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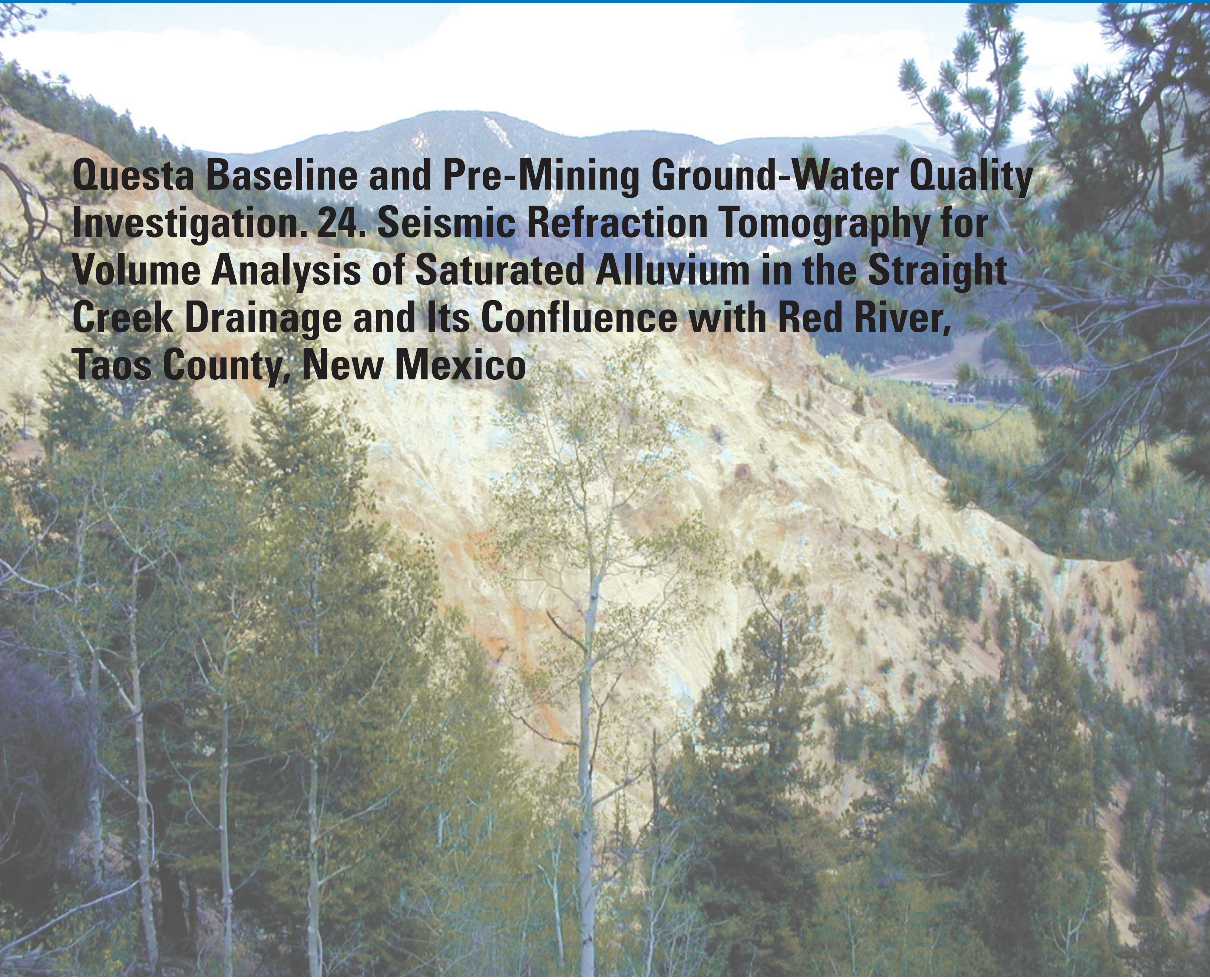

Scientific Investigations Report 2006–5166

U.S. Department of the Interior
U.S. Geological Survey

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Contents

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Conversion Factors

SI to Inch/Pound

Mulitply	By	To obtain
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Abbreviations used in this report

kg	kilogram
km	kilometer, kilometers
lb	pound
m	meter, meters
mps	meters per second
Delta-TV	offset distance, travel time, and apparent velocity
DEM	digital elevation model
NAD27	North American Datum of 1927
NGVD29	National Geodetic Vertical Datum of 1929
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WET	wavepath eikonal travel-time tomography

Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 24. Seismic Refraction Tomography for Volume Analysis of Saturated Alluvium in the Straight Creek Drainage and Its Confluence With Red River, Taos County, New Mexico

By Michael H. Powers and Bethany L. Burton

Abstract

As part of a research effort directed by the New Mexico Environment Department to determine pre-mining water quality of the Red River at a molybdenum mining site in northern New Mexico, we used seismic refraction tomography to create subsurface compressional-wave velocity images along six lines that crossed the Straight Creek drainage and three that crossed the valley of Red River. Field work was performed in June 2002 (lines 1–4) and September 2003 (lines 5–9). We interpreted the images to determine depths to the water table and to the top of bedrock. Depths to water and bedrock in boreholes near the lines correlate well with our interpretations based on seismic data. In general, the images suggest that the alluvium in this area has a trapezoidal cross section.

Using a U.S. Geological Survey digital elevation model grid of surface elevations of this region and the interpreted elevations to water table and bedrock obtained from the seismic data, we generated new models of the shape of the buried bedrock surface and the water table through surface interpolation and extrapolation. Then, using elevation differences between the two grids, we calculated volumes of dry and wet alluvium in the two drainages. The Red River alluvium is about 51 percent saturated, whereas the much smaller volume of alluvium in the tributary Straight Creek is only about 18 percent saturated. When combined with average ground-water velocity values, the information we present can be used to determine discharge of Straight Creek into Red River relative to the total discharge of Red River moving past Straight Creek. This information will contribute to more accurate models of ground-water flow, which are needed to determine the pre-mining water quality in the Red River.

Introduction

This report summarizes results from the use of seismic refraction tomography in a study area in northern New Mexico, at and near the confluence of Straight Creek with Red River, to determine approximate geometry and volumes of dry and saturated alluvium above bedrock. It is one of many publications presenting results of a U.S. Geological Survey study of ground-water quality in the Red River upstream from Questa, New Mexico (for example, Lovetere and others, 2004; Maest and others, 2004; Nordstrom, in press; and Vincent, in press). This information will be used to constrain ground-water models for a larger area of interest that encompasses Molycorp molybdenum mine (fig. 1) about 10 miles west of the study area.

The town of Questa is located beside the Red River in north-central New Mexico (fig. 1), 8 kilometers (km) west of and downstream from the Molycorp molybdenum mine, which is preparing for closure. The New Mexico Environment Department is required to ensure that pre-mining water quality exists in the river at Questa in fulfillment of a requirement for mine closure. That department invited the U.S. Geological Survey to contribute research toward the determination of the pre-mining quality of river water at the mine site.

Many natural erosional scars were present at the mine site before mining, and they still exist in the Red River drainage both upstream and downstream from the mine site. The scars are underlain by mineralized zones of pyrite-rich rocks that have weathered and eroded on the steep topography, removing all vegetative cover and allowing large amounts of material to be shed during rainstorms and snow melt (Ludington and others, 2004). This sulfide-rich material oxidizes when in contact with surface water and then contributes acidic water to the drainage system (Briggs and others, 2003; Smith, in press). That acidic water is then able to dissolve high concentrations of heavy metals. Thus, the natural watershed and the issue of pre-mining water quality are complex.

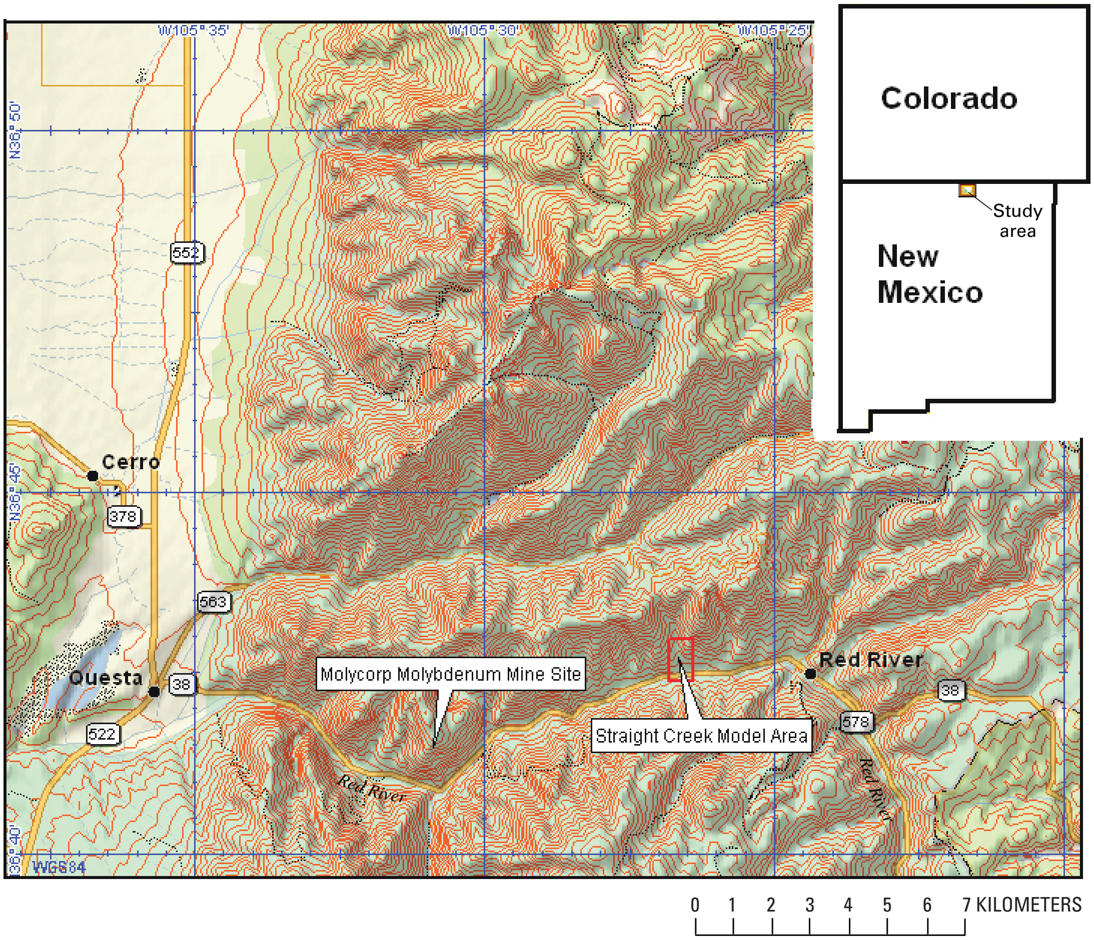

Figure 1. Straight Creek model area (red rectangle), New Mexico; located upstream from a molybdenum mine undergoing closure in 2006. Red River flows west through the southern part of model area. Base map modified from DeLorme XMap 4.502.0, 3-D TopoQuad Base Map, New Mexico North Region 3, 1999.

Straight Creek drains into Red River upstream from the mine site. Because its slopes contain natural scars (for example, SE Straight scar, fig. 2), it was identified as an analog for the mine site before mining activity. A similar but larger scar exists at the head of the Straight Creek drainage. Thunderstorms can move large amounts of debris down the valley, as indicated by mud plastered onto tree trunks (fig. 3). Alluvial material in the Straight Creek drainage is composed primarily of sulfide-rich scar detritus (Plumlee and others, in press).

Accurate ground-water models (McAda and Naus, in press; Naus and McAda, 2006) of the Straight Creek area (figs. 1 and 4) require detailed mapping of both dry and saturated alluvium. Seismic refraction tomography studies (White, 1989; Docherty, 1992; Zhang and Toksoz, 1998; Powers and Burton, 2004; Sheehan and others, 2005) provide subsurface seismic velocity measurements along survey transects that can be used to determine the depth to the water table and to bedrock.

Figure 2. SE Straight scar, viewed from the eastern slope above Straight Creek southeast toward the town of Red River.

Figure 3. The valley floor of Straight Creek, looking downstream, mantled with poorly sorted alluvial material shed from natural erosion scars and transported by thunderstorm runoff. Mudline on tree (arrow) marks high water during thunderstorm events.

In late May 2002, the U.S. Geological Survey acquired four lines of seismic data across the valley of Straight Creek (fig. 4) and analyzed them by use of a commercial refraction tomography method. We were pleased to discover that the highly variable depths to water table and bedrock were readily interpreted from the resulting velocity images. This initial seismic effort and the results are described in Powers and Burton (2004) and are briefly summarized in the next section of this report. In late September 2003, we acquired five more seismic lines across the confluence of Straight Creek with Red River and across the valley of Red River (fig. 4). This report describes the analysis and interpretation of lines 5–9 and provides images and calculated volumes of the alluvial material in the model area by use of interpolation and extrapolation of all the interpreted subsurface contact information.

Previous Work

The need for information about bedrock geometry in the Straight Creek area for use in ground-water modeling first arose in 2001. Lucius and others (2001), who applied electrical methods, discovered a lack of contrast in electrical properties between alluvium and underlying bedrock. In 2002, four lines of seismic data were acquired with the intent to process and interpret for reflections that indicated the bedrock interface. Owing to many factors—such as strong surface waves, rough interfaces, strong offline scattered energy, and loss of high-frequency content—a bedrock reflection across the profile was not confidently determined. A high-velocity refractor, however, was indicated by the pattern of first-arrival times. Evidence of this refractor led to an analysis of the data by use of a commercial seismic refraction tomography method (Rohdewald, 2003). The resulting images of compressional wave velocity versus depth and lateral position revealed interpretable contacts between dry and wet alluvium and between alluvium and bedrock. The interpreted contacts correlate well with borehole information. Analyses of seismic lines 1–4 (Powers and Burton, 2004) are summarized in the following paragraph.

Because of dry conditions, low noise requirements, budget limits, steep terrain, limited access to forested areas, and other factors, the initial seismic effort at this site used a hand-held sledgehammer as the sole wave source. The four seismic lines ranged in length from 60 to 240 meters (m), and all crossed the valley from bedrock on one side to bedrock on the other (fig. 5). Each line had a different but constant receiver spacing; the geophone intervals for lines 1–4 were 0.75, 1.0, 1.5, and 2.0 m, respectively. Source positions were located between every receiver to provide the dense coverage necessary to produce a reflection image. We found that the refraction tomography method did not require use of all source-receiver pairs to create reasonable images. However, the dense acquisition of data allowed the use of data subsets in analyses to determine the optimal coverage for future cost-efficient surveys that do not sacrifice accuracy. This experience was essential for planning the effective acquisition and imaging of five longer lines that include spans across the valley of the Red River.

Seismic Refraction Profiles

Data Collection

The locations and lengths of lines 5–9 (fig. 4) were determined in conjunction with a geomorphologist and with ground-water modelers in order to best contribute information that will improve the accuracy of ground-water flow models, which in turn support the overall research goal of determining pre-mining water quality. The lines are numbered according to priority and were acquired in that order. Given the common constraints of time, money, equipment, access, and environmental sensitivity, our objective was to create, along as many profiles as possible, accurate subsurface images that showed the shape and depth of the water table and of the bedrock surface.

A 96-channel seismic system, using cables with a maximum of 5 m between geophone take-outs, can be deployed in a single spread of live geophones a maximum of 480 m. This distance was adequate to cover the longest planned line. We acquired each line in one day by deploying all 96 geophones with cables in a single live spread and acquiring shot locations through the spread from one end of the line to the other. Tests on previous lines determined that a shot location spacing of three times the receiver spacing produced accurate images of suitable resolution within our time and cost budget.

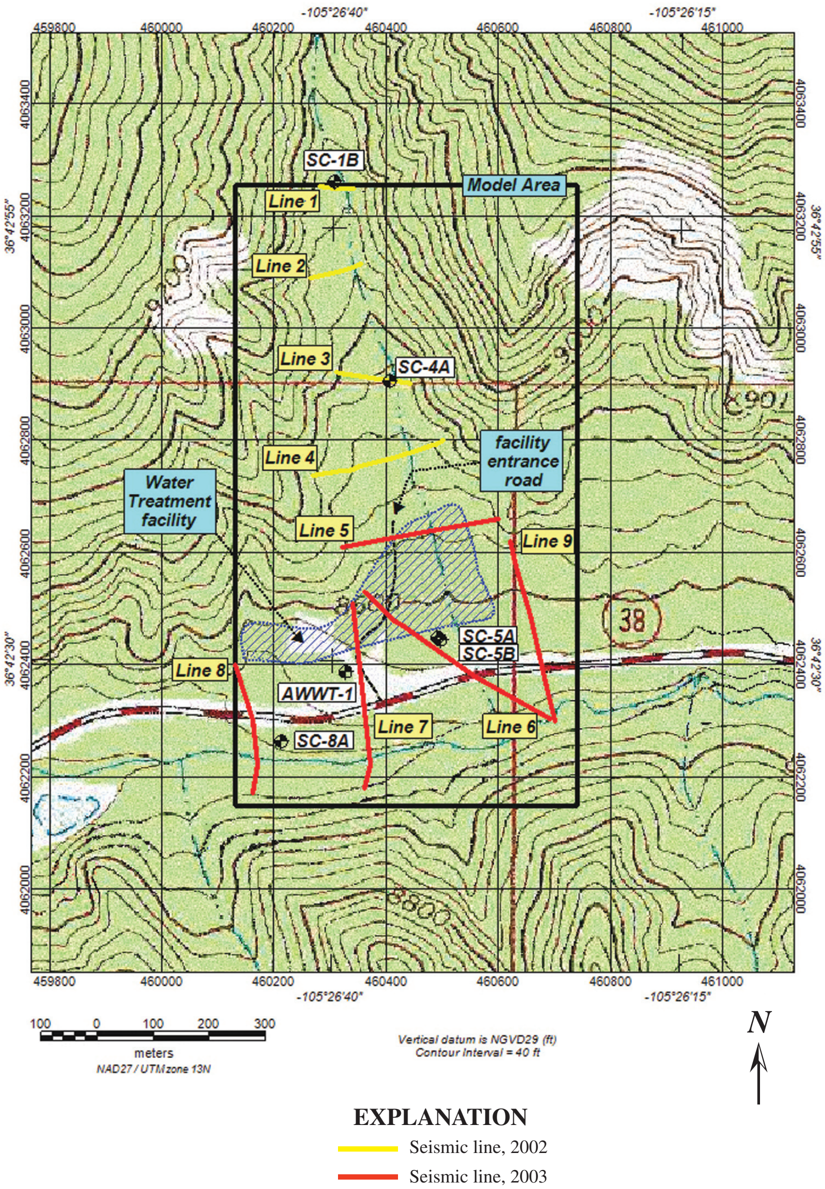

Figure 4. Locations of nine seismic lines in study area. Lines 1–4 across upper Straight Creek are discussed in Powers and Burton (2004). Lines 5–9, near the confluence of Straight Creek and Red River, are discussed in this report, which uses all nine lines to estimate the volume of basin alluvium in the model area. Borehole SC–8A and borehole SC–8B (not labeled) lie within 2 m of each other. Base map modified from U.S. Geological Survey map Red River, New Mexico, 1:24,000.

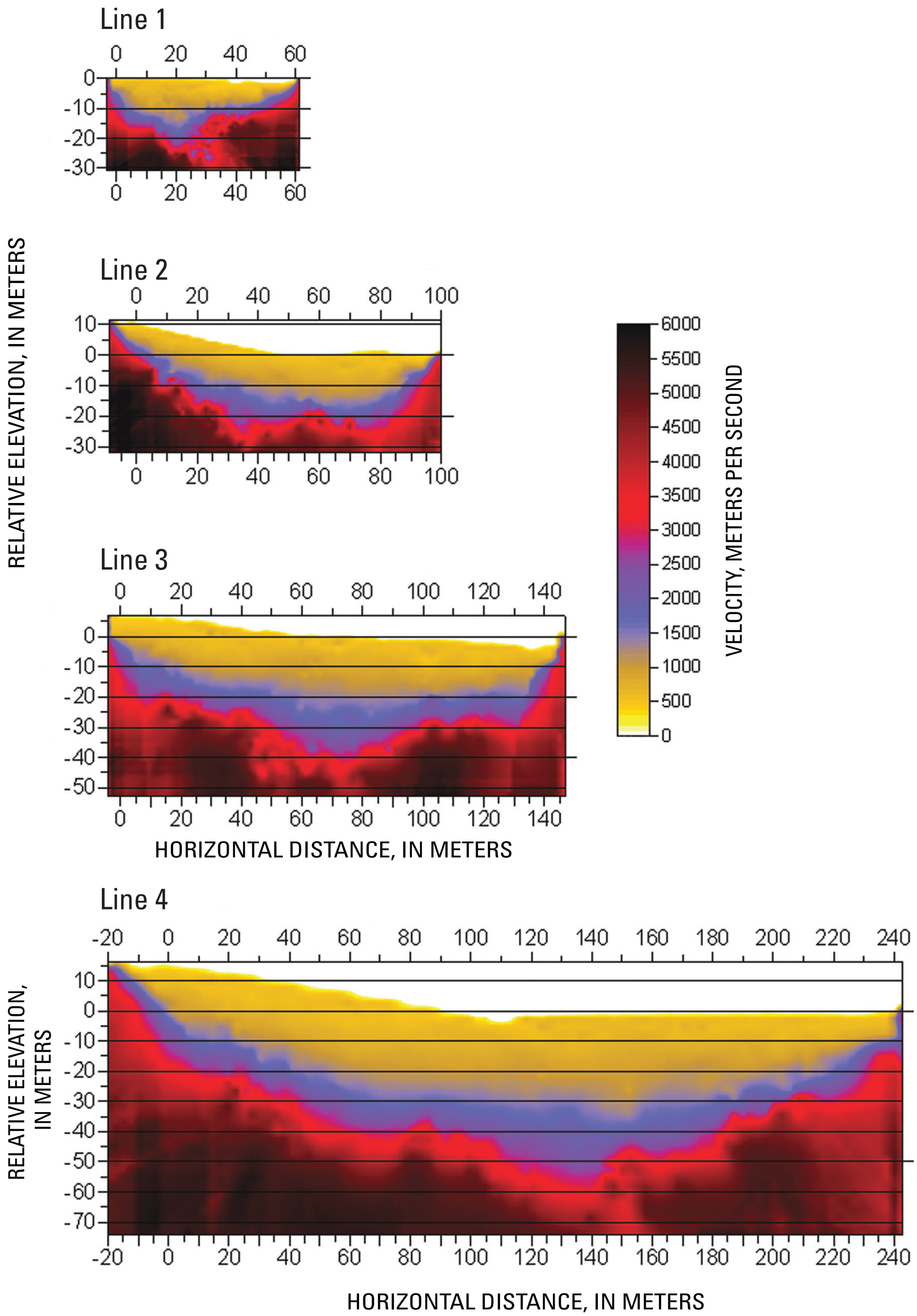

Figure 5. Velocity-depth images of seismic lines 1–4 at the same scale. Alluvium and bedrock distinguished by use of a color scale corresponding to common velocities of earth materials: dark yellow, unsaturated and unconsolidated fill (velocity 400–1,500 mps); blue, water-saturated sediment (velocity 1,600–2,000 mps); red, consolidated rock (velocity >3,000 mps).

Accurate first-arrival time picks on the data records are essential for meaningful tomographic velocity images. The energy source must be strong enough to generate clear first-arrival responses on the geophones for accurate time picks. At this site, the energy from a 9-kilogram (kg) hand-held hammer swung onto a steel plate placed flush on the ground generated first-arrival signals that were distinct from noise in the data out to source-to-receiver distances of 35 m (worst case) to 200 m (best case). Lines 5–9 ranged in length from 240 to 400 m, so that use of the hammer was effective only in the center portions of each line. For the ends of the lines, where distances to far geophones were greatest, permission was received from the Questa District Office of the Carson National Forest to use small, buried charges of ⅓ pound (lb) binary explosive. Small, binary charges are reasonably priced, portable, and powerful enough to generate good first-arrival signals at large source-to-receiver distances. Binaries (in which powder and fluid are stored in separate containers and are not hazardous until mixed) are safe and legal to transport. The major drawback to explosives is the need to drill holes in which to place the charges to prevent surface noise and disruption in sensitive locations. At this site, we used a hand-held electric rock drill powered by a portable 4,400-watt generator mounted on a small four-wheel all-terrain vehicle.

The receiver interval distance was set according to the physical line length, and each line extended across the valley from bedrock on one side to bedrock on the other. Shot locations were marked according to source type (hammer or buried charge), and off-end shots that extended past the first and last receivers provided a better image of the bedrock on the ends of the lines. The hammer was used for source locations in the middle of each line, which included locations near State Highway 38, parallel to Red River, and other cultural structures. A laser surveying instrument was used to measure topography along each line.

Data Analysis

For each of the lines 5–9, the first-arrival times and acquisition geometry, including topography, were used to compute subsurface velocity. First-arrival times were picked manually for every source-receiver pair showing clear first-arrival energy. Noisy data were excluded because the inversion routines that compute velocity as a function of depth and lateral distance are very sensitive to the accuracy of the first-arrival time picks. Bad picks will result in velocity errors. Missing or sparse data, where questionable picks are left out, will result only in a loss of detail in the velocity results.

Two commercial software packages were used to make the computations. Sheehan and others (2005) compare and discuss three commercial packages used for seismic refraction tomographic analysis, including the two used here.

The first package, Rayfract by Intelligent Resources Inc., uses a two-step procedure (Rohdewald, 2003). In the first step, automatic one-dimensional inversions are performed under every source-receiver midpoint using a top-down method, labeled Delta-TV (offset distance, travel time, and apparent velocity) that assumes multiple layers. Within each layer, velocity is increased linearly with depth such that the energy path is a circular arc (Gibson and others, 1979; Rohdewald, Intelligent Resources, Inc., written commun., 2004). This method, which is applied vertically for each midpoint and then along the line for all midpoints, results in an initial velocity model that is used in the second step. The second step is an iterative, constrained, matrix-minimization routine (named wavepath eikonal travel-time tomography) (WET) that determines a whole-model solution that best matches calculated travel times determined by use of forward modeling. In this case, it follows an algorithm described in Schuster and Quintus-Bosz (1993).

The second package, GeoCT-II by GeoTomo LLC, accepts any starting model, such as a single constant velocity or the best result from any previous analysis. It also performs an iterative, constrained, matrix-minimization inversion that determines a whole-model solution that best matches travel times calculated by use of forward modeling. However, this package follows an algorithm described in Zhang and Toksoz (1998) that differs substantially from the algorithm used in the Rayfract package in both the inversion steps and the forward-modeling routine. The GeoCT-II package also allows known velocity-depth information, as from a borehole, to be entered and used as a constraint during the computations.

Our velocity images were created by using the Rayfract package first and then the GeoCT-II package. Three images were generated in the first step by use of Rayfract (Delta-TV) and then three images with the second step (WET). By using the data from line 5, minimum, average, and maximum velocity images were generated with the Delta-TV method (left column, fig. 6*A*). Parameters were changed as needed and the images regenerated until they looked reasonable according to our understanding of local geology. The average velocity image from the first step was then used to start the second step, and three more images were generated with the WET algorithm (right column, fig. 6*A*). Again, parameters were changed as needed to make the images look reasonable; however, in general, our parameter adjustments changed the image very little. The average velocity profile generated by the final run of the WET algorithm was interpreted as the best Rayfract solution.

The GeoCT-II package allows the user to start with any model and to control lateral and vertical smoothing parameters, maximum and minimum velocity, and the number of iterations within an inversion run. As stated previously, known velocity-versus-depth information at a given position along the line can be used as a fixed-position constraint. Our use of the package in this case included inversion runs using the final Rayfract WET image as the starting model for comparison with runs based on a simple, constant starting model. We examined many combinations of lateral and vertical smoothing as well as the influence of variations on the general level of smoothing. The fixed-position constraint was used where

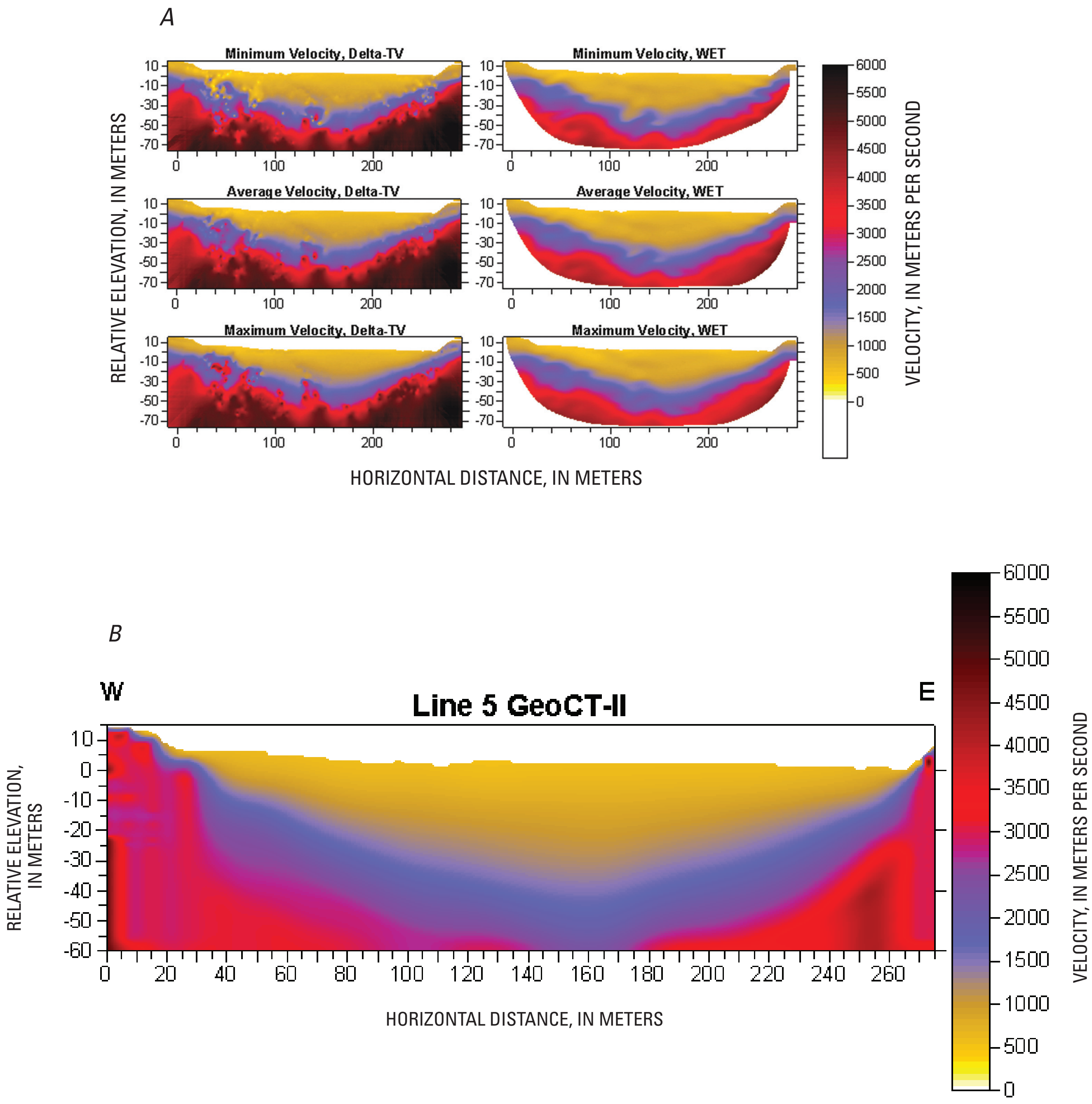

Figure 6. Seismic line 5. A, Velocity images. Sets of three images generated by different algorithms in two steps by use of Rayfract software. Best output of first step was starting model in second step. Image labeled "Average Velocity, WET" accepted as the final Rayfract image. Algorithm abbreviations: Delta-TV, offset-distance, travel time, and apparent velocity; WET, wavepath eikonal travel-time tomography. B, Final velocity image generated by use of GeoCT-II resulted from many combinations of starting models and constraints. It does not precisely represent subsurface geology but can be used to interpret general subsurface features. Alluvium and bedrock distinguished by use of a color scale corresponding to common velocities of earth materials: dark yellow, unsaturated and unconsolidated fill (velocity 400–1,500 mps); blue, water-saturated sediment (velocity 1,600–2,000 mps); red, consolidated rock (velocity >3,000 mps).

borehole information was available and with knowledge of bedrock outcrops at the line ends. The final GeoCT-II velocity image of line 5 (fig. 6*B*) shows apparent minor bedrock steps near the surface on the west (left) side of the image; those steps are the graphical result of requiring bedrock at the line end to match known outcrops by using a fixed-position constraint. Travel-time constraints on velocity at the line ends are weak, and the fixed-position constraint was used to force the bedrock slopes to approach the surface where bedrock contacts were visible in the field. This step geometry is an artifact of the lateral smoothing and probably should not be interpreted strictly.

Tomography Results

The first-arrival travel-time curves and the velocity image results are described below for lines 5–9. The final Rayfract and GeoCT-II velocity images of each line were independently interpreted for simple contacts between dry and saturated alluvium (that is, at the water table), and between saturated alluvium and bedrock. These interpretations of individual images were based only on the respective velocity image and the general correlation of velocity with type of material at this location. The two interpretations were placed together, and we interpreted a final geologic profile using all other knowledge of the site and that gained through the inversion process. A final geologic cross section honored subsurface features that appeared consistent as the inversion parameters of the software packages were varied.

Seismic Line 5

Line 5 is oriented east-west near the mouth of Straight Creek, where the creek flows into the valley of the Red River (fig. 4), and it is the lowest elevation line that crosses the Straight Creek drainage. It crosses the upper portion of the Red River municipal water treatment facility. No nearby boreholes exist that can be used to verify contact depths.

Hammer data were important for data acquisition on this line. For line 5 only, we used shotgun shell casings filled with black powder instead of buried charges at the start of the acquisition (dark red circles along the topographic profile, fig. 7*A*). They were slow to deploy because of the need to dig holes and to prepare the triggering mechanism, and at this site they did not provide energy greater than that of a hammer blow. They also produced a marked and inconsistent time delay between triggering of the system and initiation of energy propagation. In processing, a bulk shift to earlier times was determined and applied to all black powder first-arrival time picks. Black powder shell casings were not used for lines 6–9.

It is appropriate to consider the seismic profile image of this line in concert with those of the four lines presented in figure 5, as they all represent cross sections of the Straight Creek drainage as it broadens downslope. In this context, the interpretation of the relatively open and smoothly arcuate bedrock valley with a maximum depth of about 60 m (fig. 7*B*) is a reasonable approximation of the true geology and is presented with high confidence.

Seismic Line 6

Line 6, the longest of the nine lines, diagonally crosses the confluence of Straight Creek and the Red River (fig. 4). To ensure coverage of possibly deep bedrock, extra shots were positioned beyond the ends of this line to increase source-to-receiver distances. We relied more on buried charges for this line and less on the hammer (fig. 8*A*). The line crosses the highway (stations 60–65 at 240–260 m downline) and ends just short of the river.

Independent interpretations of the final velocity images from the two packages both agree with borehole data; this agreement provides confidence in the general interpretation of geology (fig. 8*B*). Two boreholes, one drilled into alluvium (SC–5A) and one into bedrock (SC–5B), are located 158 m downline and 18 m offline to the northeast (fig. 4). The depths to water table and bedrock as indicated in these boreholes (Naus and others, 2005) are displayed on the interpreted section (fig. 8*B*). The Red River does not meet the water table under line 6. Dry alluvium extends about 20 m under the river. Similarly, a borehole drilled several hundred meters downstream from this location passed through dry alluvium under the river (Naus and others, 2005; Blanchard and others, in press). The deepest part of the Red River valley is not located under the current river location at the southern edge of the drainage but is more in the central part of the valley just north of the highway. The bedrock surface at the Straight Creek drainage opening rapidly changes slope as it drops into the valley of Red River, whereas the water table retains a relatively gentle slope across the confluence.

Seismic Line 7

Line 7 is oriented north-south across the valley of Red River (fig. 4) and passes near the entrance to the Red River water treatment facility. The central part of the line, where the hammer was used, was located along the entrance road into the facility. Evidently the hammer source on the road surface generated only weak energy in the alluvium. The short gray curves indicate unclear first-arrival energy generated beyond stations 10–15 (35–52 m) (fig. 9*A*). Although the buried charges at both ends of the line provided information about the velocity at depth, the refraction tomography method yields more accurate images when the velocity solutions can be determined from the surface downward. The result is increased uncertainty in the accuracy of the image under the central part of line 7 owing to the loss of first-arrival time picks at mid-times in this segment (about stations 30–50). The borehole (AWWT–1) is located less than 10 m offline to the west and shows a depth to water that is a good match with the seismic interpretation. The water table still does not reach the surface at the river (270 m downline) although it increases in elevation just north of the river.

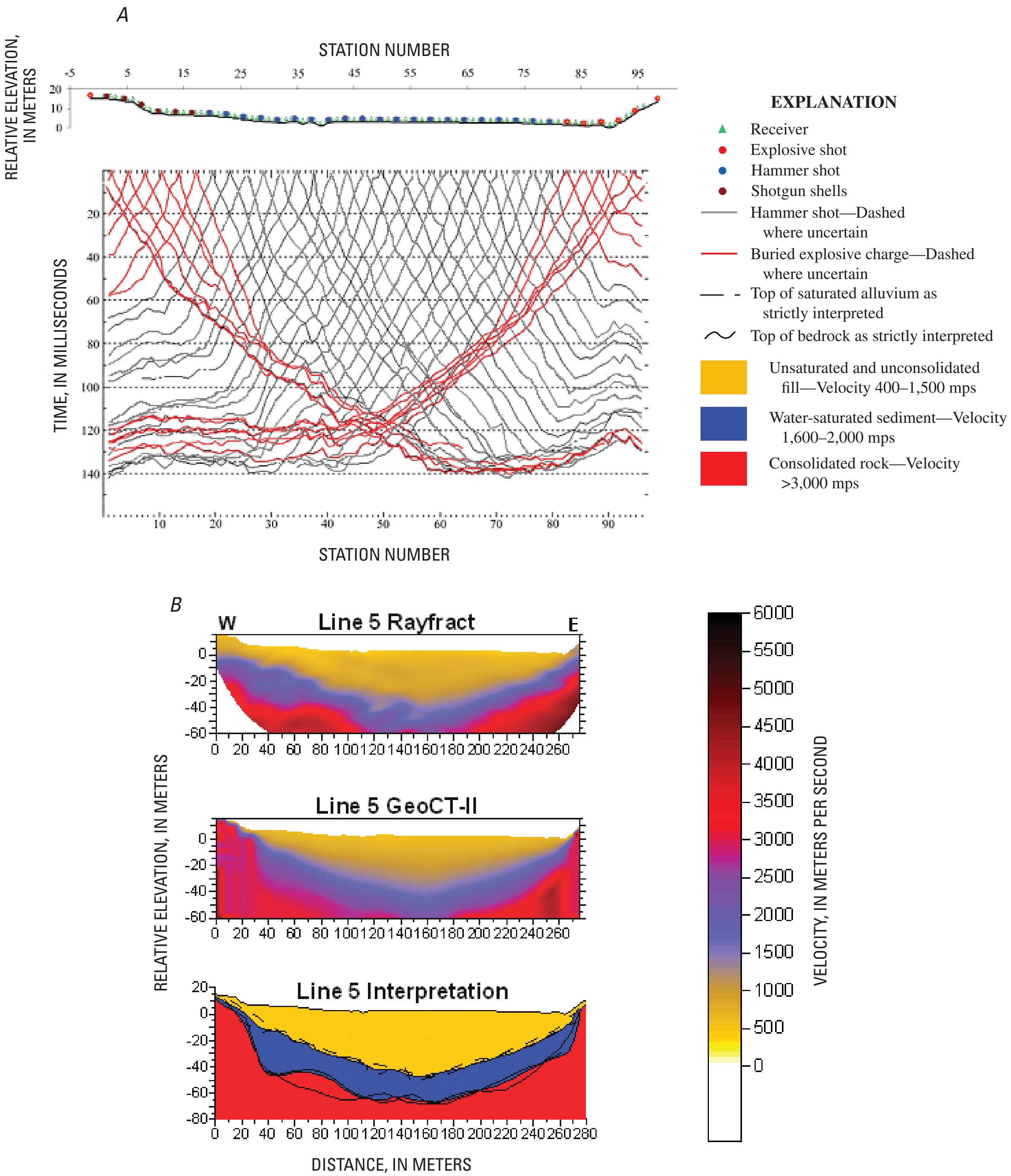

Figure 7. Seismic line 5. *A*, Locations of sources and receivers on topographic profile and first-arrival travel-time curves. Station interval 3 m; total line length about 283 m. Truncated curves or dashed sections indicate missing data where noise, low energy, or road or river crossings prevented confident picks. *B*, Final velocity images generated from first-arrival times by use of Rayfract and GeoCT-II software. Independent interpretations of each image used to generate the interpreted, color-coded, geologic cross section. All three images at same scale (1 in. = 110 m) and without vertical exaggeration.

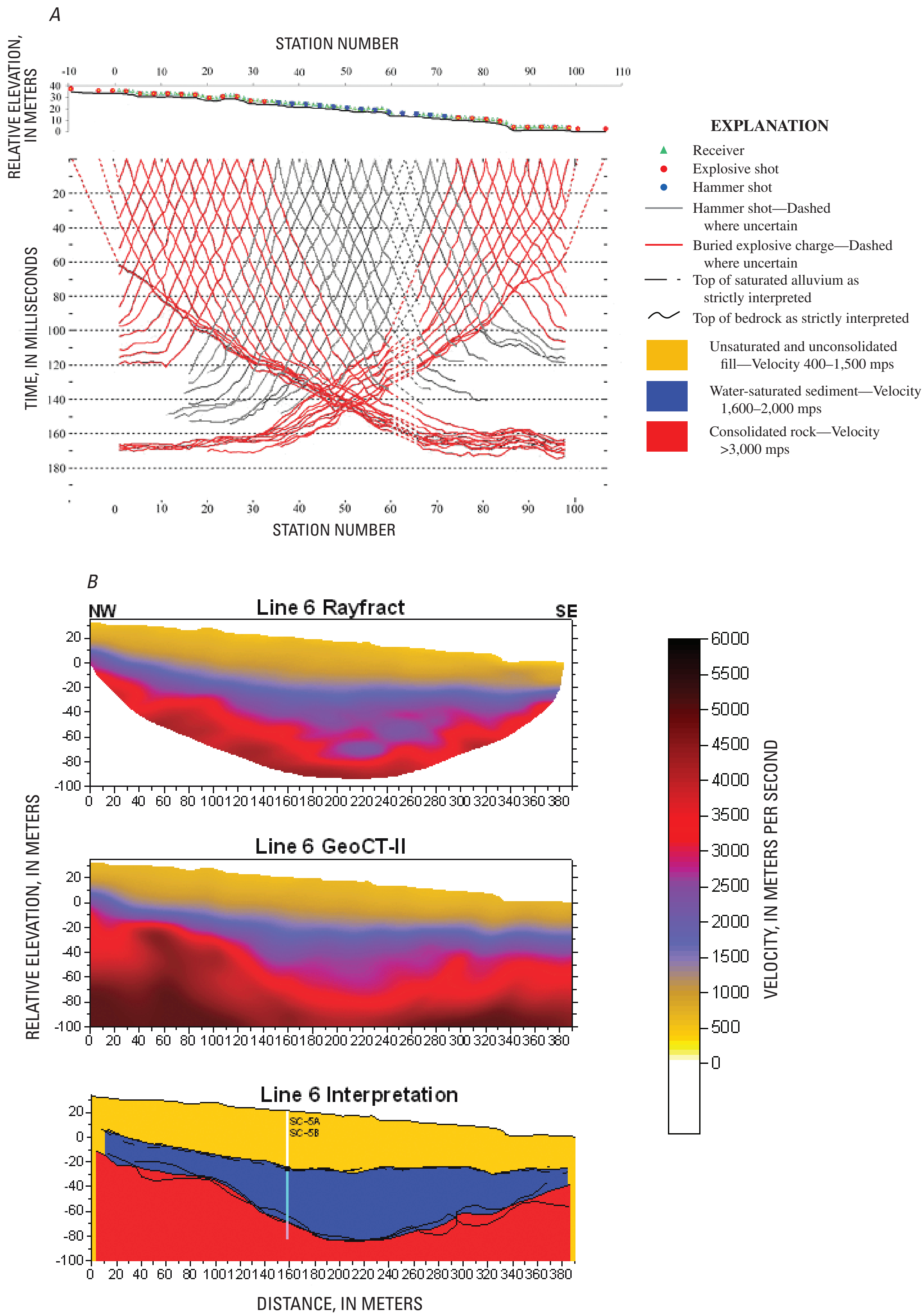

Figure 8. Seismic line 6. *A*, Locations of sources and receivers on topographic profile and first-arrival travel-time curves. Station interval 4 m; total line length almost 400 m. Gray travel-time curves dashed where estimated because location lacked geophone. For this long line crossing the Red River valley, more buried charges were used to allow confident time picks. *B*, Final velocity images generated by use of two software packages; images agree with borehole data. Slope of bedrock along Straight Creek increases where Straight Creek flows into Red River, but slope of water table retains its gentle upstream gradient. All three images at same scale (1 in. = 132 m) and without vertical exaggeration. See Naus and others (2005) for description of boreholes.

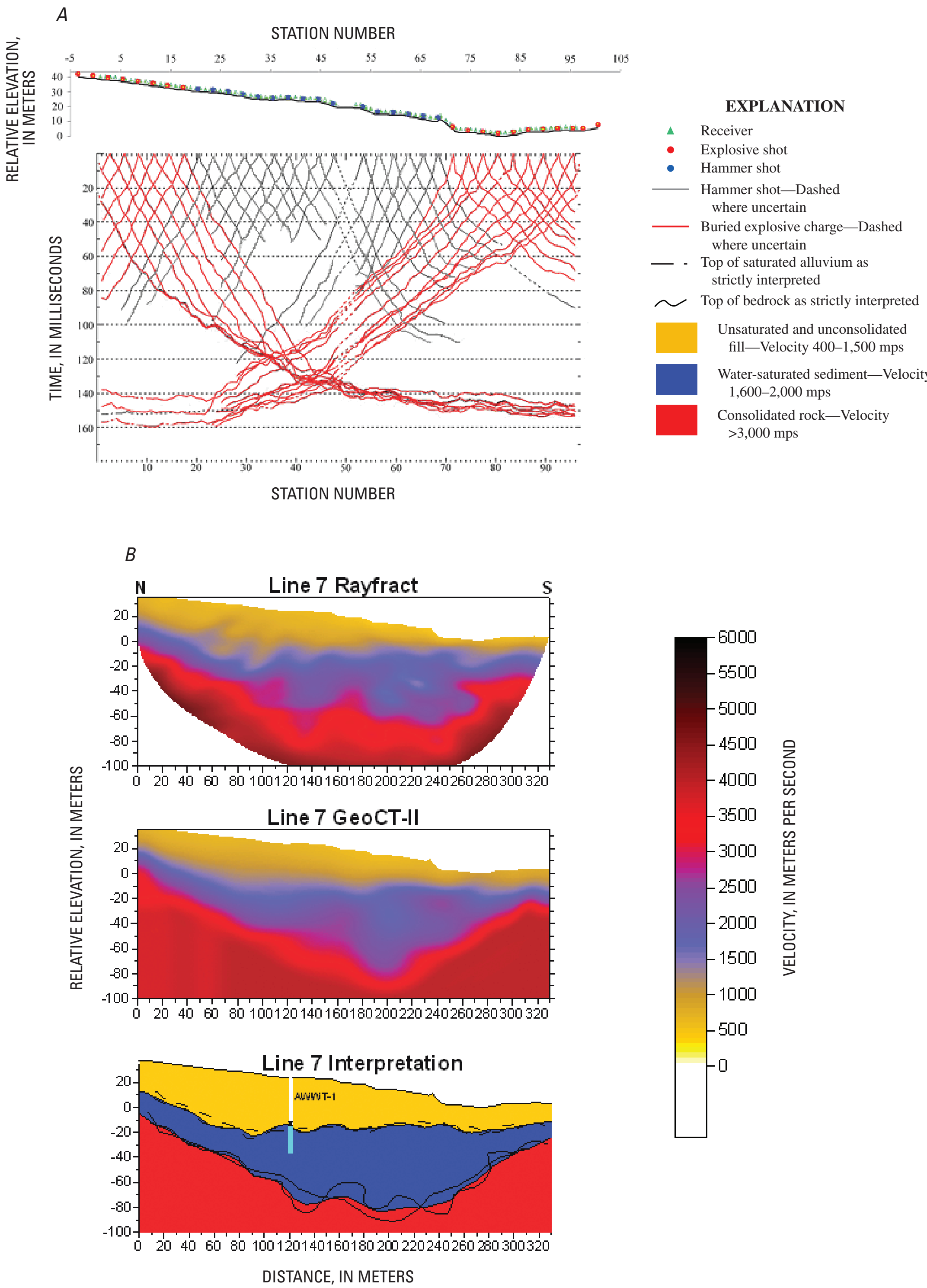

Figure 9. Seismic line 7. *A*, locations of sources and receivers on topographic profile and first-arrival travel-time curves. Station interval 3.5 m; total line length 310 m. Hammer source at stations 20–50 did not provide clear first-arrival time picks at long distances; note short gray curves in this region. End-of-line charges provide some information about velocity at depth, but accuracy of the image is reduced owing to missing information. Borehole near the seismic line confirms depth to water table near this region. *B*, Final velocity images and interpretation. The two velocity images look quite different but when interpreted show only small uncertainty, mainly in depth to central bedrock surface. Interpretation closely matches water level in borehole AWWT–1. All three images at same scale (1 in. = 132 m) and without vertical exaggeration.

The final images generated by the two software packages differ in their details of water table and bedrock in this region (fig. 9*B*). General features including approximate depth to and nature of water table and bedrock surfaces can be confidently interpreted. Both images show an irregular water table. If one uses a little imagination, the shape of the wet-dry contact in the alluvium suggests that water from the Straight Creek drainage may be turning west (down valley) and has not yet or is just starting to meet groundwater from the valley of Red River that is moving more toward the central or southern part of the valley. If this is the case, then the water in borehole AWWT–1 comes mostly from the Straight Creek drainage (see Naus and others, 2005). The junction between Straight Creek and Red River waters appears to be just north of the highway (at 190–200 m) along this line. The bedrock depth can be confidently determined only to within ±10 m along the central part of this line.

Seismic Line 8

Line 8 crosses the Red River valley downstream from line 7 (fig. 4). The line changes heading slightly at the highway and again at the river, owing to difficulty in finding a direct route through the east end of the Fawn Lakes campground and across the river. The shot curves (fig. 10*A*) show that the hammer energy does not reach bedrock in the central, deep part of the line. Even the end-of-line explosive charges just barely manage to show a slope break indicative of bedrock velocity.

Depth to bedrock in the central part of the line was not well determined. However, seismic data strongly indicate the contact between dry and wet alluvium. The contact is mounded toward the northern side of the valley, suggesting that it is not associated with the river. The water-table level in borehole SC–8A is a reasonable fit to the interpretation, given that the borehole is more than 40 m east of the line (fig. 10*B*). The flat bedrock benches on both sides of the valley are present in the two velocity images and are supported by the traveltime data.

Seismic Line 9

Line 9 crosses the valley of Red River just upstream from the confluence of Straight Creek with the Red River (fig. 4). Travel-time curves show the predominant use of buried charges; only nine hammer locations, all near the highway, were used (fig. 11*A*). The curves also show good slope breaks in bedrock velocity, even in some curves generated by hammer shots. The images for this line are strongly supported by clean, dense data.

The final velocity images and interpretation (fig. 11*B*) show an asymmetric valley with a long, smooth slope on the north and a steeper, shorter slope on the south. The Red River at this point is at the southernmost edge of the valley, but the deepest bedrock surface lies to the north, toward the center of the line. The water table appears to be at its highest elevation just south of the valley center, above the deepest surface of bedrock.

Before acquisition and interpretation of the seismic data presented here, the subsurface nature of the bedrock interface was the subject of speculation. Three simple models of the cross-sectional shape of the valley—which thus constrain alluvium volumes—had been proposed: (1) the exposed valley walls extend downward without a change in slope and produce a V-shaped valley containing a minimal volume of alluvium, (2) the bedrock walls extend downward vertically to some fixed, flat, bedrock depth and produce a rectangular-shaped valley containing a maximal volume, and (3) the bedrock walls extended downward with slopes of about 30° dip to a flat bottom producing a trapezoidal valley shape containing an intermediate volume. Vincent described the geomorphology of the area and supported the trapezoidal model (Vincent, in press). Our seismic data interpretations (for instance, fig. 11*B*) also support the trapezoidal model.

Estimating Volume of Alluvium

A U.S. Geological Survey digital elevation model (DEM) of this region and subsurface information derived from interpretations of the nine seismic lines were combined with surface interpolation and extrapolation to estimate, for the model area, three-dimensional volumes of dry and wet alluvium above bedrock. Publicly available elevation values for the model area exist on a 10-m grid; a rectangular portion of that grid of elevation values was taken from the 7.5 minute Red River DEM (fig. 12). For each seismic line grid point, seismic data provide the surface elevation and the subsurface elevations of water table and the top of bedrock.

The area used for volume analysis is in Universal Transverse Mercator (UTM) zone 13 North, which is bounded by east and west X coordinates of 460140 and 460740 m, respectively, and by south and north coordinates of 4062150 and 4063250 m, respectively. The horizontal grid is based on the North American Datum of 1927 (NAD27), and the elevations are based on the National Geodetic Vertical Datum of 1929 (NGVD29). The area is 600 m across (east-west) and 1,100 m long (north-south), or 0.66 km^2, and it contains the Straight Creek drainage and a portion of the valley of the Red River (fig. 12).

Topography on the alluvium has gentler gradients in general than the steep slopes of the exposed bedrock mountains. This slope difference and field observations were used to determine the approximate boundary between alluvium and bedrock at the surface in this area. Marking that boundary allowed us to separate the original DEM topography for the region into elevation values of exposed bedrock (on the slopes and high-elevation areas) and elevation values of alluvium (in the drainages). Surface elevation values for the area underlain by surface alluvium were blanked in the study-area grid, thus graphically removing the alluvium. For seismic line grid

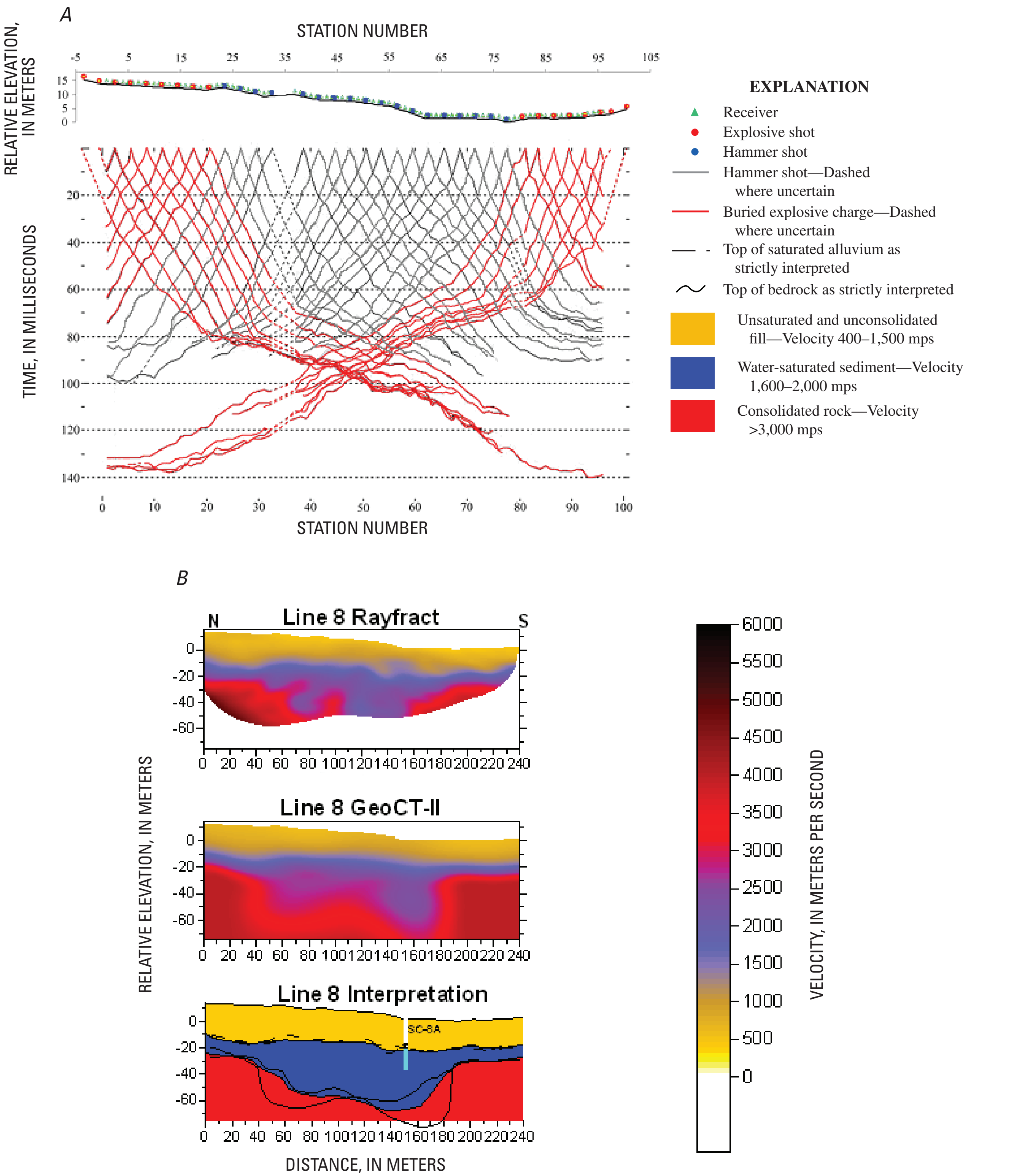

Figure 10. Seismic line 8. *A*, Locations of sources and receivers on topographic profile and first-arrival travel-time curves. Station interval 2.5 m; total line length about 240 m. Hammer-source curves do not change slope (which would indicate bedrock velocity) in the central part of the line. *B*, Final velocity images and interpretation. Depth to bedrock in central part of the line is not well determined but is 50–70 m below elevation of river surface. Water-table mound and bedrock benches supported by travel-time data. All three images at same scale (1 in. = 110 m) and without vertical exaggeration.

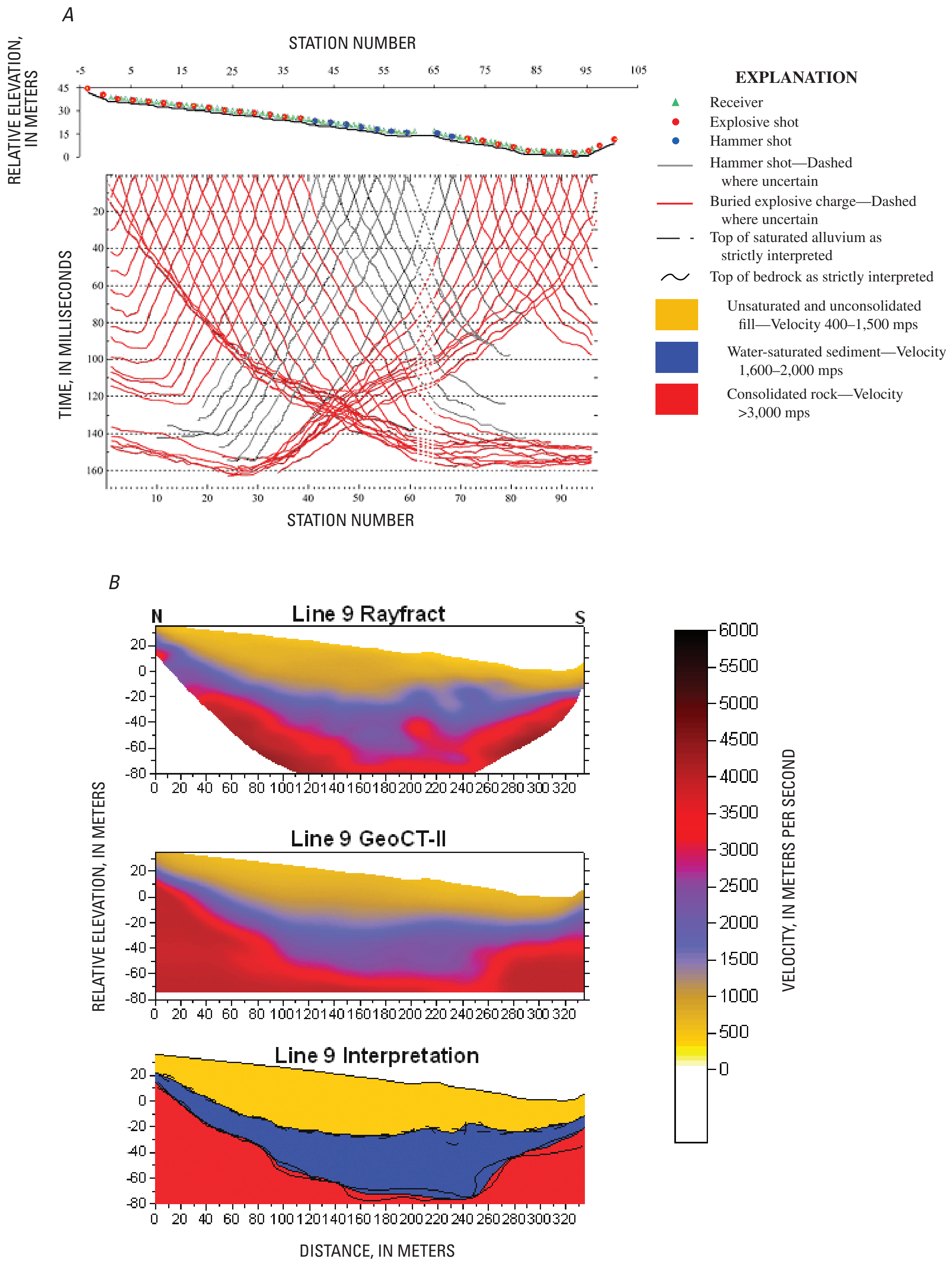

Figure 11. Seismic line 9. *A*, Locations of sources and receivers on topographic profile and first-arrival travel-time curves. Station interval 3 m; total length of line about 335 m. Coverage and data quality are very good. *B*, Final velocity images and interpretation. All three images at same scale (1 in. = 122 m) and without vertical exaggeration.

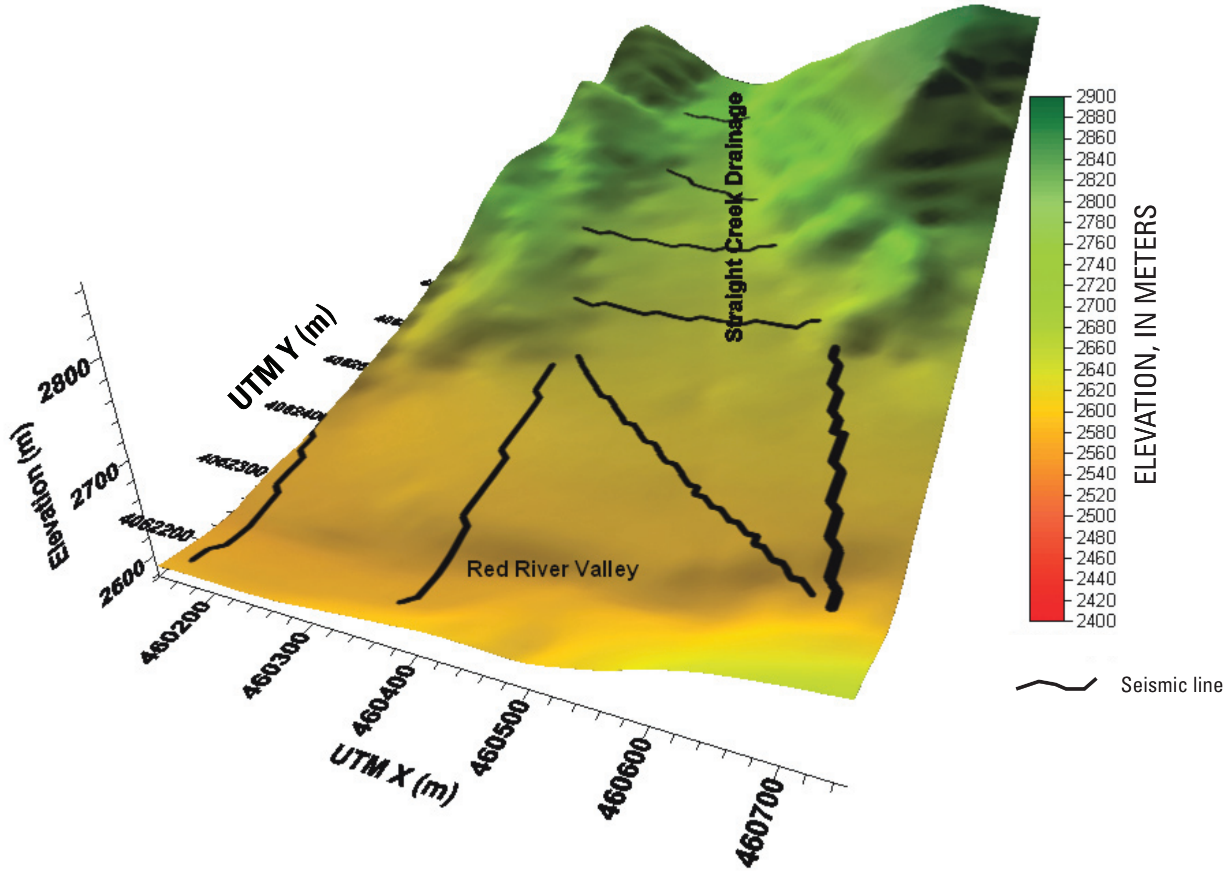

Figure 12. Configuration of absolute surface elevation values (relative to NGVD29) near confluence of Straight Creek and Red River. Generated from a U.S. Geological Survey digital elevation model that provides surface elevations on a 10×10 m XY (NAD27) grid. Seismic line locations cast to nearest 10-m-grid locations.

points, new elevations of bedrock below the alluvium were inserted from the seismic interpretations. The resulting grid contains bedrock elevation values for exposed bedrock slopes and for the seismic-line grid points. A surface interpolation and extrapolation routine was used to fill in bedrock elevations at the missing points between the lines to create a bedrock model (fig. 13).

With the same procedure, but using the elevations of the water table (instead of elevations of bedrock) obtained from interpretations of the seismic data, we created another model of the area with the dry alluvium stripped away (fig 14). In this case, the surface mapped in the valleys is the top of saturated alluvium (that is, the water table). Three grids of surface elevation values were produced by this process. They are (1) the original topographic DEM (fig. 12), (2) the surface-elevation model of the top of bedrock exposed on the slopes and buried in the valleys (fig. 13) throughout the grid area, and (3) the elevations of exposed bedrock slopes and the water table in the valleys (fig. 14). The grid was divided into a Straight Creek drainage portion and a Red River valley portion. Simple grid subtraction and volume analysis was performed to calculate the approximate volumes of dry and wet alluvium in the Straight Creek drainage and the valley of Red River (fig. 15). Because only selected segments of both the Straight Creek drainage and the valley of Red River (those within the grid shown in the figures) were analyzed, the absolute volume values in cubic meters are not as meaningful as the percentages of wet and dry material in each drainage. In the Straight Creek drainage, only 18 percent of the alluvium is saturated. In the valley of Red River, 51 percent of the alluvium is saturated. This information, along with the geometry of the bedrock and water-table surfaces, can be used to help ground-water modelers provide a more realistic understanding of subsurface flows in this area.

Conclusions

We used seismic refraction tomography in the study area to determine accurate depth to water table and bedrock across the Straight Creek and Red River drainages. In so doing, we

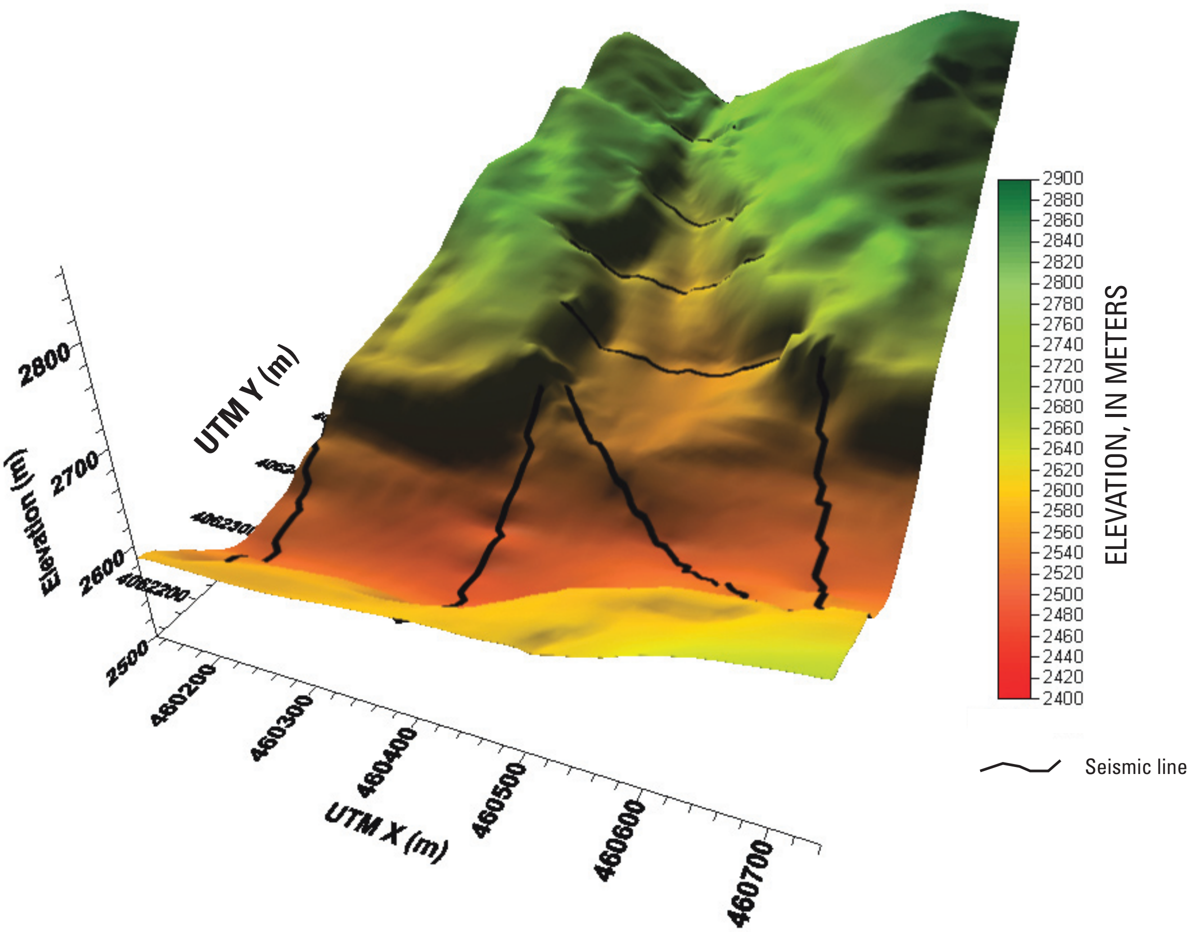

Figure 13. Configuration of top of bedrock near confluence of Straight Creek and Red River. Generated from surface-elevation values shown in figure 12 and bedrock elevation values determined from seismic lines by graphical removal of alluvium and interpolation of the bedrock surface. Seismic line locations cast to the nearest 10-m-grid locations.

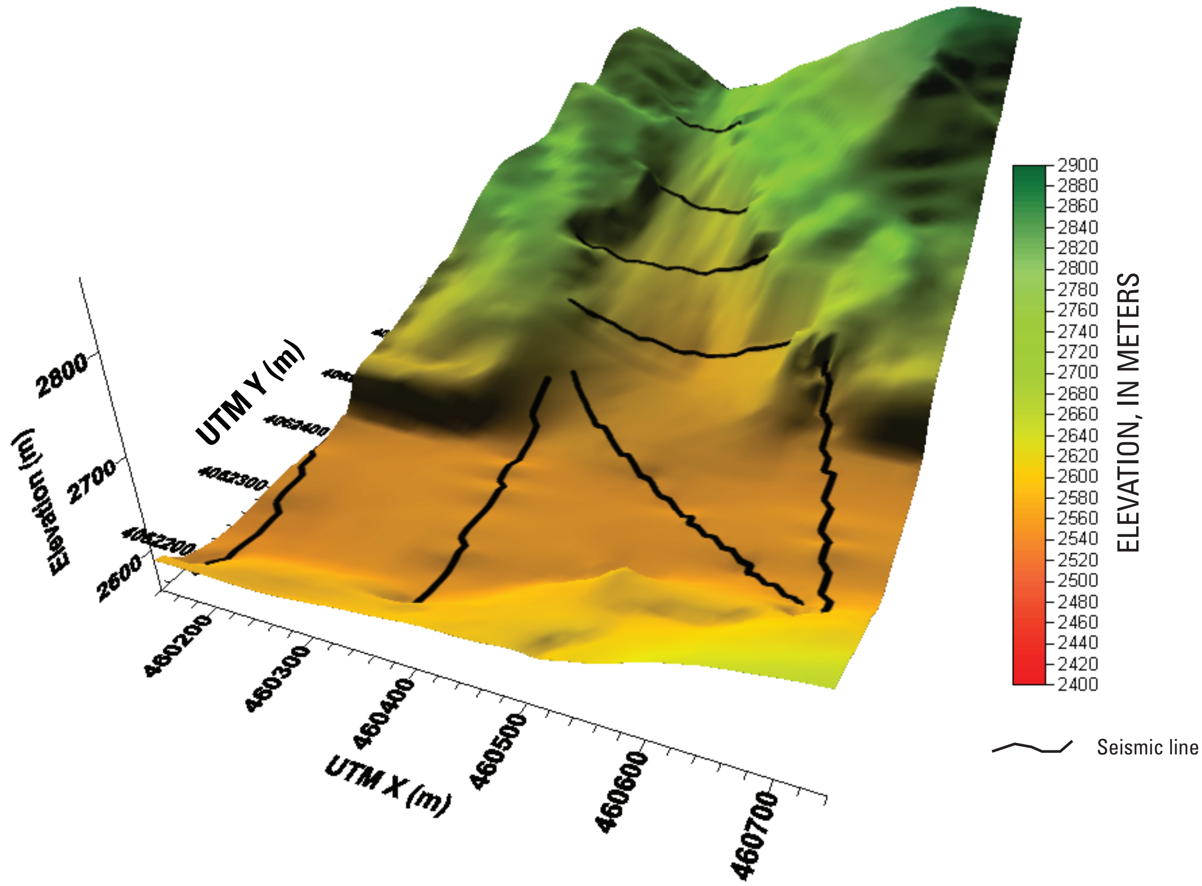

Figure 14. Configuration of water table near confluence of Straight Creek and Red River. Generated from surface-elevation values shown in figure 12 and from depth to the water table, defined by interpretation of seismic data. Dry alluvium graphically removed to reveal the water table. Seismic line locations cast to the nearest 10-m-grid locations.

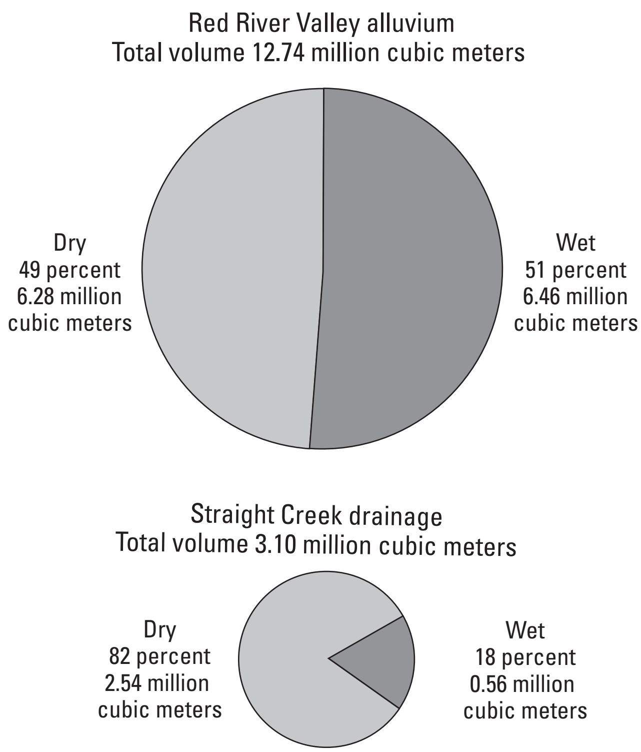

Figure 15. Proportions of wet and dry alluvium in valley of Red River and in Straight Creek drainage. Volumes of wet and dry alluvium computed by use of grid mathematics on surface elevations obtained from seismic data and then converted to more useful percentages.

determined that a shot-location spacing of three times the receiver spacing was the best choice for producing accurate, cost-effective images in this area. A hand-held, 9-kg hammer source produced clear first-arrival energy to distances of 35–200 m, depending on noise conditions and near-surface properties. The hammer was more effective in this study area than buried shell casings that contained black powder, which were time consuming to deploy and provided weak first-arrival energy. A combination of ⅓ lb buried explosive charges for larger offset shots (>180 m) and the safe, portable, cost-effective sledgehammer for smaller offset shots produced good coverage and high-quality seismic refraction data.

Images generated by two commercial refraction tomography software packages differed in consistency. We used the inconsistent results, along with travel-time curves displaying density and quality of data, as indicators of uncertainty. This approach led to interpretations that are reasonable geologically (Vincent, in press) and are a good match with the limited borehole control. In general our interpretations support a trapezoidal model, rather than a rec-tangular or V-shaped model, of surface-of-bedrock geometry in the study area.

By using seismic lines spaced no more than a few hundred meters apart, we were able to interpolate buried bedrock and water-table interfaces to determine their respective geometries throughout the model area. Using these geometries, we estimated the volume of wet and dry alluvium in the drainages. When combined with average ground-water velocity values, the information we present here can be used to determine the discharge of the Straight Creek into the Red River relative to the total discharge of the Red River moving past the mouth of Straight Creek. Alluvium in the Straight Creek drainage area within our model area is only 18 percent water saturated; alluvium within the Red River valley portion of the model area is 51 percent saturated.

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