south-facing slope. Future processing procedures will attempt to combine temperatures at a 2 meter depth with the shallow temperature gradients to minimize solar heating effects.

placed if the rock drill is required for all sites. This can likely be improved with practice.

Solar radiation effects caused by changes in albedo and topographic slope aspect can change temperatures at a 2 meter depth by several degrees. Preliminary data suggests that albedo may be a more significant factor during the warmer part of the seasonal temperature cycle. Independent measurements of albedo can be used to compensate for albedo-related solar heating effects. At Columbus Marsh, Nevada, ASTER satellite imagery was used to define a correlation between background 2M temperatures and albedo. That correlation was then used to correct the 2M temperatures for albedo, with a resultant improvement in the ability to map geothermal anomalies.

Tests of TC and RTDs indicate that although errors inherent with using TCs can be corrected for to a significant degree, RTDs provide superior data quality. Because RTDs are still required to correct for TC errors, the use of TCs is not practical.

Shallow temperature data collected over a one-year period indicate that although there is a significant temperature change from the seasonal minimum to maximum, the differences between background and anomalous heat flow areas are relative. This indicates that 2M temperature survey data can be collected throughout the year. However to minimize some environmental effects, including variations in thermal conductivity, it is best to conduct surveys over a limited time period. Base stations should be measured with each round of probing for surveys conducted for periods of longer than three or four days to determine if there is a temperature change that warrants normalizing temperature data.

Temperature gradient measurements can provide valuable additional data that can potentially be used to compensate for solar heat flux variations at the soil surface that can influence 2M temperatures. In some cases, shallow temperature gradient measurements appear to minimize temperature anomalies generated by slope aspect. However temperature gradient data adds additional levels of complication to data interpretation. Further research will be conducted on shallow temperature gradients to determine how the seasonal temperature cycle influences temperature gradients, and to determine the best approach for using temperature gradients to compensate for surface heat flux variations.

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