PROCEEDINGS, Thirty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 2007
SGP-TR-183

USE OF RAPID TEMPERATURE MEASUREMENTS AT A 2-METER DEPTH TO AUGMENT DEEPER TEMPERATURE GRADIENT DRILLING

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ABSTRACT

Temperature gradient drilling has historically been a key tool in the exploration for geothermal resources in the Great Basin, USA, but regulatory, environmental, and accessibility issues, as well as the expense of drilling, are increasingly limiting its use. In cases where thermal groundwater is not overlain by near-surface cold aquifers, it is possible to augment temperature gradient drilling with temperatures measured from a 2-meter depth. We discuss the development of a rapid, efficient, and portable 2-meter-deep temperature measurement system that obtains accurate temperatures within an hour of emplacing hollow steel probes into the ground, making it possible to map results on a daily basis so that temperature surveys can rapidly vector towards thermal anomalies. As an example, a thermal anomaly related to a 60 m (200 ft) deep thermal aquifer at the Desert Queen geothermal area, near Desert Peak, Churchill County, Nevada, USA was mapped in much greater detail with 2-meter-deep measurements than possible with previous temperature gradient drilling, demonstrating that this technique can reduce the number of temperature gradient wells needed to identify zones of thermal upwelling.

INTRODUCTION

The mapping of temperature variations at or below the earth's surface constitutes a key geothermal exploration tool, but relatively little research to improve temperature mapping methods has been done in recent years. Temperature measurements can be divided into three main categories depending on the depth below the surface at which the temperatures are measured: 1) surface measurements, 2) measurements at depths of 0 to 20 m, and 3) measurements at depths > 20 m. Each of these depth ranges has advantages and disadvantages. Surface temperatures are easiest to measure and can be mapped in detail with thermal remote sensing, but are strongly influenced by solar radiation, vegetation, and climate, which make it difficult to identify geothermal heat contributions. In contrast, temperatures measured at depths greater than 20 m are largely unaffected by daily and seasonal (annual) solar radiation and climate changes (LeSchack and Lewis, 1983), and at these depths it becomes much easier to recognize and map geothermal heat flux. Unfortunately, drilling is usually needed in order to reach those depths, so that even though the temperature information is valuable, the expense and time required to drill wells severely limits the number of data points that can be obtained.

Temperatures at depths of 0 to 20 m are affected by daily and seasonal temperature cycles at the earth's surface, but this influence is progressively reduced at greater depth. At a depth of 1 m, temperature variations induced by the 24-hour solar radiation cycle are almost completely damped out (Elachi, 1987), even though annual (seasonal) temperature changes can be appreciable. Temperatures at these relatively shallow depths can commonly be measured without drilling holes: therefore the cost and time required to measure temperatures is much less than it is for measurements made at greater depths (> 20 m).

PREVIOUS WORK

The ability of shallow (1 to 2 m) temperature measurements to detect geothermal aquifers has been extensively documented (Olmsted, 1977; LeSchack and Lewis, 1983; Trexler et al., 1982). Recent success in detecting previously unknown, blind geothermal systems in Nevada, USA with shallow temperature methods (Coolbaugh et al., 2006a, 2006b) suggests that many more undiscovered blind geothermal systems in the Great Basin could be located using this technique. Relatively deep water tables and low influx of precipitation-derived shallow cold groundwaters make this an ideal method for much of the arid western US. Reasons why shallow temperature measurements have not been more widely used in geothermal exploration in the past may include 1) such methods have typically been relatively time-consuming and not fully field-portable, and 2) time and portability issues have limited measurements of shallow temperature anomalies to a bare minimum, sometimes leaving questions as to how effective the technique is and how widely it can be applied. In this paper, we discuss the development of a fully field-portable system that can measure shallow (2 m) temperatures relatively rapidly, and we provide an example of using such a method to greatly improve the spatial resolution of a mapped geothermal aquifer.

EQUIPMENT

Primary objectives in designing the 2-meter temperature probe were to 1) minimize the amount of thermal disturbance caused by inserting the probe in the ground, 2) minimize the thermal mass or thermal inertia of the probe so that temperature equilibration would occur rapidly, and 3) make a probe with sufficient strength to penetrate rocky soils. After a couple attempts, an efficient design was developed that consisted of 2.2 m lengths of ¼" schedule 80 seamless steel pipe (0.54" OD, 0.302" ID). The pipes were welded closed on one end and hard faced using Stoody 5/32" Bare Acetylene Tube Borium®. This is a hard facing welding rod, which consists of a steel tube with crushed tungsten carbide particles in the core. Applied with an oxy-acetylene torch, a tungsten carbide-containing alloy steel tip can be formed on the bottom of the probe (Fig. 1).

Figure 1. Tungsten carbide-containing alloy tip at bottom of 2.2 meter-long hollow steel probe (0.54" OD, 0.302" ID).

The top ends of the probes are threaded to accept a hexagonal pipe cap, which prevents mushrooming from an impact hammer. Using this design, low cost probes (approximately $50 per probe) with an extremely abrasion resistant tip (borium particle hardness 9.9 on Moh's scale) capable of penetrating moderately rocky ground were fabricated. Driving of the probes is accomplished using a Milwaukee ¾" hex demolition hammer having a 19.9 lb. blow energy (Fig. 2). A ground rod driver with a ¾" bore is attached to the demolition hammer for driving the probes. Power for the 12A demolition hammer is supplied with a 2.5 kW generator.

Figure 2. Hollow steel temperature probe being driven into ground with electric demolition hammer.

The inside diameter of the steel pipe allows insertion of a ¼" temperature sensor capable of measuring temperature with a precision of 0.1°C. The sensor consists of an Omega 4.5 x 30 mm platinum resistance temperature device (RTD) (1PT100KN3045) which is sealed in a ¼ x 6" stainless steel protection tube (SS-14-6 CLOSED) and connected to a 4-wire cable for connection to a digital meter or data logger at the surface.

The steel pipes, RTDs, data loggers, demolition hammer, generator, and auxiliary equipment easily fit into the rear bed of a 2-3 person all-terrain vehicle (ATV), and the rear gate serves as a working platform for hammering the probes into the ground (Fig. 2). For this study, 40 steel rods and two RTD sensors and one digital meter and one data logger were assembled. The total cost of all equipment, including the ATV and a trailer for transportation, was under USD $11,000.

DESERT QUEEN AND DESERT PEAK AREAS

The equipment was tested in the vicinity of Desert Peak in the Hot Springs Mountains of northwestern Churchill County, Nevada, USA in an area overlain by dry unconsolidated alluvium and colluvium. Two shallow but concealed thermal aquifers occur southwest and northeast of Desert Peak (Fig. 3). Temperature gradient drilling in 1973 intercepted the southwestern aquifer, eventually leading to the discovery of a geothermal reservoir and construction of a power plant near Desert Peak (Benoit et al., 1982). The northeastern aquifer, informally referred to here as the "Desert Queen aquifer" (Fig. 3), is roughly 70 m below surface and was discovered by temperature gradient drilling in 1974. Benoit et al. (1982) suggest that this aquifer is composed of thermal fluids flowing laterally and upwards away from the Desert Peak geothermal reservoir 8 km to the southwest. Alternatively, geologic mapping and structural analysis by Faulds and Garside (2003) and Faulds et al. (2006) have identified favorable fault environments closer to the Desert Queen area that could host a second concealed geothermal reservoir.

Because the location of the Desert Queen aquifer was only approximately defined with 9 temperature gradient holes in an 18 km^2 area, it was believed that additional temperature data could be helpful in pinpointing thermal upwelling zones potentially related to a geothermal reservoir at depth. The Desert Queen area would also provide a good test of the capabilities of the 2-meter temperature probe system, because the soils are rocky with frequent cobbles or boulders in the 10-30 cm size range and because the thermal aquifer is relatively deep (70 m) compared to the length of the temperature probe (2 m).

EQUILIBRATION AND CALIBRATION

Field tests were performed to ensure that temperature probes were left in the ground long enough to equilibrate with ground temperatures and to monitor seasonal changes in ground temperatures over the course of the field study. Individual RTD sensors were calibrated to each other to minimize temperature measurement bias between instruments.

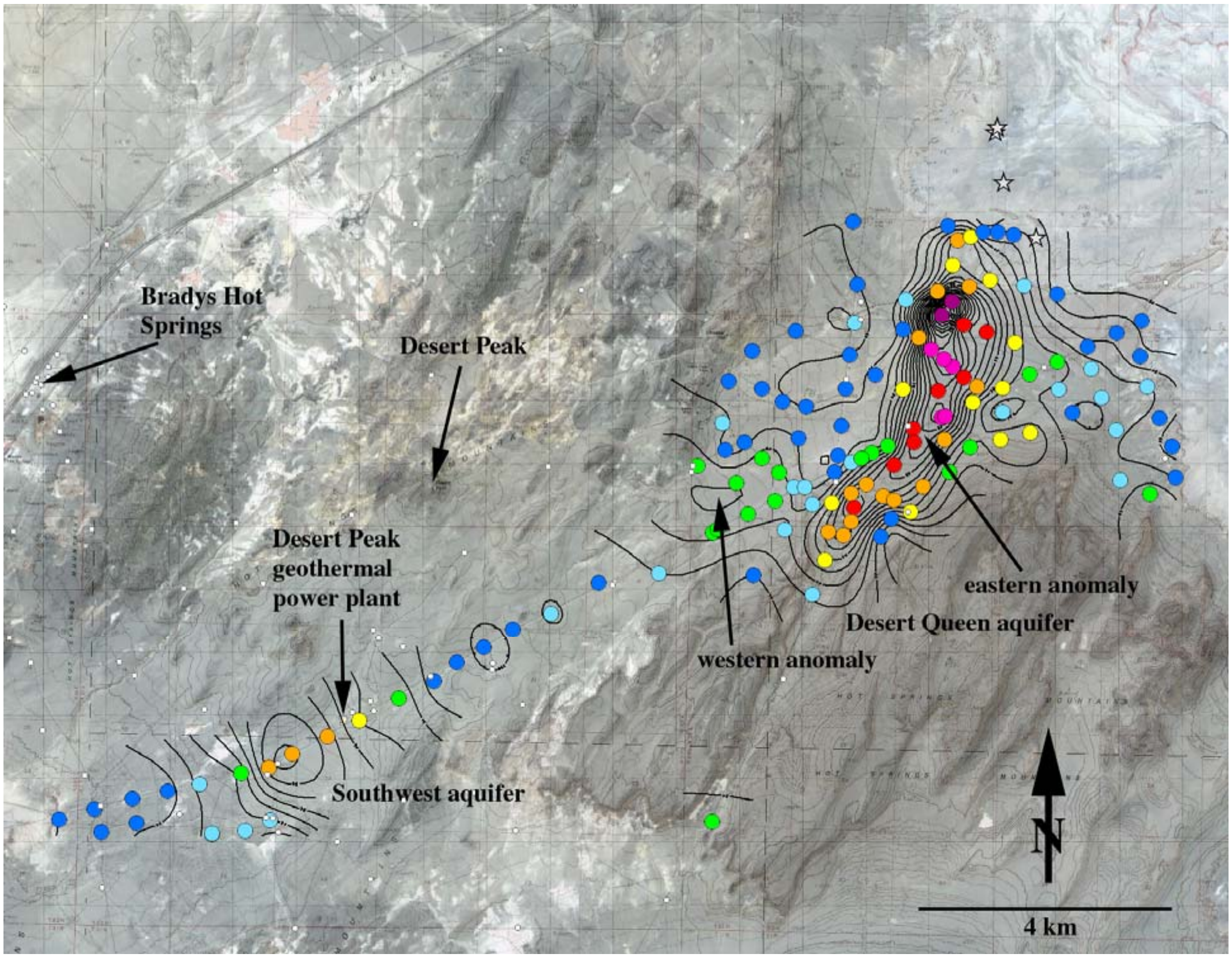

Figure 3. Temperatures at a 2-meter depth in the Desert Peak and Desert Queen areas of the Hot Springs Mountains, Churchill County, Nevada. Circle = 2-meter temperature; dark blue < 23°C, light blue = 23-24°C, green = 24-25°C, yellow = 25-27°C, orange = 27-30°C, red = 30-33°C, magenta = 33-36°C, dark purple > 36°C. Black lines are 1°C contours. Small white circles are temperature gradient wells. White stars are water wells. Background image is shaded topography superimposed on ASTER satellite bands 1-2-3.

Temperature Equilibration

Temperature equilibration was tested in a site in the study area consisting of dry, loose sand and gravel because the low soil moisture content and high pore volume of such material would have a relatively low thermal conductivity compared to most soils. Consequently the time required for equilibrium would likely be greater than at most locations. The RTD device in the bottom of the steel probe reached a full equilibrium temperature after 4 ½ hours. That point in time is defined here as the point at which temperatures at the bottom of the probe began to slowly decline at the average rate of 0.05°C/day which was equal to the seasonal temperature decline at that depth as determined by other tests described below. More importantly, the bottom of the steel probe approached within 0.1°C of the full equilibrium temperature after only 45 minutes (Fig. 4).

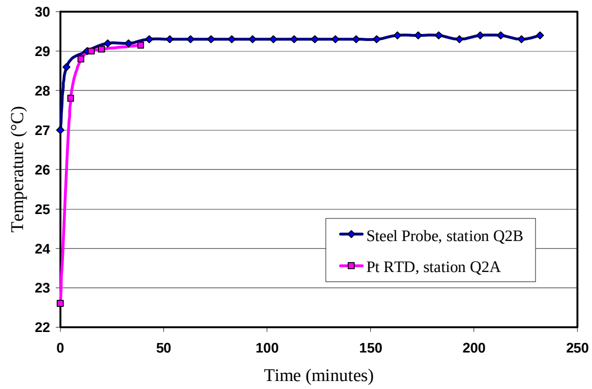

Figure 4. Time-temperature curves at the bottom of probes inserted into loose, dry sand and gravel to a depth of 2 meters. Diamond symbols mark temperatures at the bottom of a steel probe freshly inserted into the ground. Square symbols = temperatures of an RTD device inserted into a probe that had already been in the ground 27 days. At stations Q2A and Q2B equilibrium temperatures differ by 0.2°C.

When an RTD device was lowered to the bottom of a steel probe that had already been emplaced in the ground for 27 days, the temperature reached within 0.15°C of equilibrium temperature after 15 minutes and 0.1°C after 20 minutes (Fig. 4).

Seasonal Correction

The field survey took 9 days to complete over a 43 day span in October and November, 2006. During that time, ground temperatures at a 2 meter depth dropped by 2.2 to 2.5°C in response to seasonal cooling at the ground surface (Fig. 5). It was important to compensate for this effect so that temperature maps would not be biased or distorted by the date at which individual temperature measurements were made.

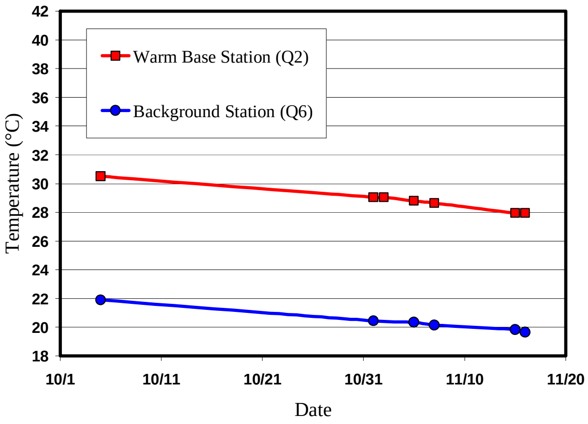

Figure 5. Seasonal changes in temperature at two base stations during the field survey at the Desert Queen and Desert Peak geothermal areas. Over a 43 day period, the temperature dropped 2.55°C at a base station overlying the thermal aquifer and 2.25°C at a background base station. The total range in uncorrected temperatures measured during the survey is represented by the y-axis, from 18 to 42°C.

Seasonal temperature changes were monitored with steel probes that remained emplaced at two base stations for the duration of the survey. One base station (Q6) monitored background temperatures while the other station (Q2) monitored temperatures overlying the thermal aquifer (Fig. 5). Temperatures decreased at both stations at a steady rate of about 0.05°C/day.

Individual temperature measurements were corrected for the seasonal effect by first calculating the average temperature drop experienced by the two base stations between the time the survey began and the time of the probe measurement in question, then adding that temperature drop to the probe temperature measurement. This procedure does not completely correct for seasonal temperature changes because the magnitude of the change will vary depending on the thermal conductivity of the soil. Thermal conductivities were not measured during this survey, but if soil compositions are relatively uniform, this temperature correction should serve as a good first approximation.

To evaluate the possibility that heat conduction in the steel rods could have changed ground temperatures at the base stations over a period of several days or weeks, three duplicate steel rods were emplaced within 1-2 meters of the original base stations. One of those rods was inserted near station Q2 after the original rod had been in place for 27 days, and the other two rods were emplaced respectively near stations Q2 and Q6 after the original rods had been in place for 43 days. The "twinned" rods yielded temperatures that were 0.2°C, 0.1°C, and – 0.1°C warmer than the original rods, suggesting that any such heat conduction effect is negligible within the measurement ability of the RTDs.

METHODOLOGY

The field survey was intentionally completed during October and November, at the end of what is typically a dry season in western Nevada and before wetter winter weather arrived. This made it possible to avoid the potential cooling effects of precipitation-derived shallow groundwater, so that the influence of heat conduction from the thermal aquifer on shallow soils could be maximized. With an ATV it was possible to emplace approximately 30 probes in an 8-hour field day. The time required to hammer one probe into the ground ranged from 10 seconds to several minutes depending on the hardness of the ground. In many cases it was clear that rocks and boulders were being broken and split by the action of the hammer, but in some instances it wasn't possible to penetrate hard ground and it was necessary to move the starting point 1-2 meters and try again. Although in some situations probe temperatures were measured within an hour or two to get rapid results, in most cases temperatures were measured on the following day because it took the entire day to emplace the probes. The temperatures were measured after leaving the RTDs in the bottom of the probe for at least 15 minutes. Global positioning system (GPS) devices were used to record the geographic coordinates of all sample stations.

After correcting the temperature measurements for seasonal effects, the data were interpolated to create a contourable temperature surface using a potential field-based minimum curvature algorithm. Minimum curvature is preferred over inverse distance or kriging because heat conduction occurs by a heat diffusion process as defined by potential field theory. Conduction-dominated temperatures constitute a scalar potential field analogous to gravitational and magnetic potential and hence can be modeled using algorithms that interpret temperature gradients in a manner consistent with a 3-D diffusion process.

RESULTS AND DISCUSSION

A total of 133 2-meter temperature measurements were obtained after 9 days of field work. In general the equipment performed well, and the authors were pleased with the ease of use. One unresolved issue is that roughly 10% of the steel probes could not be pulled out by hand after the measurements were completed. A mechanical puller is now being designed to expedite their removal in the future.

The southwest aquifer and the Desert Queen aquifer were easily detected by the field survey (Fig. 3). The difference between minimum and maximum 2-meter temperatures was 8.1°C southwest of Desert Peak and 23.3°C at the Desert Queen. Based on correlations with temperature gradient wells, the threshold value above which temperatures clearly appear related to geothermal activity is approximately 24°C.

In the Desert Queen area, if the original nine temperature gradient wells are compared with 2-meter temperatures taken from the same locations, the 2-meter temperatures do a good job reproducing the 30-meter (100-foot) deep temperature anomaly defined by the temperature gradient holes (Fig. 6). This provides evidence that the 2-meter temperature measurements are indeed mapping the thermal aquifer located approximately 70 m below surface. However, the size and shape of the thermal anomaly changes dramatically when more than 100 additional shallow temperature measurements are added to the map (Fig. 7).

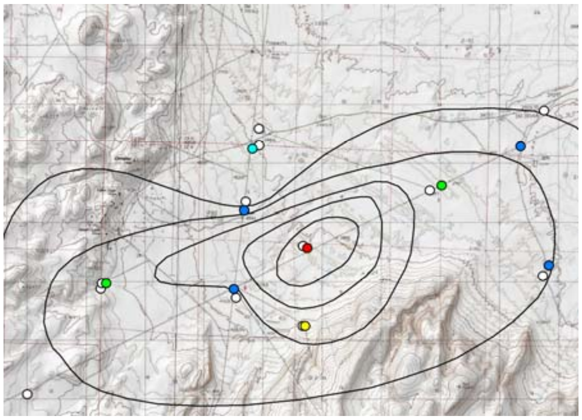

Figure 6. In the Desert Queen area, if only the 2-meter measurements close to temperature gradient holes are plotted, the thermal anomaly at 2-m depth defined by the shallow probe appears similar to that at 30-m depth defined by temperature gradient drilling. Black lines are 20°F (18°C) temperature contours at 30 m depth. White circles are gradient wells and colored circles are 2-m measurements (see Fig. 3 for key).

The temperature data provided by the 2-meter probes makes it possible to resolve the Desert Queen thermal area into two separate anomalies; a weak, broad western anomaly with peak 2-meter temperatures of 24-25°C and a stronger, narrower eastern anomaly with peak 2-meter temperatures of 30 to 43°C. Both of these anomalies are potentially significant. In the western anomaly, temperature gradient wells (Benoit et al., 1982) show that temperatures continue to increase below a depth of 100 m, suggesting the presence of a deep heat source. In the eastern anomaly, temperature gradient wells show a temperature reversal at approximately 70 meters, suggesting the presence of a flat-lying thermal aquifer at that depth (highest measured temperature = 89.6°C). The source of upwelling fluids that feed this aquifer has not been found, but several lines of evidence point to a potential upwelling zone near the southern end of this anomaly that has not been drill-tested. That evidence includes 1) surface topography, which is higher at the southern end of the anomaly, 2) the elevation of the aquifer in temperature gradient wells, also higher at the southern end, and 3) the fact that the southern end of the anomaly lies at the mouth of a long, northeast-trending canyon (Fig. 3) occupied by a normal fault. The intersection of this fault with possible east-west-striking faults near the southern end of the anomaly might be providing the opportunity for thermal fluids to rise from depth.

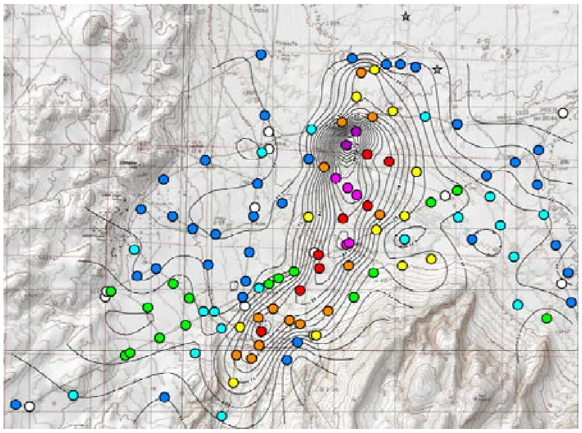

Figure 7. The shape of the thermal aquifer becomes much better defined when 100 shallow temperature measurements are added to the temperature gradient well data. Black lines and colored circles are as described in caption of Fig. 3.

The eastern anomaly is narrower (~ 1 to 1.5 km) and longer (~ 5.5 km) than previously recognized. The high length to width ratio suggests structural or lithological control on fluid flow. If the normal fault occupying the canyon southwest of the anomaly extends northeastward, it might easily provide the necessary structural control. Alternatively, because the anomaly roughly parallels surface drainages (gulleys), buried gravel channels might partially control the flow of thermal waters in the aquifer. On its northern end, the shallow temperature anomaly disappears when the thermal aquifer becomes hidden beneath shallow cold groundwaters associated with a water-saturated playa (Fig. 3).

Surface Geothermal Features

The improved resolution of the location of thermal aquifer(s) in the Desert Queen area made it possible to identify surface features whose relationship to geothermal activity had not been previously recognized. These features include carbonate tufa columns or towers. In many parts of Nevada, carbonate tufa towers formed around underwater springs in prehistoric Lake Lahontan, and they are good indicators of geothermal activity in some places, including the Pyramid Lake Paiute Reservation (Coolbaugh et al., 2006a). However, non-thermal springs can also produce carbonate tufa towers. Because the distribution of these tufas in the Desert Queen area (Fig. 8) did not appear to correlate well with the thermal anomaly defined by the earlier temperature gradient drilling and no hot springs or fumaroles are present, there was no reason to associate the carbonate formations with geothermal activity. But once the distribution of the shallow temperature anomaly was tightly defined, the association with tufa columns became clear (Fig. 9).

Figure 8. One-meter-tall carbonate tufa columns near the northern end of the eastern thermal anomaly, adjacent to a mud-flat playa.

The largest tufa towers, up to 2 m tall, occur just northeast of the highest temperatures measured by the 2-meter probes in an area between these high temperatures and a large mud-flat playa to the northeast (Fig. 8). If the highest temperatures are indicative of the closest approach of the thermal aquifer to the surface, it might be logical that past thermal springs would form between that area and the playa where the groundwater table is at or just below the surface.

Another feature potentially related indirectly to geothermal activity in the Desert Queen area is the presence of artesian wells. Two such wells occur in the mud flat near where the eastern thermal aquifer disappears beneath cold shallow groundwater in the playa (Fig. 9). Although the water issuing from these wells, at 18.7 and 16.4°C, is not hot, chemical analysis suggests a possible cooled geothermal component. Chloride (~ 5,900 mg/L) and sulfate (~ 400 mg/L) concentrations are broadly similar to those of reservoir fluids at the nearby Desert Peak and Bradys geothermal systems (chemical data from Nevada Bureau of Mines and Geology Information Office), and the quartz (no steam loss) geothermometer (Fournier, 1977; Fournier, 1981) and Mg-corrected Na-K-Ca geothermometer (Fournier and Truesdell, 1973; Fournier and Potter, 1979) yield reservoir temperature estimates of 127°C and 183°C, respectively. The difference between the two geothermometers might be caused by mixing of thermal waters with colder playa groundwaters. If so, it would help explain why the well waters are cold in spite of their relative proximity to the thermal aquifer.

CONCLUSIONS

The successful identification of thermal anomalies at both the Desert Peak and the Desert Queen geothermal areas demonstrates how easily shallow temperature measurements can be used to increase the efficiency and reduce the costs of geothermal exploration programs and provide a greater likelihood of success by: 1) locating thermal anomalies in an early stage of exploration, and 2) mapping thermal aquifers in more detail than normally possible with temperature gradient drilling, so that temperature gradient wells can be more

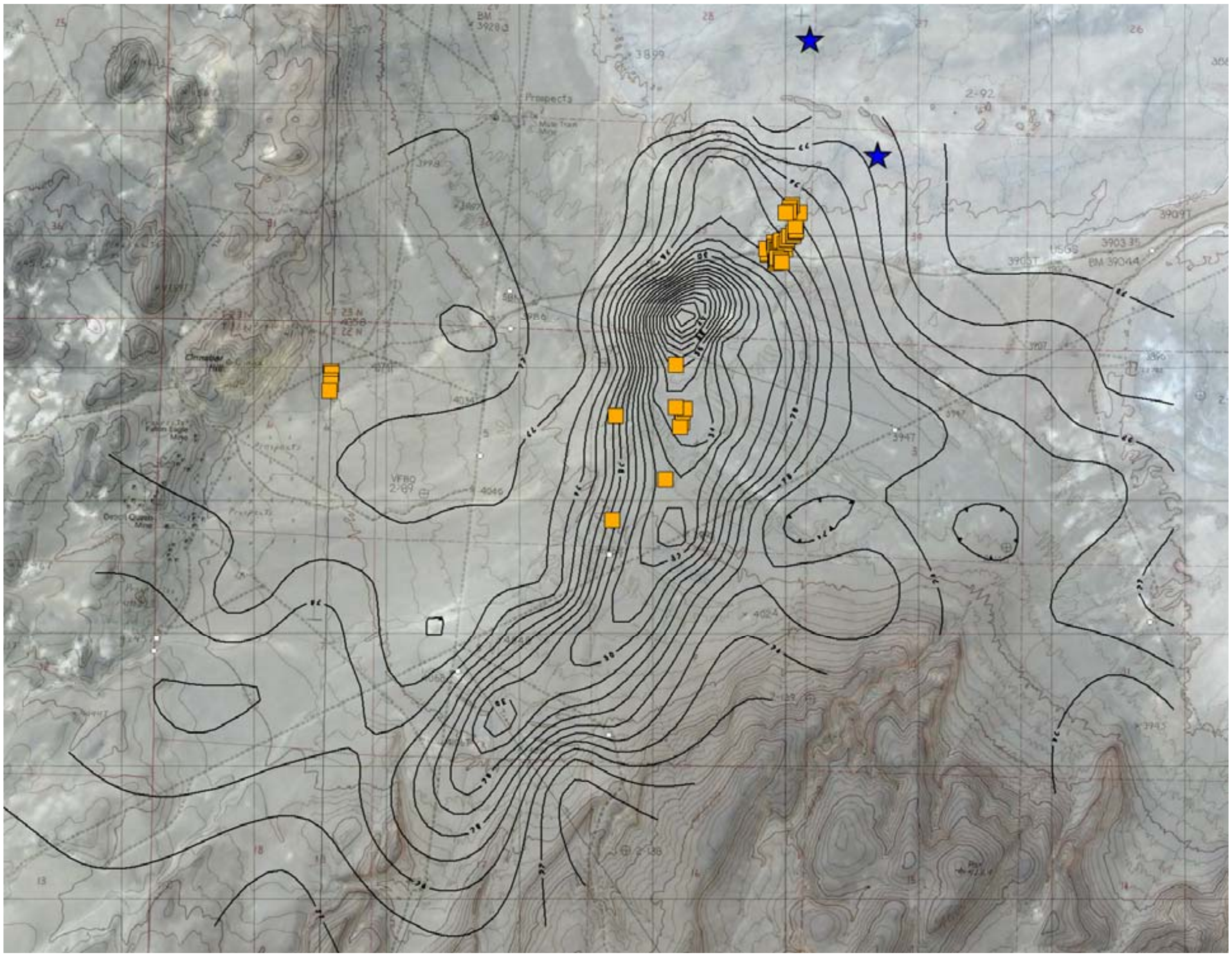

Figure 9. Location of carbonate tufa columns and artesian wells with respect to shallow temperature anomalies in the Desert Queen area. Yellow-brown squares are carbonate tufa columns. Blue stars are artesian water wells. Black lines are 1°C temperature contours. Black squares are 1km on a side. North is up. Background image is shaded topography superimposed on ASTER satellite bands 1-2-3.

accurately sited in areas of potentially upwelling geothermal fluids.

At the Desert Queen area, shallow temperature measurements were used to resolve two separate thermal aquifers. The eastern of these two aquifers may receive deeper thermal fluids from a possible upwelling zone located at its southern end where a northeast-striking normal fault may intersect with an east-striking fault. The ultimate source (geothermal reservoir) of these deeper fluids remains unknown but detailed structural mapping in progress by Jim Faulds of the Nevada Bureau of Mines and Geology is designed to identify potentially favorable structural hosts for such a reservoir. One possibility is that the relatively shallow eastern aquifer receives some or all of its fluids from the deeper western aquifer.

The eastern aquifer trends northward into a playa environment, where two artesian wells have chemistry suggestive of dilution of geothermal fluids with colder near-surface waters. The presence of tufas and fluid geothermometry are both permissive of geothermal reservoir temperatures up to 180°C.

The physiographic conditions that make the detection of relatively deep thermal aquifers possible with shallow temperature measurements at Desert Peak and the Desert Queen area are present at many other locations in the western United States. These conditions include relatively deep water tables and a low influx of precipitation-derived shallow groundwater. Efficient and rapid mapping of shallow temperatures has the potential for finding many more blind geothermal systems in the Great Basin.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to Lisa Shevenell, director of the Great Basin Center for Geothermal Energy at the University of Nevada, Reno, who provided significant material support and encouragement to pursue this research. Funding was provided by the U.S. Department of Energy under instrument number DE-FG07-02ID14311.

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