



Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 1. Depth to Bedrock Determinations Using Shallow Seismic Data Acquired in the Straight Creek Drainage Near Red River, New Mexico

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Summary

In late May and early June of 2002, the U.S. Geological Survey (USGS) acquired four P-wave seismic profiles across the Straight Creek drainage near Red River, New Mexico. The data were acquired to support a larger effort to investigate baseline and pre-mining ground-water quality in the Red River basin (Nordstrom and others, 2002). For ground-water flow modeling, knowledge of the thickness of the valley fill material above the bedrock is required.

Geophysical surveys using electrical methods were completed in 2001 (Lucius and others, 2001). They were acquired with the hope that the valley fill material would be wetter and more conductive than the bedrock. This was not the case. The boundary between the bedrock and the valley fill shows little or no contrast in electrical properties, and could not be determined with surface electrical geophysical methods.

Several monitoring wells were drilled and logged through the Straight Creek valley fill from November 2001 to February of 2002. The drillers were able to determine when they were drilling through bedrock and not fill material, but the boundary was indistinct. Geophysical logs (gamma, neutron, and electrical induction) were acquired and show changes due to variations in water quality and saturation (Paillet, 2002). The well information provides depth estimates for the top of bedrock at point locations.

When the seismic data were processed for reflection events, no clear interface could be consistently determined on any of the four lines. Fortunately, when curved-ray refraction tomography was used with the seismic first arrival times, the resulting images of interval velocity versus depth clearly show a sharp velocity contrast where the bedrock interface is expected. The images show that the interpreted buried bedrock surface is neither smooth nor sharp, but it is clearly defined across the valley along the seismic line profiles. The bedrock models defined by the seismic refraction images are consistent with the well data.

Site Description

The Straight Creek drainage is in the volcanic mountains of northern New Mexico known as the Red River district (Roberts and others, 1990). Figure 1 shows the general location of the valley. The volcanic bedrock flowed and slowly cooled over Tertiary sediments that existed on the surface 25-30 million years ago. The area was later uplifted, faulted, and intruded as part of the eastern side of the Rio Grande Rift. The resulting bedrock has areas of economic mineralization, along with areas of high pyrite content and high clay mineral content.

Characteristic “scars” exist on the local slopes (figures 2 and 3). These are natural features associated with high pyrite content, steep slopes, no soil or vegetation, and high erosion (Meyer and Leonardson, 1990). During heavy rainfall, the clay minerals lose their cohesiveness and great volumes of eroded debris flow down the valleys (figure 4). The resulting valley fill is poorly sorted material that is somewhat cemented when dry (figure 5). Tests of the surface water in the drainage in September 2001 found it to be acidic (USGS, 2001), and the bedrock interface is suspected to be rough, variable, and permeable.

Given these conditions, we were not sure if a sharp seismic velocity contrast would exist to define the subsurface boundary between the fill and the bedrock. We were also concerned about generating sufficient seismic energy at the source to penetrate the valley fill. The area is in an environmentally sensitive part of the National Forest with noise restrictions, among others, due to nesting raptors.

The Straight Creek drainage is a narrow valley, broadening as it comes down in elevation, with steep slopes on both sides. The valley floor was only 60 meters across at our highest elevation of investigation and about 250 meters across at the mouth of the creek into the Red River valley.

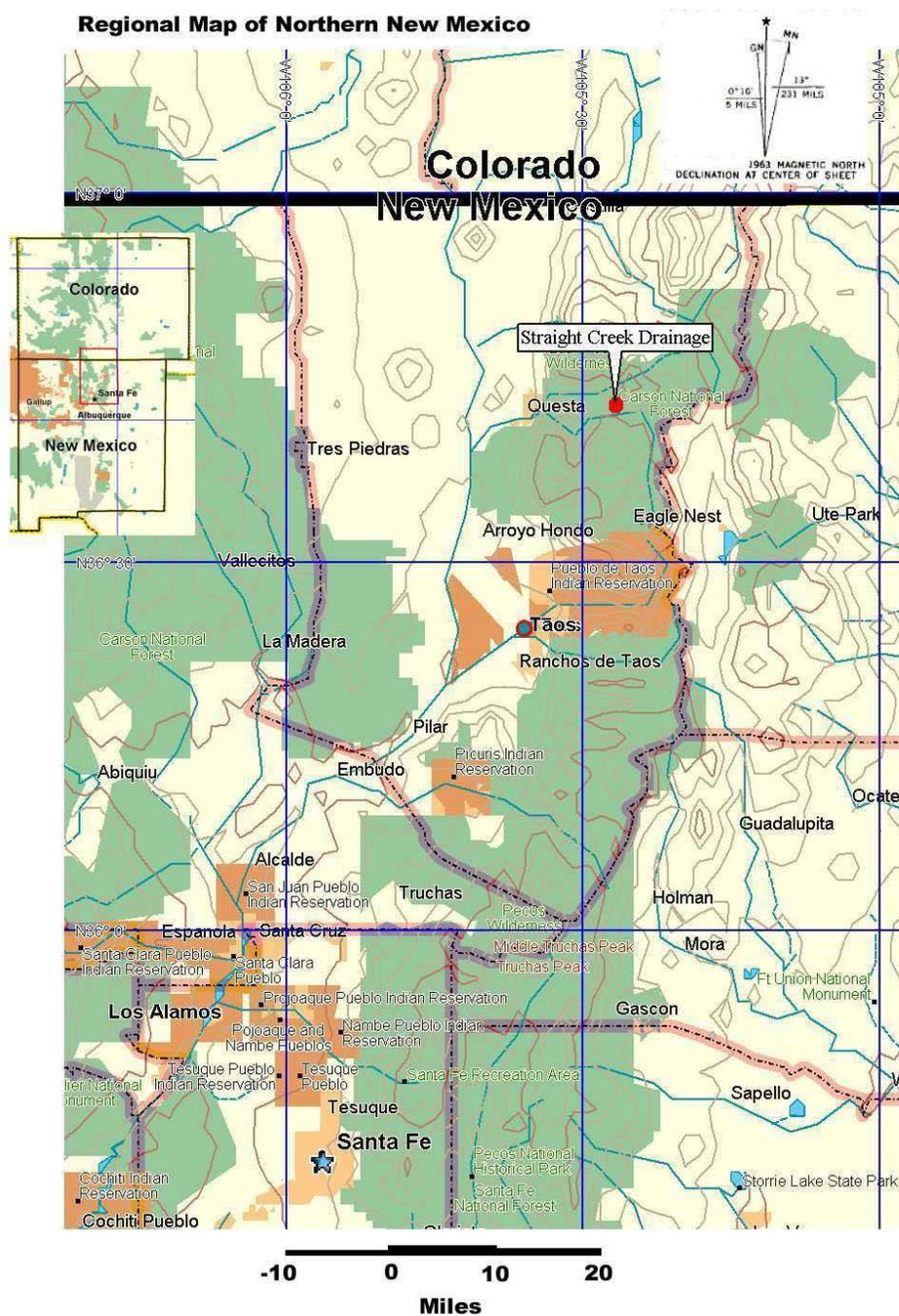


Figure 1. The Straight Creek drainage runs south into the Red River. It is east of Questa, New Mexico, and northeast of Taos.



Figure 2. View is southwest across Straight Creek showing a small scar above the valley on the west slope. These natural features occur where conditions of steep slopes, high pyrite content, natural fracture zones, and sparse vegetative cover combine.



Figure 3. View is southeast toward the town of Red River from the ridge above the east side of Straight Creek. A large feature like this also exists at the top of the Straight Creek drainage.



Figure 4. View is south down the valley floor in the dry bed of Straight Creek. Mud on the tree indicates the occurrence of high mudflow conditions. The orange pin flag at the base of the tree marks a station on Line 1.



Figure 5. The character of the valley fill material is displayed in this view of the dry creek bed just above Line 1.

Seismic Profiles

With this initial acquisition effort, we acquired four lines. The line locations are shown in figure 6. For the first three lines, we used 72 live channels with a geophone spacing of 0.75 meter, 1 meter, and 1.5 meters, respectively. For lines 2 and 3, we hammered between the first 48 geophones, moved the first 24 geophones to the end of the line, and continued hammering for 48 more positions, giving us 96 total stations. For the fourth line, we had 96 live channels but still jumped an extra 24 stations for a total of 120 stations. This resulted in line lengths of 54, 96, 145, and 241 meters, respectively. These lengths approximately matched the width of the valley floor at each location. At every source position we recorded two separate hammer blows. With post-acquisition processing, we could add the two shot records of any source position to increase the signal-to-noise ratio if desired. Figures 7 and 8 show the hammer source and the character of the valley floor for Line 1, and the steep slopes at the ends of the line.

Our intention was to process the data to create reflection profiles. In particular, we hoped to image the bedrock reflection from its known shallow depth from one bedrock slope, under the valley fill material to the other slope. We were disappointed in this effort at the lack of an identifiable bedrock reflection and by abundant reflection arrivals from off-end or off-line positions. While analyzing the data, we did notice good first arrival energy that clearly showed evidence of a high-speed layer at depth. This led us to consider simple refraction analysis. In searching for a modern program to do this analysis, we became aware of commercially available packages for refraction tomography.

Refraction tomography algorithms have evolved over the last decade. They are based on classical seismic refraction analyses (Thornburgh, 1930; Hagedoorn, 1959), combined with more recent developments in inversion theory and numerical modeling (Aki and Richards, 1980; Vidale, 1988; Aldridge and Oldenburg, 1992; Aldridge and Oldenburg, 1993). They have improved in the last few years with the most recent procedures for considering Fresnel zones while solving for a good fit of traveltimes and raypaths (Schuster and others, 1999; Watanabe and others, 1999; Lecomte and others, 2000).

After running a freely available demo version of one package, using only 10 source positions of our 96 available on Line 3, we were impressed with the result and purchased the package. We learned that our acquisition configuration was excellent, and even excessive, for refraction tomography. This allowed us to perform the imaging process on various subsets of each profile dataset and to compare the results. The images from two separate subsets of each profile are presented below (figures 9, 12, 14 and 16). The degree to which the images are alike gives us confidence in the results. Differences between the two images of each profile give a sense of the resolution of the process and the results. One should not interpret a small feature that appears in only one of the two images. Common features are probably real.

Our acquisition geometry was such that our first-arrival data do not image the bedrock wall rising at the ends of the profiles. Instead, the known location of the bedrock off the end of each line was forced into the data prior to gridding the result. For this reason, the position and nature of the bedrock as it is shown rising to the surface should be considered only an estimation.

Seismic Line Locations in Straight Creek Drainage near Red River, New Mexico

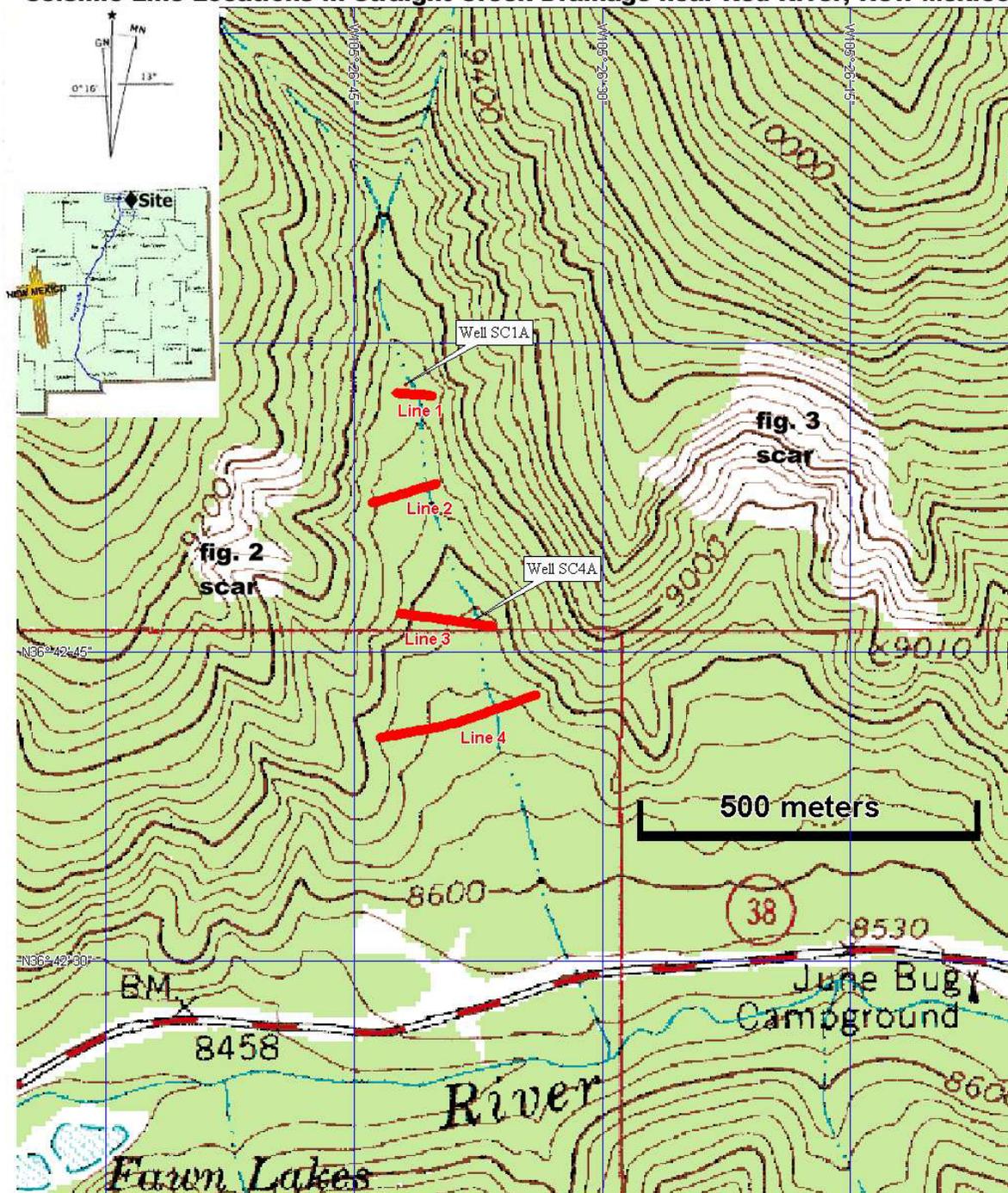


Figure 6. The locations of four seismic profiles and nearby wells are shown in the Straight Creek drainage. Straight Creek meets the Red River about 3 miles above the MolyCorp mill site.



Figure 7. Along Line 1 the valley floor is fairly level. Note the steep slope in the background marking the sharp bedrock rise. The source was a 20 lb. handheld sledgehammer striking a metal plate.

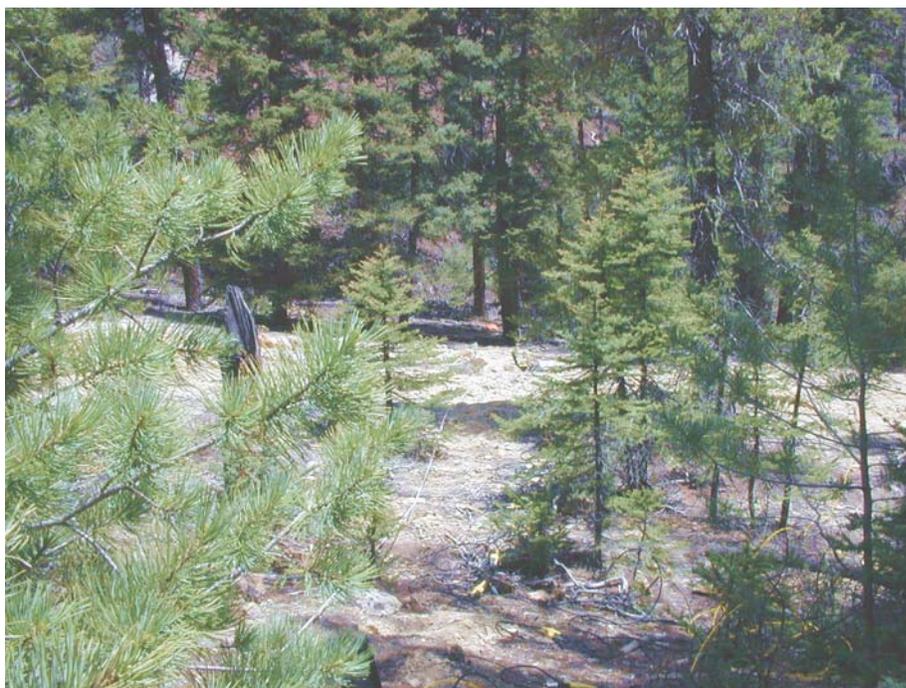


Figure 8. From the same place as the photo in figure 7 above, but now looking the other direction along Line 1, the steep slope on the other side of the valley is visible through the trees.

Line 1 Results

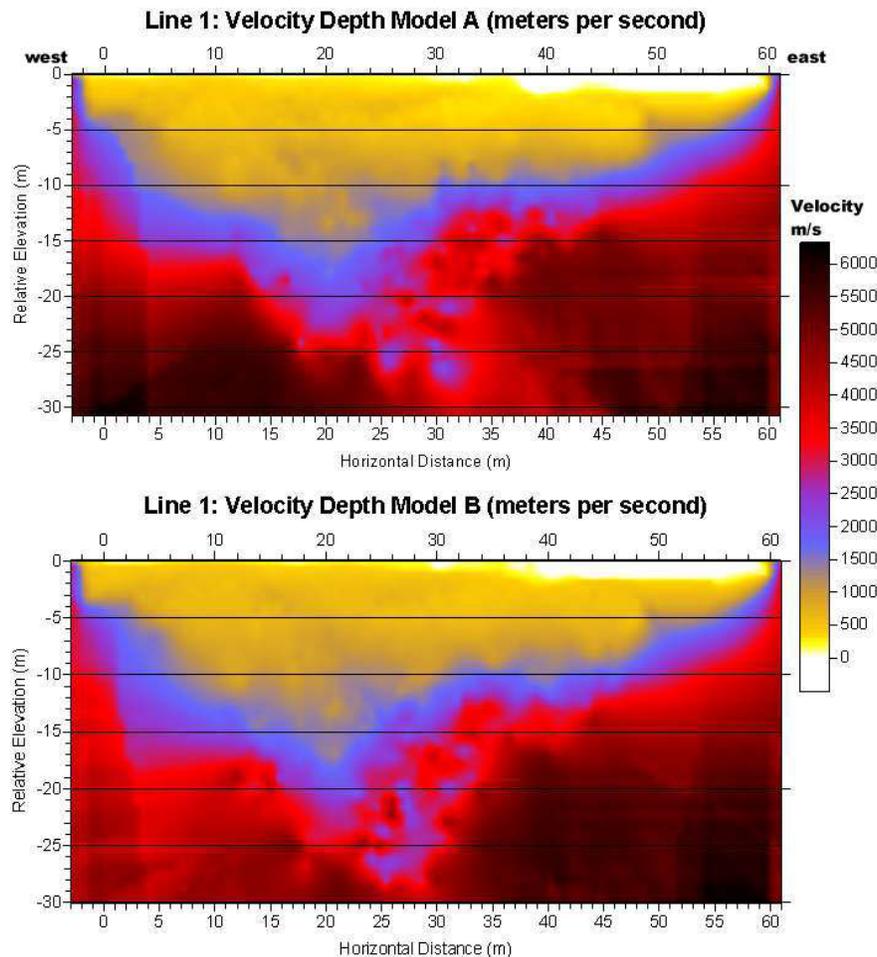


Figure 9. Two independent velocity depth models have been created with a refraction tomography algorithm. Different source-receiver travel time data, subsets of the total data for this line, were used. The yellow colors represent velocities typical of dry unconsolidated fill. The blue colors represent velocities typical of saturated unconsolidated fill or semi-consolidated dry material. The red to black colors represent velocities typical of consolidated bedrock.

Line 1 had 72 receiver stations and 73 source stations spread across 54 meters. In the images of figure 9, the lateral extent has been extended at both ends to the evident bedrock of the valley walls. The colors are as described in the figure caption, but it is important to note that blue does not always indicate saturated fill material. The images are gradational, such that if loose, dry sediment were directly against bedrock, blue would show between the low and high velocities but would not indicate wet material. In general, when the velocity is lower than 1500 meters per second (m/s), as in the yellow colors, the material cannot be fully saturated. However, velocities greater than 1500 m/s are not always due to saturated sediment. Partially cemented but dry sediment can have the same velocity as loose, wet sediment. Bedrock in an area is often defined as the first highly consolidated material encountered under the soil and unconsolidated material. Material with a seismic velocity of over 3000 m/s can be considered bedrock by definition. One notable feature of these models is the rapid velocity variation from less than 2000 m/s to over 3000 m/s, strongly suggesting a clear bedrock interface.

The two images of figure 9 were created using different source-receiver combinations. Model A used 19 of the 73 source positions, and Model B used 17 source positions. Only the first hammer blow at each station was used for both models. Other model images were created using only the second hammer blow, and all show the same degree of variation in detail and the same common features. Details that vary between the two images should not be strictly interpreted. Common features can be interpreted with reasonable confidence. In this case, even though the current streambed exists in the topographic low at about 40 meters on the horizontal scale, the deeper part of the valley is clearly between 20 and 30 meters horizontally. Also, from 25 to 35 meters horizontally, the bedrock interface is rough and indistinct as it rises from near 27 meters depth to near 15 meters depth.

Line 1 was acquired near two wells drilled early in 2002. One of the wells was completed to monitor the bedrock (Well SC-1B), and the other to monitor the alluvium (Well SC-1A). Both wells are north of Line 1. Well SC-1A is about 15 meters north of horizontal distance 15 on Line 1, and SC-1B is about 6 meters north of horizontal distance 21 meters on Line 1. Figure 10 shows results of several logs run in Well SC-1B at different stages of well completion. For more information about the design, development, and logs of the wells drilled as part of this study see Naus and others (in press).

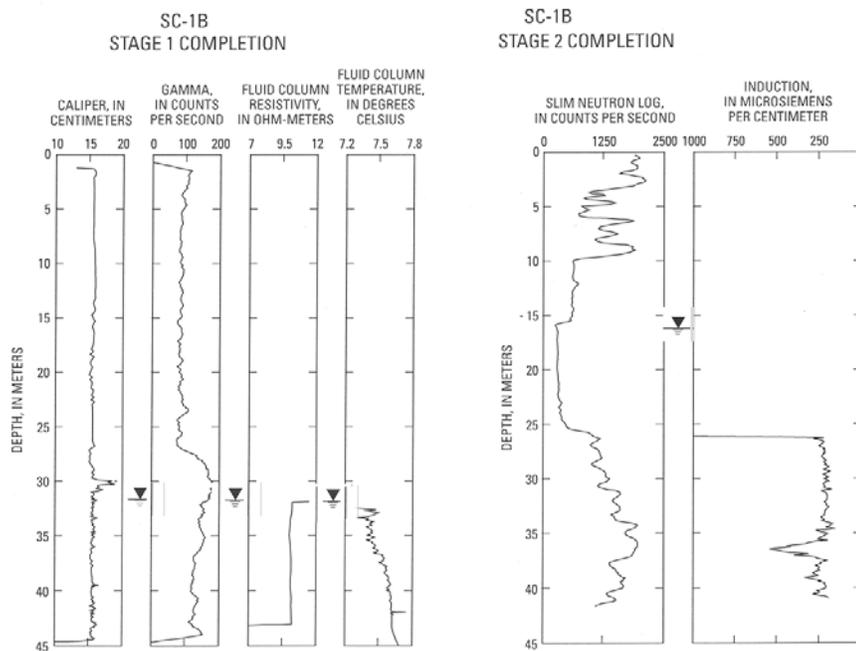


Figure 10. Well SC-1B was drilled into bedrock and completed with a screen from 39.6 to 42.7 m depth (see Naus 2004). From this data, hydrologists and consultants estimated depth to bedrock at 25.6 meters. The inverted black triangle indicates water level in the well.

The logs of SC-1B indicate saturated sediment starting at about 10 meters depth and a bedrock interface at about 26 meters depth in this hole. Figure 11 shows the results of two logs acquired in hole SC-1A. The drillers estimated depth to consolidated bedrock in this hole at about 20.5 m depth. The log data suggest saturated alluvium starting at about 8 meters depth. Most important, the data from both holes correlate well with the refraction tomography image of Line 1 (figure 9). The velocity images of Line 1 also show the potential difficulties of estimating a single, clear depth to bedrock with well data, depending on the well location.

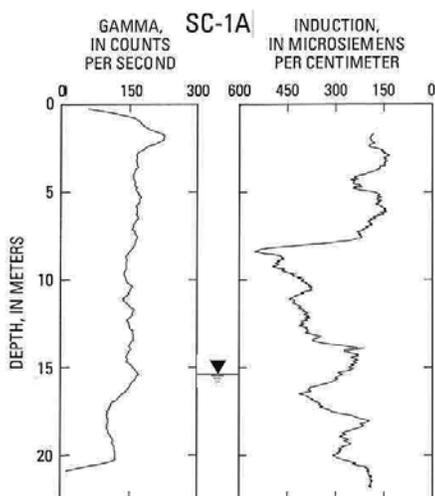


Figure 11. The induction log varies according to the electrical conductivity of the material around the borehole. Because of the poor water quality in this area, wet sediment is likely to be more electrically conductive than dry sediment. The change in saturation near this hole probably occurs at about 8 meters depth. The change from dry to wet sediment is also commonly associated with an increase of seismic velocity from less than 1500 m/s to over 1600 m/s (yellow to blue on the color scale). (Figure from Paillet, 2002. See Naus, in press, for well design.)

Line 2 Results

Line 2 was acquired about 250 meters south (downslope) of Line 1. This part of the valley has an elevated debris fan of material on the west side associated with erosion from the small scar on the slope above. We situated the line such that the western portion of it ran along the surface of this debris fan, down to the road in the center of the valley, and across the almost level valley floor to the east slope. In particular, we wondered what the shape of the bedrock interface might be under this debris fan.

Figure 12 shows the refraction tomography velocity versus depth models created from the data of Line 2. Model A used 20 of the 97 shot files, and model B used 26 shots. Both models used first-arrival times from only the first hammer blow for each included shot station. Depth to bedrock here is about the same or even a bit less than the deepest part at Line 1. However, the bedrock channel has now broadened to almost the complete width of the valley floor. It also appears to be separated into two channels nearly equal in width and depth, with just a slight bedrock rise dividing them. The bedrock slope under the debris fan on the west half of the profile is well defined. Only the portion from about 5 meters on the horizontal scale to the west end has been approximated. From 5 meters to 35 meters on the horizontal scale, this image gives a good depiction of the buried bedrock slope on the west side of the valley under the debris fan.

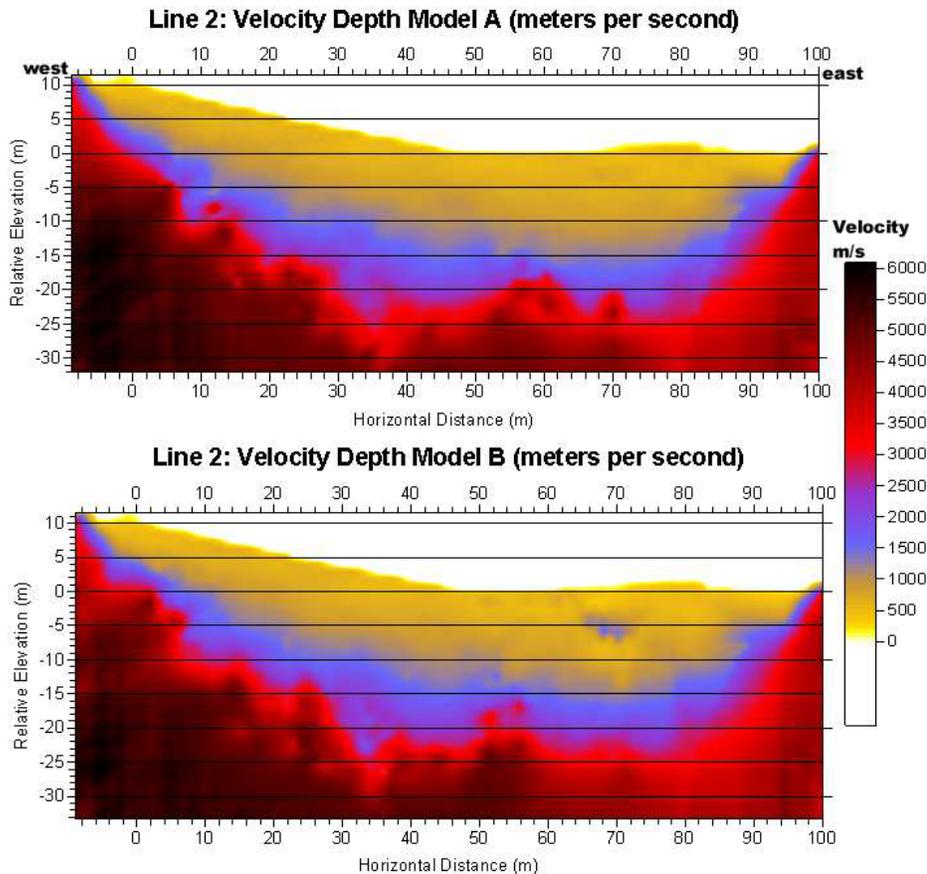


Figure 12. Two images created from separate subsets of the data acquired along Line 2 show similar subsurface features. The bedrock channel has broadened from that of Line 1, but it has not deepened. The west side of this image shows the slope of the bedrock below the debris fan of erosional material from the small scar located just above the line on the west slope.

The rough nature of this slope is not unlike the exposed bedrock on the slopes above the current valley floor. Figure 13 shows a picture of bedrock features on the east slope just above Line 1. It is possible to imagine that the buried bedrock slopes include such features.



Figure 13. This bedrock feature is currently exposed on the east slope above Line 1. Similar features may exist in the buried bedrock slopes further down in the valley. This can account for the rough appearance of the bedrock interface in the models.

Line 3 Results

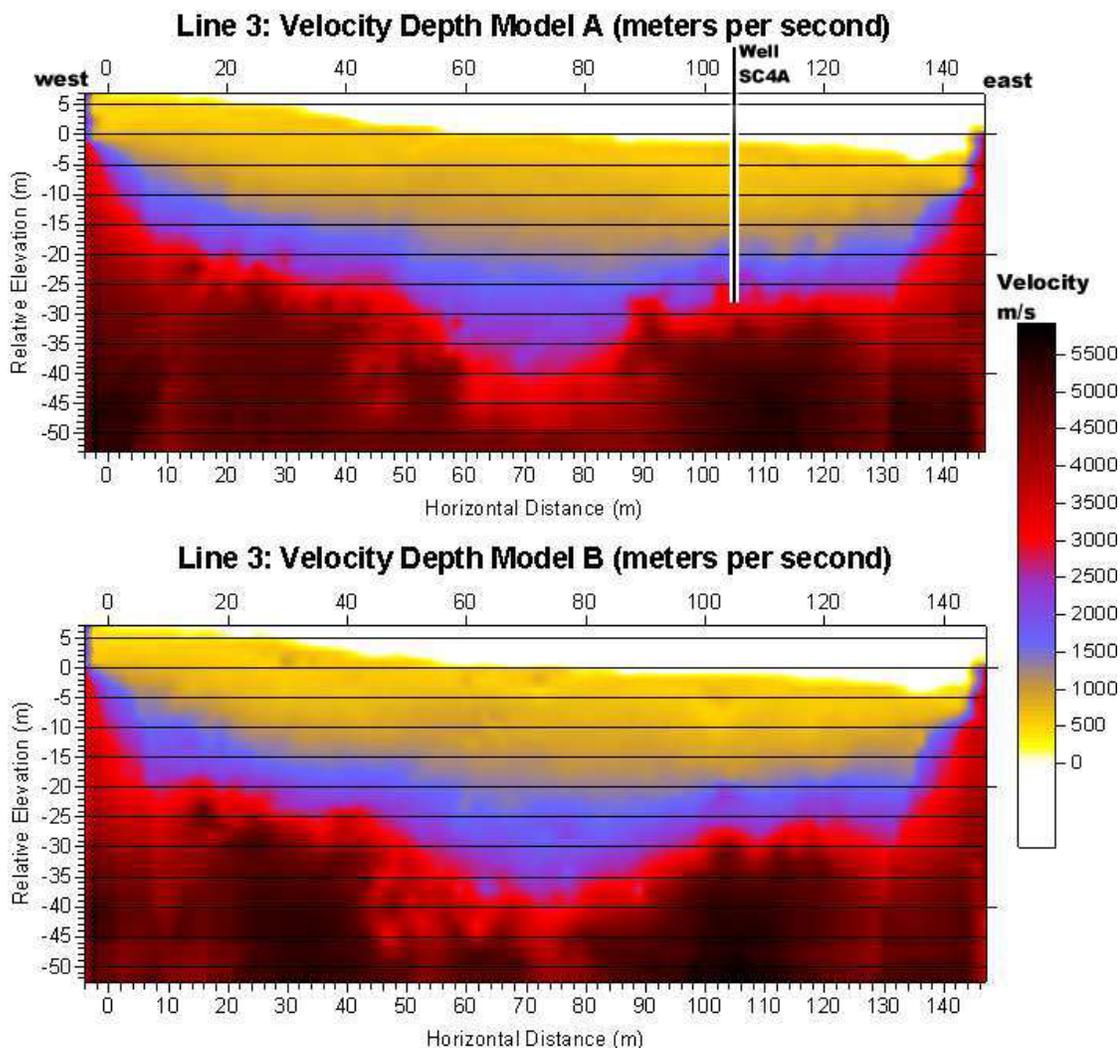


Figure 14. The velocity-depth models created from the data of Line 3 show the broad bedrock channel at about 25 meters depth, but here a central channel exists where the depth is about 40 meters. The two models were again created with separate subsets of the data. Well SC4A is just off the line at about 105 meters on the horizontal scale.

Line 3 was located to coincide with several wells. It crosses the road about 250 meters south (downslope) from Line 2. Line 3 crosses the valley from west to east with a slight southward trend, such that the west end is higher in elevation than the east end. The current dry streambed is on the far east side of the valley. Figure 14 shows the velocity-depth models for Line 3. Only the first hammer blow at each of 20 shot stations for Model A and of 34 shot stations for Model B was used.

Well SC-4A was drilled and completed as an alluvial well. The bottom of the well was meant to stop at bedrock and be screened to intercept water from the alluvium for monitoring. This well was just a meter or two off of Line 3 at 105 meters on the Line 3 horizontal scale. Figure 15 shows the gamma and induction log results from this well. The images from the seismic data show water saturated sediment at about 20 meters depth near the well and bedrock at about 28 meters depth. This correlates well with the two logs assuming the wet sediment is

more electrically conductive than the dry sediment, and the wet bedrock is a little less electrically conductive (probably a little less porous) than the wet sediment. These are both reasonable assumptions. The gamma log shows only a slight change at the bedrock interface, which is difficult to interpret without other information. The seismic images allow this slight change to be interpreted as bedrock. Because the valley fill and bedrock in this area have essentially the same mineral makeup, a lack of gamma log variation at the bedrock interface is not surprising. The decision to plug this alluvial well at 28-30 meters is consistent with our models.

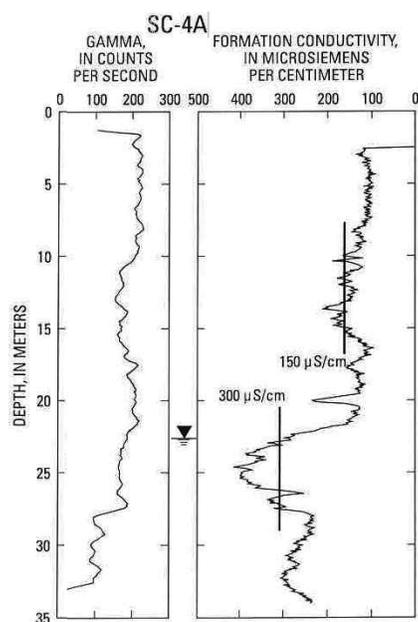


Figure 15. The logs from well SC-4A, located just off Line 3 at 105 meters on the horizontal scale, are reasonably interpreted based on the images from the seismic data. They suggest dry fill to about 20 meters, and wet fill below this to bedrock at about 28 meters. (Figure from Paillet, 2002)

Line 4 Results

Line 4 was located another 250 meters south down the road from Line 3. Line 4 is above the sewage treatment facility and the opening of the Straight Creek drainage into the Red River valley. Because the recording spread for each hammer blow was longer in this survey than the others, the first arrival energy at the far ends of the spread was weaker. This made the traveltimes picks less accurate, which in turn means the depth to bedrock in the deepest part of the valley is computed with less certainty. Figure 16 shows the refraction tomography images for this line.

Even though the data contributing to these images are somewhat noisier than that of the other lines, the two images created from separate subsets still look similar. Model A was created with data from 25 of 120 shot points, and model B was created with data from 31 shot points. Figure 17 shows the coverage in the subsurface of velocity values computed by the refraction tomography imaging algorithm. For model B, 2976 first arrival traveltimes were picked and used to calculate velocities. The velocities shown in the color images where no coverage exists, mostly deep depths at the ends of the lines, are extrapolations. The coverage section confirms that the important features showing the wet/dry and bedrock interfaces are well constrained by the velocity data.

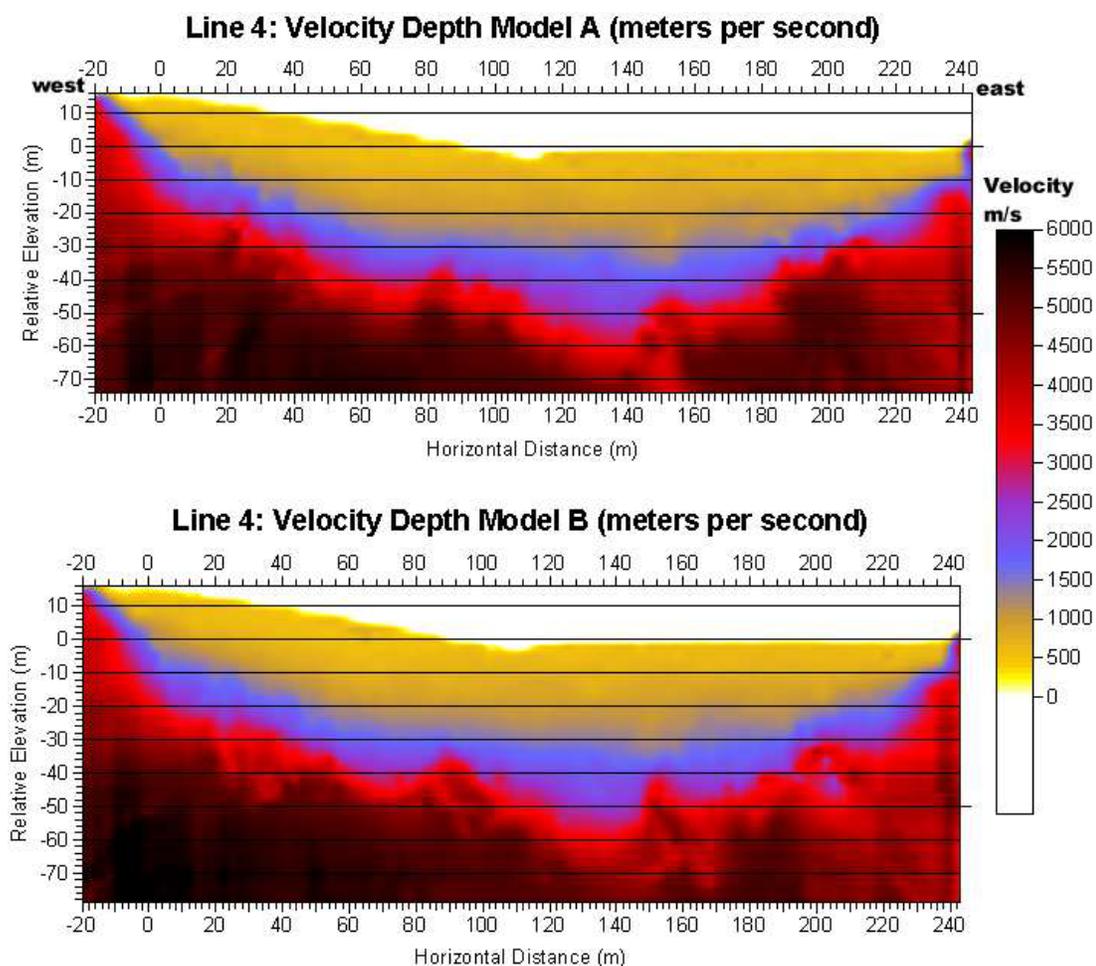


Figure 16. Two velocity depth models created from separate subsets of the Line 4 data show similar features. The deepest bedrock channel (55 meters deep) is 30 meters east of the road, which crosses this line at about 95-100 meters. A flat wet-sediment contact is at about 25 m depth.

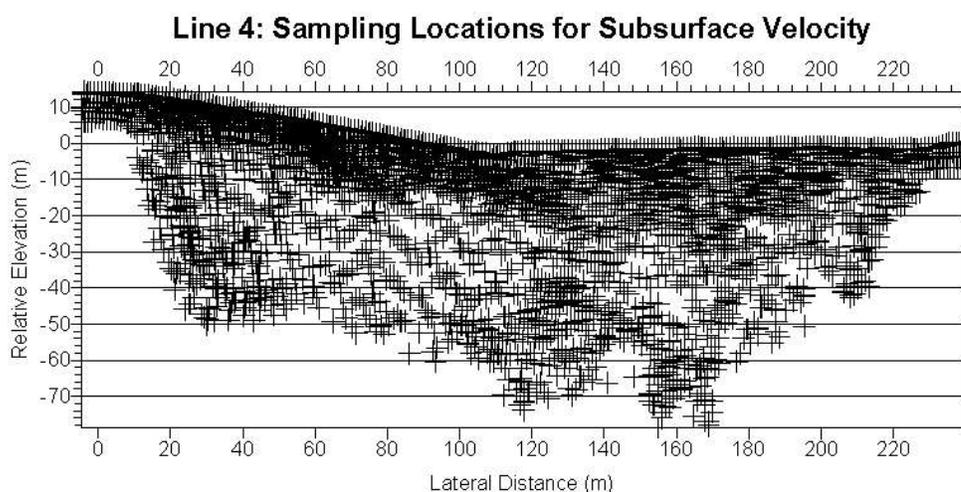


Figure 17. This image shows the subsurface coverage of velocity values computed by the refraction tomography algorithm to create model B above. Only 31 of 120 shots were used, but coverage is good over most of the image. Velocities in areas with no coverage are extrapolations.

Conclusions

Refraction tomography images, created with first arrival traveltimes of seismic data acquired in the Straight Creek drainage near Red River, New Mexico, show depths to water table and bedrock with values that are consistent with information from wells in the area. The tomographic images show subsurface velocity versus depth. Standard correlations of velocity with lithology and saturation lead to interpretations of subsurface features that are supported by independent well information.

Given the geologic and geomorphic conditions at this site, and the information from the wells, we believe our seismic models are reasonable estimations of subsurface features. The color scheme we have presented allows reasonable interpretations of bedrock as red on the images. The yellow color can be interpreted as dry to under-saturated alluvium. Blue, however, can be either fully-saturated alluvium or partially consolidated but less than fully saturated alluvium. We present two separate images of each model so that common features can be confidently interpreted, and variable features can be identified as questionable.

Acknowledgements

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