Compensation for Seasonal and Surface Affects of Shallow (Two-Meter) Temperature Measurements

Mark F. Coolbaugh[1], Chris Sladek[1], and Christopher Kratt[2]

[1]Great Basin Center for Geothermal Energy, University of Nevada, Reno, Nevada,
[2]Desert Research Institute, Reno, Nevada

Keywords

Shallow temperature, two, 2, meter, albedo, thermal diffusivity, Desert Queen

ABSTRACT

Temperature measurements at a two-meter depth have been proven effective for identifying thermal anomalies caused by shallow thermal groundwater plumes and steam-heated ground associated with geothermal systems, even where no surface manifestations are present. Nevertheless, significant non-geothermal temperature anomalies at a 2-meter depth can be produced by variations in surface solar radiation input (caused by variations in albedo and topographic slope aspect), climate (e.g. elevation lapse rate), and variations in the thermal diffusivity of soils and rocks. These non-geothermal temperature variations can either obscure underlying contributions of geothermal heat flux or have the potential to be misinterpreted as geothermal anomalies.

In this paper, we review the development status of data processing methodologies for minimizing non-geothermal temperature anomalies so that geothermal heat flux can be more accurately identified and mapped. These methodologies rely on auxiliary data, including digital elevation models (for determining elevation and slope aspect), visible-light remote sensing images (for estimating albedo), shallow temperature gradient measurements (also for estimating the effects of albedo and topographic slope), and in-situ 2-meter transient heat decay tests (for estimating thermal diffusivities).

An example is provided wherein thermal diffusivities are estimated for the Desert Queen area of northwestern Nevada using multiple 2-meter temperature measurements over the course of a year. In this case, the impact of thermal diffusivity on the 2-meter temperature anomaly appears insignificant, but surveys completed at other locations, particularly during mid-summer, have identified stronger influences.

Laboratory testing shows that established methods of making in-situ thermal diffusivity measurements can be adapted to the current 2-meter probe design in use at the Great Basin Center for Geothermal Energy. The routine use of such devices will facilitate rapid and detailed compensation for thermal diffusivities without the need for additional temperature measurements at greater depths or over longer periods of time.

Background

Shallow temperature surveys have been used extensively in the past to outline temperature anomalies at known geothermal areas. Examples of their use in the Great Basin include 1-meter-deep surveys at Soda Lake and Upsal Hogback (Olmsted, 1977); 2-meter-deep surveys at Coso, California (LeSchack and Lewis, 1983); Hawthorne and Paradise Valley, Nevada (Trexler et al., 1981); Pumpernickel Valley and Carlin (Trexler et al., 1982); and 3-meter-deep surveys at McCoy and Dixie Valley, Nevada (Lange et al., 1982). Almost all of this activity was focused towards outlining shallow thermal groundwater plumes associated with known geothermal areas, though Trexler et al. (1982) used 2-meter surveys to identify a previously unknown geothermal area northeast of Pumpernickel Valley, Nevada. The ecomomic benefits of using shallow temperature surveys to map zones of shallow thermal groundwater and thereby reduce the amount of temperature gradient and slim-hole drilling necessary to vector towards deeper, higher temperature resources has been recognized for some time.

Until recently however, shallow temperature surveys have not been extensively deployed in the field in a reconnaissance or grass-roots exploration setting, due in part to equipment technologies that placed restraints on field portability, lingering concerns about how to compensate for non-geothermal temperature variations at shallow depths, and questions about where and when the techniques work most effectively. Beginning in 2005, the Great Basin Center for Geothermal Energy (GBCGE) at the University of Nevada, Reno has been devoting significant efforts to expand the use of this technique in the Great Basin based on its successful track record in the past. Initial efforts at the GBCGE focused on updating and modernizing the equipment and methodologies to make them more rapid, efficient, and field-portable, to make it possible to move this technique fully into the realm of reconnaissance and grass-roots exploration, where it gains its greatest power in terms of the ability to contribute towards the identification of additional geothermal resources. The utility of an early prototype 2-meter survey method for defining targets for temperature gradient drilling at the Pyramid Lake Paiute Reservation, Nevada are discussed by Coolbaugh et al. (2006), and a pilot survey demonstrating full portability of an updated and modernized 2-meter survey method utilizing all-terrain-vehicles (ATVs), hollow steel pipes with tungsten-carbide-alloy tips, platinum resistance temperature devices (RTDs), electric hammers, and global positioning system (GPS) units, is described by Coolbaugh et al. (2007a) and Sladek et al. (2007) using the Desert Queen area, Nevada, as an test area.

Over the last 5 years, experimental use of the GBCGE's updated portable 2-meter survey method in an early stage, reconnaissance exploration environment has led to the identification of seven previously unknown geothermal systems, including those at Teels and Rhodes Marshes (Kratt et al., 2008), Columbus Marsh (Kratt et al., 2009; Sladek et al., 2009), east Hawthorne (Kratt et al., 2010) and at Emerson Pass, Nevada (Kratt et al., 2010). In addition, these surveys have outlined multiple-km-long thermal anomalies and helped identify potential structurally controlled upwelling zones related to single-point hot springs or hot wells at six additional areas in Nevada (e.g. Astor Pass and the southwest Smoke Creek Desert, Coolbaugh et al., 2006; northeast Gabbs Alkali Flat (Kratt et al., 2008), and Dead Horse Wells (Kratt et al., 2010). Orientation surveys have demonstrated proof-of-concept at five known geothermal areas, including the Desert Queen and Desert Peak areas, Nevada (Coolbaugh et al., 2007a), Tungsten Mountain (Kratt et al., 2008), Redlich, Nevada (Kratt et al., 2009), and west of Hawthorne (Kratt et al., 2010). These successes are almost entirely due to the portability and efficiency of the technique, which enable its deployment with minimal cost and time constraints in a reconnaissance, grass-roots setting.

The success obtained in the Great Basin using these methods is due in part to the convergence of favorable climatic and hydrologic factors. The dry, desert environment minimizes the opportunity for shallow cold meteoric groundwater recharge to disguise underlying geothermal heat flux rising from deeper, thermal aquifers. New geothermal discoveries are being made in the Great Basin because many geothermal systems in the Great Basin are blind or concealed, in the sense that hot springs or steam vents are commonly not present above thermal aquifers, because deep water tables and/or impermeable near-surface cap rocks, such as clay-rich sediments in playas, can prevent thermal waters from reaching the surface. In fact, the large number of new thermal groundwater discoveries being made with shallow temperature surveys helps corroborate previous estimates of undiscovered geothermal resources in the Great Basin (e.g., Coolbaugh et al., 2007b; Williams et al. (2009).

Another reason the technique works well for finding blind geothermal systems in the Great Basin is that, even where hot springs are not present, it is common for upwelling thermal fluids to rise in structurally controlled upwelling zones until they reach the top of the water table, at which point they typically flow laterally down the hydrologic gradient at relatively shallow depths, providing the opportunity for heat conduction to transport a thermal signature to the near-surface environment unimpeded by intervening shallow, cold, groundwater. Interestingly, in the Great Basin there are also examples of where steam-heated ground above boiling thermal waters fails to produce visually obvious fumarolic features, but shallow temperatures can nevertheless be elevated and shallow temperature surveys can rapidly identify such features.

Shallow temperature surveys are not expected to be as effective in wet climates where high rates of precipitation-related cold water recharge into shallow groundwater aquifers can muffle or disguise geothermal heat flux from deeper sources. Evidence of this has been seen in Nevada where thermal groundwater plumes have been traced with shallow temperature surveys from range-bounding faults at the upper margins of valleys downward to the margin of water-saturated playas, where the anomalies disappear, presumably due to the cloaking effects of shallow, near-surface cold groundwater. Examples include the southwestern Smoke Creek Desert (Coolbaugh et al., 2006), the Desert Queen area (Coolbaugh et al., 2007; Sladek et al., 2007), Columbus Marsh (Kratt et al., 2009) and probably Tungsten Mountain (Kratt et al., 2008) and Emerson Pass (Kratt et al., 2010).

Data Processing Methodologies

Two-meter temperature surveys can detect geothermal anomalies with a much stronger signal-to-noise signature than surface temperature surveys (e.g., thermal infrared surveys), because background temperatures at a 2-meter depth fluctuate much less than temperatures at the ground surface. The diel (24-hour) temperature cycle induced at the earth's surface by episodic solar heating and nighttime cooling is almost completely damped out at a depth of 1 meter (Elachi, 1987). Nevertheless, background temperatures at a 2-meter depth are influenced by a variety of non-geothermal-related factors which, if not accounted for, can disguise or distort the ability to detect geothermal heat contributions. These non-geothermal influences include seasonal temperature variations, which penetrate to depths of up to 20 meters (Lange et al., 1982; LeSchack and Lewis, 1983). Solar radiation effects also penetrate easily to 2 meters. Solar radiation heat input variations are caused by surface variations in surface albedo, topographic slope aspect, ground cover, evapotranspiration, and other factors. Thermal diffusivities of near-surface soils and rocks can also cause temperature anomalies at a depth of 2 meters, because thermal diffusivities govern the rate at which seasonal changes in temperatures at the earth's surface propagate downward into soils and bedrock.

A number of approaches have been developed for quantifying and modeling sources of ambient, "background" temperature variations at shallow depths of 1-3 meters. Trexler et al. (1982) employed a simple linear correction to account for seasonal temperature variations over the time-period of an individual temperature survey, which becomes important when such a survey takes weeks or months to complete (see also Coolbaugh et al., 2007a). LeSchack and Lewis (1983) provide an example of correcting 2-meter temperatures for the effects of topographic elevation using a linear adiabatic lapse rate (linearly decreasing temperatures with elevation). LeSchack and Lewis (1983) also provide an example of generating a climatological model based on seasonal weather parameters to model background temperatures. Two important influences on 2-meter temperatures are 1) surface albedo (and by analogy topographic slope), and 2) thermal diffusivities. Methods of correcting 2-meter temperatures for these effects are discussed in more detail below.

Albedo and Topographic Slope Aspect

When shallow temperature surveys cover relatively level ground with minimal changes in elevation, vegetation density, and soil moisture content, albedo can be one of the more important factors influencing 2-meter temperatures. Ingebritsen and Olmsted (1986) found that under such conditions, albedo was the dominant predictive factor for influencing 2-meter temperatures (in the absence of geothermal activity) for the Upsal Hogback geothermal area, Nevada, as documented by a linear least squares correlation (R^2) of 0.75. Similarly, we obtained a linear least squares correlation of 0.75 for background (from non-geothermal areas) 2-meter temperatures around the margins of Columbus Marsh valley (Figure 1, Sladek et al., 2009), and we have noted similarly strong influences in a number of other valleys in the Great Basin.

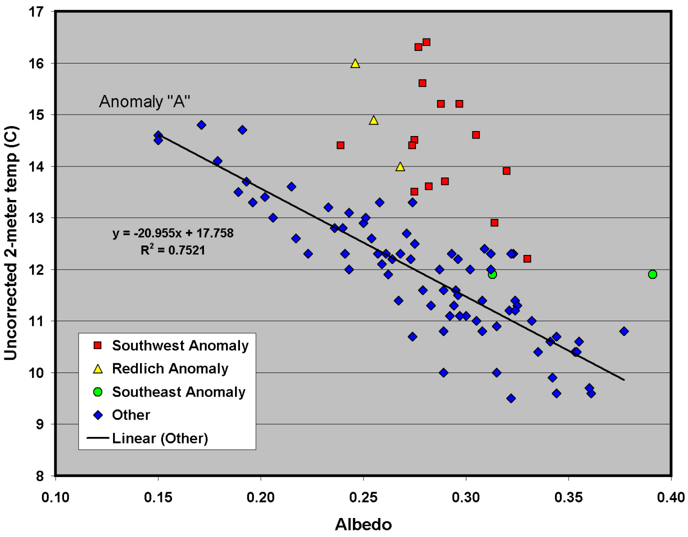

Figure 1. Correlation observed between surface albedo, as determined from ASTER satellite imagery, and temperatures at a depth of 2 meters, from the Columbus Marsh area, Nevada. Blue points are background temperatures and yellow and red points are from anomalous areas related to geothermal activity. Figure taken from Sladek et al. (2009).

In the Columbus Marsh example (Sladek et al., 2009), ASTER satellite imagery was used to rapidly determine ground albedo at each of the 2-meter temperature probe sites. To optimize the accuracy of the albedo estimate, the ASTER imagery is custom-registered to the specific area of interest using local ground control points from GPS units or from accurately registered digital topographic maps. Field testing with a field spectroradiometer was used to verify that the ASTER Level 07XT (cross-talk and atmospherically corrected imagery) was scaled correctly to actual albedo measurements measured on the ground. A potential advantage of using ASTER imagery is that the 15-meter pixel resolution of visible-light imagery results in an average albedo calculated over an area that often includes vegetation (such as salt brush or sagebrush) as well as bare ground. In those cases where shrubs are spaced within a meter or two apart from each other, a spatially averaged albedo can provide a more representative estimate of ground albedo that influences temperatures at a 2-meter depth, assuming that density variations in vegetative cover with distance are not great.

Topographic slope aspect can have a similarly large influence on 2-meter temperatures, because slopes that more directly face the sun during the middle of the day receive more solar energy than slopes facing away from the sun. Most of our temperature surveys completed to date have been conducted over relatively even ground, but a new test survey is in progress which will evaluate, model, and compensate for the effects of slope aspects in hilly terrain.

Thermal Diffusivity

Soils and rocks with differing thermal diffusivities transfer heat at different rates. Thus, seasonal temperature variations at the earth's surface are transmitted into the subsurface at rates that depend on the thermal diffusivity (winter temperature minima is experienced sooner at a 2-meter depth if the overlying rock and soil is relatively highly thermally diffusive). Deviations from average annual temperatures as a function of depth and thermal diffusivity can be modeled with an exponential decay function with a sinusoidal wave function with a surface periodicity of one year (Lange et al., 1982):

$$Ts = Ta\, e^{-mz} \cos(\omega\Delta t - mz) \qquad (1)$$

where:

Ts = seasonal temperature deviation from mean temperature.
Ta = surface seasonal temperature amplitude
$m = (\pi/\tau\ \alpha)^{0.5}$
τ = wave period (one year)
α = thermal diffusivity (= thermal conductivity/volumetric specific heat)
z = depth below surface
$\omega = 2\pi/\tau$
Δt = time elapsed since surface summer temperature peak

Under adverse field conditions, where thermal diffusivities vary from one portion of a survey area to another over a maximum range that includes contrasting areas of soil and bedrock, and when the survey is conducted near the time of peak summer surface temperatures or near minimum winter surface temperatures, temperature differences at a depth of 2 meters are predicted to be as great as 7°C (Figure 2). One approach for minimizing the effects of thermal diffusivities in areas where they are likely to present difficulties, is to conduct shallow temperature surveys during the late spring or late fall, because the polarity of the diffusivity temperature difference switches polarity from winter to summer (Figure 3).

Methods of estimating thermal diffusivities include:

1) measuring a detailed vertical temperature profile from surface to depth at a specific period of time to determine the depth of the local temperature maxima (or minima) (Lange et al., 1982), which is a function of thermal diffusivity,
2) measuring the annual temperature amplitude at a specific depth (employed herein),
3) direct field measurements using transient heating techniques in current 2-meter probes (under development herein),

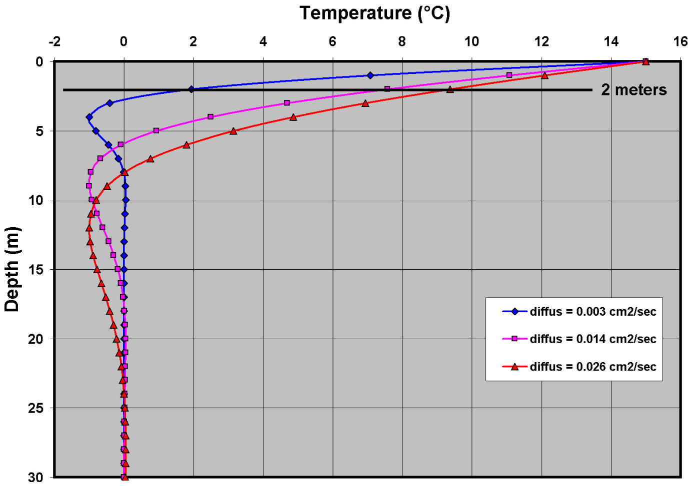

Figure 2. Temperature deviations from average annual temperatures as a function of depth for three different thermal diffusivities (a maximum range of thermal diffusivities for soils and rocks presented in Sabin (1978) at the time of maximum surface summer temperatures, and assuming an annual surface temperature amplitude of 30°C. At the time of peak summer surface temperatures, temperature differences related to thermal diffusivity at a depth of 2 meters could be as muchy as 7°C.

4) measuring the lag time between maximum or minimum surface temperatures and maximum or minimum temperatures at a specified depth (LeSchack and Lewis, 1983).

Each of these methods has its drawbacks or challenges. These include the need for multiple measurements over the course of a year (methods 2 and 4), measurements at depths greater than 2 meters (method 1), or assumptions of representativeness with depth (method 3).

Instrumentation is being developed at the GBCGE to employ transient heating and decay methodology such as that described by deVers (1952) and Shiozawa and Campbell (1990) for measuring thermal diffusivity. Despite the high thermal mass of the current 2-meter probe design, laboratory testing has shown that thermal diffusivity measurements can be made by inserting a heater and thermocouple assembly in the current 2-meter probe. After calibration with materials of known thermal diffusivities, these instruments should provide the sensitivity needed for reasonably accurate measurements of unconsolidated sediments (Figure 4). This instrumentation will be deployed in a field test survey in the summer and fall of 2010.

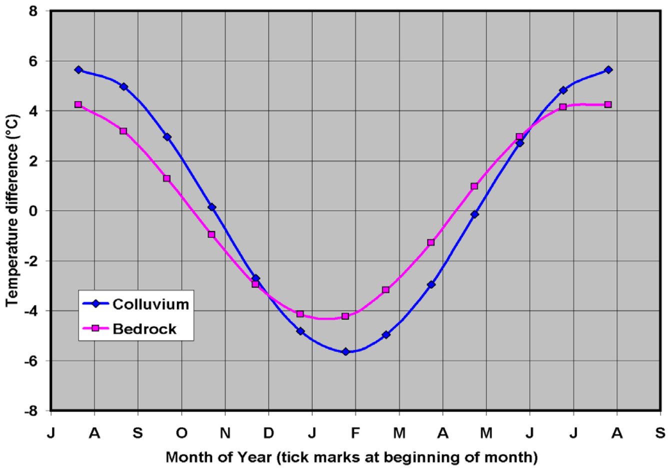

Figure 3. Temperature differences observed at a depth of 2 meters produced by soils (blue line) and rocks (magenta line) with contrasting thermal diffusivities, based on ranges of thermal diffusivities published in Sabin (1978). Temperature differences are minimized during the late spring and late fall, when temperature differences change polarity between winter and summer.

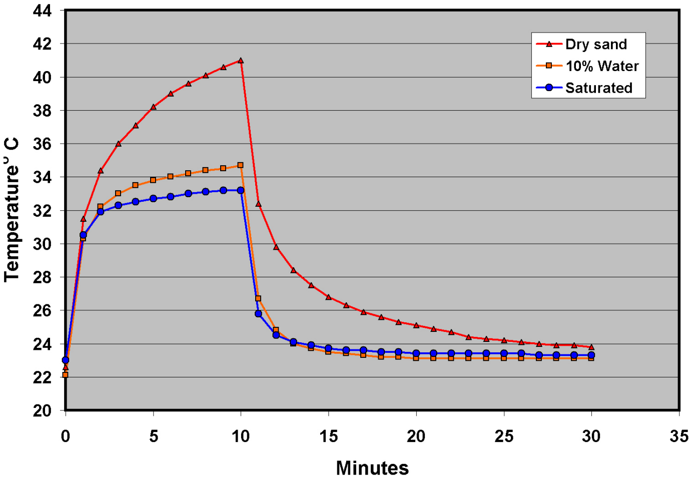

Figure 4. Heating and decay rates of an RTD temperature device inserted in a hollow steel probe of the type typically used in shallow temperature surveys by the GBCGE (Coolbaugh et al., 2007a; Sladek et al., 2007). For each curve, the probe has been surrounded with sand with differing amounts of water to mimic a range of thermal diffusivities. After calibration with materials with a range of known thermal diffusivities likely to be encountered in the field, this device should be operational.

In the meantime, a preliminary assessment of thermal diffusivity effects has been made at the Desert Queen area, where a pilot shallow temperature survey was completed in 2006 (Coolbaugh et al., 2007a; Sladek et al., 2007). This survey demonstrated the ability of modified shallow temperature equipment of the GBCGE to detect the presence of a geothermal aquifer, which was known to lie at a depth of roughly 70 meters below surface. Six locations in the field survey area (Figure 5) were selected to represent both background and geothermal areas, and temperature measurements were made at these locations over a one-year period. Method (3) above was then used to estimate thermal diffusivities at each location. This is made possible by differentiating equation (1) with respect to depth z. The resulting equation can be used to solve for thermal diffusivity if the magnitude of the annual temperature variation is known (Figure 6) at the given location at a depth of 2 meters and at a depth of 0 meters (ground surface).

For these six test locations, thermal diffusivities are estimated to range from a low of 0.004 cm^2/sec to a high of 0.008 cm^2/sec (Figure 7). The differences in temperatures (“false anomalies”) that could be caused by these thermal diffusivity variations are not greater than approximately 2°C if measured near the maximum or minimum points in the temperature cycle (2°C is roughly twice the temperature deviation measured between the two green curves, which represent one-half of the thermal diffusivity variation observed among the six samples). In the

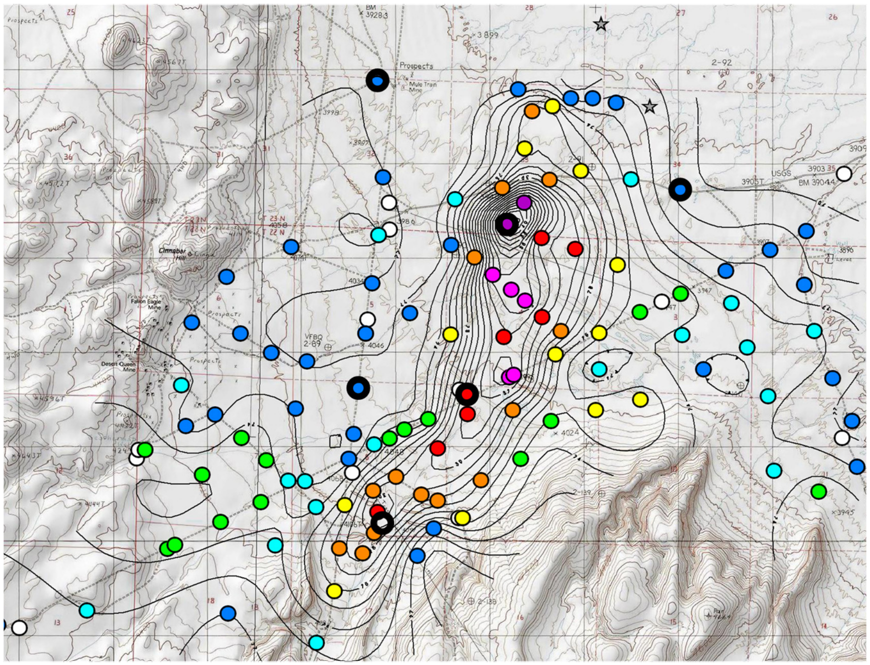

Figure 5. Shallow (2-meter) temperature anomaly of the Desert Queen area. Heavy black circles mark the locations of one-year temperature measurements used to estimate thermal diffusivities. All probes were placed into variably rocky, sandy, or silty soils. Warmer colors represent progressively warmer 2-meter temperatures, and black contour lines have divisions of 1°C. Black squares in background are 1 km on a side. North is up. Figure adapted from Coolbaugh et al. (2007a).

case of this particular survey, the magnitude of the temperature anomaly produced by geothermal heat flux (warmer colors) is of significantly greater magnitude than the effects produced by thermal diffusivity differences. The maximum difference between geothermally heated temperatures and background temperatures is approximately 24°C. Furthermore, because this survey was completed during October and November, the actual temperature differences produced by thermal diffusivity variations are likely to be less than indicated. The same is not true for all survey areas, however, and we have encountered more significant temperature variations likely caused by thermal diffusivity at other areas, as has been documented for an area in California by Lange et al. (1982) and by LeSchack et al. (1983) for the Upsal Hogback area, Nevada. Thus, it is important to be cognizant of where and when thermal diffusivities are likely to be important, and what their magnitudes are likely to be. Moisture content is most significant determining factor for thermal diffusivities, and significant contrasts in thermal diffusivities can be expected if temperature measurements in solid rock are compared to measurements in unconsolidated sediments.

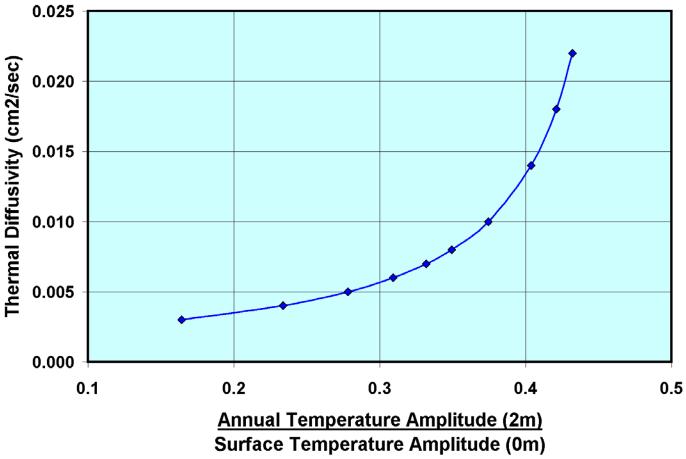

Figure 6. Thermal diffusivity can be calculated for a given depth if the magnitude of the annual temperature amplitude is known both at the given depth and at the ground surface (see text for details).

Conclusions

The ability to correct 2-meter survey results for the effects of albedo, thermal diffusivity, and other external variables, can significantly improve the accuracy of mapping geothermal heat flux with shallow temperature surveys, especially when the magnitude of the temperature anomalies is not great. Albedo can be estimated with the help of remote sensing data. A variety of approaches can be used to estimate thermal diffusivities, but it is anticipated that the deployment of transient sensors to directly measure thermal diffusivities using the same 2-meter probe used for temperature measurements may provide the most time-effective means of doing so.

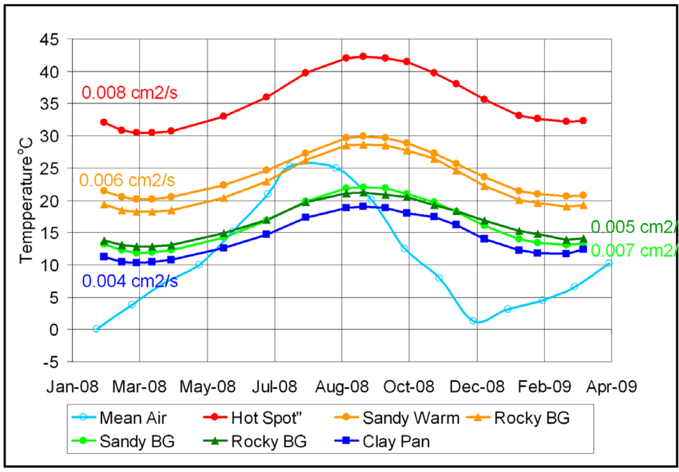

Figure 7. Thermal diffusivities and the annual temperature curve measured at two-meter depth for each of six selected sites at the Desert Queen survey area. Thermal diffusivities ranged from a low of 0.004 cm^2/sec to a high of 0.008 cm^2/sec. The highest diffusivity was measured in an area of compact, semi-lithified soils, whereas the lowest diffusivity was measured in an area of moist sediments at a low elevation near a playa. In this example, temperature anomalies caused by geothermal heat flux (warmer colors) significantly out-weigh relatively minor temperature variations produced by differences in thermal diffusivities. Figure adapted from Sladek et al. (2009).

Acknowledgements

This project was made possible by a research grant from the Nevada Renewable Energy Center, as managed by the Desert Research Institute. We gratefully acknowledge Lisa Shevenell, past director of the GBCGE, and Wendy Calvin, current director of the GBCGE, whose support and encouragement made this project possible.

References

Coolbaugh M. F., Faulds, J. E., Kratt, C., Oppliger, G. L., Shevenell, L., Calvin, W., Ehni, W. J., and Zehner, R. E., 2006, Geothermal potential of the Pyramid Lake Paiute Reservation, Nevada, USA: evidence of previously unrecognized moderate-temperature (150-170ºC) geothermal systems: Geothermal Resources Council Transactions, v. 30, p. 59-67.

Coolbaugh, M.F., Sladek, C., Faulds, J.E., Zehner, R.E., and Oppliger, G.L., 2007a, Use of rapid temperature measurements at a 2-meter depth to augment deeper temperature gradient drilling: Proceedings, 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan. 22-24, 2007, p. 109-116.

Coolbaugh, M.F., Raines, G.L., and Zehner, R.E., 2007b, Assessment of exploration bias in data-driven predictive models and the estimation of undiscovered resources: Natural Resources Research, v. 16, n. 2, p. 199-207.

De Vries, D.A., 1952, A non-stationary method for determining thermal conductivity of soil in situ: Soil Science, v. 73, p. 83-89.

Elachi, C., 1987, *Introduction to the Physics and Techniques of Remote Sensing*: John Wiley and Sons, New York, 413 p.

Kratt, C., Coolbaugh, M. F., Sladek, C., Zehner, R., Penfield, R., and Delwiche, B., 2008, A new gold pan for the west: discovering blind geothermal systems with shallow temperature surveys: Geothermal Resources Council Transactions, v. 32, p. 153-157.

Kratt, C., Coolbaugh, M. F., Peppin, B., and Sladek, S., 2009, Identification of a new blind geothermal system with hyperspectral remote sensing and shallow temperature measurements at Columbus Salt Marsh, Esmeralda County, Nevada: Geothermal Resources Council Transactions, v. 33, p. 481-485.

Kratt, C., Sladek, C., and Coolbaugh, M., 2010, Boom and bust with the latest two-meter temperature surveys: Dead Horse Wells, Hawthorne Army Depot, Terraced Hills and other areas in Nevada: Geothermal Resources Council Transactions, v. 34, this volume.

Lange, A.L., Pilkington, H.D., and Deymonaz, J., 1982, Comparative studies of geothermal surveys in 3-meter and temperature-gradient holes: Geothermal Resources Council Transactions, v. 6, p. 133-136.

LeSchack, L.A. and Lewis, J.E., 1983, Geothermal prospecting with Shallo-Temp surveys: *Geophysics*, v. 48, n. 7, p. 975-996.

Olmsted, F.H., 1977, Use of temperature surveys at a depth of 1 meter in geothermal exploration in Nevada: United States Geological Survey Professional Paper 1044-B, 25 p.

Olmsted, F.H. and Ingebritsen, S.E., 1986, Shallow subsurface temperature surveys in the Basin and Range Province – II. Ground temperatures in the Upsal Hogback geothermal area, west-central Nevada, USA: Geothermics, v. 15, n. 3, p. 267-275.

Sabin, F.F. Jr., 1978, Remote Sensing Principles and Interpretation: W.H. Freeman and Company, San Francisco, 426 p.

Shiozawa, S. and Campbell, G.S., 1990, Soil thermal conductivity: Remote Sensing Review, v. 5, p. 301-310.

Sladek, C., Coolbaugh, M. F., and Zehner, R. E., 2007, Development of 2-meter soil temperature probes and results of temperature survey conducted at Desert Peak, Nevada, USA: Geothermal Resources Council Transactions, v. 31, p. 363-368.

Sladek, C., Coolbaugh, M., and Kratt, C., 2009, Improvements in shallow (two-meter) temperature measurements and data interpretation: Geothermal Resources Council Transactions, v. 33, p. 535-541.

Trexler, D.T., Koenig, B.A., Flynn, T., Bruce, J.L., and Ghusn, G., Jr., 1981, Low-to-moderate-temperature geothermal resource assessment for Nevada: area specific studies, Hawthorne, Paradise Valley, and southern Carson Sink: United States Department of Energy Geothermal Energy Report DOE/NV/10039-3 (DE81030487), 203 p.

Trexler, D.T., Koenig, B.A., Ghusn, G. Jr., Flynn, T., and Bell, E.J., 1982, Low-to-moderate-temperature geothermal resource assessment for Nevada: area specific studies, Pumpernickel Valley, Carlin and Moana: United States Department of Energy Geothermal Energy Report DOE/NV/10220-1 (DE82018598), 177 p.

Williams, C.F., Reed, M.J., DeAngelo, J., and Galanis, S.P. Jr., 2009, Quantifying the undiscovered geothermal resources of the United States: Geothermal Resources Council Transactions, v. 33, p. 995-1002.