New Oquirrh Fault Imaging Results

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ABSTRACT

New 3-D tomographic images are computed and more accurately define the subsurface geology in the Oquirrh fault system. The new tomograms benefit from: 1) a comprehensive quality control (QC) of the traveltime picks, 2) additional processing with the 3-D traveltime tomography code, and 3) a more sophisticated 3-D visualization of the 3-D tomogram. The tomograms clearly reveal a colluvial wedge with an approximate thickness of 11 feet, which compares well with the 9.5 feet thickness measured from the trench log. Synthetic imaging tests were also conducted to examine the reliability of the 2-D and 3-D tomograms. These tests validate the claim by Morey (1996) that the 3-D tomogram is more clearly resolved at greater depths than the 2-D tomogram. This is because the 3-D raypath coverage is more dense and azimuthally isotropic than the 2-D raypath coverage.

A 2-D seismic line was acquired and reflection images from this line are presented. These reflectivity images correlate well with some of the geologic information provided by a nearby trenching study. An antithetic fault and 4 horizons are coherently imaged across the survey area. This combination of reflection images and refraction traveltime tomograms suggest a magnitude 7.0 earthquake as the size of the most recent surface rupturing event on the Oquirrh fault.

INTRODUCTION

A previous study by Morey (1996) showed that 3-D tomography can be successful in delineating the shallow subsurface strata of the Oquirrh fault zone. The 3-D tomograms were compared with 2-D tomograms, reflection images, and common offset gathers. The 3-D tomogram revealed a colluvial wedge associated with the most recent surface rupturing event on the Oquirrh fault as well as other features that correlated well with the geologic cross-section taken from the adjacent trench.
In this report, I present results from additional tomographic processing of the 3-D Oquirrh Fault data (Morey, 1996) and reflection processing of a new 2-D reflection line that intersects the 3-D survey (see Figure 1). New images of the 3-D velocity structure have been obtained by additional processing with the 3-D traveltime tomography code, and use of a sophisticated 3-D volume rendering software package. A more extensive quality control was also conducted on the entire set of 3-D traveltime picks, making use of reciprocity tests. A synthetic test was conducted using a checkerboard model to test the resolving power of the 2-D and 3-D tomography techniques.

In addition, 2-D reflection data were collected in May of 1997 and the reflection line extends both East and West of the 3-D survey area. CDP processing of the 2-D seismic data provided reflectivity images of the shallow subsurface that correlated well with the antithetic fault indicated by a trenching study (Olig et. al., 1996).
QUALITY CONTROL

Traveltime picks from the 3-D data were evaluated by use of reciprocity tests, defined in the following way. The traveltime from a given trace associated with a source-receiver pair was compared to the corresponding traveltime from the reciprocal receiver-source pair, and if the traveltime difference was above a certain threshold the traveltime was excluded from the inversion. Reciprocity demands that these two reciprocal traveltimes be equal to one another. The threshold value used for this reciprocity QC was 6 ms, or twice the picking error for data with a 12 ms source wavelet. A total of 1880 out of 85,450 picked traveltimes were rejected following the reciprocity test, and amounts to 2.2 percent of the total traveltimes tested. A plot of offset vs traveltime discrepancies that exceeded the threshold value can be seen in Figure 2. Since every receiver location was also a shot location then every traveltime had a reciprocal twin, so all traveltimes were subject to the reciprocity test.

TOMOGRAPHY RESULTS

New 3-D velocity tomograms were recomputed from the Oquirrh fault refraction data. These new images more clearly define offset, location, and the thickness of the colluvial wedge associated with a normal fault earthquake. This information is very useful because the thickness of the colluvial wedge can be used to estimate the size of the earthquake that produced this colluvial wedge (McCalpin, 1996).

These new tomograms benefit from more comprehensive QC tests, additional processing with the 3-D refraction traveltime tomography code, and the use of a 3-D volume rendering software package. The additional iterations with the 3-D tomography code used different smoothing operators, where dynamic smoothing of the velocity model helped to illuminate velocity contrasts in all three dimensions. The inversion initially used a large smoothing filter, and iteratively reduced the filter size until the length of the filter was less than the Rayleigh resolution limit. For this data set, the smoothing filter initially had a volume of 20’x20’x10’ and was iteratively reduced to a volume of 2’x2’x2’ (see Table 1), where the model volume was 142’x30’x60’. The volume of the smoothing operator was then set to 10’x2’x2’ and gradually reduced to 2’x2’x2’; repeating this procedure in the y and z dimensions enhanced the velocity contrasts in each dimension and helped to define boundaries in the image. This process also reduced the final residual from 7.3 ms to 6.9 ms. With a smoothing filter of volume 2’x2’x2’ the number of effective unknowns was 21,494 and the number of traveltime equations was 83,570.
Figure 2: 3-D reciprocity test. "*"=discrepancy between traveltimes $t(i,j)$ and $t(j,i)$. 
Table 1. Smoothing filter size vs iteration number for 3-D inversion.

<table>
<thead>
<tr>
<th>Iteration Number</th>
<th>Volume of Smoothing Operator (X-Y-Z)</th>
<th>RMS Traveltime Residual (ms)</th>
</tr>
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<tr>
<td>Iteration 1</td>
<td>20'x20'x10'</td>
<td>4.56616E-02</td>
</tr>
<tr>
<td>Iteration 6</td>
<td>10'x10'x5'</td>
<td>4.23572E-02</td>
</tr>
<tr>
<td>Iteration 8</td>
<td>5'x5'x2'</td>
<td>4.09471E-02</td>
</tr>
<tr>
<td>Iteration 10</td>
<td>2'x2'x2'</td>
<td>8.01974E-03</td>
</tr>
<tr>
<td>Iteration 12</td>
<td>10'x2'x2'</td>
<td>7.95541E-03</td>
</tr>
<tr>
<td>Iteration 13</td>
<td>5'x2'x2'</td>
<td>7.91400E-03</td>
</tr>
<tr>
<td>Iteration 14</td>
<td>2'x2'x2'</td>
<td>7.74777E-03</td>
</tr>
<tr>
<td>Iteration 15</td>
<td>2'x10'x2'</td>
<td>7.64337E-03</td>
</tr>
<tr>
<td>Iteration 16</td>
<td>2'x5'x2'</td>
<td>7.60885E-03</td>
</tr>
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<td>Iteration 17</td>
<td>2'x2'x2'</td>
<td>7.57101E-03</td>
</tr>
<tr>
<td>Iteration 18</td>
<td>2'x2'x10'</td>
<td>7.26302E-03</td>
</tr>
<tr>
<td>Iteration 19</td>
<td>2'x2'x5'</td>
<td>6.99802E-03</td>
</tr>
<tr>
<td>Iteration 20</td>
<td>2'x2'x2'</td>
<td>6.98672E-03</td>
</tr>
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</table>

Figure 3 shows the 3-D velocity tomogram using Spyglass Slicer, a 3-D volume rendering software package. This software package was used to view the image in 3-D and manipulate the color scale. Figure 4 shows an x-z slice of the 3-D tomogram sliced at y=15' for the "old" and the "new" result. The colluvial wedge region is more sharply defined in the "new" result. Figure 5 shows an x-z slice of the 3-D volume sliced at y=15' using Spyglass Slicer.

SYNTHETIC TOMOGRAPHY RESULTS

A test using synthetic traveltimes was conducted to validate the reliability of the tomographic image. This test was similar to those conducted by Dueker et al. (1993). The input model was a checkerboard of variable velocities and had the same dimensions as the area investigated with the 3-D Oquirrh fault data. The model was constructed by defining the background velocity to be similar to that found in the Oquirrh fault tomogram (see Figure 3), i.e., the velocity at the surface was defined to be 1000 ft/s and the vertical gradient was assigned as 60 ft/s/ft. The background velocity was then varied by superimposing a checkerboard of velocities, where the velocity in each 10’x10’x10’ cube differed from its neighboring velocity by 10 percent. There was no velocity variation in the y direction. The source and receiver geometry for the synthetic data was identical to that of the 3-D Oquirrh fault data set, which consisted of 48 inline stations with 3 feet spacing and 7 crosslines with a 5 feet line spacing. Each station was occupied by both a source and a receiver. These synthetic
Figure 3: 3-D traveltime tomogram computed from the traveltimes picked from the 3-D data. Note the wedge shaped low-velocity region associated with the colluvial wedge.
Figure 4: Comparison between the (top) "old" and (bottom) "new" 3-D XZ tomo-
grams sliced at $y=15'$. Notice how the colluvial wedge is imaged more sharply in the
"new" result.
Figure 5: X-Z slice of the 3-D velocity tomogram sliced at Y = 15’. The colluvial wedge is identified in the figure and is characterized by a low-velocity wedge.
tests helped define the reliable regions within the tomographic images (Dueker et al., 1993).

Figure 6 shows the results from the tomography tests on synthetic traveltime data, and suggest that 10 percent velocity variations in checkerboards of width 10 feet can be resolved to a depth of about 25-30 feet. These synthetic results also show areas where the subsurface image is distorted along the dominant direction of the raypaths. At depths greater than 20 feet and near the edges of the model the checkerboard begins to be stretched in the dominant direction of the raypaths. Figure 7 shows an image of the raypaths for the 3-D synthetic results and suggest that acute stretching effects are due to a paucity of rays at the deeper levels. Figure 8 shows an X-Z image of the raypaths for the 3-D tomogram and Figure 9 shows the raypath coverage for the 2-D result. Notice the scale of the plots and the increased ray coverage for the 3-D result.

2-D tomography tests were also conducted and the corresponding 2-D tomograms were compared to the 3-D tomogram. Figure 6 shows the upper 40 feet of an X-Z slice of the 3-D tomogram, the model, and the 2-D tomogram. The 2-D tomogram shows similar characteristics but the checkerboard pattern is slightly less resolved at depths of about 30 feet. Artifacts that are similar in shape to the raypath density variations are also observed in the 2-D result and in some areas are more severe than in the 3-D case. This is partly because the 3-D raypath coverage is more azimuthally isotropic than the 2-D raypath coverage.

2-D REFLECTION PROCESSING

Figure 1 shows an aerial photo of the field area and marks the locations of the 2-D and 3-D seismic surveys. The 2-D seismic line was positioned so it would run parallel to the trench BC-3 excavated by the Utah Geological Survey, and would intersect the 3-D survey area in the center. Shot tests were conducted, including a walk-away test, to help define the acquisition parameters. Multiple sources were tested including a Betsy seisgun, 16-pound sledge hammer, and an EWG-1 weight drop system. The 16-pound sledge hammer provided the best signal and the greatest degree of mobility and speed in the acquisition process. Following the analysis of the shot tests, shot and receiver spacings were set to be 1.5 feet. There were 96 channels active for each of the 380 shot locations covering 570 feet. The CDP sorted data were mostly 48 fold with a CDP spacing of 0.75 feet. The time sampling interval was set at 0.2 milliseconds and the total record length was 0.4 seconds per trace.

Data Sorting

The first step in the data processing was to convert from Bison seismograph format to SEGY format so processing could be done with the SU processing package. This
Figure 6: Synthetic checkerboard test. Comparison of the upper 40 feet of the (top) 3-D tomogram, (middle) the model, and (bottom) the 2-D tomogram. The 3-D tomogram appears to more clearly resolve the checkerboard pattern at the 20-30 foot levels.
Figure 7: Raypaths associated with the 3-D checkerboard test. This shows that rays penetrated to a depth of about 40 feet for this shooting geometry and velocity gradient.
Figure 8: X-Z slice of the raypath coverage for the 3-D tomographic result sliced at $y=15'$. Compare with Figure 9 and notice the increased ray coverage for the 3-D result.
Figure 9: Raypath coverage for the 2-D tomographic result. Compare with Figure 8.
was accomplished by the BIS2SEG.f program written by Y. Sun. Defining the survey geometry was the second step, and includes defining the shot and receiver locations, receiver-source offsets, common midpoint (CMP) locations, and other known parameters that affect the data processing. This was accomplished with the Fortran program "setheader.f" which assigned the previously mentioned parameters to the headers of each seismic trace. The processing flow for the Oquirrh 2-D data can be seen in Figure 10.

**Automatic Gain Control**

An instantaneous automatic gain control (AGC) was applied to the data to correct for the decrease in amplitude due to geometric spreading and attenuation (Yilmaz, 1987). This type of gain modifies the amplitudes in a time-varying manner (Yilmaz, 1987) and may not give true amplitudes in the final stacked section, but it does make deeper reflections more visible in the shot and CMP gathers. For this investigation AGC applied to the data is justified because we are interested in mapping the lateral coherency of the seismic reflectors and not the actual amplitude of the reflected energy. Figure 11 shows a raw shot gather with AGC applied.

**Shot and Receiver Statics**

Shot statics were noticeable in the shot gathers. Here, I define the shot static as the timing error associated with early or late triggering of the seismograph at each shot. The source used was a 16-pound sledge hammer impacting an eight-inch square plate. The trigger was a piezoelectric crystal securely taped to the handle of the hammer. The piezoelectric crystal sends a signal to the seismograph when the hammer impacts the plate. Discrepancies were discovered in the timing of the first arrivals at zero offset due to the piezoelectric crystal not sending the signal to the seismograph at the exact instant the hammer strikes the plate. The shot statics were calculated by sorting the data into the common offset gather (COG) domain and picking the arrival times of the air wave at an offset of 9 feet (see Figure 12). The arrival times of the air wave were corrected to the time of 9ft $\div$ 1100ft/s = .0085s. This correction was justified because the air wave travels at a constant velocity and was not dependent on the geology of the region; it should therefore arrive at a constant time for a constant offset. The shot static correction was then applied to all traces in the shot gather.

The above procedure can also be used to calculate a receiver static which is defined as the arrival time error due to the mislocation of the receiver. If the receiver is located closer to the shot than expected, then the air wave will arrive earlier than expected. The receiver static is calculated by sorting the data into the common receiver domain
Figure 10: Chart of the processing flow for the Oquirrh fault 2-D data.
Figure 11: Common shot gather for a shot at station 30 with AGC applied.
and then repeating the above steps, making the static correction to all traces in the common receiver gather.

**Common Midpoint Sorting and Muting**

The data must be sorted into the common midpoint (CMP) domain before it can be converted into a stacked section. This is important because a zero-offset section can be obtained by summing normal moveout (NMO) corrected traces in a CMP gather so that energy from a reflecting horizon is enhanced while noise is canceled (Mayne, 1962). Muting of the CMP gathers is performed to remove coherent noise such as ground-roll and the air wave. Muting is accomplished by zeroing the trace amplitudes above a polygonal curve defined by offset-time pairs. Figure 15 shows a raw CMP gather and Figure 16 shows a CMP gather after muting. Muting such as this is also important in removing post-critical reflections from the stacked section.

**Velocity Analysis**

Velocity analysis was conducted in the CMP domain using two techniques. Semblance analysis (Yilmaz, 1987) was conducted on every fiftieth CMP gather to obtain a velocity model for the data set. The semblance function is defined as:

\[ S_t = \frac{1}{n} \sum_{j=0}^{n-1} \left( \frac{1}{n} \sum_{j=0}^{n-1} q_{t,j} \right)^2. \]  

Here, \( n \) is the number of non-zero traces to be summed and \( q_{t,j} \) is the seismic trace with \( t \) equal to time and \( j \) equal to the trace number. Figure 13 shows an example of a velocity semblance analysis.

A second type of velocity analysis was conducted by applying an (NMO) correction to multiple CMP’s using a constant velocity and visually inspecting the CMP to find the velocity that best flattens the reflection events. The NMO correction is defined by:

\[ t_{nmo} = \sqrt{t^2(0) + x^2/V_{nmo}^2} - t(0), \]

where \( t(0) \) is the zero-offset traveltime, \( x \) is the offset, and \( V_{nmo} \) is the normal moveout velocity. The optimal NMO velocities were also determined by stacking a portion of the data using different velocities (Yilmaz, 1987). The initial NMO velocity model was computed from the 3-D traveltime tomogram and did not vary by more than 10 percent from the optimal NMO velocities. Figure 14 shows a portion of the stacked section for several different NMO velocities. The NMO velocities used in the final
Figure 12: Common offset gather for an offset of 9 feet. The arrows indicate the air wave, which should be flattened after a shot statics correction.
Figure 13: Semblance analysis of CMP 250 (left) and 650 (right) where the CMP interval is 0.75 ft. Darker areas correspond to larger semblance values and, typically, better stacking velocities. The solid line indicates the velocity profile for that CMP.
stacked section ranged from 800 ft/s to 8000 ft/s although the velocities deeper than 100 feet were not very well constrained.

Residual Statics

The source and receiver statics discussed earlier were insufficient to correct for the statics due to near surface velocity variations. Due to the breakdown of the surface consistency assumption (all rays are vertically incident at the near surface) we cannot apply the usual residual statics methods. As an alternative, we applied the residual statics correction known as maximum energy stacking (Qin, 1993). Maximum energy stacking was applied to correct for statics that remained in the data upon completion of the above procedures. It was discovered that maximum energy stacking removed many of the remaining statics problems in the data.

The maximum energy stacking procedure is as follows. 1) A stacked section was generated using the best NMO velocities. 2) Each trace from the CMP gather was divided into time windows, each window was cross-correlated with its respective stacked trace (i.e. master trace), and dynamic time shifts were applied to the trace to obtain the maximum correlation with the master trace. The shift was limited to ± 10 samples (which is the equivalent to .002 seconds) to restrict the shift from skipping a wave cycle.

The maximum energy stacking process described by Qin (1993) is an iterative one. The trace is first divided into a small number of time windows for cross-correlation, time shifts are applied to each trace to obtain maximum correlation with the master trace, and a new stacked section is generated. The process is repeated with the new stacked section providing the ”master traces” for correlation and with a shorter time window. For the 2-D Oquirrh fault data 4 iterations of maximum energy stacking were applied with decreasing window lengths of 1000 ms, 200 ms, 100 ms, and 50 ms. After the final iteration of maximum energy stacking, the final stacked section was generated and band-pass filtered from 80-300 Hz to smooth the transition zones between time windows. Figure 17 shows a comparison of a CMP gather with NMO applied and the same CMP gather after application of maximum energy stacking. Figure 18 shows a comparison of a portion of the stacked section before and after maximum energy stacking. Maximum energy stacking improved the coherency of events in the stacked section.

Reflection Processing Results

Figure 20 shows the final stacked section with the horizontal axis in CMP number and the vertical axis in depth. This section shows four shallow horizons that are
Figure 14: Velocity analysis of two portions of the stacked seismic section. The reflector appears to be most coherent at stacking velocities of 1000 ft/s (top) and 1150 ft/s (bottom).
Figure 15: Raw CMP 179 with a trace interval of 1.5ft. Compare with Figure 16.
Figure 16: CMP 179 after muting. Compare with Figure 15.
Figure 17: Comparison of a CMP with a NMO correction applied before (left) and after (right) maximum energy stacking.
Figure 18: Comparison of a portion of the stacked section with (bottom) and without (top) maximum energy stacking. Notice the improved coherency of reflectors in the rectangles in the bottom figure.
coherent in the foot-wall and are truncated against the Oquirrh fault. These four horizons are offset by an antithetic fault near CMP 100 and can be correlated across this antithetic fault. The location of the antithetic fault is consistent with the location indicated in the trenching log. The dip angles on the main fault and the antithetic fault are estimated from the stacked seismic section to be $85^\circ \pm 10^\circ$ and $75^\circ \pm 10^\circ$, respectively. This is consistent with the $85^\circ$ dip angle estimated in a trench study (Olig et al., 1996) along the main fault.

**INTERPRETATION**

The magnitude of prehistoric earthquakes can be estimated by the amount of net vertical tectonic displacement $T_{net}$, which can be calculated by the equation:

$$T_{net} = T_m - [(W \tan \phi) + T_a].$$

Here, $\phi$ is the tilt angle of strata over the horizontal distance $W$, $T_m$ is the vertical displacement across the main fault, and $T_a$ is the vertical component of displacement across the antithetic fault (see Figure 19). This equation shows that the net vertical displacement is the vertical displacement on the main fault minus the effects of tilting and antithetic faulting. The amount of vertical displacement, $T_m$, on the main fault is calculated from the maximum vertical thickness of the colluvial wedge in the 3-D tomogram (see Figure 21). The maximum colluvial-wedge thickness is measured to be 11.4 feet which is estimated by Ostenaa (1984) to be half the displacement on the main fault, or $T_m = 22.8$ feet.

The other components, $W$, $T_a$, and $\phi$ in equation 3 are measured from the stacked section in Figure 20. The tilt angle, $\phi$, is calculated by measuring the dip angle of horizon 1 both outside of the graben and inside the graben near the main fault. Outside of the graben horizon 1 dips 2 degrees to the West and inside the graben, near the main fault, horizon 1 dips 2 degrees to the East so the total amount of tilting on horizon 1 is $\phi = 4$ degrees. The inflection point of tilting is estimated to be at CMP 350 which suggests tilting over a distance of $W = 169$ feet. The amount of vertical displacement across the antithetic fault is measured on horizon 1 and is estimated to be $T_a = 4.3$ feet. Plugging these values into equation 3 gives an estimate of $T_{net} = 6.7'$ for the net vertical tectonic displacement. In comparison, Olig et al.’s (1996) trenching study gives a ”best estimate” of 7.2 feet for the net vertical tectonic displacement.

Using $T_m = 6.7$ feet and a regression of moment magnitude on log maximum displacement (Wells and Coppersmith, 1994) yields a magnitude estimate of 6.8 for the most recent surface rupturing event on the Oquirrh fault. This value is consistent
Figure 19: Normal fault model showing the components used to calculate net vertical tectonic displacement.
with the magnitude estimate of 7.0 by Olig et al. (1996). Carbon dating of the colluvial wedge material suggests a date of 4,300-6,900 yr B.P. for the most recent surface rupturing event on the Oquirrh fault.

Table 2. Parameters used to calculate paleoearthquake magnitude.

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<th>Source</th>
<th>3-D Tomogram</th>
<th>Stacked Seismic Section</th>
</tr>
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<tbody>
<tr>
<td>Wedge Thickness</td>
<td>11.4 feet</td>
<td></td>
</tr>
<tr>
<td>Vertical Displacement of Main Fault</td>
<td>22.8 feet</td>
<td></td>
</tr>
<tr>
<td>Tilt Angle of Horizon 1</td>
<td>4°</td>
<td></td>
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<tr>
<td>Distance Between Inflection Point and Main Fault</td>
<td>169 feet</td>
<td></td>
</tr>
<tr>
<td>Vertical Displacement (antithetic fault)</td>
<td>4.3 feet</td>
<td></td>
</tr>
<tr>
<td>Estimated Paleoeartquake Magnitude</td>
<td>6.8</td>
<td>6.8</td>
</tr>
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This estimate of paleoearthquake size based on 3-D seismic data represents the first of its kind. Stacked CDP reflection sections and refraction traveltime tomograms provide complementary information about the Oquirrh fault system: the reflection data identifies the location of antithetic faulting as well as layer tilting while the tomograms present a clear image of the colluvial wedge. This example shows the usefulness of applying complementary imaging techniques to obtain the most useful interpretation.

CONCLUSIONS

New traveltime tomograms are computed by: 1) conducting a comprehensive QC of the traveltime picks, 2) additional processing with the 3-D traveltime tomography code, and 3) use of a 3-D visualization package that provides an improved image of the subsurface velocity structure. These new images clearly reveal a colluvial wedge which can give information on the paleoseismic history of the fault.

Synthetic tests suggest the 3-D tomograms should be accurate to a depth of 25-30 feet. The 3-D synthetic tomogram is somewhat better resolved at deeper depths than the 2-D tomogram. This test also defines areas in the tomogram which may be unreliable due to poor raypath coverage.

A 2-D seismic line was acquired and showed reflection images of an antithetic fault that correlated well with trenching results. An antithetic fault and 4 horizons were
Figure 20: The final stacked section with the horizontal axis in CMP number and the vertical axis in depth. The main Oquirrh fault is located near CMP 580 and the antithetic fault is located near CMP 100.29
Figure 21: Zoom view of the colluvial wedge and thickness measurement.
coherently imaged across the survey area. The colluvial wedge was not well resolved in the reflection image, but was well-resolved in the 3-D tomogram. Therefore the reflection image and the 3-D tomogram provided complementary information that was used to estimate a magnitude 6.8 event for the most recent surface rupturing earthquake on the Oquirrh fault.

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