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Utah FORGE Reservoir: Drilling Results of Deep Characterization and Monitoring Well 58-32

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ABSTRACT

Scientific test well 58-32 was drilled to a depth of 7,536 ft (2,297 m) to obtain direct measurements on rock type, temperature, permeability and stress within the Utah FORGE reservoir. Well 58-32 encountered the top of the granite at about 3200 ft. (975 m) and the top of the FORGE reservoir at 6500 ft. (1980 m) based on expected formation temperature. Drilling tool selection kept the rate of penetration reasonable through the hard rock formation. The well was cased with 7-inch casing to a depth of 7,374 ft. (2,247 m). Core samples were collected near the top of the expected reservoir and at total depth, prior to running the casing in the hole. Injection testing and fall-off pressures provide data on the permeability of the crystalline rock. Additional data were obtained, including a suite of geophysical logs, pressure and temperature surveys, and microresistivity image logs. An injection test was conducted in the open hole section of the well. The temperature surveys indicate over 350°F (175°C) at the reservoir depth, as required for the FORGE initiative enhanced geothermal systems laboratory. The drilling and testing of 58-32 well was completed deeper than planned, ahead of schedule and under budget.

1. INTRODUCTION

The goal of the Frontier Observatory for Research in Geothermal Energy (FORGE) project administered by the U.S. Department of Energy is to establish a dedicated site where the subsurface scientific and engineering community can develop, test, and improve technologies and techniques for the creation of cost-effective and sustainable enhanced geothermal systems (EGS) in a controlled, ideal environment. Well 58-32 was drilled vertically to a depth of 7,536 ft, and is the first well of the in the Milford area FORGE Utah EGS prospect area (FORGE Deep Well Site), managed by the University of Utah, completed as part of Phase 2b of the initiative.

The Opal Mound Fault separates the Roosevelt Hot Springs hydrothermal system to the east from the conductive thermal regime surrounding the Utah FORGE site to the west. The target rock formation for 58-32 was granite and gneiss below the alluvium. The target represents a region of hot crystalline rock suitable for EGS development. The intent of the drilling was to determine the characteristics of the rock within in the target formation and at the depth and temperatures of interest.

Specific objectives of 58-32 were to:

- Investigate temperature, permeability, stress directions, stress magnitudes, and rock type to determine if reservoir conditions suitable for EGS development exist
- Gather geological and reservoir data to improve future well targeting and aid in resource modeling and assessment
- Conduct a test to determine the conditions needed to create new fractures or open existing fractures
- Drill the wells to the proposed depth within the estimated time and budget

These well objectives were achieved through geological and reservoir data that was collected and will be fundamental in the resource modeling and assessment as the project continues. The drilling and testing phases confirmed that the site meets the temperature, rock type and permeability requirements established by the DOE for an EGS site. The well was also drilled under budget, in a shorter time than planned (58 days versus 73 days planned), and 476 ft. deeper than planned.

1.2 Project Location

The 58-32 well site is located within the 1.9 square mile FORGE deep drilling site west of the Mineral Mountains, is 217 mi south of Salt Lake City and 10 miles north-northeast of the town of Milford (Figure 1). The site is located in the Milford Energy Corridor in eastern Beaver County, Utah. The entire project area is rural and covers approximately 15.5 square miles.

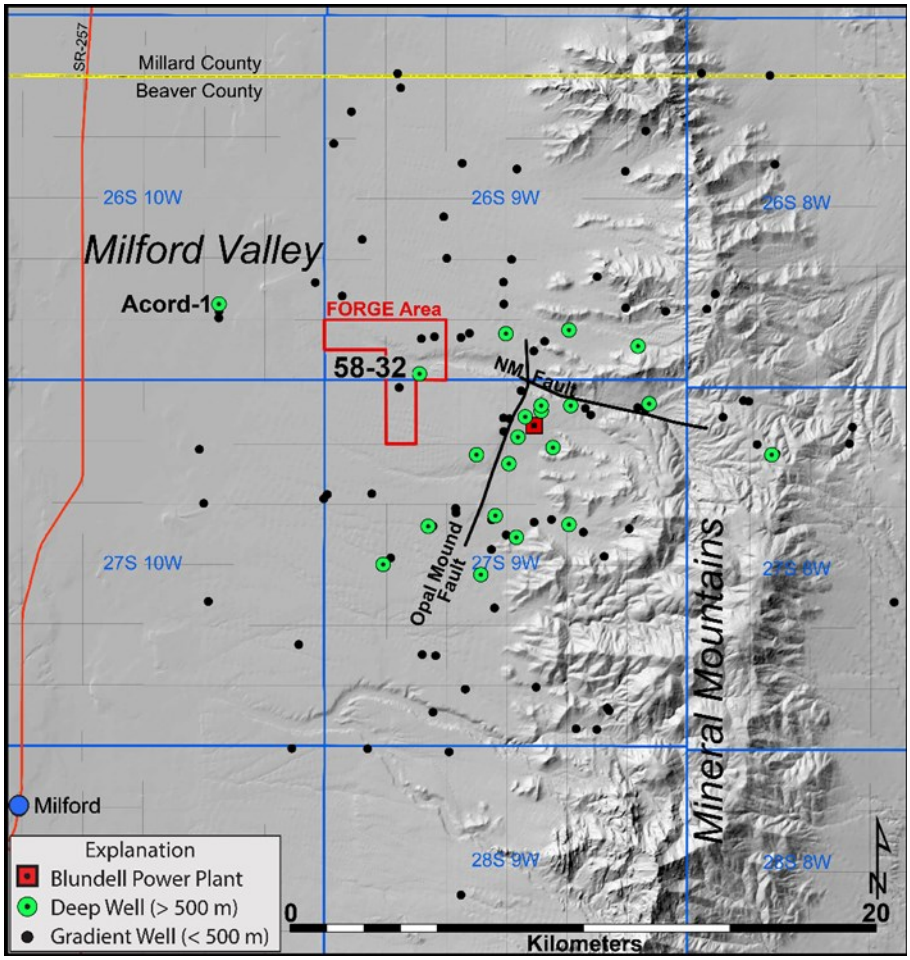

Figure 1: Location of well 58-32 in the FORGE Utah deep drilling area. More than 100 deep and shallow wells have been drilled since the 1970s.

1.2 Planned Construction

Well 53-32 (originally named MU-ESW1) was planned as a mid-size, vertical, EGS exploration well to a total depth of 7,060', with two cored intervals within the formation of interest (Figure 2). A 20" conductor casing was to be set at 40', a 17-1/2" surface hole with cemented 13-3/8" casing was planned to 300', the intermediate 12-1/4" hole with cemented 9-5/8" casing was planned to 2,100', below this an 8-3/4" hole to 7,060' was planned, with cemented 7" casing to 6,900', and open hole to total depth (TD).

The geologic prognosis for the well was based on the lithologic logs from Acord-1, 9-1, and OH 4 wells along with some gravity modeling data. Thicknesses of units were only moderately constrained by the surrounding well data. Alluvium and some rhyolitic tuff mixed in with tuffaceous valley fill and lacustrine sediment were expected to about 2,100'. Below this, the formation was expected to be interfingered zones of Precambrian biotite-quartz-feldspar gneiss and Tertiary granitic intrusive of varying composition. The formations were primarily known from the surrounding ranges.

Well 58-32 was expected to intersect the target temperature in the formation of interest at 6,500 ft. The targets for formation stress and permeability testing were below this. Core collection was planned for 6,800 to 6,830 ft. and 6,970 to 7,000 ft.

Time to drill was estimated based on expected well construction as well as using the expected rate of penetration for experience drilling in hard granitic formation. The estimated time was 64 days for drilling and testing, the anticipated was 73 days. Actual drilling and testing was completed in 63 days from commencement of drilling and to a deeper total depth of 7,536 ft.

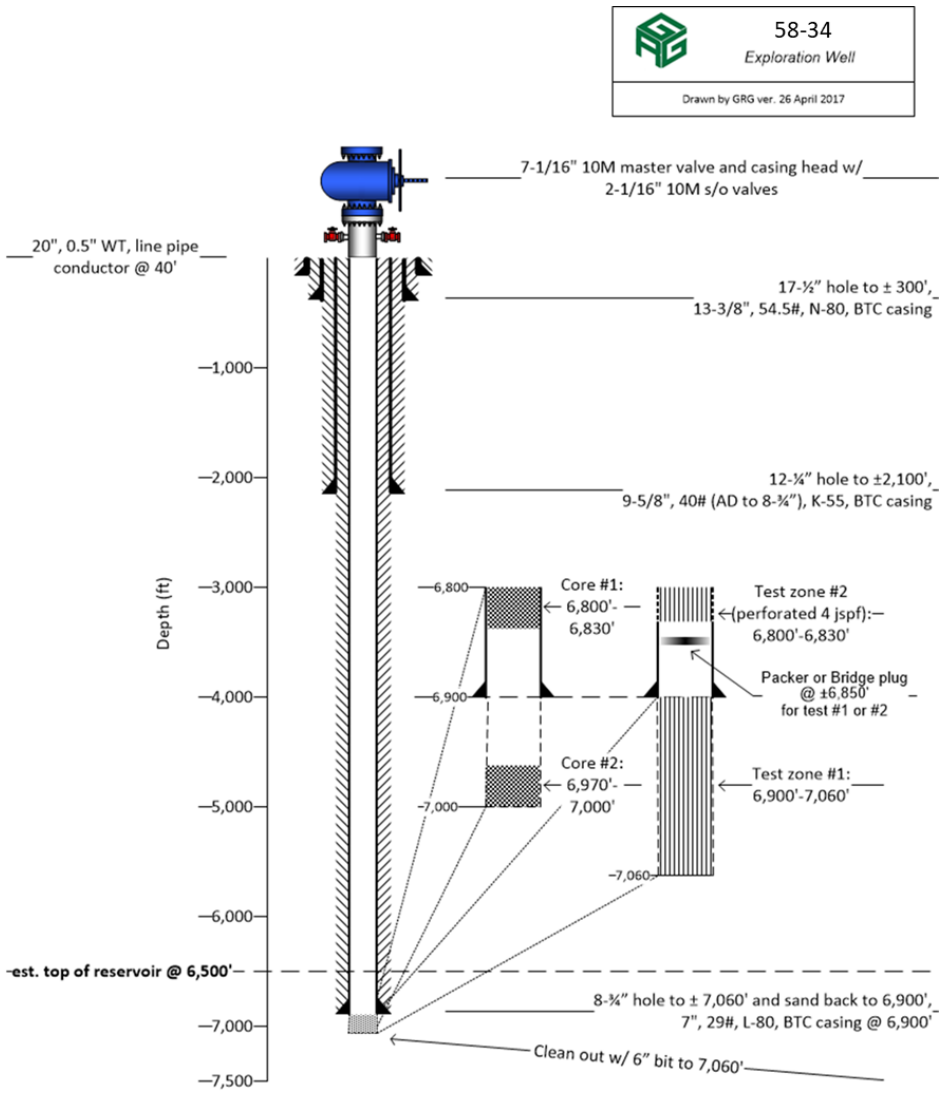

Figure 2: Planned well construction for 58-32.

2. 58-32 DRILLING SUMMARY

Prior to rig mobilization, the well pad was constructed, including setting of the cellar and drilling of mouse and rat holes. Additionally, the 20" conductor pipe was cemented with the casing shoe at 83.5 ft. in advance of the arrival of the drilling rig. The rig completed mobilization and rig up on 30 July 2017 and drilling commenced on 31 July 2017. The 17-1/2" hole was drilled to 342 ft. (relative to Kelly Bushing Height (RKB) of 21.5 ft.) and 13 3/8" casing was cemented to 338 ft. on 2 August 2017. Drilling of the 12-1/4" hole commenced on 3 August and continued to 6 August, when the casing point of 2180' was reached. The 9-5/8" casing was set and cemented at 2,172' measured depth on 7 August. The drilling of the 8-3/4" hole commenced on 8 August, and total depth of 7,536 ft. was reached on 14 September. Two cores for a total of 35 ft., were collected as part of the drilling program from two locations in the well, one at 6,800 ft. and the second at 7,440 ft.

2.1 Logging and testing summary

A full suite of geophysical open hole logs were run in the 8-3/4" section. Pressure and temperature surveys were performed at 6800' during drilling. Additionally, an acoustic image log was performed in the 8-3/4" hole from the bottom of the 9-5/8" casing to TD. After the drilling was completed, 7" blank casing was cemented to 7,375'. The bottom 161' of the hole was cleaned, left open and tested.

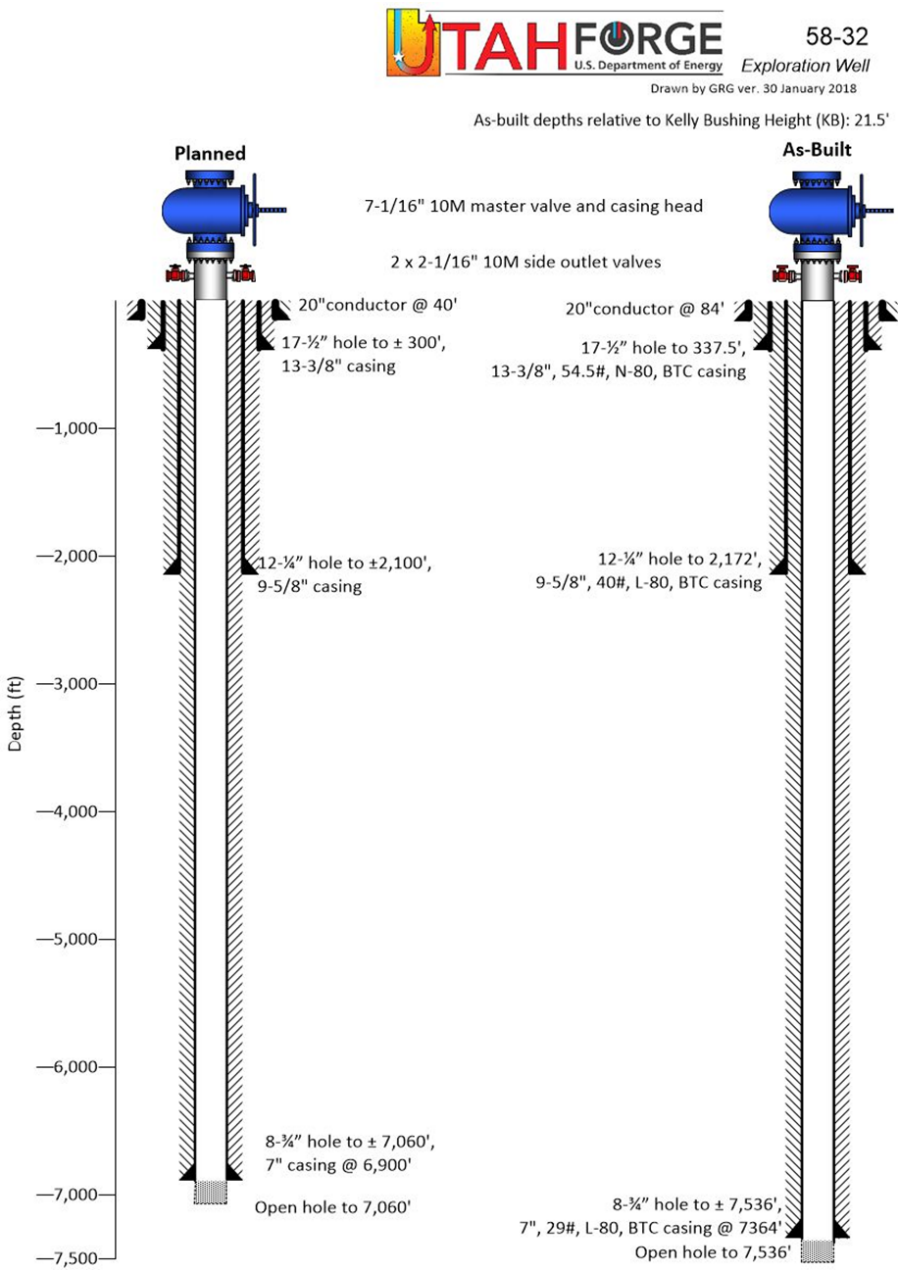

Figure 3: Planned and as-built well diagrams for 58-32.

2.2. Days versus Depth

Well 58-32 was drilled to a total depth of 7,536', 476' deeper than the planned depth of 7,060' and in less time than anticipated (Figure 4). The expected rate of penetration (ROP) in the granitic formation was difficult to predict. Additionally, several types of bits were tested within the granitic section, which led to uneven penetration rate. Anomalous penetration rates are observed at several depths and can be attributed to particular operations. Beginning at the top of the well, the initial 9-5/8" casing point at 342', the casing, cementing and nippling-up of the wellhead and BOPE was completed in half the time expected. The drilling rates through the alluvium section to were faster than anticipated. Half the time was spent than anticipated at the 9-5/8" casing point at 2,172'. The initial drilling rate out of the 9-5/8" casing was the same as the section above, an average of about 30 ft/hr, which was unexpected, as the interpretation of the wellbore cuttings indicated that the granite formation had been reached. At 3187', the bit was torqueing, and the drill string stuck at the bit, but was recovered. At the surface, it was found that a piece of the sleeve stabilizer was missing. Fishing operations to recover this piece account for the 1.5-day delay at this depth. At 5,477' the drill string was pulled out of the hole to check tools and bit, explaining the decrease in penetration rate at this depth. A new bottom hole assembly was run at 5,701' and 6,177', explaining the reduction in penetration rate at those depths. At 6,800', pressure temperature surveys were taken, and the well was allowed to heat up for several days in order to obtain multiple surveys to produce a prediction of the final heat up temperature at this depth. Also, at this depth a core sample was gathered. Additional time was spent on this activity, as the core barrel failed, requiring a fishing operation. Continued drilling to TD took another 7

days, including running in a new BHA at 7,200', and coring at 7,440'. The testing, including open hole geophysical logging, running and cementing of 7" casing to 7,375', cleaning out of the open hole, and injection took 11 days, as opposed to the 18 days that were planned for these operations.

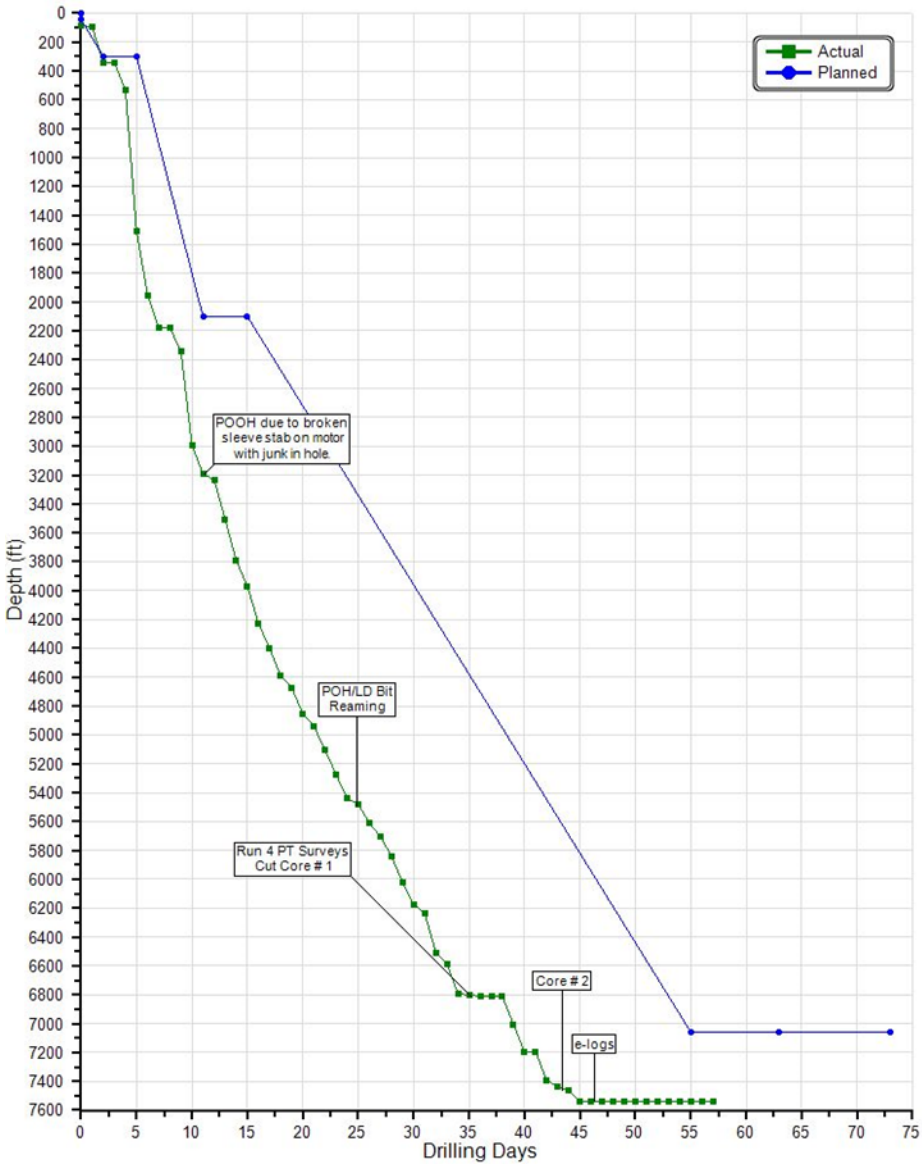

Figure 4: The planned and actual drilling Days versus Depth plots for well 58-23.

3. LOGGING AND TESTING PRELIMINARY RESULTS

3.1 Geophysical Logs

A full suite of geophysical logs was run in the open hole section of the well from the base of the 9-5/8 inch casing at 2172.4 ft and total depth (7536 ft) prior to running 7 inch casing. Geophysical logs from surrounding exploration wells were compared with the new data so that the geologic picks would be consistent with earlier interpretations (Figure 5). In addition, outcrop samples from the granitic rock units in the adjacent Mineral Mountains have been acquired and physical properties are being analyzed to provide additional constraints on the lithologies encountered in 58-32.

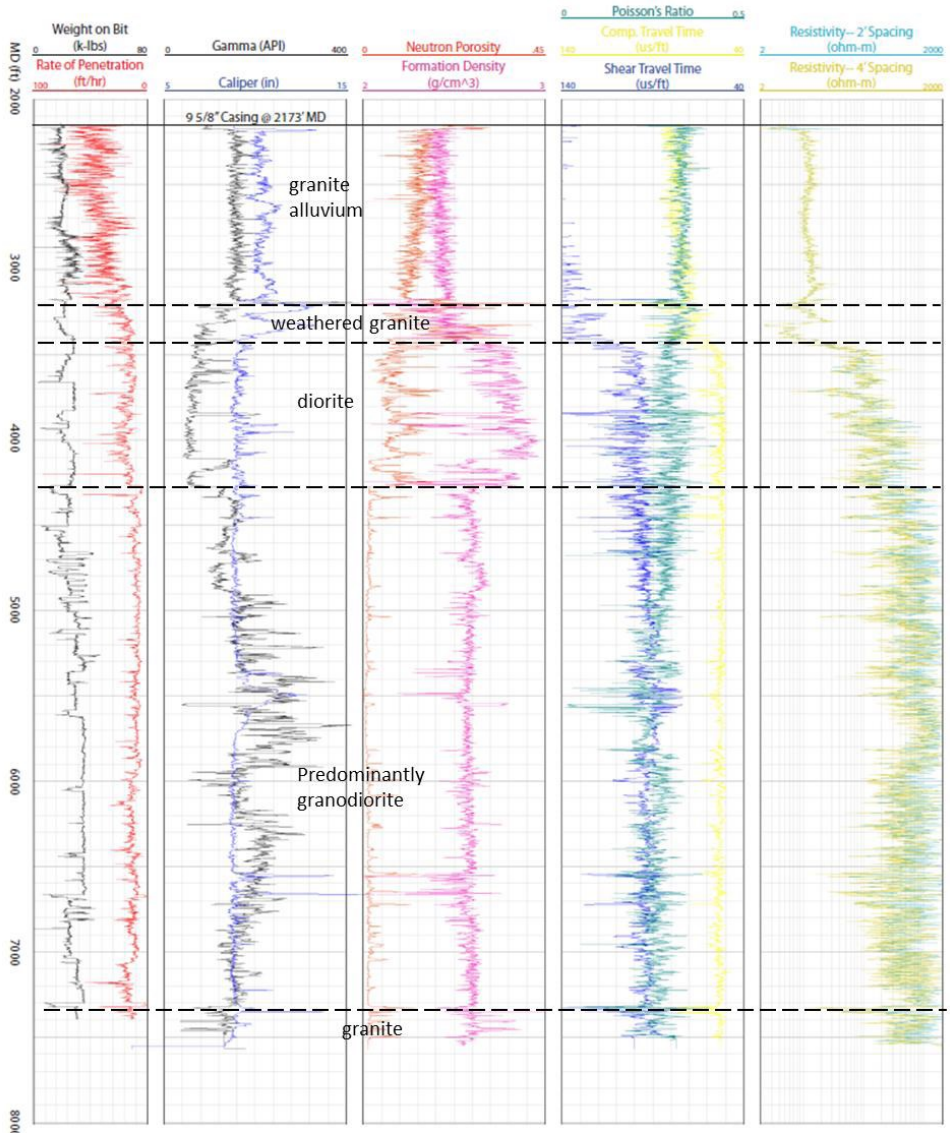

Figure 5: Preliminary compilation and interpretation of geophysical logs from 58-32.

3.1 Temperature-Pressure Surveys

The resource team monitored the daily mud temperatures during drilling as well as the and near-bottom temperatures recorded with maximum reading thermometers (MRT) during drilling. The MRT were run at the same time the single shot deviation surveys were conducted. To avoid damage to the tools and drill string, measurements were made as soon as possible after drilling stopped, typically less than an hour after mud circulation ceased. Mud temperatures in and out were recorded by the mud logger. A steady increase in heat extracted through the mud circulation demonstrated that the temperature in the hole was steadily increasing (despite the mud cooler reducing the mud temperature). The decision was made to cease drilling and mud circulation when the hole reached a depth of 6800 ft to confirm the thermal regime was close to the predicted conditions. Pressure temperature surveys were run to TD at roughly 6, 12, 18 and 24 hours after circulation stopped. Several methods were used to estimate the equilibrium temperature from the rate of thermal recovery and estimate the equilibrium temperature. These suggested a temperature of 360-380°F (180-190°C) at 6800 ft. A full heat up survey was completed on 2 November 2017, giving a maximum temperature of over 380ºF (190°C) at TD.

3.2 FMI log preliminary results

Formation MicroScanner Image (FMI) logs provide direct information on rock types, fracture abundances, fracture orientations and stress directions. The FMI tool was equipped with a four-arm caliper, which provides information on the well's ellipticity. Preliminary examination of the FMI logs indicates the upper 3176 ft of the well is composed of bedded alluvial deposits containing granitic clasts with a faulted transition from 3176 to 3196 ft. The rocks below 3196 ft. are part of the Mineral Mountains granite batholith. Both drilling induced and natural fractures are present. Fractures that are nearly vertical are more likely to represent induced fractures because the chances of encountering vertical fractures in a vertical well are low. Induced fractures provide critical information on stress directions.

FMI and Dipole Sonic Shear logs were included in the suite of the geophysical logs run in the open-hole between the 9-5/8 casing shoe and TD at 7536 ft.

3.3 Injection Testing

Injection testing is useful for determining the minimum in situ stress and the permeability. A test was conducted in the open hole section of the well just after completion of the well. Analysis of this data in ongoing.

4. CONCLUSION

Well 58-32 was originally scheduled to reach a total depth of 7060 ft., but was completed deeper (to 7536 ft.) and faster than anticipated, despite challenging hard rock drilling conditions. The drilling and testing phases confirmed that the site meets the temperature, rock type and permeability requirements established by the DOE for an EGS site. The data gathered from the well during the drilling and testing has already provided insight into the thermal and stress regime present at the Utah FORGE deep drilling site. Other geologic and geophysical data has been collected surrounding this first well before and since drilling. The site is becoming quite well characterized. The team is currently reviewing the drilling conditions and the impacts it had on the drill string and bits. This analysis will be included in the final report to the Department of Energy for this phase of the FORGE initiative, and will provide important lessons for the next activities of the project, which includes the drilling of a EGS production and injection well pair.

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