Assessment of the Alluvial Sediments in the Big Thompson River Valley, Colorado

By Adrienne Barnett *and* Karl J. Ellefsen

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Abstract

To obtain subsurface geologic information about the alluvium in the Big Thompson River valley, *S*-wave refraction data were collected along three roads that cross the valley. The traveltimes were processed to estimate velocities and thicknesses for a layered-earth model; from these models, three cross sections of the river valley were constructed. The river valleys are covered by a layer of soil, which is 0.2 to 1.5 m thick. Beneath the soil, there is one layer of alluvium at some locations and two layers at other locations. For the two westernmost cross sections, the total thickness of the alluvium ranges from about 6 to 10 m near the center of the valley and from about 2 to 6 m near the sides of the valley. The easternmost cross section is somewhat more complex than the other two, because it is near the confluence of the Big Thompson and the Little Thompson Rivers. In this cross section, the thickness of the alluvium ranges from about 8 to 10 m in the southern half of the valley and from about 3 to 13 m in the northern half. In all three cross sections, the alluvium overlies bedrock, which is the upper transition member of the Pierre Shale.

Introduction

The USGS Front Range Infrastructure Resources Project is designed to provide geologic, hydrologic, and geographic information to cities and towns in the Front Range Urban Corridor of Colorado. Because ground water and aggregate are so economically important to these communities, one part of the project involves evaluating these resources. Aggregate is defined as crushed stone, sand, and gravel that is used to construct homes, dams, highways, and so on (Langer and Glanzman, 1993, p 1).

The Big Thompson River valley is close to three cities in the Front Range Urban Corridor: Loveland, Longmont, and Greeley. Because of large size of the valley, it could be a significant resource of both ground water and aggregate to these cities. Consequently, the geology of the valley was investigated as part of the current project.

Geologic information was obtained with a seismic (*S*-wave) refraction survey because there are not enough significant exposures of the alluvial sediments, from which inferences about the entire river valley could be made. Data were collected along three roads that cross the Big Thompson River valley (pl. 1): (1) County Road 3 1300 S, which is about 7 km northwest of Johnstown; (2) County Road 13, which is about 5 km northwest of Johnstown; and (3) County Road 21 and State Highway 257, which are near Milliken. These three roads are referred to as CR 3, CR 13, and CR 21, respectively, in the rest of this report.

This report describes the collection of the seismic data, its processing, and its interpretation. The results show the thickness and the gross stratigraphy of the alluvial sediments, both of which are needed to evaluate the ground water and the aggregate resources. On the CD-ROM are the field data, software for viewing the field data, and a file called README.TXT; this file contains information on executing the software and on the format of the field data.

Geology and Field Conditions

The sediments in the Big Thompson River valley were eroded from Front Range bedrock, which crops out about 20 km west of the study area; during the Quaternary Period, the sediments were carried downstream and deposited in the valley. Throughout the valley, the sediments are overlain by soil.

The following description of the Quaternary sediments in the Big Thompson River valley is from Colton (1978). The post-Piney Creek alluvium is crossed by CR 3, CR 13 and CR 21 (pl. 1). This alluvium is about 2 to 5 m thick and consists mostly of sand and gravel with some small lenses of clay and silt (fig. 1). In the large river valleys of the Front Range, the post-Piney Creek alluvium is underlain by an older gravel alluvium; it is not known if this older alluvium is in the Big Thompson River valley. The Piney Creek alluvium is crossed by CR 21 (pl. 1). This alluvium is about 0 to 6 m thick and consists mostly of sand and gravel; it also includes organic matter and a weakly developed soil at its top. Near the edges of the river valley, the Piney Creek alluvium grades into colluvium. The Broadway Alluvium is crossed by CR 13 and CR 21 (pl. 1). This alluvium is about 3 to 5 m thick and consists mostly of sand and gravel; it also has a weakly developed soil at its top. The Broadway alluvium is found on the upper terraces of the river valley.

In the study area (pl. 1), the bedrock is the upper transition member of the Pierre Shale (Scott and Cobban, 1965). Its name is derived from its stratigraphy: the sedimentary beds are a transition from the underlying Pierre Shale to the overlying Fox Hills Sandstone. The beds are composed of friable sandstone and soft, shaly sandstone. The formation is about 600 m thick and dips between 1° and 4° to the east and southeast.

Roads CR 3, CR 13, and most of CR 21 border fields used for crops and pasture, and along CR 13 and CR 21 some fields are fenced making access somewhat difficult. Roads CR 3 and CR 13 had little traffic, and consequently there was little ambient noise in the seismograms. In contrast, CR 21 north of Highway 60 had a great deal of traffic, especially large trucks. In addition, trains occasionally traveled on two railroad tracks,

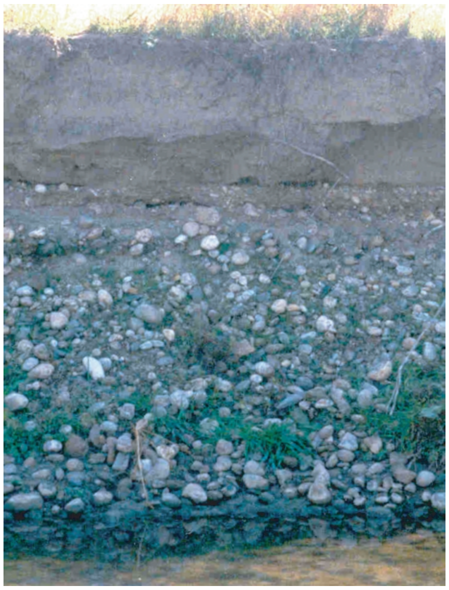


Figure 1. Exposure showing the soil and the underlying post-Piney Creek alluvium. This exposure is along the bank of the Big Thompson River near cross section *B-B′*.

which crossed CR 21. East of CR 21, heavy machinery was being used to construct new houses. Consequently, there was a great deal of ambient noise.

S-wave Refraction Method

General Description

The most common refraction method, *P*-wave refraction, was tested in the Big Thompson River valley. Although refracted *P*-waves from the water table were recorded, refracted *P*-waves from the bedrock were not (see the Appendix). Without the waves from the bedrock, the depth to the bedrock cannot be estimated; thus, *P*-wave refraction was unsuitable for this survey. Instead, *S*-wave refraction was used, and the method is briefly described here, as it is somewhat uncommon.

The seismic source, which was invented by Hasbrouck (1983), weighs about 36 kg and is about 0.3 m wide and 0.6 m long (fig. 2*A* . It has 8 spikes on its bottom that couple it to the ground; because of these spikes, the source is nicknamed the golf shoe. When the golf shoe is struck by a sledgehammer, it generates horizontally polarized *S*-waves (as well as other types of seismic waves). During a field test of various *S*-wave sources, the *S*-waves generated by the golf shoe had higher amplitudes than those generated by most other sources (Miller and others, 1992).

For field conditions like those in the Big Thompson River valley, the golf shoe generates high-amplitude S_h-waves that propagate perpendicular to the direction of the sledgehammer strike (Kähler and Meissner, 1983). In this propagation direction, 24 geophones are laid out along a line (fig. 2*B*). The geophones detect the horizontal component of particle velocity and, hence, the S_h-waves. The voltages generated by the geophones are recorded by an ES-2401 Exploration Seismograph (EG&G Geometrics, 1992).

Each side of the golf shoe is usually struck about 5 times with the sledgehammer, and the seismograms from each strike are added together by the seismograph. This technique, which is called vertical stacking, minimizes the random noise in the seismograms. If there is significant ambient noise when the data are collected, each side of the golf shoe is struck about 9 or 10 times. All strikes on one side of the golf shoe constitute one shot. There are usually two shots at each location of the golf shoe. For one shot, the golf shoe is struck on one side; for the other shot, the golf shoe is struck on the other side (fig. 2*A*). The two shots generate waves with opposite polarities, and this difference helps with the identification of the various waves in the seismograms (Hasbrouck, 1987). The two shots are often called a shot pair.

The layout of the shot pairs and the geophones is defined as the spread. If any refractor has significant dip (that is, greater than about 5°), a shot pair is needed at each end of the spread to determine the dip. Where a refractor is deep compared to the length of the spread, few waves from this refractor, if any, are recorded. In this case, additional shot pairs are added at both ends of the spread; the chosen locations depend upon the field conditions.

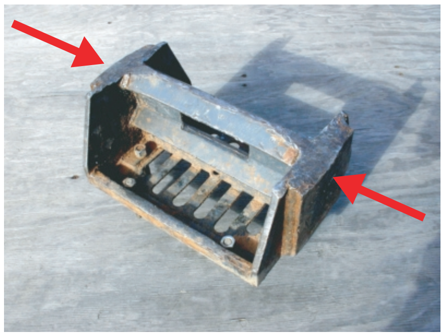
Data Collection

For many seismic refraction surveys, data are collected along a straight, continuous profile (see, for example, Telford and others, 1976, p. 363–366). However, in this investigation continuous profiles were not used for the following reasons: (1) All of the county roads border fields with crops, some of which have fences. If continuous profiles were used, some crops and some fences would have been destroyed. (2) In the South Platte River valley and other river valleys of the Front Range, the topography of the bedrock changes gradually (Smith and others, 1964). Consequently, in the Big Thompson River valley, the topography is assumed to change gradually. In this case, the numerous estimates of the depth to bedrock that would be obtained with a continuous profile would be redundant. (3) The buildings, the roads, and the railroad tracks near CR 21 make it impossible to layout a straight, continuous profile.

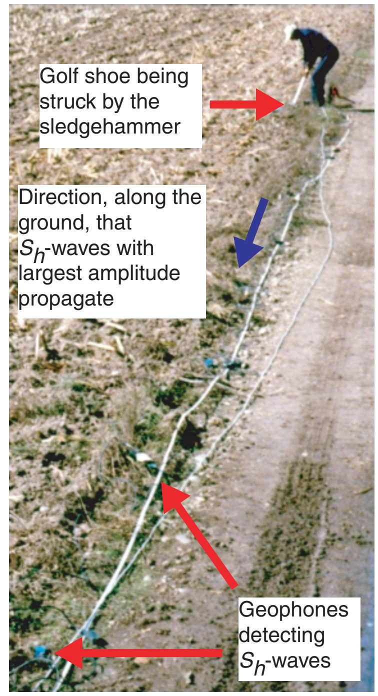
Because a continuous profile would cause so many problems, the seismic data were collected with single spreads that were located either in or alongside fields. After permission was obtained from the landowners, the spreads were laid out to avoid damaging the crops, the fences, and so on. Generally, the chosen locations were well suited for data collection for the following reasons: (1) The elevation changes along the spreads were almost zero. (2) The areas around the spreads were clear of obstacles and large vegetation.

The spreads were generally 200 to 400 m apart. There were 7 spreads along CR 3, 6 along CR 13, and 9 along CR 21 (pl. 1). The spreads are numbered from south to north; each number has the prefix A, B, or C corresponding to CR 3, CR 13, and CR 21, respectively. Along CR 21, the spreads were 0.1 to 0.3 km from the road to minimize the ambient noise from the traffic.

Figure 2. *A,* The seismic source, nicknamed the golf shoe, used to generate the S_h-waves. Red arrows indicate where the golf shoe is struck by the sledgehammer. *B,* The spread used to collect *S*-wave refraction data. Note that the direction in which the golf shoe is struck is perpendicular to the line of geophones



A



B

To record the seismograms for each spread, the seismograph digitized the analog voltages using a 15 bit converter. The sample interval for the digitization was 0.1 ms, which was small enough to record the seismograms with high fidelity. The Nyquist frequency corresponding to this sample interval was 5 kHz; because the frequencies of the recorded seismic waves were less than about 160 Hz, there was no aliasing. Some high frequency noise was removed with a high-cut filter set to 250 Hz. The recording times of the seismograms were 204.8, 307.2, or 409.6 ms; for each spread the recording time was chosen to make the refracted *S*-waves appear in about the middle of the seismograms.

For each spread, several test shots were made to determine both a suitable spacing between the geophones and a suitable spread length. Figure 3 shows a typical spread and the seismograms from a shot pair. Because the geophones in the spread are close together, the direct and the refracted *S*-waves are densely sampled. Consequently, there are many traveltimes for estimating layer thicknesses and velocities. Furthermore, the velocity of the refracted *S*-wave is about 1000 m/s, which is typical of bedrock in this area. Thus, the spread is long enough to record the refracted *S*-wave from the deepest layer that is important to the investigation.

Data Processing

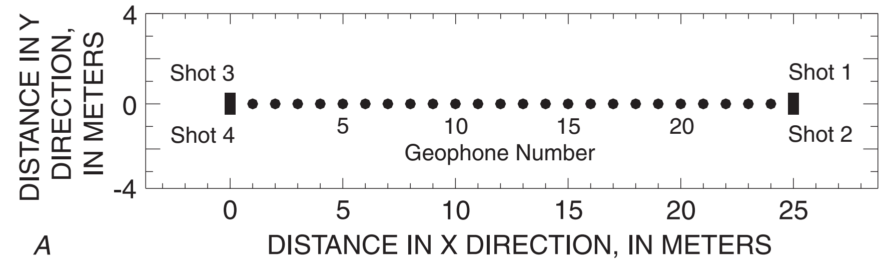
The data processing consisted of three steps. First, the data files were converted from SEG-2 format (Subcommittee of the SEG Engineering and Groundwater Geophysics Committee, 1990) to SU format (Cohen and Stockwell, 1999). Second, the initial traveltimes of the direct and the refracted *S*-waves were picked using program "pick_sw" (Ellefsen, 2000). Third, the traveltimes were processed with a commercial computer program, the "Seismic Refraction Interpretation Program" (Rimrock Geophysics Inc., 1995). For this program, the ground is represented by homogeneous, isotropic layers; the interfaces between the layers may be curved. The program estimates the velocities and the thicknesses of the layers. For this survey, the curvatures of the interfaces are small over the length of each spread, and so the curvatures are ignored.

The estimated velocities and thicknesses for all spreads are listed in table 1. In this report, the velocities and the thicknesses that are estimated for one spread are called a velocity profile. The profiles have either three or four layers. For those profiles with three layers, the middle layer is referred to as simply Middle Layer. For those profiles with four layers, the two middle layers are referred to as Upper Middle Layer and Lower Middle Layer. All velocities are rounded to two significant digits. All thicknesses are rounded to two significant digits, except those less than 1.0 m, which are rounded to the nearest 0.1 m. The velocity profile for each spread is plotted in plate 2.

Interpretation

Interpretation of the Velocity Profiles

The distributions of both the velocities and the thicknesses from the profiles (table 1, pl. 2) are shown with dot plots (Swan and Sandilands, 1995), and a typical example is shown in figure 4*A*. This plot indicates that there are 4 velocities between 50 and 100 m/s, 17 velocities between 100 and 150 m/s, and 1 velocity between 150 and 200 m/s. Thus, a dot plot is like a histogram, except that the dot plot shows the data points. Each dot plot is characterized by a range, a median, a mean, and a standard deviation, all of which are rounded to two significant digits. Both the dot plots and the statistical measures show trends that



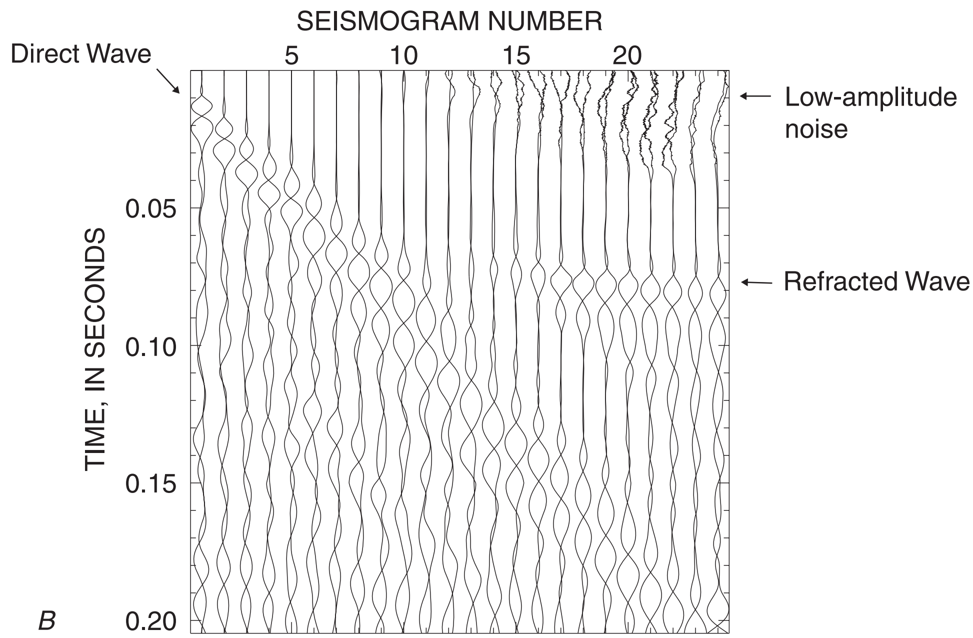


Figure 3. *A,* Map showing the layout of spread A7. *B,* Seismograms from shots 3 and 4 in the spread. The seismogram numbers correspond to the geophone numbers. The amplitudes have been adjusted using automatic gain control with a window of 0.08 s. This adjustment boosts some low-amplitude noise in seismograms 12 through 24, and it diminishes the amplitude of the refracted wave in seismograms 12 through 15.

help with the interpretation of the velocity profiles and with the construction of the cross sections.

For the top layers in the profiles, all velocities are between 80 and 150 m/s; both the median and the mean are 110 m/s (fig. 4*A*). This range in velocities is similar to that for soil or loam (Kudo and Shima, 1981; Suyama and others, 1986). All thicknesses are between 0.2 and 1.5 m; both the median and the mean are 0.6 m (fig. 4*B*). This range is consistent with the observed thickness of the soil that is exposed along river banks (fig. 1). Furthermore, the *S*-wave data were collected in fields and pastures covered with soil. For these reasons, the top layers in all velocity profiles are interpreted as being soil.

In the velocity profiles with three layers, the velocities of the middle layers range from 140 to 250 m/s (fig. 5*A*). The median is 180 m/s, and the mean is 190 m/s. In the profiles with four layers, the velocities of the upper middle layers range from 100 to 260 m/s (fig. 5*B*). Both the median and the mean are 160 m/s. In other words, the velocities for the middle layers (in the three-layer profiles) and upper middle layers (in the four-layer profiles) are similar; they cannot be distinguished on the basis of *S*-wave velocity. These velocities are typical of clays, sands, and gravels that are unconsolidated and are near the ground surface (Kudo and Shima, 1981; Meissner and others, 1985; Suyama and others, 1986). Moreover, such sediments are exposed along the river banks (fig. 1) and in local quarry pits. Thus, these layers in the velocity profiles are interpreted as being alluvium and are called alluvium with low *S*-wave velocity.

In the velocity profiles with four layers, the velocities of the lower middle layers range from 240 to 530 m/s (fig. 5*C*). The median is 420 m/s, and the mean is 400 m/s. These velocities are typical of alluvial and diluvial clays, sands, and gravels that are unconsolidated and are near the ground surface (Kudo and Shima, 1981; Meissner and others, 1985; Suyama and others, 1986); thus, these layers are interpreted as being alluvium. Because the velocities for these layers are high compared to those for the other alluvium (fig. 5*A*, *B*), these layers are called alluvium with high *S*-wave velocity.

Along cross sections *A*-*A*′ and *B*-*B*′, the velocities of the bottom layers in the profiles range from 910 to 1400 m/s; both the median and the mean are 1100 m/s (fig. 6*A*). Along cross section *C*-*C*′, the velocities of the bottom layers range from 560 to 1000 m/s; both the median and the mean are 830 m/s (fig. 6*B*). Both sets of velocities are much higher than typical velocities for unconsolidated sediments that are near the ground surface (Kudo and Shima, 1981; Meissner and others, 1985; Suyama and others, 1986). Thus, the bottom layers are interpreted as being

Table 1. Velocities and thicknesses estimated from the *S*-wave refraction data, which were collected in the Big Thompson River valley, Colorado.

[The velocity profiles have either three or four layers. For those with three layers (for example, A1), the table entry with the leaders (---) pertains to a four layer profile. Conversely, for those with four layers (for example, A2), the table entry with the leaders (---) pertains to a three layer profile. The velocities and thicknesses are plotted in pl. 2.]

	Velocity (m/s)					Thickness (m)			
Spread Name	Top Layer	Middle Layer of 3-Layer Velocity Profile	Upper Middle Layer of 4-Layer Velocity Profile	Lower Middle Layer of 4-Layer Velocity Profile	Bottom Layer	Top Layer	Middle Layer of 3-Layer Velocity Profile	Upper Middle Layer of 4-Layer Velocity Profile	Lower Middle Layer of 4-Layer Velocity Profile
A1	140	170	---	---	1100	0.6	7.0	---	---
A2	90	---	120	340	1100	0.3	---	2.3	6.6
A3	100	---	160	460	1400	0.6	---	2.6	7.9
A4	90	---	200	490	1100	0.6	---	2.8	5.6
A5	100	---	130	450	1100	0.4	---	2.4	5.5
A6	80	---	120	320	1200	0.3	---	2.2	5.6
A7	110	160	---	---	1000	0.4	3.7	---	---
B1	150	250	---	---	1100	1.0	7.6	---	---
B2	100	---	160	460	910	0.4	---	2.9	7.5
B3	130	---	190	530	910	0.5	---	3.3	4.9
B4	120	---	160	500	1100	0.2	---	3.8	7.7
B5	80	---	100	340	1200	0.2	---	2.0	3.9
B6	110	160	---	---	910	0.2	5.0	---	---
C1	130	250	---	---	780	1.2	9.0	---	---
C2	120	220	---	---	820	0.9	8.2	---	---
C3	100	---	160	350	850	1.5	---	2.3	7.1
C4	130	---	190	390	830	0.7	---	2.7	6.2
C5	110	180	---	---	1000	0.8	10.	---	---
C6	130	---	260	470	800	0.9	---	2.1	4.8
C7	140	---	190	320	970	0.4	---	3.8	9.6
C8	100	---	160	330	840	0.8	---	2.7	6.6
C9	110	140	---	---	560	0.3	2.8	---	---

bedrock. The bedrock in this area is friable sandstone and soft, shaly sandstone; measurements of *S*-wave velocity in such rocks were not found in any publications.

Construction of the Cross Sections

The interpreted velocity profiles were used to construct the cross sections. Consider, for example, the top layers in the velocity profiles in cross section *A-A′* (pl. 2). In between velocity profiles, the thickness of the top layer is unknown, and therefore it was estimated with interpolation. This procedure was used for all other layers. In some places, the alluvium with high *S*-wave velocity pinches out (for example, between profiles A1 and A2 (pl. 2)); such pinch outs are represented by jagged lines because their precise location is not known.

At three locations along cross section *A-A′* (pl. 2), the depths to bedrock, which were determined with drilling (Colton and Fitch, 1974), are about 1 to 2 m shallower than the depths estimated with the *S*-wave refraction data. The reason for the difference is interpreted to be weathering of the bedrock surface. If the weathered bedrock is thin and its velocity is lower than the velocity of the underlying, unweathered bedrock, then the presence of the weathered bedrock cannot be detected with *S*-wave

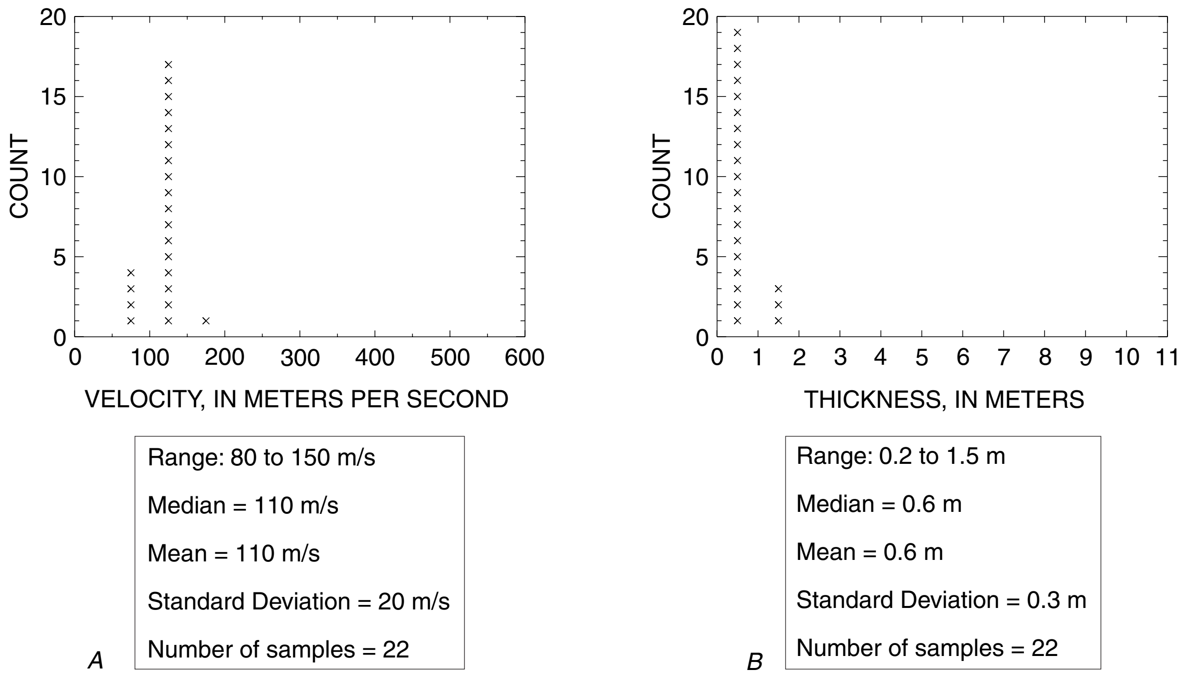


Figure 4. Dot plots and statistics of *A*, the velocities and *B*, the thicknesses for the top layers of the profiles. These layers are interpreted as soil. The velocities and the thicknesses are listed in table 1 and are plotted in plate 2.

refraction (Redpath, 1973, p. 19–23; Haeni, 1988, p. 13–16). Thus, a layer of weathered bedrock, which is 1 to 2 m thick, is included in cross section *A-A′* on the basis of the drill hole data.

The velocities of the bedrock in cross section *B-B′* are similar to those in cross section *A-A′*; furthermore, cross section *B-B′* is close to cross section *A-A′*. For these reasons, the lithology of the bedrock in both cross sections is assumed to be similar. Thus, cross section *B-B′* also includes a thin layer representing weathered bedrock.

Interpretation of Cross Sections *A-A′* and *B-B′*

Cross sections *A-A′* and *B-B′* (pl. 2) are geologically similar, and so they are interpreted together. The elevation of the bedrock (determined only by the velocity profiles) changes gradually along the cross sections (except between profiles B4 and B5). These gradual changes are consistent with the topography in the other river valleys of the Front Range Urban Corridor (Colton and Fitch, 1974). In both cross section, the elevation of the bedrock is lower in the middle of the valley (1461 to 1464 m in *A-A′* and 1454 to 1458 m in *B-B′*) than at the sides (1465 to 1467 m in *A-A′* and 1459 to 1463 m in *B-B′*). In both cross sections, the total thickness of the alluvium is about 6 to 10 m in the middle of the valley and about 2 to 6 m at the sides. (Precise thickness cannot be stated because the thickness of the weathered bedrock is not known.)

In all velocity profiles, the alluvium with low *S*-wave velocity is present. In the middle of the valley where it overlies the alluvium with high *S*-wave velocity, its thickness ranges from 2.0 to 3.8 m. Near the sides of the valley, the alluvium with low *S*-wave velocity constitutes all of the sediments; its thickness is roughly 5 m on the southern side and 2 to 3 m on the northern side. At all velocity profiles except B1, this alluvium is associated with the post-Piney Creek alluvium. All thicknesses estimated with the seismic data are consistent with thicknesses reported by Colton (1978).

The alluvium with high *S*-wave velocity is present only in the middle of the valley and is buried beneath the alluvium with low *S*-wave velocity. The alluvium with high *S*-wave velocity is about 2 to 6 m thick and is interpreted to be the older gravel alluvium beneath the post-Piney Creek alluvium.

Interpretation of Cross Section *C-C′*

At profile C1 in cross section *C-C′* (pl. 2), the elevation of the bedrock is 1450 m. The elevation generally decreases from C1 to C7 (except at C6) and increases from C7 to C9. Between profiles C1 and C5, the total thickness of the alluvium is somewhat uniform, ranging from 8.2 to 10 m. In contrast, between profiles C5 and C9, the total thickness is highly variable, ranging from 2.8 to 13.4 m.

In all velocity profiles, the alluvium with low *S*-wave velocity is present. In the middle of the valley where it overlies the alluvium with high *S*-wave velocity, its thickness ranges from 2.1 to 3.8 m. This range is consistent with the thicknesses for cross sections *A-A′* and *B-B′*. Near the sides of the valley, the alluvium with low *S*-wave velocity constitutes all of the sediments; it is about 9 m thick on the south side and 3 m on the north side. The alluvium with high *S*-wave velocity was deteced only at profiles C3, C4, C6, C7, and C8 and is 4.8 to 9.6 m thick. It is buried beneath the alluvium with low *S*-wave velocity.

Along cross section *C-C′* (pl. 1, 2), velocity profiles C1 through C4 are associated with the Broadway Alluvium, C5 with the Piney Creek Alluvium, C6 with the Broadway Alluvium, C7 with the Piney Creek Alluvium, C8 with the post-Piney Creek alluvium, and C9 with the Piney Creek Alluvium. Because of this complex order, associating these three alluviums with the alluviums with low and high *S*-wave velocities is difficult.

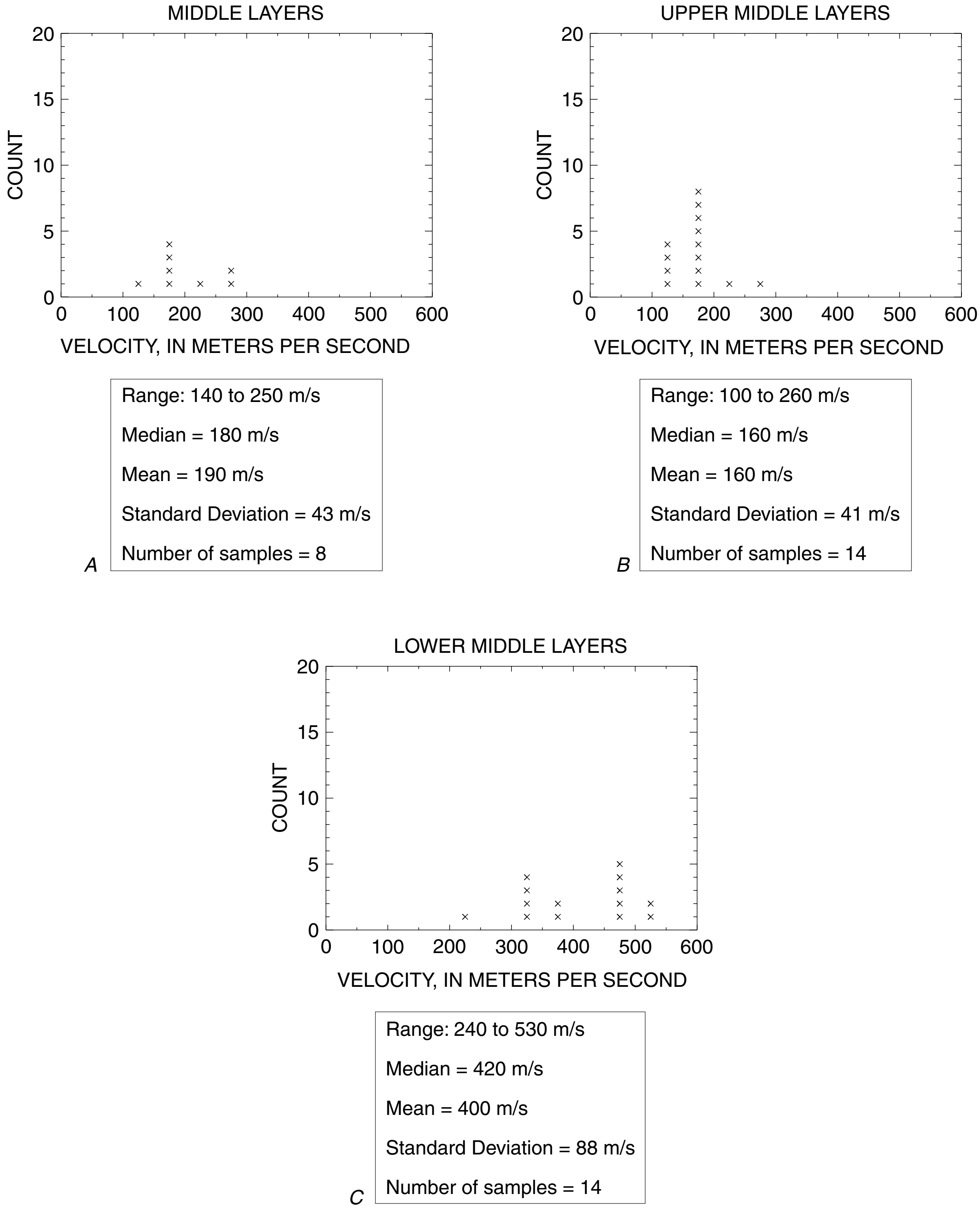


Figure 5. Dot plots and statistics of the velocities *A,* for the middle layers of those profiles with three layers, *B,* for the upper middle layers of those profiles with four layers, and *C,* for the lower middle layers of those profiles with four layers. These layers are interpreted as alluvium. The velocities are listed in table 1 and are plotted in plate 2.

Nonetheless, a few associations are straightforward for the alluvium with low S-wave velocity. At profiles C3, C4, and C6, it is associated with the Broadway Alluvium, and its thicknesses (2.3, 2.7, and 2.1 m, respectively) are only slightly less than the 3 to 5 m range reported by Colton (1978). At profiles C7 and C9, it is associated with the Piney Creek Alluvium, and its thicknesses (3.8 and 2.8 m, respectively) are within the 0 to 6 m range reported by Colton (1978). At profile C8, it is associated with the post-Piney Creek alluvium, and its thickness (3.8 m) is within the 2 to 5 m range reported by Colton (1978).

Additional Observations

While interpreting the velocity profiles and the cross sections, three additional observations regarding the sediments and the bedrock were made. Although these observations are

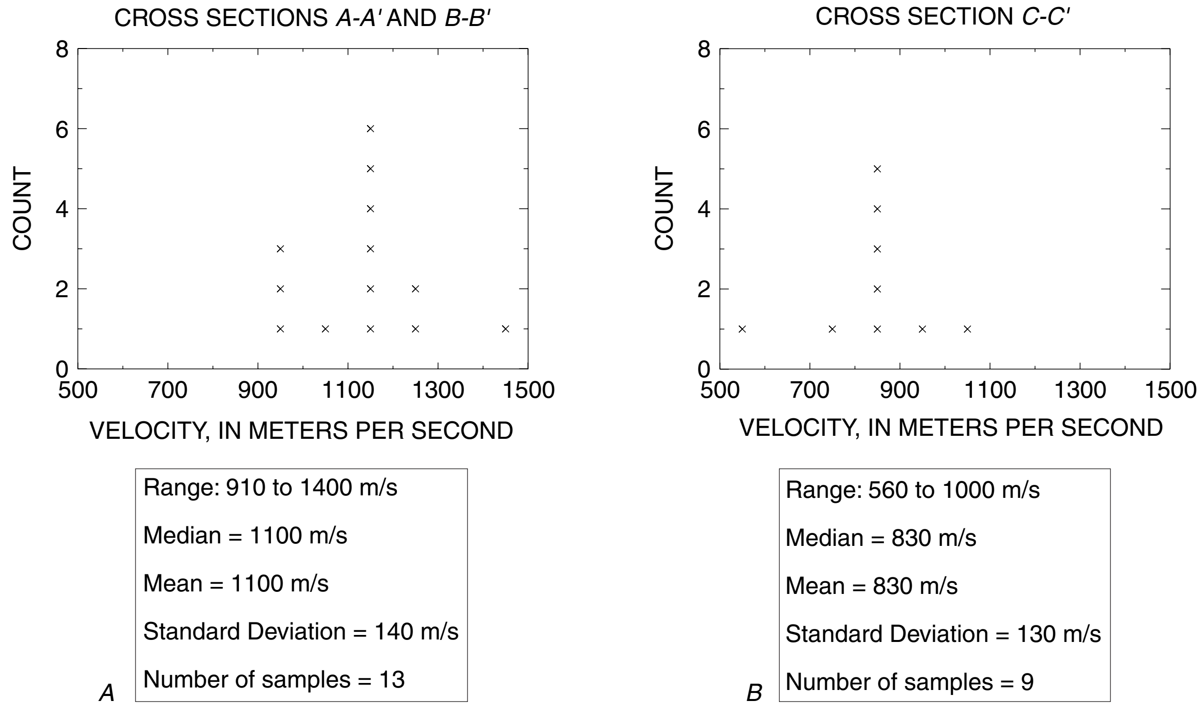


Figure 6. Dot plots and statistics of the velocities for the bottom layers along *A,* Cross sections *A-A′* and *B-B′* and *B,* Cross section *C-C′*. These layers are interpreted as bedrock. The velocities are listed in table 1 and are plotted in plate 2.

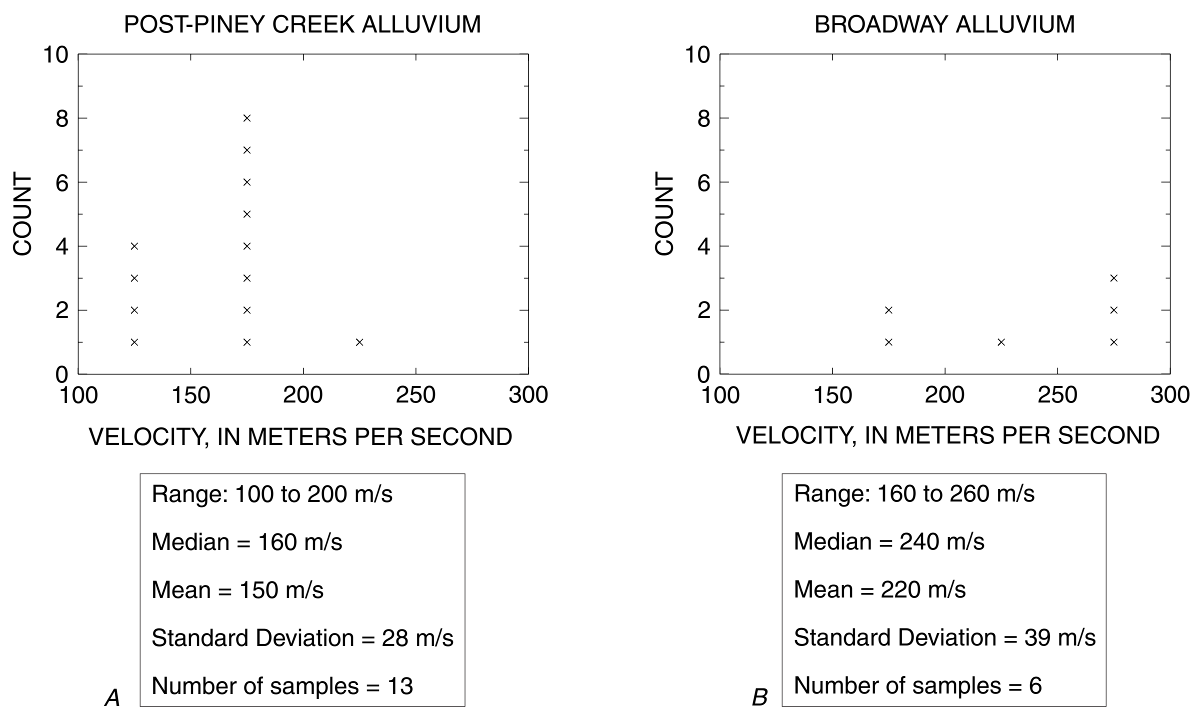


Figure 7. Dot plots and statistics of the velocities associated with *A,* the post-Piney Creek alluvium and *B,* the Broadway Alluvium. The velocities profiles associated with these two alluviums are shown in plate 2. The velocities are from the middle layers (for those profiles with three layers) and from the upper middle layers (for those profiles with four layers).

not especially useful for interpreting the cross sections, they may be helpful in future investigations. First, the range, the median, and the mean of the bedrock velocities for cross sections *A-A′* and *B-B′* are substantially higher than the corresponding quantities for cross section *C-C′* (fig. 6). The difference is interpreted as a change in lithology in the upper transition member of the Pierre Shale. Cross sections *A-A′* and *B-B′* are near the stratigraphic bottom of this formation, whereas cross section *C-C′* is near the stratigraphic top (pl. 1). Second, the range, the median, and the mean for the post-Piney

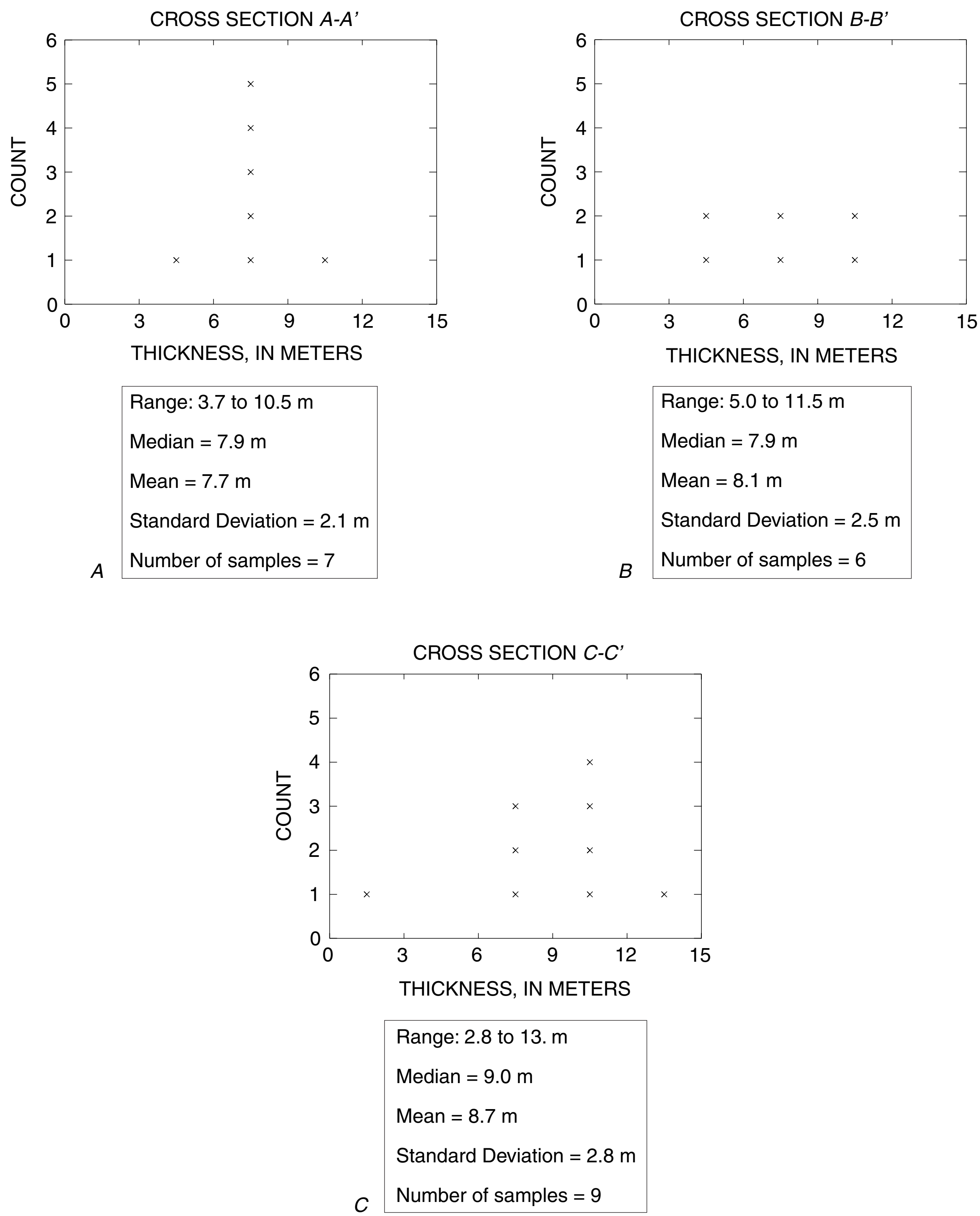


Figure 8. Dot plots and statistics of the alluvium thicknesses for *A,* cross section *A-A′*, *B,* cross section *B-B′*, and *C,* cross section *C-C′*. The thicknesses are listed in table 1 and are plotted in plate 2.

Creek alluvium are substantially lower than the corresponding quantities for the Broadway Alluvium (fig. 7). Thus, the type of alluvium affects the *S*-wave velocity. Third, in cross sections *A-A′*, *B-B′*, and *C-C′*, the mean thicknesses are 7.7, 8.1, and 8.7 m; the median thicknesses are 7.9, 7.9, and 9.0 m, respectively (fig. 8). Thus, the thickness increases about 1 m between cross sections *A-A′* and *C-C′*, which corresponds to the downstream direction of the Big Thompson River. The increase, however, is small compared to the standard deviations, which range from 2.1 to 2.8 m.

Conclusions

The velocity profiles, which were estimated with *S*-wave refraction data, have either three or four layers. The top layer always has velocities between 80 to 150 m/s and thicknesses between 0.2 and 1.5 m; this layer is interpreted as soil. The middle layers (in profiles with three layers) and the upper middle layers (in profiles with four layers) have velocities between 100 and 260 m/s; these are interpreted as alluvium and are called alluvium with low *S*-wave velocity. The lower middle layers (in profiles with four layers) have velocities between 240 and 530 m/s; these also are interpreted as alluvium but are called alluvium with high *S*-wave velocity. The bottom layers have velocities between 910 and 1400 m/s near cross sections *A-A′* and *B-B′* and between 560 and 1000 m/s near cross section *C-C′*. The bottom layers are interpreted as bedrock, which is the upper transition member of the Pierre Shale.

In cross section *A-A′* and *B-B′*, the alluvium with low *S*-wave velocity is associated with the post-Piney Creek alluvium (except at one location). The thickness ranges from about 2 to 5 m, which is consistent with measurements for the post-Piney Creek alluvium in other river valleys in the Front Range. The alluvium with high *S*-wave velocity ranges in thicknesses from about 2 to 6 m. It may be a gravel alluvium that, in other river valleys in the Front Range, is beneath the post-Piney Creek alluvium. The combined thickness of both alluviums ranges from about 6 to 10 m near the middle of the valley and from about 2 to 6 m near the sides of the valley.

In cross section *A-A′*, the depth to the bedrock determined from drilling is consistently about 1 or 2 m less than that determined from the refraction data. The likely reason for this discrepancy is that the top of the bedrock is weathered and consequently has a somewhat low velocity. The thickness of this thin, weathered zone cannot be determined from the refraction data but is estimated to be about 1 to 2 m.

In the southern half of the valley in cross section *C-C′*, the combined thickness of both alluviums ranges from 8.2 to 10 m ; in the northern half of the valley, the combined thickness of both alluviums ranges from 2.8 to 13.4 m. The stratigraphy in this cross section is somewhat complex because of its proximity to the confluence of the Big Thompson and Little Thompson Rivers.

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Appendix

The *P*-wave refraction method was tested to determine whether it would be suitable for a survey of the Big Thompson River valley. The test was conducted along CR 3 (pl. 1), where the bedrock is about 8 m below the surface, which was determined from drilling. The source was a metal plate lying on the ground, which was excited by striking it with a sledgehammer. The spread consisted of 24 geophones that measured the vertical component of particle velocity. The geophones were spaced 2 m apart; thus the spread length was 46 m, which was long compared to the bedrock depth. The seismograms were recorded by an ES-2401 exploration seismograph (EG&G Geometrics, 1992). When the source was 2, 50, and 98 m from the end of the spread, the seismograms included a direct *P*-wave and a high-amplitude, refracted *P*-wave from the water table. The seismograms, however, did not include a refracted *P*-wave from the bedrock, probably because the velocity contrast between the saturated sediments and the bedrock is too small.

Without a detectable refracted wave from the bedrock, the depth to the bedrock cannot be estimated. Thus, a significant goal of the seismic survey would not be attained, and so *P*-wave refraction was unsuitable for the survey of the Big Thompson River valley.