A Difficult Search

Why Basin and Range Systems are Hard to Find

By Maria Richards and David Blackwell – Southern Methodist University Department of Geological Sciences, Geothermal Laboratory

If the potential of geothermal systems in the Basin and Range is so high (see two prior articles in this series by Richards and Blackwell in the March-April, and May-June, 2002 editions of the GRC *Bulletin*, 2002a and 2002b), why have so few systems been developed? As noted in the first GRC *Bulletin* article, the objective of finding and developing the largest, hot targets during geothermal exploration in the 1970s and early 1980s often limited interest in Basin and Range systems. Furthermore, the large number of geothermal systems in the Basin and Range meant certain criteria were needed to limit the exploration targets. As a result, only systems that were large and had very good evidence of high temperatures were of drilling interest at the time.

The Basin and Range is an extensional system characterized by block faults. Their complex faulting pattern provides hot source fluids a pathway to reach the surface, but also contributes to creating complicated shallow geothermal anomalies (Fig. 1). Fumaroles will form above a range front fault where the upflow reaches boiling or higher temperatures below the surface. More often, the upflow enters the groundwater aquifers, flowing laterally in porous valley fill that covers the fault(s). This situation affects the location of surface manifestations that mark a geothermal anomaly.

Where upflow occurs along a fault, conductive transfer of heat generates a deep thermal aureole around the flow path, as well as the shallow convective aureole near the surface. In a simplistic model, the deep thermal aureole would be parallel with the fault, extending away from it by a distance dependant on the duration of fluid flow and the thermal conductance of surrounding rocks. The heated fluids discharging laterally, as shown in Figure 1, create the shallow aureole. Both aureoles will change in shape and size over time as the heat is transferred further from the source. Over a long period of time, the deep and shallow zones tend to converge into one thermal aureole.

By determining the shape and size of the deep and shallow thermal aureoles during drilling, the possibility of successfully drilling into the actual upflow along the fault(s) is increased. Temperature measurements can be a powerful tool and reduce expenses if used appropriately throughout the exploration and production drilling phases. But understanding the unusual characteristics of shallow Basin and Range geothermal anomalies is necessary to properly and accurately utilize temperature measurements obtained in boreholes.

Below the Surface Manifestations

The arid climate and the surface drainage pattern of the Basin and Range are complicating factors to surface manifestation development (or lack of) around the deep geothermal system. In this region, the majority of discharge from rivers and streams stays within the basin, either evaporating or recharging groundwater. Because shallow groundwater is recharged from surface drainage, it is cooler than rising geothermal fluids, and the two are tempered as they flow together through the water table (Fig. 1).

Due to high relief within the Basin and Range, valley edges are often several meters above the water table. The water table only reaches near the surface in the middle of the valleys. Thus, there are often only minimal signs of elevated temperatures, such as hot springs and chemical deposits, visible at the surface along faults in the region. Even where the water table reaches the ground surface, warm and hot springs are often offset from the original fault source. Seldom are the shallow waters either unboiled or unmixed, making it difficult to use geochemical temperature for determining the maximum reservoir temperature of a geothermal source. These typical features of Basin and Range geothermal systems limit the surface manifestations of the system and complicate the use of surface or shallow measurements to properly estimate source reservoir temperature and location.

During the initial exploration of a geothermal area, a series of shallow holes (90 to 150 m) are usually drilled. Temperature-depth (T-D) curves from these holes are used to determine where deeper drilling will occur. In examining T-D profiles, there are many different scenarios.

In the Basin and Range, T-D curves tend to be controlled by three patterns: 1) the background, 2) the shallow thermal aureole from heated lateral flow, and 3) the deep thermal aureole (at the source of upflow) (Fig. 2). The background curve (Fig. 2) has a gradient representative of the surrounding lithology and regional heat flow, generally higher thermal gradients in the valley fill, and lower linear gradients in the basement rock. The typical surface thermal aureole (Figure 2, 29-1) is characterized by a T-D curve quickly increasing to very high temperatures in the permeable zone, then a reversal to cooler temperatures, and after that warming to a gradient near the background. This pattern is referred to as a rollover or overturned T-D curve. The T-D curve representative of the deep thermal aureole (Fig. 2, B21-1) has an initially high gradient with temperatures quickly rising and then leveling off, staying at the elevated temperature or slowly continuing to increase to the bottom of the borehole.

Exploring for geothermal fluids in the Basin and Range is complex, but following a three-step process using T-D curves to assist in finding the upflow source along a fault is helpful. First, drill multiple shallow holes to determine the area of elevated groundwater temperature. The shallow holes do not necessarily represent the location of the upflow source, rather signify that one does exist. Second, drill the next set of boreholes through the zone of elevated temperatures (shallow aureole) and the temperature reversal, stopping where the temperature returns to background level. These boreholes help differentiate the shape and location of the surface and deep thermal aureoles. Third, drill an exploration well(s) into the area closest to the upflow source.

Every geothermal system will have its own signature temperature curves. Factors that can change the shape of the temperature curve are the age of vertical and lateral flow, the amount of fluid movement, source temperature, lithology, number of faults, and the characteristics of groundwater flow.

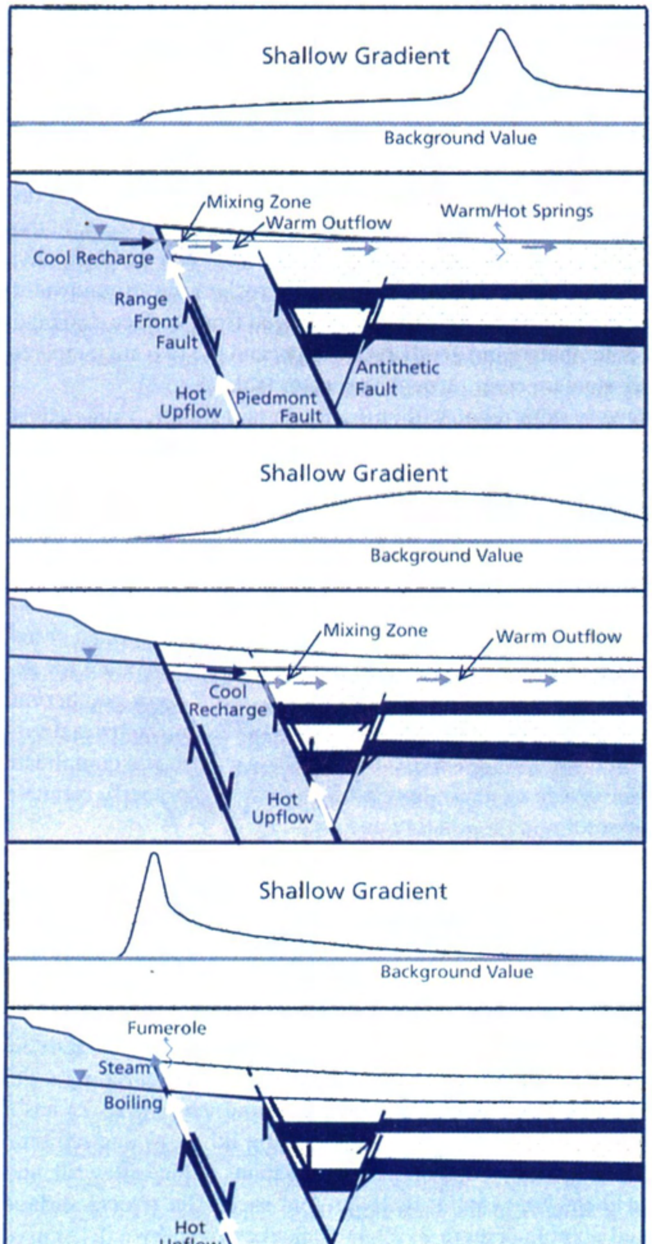

Figure 1. Three scenarios of shallow geothermal fluid movement in the Basin and Range. The hot fluids flowing along the faults interact differently with the water table, creating varied surface effects. The upper curve for each scenario represents the gradient measured in shallow (100m) exploration holes.

Thermal Exploration of Desert Peak

An excellent case history of Basin and Range exploration has been described by Benoit et al. (1982) for the Desert Peak geothermal system. Although Desert Peak is an archetypical, extensional system in some respects, it is quite different in others. The main difference is that there is no obvious major structure on which to focus exploration. The surface is covered by young volcanics and sedimentary deposits.

Currently, Desert Peak has a geothermal power plant operating at 9.9 megawatts. The heat loss from this area is substantial and suggests that the system is underdeveloped, as is the case in most of the Basin and Range (Richards and Blackwell, 2002b). There have been no new contracts for power sales to stimulate additional drilling in Desert Peak. The first drilling phase began with 53 shallow holes (to an average depth of 91.5 meters) that delineated a large, intense thermal anomaly (Benoit, et al., 1982) (Fig. 3).

Using T-D curves and a few thermal conductivity measurements, the shallow temperature gradient and heat flow anomalies at Desert Peak were mapped. From these data, it was expected that drilling anywhere in the vicinity of the elevated temperature gradients found by the shallow holess would lead to a successful geothermal exploration well. Thus, the site for geothermal exploration well 29-1 was selected based on ease of location within the middle of the thermal high. Well 29-1 was "dry" and cooler at the bottom than expected, but informative in providing more detailed temperature and lithology information (Fig. 2). A reversal in temperature at 213 meters was a surprise, but illustrated that the shallow bottom-hole temperature (BHT) found in the initial 53 temperature gradient holes outlined the shallow leakage from the deep thermal anomaly, not the deep geothermal reservoir.

To look below the masking effects of the shallow aquifer, eight intermediate (<610 meters) boreholes were drilled (Strat 1-8) (Fig. 3) to construct the shallow thermal aureole and delineate the deep thermal aureole. The Strat tests were very successful in evaluating the extent of the deeper thermal aureole. Thus, the second geothermal exploration well (B21-1) was successfully drilled near Strat-2, reaching 208°C at 1,265 meters with enough fluid volume and pressure to make it productive. Immediately afterward, well B21-2 was drilled near Strat-5 as a second exploration well. This geothermal well is 973 meters deep, with temperatures measured at 200°C. Production flow tests show B21-1 and B21-2 to be in the same reservoir (Benoit, et al., 1982) (Figs. 2 and 3). Two years later, B23-1 was drilled near Strat-7, but never put into production because of problems with well cave-in.

In reviewing the temperature-depth curves of Desert Peak boreholes, it is seen that lateral flow near the surface from the upflow along the fault is easily distinguishable by the intermediate boreholes and deep wells (Fig. 2). The shallow holes showed where surface groundwater was being heated, but were not able to define the conductive thermal aureole related to the upflow (Fig. 3). To the northeast, Strat-3 is on the very edge of the shallow thermal aureole with slightly elevated surface temperatures, but not drilled close enough to the flow zone to have developed a shallow overturn. On the opposite side of the valley, the T-D curves of well 29-1 and the Strat-1 borehole both have a high gradient that reverses, then rises again with depth.

The sharpness of the reversal for both 29-1 and Strat-1, and the gradient of the second increase are identifiers of where they are situated within the thermal aureole. Strat-1 is closer to the source of the thermal aureole. When comparing the Strat-1 and Strat-2 boreholes, the latter has only a slight change in gradient and higher temperatures where heated lateral flow temperatures are measured, signifying it is nearer to the upflow source. Geothermal exploration wells B21-1 and B23-1 appear to have been drilled into the upflow source. This is represented on the T-D curve by rapidly increasing temperatures which remained fairly constant as the well was drilled deeper.

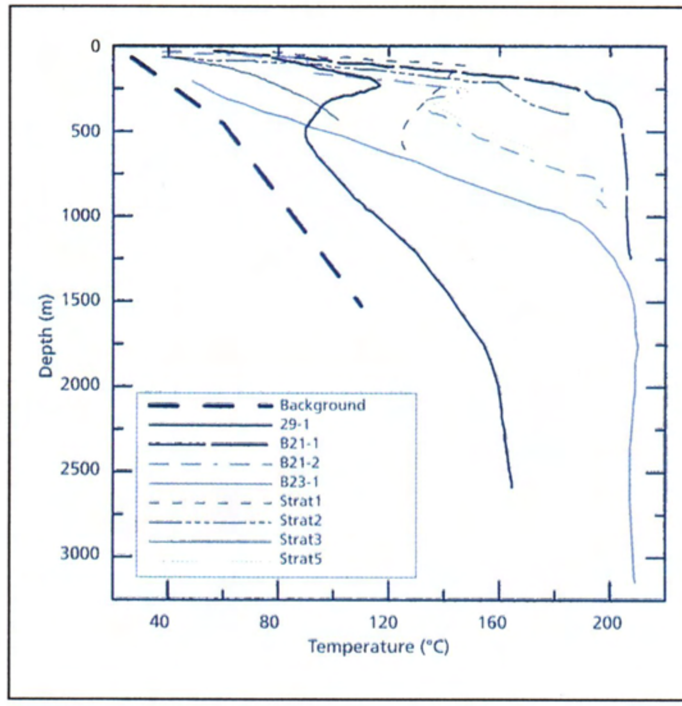

Figure 2. Selected temperature-depth (T-D) curves from Desert Peak, Nevada, with a generalized background T-D curve. See Figure 3 for borehole locations.

Beyond Desert Peak

Desert Peak is not an unusual case. Other examples of T-D curves for Basin and Range geothermal areas with shallow thermal aureoles are shown in Figure 4. The data for these T-D curves are from the U.S. Geological Survey web site's Geothermal Industry Temperature Profiles from the Great Basin (Sass et al., 1999). Each area has two example T-D curves. One curve represents a borehole drilled along the outer edge or through the shallow thermal aureole (shown as a solid line), while the second T-D curve (a dashed line) is representative of drilling closer to the source fault.

The Reese River T-D curve (a) in Figure 4 is only slightly above background by 55 meters and most likely the farthest from the source of these examples. The Reese River T-D curve (b) is still a distance from the source fault. The upflow may have existed for a long time causing the shallow and deep thermal aureoles to converge and spread further out, raising the geothermal system background temperature and thus reducing the reversal in a borehole.

The Silver Peak T-D curve (a) in Figure 4 has an unusually sharp peak at 10 meters. The 10 meter spike, if related to a thermal aureole affect, would represent a very recent hot fluid source. The Silver Peak T-D curve (b) is increasing more rapidly in temperature, but needs to be drilled deeper (generally 150 – 300 meters) to determine the extent (or existence) of an overturn. This area is close to the California border halfway between Reno and Las Vegas, so the likelihood of recent earthquakes creating new flow paths is high.

Dyke Hot Springs (Fig. 4) has a defined overturn, but the borehole still has not returned to the natural increase of its background temperature shown by T-D curve (a). Dyke Hot Springs T-D curve (b) is only slightly higher in temperature than (a) and needs to be

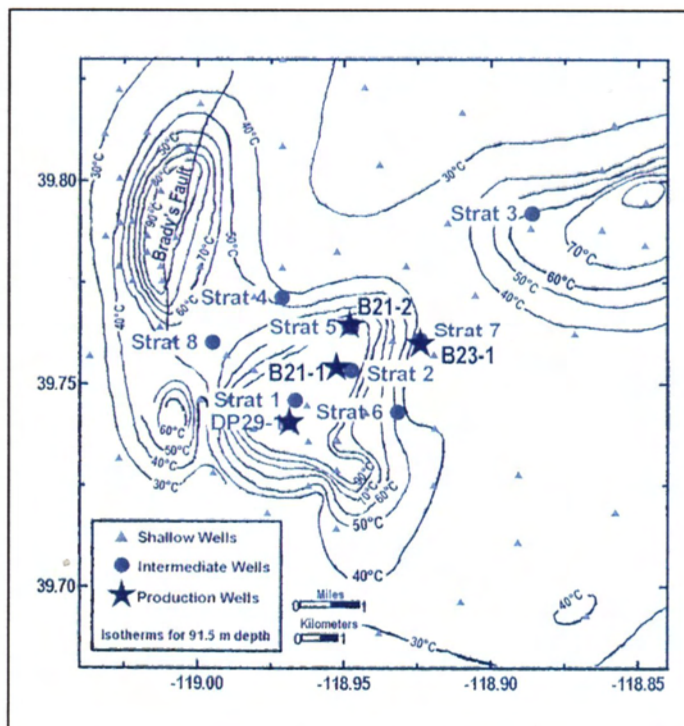

Figure 3. Exploration well locations for Desert Peak, Nevada. The contours show the temperature in the shallow temperature gradient hole. In this case, temperature could be substituted for gradients, similar to the middle profile in Figure 1.

drilled deeper to fully determine if it is closer or further from the fault source.

The two San Emidio T-D curves (a and b) shown in Figure 4 are examples of what geothermal explorationists would like to find. The pattern of a rapid increase, then a relatively sharp overturn followed by a return to the background temperature easily defines the shallow thermal aureole. The San Emidio T-D curve (b) is closer to the source of upflow, because it is hotter than curve (a) and still has not yet reached the point of overturning.

Conclusions

If Desert Peak was drilled again with today's knowledge, it would obviously be done differently. The initial geothermal exploration well (29-1) would have been drilled after the Strat tests were drilled, and the shallow and deep thermal aureoles defined. Through better understanding of how to read T-D curves, the decrease in temperatures of well 29-1 would cause concern at 900 meters, and by 2,000 meters drilling would most likely be stopped, as temperatures leveled off and it was realized that the well was too far from the upflow source. Well B23-1 would not be drilled to 3,000 meters expecting to reach substantially higher temperatures. The lesson here is that shallow gradients that seem too good to be true usually are.

Temperature-depth curves can have a variety of wiggles and bends to them. They come in all shapes and sizes as seen by the few examples provided with this article. Drill holes can effect the movement of fluids and gases both in the borehole and along the casing, also changing the shape of the T-D curve. This intra-borehole flow adds an additional complication to interpreting what is happening below the ground surface. Understanding why the T-D curves vary from the background temperature is an important aspect of geothermal exploration, especially in the Basin and Range. Yet, finding the resources to learn how to interpret T-D curves is difficult. A tutorial on T-D curves, as well as related articles, has recently been provided on the Southern Methodist University geothermal web site at: www.smu.edu/geothermal.

One outcome of technology improvements is the use of directional drilling for geothermal exploration. By measuring a well's BHT as it is drilled, the bit can be steered to follow increasing temperatures in an effort to reach the upflow source once a thermal aureole has been properly delineated. The goal should be to use knowledge gained by the 1970s and 1980s exploration efforts to reduce the amount of drilling and hit the geothermal target—the upflow source as close to the surface as possible. With today's technology improving the ease of temperature readings and the enhanced understanding of what is occurring below the ground surface, there is little reason not to use the temperature measurement tool for assisting in the exploration of geothermal systems. ■

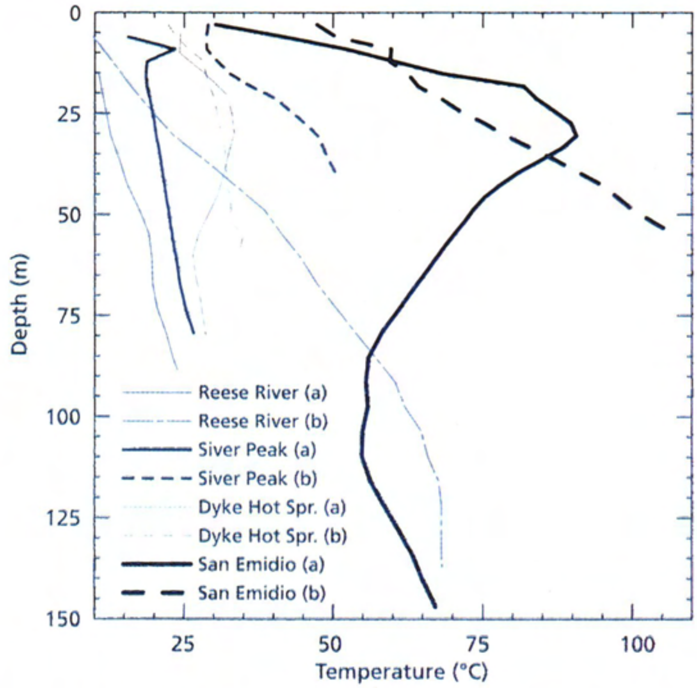

Figure 4. Examples of Basin and Range temperature-depth curves. The solid lines represent boreholes drilled in or through a shallow thermal aureole. The dashed lines represent boreholes closer to the source of the hot fluid upflow source.

References

Benoit, D., J. E. Hiner, and R. T. Forest, 1982. "Discovery and geology of the Desert Peak geothermal field: A case history," *Nevada Bureau of Mines Geological Bulletin*, 97, 82 pp.

Richards, M., and D. Blackwell, 2002a. "The Forgotten Ones: Geothermal Roads Less Traveled in Nevada," Geothermal Resources Council *Bulletin*, v. 31, no. 2, pp. 69-75.

Richards, M., and D. Blackwell, 2002b. "The Nevada Story: Turning Loss Into Gain," Geothermal Resources Council *Bulletin*, v. 31, no. 3, pp. 107-110.

Sass, J., S.S. Priest, A.J. Blanton, P. C. Sackett, S. L. Welch and M.A. Walters, 1999. *Geothermal Industry Temperature Profiles from the Great Basin*, U.S. Geological Survey Open-File Report 99-425, Version 1.0, http://wrgis.wr.usgs.gov/open-file/of99-425/webmaps/home.html.