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Gwangju, South Korea Temperature Data for 3.5 km Well

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ABSTRACT

Continuous temperature data were collected by the SMU Geothermal Laboratory and Perma Works LLC from a well bore in Gwangju, South Korea. The Hanjin D&B well was drilled to 3.502 km, with circulation stopping August 29, 2013. The precision temperature logging occurred November 21-22, 2013. In 2012 the first temperature log was completed to 2.5 km by the Korean Institute of Geoscience and Mineral Resources (KIGAM). The KIGAM log was a week after drilling fluid circulation stopped at that depth. Comparison of the temperature logs shows similar trends in temperature and the effect of the drilling fluid on the borehole. Granite is the dominant lithology from the surface to the maximum depth of the borehole. The gradient at this site is 25 °C/km from 2.0 to 3.1 km. The heat flow is 56.3 W/m^2 ± 10%. Well temperatures are expected to be 112°C at 4 km and 169°C at 7 km (±5% error) based on a thermal model. Hanjin D&B will continue to drill the well with a goal of reaching 7 km. The well is located such that it is part of a renewable energy park currently under construction. Once the drilling is completed, the well may be used for heat or possibly electricity for the site.

1. INTRODUCTION

A deep borehole was drilled in the city of Gwangju, South Korea by the Hanjin D&B Company in 2012-2013. The SMU Geothermal Laboratory and Perma Works LLC collected temperature data from the Hanjin D&B well drilled to 3.5 km and then determined the area heat flow. The well is a result of a technical drilling demonstration project. Hanjin D&B developed a new water hammer technology that is capable of drilling through granites at a higher speed than previous technology with a relatively small footprint. The Gwangju well site is near a water treatment plant and a renewable energy park currently under construction (Figure 1). The total demonstration drilling depth is designed to reach seven kilometers and for the well to be used for heat or electricity on-site as part of the renewable energy park project.

The borehole site is part of the greater tectonic province of the Okchon fold belt (Kim et al., 2001). The oldest rocks are composed of plutonic (batholith) granites of Upper Proterozoic and the more recent ones are Bulguksa granites of Cretaceous age. In the first 3.5 km of drilling, the granite is fairly consistent. Slight changes in density occur in the upper portion of the granite. At 440 meters the density is 2.6 g/cm^3, at 1.0 km the density is 2.53 g/cm^3, and at 1.530 km the density is 2.58 g/cm^3 (Kim, 2012). At 1.530 km the rock is described by Kim (2012) as biotite granite. There is a small change in lithology between the depths of 1.660 and 1.690 km where small pebbles were found. The review of the rock cuttings collected by the Hanjin D&B Company while drilling to the current depth of 3.5 km shows a similar visual composition throughout the borehole. No additional analysis has been made except for the analysis completed by Kim (2012). A granite type of rock is expected to continue to depths below 7 km, and for the temperature projection models described below, granite is used as the formation to 10 km.

Figure 1. City of Gwangju, South Korea. Hanjin D&B drilling demonstration site marked as yellow triangle. Water treatment plant is located on left side of the drilling site. Latitude: 35° 9’ 21”, Longitude: 126° 50’ 4”. North is top of map.

2. METHODS

On August 29, 2013, the Hanjin D&B well was drilled to 3.502 km and circulation was stopped. The SMU Geothermal Laboratory temperature logging occurred November 21-22, 2013. Logging of the Hanjin D&B well was completed by a team comprised of the SMU Geothermal Lab, Perma Works LLC, and on-site assistance from Hanjin D&B. The maximum operating probe temperature was limited not by the probe, rather the lithium batteries requirement of < 105°C. Low-temperature lithium batteries were used because of airline restrictions for high temperature lithium batteries being hazardous. The probe memory board was capable of collecting 4 hours of data and took readings for temperature (°C), pressure (PSI), pressure temperature (°C), and circuit board temperature (°C) at a sampling rate of one reading per second.

2.1 Instruments

The slick line and depth reader systems were supplied by Hanjin D&B. A depth counter determined the probe positioning within the well, however, due to the availability of only one depth reader, the accuracy of the depth measurement could not be verified. The depth counter did slip off the line twice during logging but was recovered within a few seconds (meters). In addition each time the probe was inserted into the well there were variations in the depth counter zero (surface) measurement related to where the counter was attached to the line and probe’s exact position. As a result, the depth measurements are not exact, rather ±1 meter. A second depth verification was based on the probe returning to the surface of the platform and the reading on the depth counter. From this we determined that the amount of line positioning difference between the counter value and the actual value to be less than five meters between all the different logging runs. This is a difference in temperature of < 0.15°C.

The probe collected the hour:minute:seconds starting when the computer memory was turned on. In the computer file, the depth measurements were tied to the temperature and pressure measurements using a surface timer (a manually operated cellular phone) and noting when the probe started its descent, time at each point of stopping for calibration, and when the probe descent reversed to return to surface. The surface times were also matched to where the probe was within the well using the pressure readings, such that when the recorded values began to consistently repeat the same pressure over minutes, it represented the probe not moving in the borehole. Use of the pressure measurement for probe movement is significant for finding situations when the line was being lowered and those at the surface thought the probe was moving deeper, but instead was hung-up in the well and stationary.

2.2 Temperature Logs of Well

Previously, there was a temperature log completed in December 2012 to a depth of 2.5 km by the Korea Institute of Geoscience and Mineral Resources (KIGAM) (Figure 2). The KIGAM temperature log was run a week after drilling fluid circulation was stopped so it is expected to have some drilling fluid disturbance. A comparison of the SMU 2013 log with the KIGAM 2012 log shows the main difference in temperature in the upper 1.250 km of the borehole, with the 2012 log cooler in this section.

During the November 2013 measurements, three temperature – pressure well logs were taken during the two days. Log 1 logged from surface to 2.0 km. Log 2 logged from surface to 3 km with the primary focus (slower speeds for tool equilibration) between 2.0 and 3.0 km (Table 1.). This log was designed to maximize the four hour memory window and overlap with the December 2012 KIGAM temperature logging. An example of the probe descent speed and length of stop duration for confirming calibration are shown for the temperature log to 3.0km in Table 1. The fully assembled well log is plotted in Figure 2.

Table 1. An example of an logging run for the well in Gwangju, South Korea

Log 2: November 22, 2013			
Time	**Depth (meters)**	**Measurement duration**	**Rate of Probe**
9:40 am	0-475	Start of log	>30 meters/minute
	475	15 minutes	
	475-1500		>30 meters/minute
	1500	11 minutes	
	1500-2000		>30 meters/minute
	2000	6 minutes	
	2000-2200		10 meters/minute
	2200	6 minutes	
	2200-2500		10 meters/minute
	2500	6 minutes	
	2500-2700		10 meters/minute
	2700	6 minutes	
	2700-3000		10 meters/minute
	3000	6 minutes	
2:41 pm	surface		>30 meters/minute

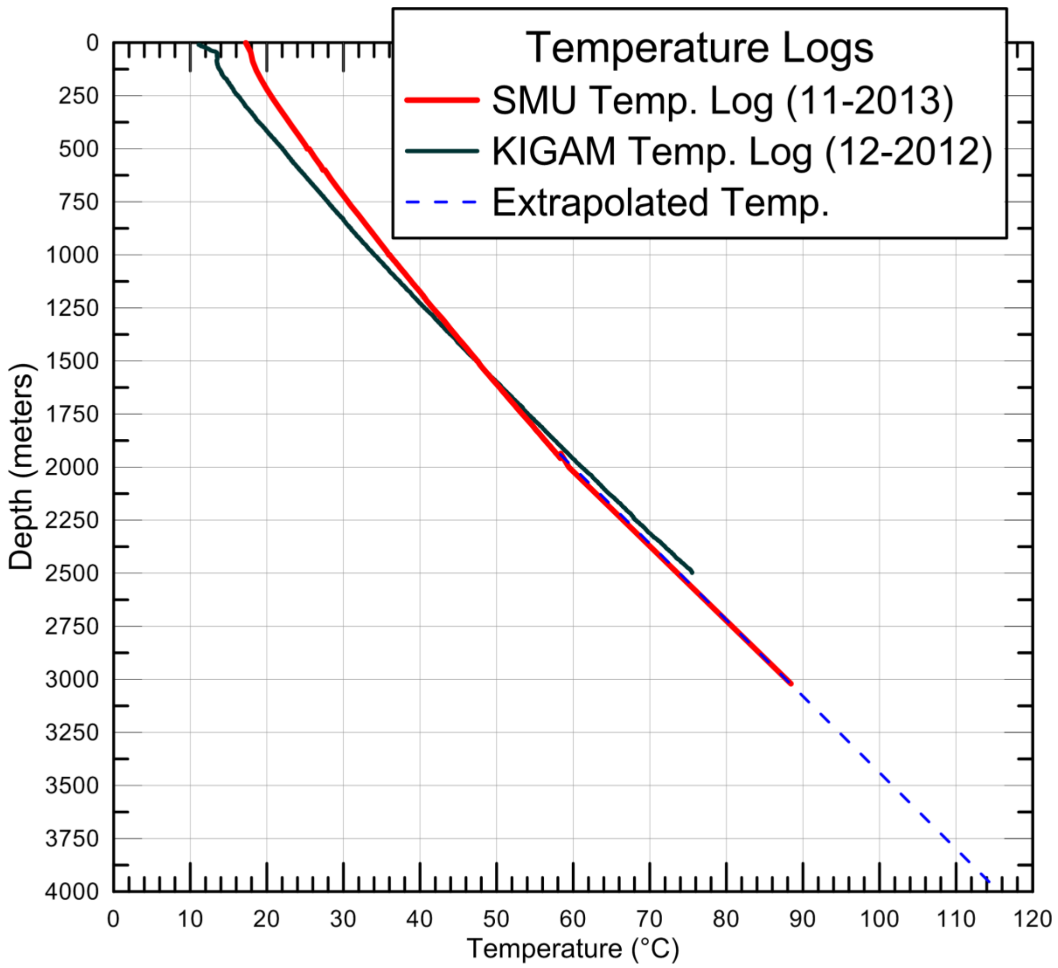

Figure 2.Temperature log of Hanjin D&B well drilled to 3.5 km and measured to 3 km.

Due to the memory limitation of the tool, it was decided to run two separate logs the second day. The first log focused on the 2.0 – 3.0 km interval to maximize the four hour memory window and overlap with the previous KIGAM temperature logging (Table 1, Figure 2). To reach the 2.0 km start point, the probe descended at speeds greater than 30 meters/minute and stopped at 475 meters for 15 minutes due to equipment malfunction. The logging then continued at similar speeds before stopping for eleven minutes at 1.5 km to calibrate with the first log. From 1.5 to 2.0 km the probe continued at speeds greater than 30 meters/minute before stopping at 2.0 km for six minutes. The rate of descent of 10 meters/minute was used from 2.0 to 3.0 km, stopping every 200 to 300 meters for depth/temperature/time correlation (Table 2). This is the longest temperature log obtained in November 2013. The upper portion of the second log matches the first log within a few tenths of a degree of each other. The third log was designed to collect data primarily from 3.0 to 3.4 km then collect temperatures at interval depths as it returned to the surface. Based on the pressure readings, it was determined that the probe did not reach a depth of more than 3.1 km because of being hung-up and not able to descend to the bottom or the well as expected. The wellbore is inclined from true vertical to a greater extent below 3.0 km, based on the drilling report from Hanjin D&B. This is most likely the reason for the probe to hang against the side and thus not descend to the full well depth.

2.3 Model of Temperature to 10 km

Based on the geology and the measured temperatures, the temperatures-at-depth to 10 km are then determined using the methodology of Blackwell et al. (2011) and Stutz et al. (2012). The November 2013 temperature-pressure data is incorporated with other published values. The model put forward by Stutz et al. (2012) requires input of mean surface temperature, known shallow temperatures values, thermal conductivity of the rock layers to basement rock, surface and mantle heat flow for the region, and heat generation (Table 2). The model calculates temperature-at-depth for each depth specified in the program starting from the known shallow temperature values, and uses the other parameters to calculate site temperatures to depths of 10 km. The published value used for heat flow was 67 ± 1 mW/m^2 for plutonic rocks in the southern area of the Republic of Korea, e.g. Kim and Lee (2007). The mean surface temperature in Gwangju is 13.8°C based on the data from the Korea Meteorological Administration (http://www.kma.go.kr/weather/climate/average_30years.jsp?yy_st=2011&stn=156&norm=Y&x=19&y=10&obs=0. Thermal conductivity values (3.2 W/mK surface to 1 km, 2.5 W/mK for 1 to 4 km, and 2.5 W/mK for deeper than 4 km) were based on established values for granite and basement rocks, e.g. Beardsmore and Cull (2001). Model 1 temperature values are as follows: 115°C at 4 km, 171°C at 7 km, and 227°C at 10 km (Table 2).

Next the data from the Technical Advisory Report (Kim, 2012) to Hanjin D&B became available after the well logging. We recalculated temperatures at depth using values from the report along with the current temperature logging data. For Model 2, the thermal conductivity values were 2.28 W/mK for the near surface interval and 2.22 W/mK for 1 to 4 km, and 2.5 W/mK for deeper than 4 km. The 25°C/km gradient from the 2 – 3 km depth temperature measurements was used with the thermal conductivity to calculate a heat flow of 56.3 mW/m^2 (Table 3). The resulting temperatures calculated with Model 2 are slightly lower than Model 1 with values of 112°C at 4 km, 169°C at 7 km, and 218°C at 10 km (Table 3). The error of the temperatures calculated from the models is 5% based on the variation in thermal conductivity and differences in temperature measurements between the different logging runs.

The values obtained from the November 2013 temperature logging are different from the December 2012 log showing that the well may not be in thermal equilibrium. Normally the well borehole is heated at the surface and cooled at deeper depths from the impact of the drilling fluid. Although the well in November 2013 had been shut-in for over 2 months when the SMU – Perma Works LLC team measured the temperatures, the drilling of the well occurred for over a year. While drilling, the fluids are moving through the borehole. A general rule is that it takes a well about one month per year of production to reestablish an *in situ* temperature depending on the type and amount of fluid produced (Blackwell personal communications). The impact of drilling fluid on geothermal wells can take months to return to *in situ* values (Yang et al., 2013). In this case it is drilling rather than production impacting the borehole. The calculations of the temperatures at deeper depths are not designed to be exact representations of the subsurface temperatures below what was measured in 2013, rather model approximations helpful in planning for the development of the site for geothermal usage.

Table 2. Values used in Model 1 for temperature calculations to 10 km based on current publication values of heat flow and thermal conductivity data for region and temperature measurements from 2013 logging.

M1- Parameter	Value
Surface Temperature	13.8°C
Temperature at 1 km	33.4 °C
Temperature at 2 km	59.4 °C
Temperature at 3 km	87.6 °C
Thermal Conductivity	3.2 W/mK
Surface Heat Flow	67 mW/m^2
Lower Crust Heat Flow	30 mW/m^2

M1 - Estimated Temperatures		
Depth	°C	error
4 km	115	± 5%
7 km	171	± 5%
10 km	227	± 5%

Table 3. Values used in Model 2 for temperature calculations to 10 km based on data from site Technical Advisory Report (Kim, 2012) and temperature measurements from 2013 logging.

M2 - Parameter	Value
Surface Temperature	13.8°C
Temperature at 1 km	33.4 °C
Temperature at 2 km	59.4 °C
Temperature at 3 km	87.6 °C
Thermal Conductivity	2.25 W/mK
Surface Heat Flow	56.3 mW/m^2
Lower Crust Heat Flow	30 mW/m^2

M2 - Estimated Temperatures		
Depth	°C	error
4 km	112	± 5%
7 km	169	± 5%
10 km	218	± 5%

3. DISCUSSION

The Hanjin D&B Company has been successful in drilling one of the deepest wells in granite. They are expecting to continue drilling in 2015 to a depth of 7.0 km. The current extrapolated temperature to 4.0 km is approximately 112°C ±5°C. This well site is an opportunity for researchers to determine how much the thermal conductivity of a granite body will change over depths from 4 to 7 kilometers. At the current rate of temperature increase the 7.0 km depth temperature would be ~169°C±8°C. It is expected that both the heat production and the thermal conductivity will decrease with increasing depth (Roy et al., 1968; Pribnow and Sass, 1995). The decrease in heat production is accounted for in the model, which calculates the 7.0 km temperature closer to 170°C, rather than the extrapolated temperature value of 187°C based on gradient alone. The ability to measure accurate, high precision temperatures in a deep borehole with a continuous well log is a desired outcome of the next well logging opportunity. The logging tool will require caliper arms to keep the tool in the center of the borehole to reduce the likelihood of it becoming stuck in the borehole, especially in sections where the borehole is less than vertical. Such a continuous temperature profile of the granite will be helpful in determining if there is water entering and/or leaving the well or if convective circulation cells occur within the well bore.

4. CONCLUSION

Many processes within the Earth's crust are temperature and pressure dependent. Properly being able to determine heat flow and expected temperatures from deeper sources is an important next step in order for the geothermal community to be successful in developing enhanced geothermal systems. The temperature estimated by Lee et al. (2010) for 4 km was approximately 90°C, the temperature found in the borehole at approximately 3 km. With each new deep borehole, the actual temperature measurement improves the methodology and geological understanding for estimating the deeper temperatures. As the Gwangju, South Korea well is drilled deeper, it will hopefully be used as a test site for thermal conductivity, pressure, stress, and temperature studies gives current researchers an opportunity to expand on the knowledge previously gained by the past deep boreholes such as the KTB in Germany and the Kola borehole in Russia (Pribnow and Sass, 1995; Popov et al., 1999).

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