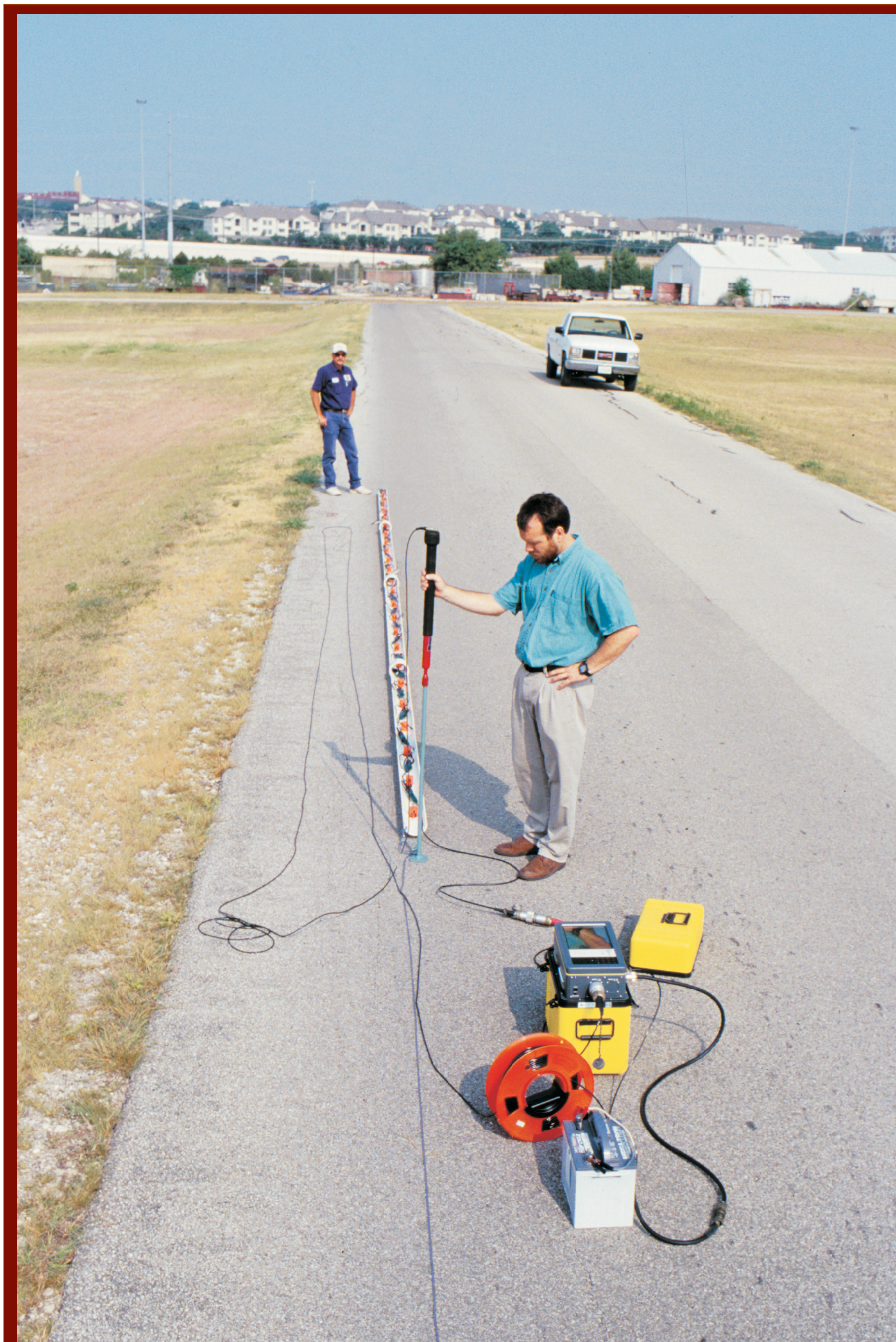

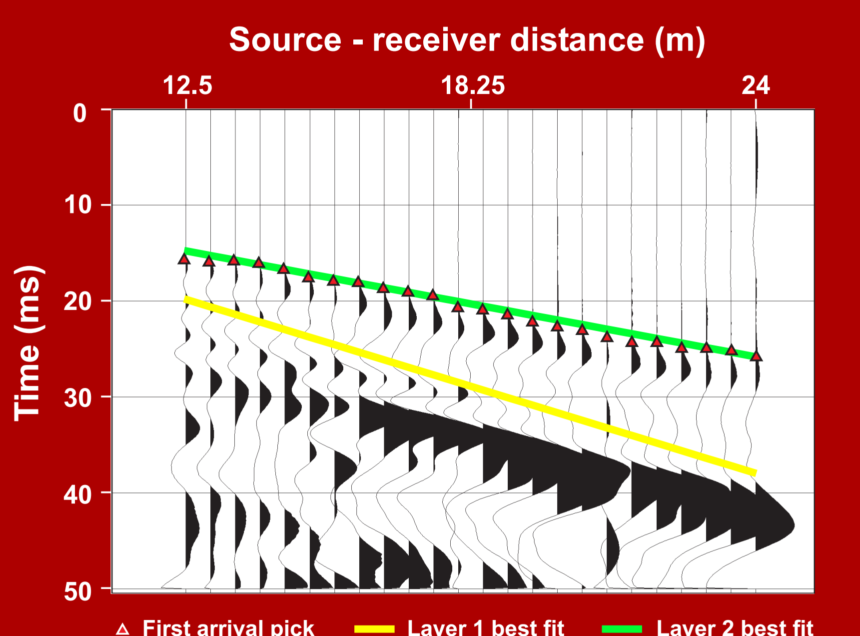

Bedrock Depth and Seismic Velocity Estimates at SRBA Training Sites in Comal, Hamilton, Pecos, Taylor, and Travis Counties, Texas

by
Jeffrey G. Paine

Bureau of Economic Geology
Scott W. Tinker, Director
John A. and Katherine G. Jackson
School of Geosciences
The University of Texas at Austin
Austin, Texas 78713-8924

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Jeffrey G. Paine

Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station, Box X
Austin, Texas 78713-8924
jeff.paine@beg.utexas.edu

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SUMMARY

During field training exercises for Texas Department of Transporation (TxDOT) staff, seismic refraction data were acquired at seven sites in six TxDOT districts using the prototype Seismic Refraction Bedrock Analyzer (SRBA). These data were acquired in a variety of settings that included bedrock depths ranging from a few tens of centimeters to more than 6 meters and bedrock types of sandstone, limestone, and mudstone. Analysis of the data acquired using the SRBA consisted of analyzing first seismic arrivals, attributing the arrivals to a direct wave traveling in the fill below the pavement and a more rapidly propagating wave that is critically refracted along the underlying bedrock surface, and creating seismic velocity models that match the observed first arrivals and allow seismic velocities and bedrock depths to be estimated.

SRBA data were acquired on U.S. 281 in the San Antonio district, I-10 in the Midland district, U.S. 84 in the Abilene district, U.S. 290 in the Austin district, U.S. 190 in the Brownwood district, and S.H. 36 in the Waco district. Compressional wave velocities measured in layer 1 and interpreted to represent compacted fill between pavement and bedrock ranged from 551 m/s to 1,117 m/s. Compressional wave velocities measured in layer 2 and interpreted to represent bedrock ranged from 1,079 m/s in sandstone to 2,964 m/s in limestone. Estimated depths to layer 2, interpreted to approximate bedrock depth, ranged from 0.33 m to 6.46 m. Depths to bedrock deeper than 6 m cannot be reliably estimated using the SRBA in its current configuration.

During the training exercises, the SRBA prototype proved to be easy to deploy, acquired data sufficient for shallow refraction analysis in a few minutes, and was used to produce reasonably accurate estimates of bedrock depth and seismic velocity in bedrock and overlying layers. Analysis of SRBA data is currently cumbersome, requiring first arrivals to be picked in one software package and then exported to another package for refraction analysis. Experience is required to pick first breaks reliably and thus obtain reasonable bedrock depth estimates. Near-term development of the SRBA prototype should include integration of first arrival picking and

refraction analysis. Longer term development might include full integration of data acquisition, first break picking, and refraction analysis in a custom software environment. These improvements would shorten the time required to estimate bedrock depth from an hour or more to near real-time.

INTRODUCTION

This report presents the results of field tests of the prototype Seismic Refraction Bedrock Analyzer (SRBA) carried out in six Texas Department of Transportation (TxDOT) districts (fig. 1) during SRBA training exercises for TxDOT staff. The prototype SRBA was constructed at the Bureau of Economic Geology (Bureau) while studying the influence bedrock type and depth have on pavement deflections measured using the Falling Weight Deflectometer (Paine, 1999; Paine and Murphy, 2000). These TxDOT-funded projects demonstrated that seismic refraction data could be acquired on asphalt pavement using a portable seismic source and an array of geophones resting on pavement. The refraction data collected by the instrument can be analyzed to reveal the seismic compressional wave velocities in fill and bedrock, and to estimate the depth to bedrock beneath the geophone array.

During this project, Bureau researchers trained staff from the TxDOT Pavement Section to deploy the instrument, acquire seismic refraction data, analyze seismic data to pick direct and refracted first arrivals, and construct seismic velocity models to fit the acquired data and estimate bedrock depth. Training exercises were held at the J. J. Pickle Research Campus at the University of Texas at Austin and at the TxDOT Pavement Section offices. Field demonstrations were conducted at seven sites in six TxDOT districts (fig. 1) in a variety of settings that included differing highway types (Interstate and U.S. routes and State highways), bedrock types and road substrates (limestone, sandstone, and alluvium), and bedrock depths (less than 1 m to more than 6 m). The instrument was designed to estimate bedrock depths to a maximum depth of about

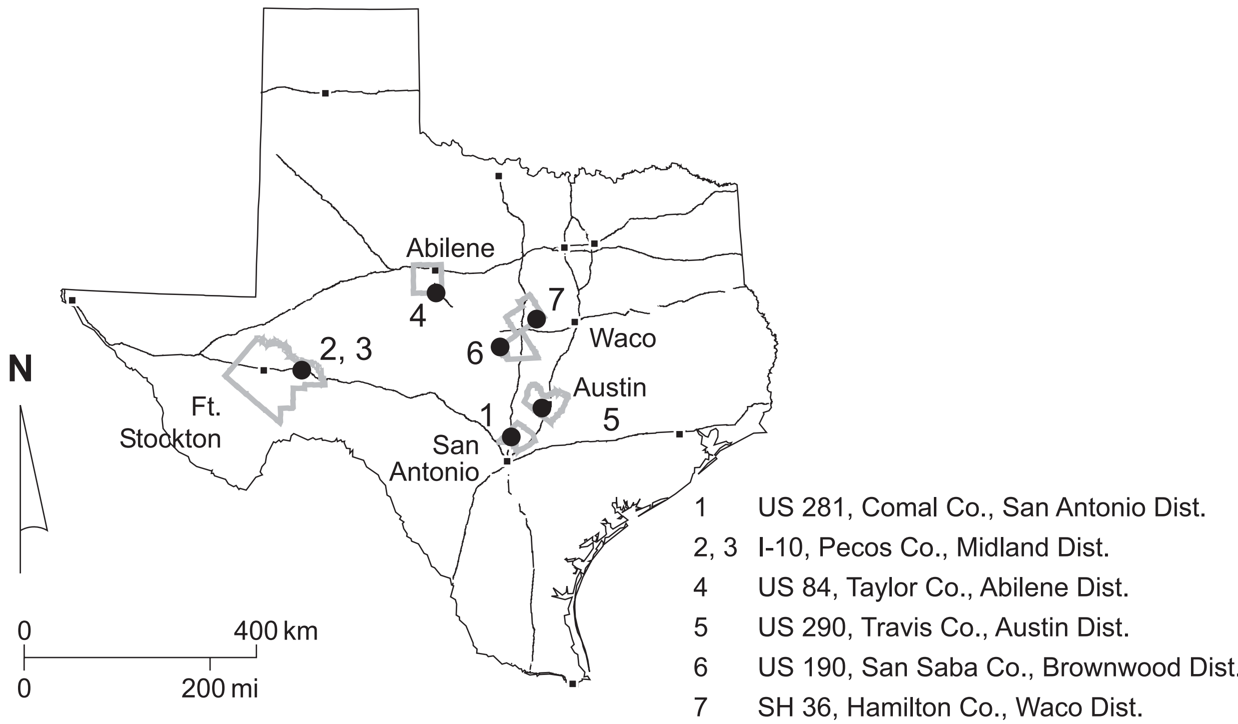

Figure 1. Map showing seven SRBA training field sites in the Abilene, Austin, Brownwood, Midland, San Antonio, and Waco Districts.

6 m; bedrock at deeper depths is not thought to greatly influence deflections measured with the Falling Weight Deflectometer (M. Murphy, TxDOT, pers. comm.).

Bureau researchers also conducted classroom and field-based training sessions for TxDOT staff and produced a training manual in print and as a web-compatible document (Paine, 2002). As a result of the training exercises, Bureau and TxDOT staff identified areas where the SRBA prototype could be improved, particularly in processing and analyzing acquired data.

METHODS

The SRBA employs seismic refraction to measure seismic velocities and estimate bedrock depths beneath pavement. Seismic refraction is a well-established geophysical method (Telford and others, 1976; Milsom, 1989) to determine compressional-wave velocity structure at depths as shallow as tens of centimeters to as deep as several kilometers. In the shallow subsurface, seismic refraction is commonly used to measure depth to the water table or to bedrock (rigid layer beneath soil and weathered bedrock). Compressional-wave velocities increase downward in most geologic settings, where relatively dry soil (compressional-wave velocities ranging from 300 to 700 m/s) is underlain by saturated soil at the water table (compressional velocities of about 1,500 m/s) or by unweathered bedrock (compressional velocities commonly more than 2,000 m/s, depending on rock type). These typically abrupt, downward increases in wave velocity refract surface-generated seismic waves along the interface between the units. The refracted waves generate wavefronts that propagate back to the surface, where they are detected by motion sensors (geophones). The time delay between seismic-source impact and first seismic arrivals at known geophone distances allows calculation of compressional velocities and thicknesses of near-surface layers, which in turn allows estimation of depth to the water table or to bedrock. In general, exploration depth increases with distance between the source and detector. For shallow investigations, the detector spread should extend from within a short distance of the source to four or more times the desired maximum exploration depth. This allows enough arrivals of both the direct wave (traveling in the surface layer only) and the critically refracted wave (traveling along the water table or at the interface between the surface layer and bedrock) to be observed to calculate accurate compressional-wave velocities for these layers.

The SRBA components include an 11.5-m-long array of 24 geophones mounted at 0.5-m intervals on foldable sections of PVC pipe, a 24-channel seismograph capable of recording at sample intervals of 0.125 milliseconds (ms) or less, and a portable seismic source (fig. 2). For the recommended shot locations (fig. 3), source to geophone offsets range from 0.25 to 5.75 m for the center shot, 0.5 to 12 m for the end shots, and 12.5 to 24 m for the far shots. Under typical conditions, these offset ranges are appropriate for bedrock depths ranging from a few tens of centimeters to about 6 m.

The complete workflow for acquiring, processing, and analyzing SRBA data is presented in detail in the SRBA manual (Paine, 2002). Briefly, at each of the seven training sites, Bureau and

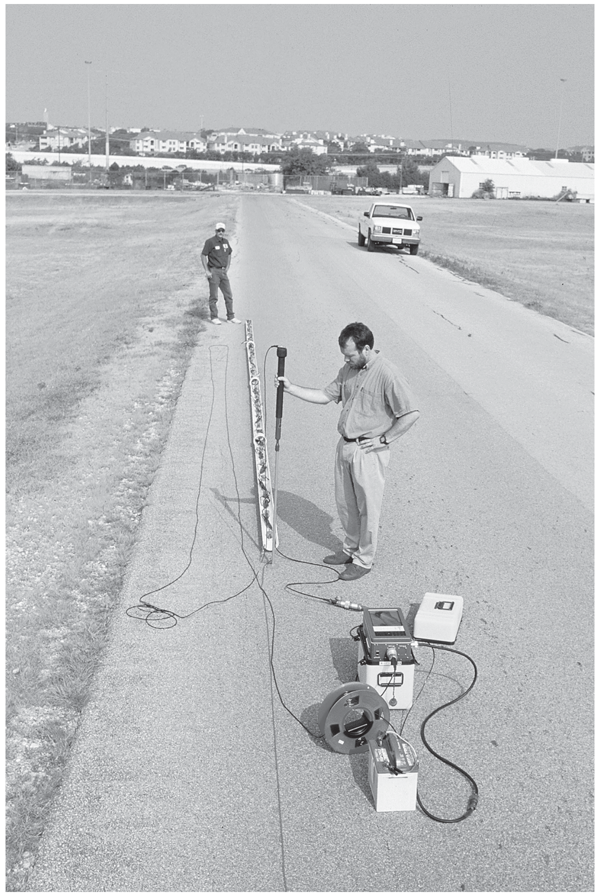

Figure 2. The SRBA prototype deployed on asphalt pavement. Shown are the seismograph, seismic source, 24-geophone array, and connecting cables.

TxDOT staff deployed the instrument at the chosen pavement location, acquired a series of five shot records (far forward, end forward, center, end reverse, and far reverse, fig. 3), imported the seismic records into the program FIRSTPIX to identify first arrivals for the direct and refracted seismic waves, exported the arrivals from FIRSTPIX to a custom Excel workbook, and constructed a seismic velocity model in the Excel workbook that produced synthetic direct and refracted arrivals that provided the best fit to the actual arrivals.

Efforts to determine actual bedrock depth at each of the sites included some combination of DCP data along the geophone array (fig. 4), augering through pavement and fill layers using a Giddings soil probe (fig. 5), and locating the array where pavement cores had been acquired

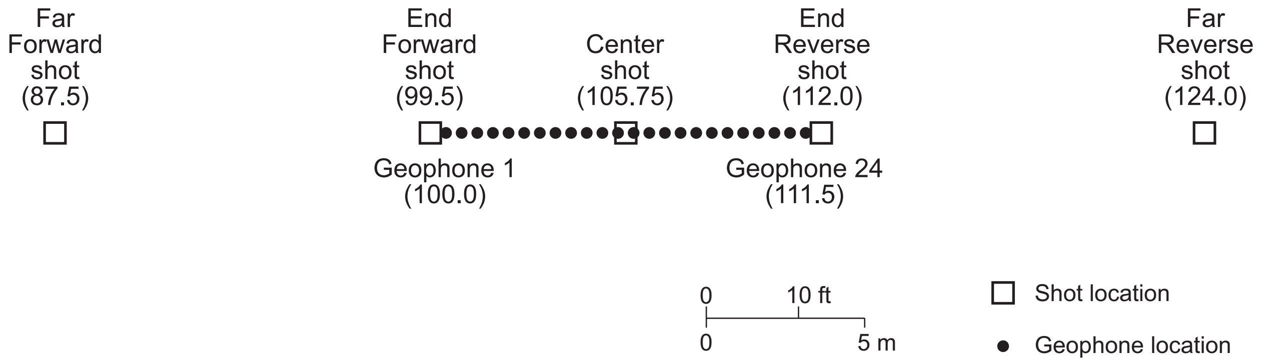

Figure 3. Position of the recommended five seismic source (shot) locations (far forward, end forward, center, end reverse, and far reverse) relative to the 24 geophone locations. Geophone 1 is customarily located at position 100.

Figure 4. TxDOT staff conducting DCP test at SRBA site on I-10 in Pecos County, Texas.

Figure 5. Bureau staff augering through pavement at SRBA site on I-10 in Pecos County, Texas.

previously. Pavement cores verified depth to bedrock at one site (and did not reach bedrock at the other), but DCP tests and soil augers both commonly met refusal at depths that are likely to be within the fill layers above lithified bedrock and could not produce defensible bedrock depths.

RESULTS

SRBA training exercises were conducted at seven sites from June 2001 to August 2002 (fig. 1 and table 1). Results from each site are presented as seismic records, first arrival picks, arrivals predicted from the best-fit seismic model, and a depth-to-bedrock cross section.

Site 1: U.S. 281, Comal County

Training site 1 is located on the outside, southbound lane of U.S. 281 south of the Guadalupe River in Comal County (fig. 1 and table 1). Bedrock at this site is mapped as the Cretaceous Glen Rose limestone (Brown and others, 1983) and is exposed in nearby outcrops. Seismic refraction data were acquired at this site in June 2001 using a sample interval of 0.5 ms,

Table 1. Field training sites. Locations were determined using GPS and are given in decimal degrees using the WGS84 datum.

Site	District	County	Highway	Latitude	Longitude	Elevation (m)	Date
1	San Antonio	Comal	U.S. 281	29.83634	-98.41161	316	6/28/2001
2	Midland	Pecos	I.H. 10, 300	30.89223	-102.20709	801	9/18/2001
3	Midland	Pecos	I.H. 10, 302	30.89135	-102.17985	847	9/18/2001
4	Abilene	Taylor	U.S. 84	32.11467	-99.72557	542	9/19/2001
5	Austin	Travis	U.S. 290	30.23558	-97.85430	270	5/1/2002
6	Brownwood	San Saba	U.S. 190	31.21770	-98.56299	349	8/1/2002
7	Waco	Hamilton	S.H. 36	31.62160	-97.90547	293	8/1/2002

a record length of 0.256 s, and both one- and four-shot stacks at each of four shot locations (fig. 6). Center-shot data were not collected.

Far-shot field records in the forward (fig. 6a) and reverse (fig. 6d) directions display clear first arrivals attributed to the critically refracted wave traveling along the bedrock surface. First refracted arrivals on these records range from 12 to 14 ms nearest to the source (12.5 m from the source) to 17 to 19 ms at the farthest source-receiver distances of 24 m. The critically refracted first arrivals extend to the end-shot records as well (fig. 6b and c), from the 12-m distance to a distance of about 7 m from the source.

At closer source-receiver distances, the first arrivals are more complex. Although not the first-arriving seismic energy, the most coherent and highest amplitude ground motion is the direct arrival associated with seismic energy traveling directly from the source to the geophones rather than being refracted at the bedrock surface. Small amplitude arrivals propagating across the record at earlier times than the direct wave probably represent either a direct wave traveling in a thin pavement layer or along a competent layer just beneath the pavement.

A two-layer seismic model constructed to fit the actual arrival times consists of a low-velocity surface layer with a compressional-wave velocity of 530 m/s underlain by a high-velocity layer with a velocity of 2,964 m/s (fig. 7 and table 2). Depth to the interpreted bedrock layer ranges from 2.16 m at the north end of the geophone array to 2.40 m at the south end of the array.

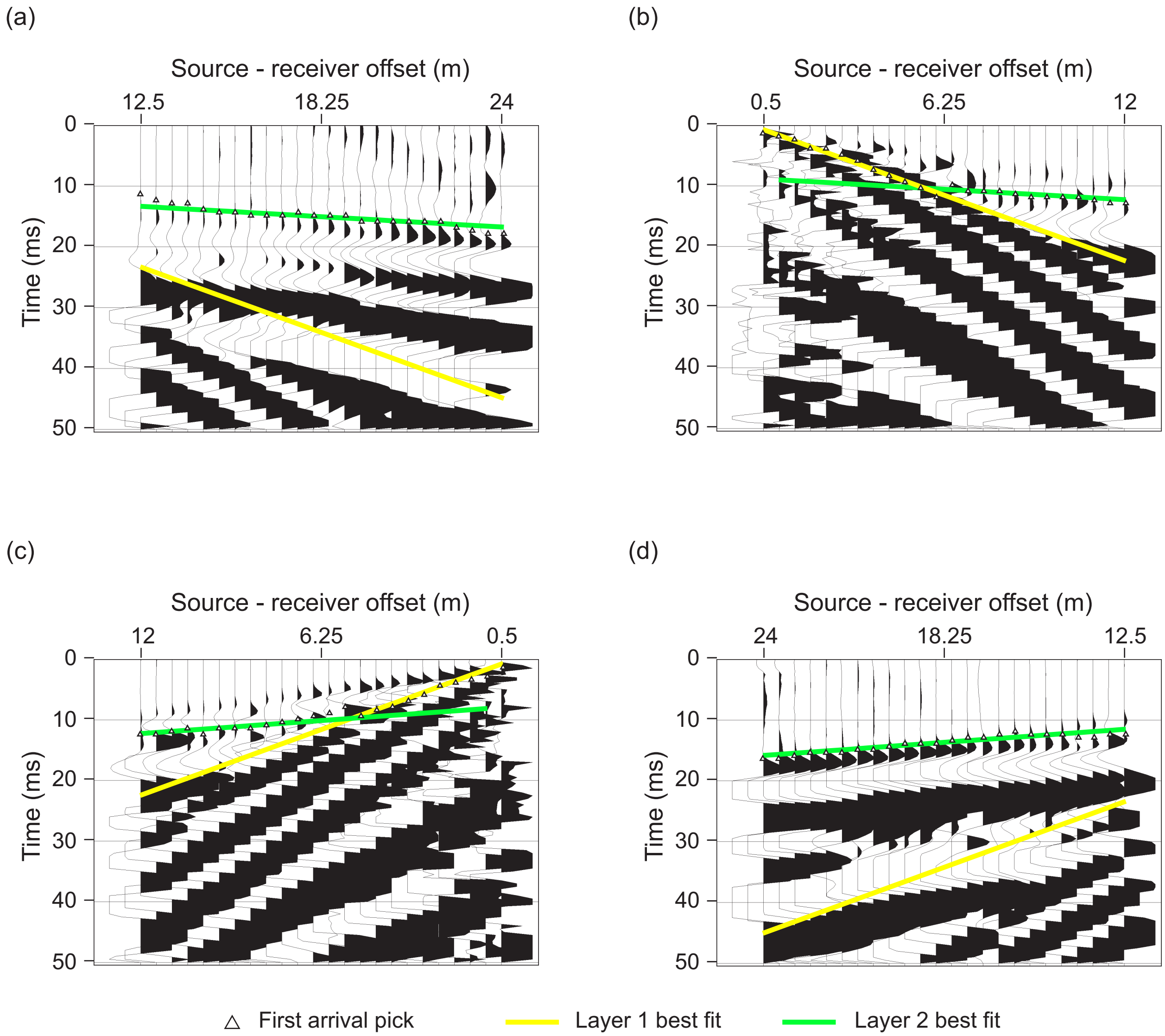

Figure 6. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 1, U.S. 281, Comal County (fig. 1). The (a) far forward, (b) end forward, (c) end reverse, and (d) far reverse shots are displayed.

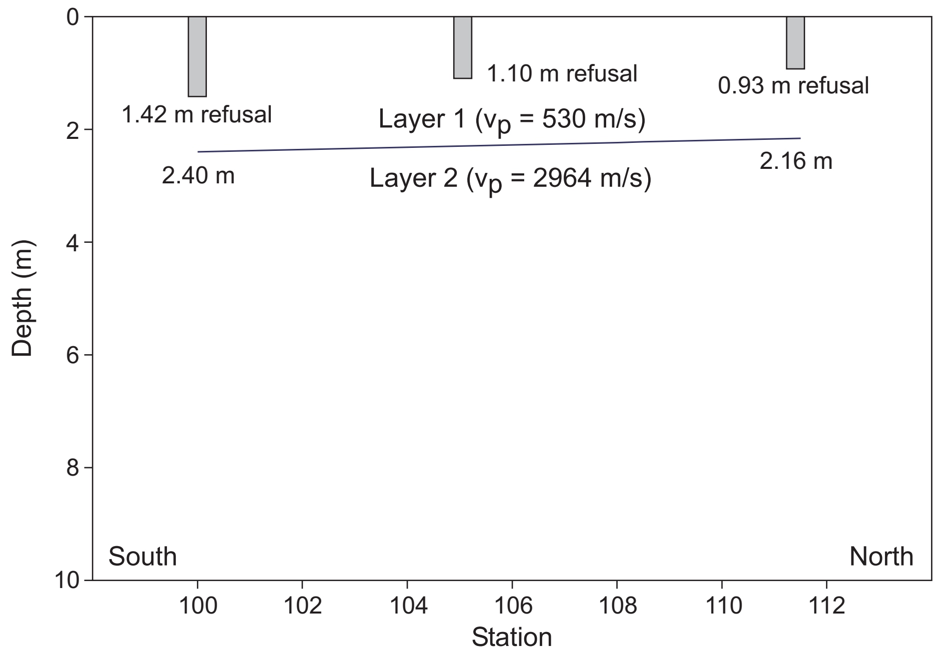

Figure 7. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 1, U.S. 281, Comal County. Also shown are maximum augered depths through pavement and fill. The auger did not reach bedrock.

Table 2. Planar-surface, two-layer refraction solutions for the seven SRBA training sites. v1 = fill velocity; v2 = bedrock velocity. Depths are those calculated for both ends of the recording array taking into account the apparent dip of the bedrock surface. Fit error is the RMS difference between the first arrival picks and the predicted arrival times calculated from layer velocities and thicknesses.

Site	Highway	v1 (m/s)	v2 (m/s)	Depths (m) Shallow	Depths (m) Deep	Dip (°)	Deep end	Fit error (ms)	Bedrock
1	U.S. 281	530	2964	2.16	2.40	1.2	South	46.9	K Glen Rose limestone
2	I.H. 10	1117	2082	2.06	2.38	1.6	West	40.7	K Segovia limestone
3	I.H. 10	551	1311	6.15	6.35	1	West	101.6	K Segovia limestone
4	U.S. 84	554	1980	6.24	6.46	1.05	South	54.7	P Clear Fork mudstone
5	U.S. 290	827	1814	1.05	1.09	0.2	West	51.9	K Glen Rose limestone
6	U.S. 190	631	1079	1.43	1.77	1.68	East	52.6	IP Strawn sandstone
7	S.H. 36	559	1962	0.33	0.51	0.9	West	36.5	K Glen Rose limestone

The bedrock layer has a shallow apparent dip of 1.2 degrees to the south. The total root-mean-square fitting error between the actual and predicted arrival times for the direct and refracted arrivals is 46.9 ms, or an average difference of less than 0.5 ms for each first arrival.

The soil auger (fig. 5) was used at three points along the geophone array in an attempt to establish actual bedrock depths. Auger-refusal depths increased from 0.93 m at the north end to 1.42 m at the south end (fig. 7), mimicking the southward-increasing depth to bedrock estimated from SRBA data. Depths estimated from the SRBA data exceed the auger-refusal depth, but it is not known whether auger refusal occurred at bedrock or at coarse fill an unknown distance above bedrock.

Site 2: I-10 Near Mile 300, Pecos County

In September 2001, Bureau and TxDOT staff acquired SRBA data at training site 2 east of mile marker 300 on the outside, eastbound lane of I-10 in Pecos County (fig. 1 and table 1). Geologic maps indicate that bedrock is the Cretaceous Segovia limestone (Anderson and others, 1995). SRBA data were acquired at a 0.125 ms sample interval for durations of 63 or 125 ms. Both one- and four-shot stacks were acquired at each source point.

Seismic data records show clear first arrivals for both the direct and refracted waves (fig. 8). For the far forward and far reverse shots (fig. 8a and e), arrivals interpreted to be from the bedrock refraction arrive at about 10 ms 12.5 m from the source, increasing to about 15 ms 24 m from the source. The end shots (fig. 8b and d) record the interpreted bedrock refraction as the first arrival beyond a source-receiver distance of about 6 m. Closer to the source, the first arrivals are assigned to the direct wave traveling solely in the fill layer above bedrock. First arrivals on the center shot record (fig. 8c) are all close enough to the source to be from the direct wave.

The two-layer seismic model providing the best fit to the observed arrival times consists of an upper layer with relatively high seismic velocity (1,117 m/s) overlying a higher velocity layer (2,082 m/s) at depths increasing from 2.06 m at the east end of the geophone array to 2.38 m at

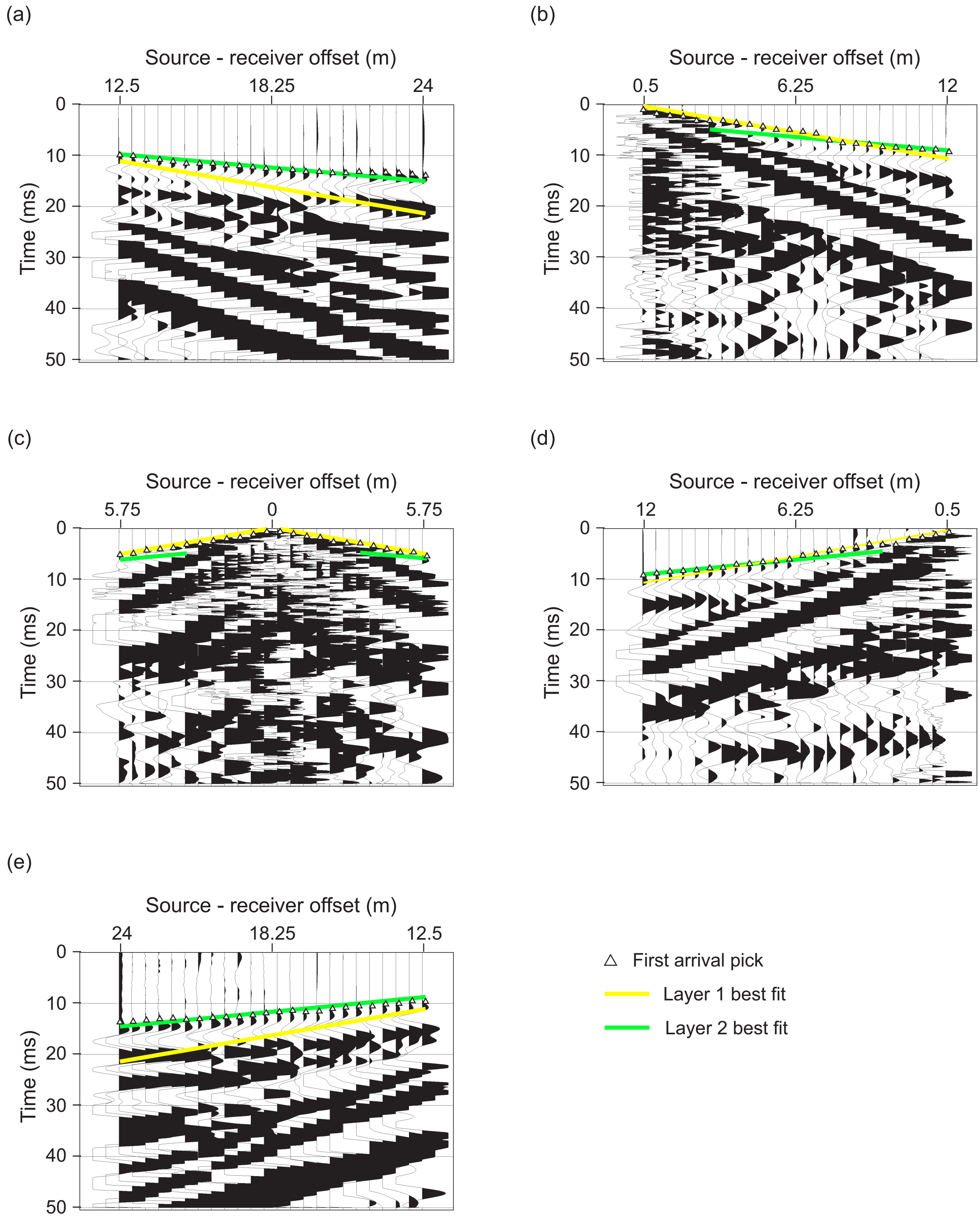

Figure 8. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 2, I-10 near mile marker 300, Pecos County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

the west end (fig. 9 and table 2). The upper, lower velocity layer is interpreted as representing compacted fill above bedrock. The lower, higher velocity layer is interpreted as the bedrock surface, which has an apparent dip of 1.6 degrees toward the west. Total fitting error is 40.7 ms, an average of 0.34 ms difference between each actual and predicted first-arrival time.

This is the only training site where bedrock depths have been reliably established. Auger refusal depths of 1.52 m at the west end of the geophone array and 1.78 m at the east end represent minimum depths to bedrock, whereas a pavement core acquired by TxDOT less than 2 m from the east end of the geophone array encountered bedrock at 2.34 m. Estimates of bedrock depth made from SRBA data are greater than the minimum depths represented by auger refusal and similar to the actual bedrock depth established in the nearby pavement core.

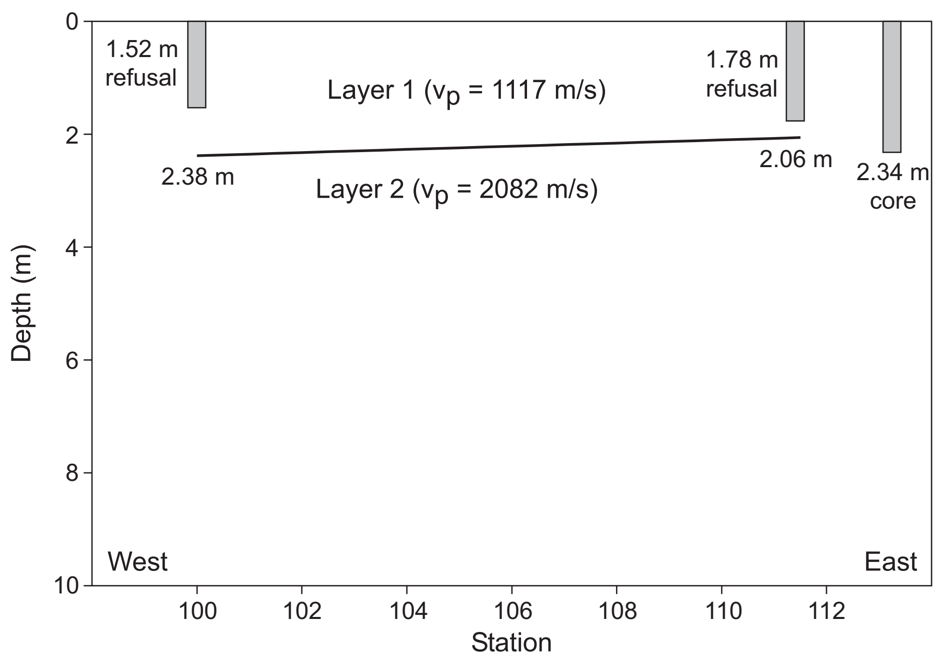

Figure 9. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 2, I-10 near mile marker 300, Pecos County. Also shown are maximum augered depths through pavement and fill and actual bedrock depth reported from a nearby pavement core. Based on core data, the auger did not reach bedrock.

Site 3: I-10 Near Mile 302, Pecos County

Training site 3 is located less than 2 mi east of site 2 (fig. 1) on the outside, eastbound lane of I-10. Geologic maps show recent, poorly lithified deposits at the surface (Anderson and others, 1995), suggesting greater depth to bedrock than at site 2. SRBA data were acquired using a 0.125 ms sample interval and a recording duration of 64 ms. Both single and multiple shots formed the seismic data files recorded at the far, end, and center shots. Multiple-shot records included either four or eight stacked seismic pulses.

Seismic energy recorded at this site (fig. 10) differs greatly from that acquired at site 2, where bedrock is shallow. Most of the first arrivals on the center, end, and far shots are interpreted to be from the direct wave; arrivals from waves refracted along the interpreted bedrock interface are the first arrivals at only the farthest source-receiver distances on the far forward (fig. 10a) and far reverse (fig. 10e) shot records. The crossover point from the direct arrival to the critically refracted arrival is at a source-receiver distance of about 20 m in both the forward and reverse propagation directions.

The layer 1 seismic velocity that provides the best fit to the actual direct-wave arrival times is 551 m/s (fig. 11 and table 2). Layer 2 velocities are calculated to be 1,311 m/s, but are poorly constrained due to the relatively small number of refracted arrivals used to calculate the velocity. Using these velocities and the observed arrival times, depth to the higher velocity layer is estimated to be 6.15 m on the east end of the array and 6.35 m on the west end. Total fitting error of 101.6 ms is the highest of all training sites, reflecting the difficulty in accurately picking first-arrival times for the direct wave. The calculated velocity of the interpreted bedrock layer is relatively low and may misrepresent the actual bedrock velocity, potentially resulting in underestimated depth to bedrock.

Core, auger, and geologic data are consistent with deep bedrock depth at this site. A pavement core taken at the center of the geophone array reached 2.97 m without encountering bed-

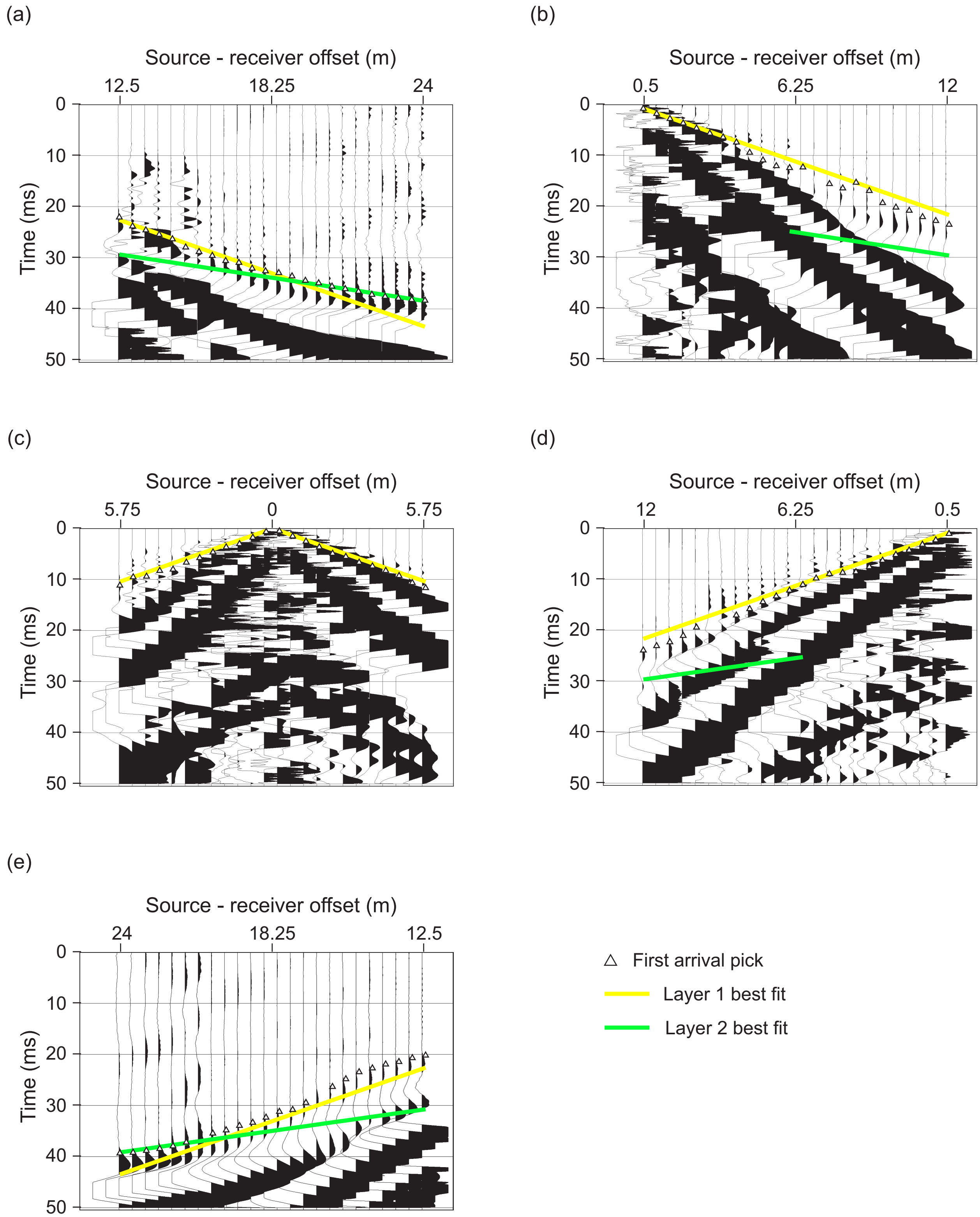

Figure 10. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 3, I-10 near mile marker 302, Pecos County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

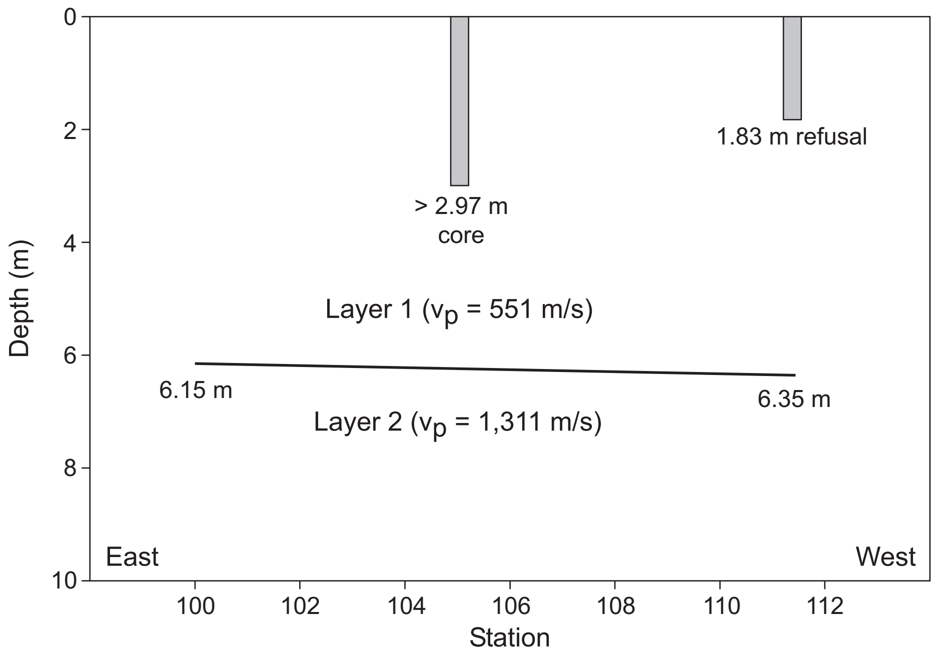

Figure 11. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 3, I-10 near mile marker 302, Pecos County. Also shown are maximum augered depth through pavement and fill and maximum depth reached by coring at the site. Neither the auger nor the core reached bedrock.

rock. Auger refusal was reached at 1.83 m at the west end of the array, far shallower than the depth reached by the pavement core nearby and the depth estimate obtained from SRBA data.

Site 4: U.S. 84, Taylor County

SRBA data were acquired at training site 4 in September 2001 along the southbound lane of U.S. 84 south of Abilene, Texas (fig. 1 and table 1). Permian-age mudstone of the Clear Fork formation is mapped at this site (Brown and others, 1972). Elevation of the highway several meters above the surrounding land surface indicates relatively deep bedrock. SRBA data were acquired at a 0.125 ms sample interval for 128 ms using single and multiple source blows at each source point.

The crossover point is clear between first arrivals assigned to the direct wave in the fill layer and the refracted wave traveling partly in bedrock (fig. 12). First arrivals on the near-source seismic records for the center (fig. 12c) and end (fig. 12b and d) shots are all assigned to the

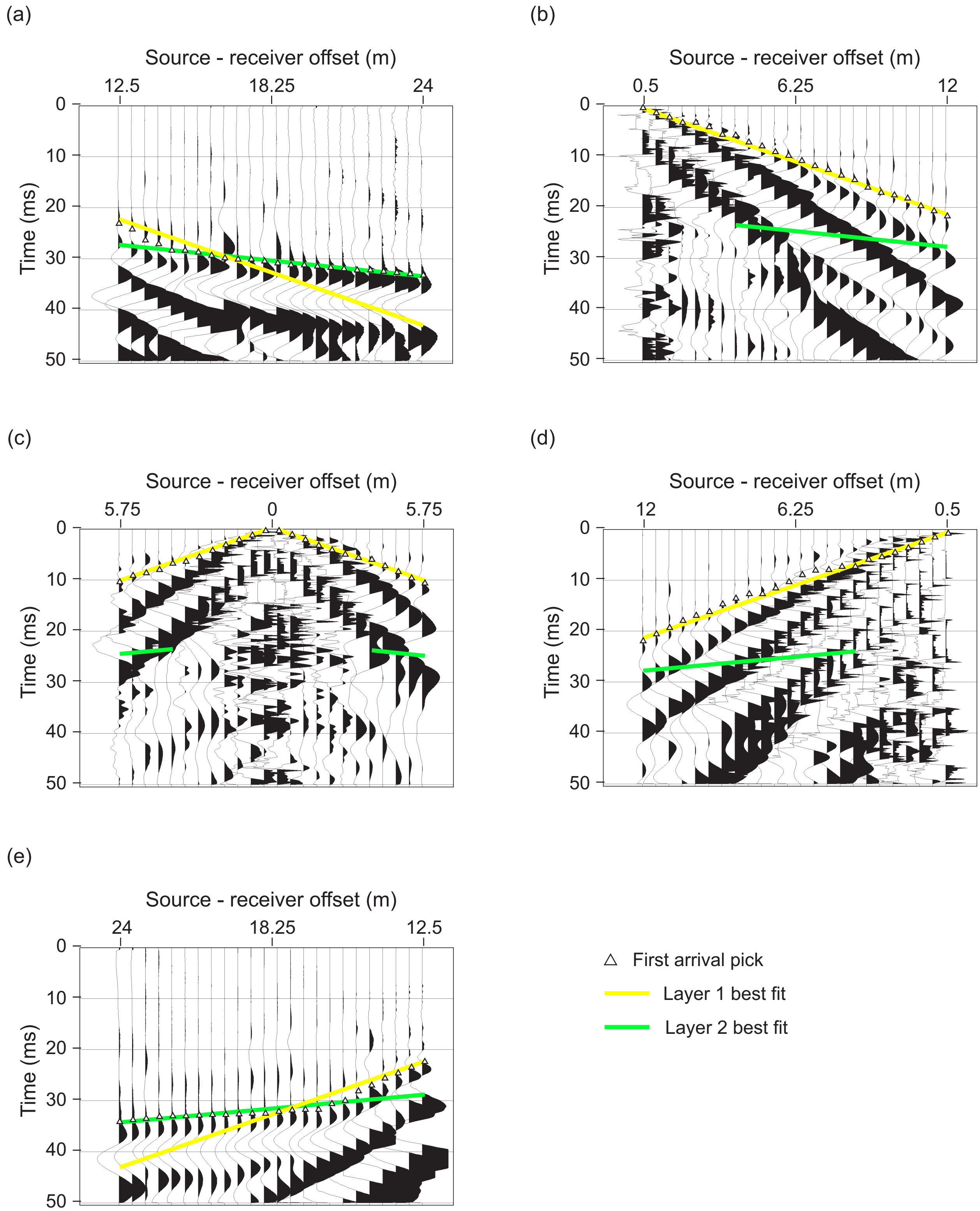

Figure 12. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 4, U.S. 84, Taylor County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

direct wave. Only on the far shots does the refracted wave become the first arrival at source-receiver distances of 16 m and more (fig. 12a and e).

The seismic velocity model that provides the best statistical fit to the actual first arrivals includes a thick, low velocity layer at the surface underlain by a high-velocity layer interpreted as bedrock (fig. 13 and table 2). The surface layer, layer 1, has a modeled velocity of 554 m/s and thickens from 6.24 m at the north end of the array to 6.46 m at the south end. Layer 2, interpreted to represent bedrock, has a seismic velocity of 1,980 m/s and an apparent dip of about 1 degree toward the south. The total fitting error of 54.7 ms translates to an average error of less than 0.5 ms for each seismic trace.

Using the soil probe, auger refusal was reached at shallow depths of 1.1 to 1.2 m at both ends of the array. These values cannot be compared to bedrock depths estimated from SRBA data

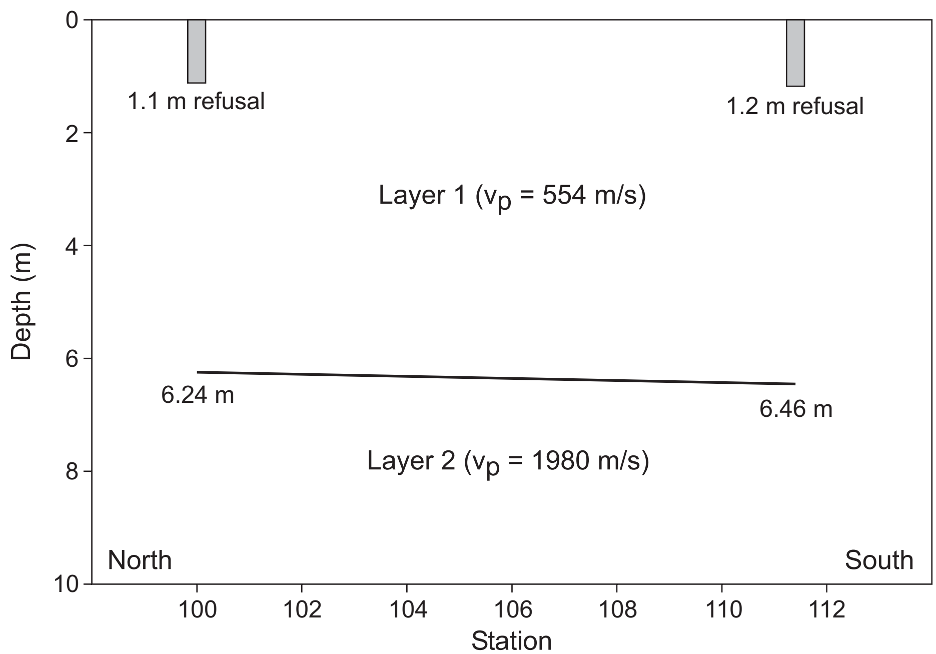

Figure 13. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 4, U.S. 84, Taylor County. Also shown are maximum augered depth through pavement and fill. Based on the elevation of the pavement above the surrounding land surface, the auger did not reach bedrock.

at this site because the road has been elevated several meters above the surrounding land surface by filling. Auger refusal occurred within a relatively competent or coarse-grained layer within the fill material.

Site 5: U.S. 290, Travis County

SRBA data were acquired along a U.S. 290 access road in western Travis County in May 2002 (fig. 1 and table 1). Geologic maps indicate that the area is underlain by the Cretaceous Glen Rose limestone at relatively shallow depths (Proctor and others, 1974). Seismic data were acquired at a sample rate of 0.125 ms with a record duration of 128 ms. Far forward and reverse locations were recorded using 8 stacked shots; end and center locations were recorded using 8 stacked shots. Multiple shots helped improve the relative strength of the seismic signal by minimizing random ambient noise.

Seismic records acquired at this site reveal relatively early first arrivals that are associated with shallow bedrock (fig. 14). The crossover between first arrivals attributed to the direct wave traveling in the surface layer only and the refracted wave traveling partly in bedrock is found relatively close to the source at source-receiver distances of about 4 m (fig. 14 b, c, and d). At longer source-receiver offsets on the far forward (fig. 14a) and far reverse (fig. 14e) shots, the critically refracted wave arrives at times as early as 9 ms at 12.5-m offset and 14 ms at 24-m offset.

The two-layer seismic model provides a good fit to the observed arrival times (fig. 15 and table 2). The layer 1 velocity is high (827 m/s) relative to other sites. Layer 1, representing fill above bedrock, is estimated to be 1.05 to 1.09 m thick, thickening slightly toward the west end of the array. Layer 2, interpreted to represent bedrock, has a seismic velocity of 1,814 m/s. The bedrock surface has a slight apparent dip of less than 1 degree to the west. A total fitting error of 51.9 ms indicates that predicted arrival times match actual arrival times with an average difference of less than 0.5 ms for each arrival time.

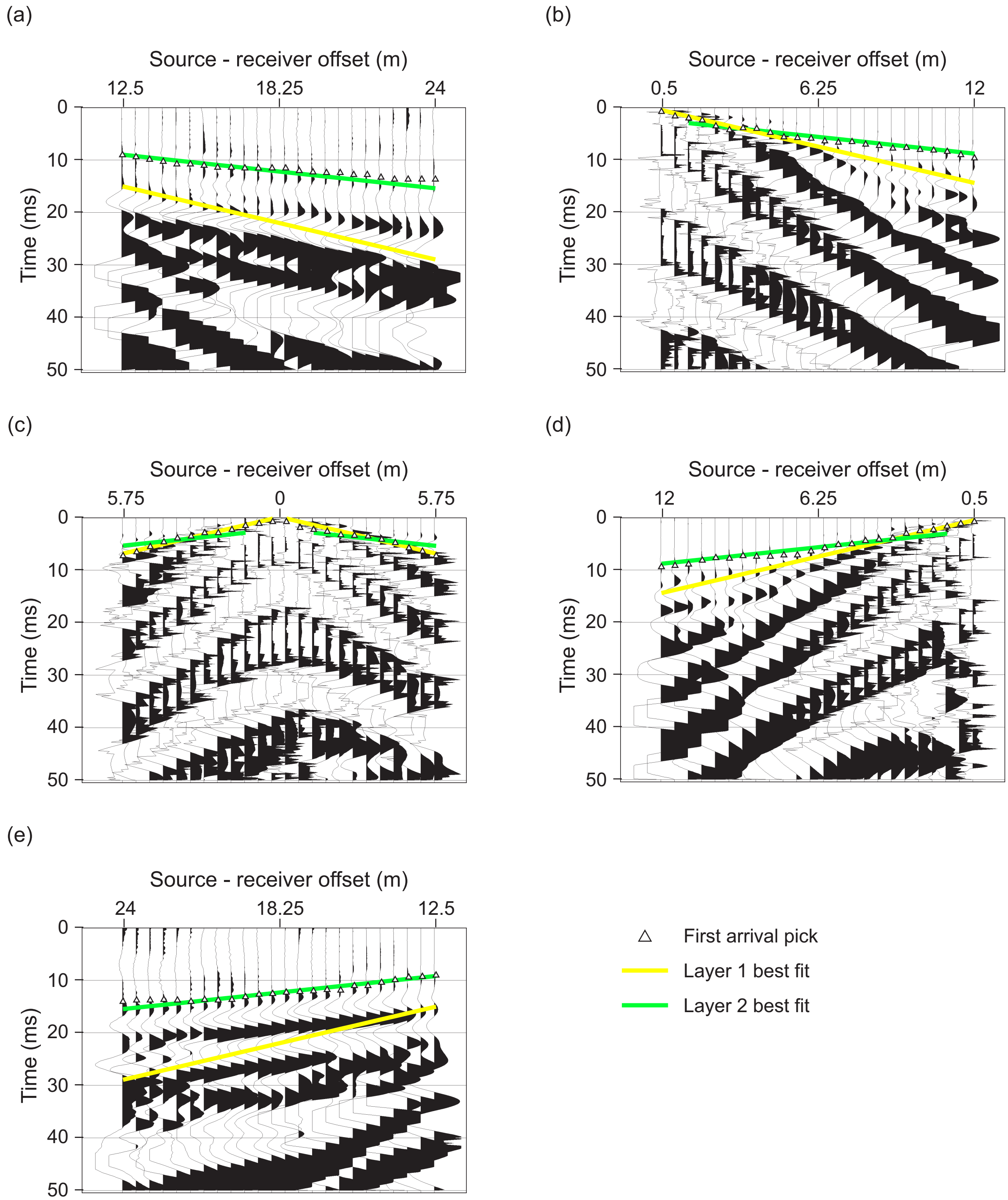

Figure 14. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 5, U.S. 290, Travis County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

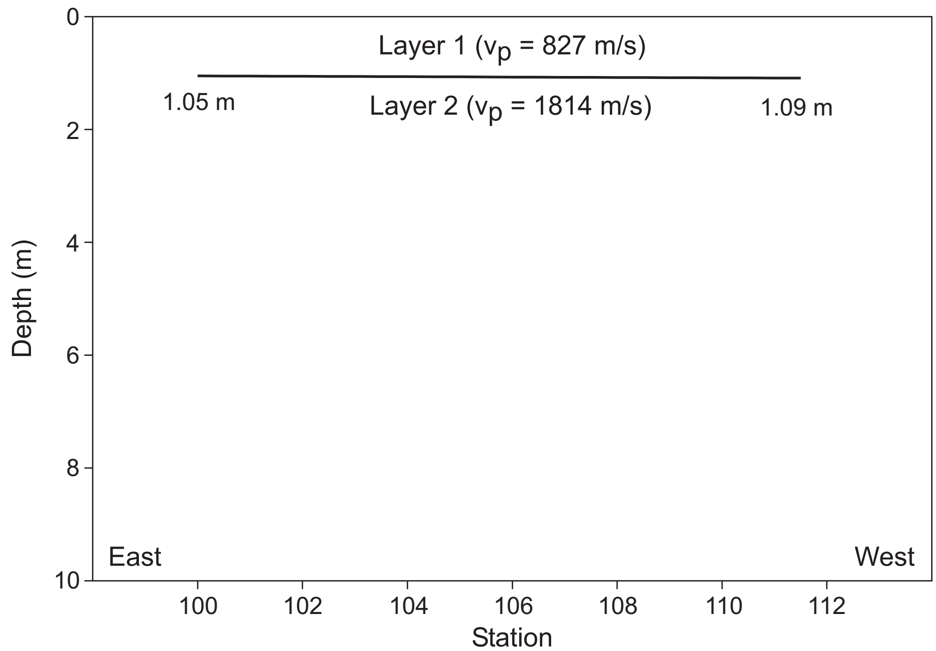

Figure 15. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 5, U.S. 290, Travis County.

Because auger refusal depths were unreliable bedrock depth indicators at other sites, no augering was attempted at sites 5, 6, and 7. DCP tests reached refusal at 0.86 m at the center of the geophone array and did not reach refusal depth before test abandonment at 0.96 m at the east end of the array.

Site 6: U.S. 190, San Saba County

Training site 6 is located near the eastern end of the Colorado River bridge on U.S. 190 in San Saba County (fig. 1 and table 1). SRBA data were acquired in August 2002 on the paved apron adjacent to the road. Mapped Pennsylvanian Strawn sandstones (Kier and others, 1976) crop out nearby, indicating relatively shallow bedrock. Data were recorded for 64 ms at a sample interval of 0.125 ms using eight stacked shots at the far locations and four stacked shots at the end and center locations.

All first arrivals for the center shot record are attributed to the direct wave traveling only in the low velocity surface layer (fig. 16c). At slightly longer source-receiver distances of as much as 12.5 m for the end shots, the crossover point from direct to refracted arrivals is visible at about 6 m from the source (fig. 16b and d). The remainder of the first arrivals on the end shots and all of the arrivals on the far shots (fig. 16a and e) are attributed to the critically refracted wave traveling partly along the bedrock surface. Arrival times on the far shots are relatively late, increasing from about 16 ms at a distance of 12.5 m from the source to about 25 ms at a distance of 24 m from the source. The far forward (fig. 16a) and far reverse (fig. 16e) shots are not perfectly symmetric, suggesting dip and undulation on the bedrock surface.

A layer 1 velocity of 631 m/s provided the best fit for the first arrivals attributed to the direct arrival (fig. 17 and table 2). Layer 2, interpreted to represent sandstone bedrock, had a relatively low seismic velocity of 1,079 m/s. The estimated depth to bedrock increases from 1.43 m at the west end of the geophone array to 1.77 m at the east end. The model fits the observed data reasonably well; a total fitting error of 52.6 ms averages less than 0.5 ms for each first arrival.

Site 7: S.H. 36, Hamilton County

The final training site is located on the westbound lane of S.H. 36 west of the Leon River bridge in Hamilton County (fig. 1 and table 1). Shallow bedrock, exposed in the highway right-of-way, is mapped as Cretaceous Glen Rose limestone (Proctor and others, 1970). SRBA data were acquired in August 2002 using a record duration of 64 ms, a sample interval of 0.125 ms, eight stacked shots at the far locations, and four stacked shots at the end and center locations.

Only the closest geophones to the seismic source receive the direct wave as the first arrival (fig. 18). The crossover distance separating the direct-wave first arrivals from the refracted-wave first arrivals is 1 to 2 m from the source. The direct wave can be identified a short distance farther from the source, but it has been overtaken by the refracted arrival traveling partly along the bedrock surface. Clear first arrivals at farther distances from the source, visible between 8

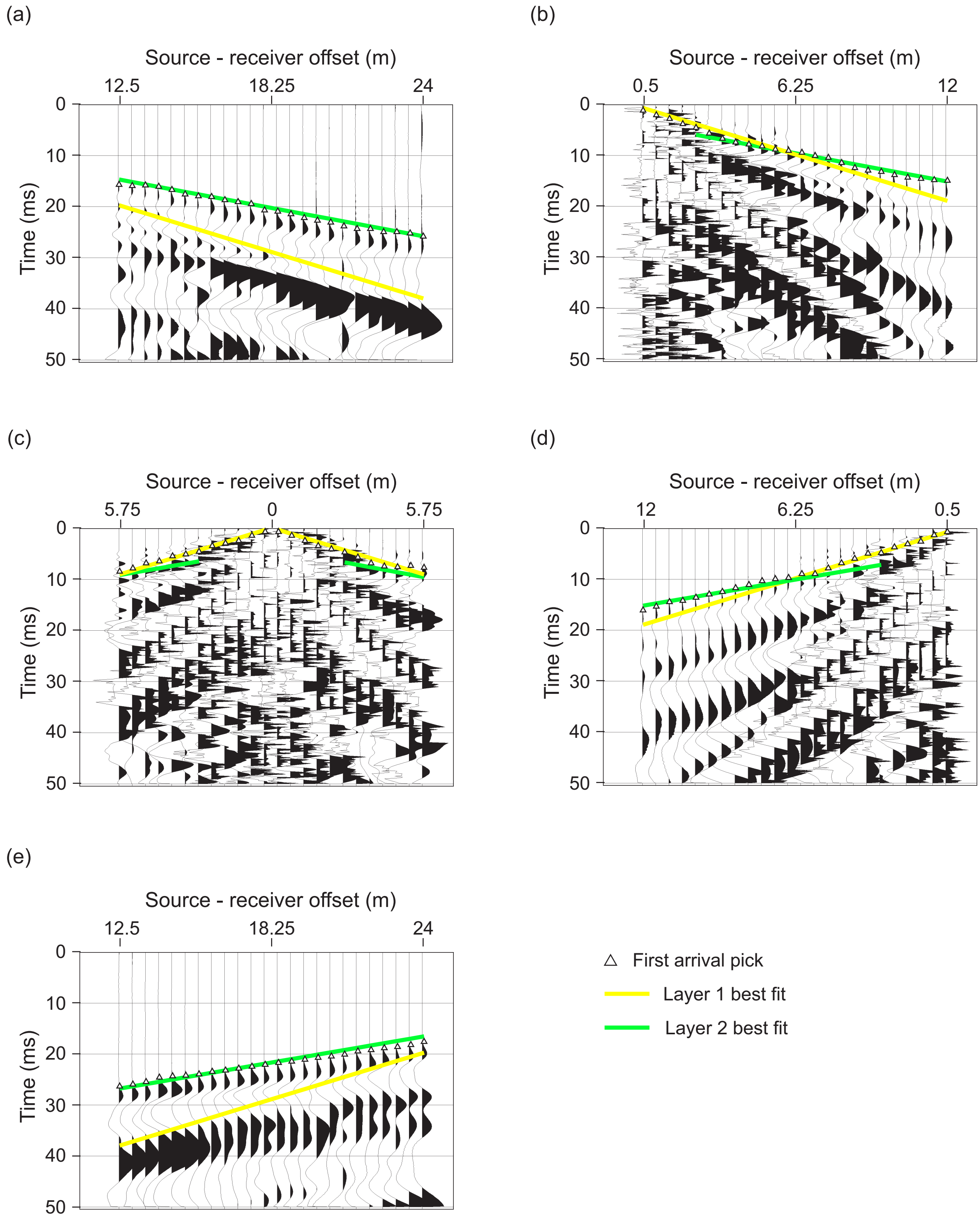

Figure 16. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 6, U.S. 190, San Saba County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

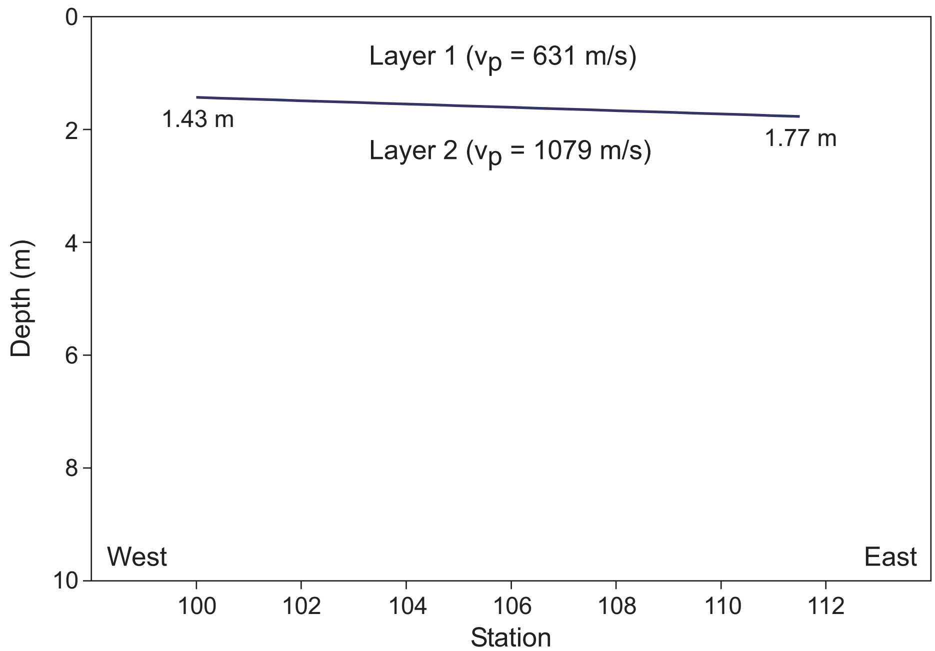

Figure 17. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 6, U.S. 190, San Saba County.

and 12 ms on the far forward (fig. 18a) and far reverse (fig. 18e) shot records, are attributed to the refracted arrival.

Layer 1 velocity calculated from the relatively small number of direct arrivals is 559 m/s (fig. 19 and table 2). Layer 2 velocity, 1,962 m/s, is well constrained by a large number of first arrivals attributed to the critically refracted wave. As expected from the short crossover distance and exposed bedrock nearby, bedrock is estimated to be as shallow as 0.33 m beneath the east end of the geophone array and 0.51 m beneath the west end. Bedrock has an apparent dip to the west of slightly less than 1 degree. Total fitting error of 36.5 ms is the lowest of all training sites, averaging less than 0.4 ms for each actual and synthetic first-arrival pair.

CONCLUSIONS

Comparisons of seismic records acquired in varied settings in six TxDOT districts demonstrate that bedrock depth and type strongly influence near-source seismic data. These data can be

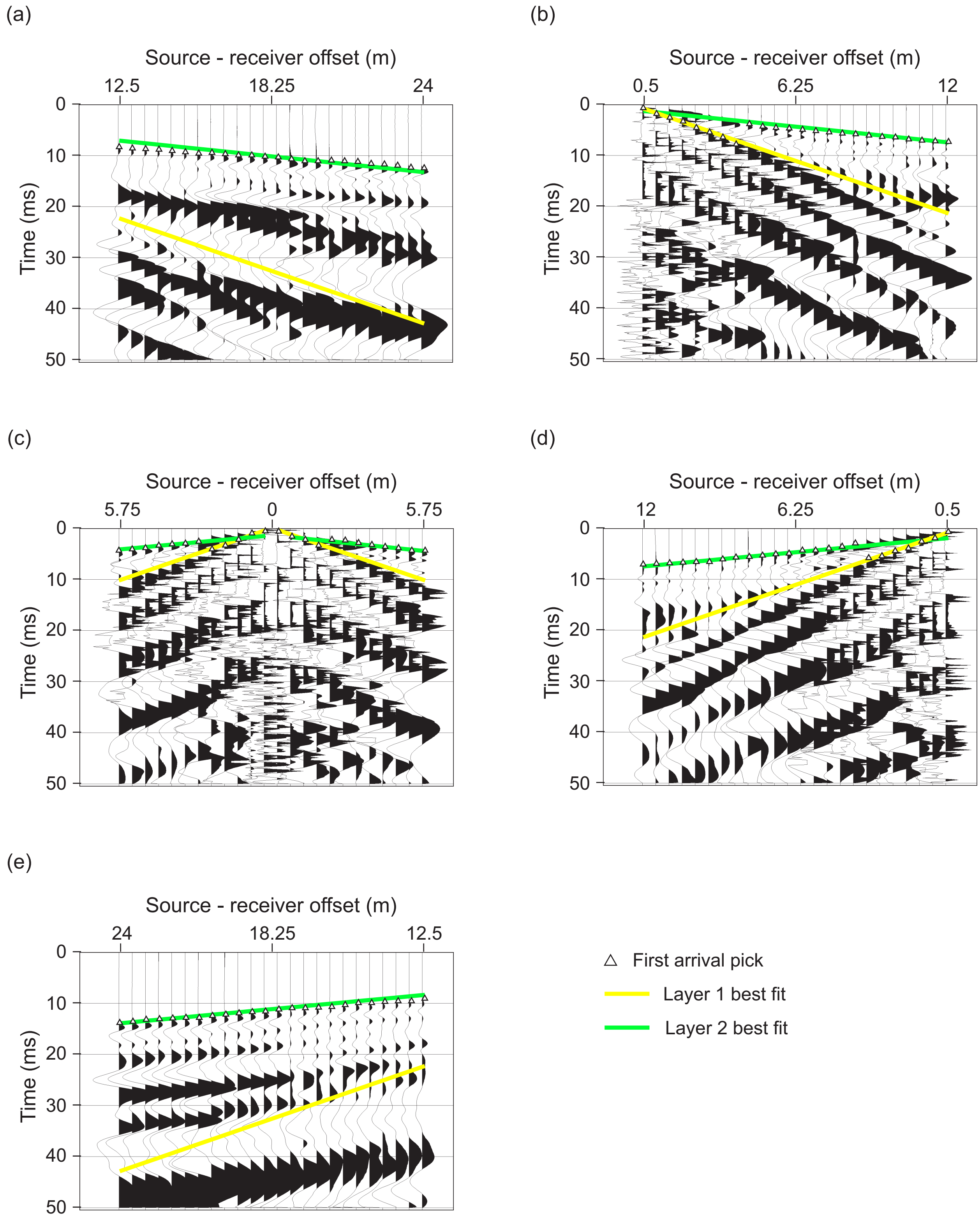

Figure 18. Seismic records, first arrival picks, and synthetic arrivals for SRBA site 7, S.H. 36, Hamilton County (fig. 1). The (a) far forward, (b) end forward, (c) center, (d) end reverse, and (e) far reverse shots are displayed.

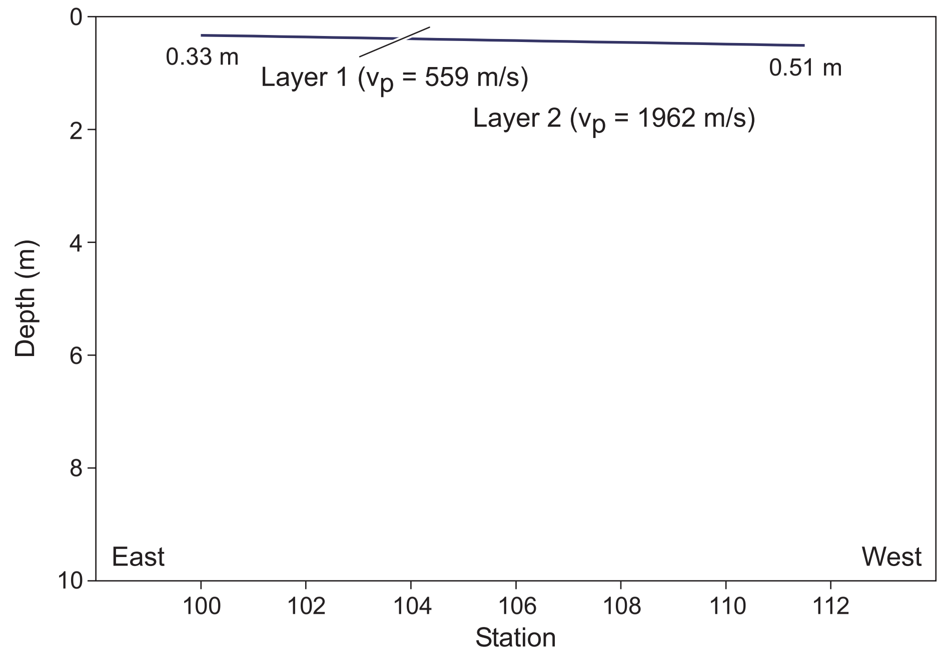

Figure 19. Cross section showing estimated depth to bedrock beneath the geophone array at SRBA site 7, S.H. 36, Hamilton County.

readily acquired using the SRBA prototype and can be analyzed and interpreted to estimate seismic compressional wave velocity in sub-pavement fill and bedrock. Seismic velocities and arrival times can then be used to estimate depth to bedrock beneath the geophone array.

Attempts to determine the accuracy of bedrock depth estimates based on SRBA data were hindered by the inability of narrow-diameter soil augers and DCP instruments to penetrate coarse-grained fill layers above actual bedrock. At the one site where bedrock depth was firmly established by pavement coring, actual bedrock depth was within the depth range estimated from SRBA data.

SRBA data are easily and rapidly acquired, requiring only a few minutes for deployment and data acquisition at each site. Data analysis is currently cumbersome, requiring data transfer from the seismograph to another computer and software package for first arrival analysis and subsequent data transfer to a custom spreadsheet for refraction analysis. This process can require an hour or more to complete, making it difficult to quickly produce reliable bedrock depth estimates. Further development of the SRBA should include custom software development to integrate first arrival and refraction analysis. Eventually, software controlling data acquisition should be integrated as well, simplifying the data acquisition and analysis process, improving the accuracy of the results, and providing bedrock depth estimates within minutes of data acquisition.

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