Seismic Reflection Profiling at the FORGE Utah EGS Site

John Miller¹, Rick Allis², Christian Hardwick²

¹Consulting Geophysicist, ²Utah Geological Survey

Keywords

Seismic reflection surveys, Roosevelt Hot Springs, Milford, Utah, EGS, FORGE,

ABSTRACT

New three-dimensional multichannel and two-dimensional seismic reflection data were acquired across, and extending eastward and westward from, the FORGE Utah site in November 2017 and were processed and interpreted between December 2017 and February 2018. These data supplement two previously existing two-dimensional seismic lines located adjacent to the south and west edges of the site that were licensed in September and October 2017 from Seismic Exchange, Inc. The data image two broad rock types comprising basin fill sediments and crystalline basement rocks; the latter is mostly made of Miocene granitoids that will host the proposed EGS reservoir. The contact between these rock types forms an inclined surface that dips 20° - 30° west and appears as a strong reflection on all seismic lines within and to the south of the site. These data add to numerous independent datasets, including new geological, geophysical, and geochemical surveys, plus drilling and logging of the new deep vertical well 58-32 to 7536 ft (2248 m) depth and help to confirm the suitability of the FORGE Utah site for development of an underground EGS laboratory. This paper briefly describes the data acquisition effort and processing techniques used to create the seismic images, and focuses on the interpretation of the 3D survey. The key finding is a west-dipping valley and ridge structure to the granitoid surface. The simplest interpretation is that the granitoid surface is likely an erosional feature similar in scale to the western flank of the Mineral Mountains, rather than the previously interpreted detachment fault surface. This does not preclude detachment tectonics occurring during basin evolution.

1. Introduction

In support of the effort by the U.S. Department of Energy (DOE) to establish an enhanced geothermal systems (EGS) laboratory in the western USA, a large amount of new three-dimensional (3D) and two-dimensional (2D) multichannel seismic reflection data were acquired across (3D) and extending eastward and westward (2D), from the FORGE site near Milford, Utah. The 3D survey covered an area of ~7 mi² (~17 km²) centered on the new vertical test well (58-32) and each 2D line was ~2.5 (4 km) miles long. In addition, two previously existing 2D
multichannel seismic reflection lines were licensed from Seismic Exchange, Inc. (SEI) with limited publication rights (referred to here as lines 5 and 11).

A location map of the all the seismic reflection data purchased by FORGE Utah is given in Figure 1. In the center is the 3D area, a series of 13 source lines and 27 receiver lines resulting in 170 “inlines” oriented W-E and 213 “crosslines” oriented S-N. Two new 4 kilometer-long 2D seismic lines (301 and 302) extend east and west from the patch and consist of 161 receiver locations with source points at each receiver, except for points that were close to pipelines or other hazards. These lines provided ties to a 3.8 km-deep well (Acord-1) near the middle of the basin, and to granitoid outcrop at the eastern flank of the Mineral Mountains. Lines 5 and 11 were recorded in 1979 and are oriented roughly S-N along Antelope Pt. Rd., and E-W near Geothermal Plant Rd.

Figure 1: Seismic survey locations. The 3D survey area comprises red lines (vibrator point locations 50 m apart), and +: geophone locations (oriented N-S, 50 m apart). Red lines 301 and 302 are new 2D seismic lines; heavy black lines are 2D lines licensed from Seismic Exchange, Inc. with limited publication rights.
A more complete write-up of the seismic acquisition, processing, and interpretation is being prepared as part of a bulletin on the geological characteristics of the Utah FORGE site being published by the Utah Geological Survey.

2. Acquisition and Processing

Lines 5 and 11 were purchased from Seismic Exchange, Inc. with limited publication rights (GSI-SU-5, and GSI-SU-11 on http://gis.seismicexchange.com/1/). These purchases included unprocessed digital field data and data reprocessed in 2016 in standard Society of Exploration Geophysicists Y format files (SEG-Y; Barry et al., 1975), images of the processed cross sections in TIFF graphics format (Aldus Corporation, now Adobe Systems, 1986), and navigation and other support data. In addition, both lines were originally processed in 1979 and that version of the processing only exists as a graphic image. The reprocessed version of line 11 gave a superior image to the 1979-processed TIFF image, so we used that line and seismic- and well-derived velocities to convert the digital traces from time to depth. However, the 1979-processed TIFF image of line 5 gave a superior image to that of the 2016 reprocessing, resolving the basement reflection especially well. Because there were no digital data of the 1979 processing, we identified a contractor with specialized software that could convert the graphic image into individual digital traces (raster to vector conversion). Using these digital traces and a velocity model created from a combination of seismic- and well-derived velocities, we converted the digital data from time to depth.

In November 2017, Paragon Geophysical Services, Inc. of Wichita, Kansas began work in the 3D survey area and 2D lines 301 and 302 (Figure 1). There were 1,114 source points and 1,741 receiver points in the 3D area. Receivers were located at 50 m intervals and source points were energized at 50 m intervals (Figure 2). All receivers were active for each source point. The energy source used for both the 2D and 3D surveys was the Vibroseis method consisting of two I/O AHV IV 364 and 365 vibrators spaced 30 feet apart. Each vibrator imparts 62,000 lbs. of peak force and was operated at 70% of peak force. The Vibroseis sweep was linear, 4–84 hz, 12 s long, with 4 sweeps per source point.

The new 2D data were organized into Common Depth Point (CDP) bins along each line, spaced 12.5 m apart. The 3D data were organized geometrically into CDP bins spaced 25 m apart, and were further organized into the “inlines” and “crosslines” (details in Figure 2). All data exhibited a considerable amount of noise including ground roll and air blast from the vibrators. Extensive testing was performed to design a model-based filter to remove as much of this noise as possible. The noise was not coherent enough to be removed completely, but it was sufficient to condition the data for input to processing flow. Details of the recording and processing are in 2018 Topical Report for Utah FORGE submitted to DOE and are being included in paper being prepared for the UGS Bulletin referred to above.

3. Interpretation

All lines shown here are plotted relative to an elevation datum of 1800 m asl, and have no vertical exaggeration. The ground surface increases from 1500 m asl near the axis of Milford Valley close to Acord-1, to about 1800 m asl high on the alluvial fan adjacent to the western flank of the Mineral Mountains. Line 11, running 13 km northward along Antelope Pt. Rd., is shown first because it illustrates that there is not a simple pattern of basin fill draped over
granitoid bedrock (Figure 3). The central portion of the line shows a 6 km-wide sub-basin in the assumed granitoid bedrock with a vertical relief of about 500 m. Truncated reflectors on the south side of this sub-basin suggest infilling sediments have been partially eroded, and point to cycles of erosion and deposition during the evolution of Milford Valley and the Mineral Mountains. The near-surface lake sediments, which transition to underlying volcaniclastic sediments at about 1 km depth in Acord-1 (Hintze and Davis, 2003; Jones et al., in prep), gently dip towards the north and appear to be about 1.7 km thick at the north end of the profile (2 km below 1800 m datum). Deformation of the lake sediments between 8 and 12 km along the profile, and coinciding with a topographic high in the ground surface, appears to indicate faulting. The true dip of the faults may be obscured if the profile intersects the faults at a narrow angle.

Figure 2. Details of the source and receiver points, the FORGE boundary (red dashes), N-S crosslines (green dashes) and W-E inlines (blue dashes) chosen for discussion. Well 58-32 is the FORGE well drilled during 2017, and wells 9-1, 82-33, and OH-4 are exploration wells drilled in the late 1970s that penetrated granite. CDP bins and inline and crossline numbering system are around the outside of the figure.
Selected lines from the 3D survey are now discussed to illustrate the character of the granite surface and the basin fill beneath the FORGE site. Figure 2 shows the locations of the four N-S crosslines and the three W-E inlines that will be highlighted.

The reflection imagery from crossline 105, which runs N-S through FORGE well 58-32, is shown in Figure 4. The main feature is the strong reflector from the granite surface with undulations between 1000 and 1200 m below the 1800 m asl datum. Checks from where inlines cross this line confirm the pick of the granite surface. The uncertainty in this pick is about ± 50 m. In the vicinity of well 58-32 there are strong reflectors over a 300 m interval immediately above the granite surface. The FMI log in the open hole of 58-32 below casing set at 670 m depth shows a matrix-supported boulder field in this depth interval above the granite surface. The seismic reflection imagery suggests the lateral dimensions of the boulder field is about 1 km in a N-S direction and centered close to 58-32. Figure 4 also shows the potential location of the future FORGE reservoir if it is constrained by 175°C and 225°C isotherms (Allis et al., 2018).

Inline 95 is a W-E section through well 58-32 (Figure 5). The granite surface generally dips west at 20 ± 5 degrees, although near to 58-32 the dip steepens into what other lines confirm as a west-trending valley. The zone of strong reflectors above the granite surface at 58-32 is only about 250 m wide in a W-E direction, suggesting that this boulder field was deposited against the west flank of the proto-Mineral Mountains. The upper surface of the volcanoclastic unit identified in line 301 mostly occur at 900 m below the datum and lap against the boulder field just discussed. There is a valley, or broad channel, in this surface near the west side of the line that is about 1 km wide and about 200 m deep on this section. Reflections within the granite on the east side of the section are thought to be a combination of side reflections and multiples, and therefore spurious.
Crossline 120 runs N-S through the east side of the FORGE site (Figure 6). It is 375 m east of crossline 105 shown in Figure 4. The granite surface is the only coherent reflector, and it undulates between 850 and 1000 m below the datum. The reflective boulder field seen in Figures 4 and 5 is not present on this line.

Crossline 90 is 375 m west of crossline 105 (Figure 7). This shows a major valley cutting across the section, with its axis at about 1500 m below the datum and located beneath the present-day NM Wash. This valley is about 1.5 km wide and 300–400 m deep. The scale of this valley is an order of magnitude larger than NM Wash, which is typically about 50 m wide and 30 m deep where it cuts across the FORGE site. The top of the volcanoclastic section overlying the granite is poorly imaged, but clearly has an undulating surface. The deepest point is in a channel (or wash) located in the same position as the valley in the granite surface. As the basin filled with volcanoclastics and sediment eroded off the proto-Mineral Mountains to the east, it appears that a major drainage was located beneath the FORGE site for most of the depositional history (> 20 m.y.)

![Figure 4. Crossline 105 extends N-S through FORGE well 58-32. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery has depth (m) below the datum of 1800 m asl. There is no vertical exaggeration; NM Wash can be seen about 250 m north of well 58-32. Yellow dashes are the geologic interpretation of the granite surface. The red-dashed box outlines the location of the future reservoir beneath the FORGE site assuming temperature constraints of 175–225°C. Depths in meters.](image)
Figure 5. W-E section through FORGE well 58-32. Annotations the same as in Figure 4.

Figure 6. Crossline 120, which runs N-S through the east side of the FORGE site (location on Figure 2). Depths in meters.
Figure 7. Crossline 90, which runs N-S through the center of the FORGE site, 375 m west of well 58-32. Depths in meters.

Crossline 75 runs parallel to the west side of section 32 in the FORGE site and crosses near the proposed drilling pad for drilling the deep, deviated wells during Phase 3 (Figure 2). This line shows the same valley imaged in Figure 7 (375 m to east), having similar dimensions and centered beneath the south side of NM Wash. The picks of the granite surface from the inlines that cross this line confirm smooth sides and an erosional origin to the valley. The top of the volcaniclastics unit has the same characteristics as that seen in Figure 7, with a 100-m-deep channel present at about 900 m datum-depth beneath NM Wash (750 m true depth).

Two W-E lines across the north and south parts of the FORGE site are shown in Figure 9 for completeness. The main difference between these two lines is the increased dip and depth of the granite surface beneath north FORGE. At crossline 50 the surface is at 1600 m below datum in the north compared to 1400 m beneath south FORGE. In both cases there are spurious reflections from within the granite.
Figure 8. Crossline 75, which runs N-S through the west side of section 32 in the FORGE site. The red crosses are picks of the granite surface from where the inlines cross crossline 75. They confirm a smooth granite surface to the buried valley beneath the west side of the FORGE site. Depths in meters.

Synthesis and Conclusions

The identification of the reflections from the granite surface in the 3D survey area and the adjacent 2D lines has been integrated with the gravity interpretations of basin-fill thickness (Hardwick et al., 2018) in Figure 10. Although the average westward dip of the top of the granite is 25 ± 5 degrees, the 3D survey area reveals a valley and ridge structure. The westward orientation of the main valley, and high-resolution imagery of a truncated package of horizontal sedimentary layers on the south flank of the valley imaged beneath Antelope Pt. Rd., indicates an erosional origin to most of the features. The scale of the valley is similar to those seen in the western flanks of the Mineral Mountains today, suggesting the buried topography represents an early phase of uplift and erosion of the Mineral Mountains. Smaller scale valleys and channels are also seen in the overlying basin-fill sediments, confirming an ongoing process of erosion of the Mineral Mountains and deposition of basin-fill deposits over the last 30 m.y.
Figure 9. Inlines 40 and 130. Both lines have spurious reflections within the granite on the east side. Depths in meters.
Early interpretations of the 2D line 5 near Geothermal Plant Rd. proposed that the granite surface may be a low-angle detachment surface along which extensional movement occurred as the basin was formed (Barker, 1986; Smith et al., 1989; Figure 11). The seismic interpretation presented here indicates that the granite surface is likely erosional and not a fault surface. This does not preclude detachment tectonics occurring during basin evolution, only that there is no evidence for it beneath the FORGE site.

Line 5 is consistent with the 3D inlines in the FORGE site which do not show offsets caused by faults in the granitoid surface, or in surfaces identified in the basin fill. There is a lack of coherent reflectors where the Opal Mound fault is crossed, and to the east where the line crosses the Blundell production wells. Production wells tap into high-permeability fractures over a 1 km-wide zone east of the Opal Mound fault, but these were not imaged in line 5. Although not displayed in this paper, the 2D line 302, which crossed the northern end of both the Opal Mound fault and proven deep permeability of the Blundell wellfield, was able to image the granitoid surface at shallow depth (100 – 300 m depth), but did not have coherent reflectors within the granitoid bedrock.
Figure 11. Interpretation of 2D seismic line 5. The reflections are tied to where the west end of the line intersects line 11 (Figure 3), which in turn was tied to the stratigraphy in Acord 1. A channel is evident in the near-surface alluvium where the present-day Opal Mound Fault Wash occurs. The granitoid surface is encountered at 230 m depth in well 9-1 (well 9-1 is 0.7 km northwest of Opal Mound fault and the line 5).

Acknowledgments

This work was sponsored by the DOE EERE Geothermal Technologies Office project DE-EE0007080 Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site (Managing PI, Joe Moore). We thank Paragon Geophysical Services, Inc. of Wichita, Kansas for the data acquisition, and STAR Geophysics, Inc. of Oklahoma City, Oklahoma, for preliminary processing of the data. 2D lines 5 and 11 were purchased from Seismic Exchange, Inc., Denver, with limited publication rights.

REFERENCES


Jones, C., Moore, J., and Simmons, S. “Petrographic analyses of cuttings and core from wells Acord-1 and FORGE 58-32; Beaver County, Utah.” In prep.