Development of 2-Meter Soil Temperature Probes and Results of Temperature Survey Conducted at Desert Peak, Nevada, USA

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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, temperatures measured at a depth of 2-meters is an efficient method for mapping thermal anomalies at a high level of detail. This is useful for augmenting deeper gradient drilling and for initial exploration of untested areas. We discuss the development and testing 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 in towards thermal anomalies. In testing the method developed, it was possible to map in much greater detail a 60 m (200 ft) deep thermal aquifer at the Desert Queen geothermal area, near Desert Peak, Churchill County, Nevada, USA, demonstrating that this technique can reduce the number of temperature gradient wells needed to identify zones of thermal upwelling. The probes are capable of penetrating moderately rocky ground, but improvements could extend their use to very rocky or indurated ground such as caliche and silicification.

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 temperatures at the surface are strongly influenced by solar radiation, vegetation, and climate, and as a consequence, geothermal heat contributions can be difficult to identify. 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 the further one goes below the surface. 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 often 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 today using this technique.

Probe Design and Development

Our initial attempts at shallow temperature measurements were conducted at a depth of approximately 1m by driving a 15 mm diameter steel rod into the ground, removing it, and then placing a 10 mm diameter thermocouple probe into the open hole. Because of the low mass of the 15 mm steel rod and the thermocouple probe used, and minimal soil disturbance, the temperature equilibrates in a short period of time, typically within 30 minutes. This method is low cost and highly portable, requiring only the steel rod, a heavy hammer, locking pliers (to extract the steel rod), and the thermocouple probe and meter. However, with further experimentation, it was found that thermal anomalies were better defined at a depth of 2 m at Pyramid Lake, NV using a hand soil auger to drill a hole, within which a thermocouple probe was placed to immediately measure the temperature (Coolbaugh et al, 2007). There are several disadvantages to this approach including 1) holes drilled in loose sand and gravel will not stay open during drilling, 2) rocky soils cannot be penetrated, 3) temperatures measured at the bottom of the holes can be subject to error if soils have sloughed into the hole or if friction effects during drilling were appreciable.

It was believed that if good temperature anomalies could be defined using a relatively crude augering technique, (Coolbaugh et al., 2007), that even better results could be obtained by custom designing a shallow temperature probe. It was decided that 2 m would be our target depth. The over all goal was to produce a detailed temperature map of approximately 100 data points with approximately one week of field time. The following constraints were set for our design: 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, 3) make a probe durable enough to penetrate rocky soils and relatively low cost. Several models of hand and light duty power soil augers were researched, but augers were ruled out because of soil disturbance and resulting longer equilibration time, and difficulty of drilling in rocky ground. This led us back to our original concept of a 15 mm steel rod and thermocouple probe. However, a temperature sensor would need to be incorporated into the rod that was to be emplaced into the ground. The idea of integrating a thermocouple into a ridged probe similar to the 10 mm thermocouple probe we were using for 1 m temperature measurements was considered but abandoned because of the following factors: added cost of building a large number of probes, the need to calibrate each probe, and the susceptibility of the thermocouple and wiring to damage during emplacement into the ground. This led to the development of a simpler design using a hollow probe within which a thermocouple could be inserted after the probe is driven into the ground. Since a thermocouple would not be part of the probe itself, a higher accuracy but more delicate RTD (resistance temperature device) or thermistor could be used instead of a shock resistant, but less precise thermocouple. A platinum RTD was selected because of use in other field equipment on hand.

Figure 1. Tungsten carbide hammer drill insert silver-soldered on tip of ¼" schedule 40 steel pipe probe. This design was abandoned in favor of the model shown in Figure 2.

The first probe design consisted of a 2.2 m length of ¼" schedule 40 steel pipe, with a tungsten carbide hammer drill insert silver-soldered on the bottom (Figure 1). We used a Hilti TE 15 hammer drill for driving the probes 2 meters into the ground. This initial design showed promise, but the Hilti TE 15 did not have sufficient impact or rotational torque to penetrate two of the four sites we tested. More seriously, at the fourth test site the probe broke off just below the weld for an adapter connecting the pipe probe to the TE 15 chuck. This indicated that a different coupling design was needed for use with a hammer drill, and that the use of hardened steel may be required since it was evident that higher torque and/or impact was needed. Because hardened steel probes would significantly increase the cost, we decided to test a heavier wall probe design and an impact-only method of driving the probe. The impact-

Figure 2. Final probe design with hard-faced tip and hex cap on top end of ¼″ schedule 80 seamless steel pipe. Close up shows tungsten carbide particle-containing hard-faced tip. (Note probe shown is 12" long for illustration purposes.)

only method also significantly reduces the safety hazards from probes breaking due to metal fatigue and rotational torque; since the probes would still be made from mild steel pipe they are more likely to bend than break catastrophically. We selected a Milwaukee ¾" Hex Demolition Hammer having a 19.9 lb blow energy and a ground rod driver for coupling the hammer to the probes. The ground rod driver is made of hardened steel, locks into the demolition hammer, and has a 4" by ¾" bore which fits over the top of the probe for driving it into the ground. This eliminates the need to directly couple the probe to the hammer. Seamless ¼" schedule 80 steel pipe was selected to make the more durable 2.2 m probe. The pipes were welded closed on one end and hardfaced using Stoody 5/32" Bare Acetylene Tube Borium®. This is a hardfacing welding rod containing 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 end of the probe (Figure 2). Using this design, low cost probes with an extremely abrasion resistant tip (borium particle hardness 9.9 on Moh's scale) capable of penetrating moderately rocky ground were fabricated. Initially, four of the hardfaced probes were made for a pilot test. An insert was placed on the top of the probe in a attempt to reduce mushrooming from the impact of the demolition hammer; however, after several uses, mushrooming prevented insertion of a ¼" diameter temperature sensor, and minor filing was required to allow clearance for the temperature sensor. To prevent mushrooming, in our final design, the top end of the probes was threaded to accept a hex pipe cap that would fit inside of the ground rod driver bore.

Sensors and Instrumentation

The temperature sensor is a platinum RTD assembled in-house using an Omega 4.5 x 30 mm 100 Ω Pt RTD connected to a 4 wire cable and potted in a ¼ x 6" stainless steel protection tube (Figure 3). Two RTD temperature sensor assemblies were built. Two different digital RTD meters were used, an Omega HH200A meter and an Omega HH2001P logging meter with optical/RS232 docking module. Both meters use a mini 4 pin connector for connection to the RTD probes; however, connector wiring is different for each one, so an adaptor cable was required for the meters to be interchanged with the temperature sensors. The logging meter can be used for either real-time measurements or logging the temperature at specified time intervals, and can store a maximum of 250 readings. The two RTD sensors and meters were calibrated against each other for correlation of temperature data.

Figure 3. RTD sensor potted in ¼" stainless tune with 4 wire cable and miniature connector.

Desert Queen and Desert Peak Test Areas

The equipment was tested in the vicinity of Desert Peak in the Hot Springs Mountains of northwestern Churchill County, Nevada, USA. Two shallow but concealed thermal aquifers occur southwest and northeast of Desert Peak (Figure 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", 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 by Faulds et al. (2004) has 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 is 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 second 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 and boulders, and because the thermal aquifer is relatively deep (70 m) compared to the length of the temperature probe (2 m), and no hot springs or other surface thermal expressions are known to be present.

Pilot Test at Desert Queen

For our initial tests we used a portable generator in the back of a pick up to power the demolition hammer. One person then stood on the tailgate and operated the hammer and the second person positioned the probe. One or two pairs of 10" locking pliers were used for extracting the probes with a twisting and pulling motion. Only two sites required a second attempt for a successful penetration to 2 m. Two reference stations were established; one near a temperature gradient hole with the highest temperature in the Desert Queen thermal anomaly, and one in a location where background thermal gradients were measured. During the pilot test it was possible to remove all the probes by hand using the 10" locking pliers, but it was later found that in roughly 10% of cases, a puller would be required.

During the initial field test, in spite of extra time required for monitoring the temperature of several probes for up to 30 minutes to gather initial temperature data and estimate equilibration times, we were able to make 12 temperature measurements in one day. In a 24-hour test using the data logger at one of the reference stations, the RTD reached full equilibrium temperature after 4 ½ hours. That point is defined as the point when the temperatures at the bottom of the probe began to decline at the average rate of 0.05°C/day which is equal to the seasonal temperature decline at that depth as determined by other tests described below. More importantly, the probe approached within 0.1°C of the full equilibrium temperature after only 45 minutes (Figure 4), and when an RTD device was lowered to the bottom of a probe that had been in place for several days, the temperature reached within 0.15°C of equilibrium temperature after 15 minutes and 0.10°C after 20 minutes (Figure 4). Because we were able to get accurate temperature readings within one hour of installing the probes, we were able to verify that the method was in fact detecting strong shallow temperature anomalies, and we modified our initial survey plans to begin mapping the temperature anomaly as the day progressed.

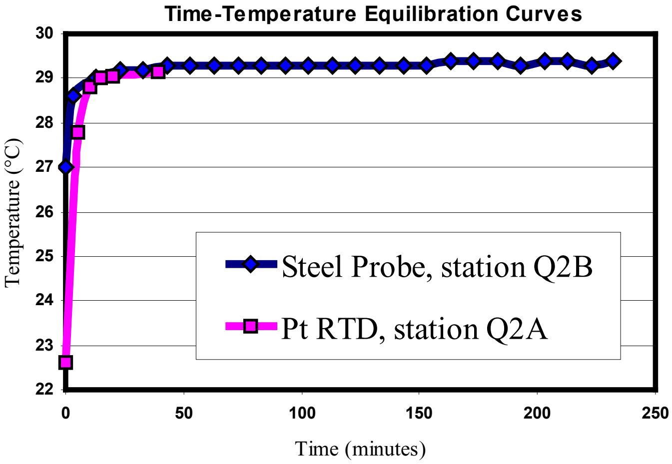

Figure 4. Time-temperature curves at the bottom of probes inserted into loose, dry sand and gravel to a depth of 2 meters. Diamond symbols mark temperatures at the bottom of a steel probe freshly inserted into the ground. Square symbols = temperatures of an RTD device inserted into a probe that had already been in the ground 27 days. At stations Q2A and Q2B equilibrium temperatures differ by 0.2°C. (From Coolbaugh et al., 2007).

Desert Queen and Desert Peak Final Test

After evaluating the results of the pilot survey and inspection of ware on the probes, 40 additional probes, with threaded caps, were constructed. A simple puller incorporating a ratchet type hand wench (come along) was constructed for pulling stuck probes out of the ground. A four-wheel drive all-terrain vehicle (ATV), generator, and trailer were purchased to increase mobility beyond sites easily accessible from established roads. The ATV selected was a Polaris Ranger. The Polaris Ranger provides seating for three people and ample cargo room for all field gear. The total cost for all equipment, including the ATV and trailer for transportation, was under USD $11,000 (Figure 5).

Figure 5. 1/4" steel pipe probe being driven into ground with electric demolition hammer, and complete field setup of utility vehicle with approximately 20 2.2m probes, demolition hammer, generator. (From Coolbaugh et al., 2007).

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 (Figure 6). 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. Seasonal temperature changes were monitored with probes that remained emplaced at the 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 (Figure 6). Temperatures decreased at both stations at a steady rate of about 0.05°C/day.

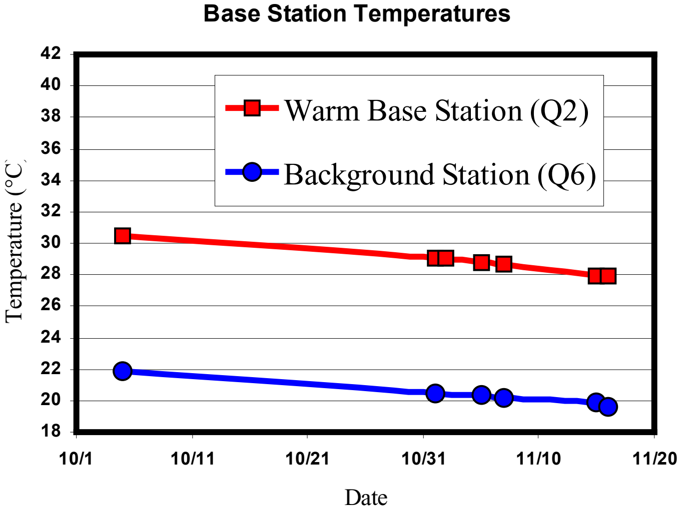

Figure 6. Seasonal changes in temperature at two base stations during the field survey at the Desert Queen and Desert Peak geothermal areas. Over a 43 day period, the temperature dropped 2.55°C at a base station overlying the thermal aquifer and 2.25°C at a background base station. The total range in uncorrected temperatures measured during the survey is represented by the y-axis, from 18 to 42°C. (From Coolbaugh et al., 2007).

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 specific probe measurement and 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 probes could have changed ground temperatures at the base stations over a period of several days or weeks, three duplicate probes were emplaced within 1-2 meters of the original base stations. One duplicate probe was inserted near station Q2 after the original probe had been in place for 27 days, and the other two probes were emplaced respectively near stations Q2 and Q6 after the original probes had been in place for 43 days. The "twinned" probes yielded differences of +0.2°C, +0.1°C, and – 0.1°C with respect to original probes, suggesting that any such heat conduction effect is negligible within the ability of the RTD to measure it.

Results and Discussion

All the equipment preformed well and exceeded some of our expectations. In 9 days of field work a total of 133 temperature measurements were made. A few locations posed significant problems when attempting to drive the probes. These areas contained frequent cobble sized and larger rocks, buried travertines or tufa, sinters, or thick caliche. The fact that the survey could be adjusted in real time by measuring initial temperature at some locations allowed us to tighten up the survey for more detail in key areas. In less than 15 minutes it was sometimes possible to determine whether the temperature was likely to be higher or lower than the previous location and then direct the location of the next holes accordingly.

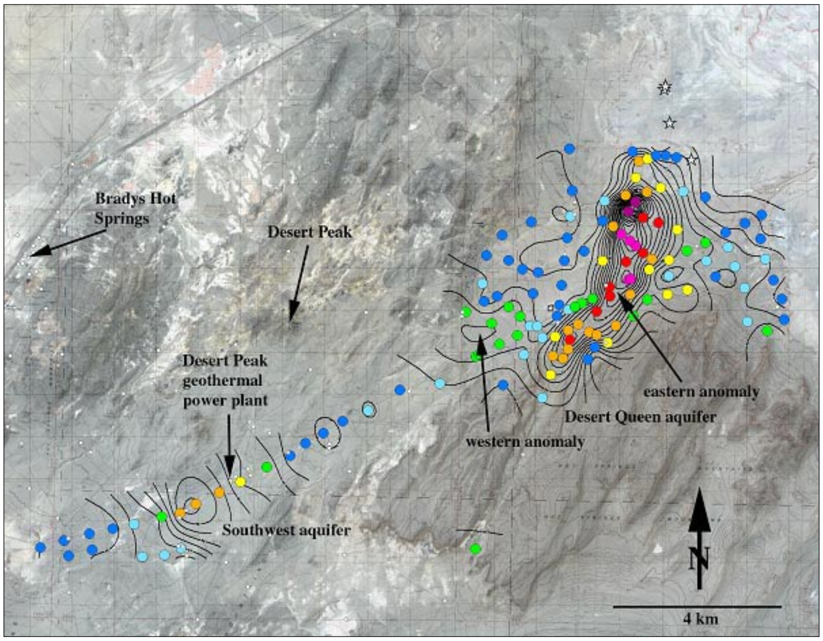

Figure 7. Temperatures at a 2-meter depth in the Desert Peak and Desert Queen areas of the Hot Springs Mountains, Churchill County, Nevada. Circle = 2-meter temperature; dark blue < 23°C, light blue = 23-24°C, green = 24-25°C, yellow = 25-27°C, orange = 27-30°C, red = 30-33°C, magenta = 33-36°C, dark 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. (From Coolbaugh et al., 2007).

Thermal aquifers southwest of Desert Peak and at the Desert Queen area were easily detected by the field survey (Figure 7). 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 are consistent in reproducing the 30-meter (100-foot) deep temperature anomaly defined by the temperature gradient holes. This provides evidence that the 2-meter temperature measurements are indeed mapping the thermal aquifer located approximately 70 m below surface. 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 (Figure 7) occupied by a normal fault. The intersection of this fault with a possible east-west-striking range bounding fault near the southern end of the anomaly might provide a conduit for thermal fluids.

Conclusions

The equipment preformed well and exceeded many of our expectations. Significant difficulties were encountered in a few areas, indicating that the method is limited to moderately rocky ground and minimal induration. The successful identification of thermal anomalies at both the Desert Peak and the Desert Queen geothermal areas demonstrates how easily shallow temperature measurements can increase the efficiency of geothermal exploration programs and provide a greater likelihood of success by; 1) locating thermal anomalies in an early stage of exploration, 2) mapping thermal aquifers in more detail than normally possible with temperature gradient drilling, so that temperature gradient wells can be more accurately sited in areas of potentially upwelling geothermal fluids. 3) potentially reducing the number of gradient holes required, thereby reducing overall costs and permitting issues.

Improvements

Although we were successful in deploying a large number of the ¼" pipe probes, problems were encountered in several areas due to large rocks, tufa, and carbonate cemented ground, indicating that this method is limited to applications where the ground is only moderately rocky. The use of a small conventional air powered rock drill could expand the application into rockier or more indurated ground. Portable light duty drills and compact compressors that would fit in the ATV used in this study are available.

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