Shallow Temperature Surveys for Geothermal Exploration in the Great Basin, USA, and Estimation of Shallow Aquifer Heat Loss

Mark Coolbaugh¹, Chris Sladek², Richard Zehner³, and Chris Kratt⁴

¹Great Basin Center for Geothermal Energy, UNR, Reno, NV
²Dept. of Geological Sciences & Engineering, UNR, Reno, NV
³Geothermal Development Associates, Reno, NV
⁴Zonge Geoscience Inc., Reno, NV
sereno@dimcom.net • csladek@unr.edu • rzhener@gdareno.com
christopher.kratt@gmail.com

Keywords
Blackwell, heat loss, heat flux, heat, flux, loss, shallow, temperature, survey, aquifer

ABSTRACT

Temperature gradient and free-well temperature surveys, championed by David Blackwell, have been responsible for a significant number of blind geothermal discoveries in the Great Basin of the western USA. Because of cost and permitting issues, it is not always possible to drill temperature gradient wells in the early stages of green-fields exploration. Other temperature survey methods help fill in the gap, including shallow temperature surveys (typically to depths of 1-2 meters) and Geoprobes (to depths of up to 30 meters). Significant progress has been made in the development and improvement of these more reconnaissance-oriented surveys, which have contributed to the discovery of more than a half-dozen previously unknown geothermal systems in the Great Basin in the last six years.

Temperature surveys play a particularly important role in the Great Basin, where few upper crustal magmatic sources of heat exist, and no a priori assumptions can be made about the availability of adequate temperatures at economical reservoir depths. The dry desert of the Great Basin is especially favorable for temperature surveys. Low precipitation rates reduce interference from shallow cold groundwater, which can disguise deeper-seated heat signatures. Just as important, the dry clastic sediments and soils that cover the surface of many basins have low thermal conductivities, which accentuates the near-surface temperature gradient, making it easier to detect thermal anomalies with shallow (2-meter) temperature measurements. In this environment, conductive heat released from thermal aquifers at depths of 50-100 meters commonly generate strong 2-meter temperature anomalies (8+°C), and thermal modeling indicates that significant anomalies (4°C) can be generated from 100°C aquifers located at depths of up to 200 meters. More subtle anomalies near the threshold of detection (2°C) may be detected under ideal circumstances from the conductive heat released from reservoirs ≥1 km in depth.

Moderate temperature, relatively shallow geothermal reservoirs, such as those being exploited at the Campbell (Wild Rose) and Salt Wells, NV geothermal power plants, are easily detected with 2-meter temperature surveys.

Shallow temperature data can also be used to estimate geothermal heat loss, by converting temperature anomaly values (2-meter temperature in anomalous area minus background 2-meter temperature) into equivalent mean temperature gradients and multiplying by thermal conductivities over the areas involved. In spite of the fact that temperature gradients at a depth of 2 meters vary continuously over the course of a year in response to seasonal changes in surface temperatures, mean annual temperature gradient can be estimated using a single set of temperature data obtained at one time of the year, if background temperatures at 2 meters are also measured and if thermal diffusivities are reasonably constant throughout the survey area. This is possible because the magnitude of a 2-meter temperature anomaly at an individual point is relatively constant with time, and because a predictable linear relationship exists between the 2-meter temperature anomaly and the associated mean annual temperature gradient. With knowledge of the shallow thermal conductivity, heat loss can then be calculated.

Because of the limited depth sensitivity, estimates of heat loss from 2-meter temperature measurements are more closely tied to near-surface fluid convection rates than similar estimates from deeper temperature gradient wells. In combination with heat loss from thermal springs (where present), shallow aquifer heat loss can provide an estimate of the natural convective heat transport rate to the near-surface environment, which carries implications for minimum geothermal power production. Estimates of heat loss from shallow thermal aquifers associated with geothermal systems in the Great Basin range up to 20 MWt, which is of similar magnitude to the production rate at many Great Basin geothermal power plants.

Introduction

Temperature gradient drilling and measurement of temperatures in “free wells” (wells drilled for purposes other than
geothermal exploration, including water wells, oil wells, and mineral exploration holes) have played key roles in the discovery of many blind geothermal systems in the Great Basin of the western United States. Blind systems identified with the help of temperature gradient drilling include Adobe Valley, Alum, Black Warrior, Desert Peak, Carson Lake, Desert Peak, Desert Queen, Eleven Mile Canyon, Fireball Ridge, Gabbs Valley, Granite Springs, McCoy, Pirouette Mountain, Rye Patch, Salt Wells, and Upsal Hogback. Blind systems identified with other types of drilling, and with subsequent down-hole temperature measurements in these holes, include Reese River (uranium exploration), Fish Lake Valley and Stillwater (oil exploration), Emigrant Pass (borate exploration), Blue Mountain, McGimness Hills, and Tungsten Mountain (gold exploration), and Silver Springs and Corner Canyon (water well drilling).

Because of expense and permitting issues, it is not always cost effective or convenient to conduct temperature gradient drilling during the early stages of geothermal exploration, and free wells are not everywhere present. Two-meter temperature surveys and Geoprobe surveys have helped fill in the gap to provide rapidly deployable and economical temperature surveys during greenfields exploration. When temperature anomalies are found, they can provide justification for more detailed exploration, including temperature gradient drilling.

Shallow temperature surveys have been used for decades to map thermal anomalies associated with geothermal activity (Olmsted, 1977; Trexler et al., 1981, 1982; Lange et al., 1982, LeSchack and Lewis, 1983; Olmsted and Ingebritsen, 1986). Recently, significant improvements have been made to 2-meter equipment and methodologies; these improvements include the use of all-terrain-vehicles (ATVs), digital platinum resistance temperature devices (RTDs), electric hammers powered by portable generators, and tungsten-carbide-tipped hollow steel probes (Coolbaugh et al., 2007; Sladek et al., 2007). Addition of portable drills by Sladek et al. (2009) and by Glenn Melosh and Max Wilmarth for Geoglobal Energy LLC has expanded application of the method into areas of bedrock.

These improvements in efficiency have enabled 2-meter temperature surveys to be moved from a project setting into an early stage greenfield exploration setting, and this has resulted in the surveys playing key roles in the discovery of a number of previously unknown geothermal systems. These include Teels Marsh, Rhodes Marsh, and southwest Columbus Marsh in Mineral and Esmeralda Counties, NV (Krat et al., 2008, 2009; Coolbaugh et al., 2013), East Hawthorne, Mineral County, NV (Krat et al., 2010), Emerson Pass, Washoe County, NV (Krat et al., 2010; Shevenell et al., 2014), and at least two other areas identified by private companies whose data remain confidential.

As an intermediate step between 2-meter temperature surveys and temperature gradient wells, Zehner et al. (2012) have recently demonstrated the efficient use of Geoprosbes to measure vertical temperature profiles and obtain water samples to depths of over 30 meters. While the technology requires medium-sized trucks, no drilling is required and the surveys can be completed much more rapidly and economically than temperature gradient drilling. The method was used effectively to validate 2-meter temperature anomalies at a blind geothermal system in Teels Marsh by intercepting (and sampling) near-boiling thermal waters at a depth of 36 meters (Zehner et al., 2012). Since no drilling is required, water samples obtained with this method are not contaminated with drilling fluids.

The remainder of this paper describes a method for estimating heat loss associated with shallow thermal aquifers, and discusses depths to which thermal aquifers can be detected with 2-meter temperature surveys.

**Heat Loss Estimates**

Calculation of heat loss associated with shallow temperature anomalies is one manner of providing a scale factor or index to quantify the size and significance of a thermal anomaly. Similar heat loss calculations based on deeper temperature gradient wells have been used to provide broad constraints on rates of geothermal power sustainability (Wissian et al., 2001; Richards and Blackwell, 2002). Because 2-meter temperature surveys as currently deployed usually lack the sensitivity for easily detecting the conductive heat signature of deeper geothermal reservoirs (>1 km depth), anomaly detection typically requires the presence of shallow thermal aquifers or steam-heated zones that can generate the relatively high near-surface temperature gradients required for detection (approximately 1°C/meter), given current 2-meter technology and ambient noise levels. Assuming a stable temperature configuration with time, heat lost through conduction from a shallow thermal aquifer must be replaced or sustained with incoming heat from convecting fluids rising from depth. In such circumstances, the conductive heat loss measured from a shallow aquifer provides a minimum constraint on the rate of heat convection from depth. The estimates are considered minimum constraints because heat is also dissipated through mixing with cold shallow groundwater, and overlying zones of cold shallow groundwater commonly conceal the full extent of thermal aquifers.

Estimation of heat loss from shallow temperature measurements offers challenges compared to similar calculations from deeper wells because, unlike deeper wells, temperatures at depths of 2 meters are not constant with time. Due to seasonal heating and cooling at the ground surface, temperatures are continuously changing in the subsurface to depths of up to 20 meters (Lange et al., 1982; LeSchack and Lewis, 1983), and the temperature gradient is therefore also changing (Fig. 1). This means that shallow temperature gradients measured at any point in time are generally not representative of long-term averages. Furthermore, whenever temperatures are changing at a given depth, heat is also being either stored or extracted from the rock and/or soil. In these circumstances, heat flow calculated at greater depths where temperatures are constant will not equal shallow heat flow unless heat storage terms are included in the equations. These difficulties can be addressed if mean temperature gradients can be calculated over the course of a year to account for the annual solar heating/cooling cycle, and if it can be assumed that near-surface ground temperatures are the same at the beginning and end of the year (so that heat storage terms sum to zero). In a related companion analysis completed last year (Coolbaugh and Sladek, 2013), multiple measurements over a year were used to document the cyclic variation of 2-meter temperature gradients, calculate thermal diffusivities, and ultimately, calculate mean annual heat loss.
In the current paper, a procedure is presented whereby mean long-term heat loss can be approximated using a single set of 2-meter temperature data without the need for multiple measurements over time. Evidence that this is possible is provided by the observation that the magnitude and size of most 2-meter temperature anomalies are remarkably similar throughout a year, in spite of the fact that absolute temperatures progressively change from winter to summer (LeSchack and Lewis, 1983; Sladek et al., 2009). Crews at the Great Basin Center for Geothermal Energy, and some private companies, have run such surveys in northern Nevada during all seasons without concerns that the size and magnitude will be overly affected by seasonal influences (exceptions may occur after periods of heavy precipitation or other significant episodic groundwater events). This general observation is verified quantitatively in Fig. 2, which illustrates the seasonal variation of 2-meter temperatures at selected locations in the Desert Queen geothermal area. The anomaly magnitudes, as measured by the difference in temperature between anomaly and background (dashed lines), vary only 6% on average, relative to the mean anomaly over the year (Table 1), in spite of the fact that actual 2-meter temperatures vary considerably over the same time period (Fig. 2) as a result of seasonal surface temperature variations.

If a relationship can be defined between the relatively constant 2-meter temperature anomaly (dashed lines shown in Fig. 2) and the mean annual temperature gradient at a depth of 2 meters, it would be possible to estimate mean annual heat flux. Such a relationship was derived at the Desert Peak geothermal area, NV (Fig. 3), whereby mean long-term heat loss can be approximated using a single set of 2-meter temperature data without the need for multiple measurements over time. Evidence that this is possible is provided by the observation that the magnitude and size of most 2-meter temperature anomalies are remarkably similar throughout a year, in spite of the fact that absolute temperatures progressively change from winter to summer (LeSchack and Lewis, 1983; Sladek et al., 2009). Crews at the Great Basin Center for Geothermal Energy, and some private companies, have run such surveys in northern Nevada during all seasons without concerns that the size and magnitude will be overly affected by seasonal influences (exceptions may occur after periods of heavy precipitation or other significant episodic groundwater events). This general observation is verified quantitatively in Fig. 2, which illustrates the seasonal variation of 2-meter temperatures at selected locations in the Desert Queen geothermal area. The anomaly magnitudes, as measured by the difference in temperature between anomaly and background (dashed lines), vary only 6% on average, relative to the mean anomaly over the year (Table 1), in spite of the fact that actual 2-meter temperatures vary considerably over the same time period (Fig. 2) as a result of seasonal surface temperature variations.

If a relationship can be defined between the relatively constant 2-meter temperature anomaly (dashed lines shown in Fig. 2) and the mean annual temperature gradient at a depth of 2 meters, it would be possible to estimate mean annual heat flux. Such a relationship was derived at the Desert Peak geothermal area, NV (Fig. 3),

![Figure 1. Temperature gradient as a function of time at 1.75 meter depth for two stations in the Desert Peak area. Station 12E (upper red curve, diamonds) is within a stronger portion of the shallow temperature anomaly and has a calculated mean annual heat flux of 2,300 mW/m², but still experiences negative temperature gradients for a short period in the summer. Station 14L (lower blue curve, triangles) is from a weaker portion of the shallow temperature anomaly and has a calculated mean annual heat flux of 510 mW/m². Temperature gradients at station 14L are negative for significant portions of the year, but positive gradients clearly outweigh negative gradients. Figure taken from Coolbaugh and Sladek (2013).](image1)

![Figure 2. Annual temperatures at a depth of 2 meters from the Desert Queen geothermal area, Churchill County, NV. Solid blue curves represent background temperatures within the piedmont where the temperature anomaly occurs, whereas the solid black line represents cooler temperatures adjacent to a playa (not used for background calculations). Solid red, orange, and green lines come from thermally anomalous areas. Dashed lines represent the difference between anomalous 2-meter temperatures and average background temperatures throughout the year for the red, orange, and green stations. For instance, the red solid line minus the average of the two blue lines results in the red dashed line. Note that the temperature anomalies (dashed lines) remain nearly constant throughout the year while the absolute temperatures change seasonally. Figure adapted from Sladek et al. (2009).](image2)

### Table 1. Percent errors associated with substituting the temperature anomaly (anomalous temperature minus background) measured at one point in time for the mean anomaly value for the same station. The three stations are the same as those depicted with the dashed lines in Fig. 2 for the Dixie Queen area.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station °C Ave</th>
<th>Station °C Ave</th>
<th>Station °C Ave</th>
<th>Station °C Ave</th>
<th>Absolute % Difference RockyWm minus Bckgrnd</th>
<th>Absolute % Difference SandyWm minus Bckgrnd</th>
<th>Absolute % Difference Hot Spot minus Bckgrnd</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-Jan-08</td>
<td>13.4</td>
<td>19.4</td>
<td>21.4</td>
<td>32.0</td>
<td>3.9</td>
<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td>16-Feb-08</td>
<td>12.6</td>
<td>18.5</td>
<td>20.5</td>
<td>30.8</td>
<td>5.5</td>
<td>2.5</td>
<td>5.4</td>
</tr>
<tr>
<td>29-Feb-08</td>
<td>12.3</td>
<td>18.2</td>
<td>20.2</td>
<td>30.4</td>
<td>5.6</td>
<td>2.5</td>
<td>5.9</td>
</tr>
<tr>
<td>14-Mar-08</td>
<td>12.4</td>
<td>18.2</td>
<td>20.2</td>
<td>30.4</td>
<td>6.8</td>
<td>0.9</td>
<td>6.3</td>
</tr>
<tr>
<td>31-Mar-08</td>
<td>12.7</td>
<td>18.5</td>
<td>20.5</td>
<td>30.7</td>
<td>6.4</td>
<td>1.8</td>
<td>6.1</td>
</tr>
<tr>
<td>17-May-08</td>
<td>14.6</td>
<td>20.4</td>
<td>22.4</td>
<td>33.0</td>
<td>6.3</td>
<td>1.8</td>
<td>4.1</td>
</tr>
<tr>
<td>24-Jun-08</td>
<td>16.9</td>
<td>22.9</td>
<td>24.6</td>
<td>36.0</td>
<td>3.0</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>29-Jul-08</td>
<td>19.8</td>
<td>26.3</td>
<td>27.3</td>
<td>39.7</td>
<td>5.2</td>
<td>2.0</td>
<td>3.7</td>
</tr>
<tr>
<td>3-Sep-08</td>
<td>21.5</td>
<td>28.5</td>
<td>29.7</td>
<td>42.1</td>
<td>13.4</td>
<td>7.1</td>
<td>7.3</td>
</tr>
<tr>
<td>18-Sep-08</td>
<td>21.6</td>
<td>28.7</td>
<td>29.9</td>
<td>42.3</td>
<td>14.2</td>
<td>7.8</td>
<td>7.5</td>
</tr>
<tr>
<td>8-Oct-08</td>
<td>21.4</td>
<td>28.6</td>
<td>29.7</td>
<td>42.0</td>
<td>16.7</td>
<td>8.5</td>
<td>7.4</td>
</tr>
<tr>
<td>27-Oct-08</td>
<td>20.7</td>
<td>27.7</td>
<td>28.9</td>
<td>41.5</td>
<td>12.5</td>
<td>6.5</td>
<td>8.2</td>
</tr>
<tr>
<td>20-Nov-08</td>
<td>19.5</td>
<td>26.4</td>
<td>27.3</td>
<td>39.7</td>
<td>12.1</td>
<td>1.3</td>
<td>5.1</td>
</tr>
<tr>
<td>4-Dec-08</td>
<td>18.8</td>
<td>25.5</td>
<td>26.5</td>
<td>38.4</td>
<td>8.4</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>10-Dec-08</td>
<td>18.3</td>
<td>24.6</td>
<td>25.7</td>
<td>38.0</td>
<td>3.0</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>4-Jan-09</td>
<td>16.4</td>
<td>22.2</td>
<td>23.6</td>
<td>35.6</td>
<td>5.4</td>
<td>6.4</td>
<td>0.1</td>
</tr>
<tr>
<td>4-Feb-09</td>
<td>14.6</td>
<td>20.1</td>
<td>21.5</td>
<td>33.1</td>
<td>11.4</td>
<td>9.9</td>
<td>3.6</td>
</tr>
<tr>
<td>20-Feb-09</td>
<td>14.1</td>
<td>19.6</td>
<td>21.0</td>
<td>32.7</td>
<td>11.5</td>
<td>10.0</td>
<td>3.1</td>
</tr>
<tr>
<td>18-Mar-09</td>
<td>13.5</td>
<td>19.1</td>
<td>20.7</td>
<td>32.2</td>
<td>9.9</td>
<td>6.1</td>
<td>2.6</td>
</tr>
<tr>
<td>2-Apr-09</td>
<td>13.7</td>
<td>19.3</td>
<td>20.8</td>
<td>32.3</td>
<td>9.9</td>
<td>7.4</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>16.4</strong></td>
<td><strong>22.6</strong></td>
<td><strong>24.1</strong></td>
<td><strong>35.7</strong></td>
<td><strong>8.5</strong></td>
<td><strong>4.5</strong></td>
<td><strong>4.4</strong></td>
</tr>
</tbody>
</table>

Average error for the three stations: 5.8%
where temperatures at depths 1.5 and 2.0 m were measured at 5 different times of the year to directly calculate mean temperature gradients, thermal diffusivities, and mean temperatures (Sladek et al., 2012; Coolbaugh and Sladek, 2013). The linear trend line in Fig. 3 is not a best-fit line, but instead is a simplified equation predicting the theoretical relationship between mean annual temperature gradient and the mean annual temperature anomaly at a depth of 2 meters. The equation is derived in the following steps:

\[
(1) \quad g_a = \frac{(T_{2a} - T_{oa})}{z} \\
(2) \quad g_b = \frac{(T_{2b} - T_{ob})}{z} \\
(3) \quad z = 2 \text{ meters}
\]

Where:
- \(g_a\) = mean temperature gradient at an anomalous location A
- \(T_{2a}\) = mean temperature at 2-meter depth at anomalous location A
- \(T_{oa}\) = mean ground surface temperature at anomalous location A
- \(g_b\) = mean temperature gradient at a representative background location
- \(T_{2b}\) = mean temperature at 2-meter depth at background location
- \(T_{ob}\) = mean ground surface temperature at background location
- \(z\) = vertical distance between the surface and subsurface points of measurement

These equations by themselves are not useful for calculating mean temperature gradient because they rely on the determination of mean ground surface temperature. Mean ground surface temperatures are difficult to estimate because surface temperatures, in addition to changing with the seasons, vary widely over the course of a single day; for example, Coolbaugh (2003) documented 24-hour surface temperature variations in the Desert Queen area of more than 50°C. Exacerbating the challenge is the fact that surface temperatures can be challenging to measure because of the rapid change in temperature at the ground-air interface and the tendency of temperature-measuring devices to absorb incoming solar radiation if directly exposed to sunlight. Fortunately, the above equations can be combined together to eliminate the surface temperature terms, if it is assumed that mean surface temperatures at the anomalous location and the background station are equal. After rearrangement, equation (2) is subtracted from equation (1) to obtain:

\[
(4) \quad T_{2a} - T_{2b} = 2(g_a - g_b) + T_{oa} - T_{ob}
\]

After cancellation of the surface temperature terms, and with further rearrangement:

\[
(5) \quad g_a = \frac{(T_{2a} - T_{2b})}{2} + g_b
\]

In other words, with the assumptions employed, the mean annual temperature gradient (\(g_a\)) is linearly related to the mean 2-meter temperature anomaly (anomalous temperature minus background temperature) plus the background temperature gradient (\(g_b\)). The mean background temperature gradient was calculated by dividing the regional heat flux predicted by Blackwell and Richards (2004) by the local thermal conductivity at a depth of 2 meters. Equation (5) fits the independently calculated gradient and temperature anomaly data from Desert Peak remarkably well (Fig. 3).

Based on the evidence depicted in Fig. 2, it is possible with reasonable approximation to replace the mean temperature anomaly (\(T_{2a} - T_{2b}\)) in equation (5) with the temperature anomaly measured at a single point in time. This makes it possible to estimate heat loss from one set of temperature measurements (that is, from one temperature survey). This approach was utilized to estimate heat loss associated with 2-meter temperature anomalies at 12 geothermal areas in Nevada (Table 2). Thermal conductivities at each area were assumed to equal the mean thermal conductivity (0.617 W/m°C) calculated for the Desert Queen and Desert Peak area soils (Coolbaugh and Sladek, 2013). This is considered a reasonable approximation of thermal conductivity because the dry, sandy to rocky soils are broadly similar in most of the survey areas. Background heat loss was not included in the calculations, in order for heat losses to solely represent the anomalous flux attributed to geothermal activity.

**Figure 3.** Relationship between mean annual temperature gradient and mean annual temperature for 2-meter temperatures in the Desert Peak geothermal area. Data were calculated using measurements of temperature at 1.5 and 2.0 meter depths at 5 different times of year. Blue line is not a best-fit line, but instead is based on the theoretical relationship expressed by equation (5) (see text). Adapted from Coolbaugh and Sladek (2013).

**Depth Detection Limits for 2-Meter Surveys**

The successful use of 2-meter temperature surveys to identify blind geothermal systems in the Great Basin (Coolbaugh et al., 2006, 2007; Sladek et al., 2007; Kratt et al., 2008, 2009, 2010) is partly due to especially favorable subsurface geologic and hydrologic environments. Firstly, the dry desert climate characteristic of the Great Basin reduces the opportunity of precipitation to influence subsurface temperatures, and also reduces the areal extent of cold groundwater aquifers that can absorb conductive heat from underlying thermal aquifiers. Despite this dry environment, most of the geothermal temperature anomalies identified to date show clear evidence of concealment and/or termination against areas of shallow groundwater. The two most common forms of “interference” from shallow cold groundwater are 1) presence of shallow cold groundwater in valley bottoms and playas.
119

COOLBAUGH, et al. (e.g., Desert Queen, Tungsten Mountain, Teels Marsh, Rhodes Marsh anomalies, see Coolbaugh et al., 2007, 2013 and Kratt et al., 2008), and 2) presence of shallow cold groundwater beneath alluvial fans and ephemeral streams draining from side canyons into larger valleys (e.g. Tungsten Mountain, Teels Marsh, West Hawthorne, Emerson Pass anomalies, see Kratt et al., 2008, 2010, and Coolbaugh et al., 2013).

Detection of conductive heat plumes is also heavily favored in piedmont areas adjacent to valleys, where progressively increasing thermal conductivities with depth accentuate near-surface temperature gradients while minimizing temperature drops with depth in bedrock. This phenomenon is illustrated in Fig. 4, a profile of temperature gradient well #52 (Benoit et al., 1982) drilled near the central portion of the Desert Queen 2-meter temperature anomaly (Fig. 5). Peak temperatures in the well are interpreted to represent a near-boiling thermal aquifer (89.6°C) at a depth of 67 meters. The 2-meter temperature anomaly at the surface is a very robust 7.7°C. The existence of similar temperature anomalies north and south of the well (up and down the hydrologic gradient, Fig. 5), argue against local thermal contamination of the near-surface environment from convection in the well. Between the surface and the thermal aquifer, the temperature profile consists of three principal linear temperature gradients which are believed to correspond to geologic materials with constant thermal conductivities - poorly consolidated and typically very dry alluvium from 0-3 meters, compact alluvium from 3-36 meters, and probable bedrock below 36 meters.

![Figure 4. Temperature profile for gradient well #52 from the Desert Queen area, Churchill County, NV. Location of well with respect to the thermal aquifer and 2-meter temperature data is shown in Fig. 5. The near surface temperature gradient from 0-3 meters is significantly greater than the gradient in deeper portions of the hole, which serves to accentuate the 2-meter temperature anomaly. Data from Benoit et al., 1982.](image)

**Table 2.** Calculated heat loss, temperature contrast, and size of 2-meter temperature anomalies at a number of geothermal areas in Nevada. Heat loss = (ga-gb)*K*A, where ga - gb = anomalous temperature gradient, K = thermal conductivity (a value of 0.617 W/m°C was used), and A = surface area of anomaly. Heat losses are summed over multiple contoured levels of temperature anomaly for each of the prospect areas listed. All of these aquifers are blind in the sense that there are no current hot springs associated with them, with the exception of Bonham Ranch. Data from Great Basin Center for Geothermal Energy at the University of Nevada, Reno and based in part on published data (Coolbaugh et al., 2007; Sladek et al., 2007; Kratt et al., 2008, 2009, 2010).

<table>
<thead>
<tr>
<th>Area</th>
<th>Maximum 2-m Temp</th>
<th>Background Temp</th>
<th>Temp C Max - Min</th>
<th>Length (km)</th>
<th>Width (km)</th>
<th>Area (km²)</th>
<th>Heat Loss (MWt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astor Pass</td>
<td>26.3</td>
<td>19.8</td>
<td>6.5</td>
<td>3.0</td>
<td>2.0</td>
<td>6.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Bonham Ranch</td>
<td>23.2</td>
<td>16.8</td>
<td>6.4</td>
<td>3.7</td>
<td>1.0</td>
<td>3.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Desert Queen</td>
<td>43.9</td>
<td>22.3</td>
<td>21.6</td>
<td>5.8</td>
<td>1.6</td>
<td>9.3</td>
<td>17.7</td>
</tr>
<tr>
<td>Tungsten Mountain</td>
<td>26.7</td>
<td>16.2</td>
<td>10.5</td>
<td>5.0</td>
<td>1.2</td>
<td>6.0</td>
<td>8.6</td>
</tr>
<tr>
<td>Teels Marsh</td>
<td>35.0</td>
<td>18.2</td>
<td>16.8</td>
<td>5.0</td>
<td>2.4</td>
<td>12.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Rhodes Marsh</td>
<td>26.7</td>
<td>18.6</td>
<td>8.1</td>
<td>4.8</td>
<td>1.3</td>
<td>6.2</td>
<td>8.1</td>
</tr>
<tr>
<td>SW Columbus Marsh</td>
<td>16.4</td>
<td>11.4</td>
<td>5.0</td>
<td>4.1</td>
<td>1.7</td>
<td>7.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Gabbs Valley</td>
<td>21.0</td>
<td>18.0</td>
<td>3.0</td>
<td>3.0</td>
<td>2.2</td>
<td>6.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Campbell (Wild Rose)</td>
<td>38.2</td>
<td>19.5</td>
<td>18.7</td>
<td>5.8</td>
<td>2.4</td>
<td>13.9</td>
<td>24.5</td>
</tr>
<tr>
<td>Hawthorne West</td>
<td>23.6</td>
<td>21.9</td>
<td>3.7</td>
<td>6.7</td>
<td>2.3</td>
<td>13.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Hawthorne East</td>
<td>31.8</td>
<td>21.9</td>
<td>9.9</td>
<td>10.0</td>
<td>2.2</td>
<td>22.0</td>
<td>12.2</td>
</tr>
<tr>
<td>Emerson Pass</td>
<td>60.0</td>
<td>12.0</td>
<td>48.0</td>
<td>4.0</td>
<td>0.8</td>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Mean Values: 13.2 5.1 1.8 9.3 8.9

**Figure 5.** Two-meter temperature anomaly at Desert Queen, Churchill County, NV. Thermal fluids are believed to flow upwards from depth into the aquifer near the southern end of the anomaly and flow northward, eventually flowing beneath, and mixing with, shallow groundwater in the playa. Colored circles = 2-meter temperatures: dark blue < 23°C, light blue = 23-24°C, green = 24-25°C, yellow = 25-27°C, orange = 27-30°C, red = 30-33°C, magenta = 33-36°C, dark purple ≥ 36°C. Black lines are 1°C contours. Small white circles are temperature gradient wells. White stars are artesian water wells. Background image is shaded topography superimposed on ASTER satellite bands 1-2-3. Figure modified from Coolbaugh et al. (2007).
Great Basin. The temperature reversal below 67 meters is taken as evidence of the presence of a laterally flowing aquifer that over-rides cooler temperatures below it (Benoit et al., 1982).

Interestingly, if the curving temperature profile between 0 and 67 meters in Fig. 4 is replaced by a single geologic unit with constant thermal conductivity (solid black line labeled “D average Gradient” in Fig. 4), it would yield a 2-meter temperature gradient of 1.1°C/m, which when substituted into equation (5), yields a predicted 2-meter temperature anomaly of only 1.9°C, instead of the actual 7.7°C. A 1.9°C temperature anomaly lies at the threshold of significance when compared with the cumulative noise levels commonly observed in these types of surveys, suggesting that without the benefit of a near-surface low-conductivity layer underlain by more conductive rock, the Desert Queen thermal aquifer would not be detectable. Conversely, if the thermal aquifer, modeled at a boiling temperature of 97°C, were to lie at greater depths within the same bedrock material as that encountered between 36 and 67 meters, simple modeling (see Table 3 for model parameters) predicts that an easily detectable 4.5°C two-meter anomaly would be generated from the aquifer at a depth of 200 meters, and the threshold of detection (2°C) would be generated by the same temperature aquifer at a depth of 600 meters.

Table 3. Parameters used for a simple, 3-layer conductive model of heat flow above an aquifer or reservoir of constant temperature at specified depth. Depth to the reservoir is the sum of the thickness of the three layers, which are listed in order of increasing depth. Thermal conductivities are those calculated for well #52 at Desert Queen, based on observed temperature gradients in the well and measured mean annual near-surface heat flow. In the model, heat flux and temperature gradients vary depending on specified constraints of temperatures, depths, and thicknesses.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Well 52 Thickness (m)</th>
<th>Well 52 $\frac{dT}{dz}$ (°C/m)</th>
<th>K (W/m°C)</th>
<th>Well 52 Heat Flux (W/m²)</th>
<th>Model Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3.655</td>
<td>0.617</td>
<td>2.26</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>33.6</td>
<td>1.515</td>
<td>1.489</td>
<td>2.26</td>
<td>variable</td>
</tr>
<tr>
<td>3</td>
<td>30.4+</td>
<td>0.338</td>
<td>6.672</td>
<td>2.26</td>
<td>variable</td>
</tr>
</tbody>
</table>

In spite of the relatively deep level at which some thermal aquifers can be detected with 2-meter surveys, it is more challenging to directly detect deeper, higher temperature reservoirs that produce power in the Great Basin, if they release heat only by conduction. However, under appropriate circumstances, they can be detected. For example, using the model parameters listed in Table 3, a relatively high temperature 200°C reservoir at a 1,300-meter-depth would yield a predicted 2-meter temperature anomaly of 1.4°C if alluvium were 300 meters thick (using the thermal conductivities present in the Desert Queen well of Fig. 4), and a 2-meter temperature anomaly of 2.5°C if alluvium were only 36 meters thick. The 2.5°C anomaly lies just above the threshold of detection, indicating that under ideal circumstances, represented by thin layers of low-conductivity sediments overlying much thicker zones of bedrock with relatively high conductivity, the conductive heat signature of deeper geothermal reservoirs could be detected with 2-meter surveys, although the signal-to-noise ratio would not be high. In reality, deeper reservoirs often leak some fluids into the intermediate to shallow environment, accentuating near-surface temperature gradients and increasing the magnitude of shallow anomalies. This leakage can be in the form of an outflow plume, which is the most common feature detected by shallow temperature surveys. Past shallow temperature surveys directly overlying known geothermal reservoirs (e.g., Coso, described by LeSchack and Lewis, 1983) may involve the detection of some combination of conductive and convective heat transport.

Shallower, more moderate temperature geothermal reservoirs are more easily detectable with 2-meter surveys. Two examples of such reservoirs are provided by the currently producing Campbell (Will Rose) geothermal system, Mineral County, NV and Salt Wells geothermal system, Churchill County, NV. At Campbell, as documented by Delwiche (2013), the reservoir is hosted in basin-fill sediments at depths as shallow as 50 meters, at a temperature of 130°C. This yields a minimum predicted and easily detectable, 2-meter temperature anomaly of 4.4°C, based on a linear projection of the temperature gradient from the reservoir to the surface without the benefit of likely near-surface, lower-conductivity sediments. Actual 2-meter temperature anomalies measured over the Campbell reservoir range up to 16°C (Kratz et al., 2010). Similar to Desert Queen, the contrast between the linear-predicted and actually measured temperature anomalies is likely attributable to near-surface low-thermal-conductivity materials that enhance the near-surface temperature gradient. These statistics, plus the fact that the spatial position of the 2-meter temperature anomaly closely overlies the production zone at Campbell (Delwiche, 2013), indicate that the 2-meter temperature anomaly is primarily detecting the conductive heat signature of the reservoir itself.

The relatively shallow geothermal reservoir being produced at Salt Wells, at depths of 60 to 150 meters and temperatures of 135-143°C (Nevada Division of Minerals data), also appears directly detectable with 2-meter temperature surveys. Minimum predicted 2-meter temperature anomalies, based on a linear projection of reservoir temperatures toward the surface, range from 1.9 to 2.1°C. Actual measured 2-meter temperature anomalies in this area average approximately 6-7°C (Skord et al., 2011). This “enhanced” anomaly signal is consistent with that of the Desert Queen and Campbell areas, which is not surprising given the presence of dry sands and gravels at the surface with thermal conductivities substantially lower than that of underlying volcanic rock that hosts the reservoir at Salt Wells.

**Discussion and Conclusions**

Heat loss estimates for a dozen 2-meter temperature anomalies in Nevada range from 3 to 24 MWt, averaging 9 MWt (Table 2). In many cases these are minimum estimates, because many of the anomalies are partially bordered by areas where shallow cool groundwater is likely to exist or partly occur in areas where colluvium may have thermal conductivities higher than the value used in the calculations (e.g. Emerson Pass, see Shevenell et al., 2014). The Desert Queen anomaly (Fig. 5) is one example of a minimum estimate, because the anomaly rapidly looses strength and disappears as it approaches a playa with cold shallow groundwater fed by the Humboldt River. Anomalous fluid geothermometry from cold artesian wells in the playa provide evidence that thermal fluids are penetrating the playa environment and mixing with shallow groundwater (Fig. 5, Coolbaugh et al., 2006). Some of the 2-meter temperature anomalies included in...
Table 2 could easily be twice or more their current size, were it not for the disguising effects of shallow cold groundwater, including anomalies at Bonham Ranch (Coolbaugh et al., 2007), Desert Queen (Coolbaugh et al., 2006), Tungsten Mountain (Kratt et al., 2008), Teels and Rhodes Marshes (Coolbaugh et al., 2013), and West Hawthorne (Kratt et al., 2010).

Most of the anomalies listed in Table 2 are believed to be associated with shallow thermal liquid outflow plumes. Exceptions include Campbell (Wild Rose), where the temperature anomaly directly overlies the geothermal reservoir (Delwiche, 2013), which in this case occurs at relatively shallow depths within Quaternary sediments, and Emerson Pass, where a portion of the 2-meter temperature anomaly is believed to have steam-heated ground along a controlling fault (Shevenell et al., 2014). With the exception of Rhodes and Columbus Marsh, drilling and/or Geoprobes (e.g., Teels Marsh, see Zehner et al., 2012), although shallow at times, have confirmed the presence of hot water in the subsurface beneath all of these temperature anomalies.

Heat loss estimates from geothermal systems have been used to place broad constraints on sustainable power production (Wissian et al., 2001; Richards and Blackwell, 2002). In this context, heat loss calculated from 2-meter temperature surveys can carry special significance where the surveys are detecting thermal aquifers located within 100 to 200 meters of the surface. If geothermal fluids upwelling from depth are replacing the conductive heat lost from the shallow aquifer, estimates of heat loss provide a minimum constraint on the rate of convection of thermal energy into the near-surface environment. This convection typically occurs along structural conduits (i.e., fault-related structures); if drilling is able to intersect those same structures at focused locations of fluid flow, geothermal energy production of the same order of magnitude as the heat loss may be possible.

Heat loss estimates based on 2-meter temperatures have been made for two areas currently under production, at Campbell (Wild Rose), Mineral County, NV and Desert Peak, Churchill County, NV. The Don Campbell power plant produces a net 16 MWe (Delwiche, 2013), which compares well with 24 MWt of heat loss estimated from the overlying 2-meter temperature survey. Gross power production from Don Campbell may be even closer to the shallow heat loss estimate. Net and gross production from the Desert Peak geothermal plant from mid-2012 to mid-2013 averaged approximately 10 and 13 MWe, respectively (Nevada Division of Minerals data), which compares well with a 9.5 MWt heat loss estimate from a 2-meter survey covering the same area (Coolbaugh and Sladek, 2013).

A number of other geothermal areas listed in Table 2 have significant shallow heat losses associated with them, but are not in production. Geothermal drilling at most of these prospects is either non-existent (e.g., Bonham Ranch, Teels Marsh, Rhodes Marsh, Columbus Marsh) or is insufficient to fully test the potential for economic production. The magnitude of the estimated shallow heat losses suggest that subsurface convection rates at many of these localities might be sufficient to support power production. In any case, the calculated heat losses represent minimum estimates of the total rate of thermal energy convected into the near-surface environment. Significant heat can be dissipated through mixing with shallow cold groundwater, and shallow cold groundwater commonly overlies portions of the conductive thermal footprint.

Indeed, some economic geothermal reservoirs will not have any detectable shallow temperature anomaly either because shallow outflow aquifers are not present, or because they are completely hidden by overlying cold groundwater aquifers.

The methodology presented in this paper demonstrates that mean annual heat loss can be calculated from a single set of 2-meter temperature measurements. For such an estimate to be representative, soil properties, particularly thermal diffusivity and thermal conductivity, should be uniform. If not uniform, their variation should be accounted for in the calculations. It is especially important that the thermal diffusivities of background temperature measurement points be representative of the survey area as a whole, because if they are not, calculated temperature anomalies could be either too high or too low. Other factors, including albedo, elevation, topographic slope, vegetation, and soil moisture may also need treatment depending on local circumstances. The use of multiple stations to estimate background 2-meter temperatures is recommended.

Finally, it is noted that the dry, desert environment that characterizes the Great Basin is ideal for shallow temperature surveys. A lack of shallow cold groundwater in many places makes it possible to detect the conductive heat signature from thermal aquifers up to 200 meters deep, and under ideal circumstances, the conductive signatures of reservoirs ≥1 km in depth may be detectable. The ideal situation for detection of thermal anomalies is presented where dry, porous low-conductivity soils overlie higher conductivity bedrock present at relatively shallow depths. In areas of outcropping bedrock, which typically have higher thermal conductivities than dry soil, it is more challenging to detect thermal anomalies with 2-meter survey equipment, because temperature gradients will be lower. This is true even though heat flux may be the same as at nearby equivalent areas covered by unconsolidated sediments.

Acknowledgements

We wish to acknowledge the support of the Great Basin Center for Geothermal Energy, beginning with Lisa Shevenell, past director of the center, and continuing with Wendy Calvin, current director. Field work at Desert Queen was funded largely through U.S. Department of Energy instrument number DE-FG07-02ID14311, and field work at Desert Peak was funded largely through a research grant from the Nevada Renewable Energy Center, managed by the Desert Research Institute. Field access at Desert Peak was kindly provided by Ormat Technologies Inc. Nick Hinz helped with data and interpretation of the Salt Wells geothermal system. Dick Benoit provided input on geothermal systems identified from temperature gradient and free well drilling. This paper has significantly benefited from suggestions and observations provided by Lisa Shevenell.

References


