2018-2019 reprocessing of the 2D and 3D multichannel seismic surveys at the FORGE Utah EGS Laboratory

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Introduction

In November 2017, a new ~7 mi^2 (~17 km^2) three dimensional (3D) multichannel seismic reflection survey and two 2.4 mile (4 km) long two dimensional (2D) multichannel seismic lines were collected over, and extending east and west from, the Utah FORGE site. In addition, in September and October 2017, two previously existing seismic lines (legacy 2D data) adjacent to the FORGE site, ~7 miles (11 km) and ~8.5 miles (14 km) long, were licensed from Seismic Exchange, Inc. (SEI) with limited publication rights. The locations of these data are given in Figure 1.

Utah FORGE personnel performed data enhancement and depth conversion on the SEI data in late 2017. The new 2D and 3D data were collected by Paragon Geophysical, of Wichita, Kansas, who subcontracted with Star Geophysics, Inc., of Oklahoma City, Oklahoma, to process these newly-collected data. Unfortunately, only Line 301was processed by Star, with FORGE personnel performing minimal processing on Line 302. The quality of the migration of the 3D data by Star was not high. However, the unmigrated version of the 3D data was of sufficient quality to interpret the alluvial basement reflection. The unmigrated data indicate that the granite surface is continuous and undulatory and lacking in any evidence of subvertical fault offsets beneath the FORGE site (Miller and Allis, 2018, Miller et al., 2018, Miller et al., 2019, Hardwick et al., 2019, Simmons et al., 2019).

Because the initial efforts as described above were incomplete, it was decided to have the new 3D and legacy 2D data reprocessed using state of the art techniques. The goal of the reprocessing was to further refine the seismic interpretation for improved imaging of the valley fill-granite contact, and of the deposits above the granite basement. Special attention was paid to the prestack removal of noise such as ground roll and any other noise identified by testing. In addition, depth imaging was performed.

An invitation to bid on reprocessing the Utah FORGE data was issued in August, 2018. The bid was awarded to Land Seismic Noise Specialists (LSNS) of Denver, Colorado, in September. 2018. The LSNS bid proposed a plan to analyze and remove the noise present in the data and to perform all requested reprocessing and depth imaging. The data were delivered to LSNS on September 15, 2018, with the expectation that the work would be completed by December 31, 2018.

This report describes LSNS efforts up to and including delivering the processed data for interpretation. A complete list of products that were delivered is given elsewhere in this report.

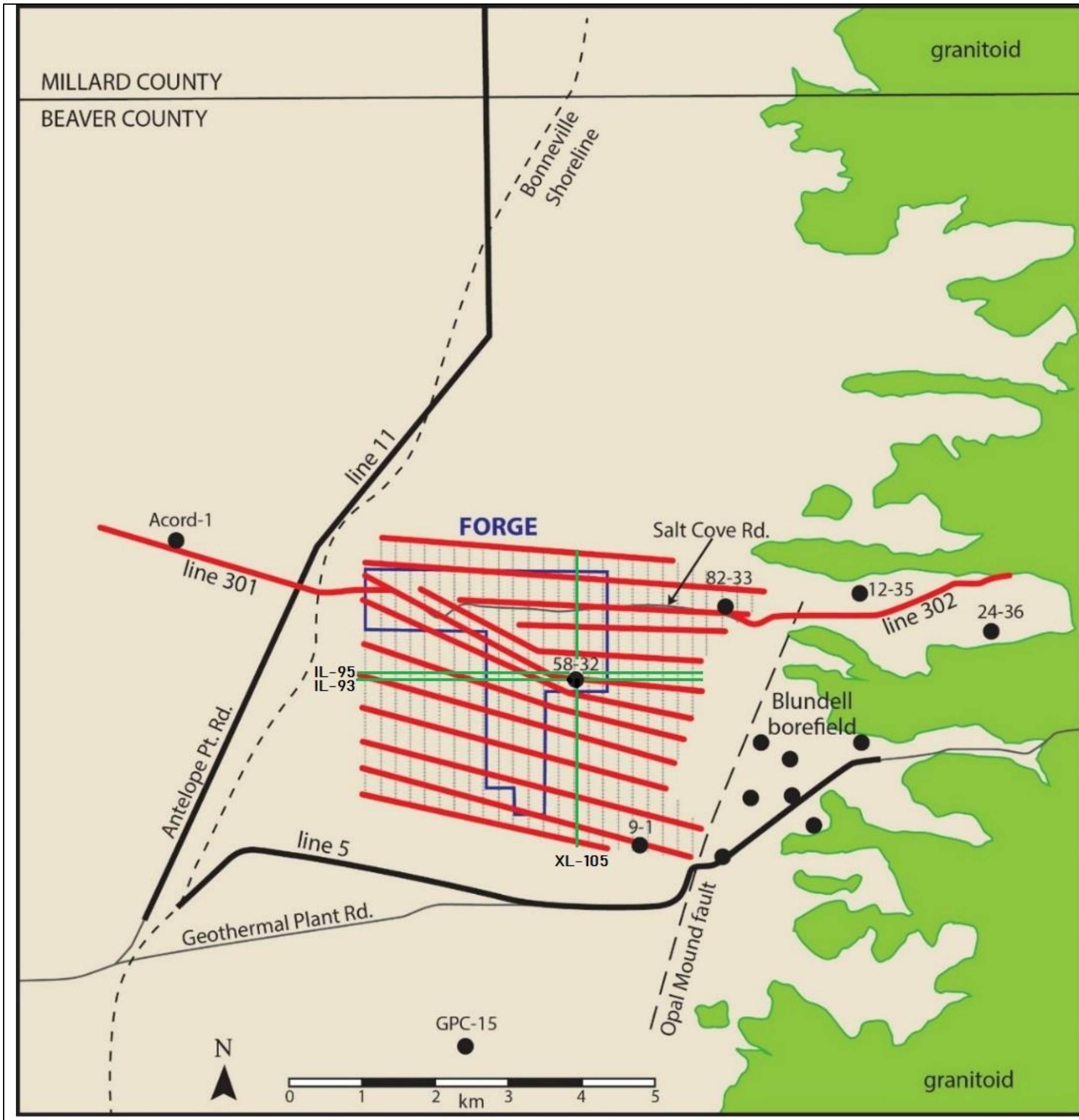


Figure 1: Seismic survey profile locations. The 3D survey area comprises 13 red source lines (vibrator point locations 50 m apart), and 27 gray geophone lines geophone locations (oriented N-S, geophone interval 50 m). Red lines 301 and 302 are new 2D seismic lines; heavy black lines labeled 5 and 11 are legacy 2D lines licensed from Seismic Exchange, Inc. After Miller et al. (2019). Green lines are 3D inlines (IL) and crosslines (XL) discussed in this report.

Review of 3D and 2D Recording.

As explained in Miller et al. (2019), the new 3D data were recorded using 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 (Figures 1 and 2). All receivers were active for each source point. The 3D data were organized geometrically into CDP bins spaced 25 m apart and were further organized into 170 “inlines” oriented west-east and 213 “crosslines” oriented south-north (details in Figure 2). 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 (Figure 1). These new 2D data were organized into Common Depth Point (CDP) bins along each line, spaced 12.5 m apart. The energy source used for both the new 2D and 3D 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. Legacy 2D 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. (Figure 1).

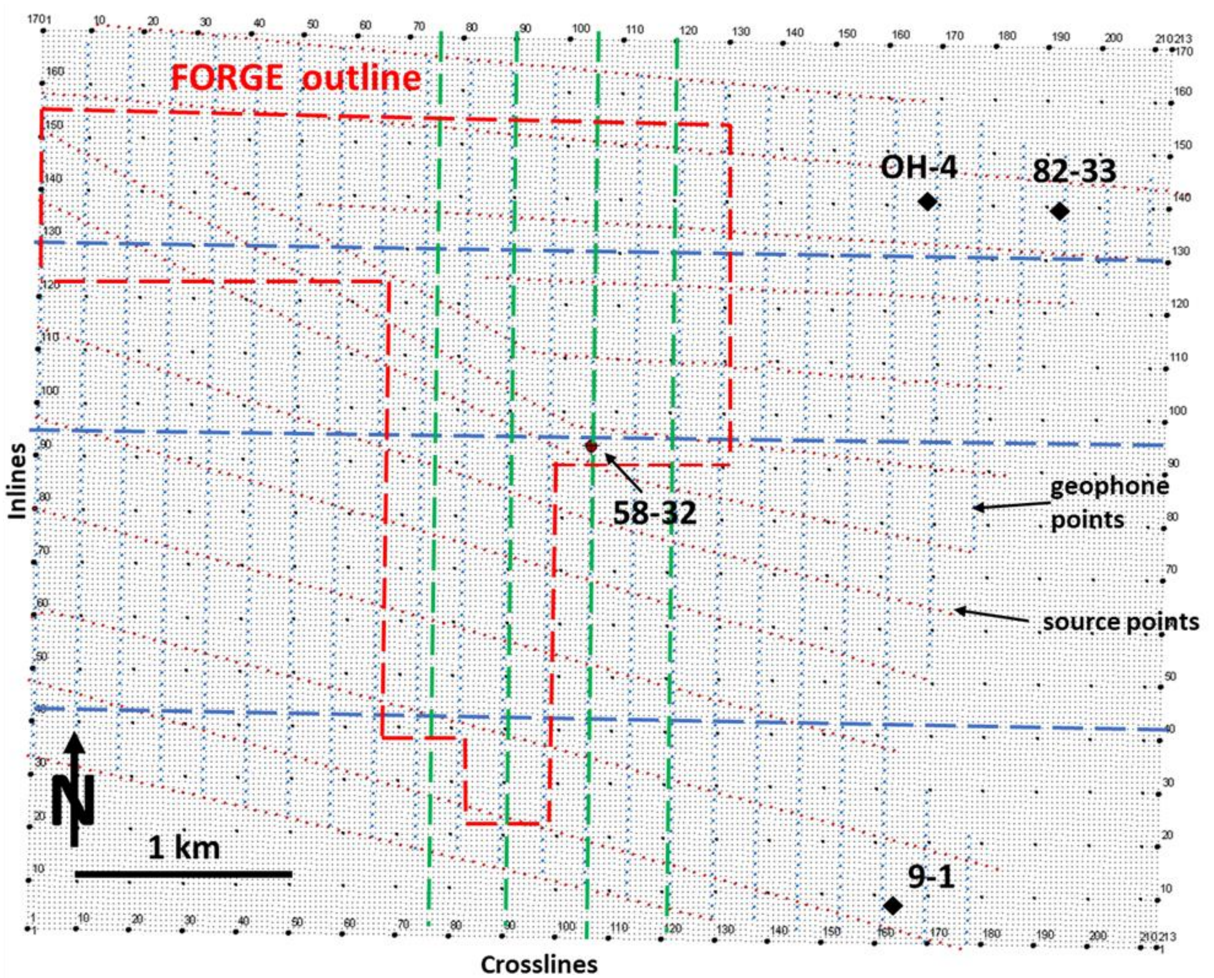


Figure 2. Details of the source and receiver points, the Utah FORGE boundary (red dashes), north-south crosslines (green dashes) and west-east inlines (blue dashes) are lines chosen for discussion in Miller et al. (2019). Well 58-32 is the FORGE well drilled during 2017, and wells 9-1, 82-33, and OH-4 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. After Miller et al. (2019).

Horizontal Limits of 3D and 2D Survey Coverage.

In a 3D seismic survey, the full areal extent of the survey may not necessarily be valid for interpretation. The reason for this is twofold and both are referred to as "edge effects". First, for each CDP bin, it is desirable to have traces with a large distribution of source-receiver offsets, i.e. traces whose source-receiver offset is small (sometimes coincident) and those that have a large offset, referred to as high fold. High fold facilitates accurate velocity determination and provides a good signal to noise ratio (*Schlumberger, 2019a).* Second, the migration process, which attempts to accurately position the reflections in space, usually requires reflected energy from all directions about each CDP bin (*Schlumberger, 2019b)*. Neither of these two conditions is met at the edges of the survey. At the edges there are few traces contributing to the CDP bins (low fold), and there are naturally no traces outside the edges of the survey. The migration edge effects which are sometimes referred to as migration artifacts, manifest as upwardly curved events.

Figure 3 shows the relative fold distribution for the FORGE 3D survey. Dark blue indicates CDP bins with the lowest fold (and a limited range of source-receiver offsets); red indicates CDP bins with the highest fold and largest possible distribution of source-receiver offsets. The white square in the center of the figure indicates generally where the interpretations will be most valid; Outside of this white square, the data may be contaminated by edge effects and interpreters should exercise caution when making geological interpretations. Figure 4 shows the edge effect on the southern end of crossline XL-105. These upwardly turned reflections are primarily a migration edge effect (artifact), but are partially due to low fold as well.

Figure 5 illustrates edge effects on inline IL-95. The top is an unmigrated time section and lacks coherent reflections on the west end of the line, possibly because of low fold in that area. The east end is an example of low fold as the line approaches the edge of the survey, but signal from the granite reflector is strong to the edge of the survey. The green vertical line indicates the eastern extent of shallow surface coverage. The bottom shows edge effects on both the east and west ends of the line. The west end has upturned energy which is an artifact of migration where there is little to no signal and should be considered invalid. However, the east end shows the granite reflection extending to the east of the green line. This phenomena is also an edge effect but can be considered valid information. The migration process will necessarily move a dipping reflector toward the updip direction and, because the granite reflection is so strong in this area, it can be interpreted as valid information. However, the deeper energy is a migration edge effect because there is no coherent energy in that area on A, above.

Migration edge effects are also present on the new 2D data but are much less severe. The reason for this is that these lines utilized a regular recording configuration, i.e. there was a source point coincident at every receiver point. This configuration causes a linear fold reduction at the end of each line and also insures that there is shallow energy recorded to the end of each line, greatly reducing migration edge effects.

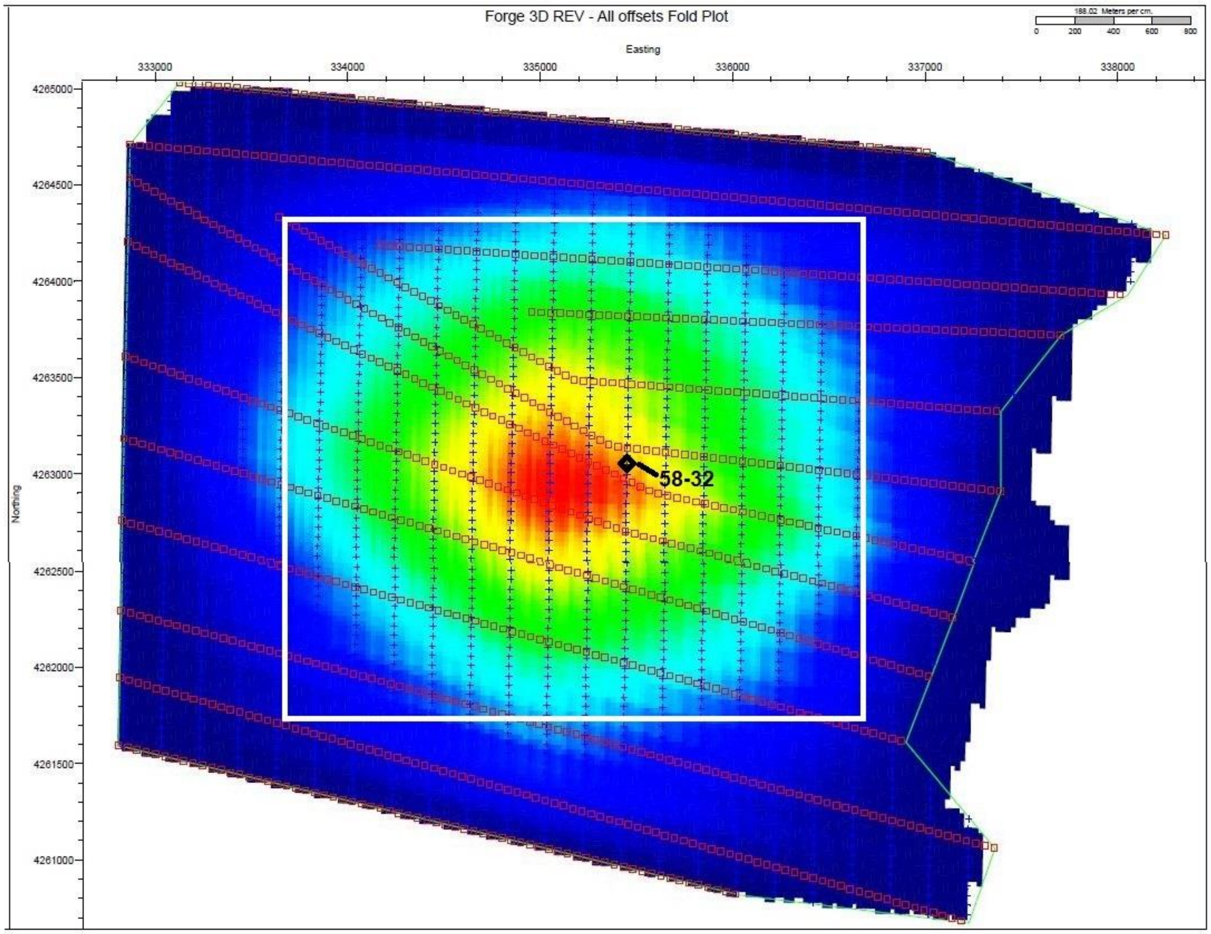


Figure 3. Diagram indicating relative minimum and maximum seismic fold (number of traces contributing to a CDP bin) based on the 3D recording configuration. Blue = Minimum fold; Red = maximum fold. White box indicates the general area where the 3D data should not be affected by edge effects of low fold and migration artifacts. Care should be taken when interpreting data outside of this box.

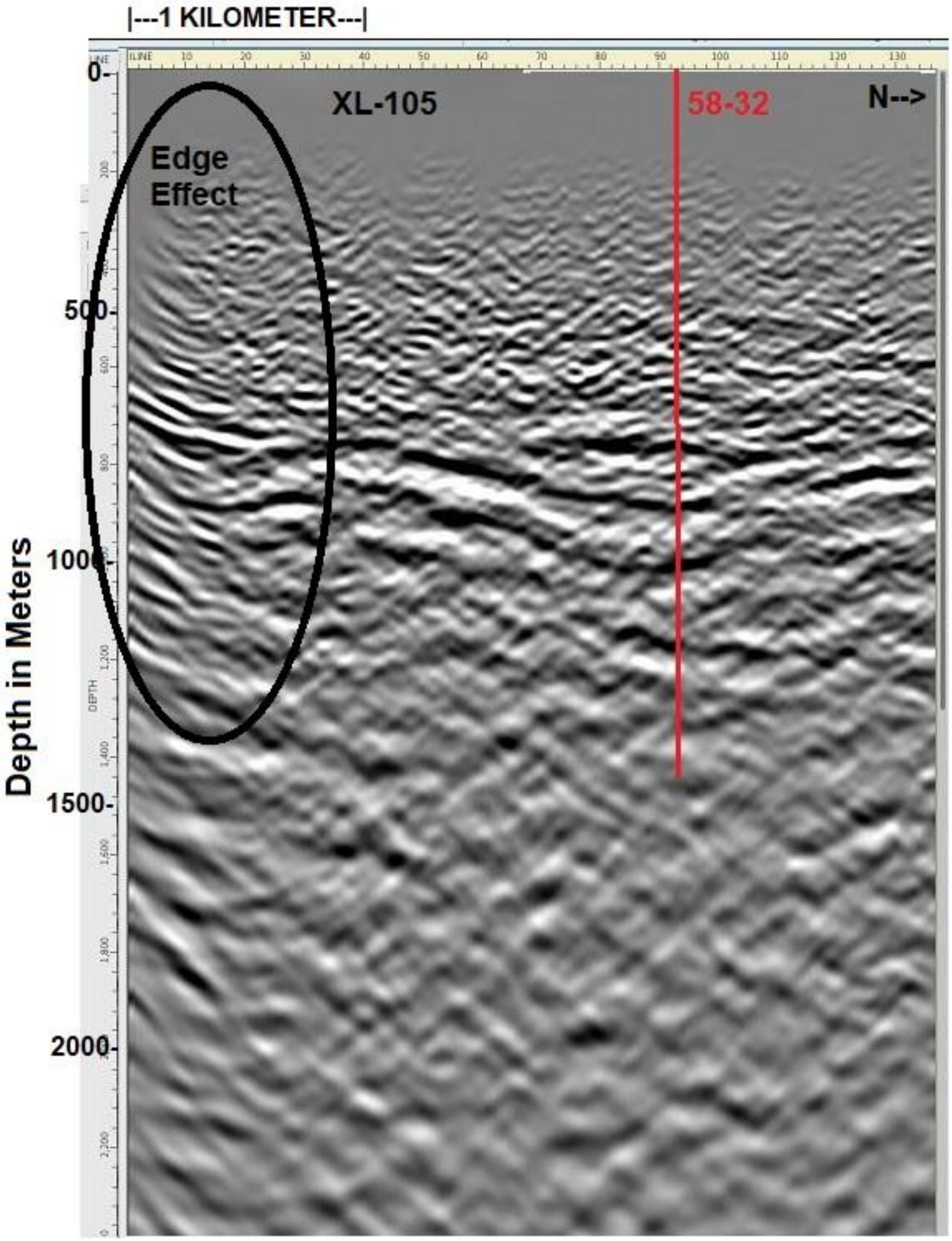


Figure 4. North-south crossline 105 (XL-105) intersecting test well 58-32 indicating the 3D "edge effect" at the southern end of the line. This effect arises from the low fold and the migration process (migration artifact) and should not be considered valid information.

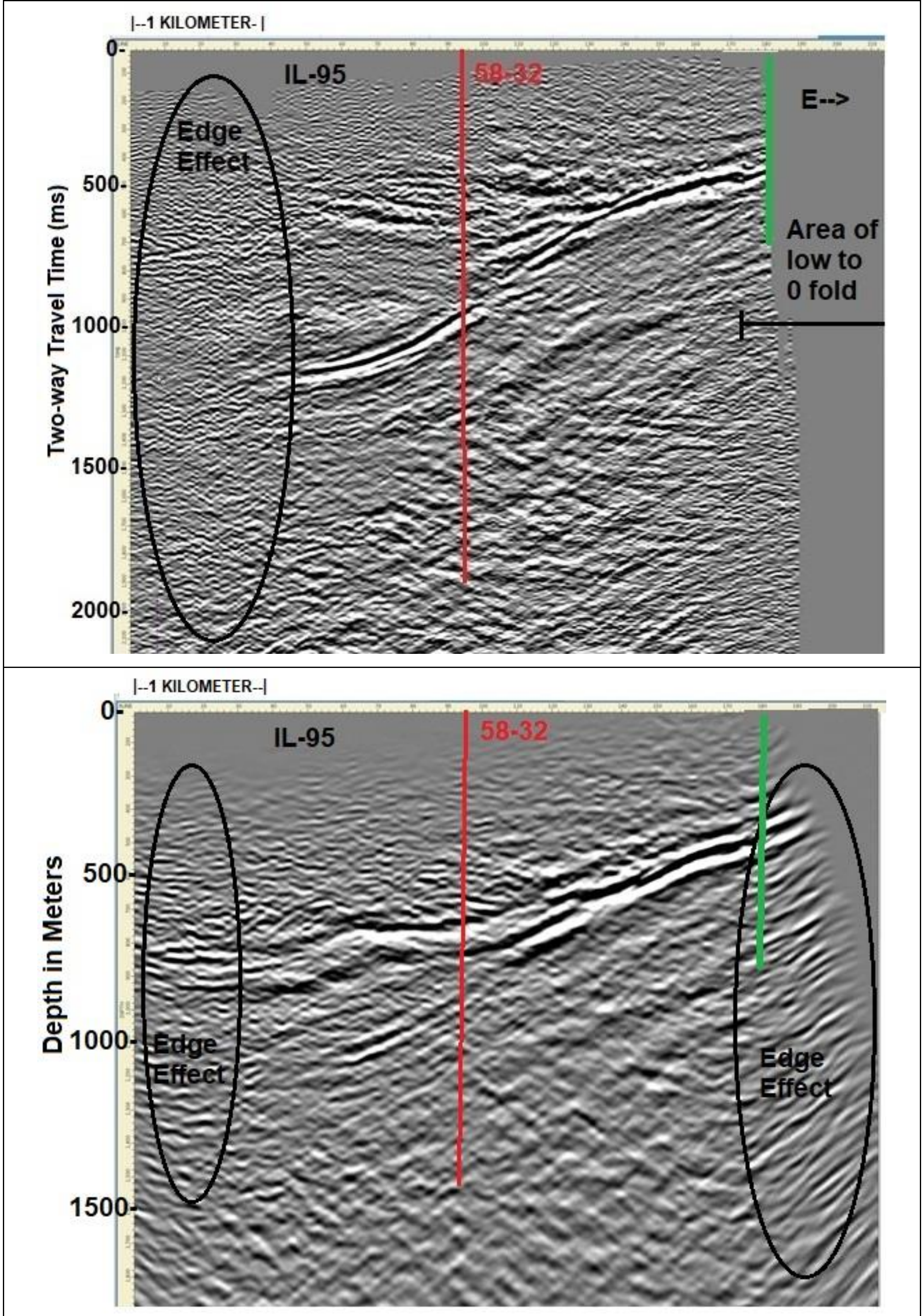


Figure 5. Top: Unmigrated time shows lack of reflections on the west, possibly because of low fold; also indicated is low fold on the east end. Vertical green line indicates eastern extent of shallow surface coverage. Bottom: Migrated depth of A. Migration edge effects can be seen on the west end. The granite reflection has migrated east of the green line which is valid. Migration artifacts are deeper.

Comparison of Processing Flows utilized by LSNS and Star Geophysics, Inc.

Table 1 gives a comparison of the processing flow used by LSNS compared with that of Star Geophysics, Inc. The following are the significant differences in the two processing flows:

- LSNS performed two passes of noise attenuation (Table 1, steps 3 and 7) whereas Star's attempt at noise removal was unsuccessful.
- Both companies applied refraction statics and deconvolution, but in a different order.
- Star applied a process called "trim statics" at step 8. This process is a method by which reflected energy between traces is "forced" to line up in a coherent manner, independent of the geology. It is a process that is sometimes necessary when data contains excessive noise, and its application may be indicate that Star was unable to achieve precise noise removal.
- The lack of trim statics in the LSNS flow indicates that random and coherent noise was successfully identified and removed.
- Star's 3D processing ended at their unmigrated stack subsequently followed by depth conversion.
- LSNS performed both prestack time and prestack depth migration.

Table 1: Generalized Processing flow performed by LSNS compared with Star Geophysics, Inc. Complete details of Star's processing can be found in Miller and Allis (2018).

Step	Land Seismic Noise Specialists (All 3D and 2D data)	Star Geophysics, Inc. (3D and 2D Line 301 only)
1	Geometry corrections, QC Trace edits, and refraction statics calculation and application	Geometry corrections
2	Amplitude balancing	Gain Recovery and trace amplitude equalization
3	Pre-deconvolution noise attenuation: airblast denoise, spectral edit denoise, proprietary LSNS denoise	Attempted noise removal failed.
4		Bandpass Filter & Surface Consistent Spiking Deconvolution
5		Refraction Statics
6	Iterative velocity and residual statics analysis (2 passes)	Iterative velocity and residual statics analysis
7	Spiking Deconvolution (180ms filter) and post-deconvolution noise attenuation – spectral edit and despike	
8		Trim Statics
9	Offset bin interpolation (3D only)	5D Offset bin interpolation (3D only)
10		Stacking Velocity Analysis
11		CDP Stacking and post stack scaling
12	CDP Stacking and post stack enhancements	Depth Conversion (3D only)
13		Post Stack time migration (2D Line 301 only)
13	Pre-stack time migration velocity analysis on migrated gathers	
14	Pre-stack time migration and post-stack enhancements	
15	Pre-stack depth migration velocity analysis and model building	
16	Pre-stack depth migration using an estimated anisotropic velocity model and post-stack enhancements	
17	Bandpass Filter (4-8-80-120 hz)	

Details of LSNS reprocessing

LSNS began processing the data in late September, 2018. Time processing began on the new 3D survey, Line 301 and 302. Two problems were immediately encountered. First was difficulty in creating a refraction statics solution, a process that compensates for lateral variations in near surface velocity. Unusually large variations in near surface velocity were encountered in the Utah FORGE area, but refraction statics solutions were eventually obtained. Second, severe random and coherent noise issues were encountered. Although this was expected, it took much longer to solve the noise problems than was originally anticipated. LSNS used proprietary software which uses a machine learning denoise algorithm to search for consistent and repeatable noise patterns in the shot and receiver domains of the data and removes them (LSNS, written communication). It was also determined that velocities of the sediments above the top of granite in the study area were directionally dependent, i.e. the velocity needed to create a correct subsurface image was sometimes different depending upon the azimuth between the source and receiver. For example, a common reflection point might be imaged by numerous combinations of sources and receivers. In some cases the velocity needed to image that reflection point would be significantly different if the azimuth between source and receiver was 90 degree (east-west) vs. an azimuth of 180 degrees (north-south) and similarly for other azimuths. This phenomenon required extensive testing in order to estimate the velocity field.

Except for 2D Line 302, the datum of all data presented in this report is 1,800m asl. Because the surface elevations of Line 302 are much higher than 1,800m, a datum of 2,100m asl was used for this line.

3D processing

A comparison of the original processing by Star Geophysics and the new processing by LSNS, is given in Figure 6. This is an unmigrated time version of 3D inline IL-95 which passes 50m north of test well 58-32. Because we did not receive a migrated version of the 3D survey from Star, a comparison of unmigrated time processing is the only direct comparison that can be made. The original processing shown at the top exhibits problems that have been resolved by the new processing (bottom). The yellow oval marked A indicates poorly resolved alluvial sediments; the yellow oval marked B indicates some type of coherent noise and possibly multiple reflections. There is a curious lack of any reflective energy above the horizontal line at approximately 550 ms. The new processing is a better product in all respects, and especially so in resolving the granite reflection to the eastern end of the survey.

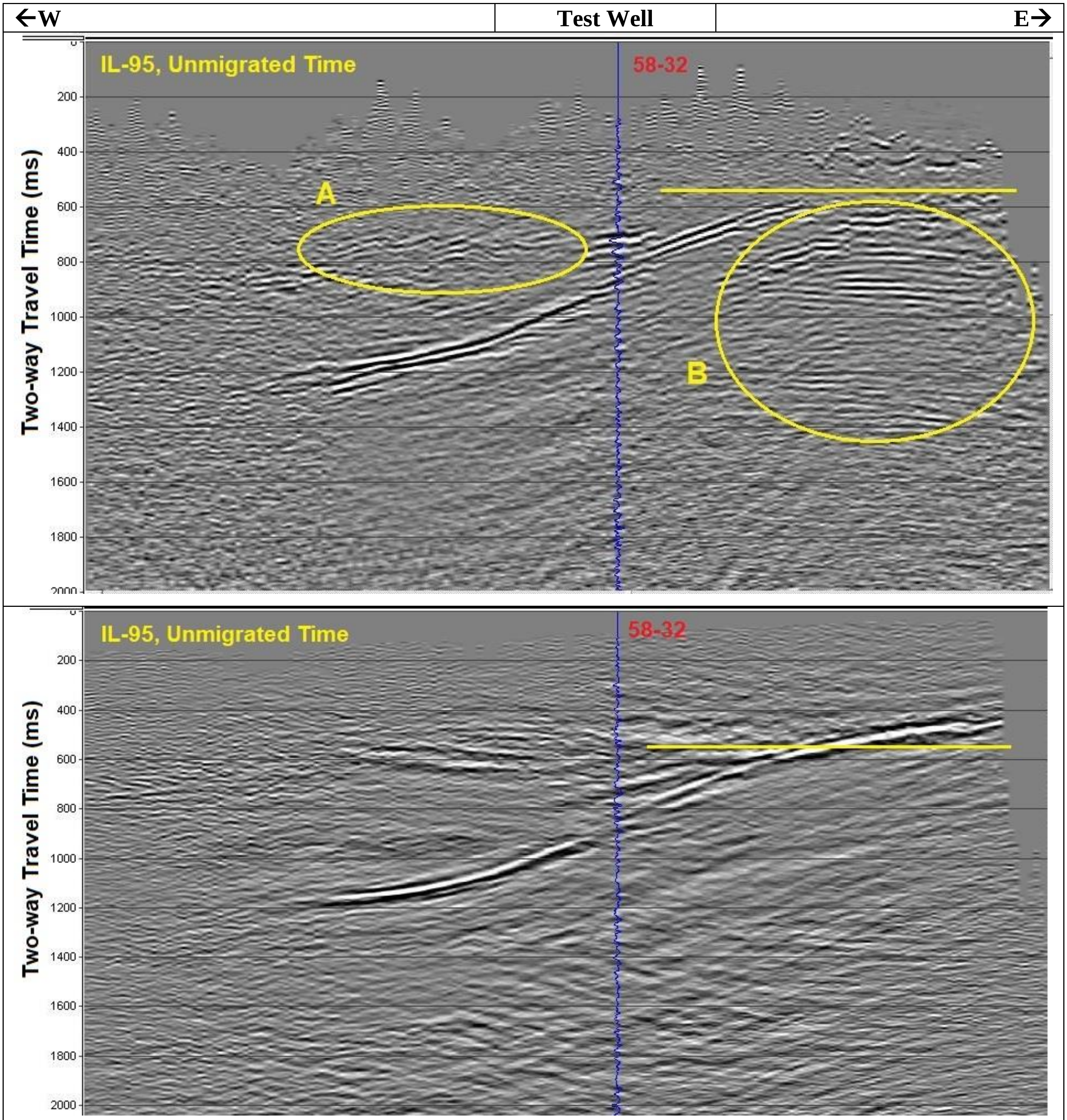


Figure 6. Direct comparison of unmigrated time processing.
Top: Star Geophysics product. Yellow oval labeled A indicates poorly resolved alluvial sediments; yellow oval marked B indicates coherent noise and possibly multiples. All reflections appear to disappear above the horizontal line, including that of the granite. Bottom: LSNS result. Sediments are better resolved, coherent noise and multiples are eliminated. There is reflective energy above the yellow line including the granite reflection which extends to the east end of the line. The projected location of test well 58-32 is shown in blue.

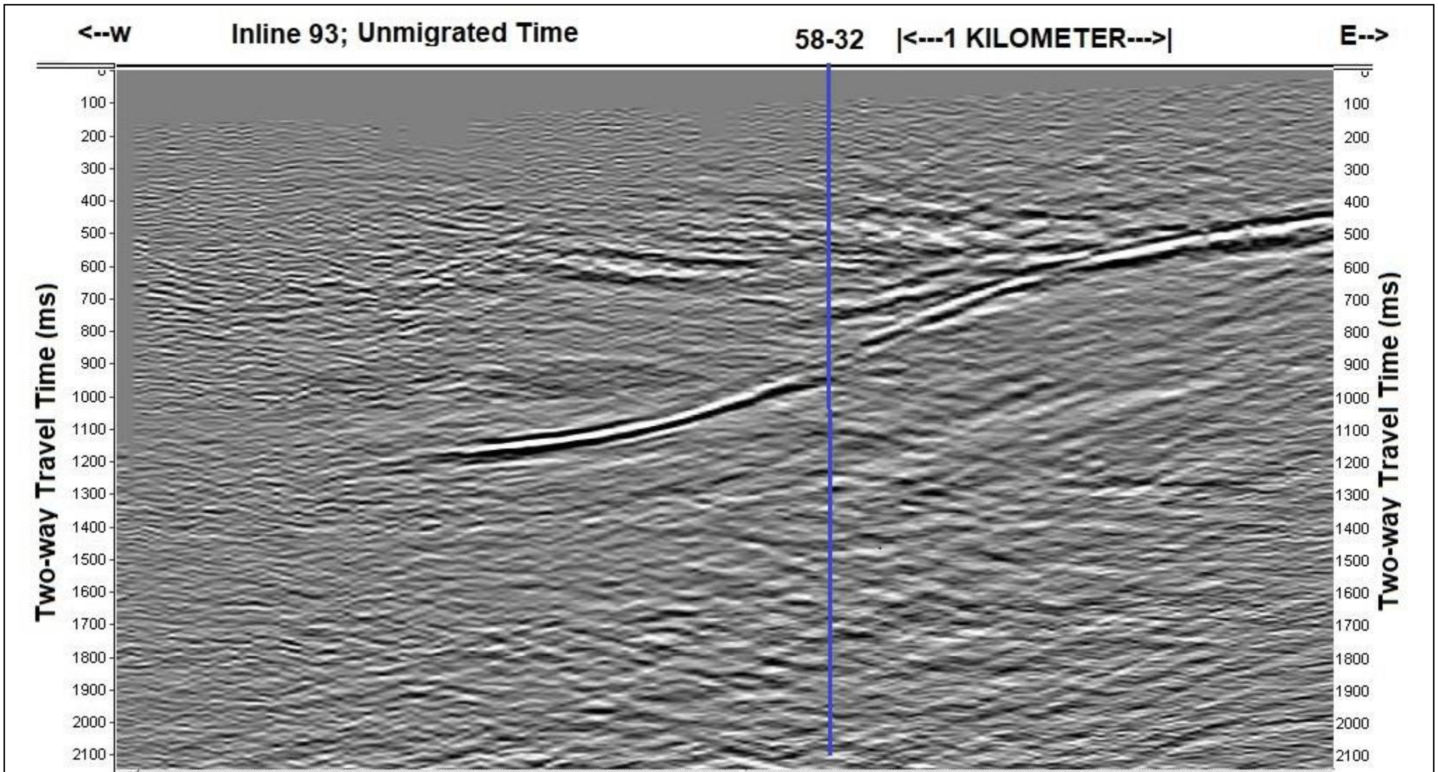
Subsequent to creating the unmigrated time volume, both prestack time and prestack depth migration were performed. A considerable amount of time was spent determining the optimum velocity model for migration. The velocity model determined directly from the seismic data was highly azimuth-dependent, meaning the velocity field changed depending on the azimuth between the source and receiver (horizontal anisotropy). It is surmised from this anisotropy that there was non-uniform sedimentation processes during basin evolution, but this cannot be stated conclusively without additional well data.

Unfortunately, it was not possible to fully account for this horizontal anisotropy (parameter epsilon) when migrating this data set because longer source-receiver offsets and additional well data were needed. However, a migration algorithm that used an estimated anisotropy parameter in the vertical direction (parameter delta) was shown to migrate the depth of the granite interface on the seismic data to that of test well 58-32. The delta parameter also affects the migration raypaths and thus has a horizontal effect. The improved imaging away from the well using this method, as opposed to the standard (delta=0) migration method, gives further confidence that the parameter used, and the imaging result, is correct (LSNS, written communication).

Figures 7 and 8 give a comparison of the 3D processing progression using inline IL-93 which intersects test well 58-32. This line is 50m south of IL-95 shown in Figure 6 and has a similar appearance. Figure 7, top, shows the unmigrated time section of IL-95 and Figure 7, bottom, shows the prestack migrated time version. The time sections indicate that the granite reflection is laterally continuous, with no vertical offsets within the resolution of the seismic data (refer below for a discussion of the limits of vertical resolution). Another indication of vertical offset would be diffracted energy in the unmigrated version (Figure 7, top) and no diffractions are seen.

Figure 8 shows the prestack depth migration of IL-93 using the estimated anisotropic migration; uninterpreted (top) and interpreted by the author (bottom). Again, the top of granite reflection is interpreted to be continuous. The depth at test well 58-32 is indicated by the horizontal amber line. This depth corresponds well with the granite depth as determined by logs and cuttings in well 58-32. The reader is reminded that the datum of this line is 1,800m asl. The surface elevation at well 58-32 is 1,685m asl.

The question of how much vertical offset in the top-of-granite surface can be detected using the reflection seismic method can be answered using the ¼ wavelength principle (Yilmaz, 2001). This principle states that the minimum offset that can be detected is approximately ¼ of the dominant frequency of the seismic wavelet. In this survey, the dominant frequency of the data is 30 Hz (f) and the velocity immediately above the top of granite is 3000 m/s (v). Therefore, the wavelength, v/f, is 100 m. So, using the ¼ wavelength principle we can expect to detect offsets in the granite reflector of 25m or greater. This principle is a function of the recording process and the earth properties, and thus in principle applies both to the STAR and LSNS processing. However, the domain over which this best resolution pertains is significantly greater for the LSNS results due to superior noise removal and velocity estimation.



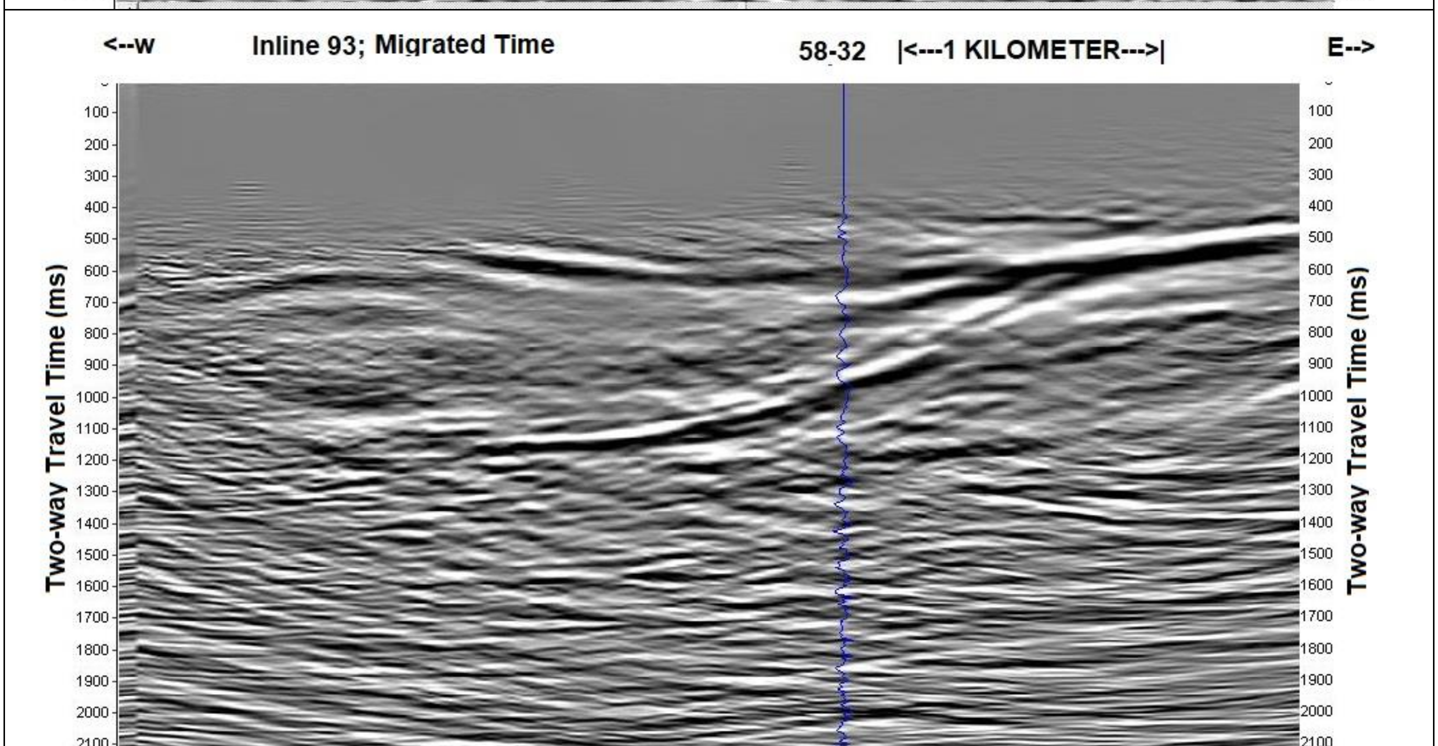


Figure 7. Top: Unmigrated Time processing; for IL-93 showing features similar to that of IL-95 (Figure 6, bottom). This line is 50m south of IL-95. Bottom: Migrated time version of top, showing a horizontally continuous reflection from the top of granite with no significant vertical offset. The location of test well 58-32 is shown in blue.

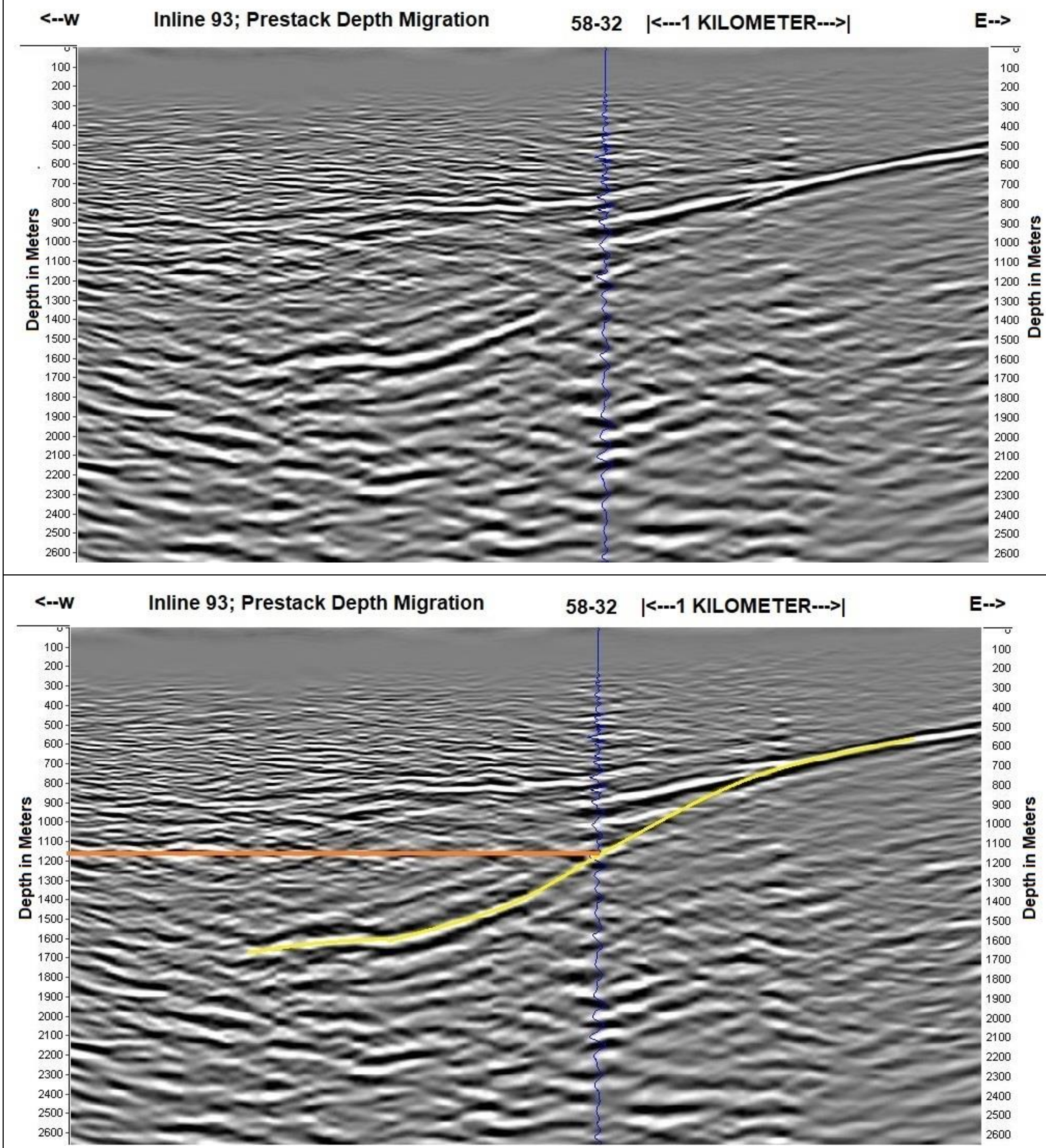


Figure 8. Top: Uninterpreted estimated anisotropic prestack depth migration. Bottom: Interpreted version of the top. Yellow line indicates the author's interpretation of the top of granite reflector. The horizontal amber line indicates the depth to top-of-granite at test well 58-32. This depth corresponds well with the depth of granite from logs and cuttings in well 58-32. The location of test well 58-32 is shown in blue.

2D Processing

Four 2D lines were processed by LSNS; Lines 301 and 30, recorded in 2017 and lines 5 and 11, proprietary lines licensed by Utah FORGE in late 2017 from SEI. In Phase 2C, only lines 301 and 302 were processed from the field data. Lines 5 and 11 were processed by SEIMAX Technologies, a processing company contracted by SEI, and digital time sections were provided to Utah FORGE. These two lines were converted to depth by FORGE Utah personnel using well data and velocities provided by SEI (Miller and Allis, 2018).

The generalized processing flow is given in Table 1.

2D Line 302

2D Line 302 was recorded along Salt Cove Road in 2017 and extends 4 kilometers east from the 3D survey data area (Figure 1). This line images the shallow reflection from the top of granite. As stated in the introduction, Utah FORGE personnel had minimally processed this line and it appeared that the granite formed a shallow basin. However, LSNS applied the refraction statics process to this line, a process that compensates for near-surface velocity variations, and the result was a significant improvement: the basin proved to be an artifact of this near surface velocity variation. Figure 9 illustrates the improvement. The top is the unmigrated time section processed by Utah FORGE personnel. The bottom is the LSNS version of the unmigrated time section after application of refraction statics. LSNS continued processing this line to the point of prestack depth migration (not shown).

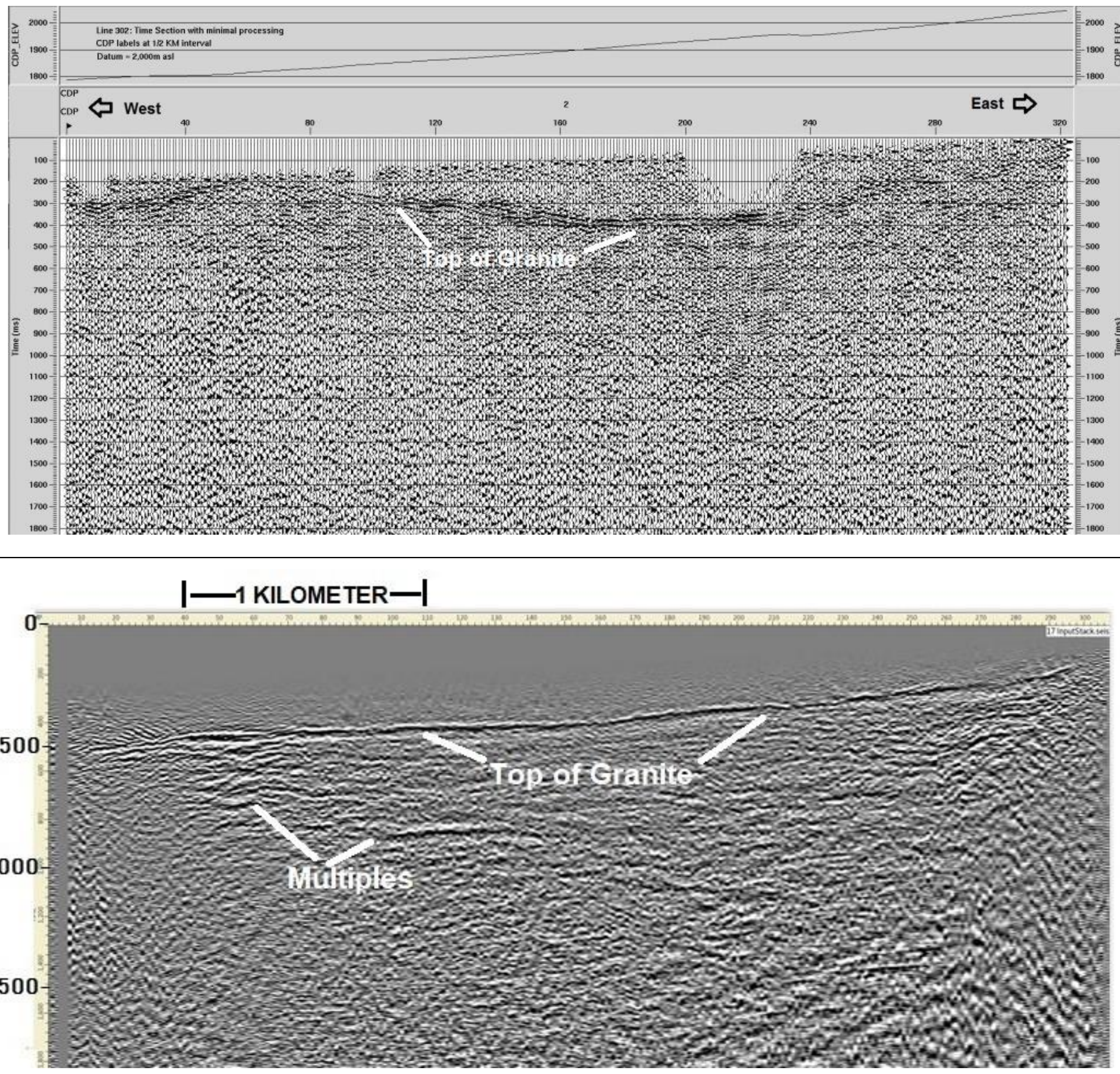
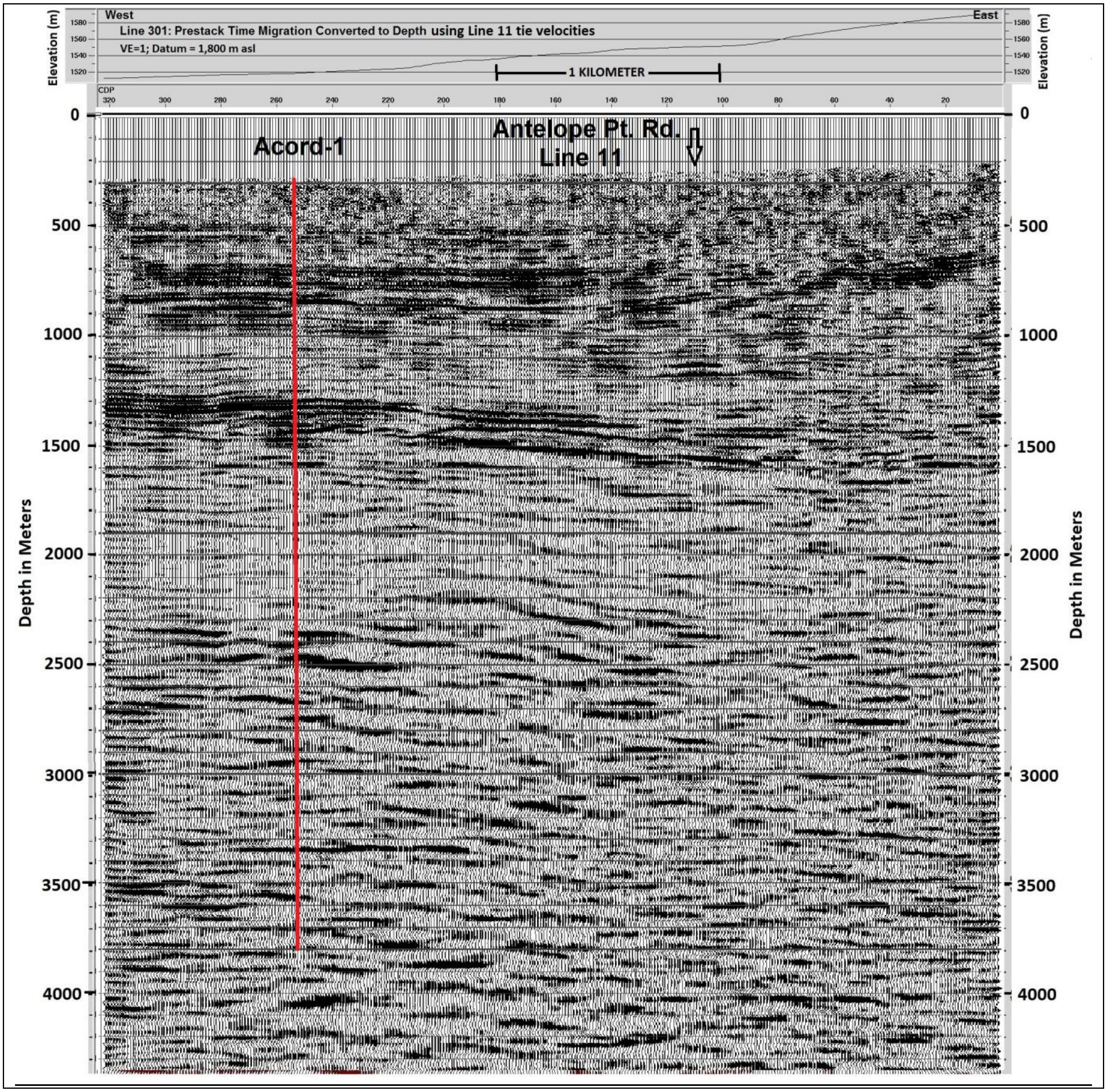


Figure 9. 2D Line 302. Top: Unmigrated time after minimal processing by Utah FORGE personnel. Bottom: Unmigrated time after processing by LSNS using refraction statics showing that the shallow basin is an artifact of near surface lateral velocity variations. Note: the datum of LSNS processing is 2100m asl; 100m above that of Utah FORGE's processing.

2D Line 301

2D Line 301 was recorded along Salt Cove Road in 2017 and extends 4 kilometers west from the 3D survey (Figure 1). Star Geophysics provided a prestack time migrated version of this line and Utah FORGE personnel converted this version to depth using well velocities and tie velocities from its tie point with Legacy Line 11 (Miller and Allis, 2018). LSNS provided a prestack depth migrated version of this line. Figure 10 shows the Star processing (top) compared with the LSNS prestack depth migration processing (bottom). Above 1500m the two versions are similar, but below that depth the LSNS processing shows much greater reflectivity and has reflections dipping up and to the east on the east end which should be expected as the line approaches the 3D survey.



West
East
Line 301: Prestack Time Migration Converted to Depth using Line 11 tie velocities
VE=1; Datum = 1,800 m asl
1 KILOMETER
Elevation (m)
CDP
Acord-1
Antelope Pt. Rd.
Line 11
Depth in Meters

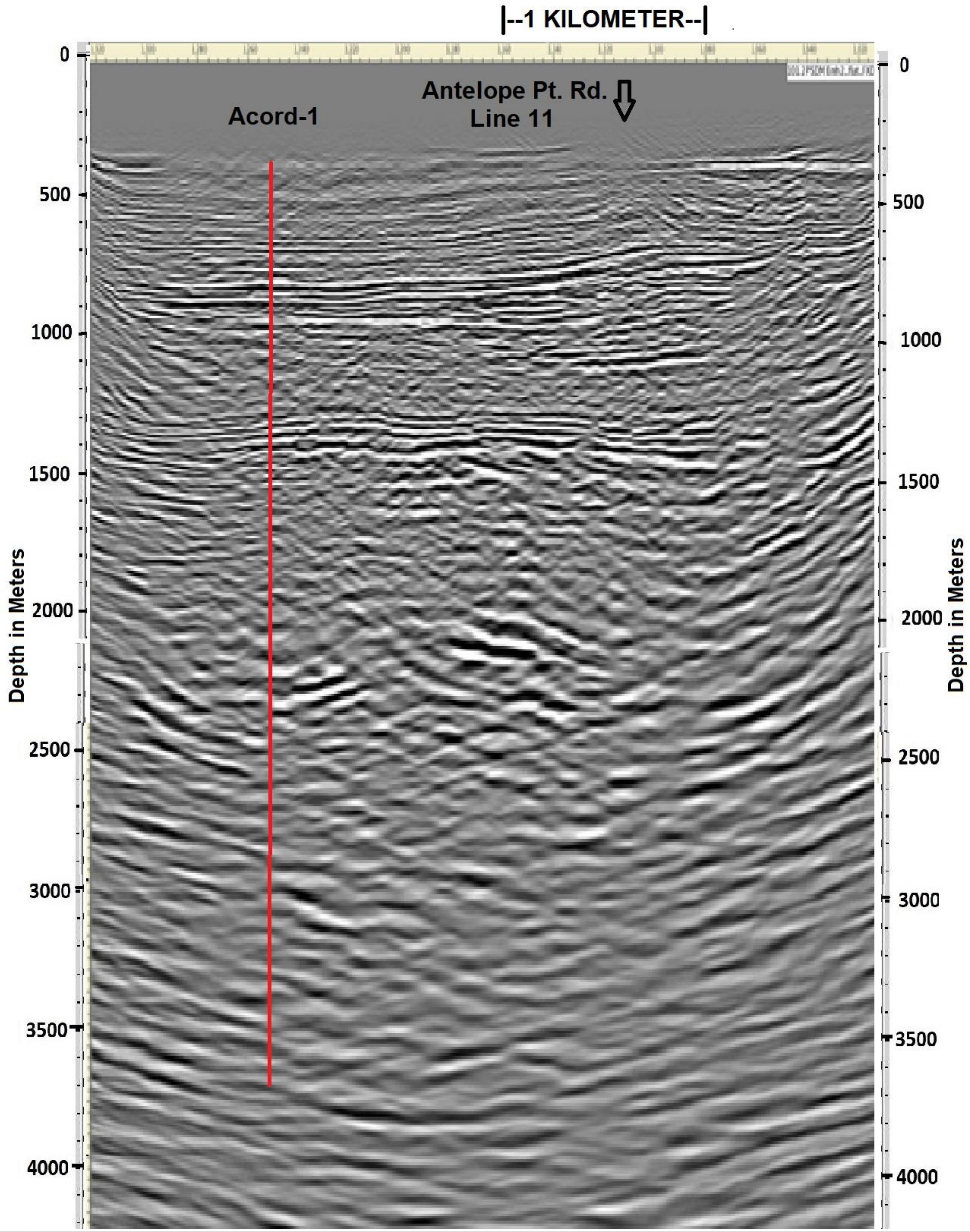


Figure 10: Top: 2D Line 301 processed by Star through prestack time migration; converted to depth by Utah FORGE personnel (after Miller and Allis, 2018). Bottom: Version processed by LSNS through prestack depth migration. LSNS processing shows greater reflectivity below 1500m and reflections dipping up and to the east going into the 3D survey, which should be expected). Location of Acord-1 exploration well and tie point with Legacy Line 11 at Antelope Point Road are indicated.

2D Legacy Line 5

2D Line 5 was recorded in 1978 along and near geothermal plant road, south of the Utah FORGE 3D survey (Figure 1). Among all of the 2D lines, this line proved to be the most difficult to image. The line was initially processed in 1979 by the company that recorded the data; it was reprocessed in 2016 by SEIMAX Technologies, a processing company under contract to SEI. Only a Tiff image of the 1979 processing was available. We identified a company to convert that image to SEG-Y digital traces. Utah FORGE personnel converted that image to depth using a combination of velocities from well 58-32 and well 9-1, projected onto the line's location (Figure 1, Miller and Allis, 2018). Figure 11, top, shows the result. The 2016 reprocessing did not resolve the granite reflection nearly as well as the 1979 processing and that result is shown in Figure 11, bottom. The granite reflection is faint and subhorizontal reflections are poorly resolved relative to the 1979 processing.

LSNS also encountered difficulty imaging the top of granite reflection. However, they were successful in imaging the subhorizontal reflections as laterally continuous and the top of granite can be inferred by the truncations of these reflections as well as a faint dipping reflection. The prestack depth migrated result is shown in Figure 12.

The 1979 processing appears superior to both the 2016 and current reprocessing. The 1979 processing company no longer exists and there is no record of the personnel that did the processing. Both LSNS and Utah FORGE personnel have discussed this discrepancy at length but cannot determine the reason for the apparent fidelity of the 1979 result.

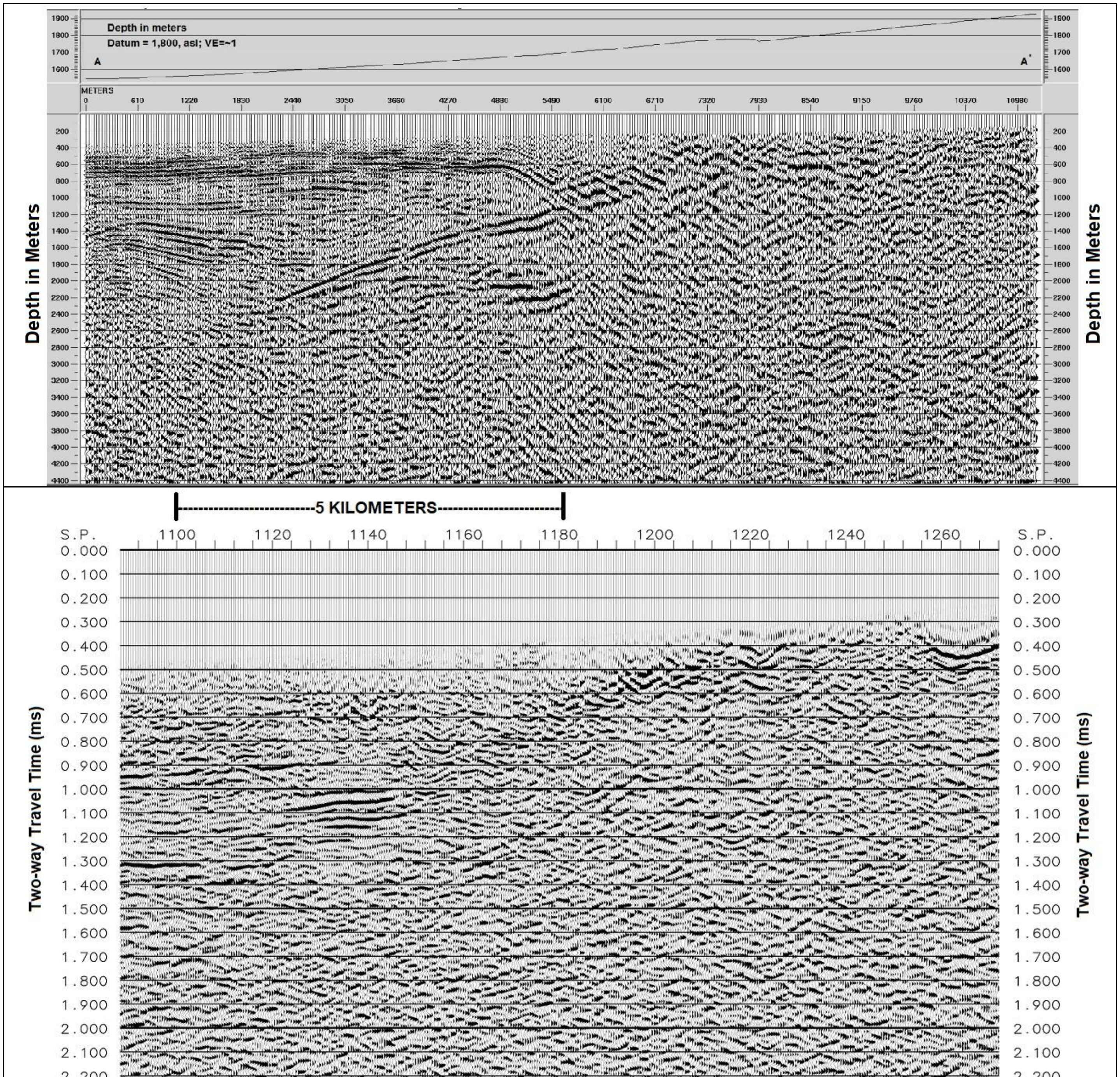


Figure 11: Legacy Line 5. Top: processed in 1979, reformatted from Tiff image to Seg-Y digital traces and converted depth using a combination of velocities from well 58-32 and well 9-1, projected onto the line's location. (after Miller and Allis, 2018). Bottom: reprocessed in 2016 through prestack time migration. The granite reflection is very faint and subhorizontal reflections are poorly resolved.

Seismic data are owned or controlled by Seismic Exchange, Inc.; Interpretation where shown, is that of Utah FORGE.

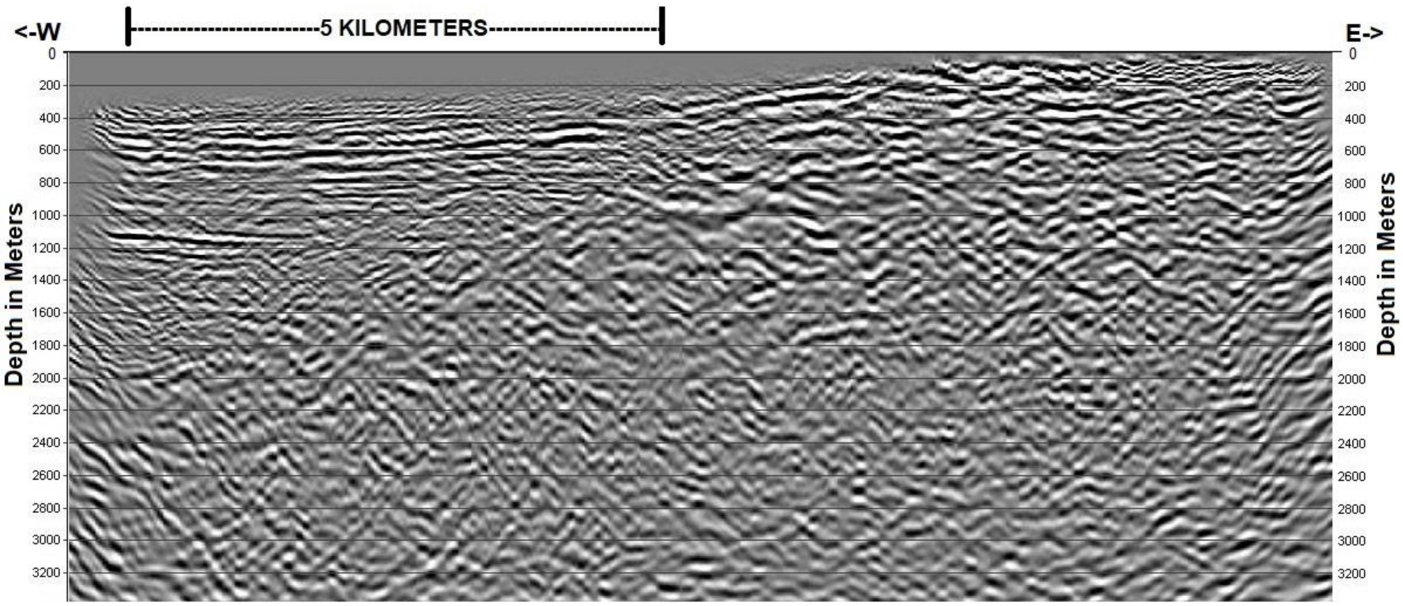


Figure 12: Legacy Line 5. Prestack depth migration by LSNS. Subhorizontal reflections are better resolved than in the 2016 reprocessing shown in Figure 11, bottom.
Seismic data are owned or controlled by Seismic Exchange, Inc.; Interpretation, where shown, is that of Utah FORGE.

2D Legacy Line 11

2D Line 11 was recorded in 1979 along Antelope Point Road, west of the Utah FORGE 3D survey (Figure 1). The line was initially processed in 1979 by the company that recorded the data; it was reprocessed in 2016 by SEIMAX Technologies, a processing company under contract to SEI. In contrast to Line 5, the 2016 processing of Line 11 was far superior to the 1979 processing. Utah FORGE personnel used the prestack time migrated version of the line and converted it to depth using the processing velocities provided by SEI (Figure 13, top). LSNS performed prestack depth migration (Figure 13, bottom). Both processed versions are of high quality. LSNS reported that detailed velocity analysis was required because of large lateral velocity changes. The LSNS processing seems to have resolved the shallow portion of the anticline on the north side of the line as a continuous feature, whereas it appears faulted in the 2016 processing. However, this portion of the line is well north of the Utah FORGE study area.

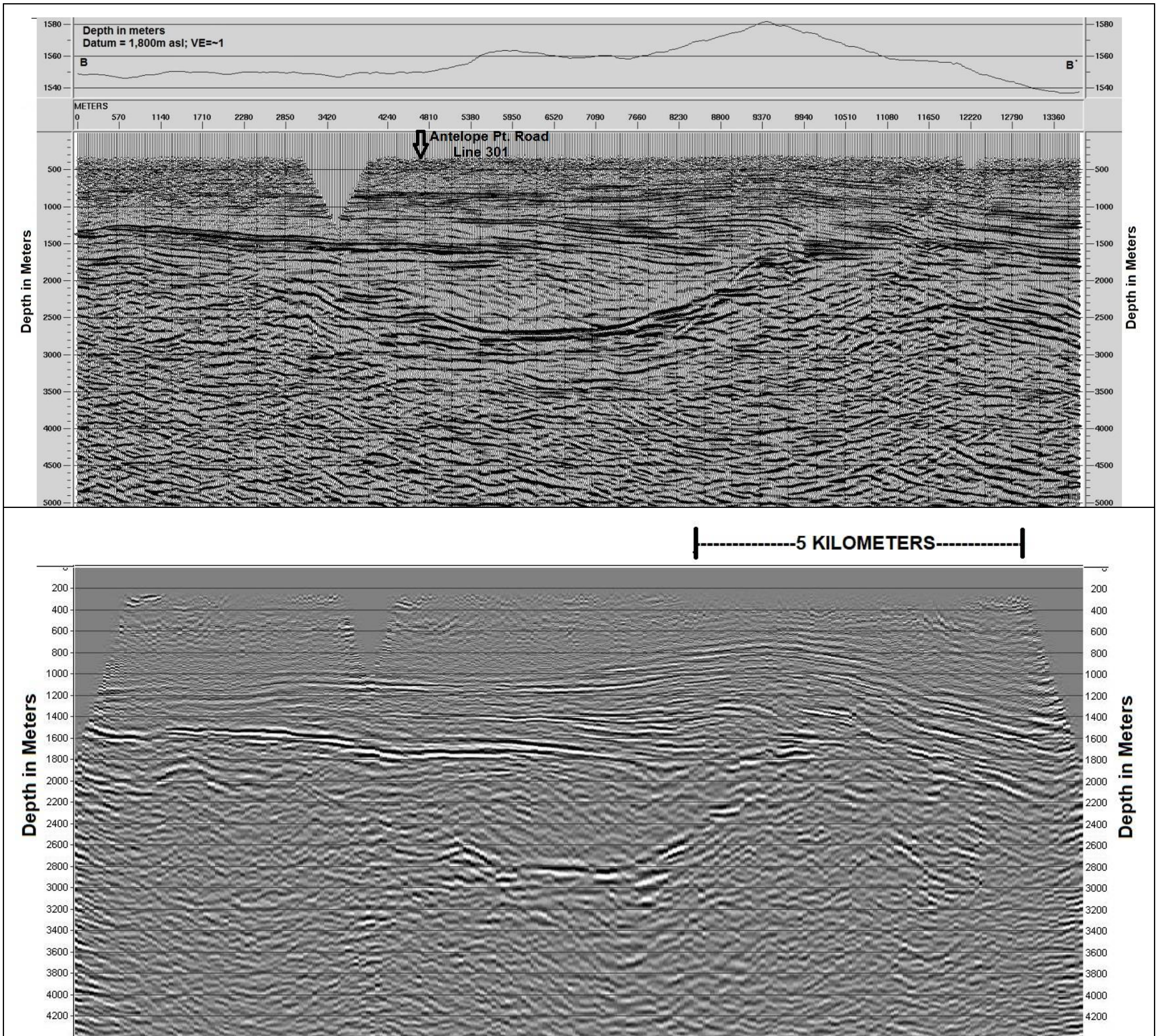


Figure 13. Legacy Line 11. Top: Prestack time migration provided by SEI, converted to depth by Utah FORGE using the processing velocities provided (after Miller and Allis, 2018). Bottom: Prestack depth migration by LSNS. Both versions of the processing are of high quality.
Seismic data are owned or controlled by Seismic Exchange, Inc.; Interpretation, where shown, is that of Utah FORGE.

Deliverable Items Received

As mentioned in the Introduction, reprocessing was necessary because the efforts of Star Geophysics, Inc. were incomplete. Star processed the 3D survey to the point of unmigrated time and depth and 2D Line 301 to the point of pretstack time migration but did not process 2D Line 302. LSNS delivered all required items. Table 1 gives a comparison of the items required of, and subsequently delivered by, both companies.

Table 2. Deliverable products received from LSNS and Star Geophysics, Inc. N/A = Not applicable, i.e. not a required deliverable item.

	Deliverable item	**Delivered by LSNS**	**Delivered by Star**	**Comments**
1	Final unmigrated gathers (without NMO)	Yes	Yes	LSNS delivered 2D Lines 5, 11, 301, 302, and the 3D survey as required.
2	Final RMS velocities	Yes	Yes	
3	Unmigrated time stack	Yes	Yes	
4	Unmigrated time depth	N/A	Yes	
5	Poststack time migrated stack	Yes	Yes #	Star processed the 3D survey and 2D Line 301 as indicated. 2D Line 302 was not processed. # Line 301 only
6	Prestack Time Migrated gathers	Yes	No	
7	Prestack Time Migrated stack	Yes	Yes #	
8	Prestack Time Migrated stack (enhanced)	Yes	No	
9	Final Prestack Time Migration velocities	Yes	No	
10	Prestack Depth Migrated gathers	Yes	No	
11	Prestack Depth migrated stack	Yes	No	
12	Prestack Depth Migrated stack (enhanced)	Yes	No	
13	Final Prestack Depth Migration velocities	Yes	No	
14	Processing flows and parameters	Yes	Yes	
15	Interpretation	N/A	No	
16	Final digital report	Yes	No	

Conclusions

The reflection seismic reprocessing carried out by LSNS provided Utah FORGE with a superior product than previously obtained. LSNS delivered to Utah FORGE all of the items required by the contract between LSNS and Utah FORGE.

All of the reflection data have been processed through prestack depth migration. The newly-reprocessed 3D survey has superior shallow and lateral resolution due to improved noise removal and velocity estimation. 2D Line 301 has increased reflectivity at depth and shows upturned reflections on the east approaching the Utah FORGE site as should be expected; 2D Line 302 shows the granite reflection to be planar and dipping up to the west as opposed to minimal processing by Utah FORGE personnel that indicated it may be a shallow, undulating basin.

Reprocessing of Legacy Lines 5 and 11 generally reproduced the results of the 2016 reprocessing provided by SEI. Reprocessing Legacy Line 5 does not answer the question of why the 1979 processing appears superior to both the reprocessing performed in 2016 and for this project.

References

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Appendix: Files Delivered to Utah FORGE

The results of the reprocessing were delivered to Utah FORGE using File Transfer Protocol (FTP) in April 2019. All seismic data files are in digital form as industry-standard SEG-Y format (Barry and others, 1975). The 3D survey and 2D Lines 301 and 302 are available to the public. Legacy 2D Lines 5 and 11, licensed from Seismic Exchange, Inc., are proprietary and are not available to the public except for the derivative depth images presented in this report.

Table 2 gives a list of all the deliverable products received from Land Seismic Noise Specialists (LSNS). Table A1 gives a list of digital files received from LSNS including 1), Loadsheets; 2), Final processing report by LSNS; 3), stacked processed files in SEG-Y format including Unmigrated Time, Prestack Time Migration (PSTM), and Prestack Depth Migration (PSDM); 4), Velocities used for PSDM in SEG-Y format; 5), exact file sizes; and 6), file names. For Legacy Lines 5 and 11, the navigation was defined in feet and so the calculated migration velocities were defined in ft/sec. The initial PSDM file has depth in feet, but a second PSDM file with depth in meters and a datum of 1,800m asl was generated in order to be consistent with the other lines. Both files were included with the delivered data. For the 3D survey, there is an enhanced, Poststack Time Migrated file, "Forge3d_Poststack_Time_Migration_FXYDecon_Stack.segy", included with the delivered items.

Each SEG-Y format file contains a standard text header, referred to as the EBCDIC header, that describes the contents of the file. Figure A1 gives an example of the text header from the 3D processed file "Forge3d_ANI_PSDM_Stack_Enh.segy". This header contains at a minimum:

1. Year recorded and year processed
2. Sample interval and data trace length
3. Navigation coordinate system
4. Datum and datum correction velocity
5. Coordinates of the corners of the survey (3D survey only)
6. Processing flow
7. Trace header byte locations for various trace header words, which should be sufficient to load the data into a seismic interpretation system. These are: CMP X, CMP Y, CMP bin elevation and Final datum static.

Note that for 3D data, the inline (IL) and crossline (XL) numbers are two byte integers, located in bytes 9-10 and 13-14, respectively.

Table A2 gives a list of additional files received from LSNS including 1), unstacked CMP gathers in SEG-Y format including data input to migration, PSDM, and PSTM with Normal Moveout (NMO) removed; 2), velocities used for PSTM in SEG-Y format; 3), exact file sizes; and 4), file names. The input to migration file contains data processed to the point immediately prior to migration. This file, with NMO applied and stacked, will give an unmigrated time section. The PSTM with Normal Moveout removed is suitable as input for future velocity analysis on migrated time data. For the 3D data, there is a second file with source-receiver offsets interpolated in order to give each CMP gather the same number, and values, of offsets (regularization). This file is the one that was input to PSDM and PSTM. For Line 302, there are two PSDM files, one with all source-receiver offsets included; the other with only the nearest 15 offsets (12-712m). This offset-limited file is the one that was stacked as the final PSDM. The reason for limiting the offsets is that there was no useful reflectivity recorded below the shallow granite reflection and thus offsets greater than 712m only contained noise.

The trace headers byte locations for the CMP Gather files conform to the standard SEG-Y (REV 1) header mappings as given by Barry et al (1975) with the following additions: CMP bin elevation: bytes 205-208; Floating datum: bytes 209-213; Final datum static: bytes 213-216.

Line: Data Type	Size in bytes	File Name
ALL: Loadsheets	83,968	Loadsheets-for-3D-and-2D.xls
ALL: Digital Report	30,678,796	LSNS_Final_Processing_Report_Forge.pdf
301: PSDM Enhanced	7,785,924	Line_301_PSDM_Enh.segy
301: PSDM UnEnhanced	7,785,924	Line_301_PSDM_UNEnh.segy
301: PSDM Interval Velocities	428,364	Line_301_PSDM_Interval_Velocity.segy
301: Unmigrated Time	5,217,924	Line_301_Unmigrated_Stack.segy
301: PSTM Enhanced	5,217,924	Line_301_PSTM_Stack_Enh.segy
301: PSTM UnEnhanced	5,217,924	Line_301_PSTM_Stack_UnEnh.segy
302: PSDM Enhanced	7,446,508	Line_302_PSDM_Enh.segy
302: PSDM UnEnhanced	7,446,508	Line_302_PSDM_UNEnh.segy
302: PSDM Interval Velocities	357,920	Line_302_PSDM_Interval_Velocity.segy
302: Unmigrated Time	4,990,508	Line_302_Unmigrated_Stack.segy
302: PSTM Enhanced	4,990,508	Line_302_PSTM_Stack_Enh.segy
302: PSTM UnEnhanced	4,990,508	Line_302_PSTM_Stack_UnEnh.segy
L5: PSDM Enhanced (depth in feet)	3,622,716	Line_L5_PSDM_Enh.segy
L5: PSDM Enhanced (depth in meters)	2,147,676	Line_L5_PSDM_Enh_Meters.segy
L5: PSDM UnEnhanced (depth in feet)	3,622,716	Line_L5_PSDM_UnEnh.segy
L5: PSDM UnEnhanced (depth in meters)	2,147,676	Line_L5_PSDM_UnEnh_Meters.segy
L5: PSDM Interval Velocities	737,316	Line_L5_PSDM_Interval_Velocity.segy
L5: Unmigrated Time	3,886,116	Line_L5_Unmigrated_Time_Stack.segy
L5: PSTM Enhanced	3,958,112	Line_L5_PSTM_Enh.segy
L5: PSTM UnEnhanced	3,958,112	Line_L5_PSTM_UnEnh.segy
L11: PSDM Enhanced (feet)	27,409,764	Line_L11_PSDM_Enh.segy
L11: PSDM Enhanced (meters)	27,409,764	Line_L11_PSDM_Enh_Meters.segy
L11: PSDM UnEnhanced (feet)	27,409,764	Line_L11_PSDM_UnEnh.segy
L11: PSDM Interval Velocities	1,407,028	Line_L11_PSDM_Interval_Velocity.segy
L11: Unmigrated Time	6,138,048	Line_L11_Unmigrated_Time_Stack.segy
L11: PSTM Enhanced	6,138,048	Line_L11_PSTM_Enh.segy
L11: PSTM UnEnhanced	6,138,048	Line_L11_PSTM_UnEnh.segy
3D: Anisotopic PSDM Enhanced	153,678,840	Forge3d_ANI_PSDM_Stack_Enh.segy
3D: Anisotopic PSDM UnEnhanced	153,678,840	Forge3d_ANI_PSDM_Stack_UnEnh.segy
3D: Anisotopic PSDM Interval Vels	7,947,900	Forge3d_ANI_PSDM_INT_Velocity.segy
3D: Unmigrated Time	235,171,944	Forge3d_Unmigrated_Time_Stack.segy
3D: Poststack Time Migration Enhanced	235,171,944	Forge3d_Poststack_Time_Migration_ FXYDecon_Stack.segy
3D: PSTM UnEnhanced	121,067,944	Forge3d_PSTM_Stack_Enh.segy
3D: PSTM UnEnhanced	121,067,944	Forge3d_PSTM_Stack_UnEnh.segy

Table A1. List of files received from LSNS including Loadsheets, Final processing report, stacked processed files including Unmigrated Time, Prestack Time Migration (PSTM), Prestack Depth Migration (PSDM), Velocities used for migration, exact file sizes, and file names. 301: 2D Line 301, 302: 2D Line 302, L5: Legacy Line 5, L11: Legacy Line 11, 3D: 3D Survey.

Line: Data Type	Size in bytes	File Name
3D: Gathers before offset regularization (Unmigrated Time without NMO)	9,277,734,912	Forge3d_PreReg_Gathers.segy
3D: Gathers after offset regularization (Input to Migration)	5,965,304,292	Forge3d_Reg_Gathers.segy
3D: PSTM Gathers (NMO removed)	7,991,116,080	Forge3d_PSTM_Gathers.segy
3D PSDM Gathers	3,995,559,840	Forge3d_PSDM_Gathers.segy
3D: PSTM Migration Velocities	6,687,900	Forge3d_PSTM_RMS_MigVel.segy
L5: Gathers Input to Migration	61,982,352	Line_L5_PrePSTM_Gathers.segy
L5: PSDM Gathers	90,481,500	Line_L5_PSDM_Gathers.segy
L5: PSTM Gathers (NMO removed)	98,866,400	Line_L5_PSTM_GathersUnNMO.segy
L5: PSTM Migration Velocities	1,032,616	Line_L5_PSTM_RMS_MigVel.segy
L11: Gathers Input to Migration	87,318,144	Line_L11_PrePSTM_Gathers.segy
L11: PSDM Gathers	601,731,888	Line_L11_PSDM_Gathers.segy
L11: PSTM Gathers (NMO removed)	147,230,352	Line_L11_PSTM_Gathers_UnNMO.segy
L11: PSTM Migration Velocities	311,028	Line_L11_PSTM_RMS_MigVel.segy
301: Gathers Input to Migration	213,124,880	Line_301_PrePSTM_Gathers.segy
301: PSDM Gathers	389,119,800	Line_301_PSDM_Gathers.segy
301: PSTM Gathers (NMO removed)	276,362,772	Line_301_PSTM_Gathers_UnNMO.segy
301: PSTM Migration Velocities	723,924	Line_301_PSTM_RMS_MigVel.segy
302: Gathers Input to Migration	95,274,660	Line_302_PrePSTM_Gathers.segy
302: PSDM Gathers-Offsets:12-712m	558,235,648	Line_302_PSDM_Gathers_Near_Offsets.segy
302: PSDM Gathers-Offsets:ALL	558,235,648	Line_302_PSDM_Gathers_All_Offsets.segy
302: PSTM Gathers (NMO removed)	174,545,380	Line_302_PSTM_GathersUnNMO.segy
302: PSTM Migration Velocities	692,508	Line_302_PSTM_RMS_MigVel.segy

Table A2. List of unstacked, CMP gathers files received from LSNS including those input to Migration (for 3D both with and without offset regularization), Prestack Time Migration (PSTM) without Normal Moveout applied, Prestack Depth Migration (PSDM), velocities used for PSTM, exact file sizes, and file names. 301: 2D Line 301, 302: 2D Line 302, L5: Legacy Line 5, L11: Legacy Line 11, 3D: 3D Survey, RMS: Root Mean Squared

```
C 1 CLIENT: USGS/University of Utah PROCESSOR: Land Seismic Noise Specialists
C 2 LINE Forge3d AniPSDM Stack Enhanced     AREA Utah
C 3 YEAR ACQUIRED: 2017    YEAR PROCESSED: 2019
C 4 SAMPLE INT: 5m       TRACE LENGTH: 5000 m
C 5
C 6 COORD SYSTEM:METRIC GEODETIC DATUM:NAD83 UTM 12 N
C 7 PROJECTION:MOLODENSKY/TM
C 8
C 9 DATE:4/12/2019
C10 DATUM: 1800 m      REPLACEMENT VELOCITY: 2500 m/s
C12 CMP Bin : 25m x 25m
C13 PRODUCT: PSDM Stack Enhanced
C14 IL 1,   XL 1,  (332800.5,  4260778.0 )
C15 IL 170, XL 1,  (322874.25, 4265002.25)
C16 IL 170, XL 213,(338173.44, 4264910.0 )
C17
C18
C19
C20
C21 PROCESSING FLOW:
C22 GEOMETRY ASSIGNMENT AND QC,TRACE EDITS,REFRACTION STATICS.
C23 AIRBLAST DENOISE,SPECTRAL EDIT DENOISE,LSNS DENOISE
C24 QCOMP 100, DECON (OP 180 ms PRW 0.01%)
C25 VELOCITY ANALYSIS AND RESIDUAL STATICS LOOPS (TWO ROUNDS)
C26 VELOCITY ANALYSIS AND RESIDUAL STATICS LOOPS (TWO ROUNDS)
C27 POST DECON NOISE ATTENUATION -  SPECTRAL EDIT and DESPIKE
C28 RESIDUAL STATICS, AGC, Interpolation on OFFBINs, Anisotrpoic PSDM,
C29 BILATERAL FILTER OFFBINS, Bandpass 4-8-80-120 Hz, STACK
C30 FXY Decon 3x4 filter width
C31
C32 CMP_X: byte 189 4 byte ibm real
C33 CMP_Y: byte 193 4 byte ibm real
C34 BIN_ELEV byte 53 4 byte
C35 HEADER FOR FINAL DATUM CMP_STAT: byte 201 4 byte ibm real
C36
C37
C38
C39 SEG Y REV1
C40 END EBCDIC
```

Figure A1: Example of the EBCDIC text header from 3D processed file "Forge3d_ANI_PSDM_Stack Enh.segy". This file contains prestack depth migrated data. Year recorded, year processed, navigation coordinate system, survey endpoint coordinates, and processing flow are given. In addition, trace header locations for CMP X, CMP Y, CMP bin elevation and final datum static are provided which is sufficient to load the data into a seismic data interpretation system.

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