Mapping Hydrothermal Upwelling and Outflow Zones: Preliminary Results from Two-Meter Temperature Data and Geologic Analysis at Lee Allen Springs and Salt Wells Basin

Justin Skord[1, 2], Patricia H. Cashman[1, 2], Mark Coolbaugh[1, 2], Nicholas Hinz[1, 3]

[1]Great Basin Center for Geothermal Energy
[2]Department of Geological Sciences and Engineering, University of Nevada, Reno
[3]Nevada Bureau of Mines and Geology

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ABSTRACT

Two-meter temperature surveys have been conducted at Salt Wells Basin and Lee-Allen Springs geothermal areas with the objective of distinguishing and mapping zones of upwelling and outflow. The ability to do this may help maximize their development potential. Geothermometers of these areas suggest the presence of high temperature reservoirs, but Lee Allen Springs remains undeveloped and geothermometer data at Salt Wells Basin suggests this area is under-developed. At Lee Allen Springs, a strong shallow temperature anomaly has been mapped in the area of Lee Hot Spring. This anomaly consists of temperatures locally exceeding 40°C at two meters depth, covering an east-west trending area approximately one kilometer in length. Preliminary interpretations map this area as an upwelling zone with outflow to the west and east. Also, this zone may reflect an unmapped subsurface east-west trending fault zone. Other, more subtle anomalies, found at Lee Allen springs indicate a possible second upwelling zone near a fault intersection between a north-northeast striking east dipping normal fault and a northwest striking dextral fault. At Salt Wells Basin, a large north-south trending temperature anomaly has been mapped. A group of subtle temperature anomalies along Simpson Pass, south of the current production area, are interpreted as an upwelling zone with a complex outflow to the north along the eastern flank of the Bunejug Mountains. The data suggest there may be additional upwelling zones north of Simpson Pass. Additional temperature survey work, geologic and geophysical surveys, and soil gas surveys may help test the upwelling and outflow interpretations.

Introduction

Most geothermal systems in the Basin and Range have an upwelling and an outflow zone. An upwelling zone is where steam and hydrothermal fluids travel upwards through permeable fault-zones to reach the near-surface. The fluid then commonly flows laterally along the hydrologic gradient, generating an outflow zone (e.g. Richards and Blackwell, 2002; Figure 1). Identification of upwelling and outflow zones is important for exploration and development of geothermal. If drilling targets a fault that is not responsible for upwelling the most productive portion of the system is unlikely to be tapped. An equally undesirable problem arises when drilling targets an outflow zone and temperatures increase rapidly at shallow depths but begin to decline at greater depths. Also, since upwelling is commonly associated with fault zones, the shape and extent of the thermal anomaly could

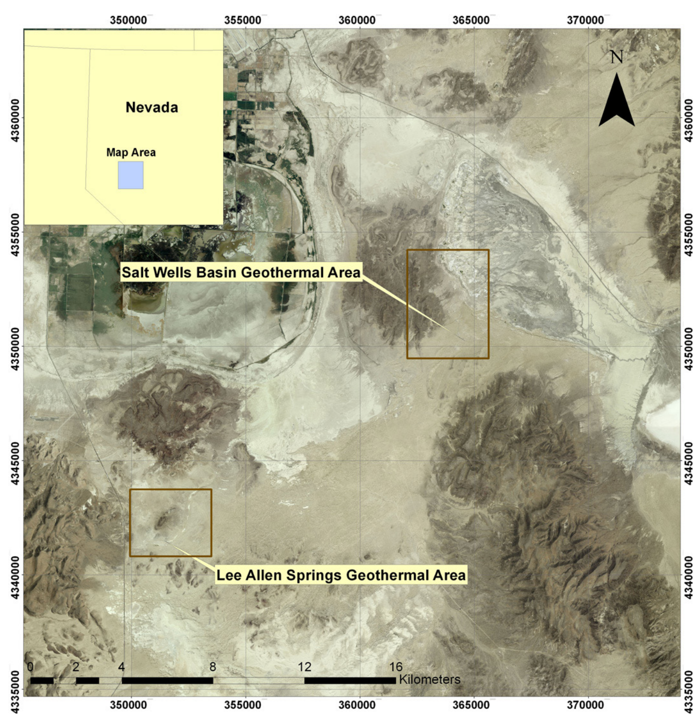

Figure 1. Map showing location of the two survey areas, Lee Allen Springs and Salt Wells Basin. These two geothermal areas are located in Churchill County, Nevada roughly 20km apart from each other.

give more detailed information on the geometry of key faults controlling the geothermal system. It can also suggest the presence of undiscovered subsurface faults. However, any of these interpretations are contingent on accurate differentiation between upwelling and outflow.

In recent years the Great Basin Center for Geothermal Energy has developed improvements to the shallow temperature survey method (e.g. Coolbaugh 2007; Sladek, 2009; Kratt 2009). This project tests the ability of this method to answer specific questions on the structural controls of geothermal areas, with specific emphasis on defining upwelling and outflow zones. The survey areas are Lee Allen Springs and Salt Wells Basin. These two geothermal areas are located in Churchill County, Nevada roughly 20km apart from each other (Figure 1). The surveys were designed and interpreted based on existing knowledge of known thermal features, fault locations, and hydrologic gradients. Various additional methods can be utilized to test these interpretations.

Interpreting Upwelling and Outflow from Shallow Temperatures

The shallow temperature expressions of both the upwelling zone and the outflow zone can range from subtle to strong. Areas of upwelling are typically located near valley edges where the water table is deeper than towards the middle of the valley. It is for this reason that hot springs, mineral deposits, or high shallow temperatures are commonly displaced from the actual upwelling zone. One key exception is when a large amount boiling occurs the upwelling zone may become heated by rising gases generating high shallow temperatures (Richards and Blackwell, 2002).

These processes are partly depicted in Figure 2. In Figure 2a extensive boiling from the upwelling fluid reaches the surface generating high two-meter temperatures. The outflow zone is represented by a gradual tapering off of two-meter temperature anomalies with distance along the hydrologic gradient. In figure 2b there is little or no boiling at the upwelling zone which generates a subtle shallow temperature anomaly; due to a shallowing of the water table along the hydrologic gradient the outflow meets the surface generating a high shallow temperature anomaly.

Based on these models, shallow temperature data can be used as a framework for making upwelling and outflow interpretations. However, uncertainty can arise when high shallow temperatures are found in areas where no faults are currently mapped. Is it the result of outflow reaching the surface or could it suggest upwelling from an unmapped fault? Incorporation of additional datasets could help resolve this uncertainty. Geophysical surveys could help define unmapped subsurface faults controlling upwelling (e.g. Hinz and others, 2010); Hydro-geologic studies provide detailed insight into the hydrologic gradient of an area that would control outflow (e.g. Morgan, 1982); and soil gas surveys can help detect geothermal gases associated with an upwelling zone (e.g. Lechler and others, 2009).

Study Areas

Lee Allen Springs

Lee Allen Springs is a blind geothermal system discovered in the early 1900's when agricultural drilling led to the formation of Lee Hot Springs but this system remains undeveloped. Geothermometer temperatures calculated from Lee Hot Spring waters suggest a reservoir temperature of 170°C (e.g. Hinz, 2008). In 1978 an exploration well was drilled near Lee Hot Spring to a depth of 919 meters. At 610 meters they encountered high flow rates but temperatures were too low; at the bottom of the hole (919 meters) a temperature of 119°C was measured but the flow rate was low (e.g. Mariner and others, 1974; Hinz and others, 2008; 2010).

Several key features of Lee Allen Springs are shown in Figure 3. The main geothermal features include Lee Hot Spring, Tufa deposits, and opal-cemented Quaternary sediments (Figure 3). The tufa deposits and opal cemented sediments have been used to map and interpret the areas structural geology (e.g. Hinz 2008). Structurally, Lee Allen Springs is interpreted to lie within a pull-apart block where a series of right stepping right lateral faults intersect a northeast striking eastward dipping normal fault (Figure 3; Faulds and others, 2006; Hinz and others, 2008; 2010). Based on topography, the hydrologic gradient begins at the northern end of a central ridge, then moves into a drainage that has two different slope directions (Figure 3).

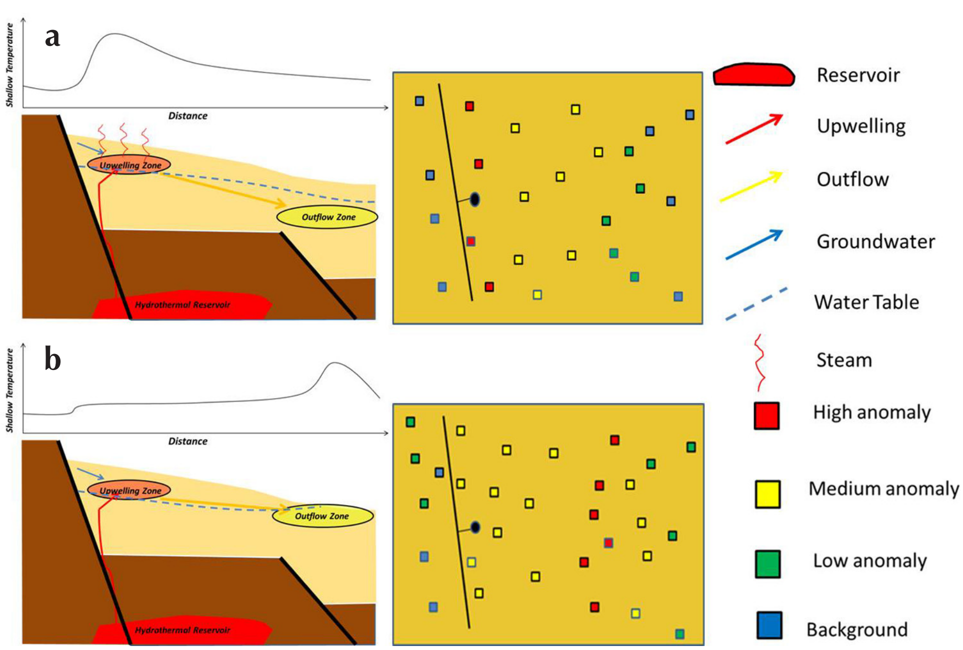

Figure 2. Schematic cross section of a geothermal system showing two variations of the upwelling and outflow process (modified from Richards and Blackwell, 2002) and expected two-meter temperature distribution in map view. In Figure 2a steam from boiling processes generates high shallow temperatures at the upwelling zone. In Figure 2b less boiling and a deeper water table along the valley edge generates only moderately high shallow temperature anomalies at the upwelling; the outflow reaches the surface towards the middle of the valley.

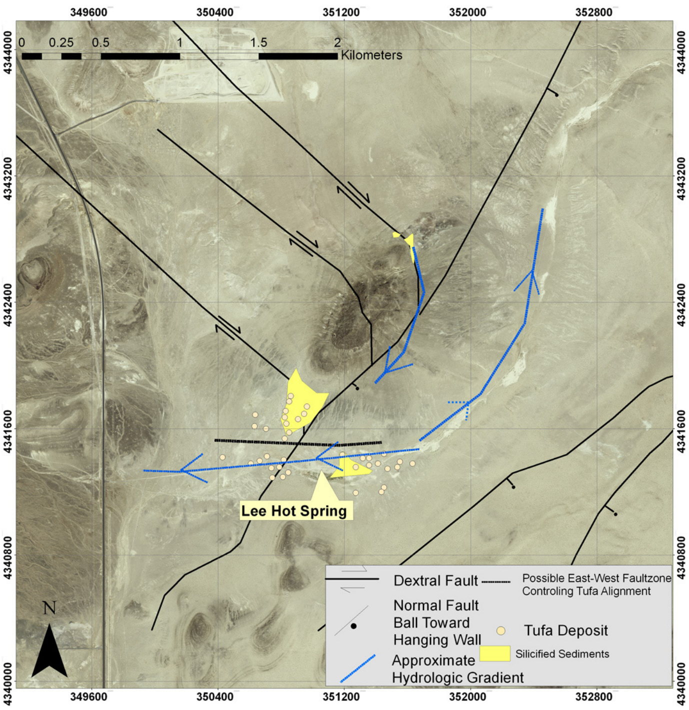

Figure 3. Map showing the Lee Allen Springs geothermal area showing some of the known geothermal features, key mapped faults (modified from Hinz and others, 2010), and a general hydrologic gradient (interpreted from the areas topography and geomorphology).

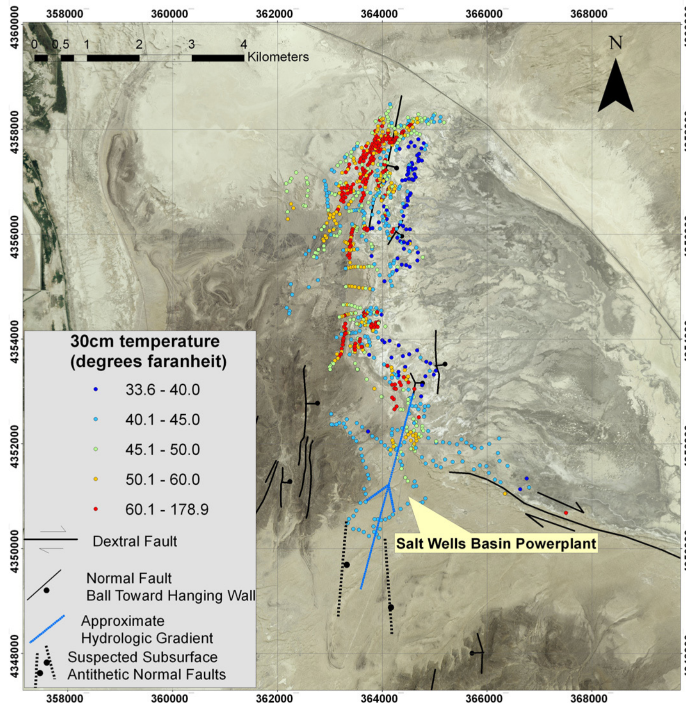

Figure 4. Map showing the Salt Wells Basin geothermal area showing some of the known geothermal features, key mapped faults (modified from Morrison, 1964), and a general hydrologic gradient (interpreted from the areas topography and geomorphology).

Salt Wells Basin

Salt Wells Basin is also a blind geothermal system and it has an operating power plant with a generating capacity of ~15MW. Previous studies mapped numerous geothermal features including several intermittent hot springs and seeps, opal cemented sands and muds, and borate deposits (Coolbaugh, 2006). Geothermometers from the springs and seeps suggest a reservoir temperature of 190 and the power plant is producing from fluid with a temperature of ~140°C (e.g. Coolbaugh and others, 2006; Faulds and others, 2006). This suggests that a higher temperature reservoir could exist at depth but it has not yet been encountered with drilling.

Key features and datasets related to Salt Wells Basin are shown in Figure 4. The production area is located near Simpson Pass between the Cocoon and Bunejug Mountains. Based on elevation, the hydrologic gradient likely begins at these nearby mountains, moves into Simpson Pass, and then northward into Salt Wells Basin (Figure 4). A 30cm temperature survey mapped a large thermal anomaly that covers large portions of the basin (Figure 4; Coolbaugh 2006). The 30cm survey was unable to detect any anomalous temperatures in the area of Simpson Pass, immediately south of the production area, which indicates that most of the anomaly is likely associated with outflow processes (Figure 4). Current theories hypothesize that upwelling is occurring in the Simpson Pass area and is controlled by north-striking and steeply dipping antithetic normal faults (Figure 4; Faulds 2006). The exact location and geometry of these faults is poorly constrained because much of the area is buried by Lake Lahonton dune sands (Morrison 1964).

The Two-Meter Temperature Survey Method

The techniques used in this study have incorporated recent modifications to the long-standing shallow temperature survey method (Coolbaugh and others, 2007; Sladek and others, 2009). The fieldwork is conducted primarily from an ATV (All-Terrain-Vehicle) allowing for maximized mobility in rugged terrain and rapid access to equipment. Steel temperature probes with tungsten tips are used, making ground penetration easier. The low thermal mass of the equipment allows for shorter equilibration times. Temperature is measured from a Resistance Temperature Device (RTD) that is lowered through the hollow probe. Surface and near-surface phenomena influence two-meter temperatures and in some circumstances can obscure underlying contributions of geothermal heat. The most common surface or near-surface phenomena are seasonal temperature drift, albedo, slope aspect, elevation, and thermal diffusivity. Corrections and consideration of these effects can improve the identification and delineation of geothermal heat flux with two-meter temperature surveys (Sladek and others; Coolbaugh and others, 2010).

Results

Lee Allen Springs

Approximatel 50 stations at Lee Allen Springs were measured from February to May 2011. The data were corrected for seasonal drift by measuring temperature change of several base stations. All of the base stations increased by roughly 3°C from February to May. Corrections for albedo, slope aspect, and thermal diffusivity haven't been applied to the data yet. Two meter tempetatures ranged from as low as 10°C to as high as 65°C. Several stations with temperatures greater than 40°C cover an east-west trending oval shaped zone approximately 1 km long (Figure 5). Temperatures decrease rapidly to the north and south of this zone and more gradually to the west. To the east of this zone temperatures decrease to less than 20°C and then increase to ~30°C moving further east. At the north end of the central ridge three stations (LA 29, Lam12, and LAm 13; Figure 5) form a subtle anomaly with temperatures between 14-15°C.

Salt Wells Basin

Approximatel 50 stations were measured at Salt Wells Basin from February to May 2011. The data were corrected for seasonal drift by measuring temperature change of several base stations. The base stations increased by roughly 4°C from February to May. Corrections for albedo, slope aspect, and thermal diffusivity remain haven't been applied to the data yet. Two-meter temperatures ranged from as low as 10°C to as high as 45°C. The data show high temperatures forming a large, roughly north-south trending oval shaped anomaly several kilometers long (Figure 6). Much of Simpson Pass is represented by subtle to moderate temperature anomalies (13-25°C) . The highest temperature stations are located north of the production closer to the basin's playa (Figure 6).

Interpretations

Lee Allen

Preliminary interpretations of upwelling and outflow for Lee Allen Springs are shown in Figure 5. The large zone of temperatures greater than 40°C associated with the Lee Hot Spring is interpreted as an upwelling zone with both a west-directed and east-directed outflow. The subtle anomalies (LA 29, Lam12, and LAm 13; Figure 5) at the north end of the central ridge are interpreted as part of an upwelling zone because it occurs close to mapped faults, silicified sediments, and it is at an elevational high-point within the survey area. The high temperature at station Lam5 likely reflects the convergence of the two outflows associated with each of the interpreted upwelling zones (Figure 5).

Salt Wells

Preliminary interpretations on upwelling and outflow are shown in Figure 6. The moderate temperature anomalies of Simpson Pass have been interpreted as the main upwelling zone of the Salt Wells Basin geothermal sysem (Figure 6). High thermal anomalies at this area are likely being prevented by thick sand-ramp deposits in this area. The outflow is interpreted to be along the eastern flank of the Bunejug Mountains. The presence of mapped fault scarps along the interpreted outflow zone may indicate additional upwelling activity in this area. For this reason one of the high anomalies along the outflow (SW 20; Figure 6) has been interpreted as a possible upwelling zone.

Further Work

Further survey work and integration of more datasets is needed in order to test interpretations of upwelling and outflow at Lee Allen Springs and Salt Wells Basin. At Lee Allen Springs further survey work near Lee Hot Spring could provide insight into a suspected subsurface east-west trending structure. At Salt Wells Basin more data in the Simpson Pass area could provide insight into suspected subsurface antithetic faults that may control upwelling. Gravity modeling could be completed from existing geologic and geophysical data which could help find subsurface

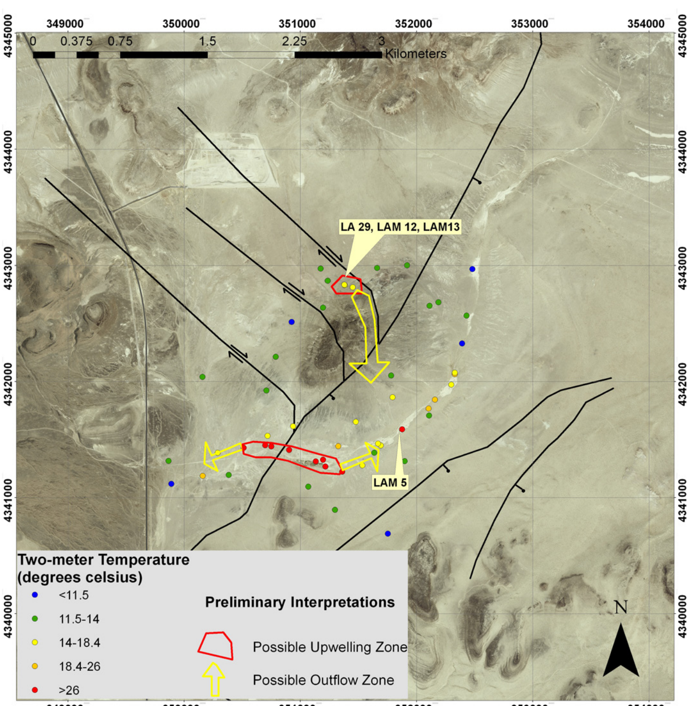

Figure 5. Map showing preliminary upwelling and outflow interpretations from an initial two-meter temperature survey at Lee Allen Springs.

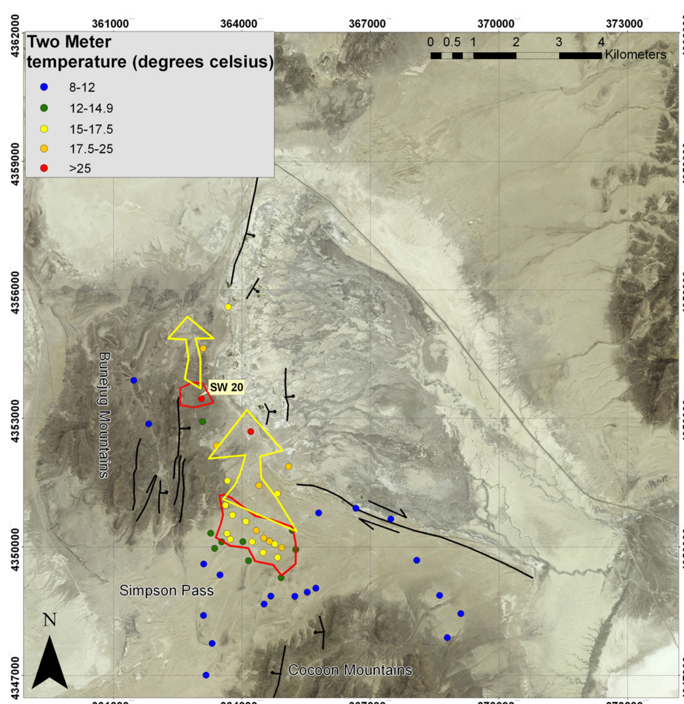

Figure 6. Map showing preliminary upwelling and outflow interpretations from an initial two-meter temperature survey at Salt Wells Basin.

fault zones and that may be associated with upwelling. Soil gas surveys are currently being planned by the Great Basin Center for Geothermal Energy which may help detect geothermal gases associated with upwelling.

Conclusions

Many geothermal areas, including Lee Allen Springs and Salt Wells Basin, have upside potential for geothermal energy production since geo-thermometer temperatures are higher than temperatures measured from wells completed to date. Two-meter temperature surveys can be used as a framework for Mapping upwelling and outflow zones which may help plan and increase development of these areas. The design and interpretation of the surveys must be based in part on a knowledge of structural geology and the hydrologic gradient. Interpretations can be strengthened by adding other datasets including geophysical and soil gas surveys. Finally, if upwelling zones can be mapped in detail, potential subsurface structures controling upwelling may be identified.

Acknowledgements

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