INTERPRETATION OF SEISMIC REFLECTION SURVEYS NEAR THE FORGE ENHANCED GEOTHERMAL SYSTEMS SITE, UTAH

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ABSTRACT

New three-dimensional multichannel and two-dimensional seismic reflection data were acquired across, and extending eastward and westward from, the FORGE EGS site in Utah in November 2017; data 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 distinct lithofacies comprising basin fill sediments and crystalline basement rocks; the latter are mostly Miocene granitic rocks that will host the proposed EGS reservoir. The contact between these rock types forms an inclined surface that generally dips 20° to 30° west and appears as a strong reflection on all seismic lines within and to the south of the site. This paper (1) briefly describes the data acquisition effort and processing techniques used to create the seismic images, (2) focuses on the interpretation of the 2-D and 3-D surveys, (3) sufficiently images the FORGE site for detailed interpretation of basin evolution and orogenic uplift, (4) ties seismic interpretation with FMI logs and gravity surveys, and (5) reveals new interpretation of the Milford Valley and the Mineral Mountains evolution. The key finding is a west-dipping valley and ridge structure to the granitic surface. The simplest interpretation is that the granitic 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 but the 3-D image of the granitic surface shows otherwise for this feature.

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, ~7 mi^2 (~17 km^2) of new three-dimensional (3-D) multichannel seismic reflection data were acquired across the Frontier Observatory for Research in Geothermal Energy (FORGE) site, centered on the new vertical test well (58-32) near Milford, Utah. Two new ~2.5 (4 km) mile long two-dimensional (2-D) multichannel seismic reflection lines were also acquired, extending east and west from the FORGE site. In addition, two previously existing 2-D 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 seismic reflection data purchased by FORGE Utah is given in Figure 1. In the center is the 3-D area, a series of 13 source lines and 27 receiver lines resulting in 170 "inlines" oriented west-east and 213 "crosslines" oriented south-north. The two new 4-kilometer-long 2-D seismic lines (301 and 302) extend east and west from the 3-D survey area 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, as well as to granitic outcrops at the eastern flank of the Mineral Mountains. Lines 5 and 11 were recorded in 1979 and are oriented roughly south-north along Antelope Pt. Rd., and oriented east-west near Geothermal Plant Rd.

ACQUISITION AND PROCESSING

Lines 5 and 11 were purchased from SEI with limited publication rights (GSI-SU-5, and GSI-SU-11 on https://web.seismicexchange.com/1/). These purchases included (1) unprocessed digital field data and data reprocessed in 2016 in standard Society of Exploration Geophysicists Y format files (SEG-Y; Barry et al., 1975), (2) images of the processed cross sections in TIFF graphics format, developed by Aldus Corporation, now Adobe Systems (Murray and vanRyper, 1996), and (3) navigation and associated support data. In addition, both SEI 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

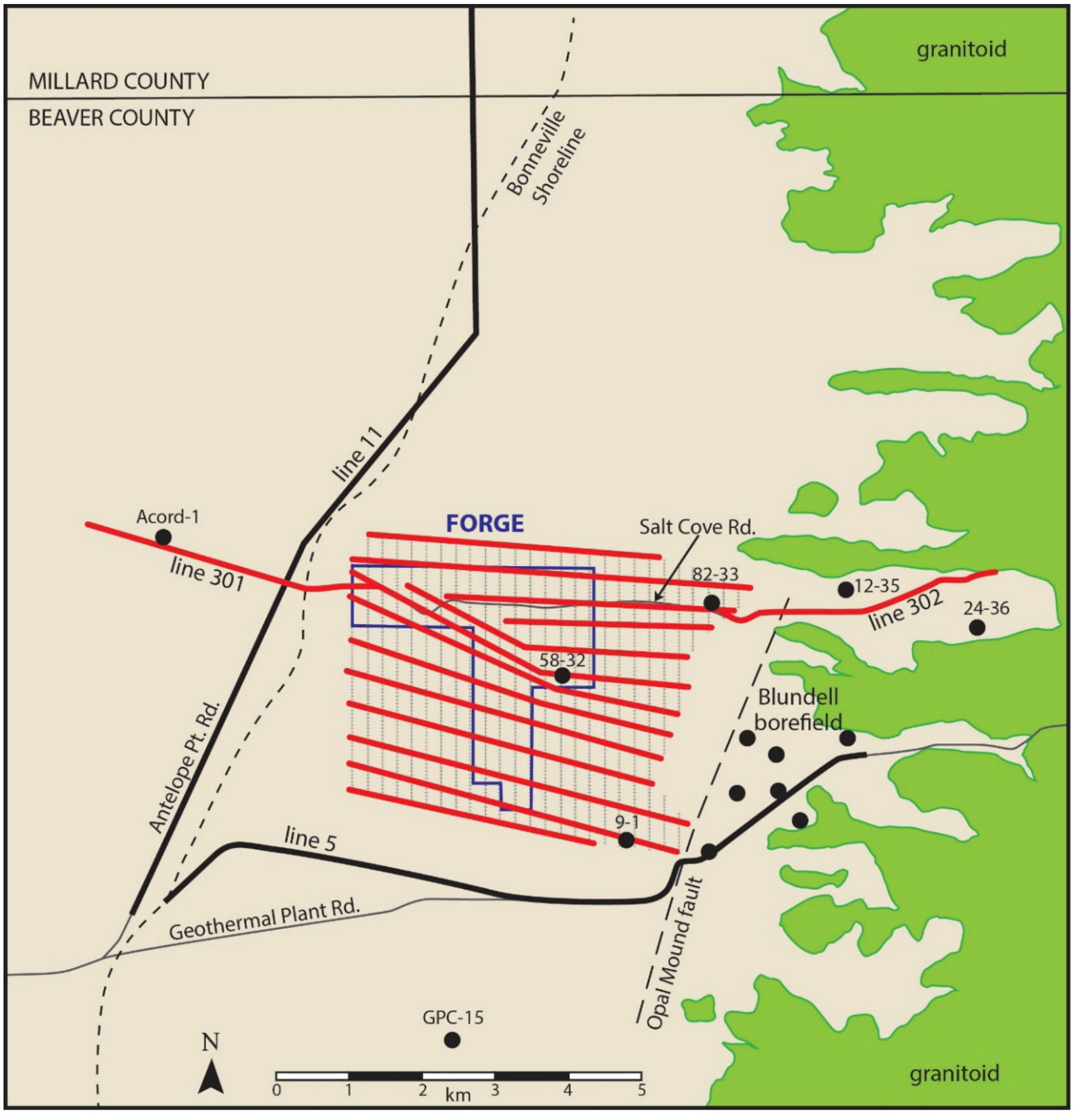

Figure 1. *Seismic survey locations. The 3-D survey area comprises red lines (vibrator point locations 50 m apart), and geophone locations (oriented north-south, 50 m apart). Red lines 301 and 302 are new 2-D seismic lines; heavy black lines are 2-D lines licensed from Seismic Exchange, Inc. with limited publication rights. Black circles are well locations. Granitic outcrop is given by the green contour.*

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 by using a 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 3-D survey area and 2-D lines 301 and 302 (Figure 1). There were 1,114 source points and 1,741 receiver points in the 3-D 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 2-D and 3-D surveys was a 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 produced a 4-48 Hz linear excitation that was 12 seconds in duration with four sweeps per source location.

The new 2-D data were organized into Common Depth Point (CDP) bins along each line, spaced 12.5 m apart. The 3-D 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 the processing flow.

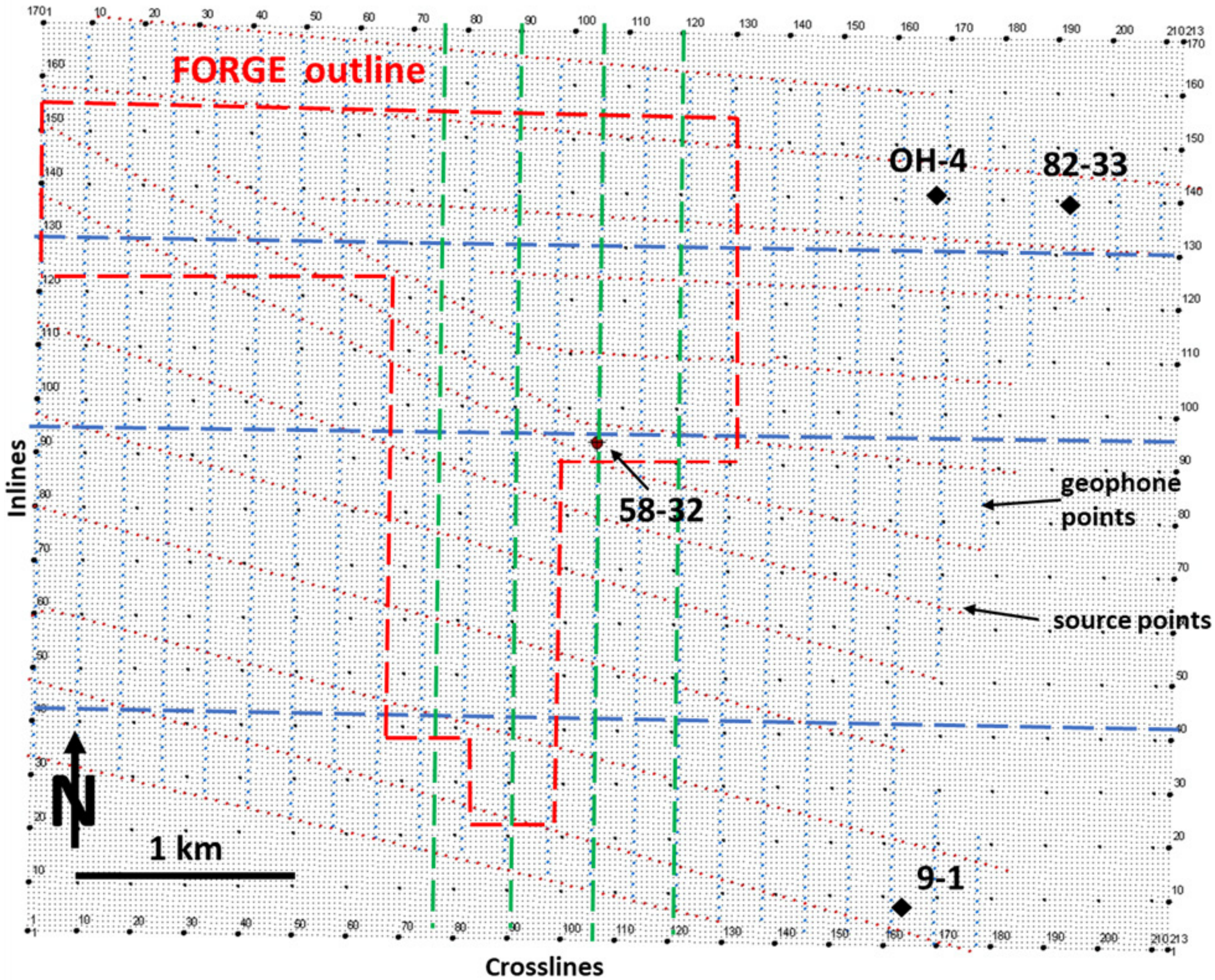

Figure 2. *Details of the source and receiver points, the FORGE boundary (red dashes), north-south crosslines (green dashes) and west-east inlines (blue dashes) chosen for discussion. Well 58-32 is the FORGE well drilled during 2017, and wells 9-1, 82-33, and OH-4 are exploration wells drilled in the late 1970s that penetrated granitic bedrock. CDP bins as well as inline and crossline numbering system are displayed around the perimeter of the figure.*

The main source of uncertainty in reflection seismic profiling rests with the determination of velocity directly from the seismic data and subsequent depth to the reflecting interfaces. Velocity determination depends on adequate source-receiver offset (the distance between the seismic source and the receiver farthest away from it) relative to the depth of the target that is to be imaged. The maximum source-receiver offset in the 3-D area, greater than 3000 m, is suitable for determining the velocity field with a high degree of confidence. In addition, we measured velocity and depth in well 58-32 which assisted in calibrating the velocity analysis. To test the accuracy, we used inline 93 which intersects the well. We converted that line from time to depth using only the well velocities, and then converted it to depth using seismic-derived velocities. The difference in depth to the granitic interface was less than 20 m, which at 1000 m total depth to the granitic interface is less than 2% difference. In addition, the velocity field away from the wellsite was quite homogeneous, and structural contours above of the granite, which were derived from the seismic data, integrate seamlessly with gravity modeling by Hardwick et al. (2019).

INTERPRETATION

All lines discussed in this report except line 302 are plotted relative to an elevation datum of 1800 m above sea level (asl) and most have no vertical exaggeration (line 302 datum is 2000 m asl because of the higher ground elevation). The ground surface generally increases from 1500 m asl near the axis of Milford Valley close to Acord-1, to about 1800 m asl on the alluvial fan adjacent to the western flank of the Mineral Mountains.

2-D Lines

Line 11, extending 13 km northward along Antelope Pt. Rd., illustrates a complex pattern of basin fill draped over granitic bedrock (Figure 3). The central portion of the line crosses a 6-km-wide sub-basin in the assumed granitic 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, which indicates 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., 2018), 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 because the profile intersects the faults at a narrow angle.

Line 301 extended west from the 3-D survey area, crossing line 11 and tying into the known stratigraphy in Acord-1. This well is the deepest in Milford Valley (3.8 km) and penetrated granitic basement at 3.0 km. The overlying basin fill comprised lacustrine sediments near surface, and the underlying volcaniclastic sediments had several thin andesite lava flows at 2.2 km depth (Jones et al., 2018). The line is shown in Figure 4 with reflecting horizons highlighted.

The lake sediments are characterized by fine, near-horizontal layering across the entire line. Near the eastern end of the line there may be a transition to alluvial-fan deposits that dominate the upper part of the 3-D survey area. The top of the volcaniclastic unit dips eastward to a low point of 1600 m below the 1800 m asl datum where the line crosses Antelope Pt. Rd. East of this subtle basin the top surface of the volcaniclastics rises to above 1000 m below the datum near the eastern edge of the line (adjacent to the west edge of the 3-D survey area.) The andesite lavas within the volcaniclastic unit dip towards the east and appear to fade out and disappear around the middle of the line. Possibly the andesite lavas lap against the west-dipping granitic bedrock, which is not clearly imaged by seismic reflections.

According to the gravity interpretation by Hardwick et al., (2019), the earliest phase of basin filling had a depocenter about 4 km west of Acord-1. Thus, the center of the valley may have been beneath Antelope Pt Rd. by the time the lake sediments began to be deposited. Today the center of the valley is again to the west of Acord-1.

A minimally processed version of line 302 is also included here because it reveals a surprisingly deep buried valley beneath the western flanks of the Mineral Mountains (Figure 5). The line traverses Salt Cove valley at the eastern end of Salt Cove Rd. (Figure 1). It crosses the Opal Mound fault between CDP 50 and 100. Injector well 12-35 is midway along and north of the line.

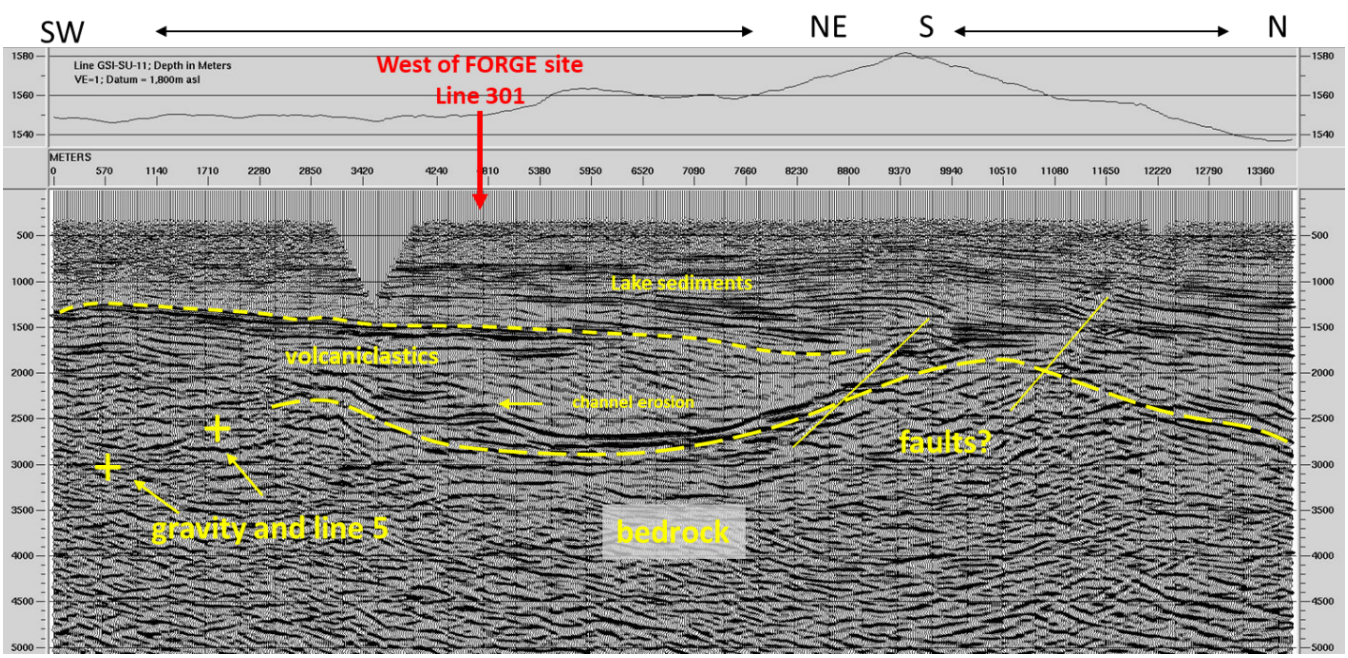

Figure 3. *Line 11 along Antelope Pt. Rd. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. The west edge of the 3-D survey area is 0.5 km east of the profile at the 5-km mark. Acord-1 is 2 km west from where line 301 intersects the profile (refer to Figure 1). Seismic data are owned or controlled by Seismic Exchange, Inc.; interpretation is from this study for the FORGE project.*

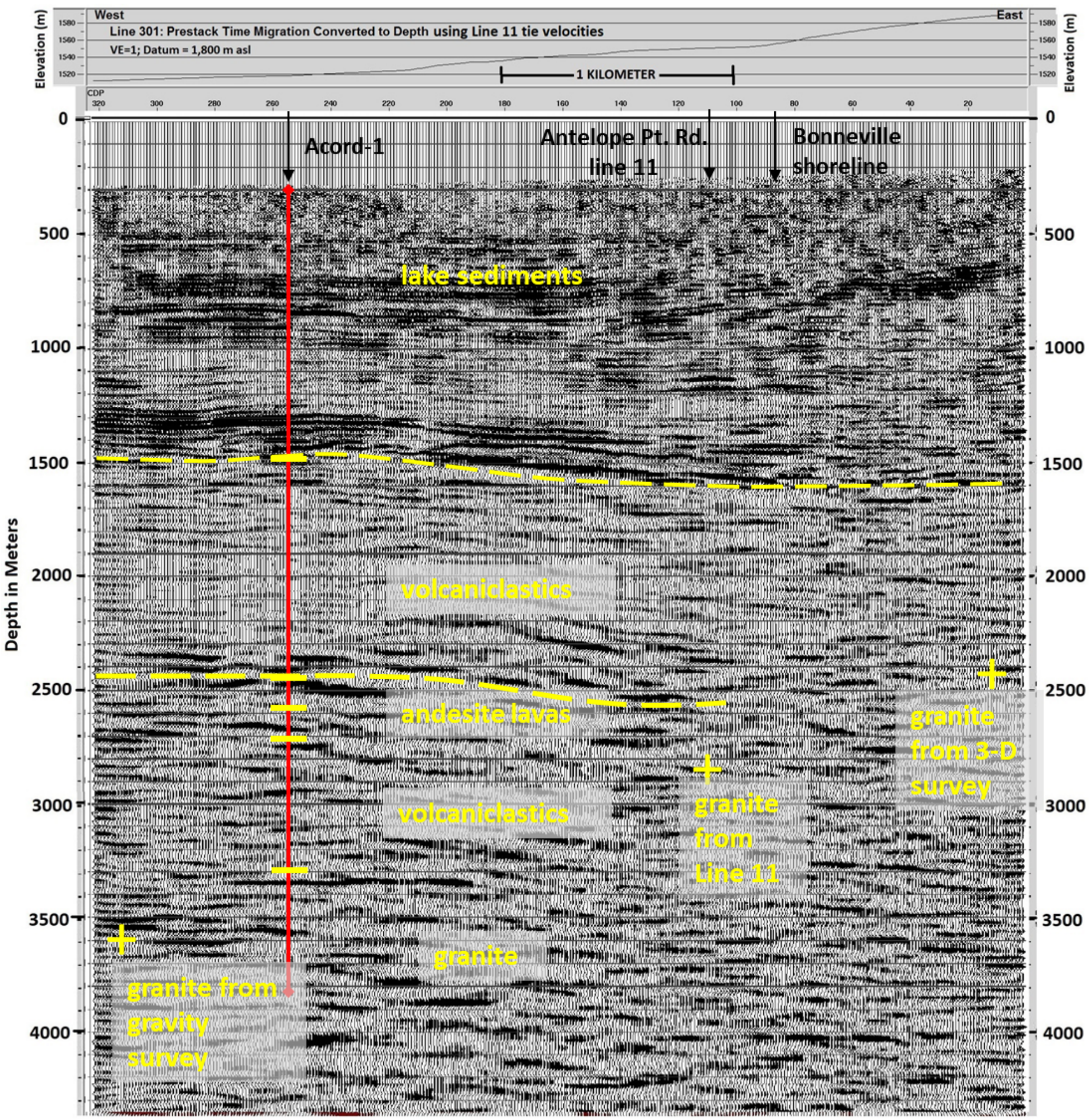

Figure 4. *Line 301 with several reflectors highlighted. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. Because zero-depth is at the 1800 m asl datum, 280 m needs to be subtracted from the depth axis to get depth below ground surface at Acord-1. Line location is shown on Figure 1.*

An abandoned exploration well 24-36 is near east end of the line. These wells are near the north and south edges of the valley, respectively, and both penetrated granite at relatively shallow depth. Line 302 shows the granitic surface as an undulating reflector with the maximum depth at a two-way travel time of 400 ms. Assuming a near-surface velocity of 2 km/s (shallow velocity in GPC-15; Glenn and Hulen, 1979), this is a depth of about 400 m. This occurs where the valley is widest, being about 1.2 km at that point. It will be shown later that the dimensions of the infilled valley beneath line 302 are similar to the buried valley in the granite beneath the west FORGE site revealed by the 3-D survey. The granitic surface in the vicinity of the Opal Mound fault is too shallow to be imaged by seismic reflections.

We note here that line 302 is undergoing reprocessing and initial results indicate that the undulating nature of the granitic reflector may be an artifact of lateral velocity variations in the alluvium above the reflector.

Line 5, extending mostly west-east from Antelope Pt. Rd. to east of the Blundell production wellfield, images a reflector with a constant dip into the basin to the west. Early interpretations proposed that the granitic 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 6). The

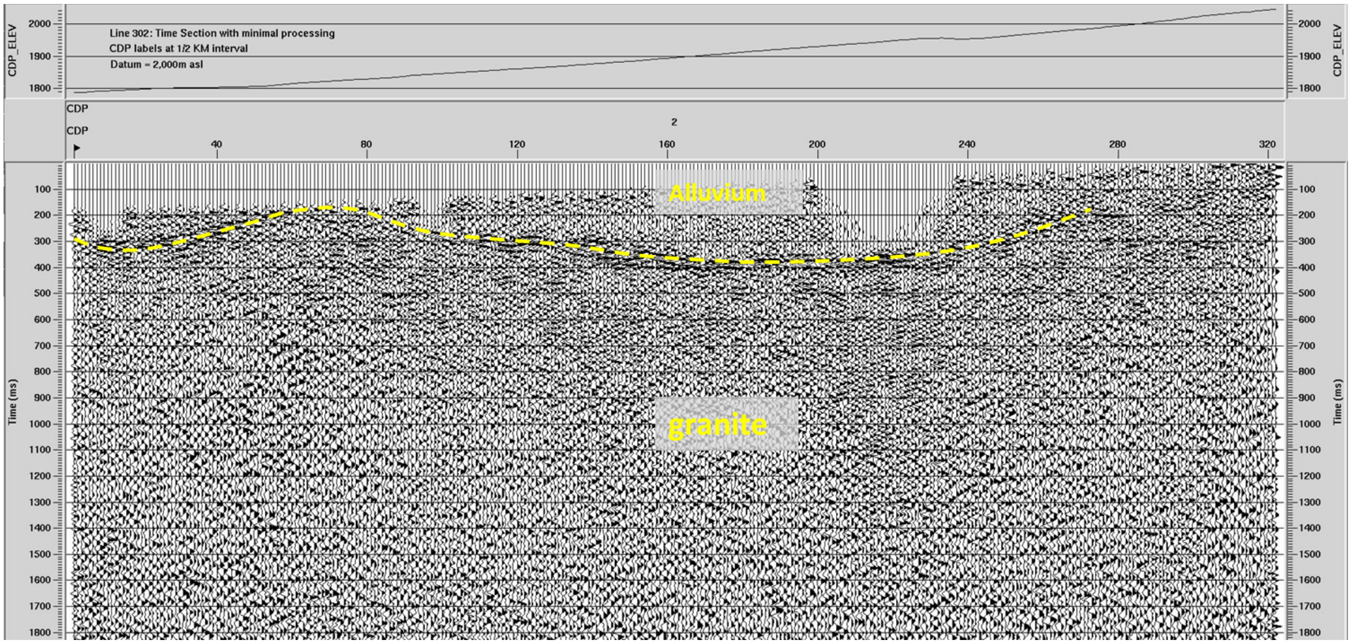

Figure 5. *Time section of line 302 (location shown on Figure 1). The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 2000 m asl. There is no vertical exaggeration. The maximum depth of the infilled valley around CDP 200 is about 400 m assuming a two-way travel time of 400 ms and velocity for the fill of 2 km/s. Note the elevation datum is 2000 m asl on this line because of the higher surface topography.*

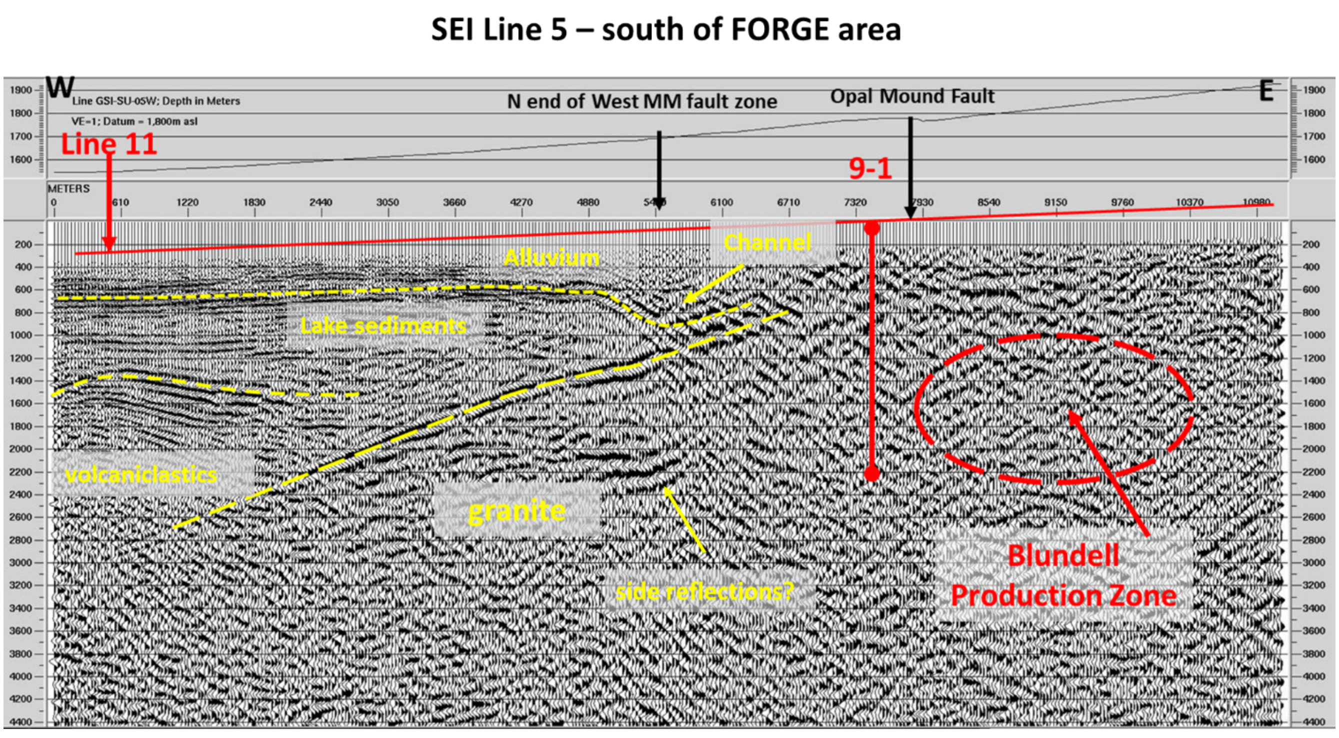

Figure 6. *Interpretation of 2-D seismic line 5. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. The reflections are tied to where the west end of the line intersects line 11 (Figure 3), which in turn was tied to the stratigraphy in the Acord-1 well. A channel is evident in the near-surface alluvium where the present-day Opal Mound fault wash occurs. The granitic surface is encountered at 230 m depth in well 9-1 (well 9-1 is 0.7 km northwest of the Opal Mound fault and line 5).*

seismic interpretation presented here indicates that the granitic surface is likely erosional and not a fault surface. This is based on the valley and ridge morphology on the granitic surface revealed by the north-south crosslines in the 3-D survey discussed in the next section.

Line 5 does not show obvious offsets caused by faults in the granitic surface, or in surfaces identified in the basin fill. The north-trending West Mineral Mountains fault zone appears to diminish where it crosses Geothermal Plant Rd. (Kirby et al., 2019; Knudsen et al., 2019) and if present, would cross line 5 between 4900 and 5500 m from the west end of the line (Figure 6). Farther east, there is a lack of coherent reflectors both where the Opal Mound fault is crossed (7700 m), and even farther east where the line crosses the Blundell production wells (7800–10,000 m). Production wells tap into high-permeability fractures over a 1-km-wide zone east of the Opal Mound fault; these were not imaged in line 5.

3-D Imagery

Selected lines from the 3-D survey are now discussed to illustrate the character of the granitic surface and the basin fill beneath the FORGE site. Figure 2 shows the locations of the four north-south crosslines and the three west-east inlines that will be highlighted.

The reflection imagery from crossline 105, which runs north-south through FORGE well 58-32, is shown in Figure 7. The main feature is the strong reflector from the granitic 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 granitic 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 granitic surface. The Formation Micro-Imager (FMI) log acquired in the open hole section of 58-32 below casing set at 670 m depth shows a matrix-supported boulder field in this depth interval above the granitic surface (Forbes et al., 2019). The seismic reflection imagery suggests the lateral dimensions of the boulder field is about 1 km in a north-south direction and centered close to 58-32. Figure 7 also shows the potential location of the future FORGE reservoir if it is constrained by 175°C and 225°C isotherms (Allis et al., 2019).

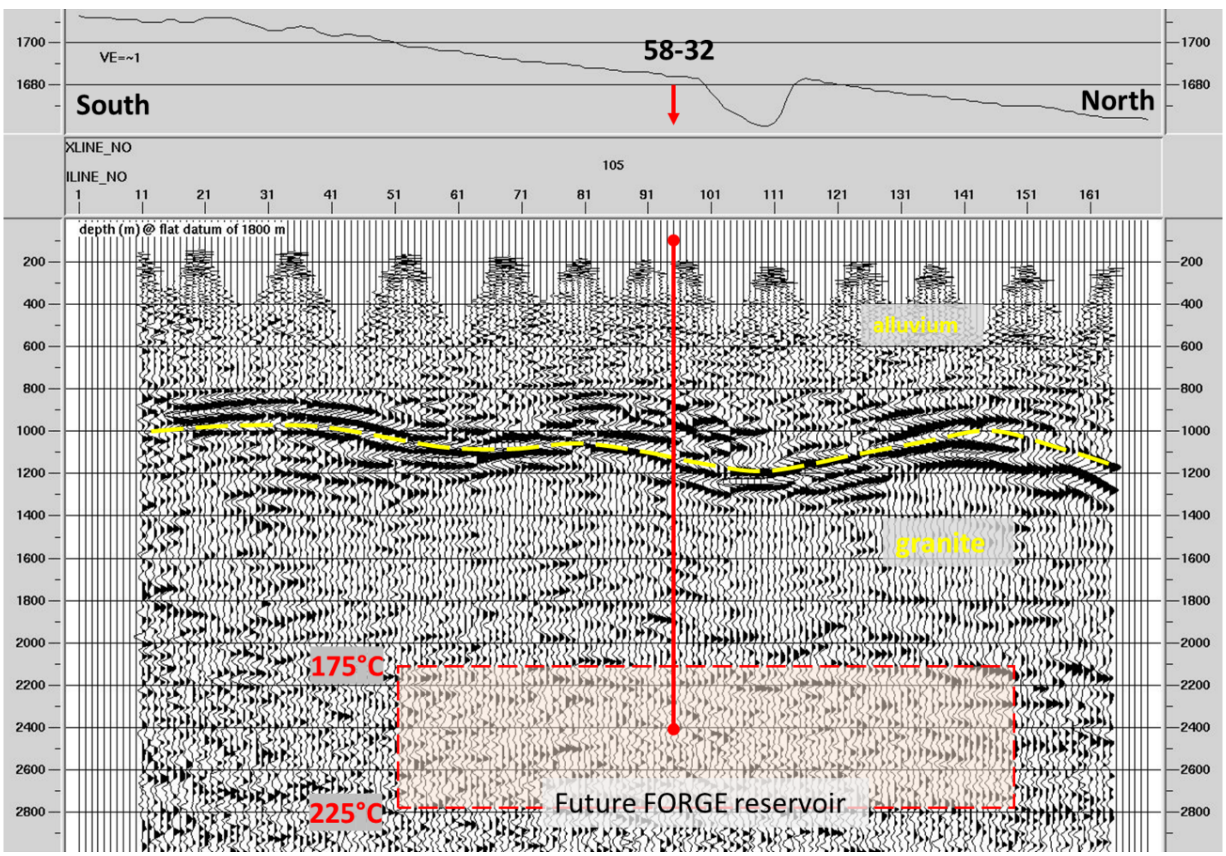

Figure 7. *Crossline 105 extends north-south through FORGE well 58-32. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. NM Wash can be seen on the topographic profile about 250 m north of well 58-32. Yellow dashes are the geologic interpretation of the granitic surface. The red-dashed box outlines the location of the future reservoir beneath the FORGE site assuming temperature constraints of 175°–225°C.*

Inline 95 is a west-east section through well 58-32 (Figure 8). The granitic 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 granitic surface at 58-32 is only about 250 m wide in a west-east direction, suggesting that this boulder field was deposited against the west flank of the proto-Mineral Mountains. The upper surface of the volcaniclastic unit identified in line 301 mostly occurs at 900 m below the datum and laps 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 north-south through the east side of the FORGE site (Figure 9). It is 375 m east of crossline 105 shown in Figure 7. The granitic surface is the only coherent reflector, and it undulates between 850 and 1000 m below the datum. The reflective boulder field seen in Figures 7 and 8 is not present on this line.

Crossline 90 is 375 m west of crossline 105 (Figure 10). 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 is cuts across the FORGE site. The top of the volcaniclastic 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 granitic surface. As the basin filled with volcaniclastics 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 (more than 20 million years).

Crossline 75 (Figure 11) extends 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 granitic surface from the inlines that cross this line confirm smooth sides and an erosional origin to the valley. The top of the volcaniclastic 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 west-east lines across the north and south parts of the FORGE site are shown in Figure 12 for completeness. The main difference between these two lines is the increased dip and depth of the granitic 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.

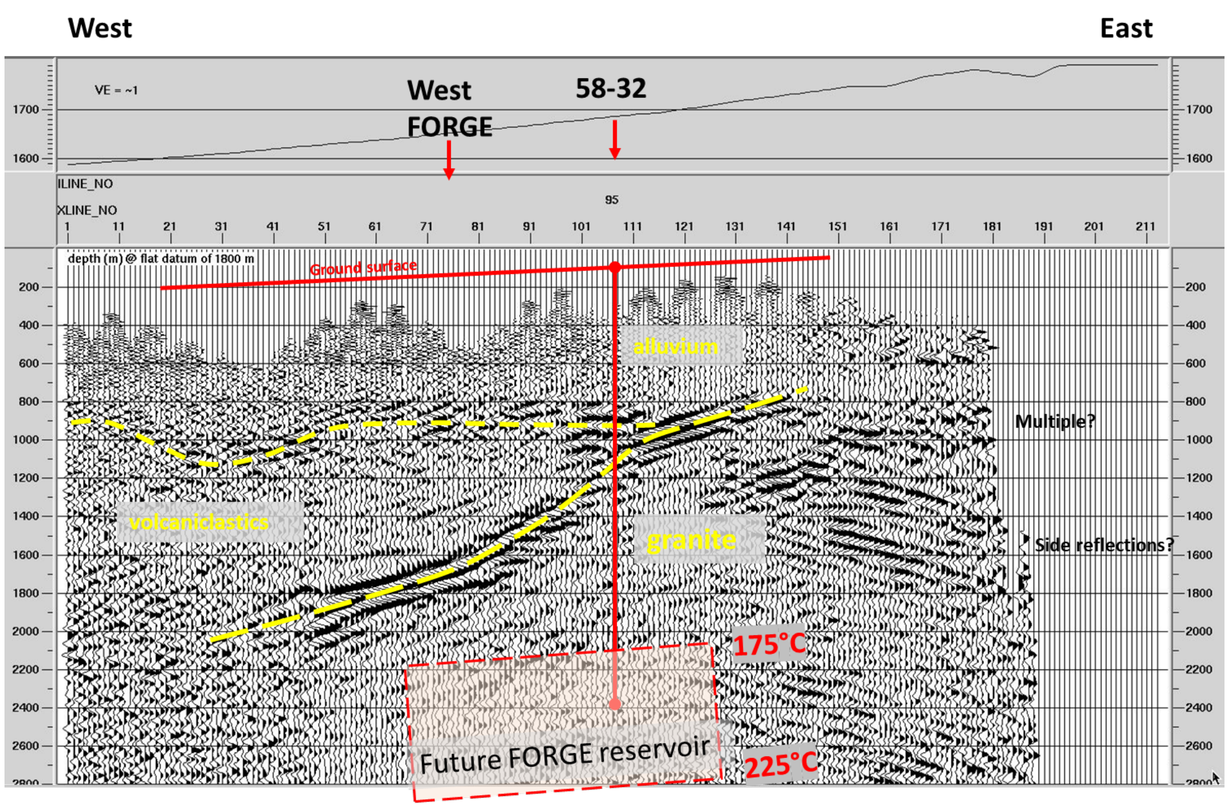

Figure 8. *West-east section through FORGE well 58-32 on inline 95. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. Annotations are the same as in Figure 7.*

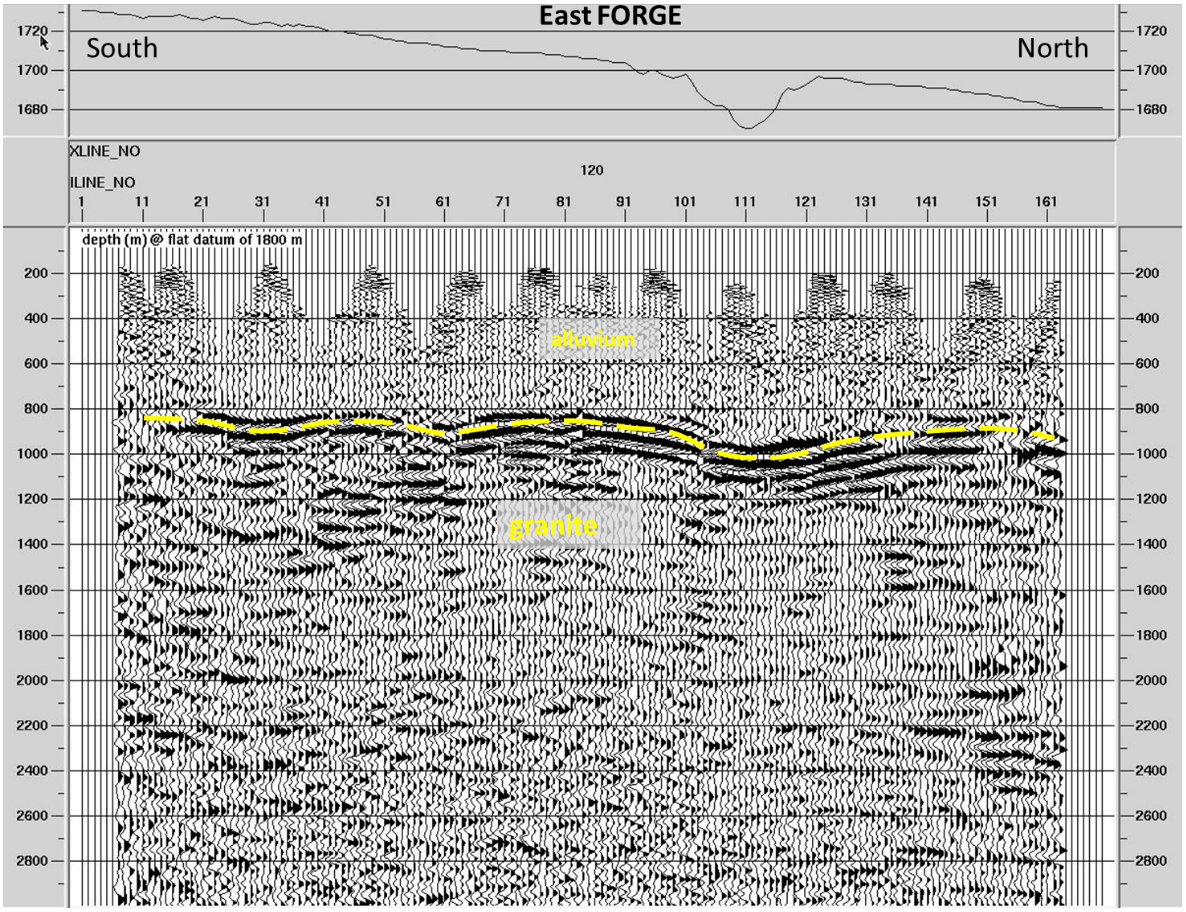

Figure 9. *Crossline 120, extending north-east through the east side of the FORGE site (location on Figure 2). The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration.*

CONCLUSIONS

The identification of the reflections from the granitic surface in the 3-D survey area and the adjacent 2-D lines has been integrated with the gravity interpretations of basin-fill thickness (Hardwick et al., 2019) in Figure 13. Although the average westward dip of the granitic surface is 25 ± 5 degrees, the 3-D 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. (line 11), indicate 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 earlier phases 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 million years. This interpretation does not preclude detachment tectonics occurring during basin evolution as proposed by Bartley (2019), but the detailed 3-D image of the surface of the granite indicates that this feature is not of tectonic origin.

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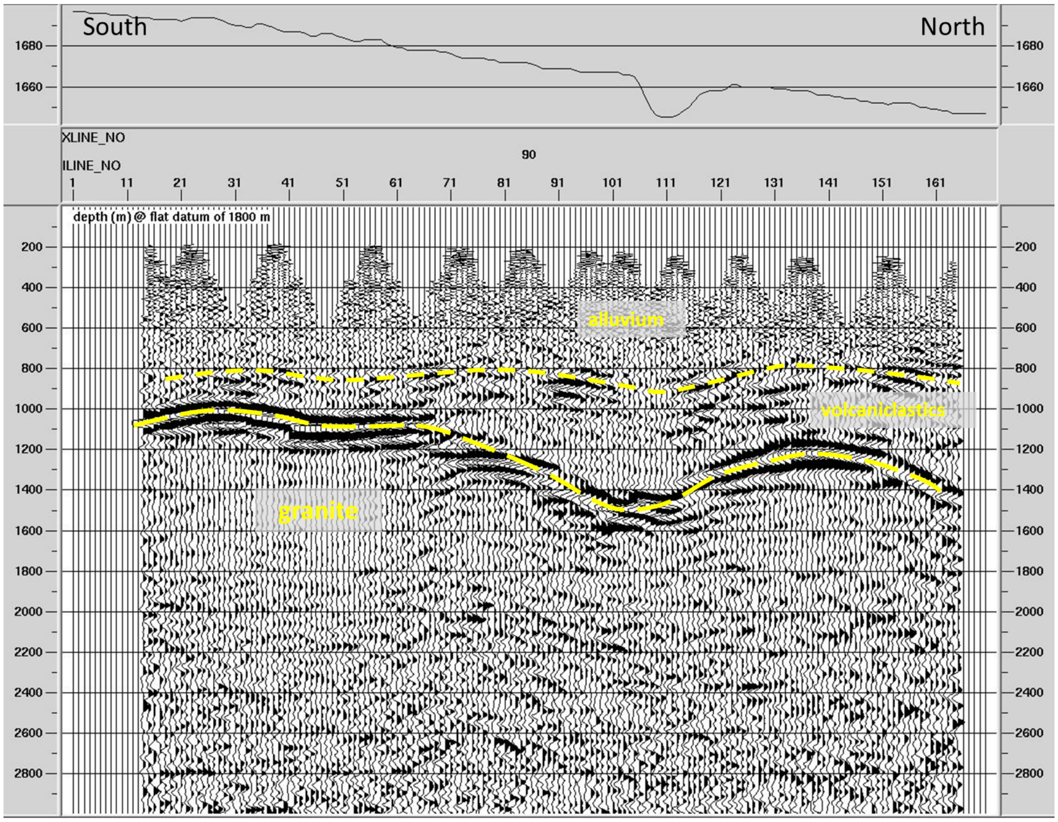

Figure 10. *Crossline 90, which extends north-south through the center of the FORGE site, 375 m west of well 58-32. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration.*

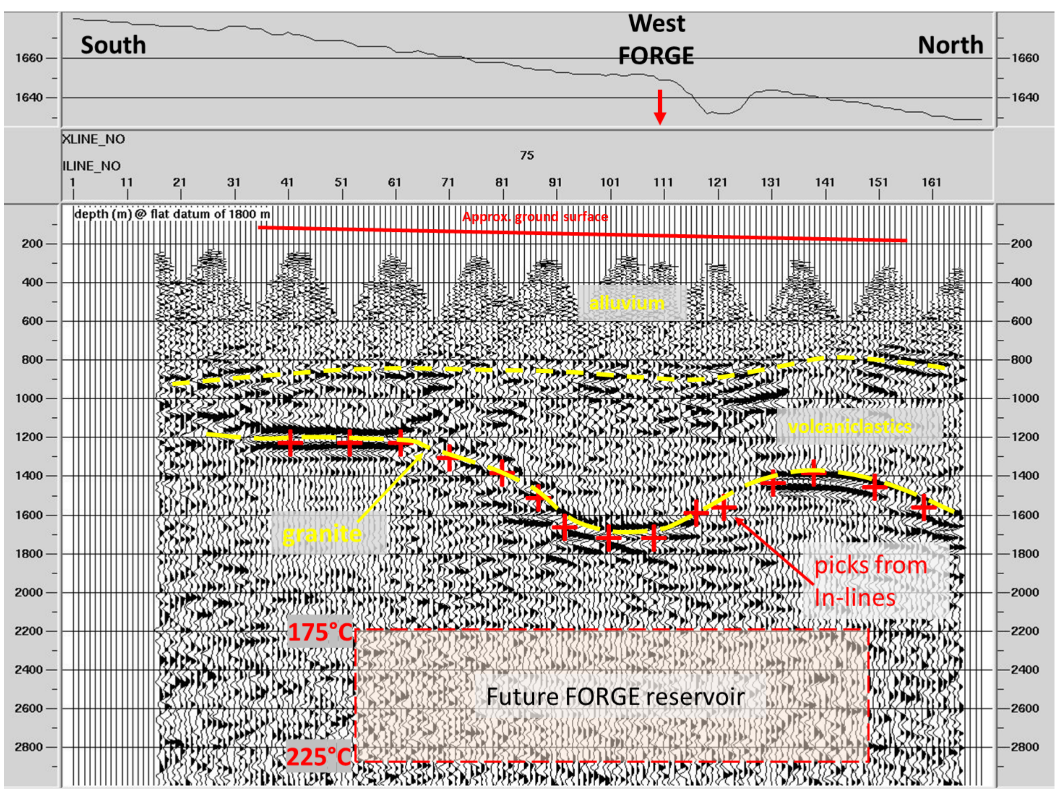

Figure 11. *Crossline 75, which extends north-south through the west side of section 32 in the FORGE site. The upper graph shows the surface topography (m asl), and the lower graph shows the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. The red crosses are picks of the granitic surface from where the inlines intersect crossline 75. They confirm a smooth granitic surface to the buried valley beneath the west side of the FORGE site.*

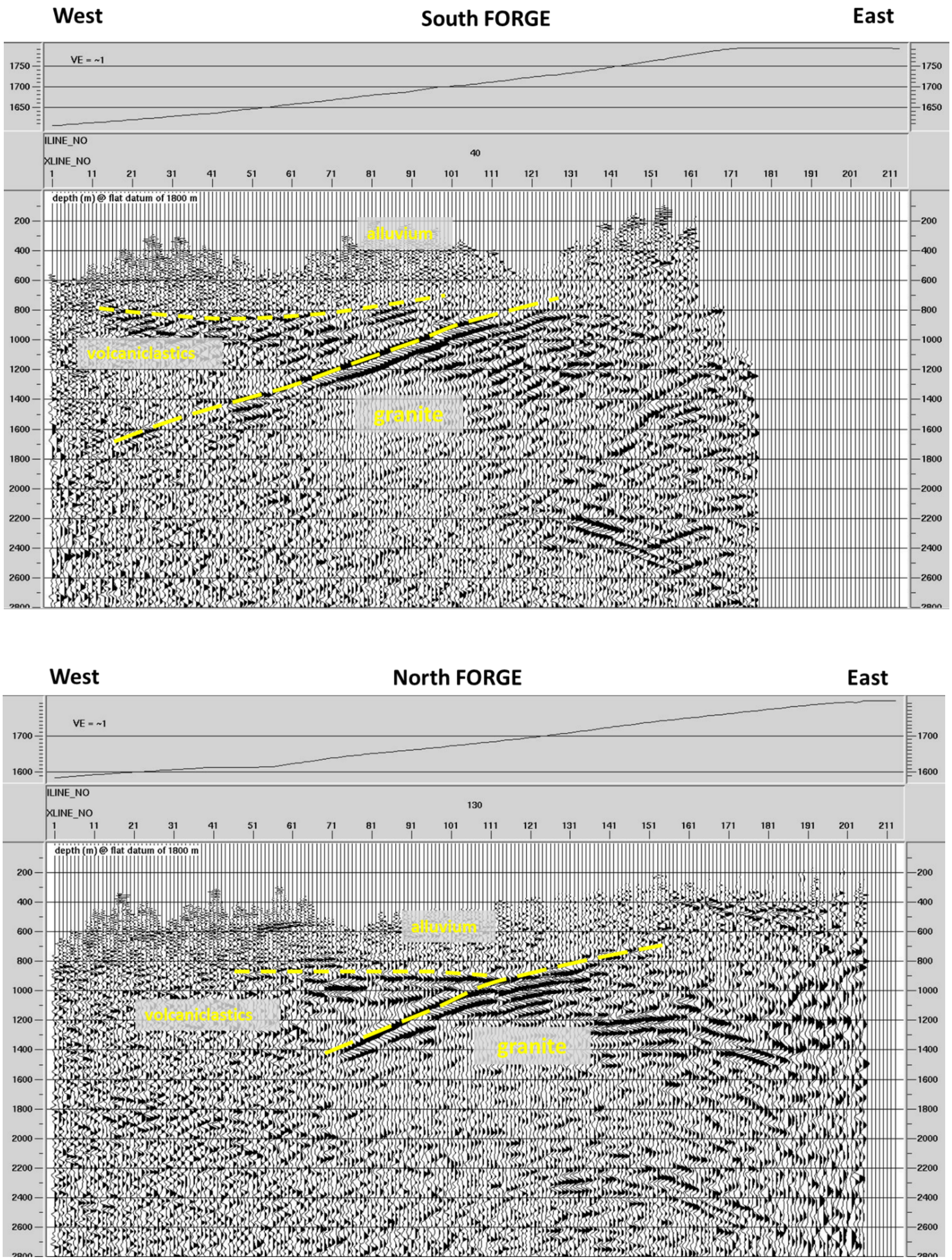

Figure 12. *Inlines 40 and 130. The upper graphs show the surface topography (m asl), and the lower graphs show the reflection imagery in depth (m) below the datum of 1800 m asl. There is no vertical exaggeration. Both lines have spurious reflections within the granite on the east side.*

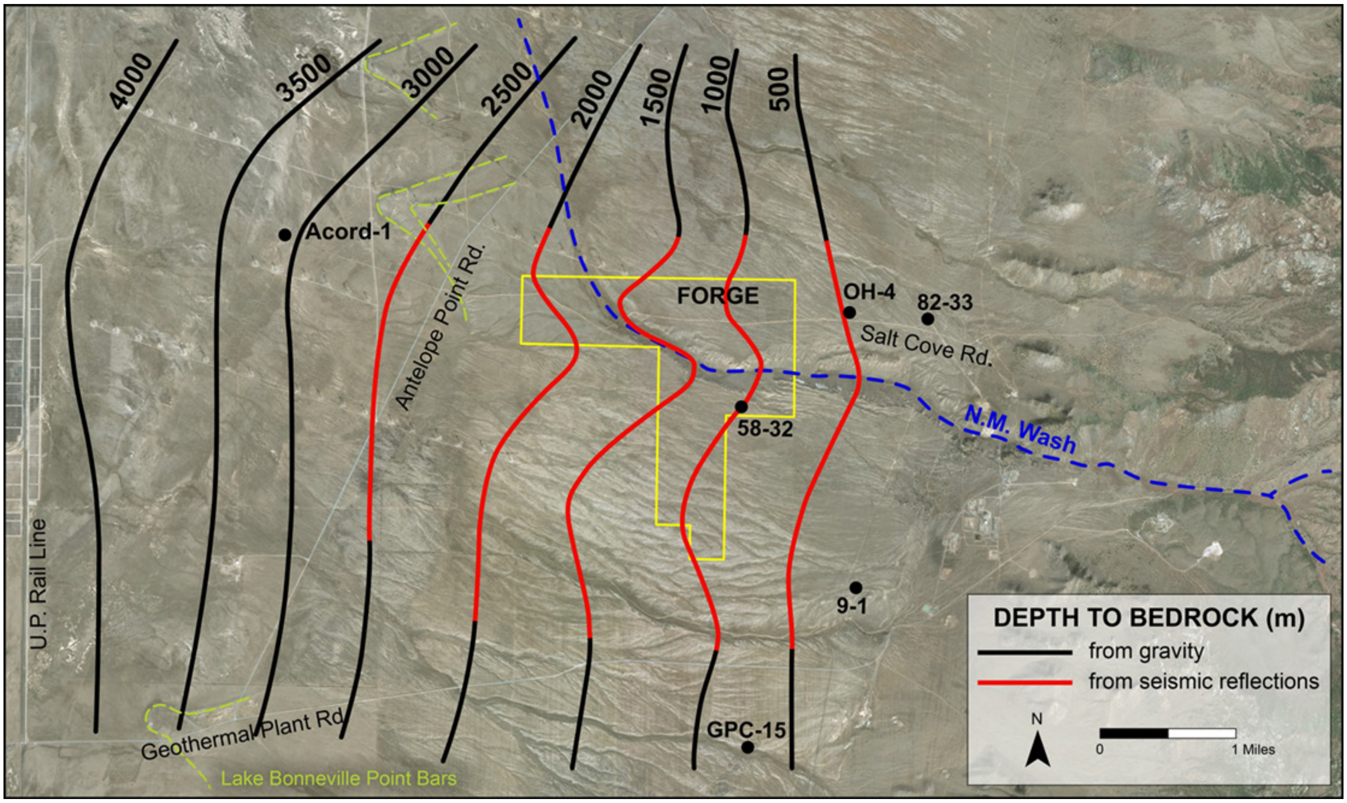

Figure 13. *Structural contours on the top of the granitic bedrock around the FORGE site. The contours are derived from integration of the picks from seismic reflection surveys and from gravity modeling by Hardwick et al. (2019).*

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