Reconnaissance Shallow Seismic Investigation of Depth-to-Bedrock and Possible Methane-bearing Coalbeds, Galena, Alaska

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Galena from an airplane

Yukon River at sunset

Shotpoint "blowout" during seismic acquisition

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ABSTRACT

A reconnaissance shallow seismic reflection/refraction investigation in and around the city of Galena, Alaska suggests that Tertiary and/or Cretaceous bedrock, and possible coalbeds within the Cretaceous, is at least as deep as 550 feet in the immediate vicinity of town. Rock could be deeper than 1000 feet under alternate interpretations. Reflections recorded in these data are believed to be from the sediment/bedrock interface. Analysis of these reflections and associated refractions indicates that this interface, interpreted at most of the six profile locations, has a high seismic velocity, possibly indicating non-sedimentary rock (e.g. volcanic or igneous).

INTRODUCTION

The City of Galena, Alaska, has interest in obtaining a local methane gas supply to supplement their heating and electrical needs. It has been proposed that Cretaceous coalbeds, observed in outcrop at Hartnet Island, roughly 12 miles east of Galena and roughly 20 to 30 miles west of Galena near Koyukuk and Nulato, might provide a source of methane gas. However, the depth of these possible coalbeds beneath the city is critical to determine their viability as an economic methane source. Without knowing the total thickness of the late-Tertiary (?) to Quaternary section, the total depth to Cretaceous strata and thus a drilling method cannot be determined. To help estimate the possible drilling depth to Cretaceous and older rock, we acquired high-resolution seismic reflection/refraction data at six sites in and near the city of Galena (Figure 1). These data provide information on depths to reflecting geologic boundaries that may be the sediment/bedrock boundary.

Figure 1. Map of City of Galena, Alaska, and seismic profile locations. Red lines are approximate locations of 60 receivers for each of six profiles (receivers spaced 10 m apart along each profile). Stars are locations of seismic shot points off profile ends, which were needed for deeper coverage. Map base is USGS 1:63,360 Nulato Quadrangle.

GEOLOGIC SETTING

Based on published geologic information (Bradley, 1938; Pewe, 1948; Cass, 1959; Patton and Hoare, 1968; Nakanishi and Dorava, 1994) and field evidence (C. Barker, unpublished data), we make the following observations: 1) The Cretaceous section in the Galena area, based on aeromagnetic response, is on the order of several thousand feet thick; 2) Regionally, the Upper Cretaceous strata contain approximately 800 ft. of coal-bearing strata. As this unit is poorly exposed in outcrop, the cumulative thickness of coalbeds in this unit is unknown; 3) Much of the Cretaceous section is non-coal bearing and significant erosion of the upper part of this section would likely remove the coal-bearing unit; 4) Coal-bearing rocks are mapped as exposed in the banks of the Yukon River on either side of Galena, at Hartnet Island some 12 miles east of Galena and some 20 to 30 miles west of Galena near Koyukuk and Nulato; 5) Coals in the Koyukuk and Nulato areas exist as discontinuous pods rather than as laterally extensive seams; 6) The coal bed exposed at Hartnet Island is approximately 9 feet thick and dips about 70° to the southeast, away from the city of Galena; 7) There is also the possibility that coal deposited in mid-Tertiary grabens is present beneath or near Galena.

From these observations, it is likely that Cretaceous or Tertiary rocks underlie Galena beneath the near-surface late Tertiary(?) to Quaternary fluvial plain deposits of the Yukon River. It is unknown whether the Cretaceous or Tertiary strata beneath Galena contain coal. Because the coal-bearing section is in the uppermost Cretaceous section, it is possible that it has been eroded away, possibly by the Yukon River in the late Tertiary(?) to Quaternary. At least 360 feet of soft, water-saturated, fluvial and swamp-derived sediments were penetrated without hitting the underlying Cretaceous unit in a water well drilled by the City of Galena in 1998. No other deep drill hole information is known to exist within the immediate area.

SEISMIC DATA ACQUISITION AND PROCESSING

The signal we use in the seismic data to extract information, such as the depth of the sediment/bedrock interface as well as general stratigraphic layering, is in the form of reflected and refracted sound waves that are directly dependent on velocity (and density) variations in the subsurface. The reflection amplitude is proportional to the velocity (and density) contrast across the boundary. A diagram showing basic reflected and refracted signal travel paths for a single seismic wave initiated at the surface is shown in Figure 2. Depths are estimated by identifying the signal type and by analyzing signal travel times. Inherent error in interpretation occurs because of our lack of knowledge of the velocity structure and geometry of geologic layering. Noise recorded in the data from wind, traffic, and electrical sources (60-Hz transformers, radio transmitters) also degrade data quality and therefore the interpretation accuracy. Two types of seismic waves are important for this study: compressional (or P)-waves, and shear (or S)-waves. S-waves typically travel at 60% the velocity of P-waves. We designed our study to focus on P-waves, and these are primarily what was recorded by our instrumentation. Unless otherwise stated, all reference to seismic waves in the text will refer to P-waves.

The seismic reflection/refraction data were acquired at six sites over a five-day acquisition period in September 2000 (Figure 1). The profiles are labeled from 1 to 6, and were acquired at the following locations: 1) north of the Galena airport; 2) along the bike path through the city of Galena; 3) roughly midway between Galena and the old Campion air base; 4) old Campion air base; 5) north of the AM radio tower and south of Profile 4; and 6) southwest of Profile 5 ending near the Yukon River. The general seismic

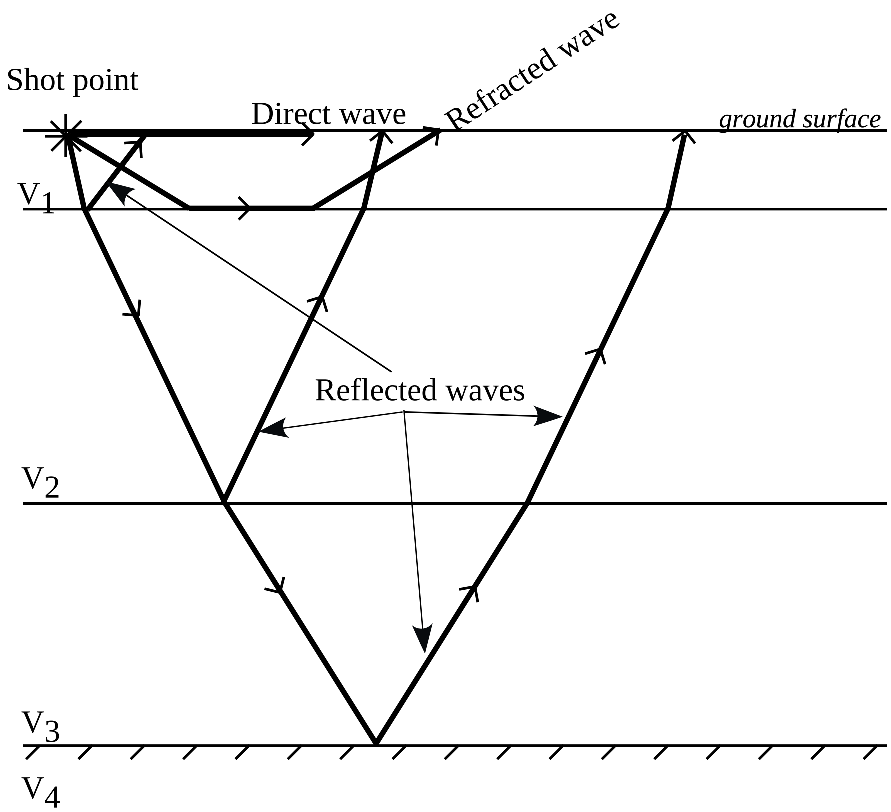

Figure 2. Simplified diagram of selected travel paths for a single seismic wave from a shot point at the ground surface. Velocities increase with depth (V_4>V_3>V_2>V_1) and no refractions from the two deeper interfaces are shown. Seismic reflections are generated where velocity and material density changes across a boundary. Both P- and S-waves generate direct waves, reflections, and refractions

acquisition parameters for these profiles are listed in Table 1. Topographic survey data were acquired by GPS. The accuracy of these survey data was poor, typically no better than ± 15 ft, due to thick tree cover generally in the vicinity of the profiles (hence poor satellite coverage).

Estimating the amount of Kinestik® seismic explosive used per source point in an ad hoc manner was a primary acquisition difficulty. The farther from the receiver locations, the more explosive was used, but sometimes the amount was underestimated because of unknown local site conditions, making the seismic signal weak and therefore difficult to analyze at farther receiver distances. Because of the reconnaissance nature of the investigation and the limited budget, the explosives had to be carefully rationed and therefore we rarely had the luxury of re-shooting a source point. Another major problem we encountered was the source hole depth and diameter. The drilling rig provided by the City of Galena drilled an excellent hole for charges of 1-pound and less. But for larger charges, a smaller diameter hole and/or a deeper hole would have been advantageous because the higher energy shots often "blew out" the recently excavated back-filled dirt. The energy released during these blowouts dramatically decreased the energy sent into the ground as seismic signal.

Table 1. Generalized Acquisition Parameters for Galena Seismic Data

Parameter	Description
Source type	Kinestik® seismic explosive
Source size	Single shot hole 6-8 feet deep with 1/3 to 4 pounds of explosives (dependent on distance to receivers)
Source point interval	Relative to receiver spread: in the middle,16.4 ft off each end, 985 ft off each end, and 1970 ft off each end (when possible)
Receiver type	8-Hz resonant frequency, vertical component geophone
Receiver array	Single geophone per station
Shooting geometry	60 channels, deployed out as linearly as possible. Sources as in-line as practical
Station interval	32.8 ft
Field filters	60 Hz notch
Recording system	Geometrics 60-channel StrataVisor
Sampling rate	1 millisecond
Recording time	2 seconds

Kinestik® is a registered trademark of Kinepak Corporation

Data processing was limited only to steps necessary to maximize coherent reflection and refraction signals (Table 2). CDP stacking (i.e. to make a stacked seismic section), a technique universally used in the oil industry, was unsuccessful at enhancing these data. This was primarily because the very limited number of shot records obtained did not yield adequate coverage for this technique. Some additional signal enhancement was achieved by combining traces at similar source and receiver offsets from all shots at each profile location (‘sort and stack’ step in Table 2). Shot records prior to this final processing step are shown in the Appendix.

In the following section, the data are presented after all of the above steps have been performed (Table 2). The data are shown as recording time versus distance from the receiver spread midpoint. Interpretations are made using industry-standard algorithms for estimating depths of reflecting and refracting boundaries (sometimes referred to herein as interfaces; e.g. Telford et al., 1990). As will be noted, the earliest (in time) seismic events are often difficult to differentiate and thus are often referred to as “direct arrival/refraction,” indicating this ambiguity.

Table 2. Generalized Data Processing Steps for Galena Seismic Data

Processing Step	Comment
Data Reformat	Convert field data to processing format
Geometry	Install topographic coordinate data into trace headers
Trace Edit	Omit bad traces and change incorrect trace polarities
Bandpass Filter (Hz)	Limit frequency range to optimize signal (40-to-500 Hz pass band).
Automatic Gain Correction	Adjust amplitudes using 500 ms gain window
Deconvolution	Compress wavelet and attenuate reverberation using adaptive algorithm with 200 ms operator length
Elevation Statics	Time-shift traces based on station elevation differences to better align recorded signal from receiver to receiver
Sort and Stack	Sort all traces at each profile location by offset (distance from source to receivers) and add these common-offset traces together. Display as a single ensemble centered at the midpoint of the receiver stations

GEOLOGICAL INTERPRETATION

Based on limited knowledge of the depositional environment, it is believed that the Yukon Valley basin sediments are relatively homogeneous in terms of their seismic characteristics. Lateral variation in deposition and limited compaction time (few million years) often make seismic reflection/refraction signal small across sedimentary layer boundaries. It is reasonable to infer that one of the first continuous and observable seismic contacts is between the Quaternary/Tertiary saturated sediments and Tertiary/Cretaceous bedrock. In the following interpretations, we thus assume one of the first continuous and observable reflections/refractions at farthest source-receiver offsets on each profile are from this sediment/bedrock interface. It should be remembered, however, that both observable reflections within the sediments will occur and that the sediment/bedrock velocity (and density) contrast may not be high enough to detect.

Permafrost was present in almost every drilled shot hole. It appeared to be thick (based on the seismic data, on the order of 100 feet or greater) and continuous at all of the sites we investigated. It had been hoped that this high-velocity layer would be thin to non-existent at some locations, allowing the use of seismic refraction modeling techniques that utilize direct and first-refraction arrivals. However, the direct and refraction arrivals in these data have traveled almost entirely from permafrost, as suggested by their arrival velocities between 11400 and 13120 ft/s, which rendered this part of the data unusable for refraction analysis of bedrock depth. Therefore, this left us with the analysis of reflection events and later refraction events within the seismic data. The disadvantages of analyzing these later events on data acquired in reconnaissance mode such as these include: 1) it is more difficult to accurately define boundary depths;

and 2) layer dip is not easily resolvable. In general, all depths estimated from these data have an accuracy of ± 100 ft.

Numerical Simulation of Shot Record for Assumed Flat-Layer Sub-Surfaces

We utilized a numerical modeling technique (elastic two-dimensional finite-difference modeling; Larsen, 1992) to investigate the effect bedrock depth beneath permafrost and saturated sediments had on the recorded data. Modeling was performed to better qualify our interpretation. The velocity structure used in the finite-difference modeling is somewhat constrained by the seismic data. The models were comprised of four layers that represent: 1) unfrozen surface soils and mud; 2) permafrost sediments; 3) Quaternary/late Tertiary unfrozen and unconsolidated deposits; and 4) Tertiary/Cretaceous bedrock. The layers were all assumed to be horizontal. Dipping layers would yield different results depending on the steepness of dip.

Direct-arrival, reflection, and refraction measurements of the field data helped determine seismic velocities in the upper three layers. Velocities in the bedrock layer were inferred from comparison of outcropped rock with typical velocity ranges for these rocks. P-wave velocities ranged from 2640 ft/s to 13200 ft/s across the four layers, with corresponding S-wave velocities ranging from 1320 ft/s to 7920 ft/s. Densities varied from 2.2 gram/cm^3 to 2.6 gram/cm^3, and were derived from published values for the assumed materials (e.g. Telford et al., 1990). No attenuation was incorporated in the simulations, and only event arrival times were used to assess modeling results. Because the goal of this modeling was primarily to determine bedrock depth under permafrost and saturated unfrozen sediment, no attempt was made to model thin coal deposits within the bedrock.

Several of the simulated shot records created for this study are shown in Figure 3. Layer 1 (surface soil/mud) was set at 6.5 ft thick, and layer 2 (permafrost) was set at 100 ft thick. The thickness of layer 1 was determined based on drilling, while that of layer 2 was estimated from the seismic data and from previously existing drilling information. In general, these thicknesses permit a reasonable match of the direct and refracted arrivals within the actual seismic data. Bedrock depth and layer velocities were varied between each model. As bedrock gets shallower and/or sediment velocity changes, the arrival time of the bedrock reflection changes accordingly (R_b in Figure 3). Similarly, an event labeled R_f (Model B), which is the refraction off bedrock, appears sooner in the record as bedrock becomes shallower. If bedrock is as shallow as 200 ft (Model E), both R_b and R_f become masked by the direct and refracted arrivals from the permafrost layer. Modeling such as this is important to better qualify what seismic interfaces may be within the complex shallow velocity structure around Galena.

Profile 1

Profile 1 was acquired north of the Galena airport. The first events on the seismic record are direct-and-refraction arrivals with an average velocity of 11500 ft/s (Figure 4). By 1980 ft offset from the profile midpoint, the direct-arrival/refraction has died out. This is probably caused in part by use of undersized seismic charges at far offsets, as well as by the permafrost thickness along the profile and the decrease in velocity with depth beneath the permafrost. At offsets between 2000 and 2970 ft and after 0.25 s recording time, a coherent event is observed that is labeled as R_1. Unfortunately, after exhaustive analysis, it was not clearly resolvable as either a reflection or refraction. If it is a reflection, then it moves out at a velocity of approximately 8250 ft/s and would emanate

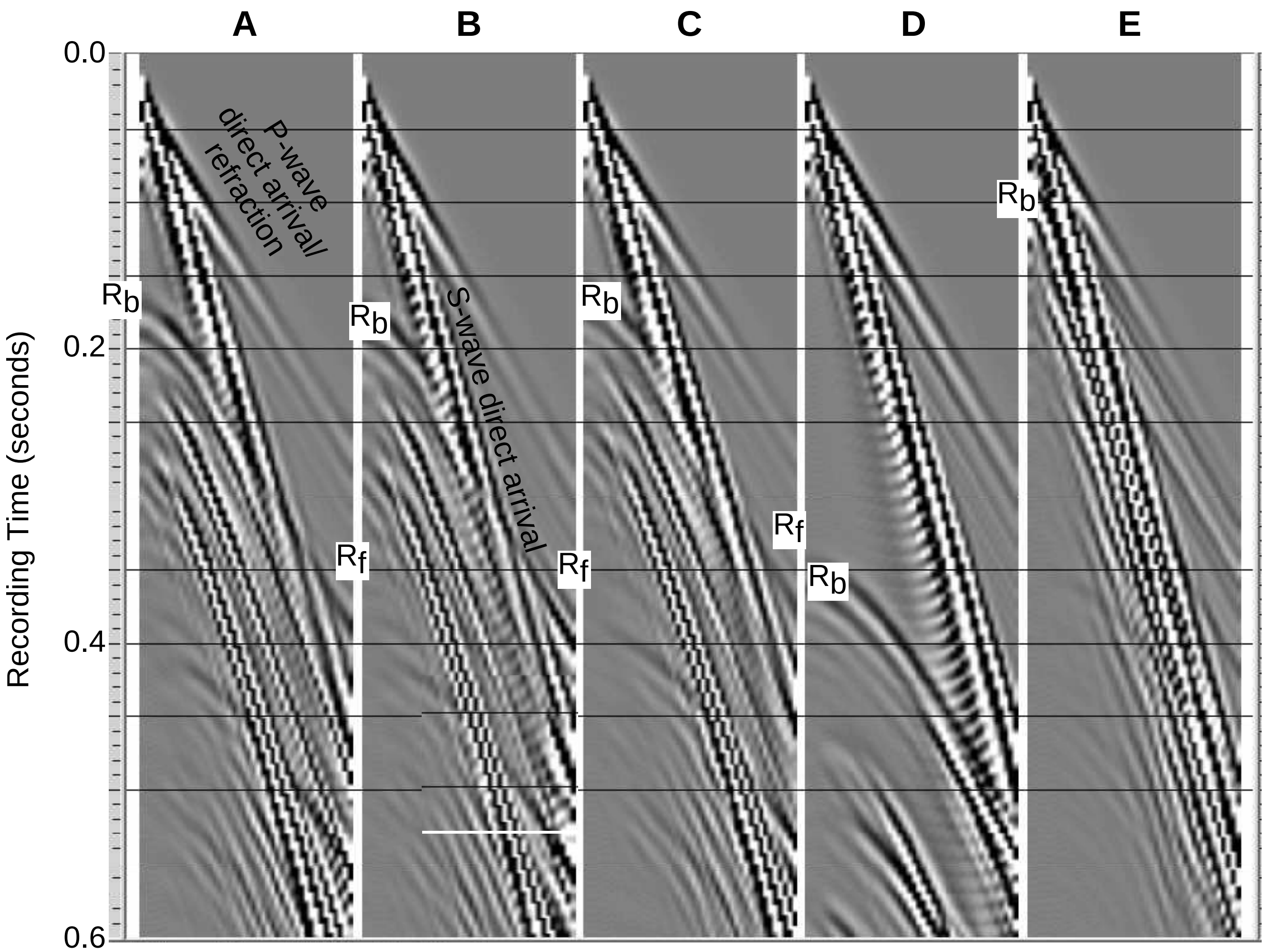

Figure 3. Synthetic seismic shot records generated with finite-difference numerical modeling. All models consist of four layers, as discussed in text. Bedrock reflection is labeled R_b on each record. Refraction from bedrock is labeled as R_f. Model **A** has bedrock at 550 ft depth and has 100 ft of permafrost. Model **B** has bedrock at 550 ft depth and permafrost velocity at 92% of model **A**. Model **C** has bedrock at 550 ft depth and saturated sediment velocity at 110% of model **A**. Model **D** and **E** are also similar to model **A** but with bedrock at 1100 ft and 200 ft depths, respectively. As bedrock gets shallower and/or velocity of sediments increases, bedrock reflection arrives earlier in recording. Even in synthetic shots such as these, with simple flat layer geology, complexity of seismic wave field is apparent.

from a reflector estimated at about 1100 ft ± 100 ft depth. If event R_1 is a refraction, then it emanates from a seismic interface that dips to the southeast and ranges in depth from 550 ft to 800 ft, ± 100 ft, along the profile. The coherent event arriving just after R_1 is possibly another reflection, R_2, moving at a velocity of about 6270 ft/s. If R_2 is a reflection, then it would be from a reflector at about 650 ft depth. Given the assumptions discussed in the previous section, we believe that R_2 is the reflection and R_1 is the refraction from bedrock beneath Profile 1, at an average depth of 650 ft. The bedrock velocity of approximately 11150 ft/s is higher than one would anticipate for young sedimentary rock, suggesting that the reflector may be a volcanic or igneous rock.

Profile 2

Profile 2 was acquired along the bicycle path on the north side of the main road through Galena (Figure 1). These data are similar in overall appearance to those acquired along Profile 1. The first arrivals at this site average 12200 ft/s, slightly faster than at Profile 1 (Figure 5). Just as observed on Profile 1, the first coherent event at offsets beyond 2000 ft is not clearly resolvable as either a reflection or refraction. If event R_1 is a reflection, then it moves out at a velocity of approximately 8250 ft/s and would be from a reflector estimated at about 900 ft depth. If it is a refraction, then it is from a boundary that dips gently west and ranges in depth from 510 ft to 575 ft. The coherent event R_2, may be a reflection that moves out at a velocity of about 6600 ft/s. As in the case of profile 1, if R_2 is a reflection, then R_1 is its corresponding refraction from a boundary at roughly 550 ft depth. The estimated bedrock velocity beneath Profile 2 (assuming the reflection/refraction are from bedrock) is also higher than anticipated for sedimentary

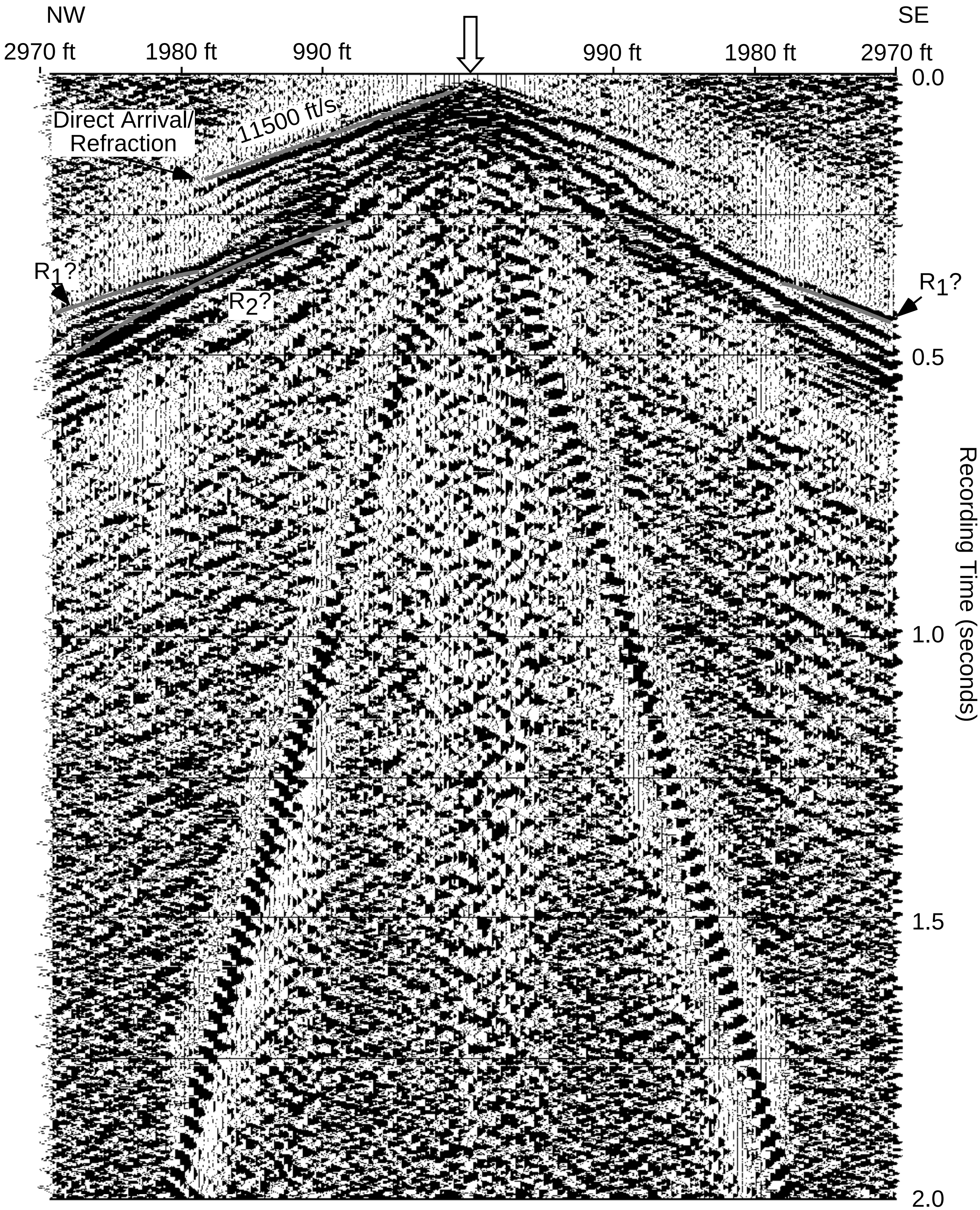

Figure 4. Data from 5 shots recorded on Profile 1, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread profile. Refraction and direct arrival energy are the first coherent events seen near the start of recording time. A possible reflection or refraction is labeled R_1. Another possible reflection believed to be from bedrock is labeled R_2. If R_2 is a reflection, then R_1 is the refraction from the same interface.

rocks, at 10560 ft/s.

Profile 3

Profile 3 was acquired about 3 miles east of Profile 2 along the main road between Galena and the old Campion air base. These data have the most prominent and fastest P- and S-wave direct and refracted arrivals of all the profiles, as observed on the eastern side of the receiver array midpoint (Figure 6). These data are also unique among the profiles because of deeper apparent reflections and a series of high-velocity apparent reflections seen at less than 0.5 seconds recording time at far offsets on the eastern side of the profile (below R_1). Analysis of the east-side direct arrival/refraction suggests a change in lithology at about 300 ft depth, and this probably indicates a change in frozen material or thicker permafrost at this location. The direct and refraction arrivals on the western side of the midpoint are similar to those observed on Profiles 1 and 2. However, estimated reflection velocities indicate the reflectors are quite deep, over 1100 ft. The event labeled R_1 is the best-guess bedrock interface; its depth is approximately 750 ft. Overall, the data on profile 3 are complex and may be indicative of thick permafrost coupled with geologic structure and rapid lateral change in rock type.

Profile 4

Profile 4 was acquired along the abandoned landing strip at the old Campion air base. Although over 6 miles from Galena, this site was selected to determine if bedrock might be shallower underneath the topographic high at the old base (Figure 1) and therefore more economic to drill. These data show two events believed to be reflections (Figure 7). The velocity of the shallow event R_1 travels at roughly 10230 ft/s, sufficiently fast to have traveled through a significant section of frozen sediment or bedrock. We

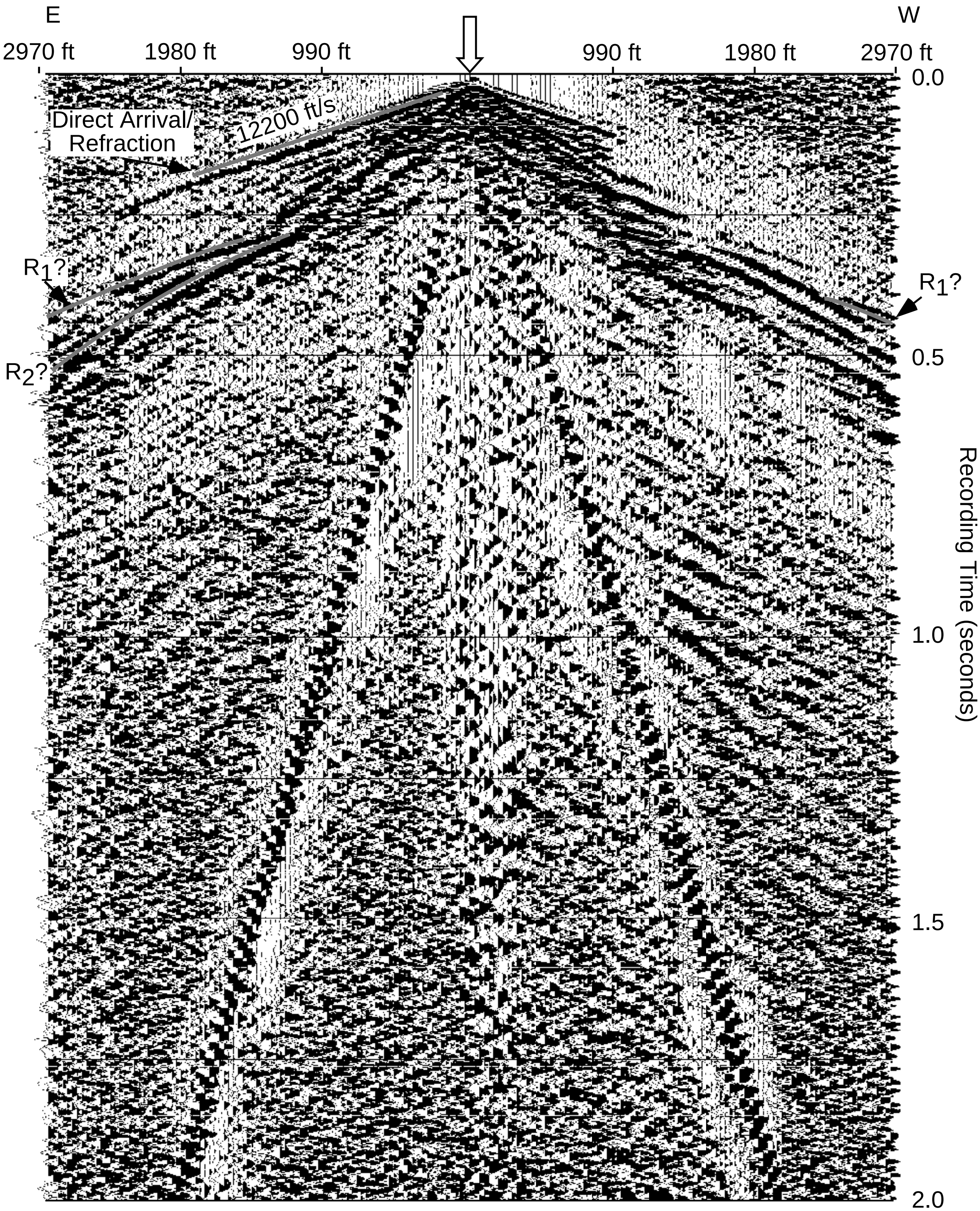

Figure 5. Data from 5 shots recorded on Profile 2, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread profile. Refraction and direct arrival energy are the first coherent events seen near the beginning of recording time. A possible reflection or refraction is labeled R_1. Another possible reflection believed to be from bedrock is labeled R_2. If R_2 is a reflection, then R_1 is the refraction from the same interface.

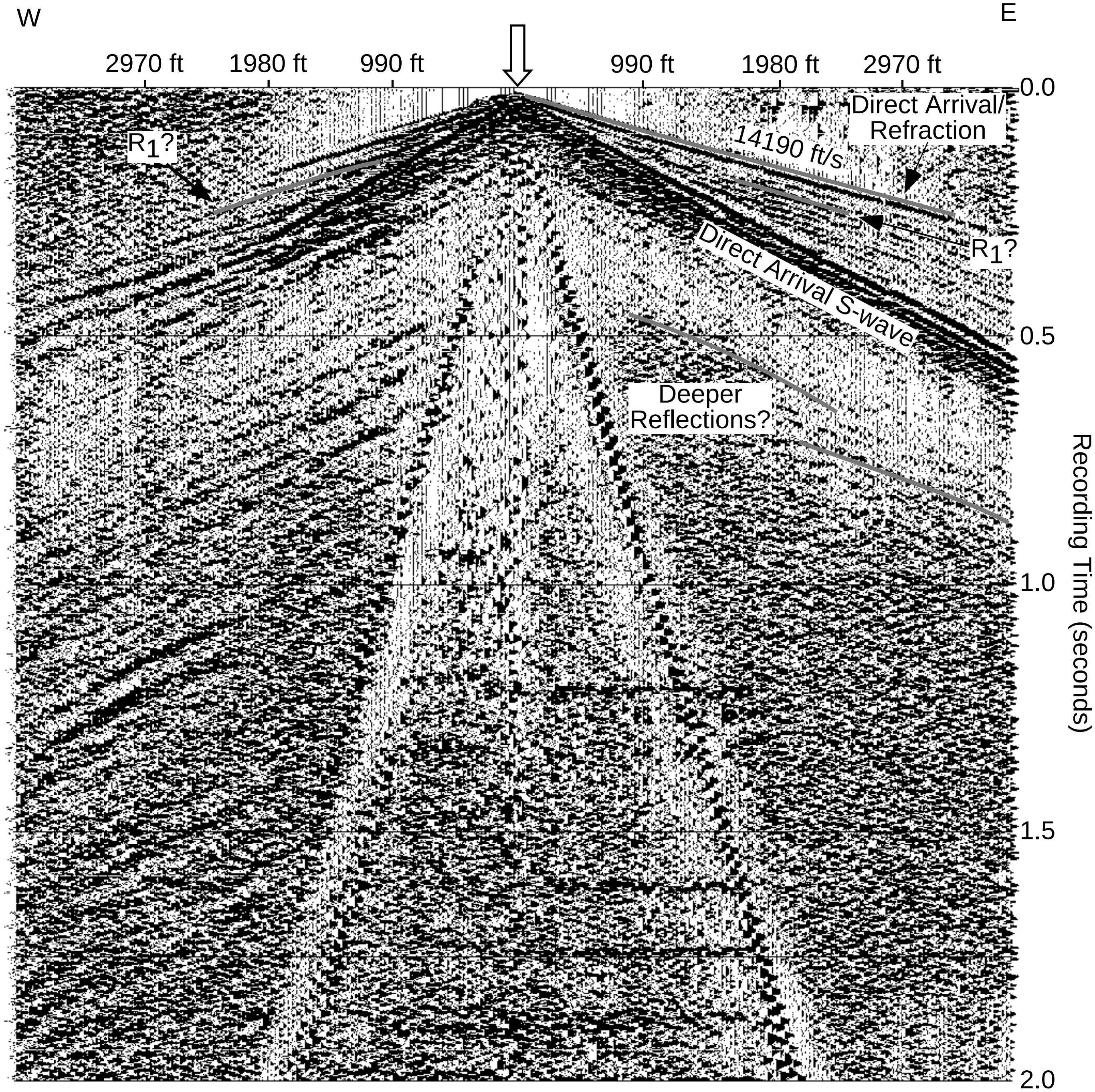

Figure 6. Data from 7 shots recorded on Profile 3, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread profile. Refraction and direct arrival energy are the first coherent events seen near the beginning of recording time. A possible reflection is labeled R_1. A set of possible deeper reflections are seen below the S-wave direct/refracted arrival.

interpret this event to be from a bedrock interface at approximately 720 ft depth. The deeper possible reflection event, R_2, arrives much slower at 6940 ft/s. Analysis suggests it would be from a reflector at roughly 900 ft depth.

Profile 5

Profile 5 was acquired southeast of Profile 4, still within the perimeter of the old Campion air force station. The data suggest a thinner layer of permafrost than at Profile 4 and reveal several apparent reflections (Figure 8). Both the direct and first refracted arrivals, traveling at about 10230 ft/s, are slower than those observed along Profile 4. Event R_1 is most likely a reflection that travels at a velocity of approximately 7425 ft/s. Event R_2 is believed to be either a reflection or refraction from a deeper event. If a refraction, the seismic event is from an boundary at a depth of about 600 ft. A weak possible reflection correlates roughly with this depth. Event R_1 is interpreted as evidence of bedrock at about 415 ft, while event R_2 is believed to be from an inter-bedrock boundary.

Profile 6

Profile 6 was acquired along the last accessible stretch of road southwest of Campion air base. These data were acquired to image any shallow rock layers near the river and off the topographic high of Profiles 4 and 5. Unfortunately, this profile located on the most crooked road, had the most topographic variation, and had the poorest elevation control of any acquired in this study. These factors contributed to low-quality processed data that required the omission of the westernmost shot data (Figure 9; see Figure A6 for unsorted shot records). Even after extensive processing, the data are difficult to interpret because of the noise introduced by line geometry errors. The non-

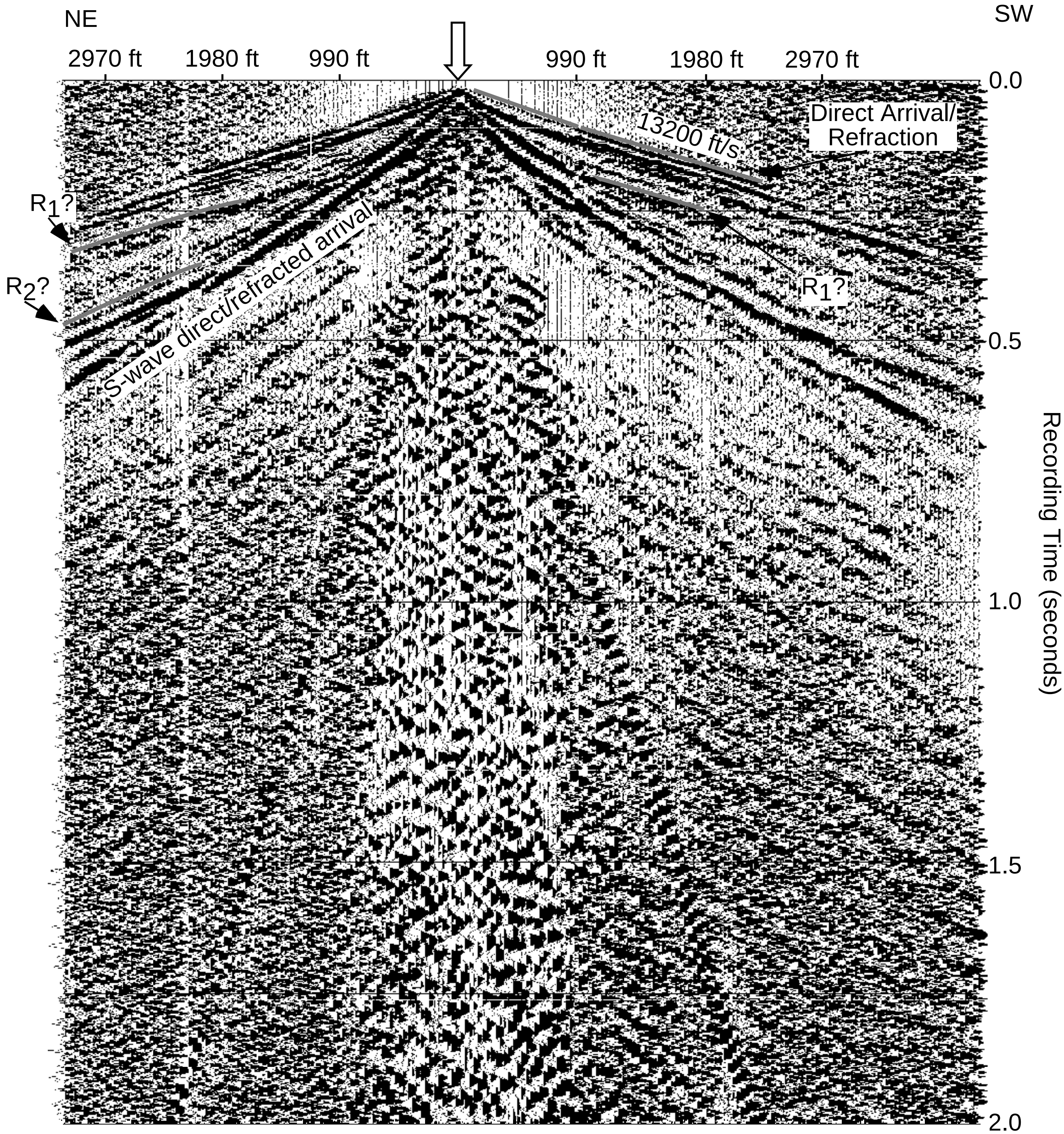

Figure 7. Data from 7 shots recorded on Profile 4, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread profile. Refraction and direct arrival energy are the first coherent events seen near the beginning of recording time. A possible reflection is labeled R_1. A second possible deeper reflection or refraction is seen above the S-wave direct/refracted arrival.

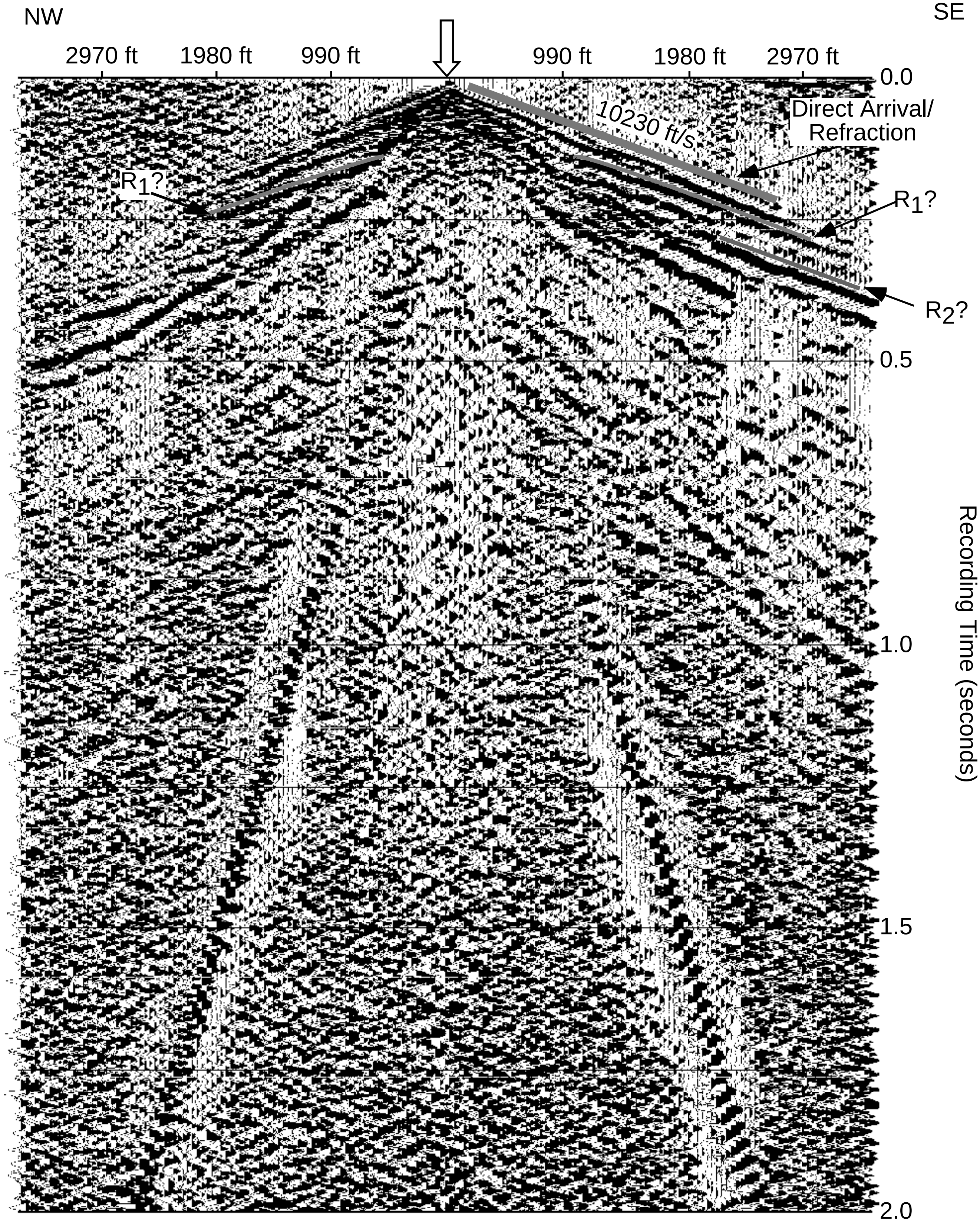

Figure 8. Data from 5 shots recorded on Profile 5, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread. Refraction and direct arrival energy are the first coherent events seen near the beginning of recording time. A possible reflection, R_1, is believed to be from the sediment/bedrock boundary. A second possible deeper reflection or refraction, R_2, is probably from an inter-bedrock boundary.

continuous, rough appearance of the direct/refraction arrival is indicative of this problem. Nonetheless, a possible reflection is interpreted at offsets beyond 1000 ft. This event, again labeled R_1, arrives at significantly different times on the western and eastern ends of the profile. Even though elevation timing corrections were made (Table 2), much of this difference may be due to poor topographic data. This event averages out to be from a boundary at roughly 800 ft depth. We do not have much confidence in the accuracy of this value.

DISCUSSION AND CONCLUSIONS

A direct comparison between the data from the northwestern half of profile 1 and a best-fit synthetic model are shown in Figure 10. The model consisted of a combined 650 ft of soil, permafrost, and sediment over bedrock. The bedrock reflection beneath the shot on the synthetic record is clearly visible. On the real data it is not, primarily because of coherent and random noise in the real world that is not predicted by the numerical simulation. In general, seismic events such as the direct/refracted P- and S- waves match up fairly well between the real and synthetic data. Events labeled R_b and R_f on the synthetic data are known to be from the bedrock interface from the model. These events align with similar events in the real data. We therefore believe these events in the real data are from bedrock, as interpreted.

In the case of Profile 4, at the Campion air strip, synthetic modeling corroborates the assumption that permafrost is thicker than at the previous sites (Figure 11). Profile 4 was selected for this comparison because it is in an area where the seismic events are different than at Profiles 1 and 2. The model consists of 450 ft of permafrost compared

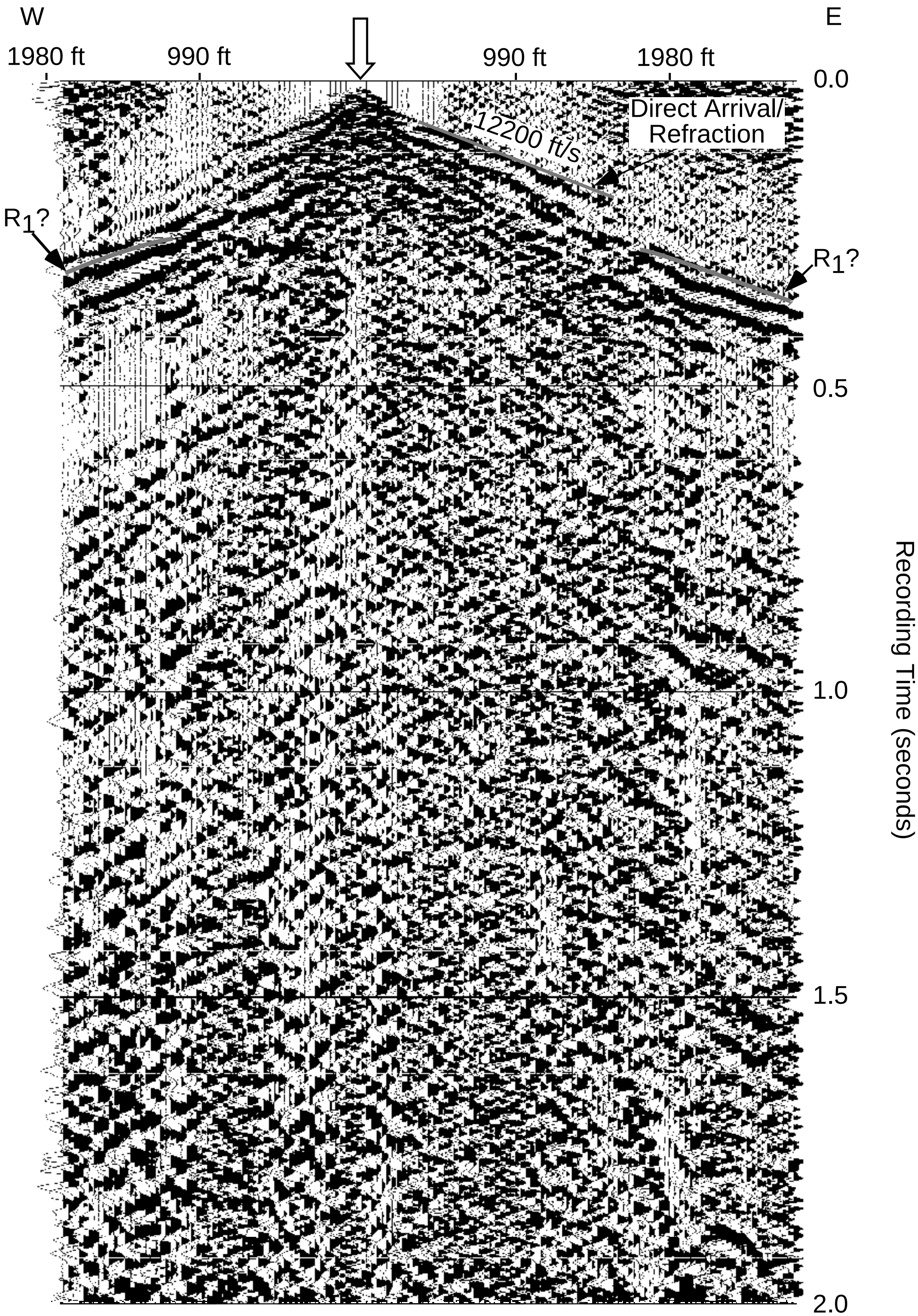

Figure 9. Data from 4 of 5 shots recorded on Profile 6, sorted by shot-receiver offset distance. White arrow is at the mid-point of receiver spread. Refraction and direct arrival energy are the first coherent events seen near the beginning of recording time. A possible reflection or refraction is labeled R_1. Data quality was lowest on this profile because of line geometry problems.

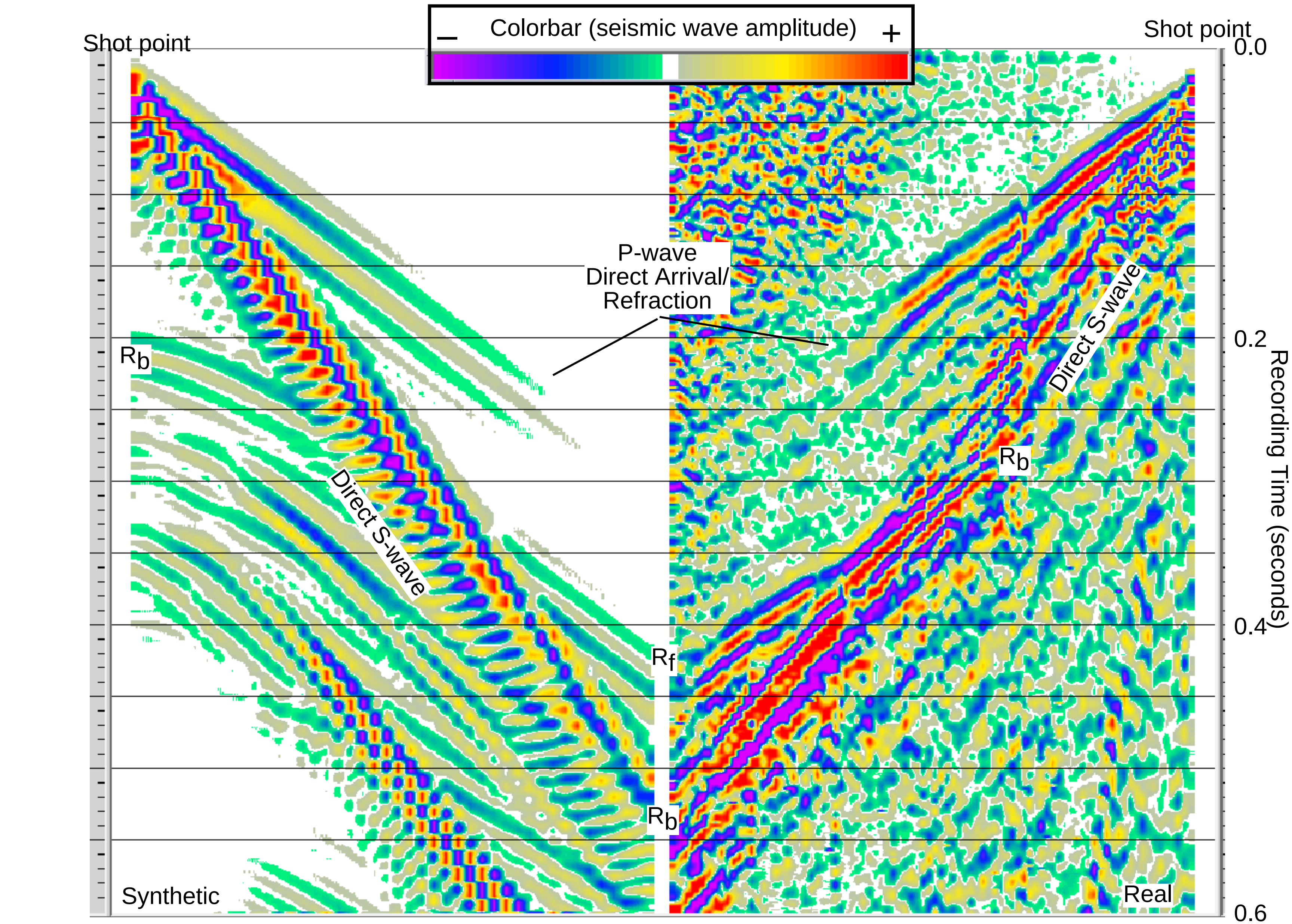

Figure 10. Comparison between a synthetic shot and half of data acquired along Profile 1. Synthetic model consisted of 100 ft of permafrost and 550 ft of sediment over bedrock. Both P- and S-wave direct arrival/refractions match reasonable well, as does the interpreted bedrock reflection (R_b) and refraction (R_f) . Bedrock depth in model of 650 ft is consistent with observed events in data.

with 100 ft in the model of Figure 10. Unfrozen sediment thickness is 150 ft below permafrost and overlying bedrock. As seen in Figure 11, the general pattern of arrival times in the real data matches up with arrivals in the synthetic data. The thicker permafrost causes the bedrock reflection R_b to arrive much sooner in time while any possible bedrock refraction is masked by the direct and refracted P- and S- waves travelling through the permafrost and sediments.

A cross section of interpreted bedrock depth is presented in Figure 12. The interpreted depth is projected on to a cross section line from the midpoint of each receiver array for Profiles 1 through 5. Datum for the cross section is set at 150 feet, roughly the mean elevation at Profile 1. Bedrock does not appear to get shallower than approximately 550 feet in the immediate vicinity of Galena, beneath Profiles 1, 2, or 3. It appears to shallow somewhat toward the southeast of Galena, beneath profile 5, but the evidence for this is not strongly compelling given the complexity of this data set. Even vertically exaggerated 4:1, the interpreted surface is quite flat overall. It is important to remember that what has been interpreted as bedrock may be simply a high-velocity unit within the sediment package or within a sequence of rock. Further, the velocity contrast at the late-Tertiary (?)/Quaternary sediment and rock boundary may not generate an interpretable reflection or refraction large enough to image. Of potential interest, the bedrock velocities appear to be sufficiently high to suggest the existence of a non-sedimentary unit such as a volcanic or igneous rock. Both rock types have been mapped regionally along the Yukon River (about 12 miles both west and northeast of Galena), so their existence in the vicinity of Galena may not be surprising (Bradley, 1938; Cass, 1959).

Because of the complexity of the near-surface velocity structure (from the

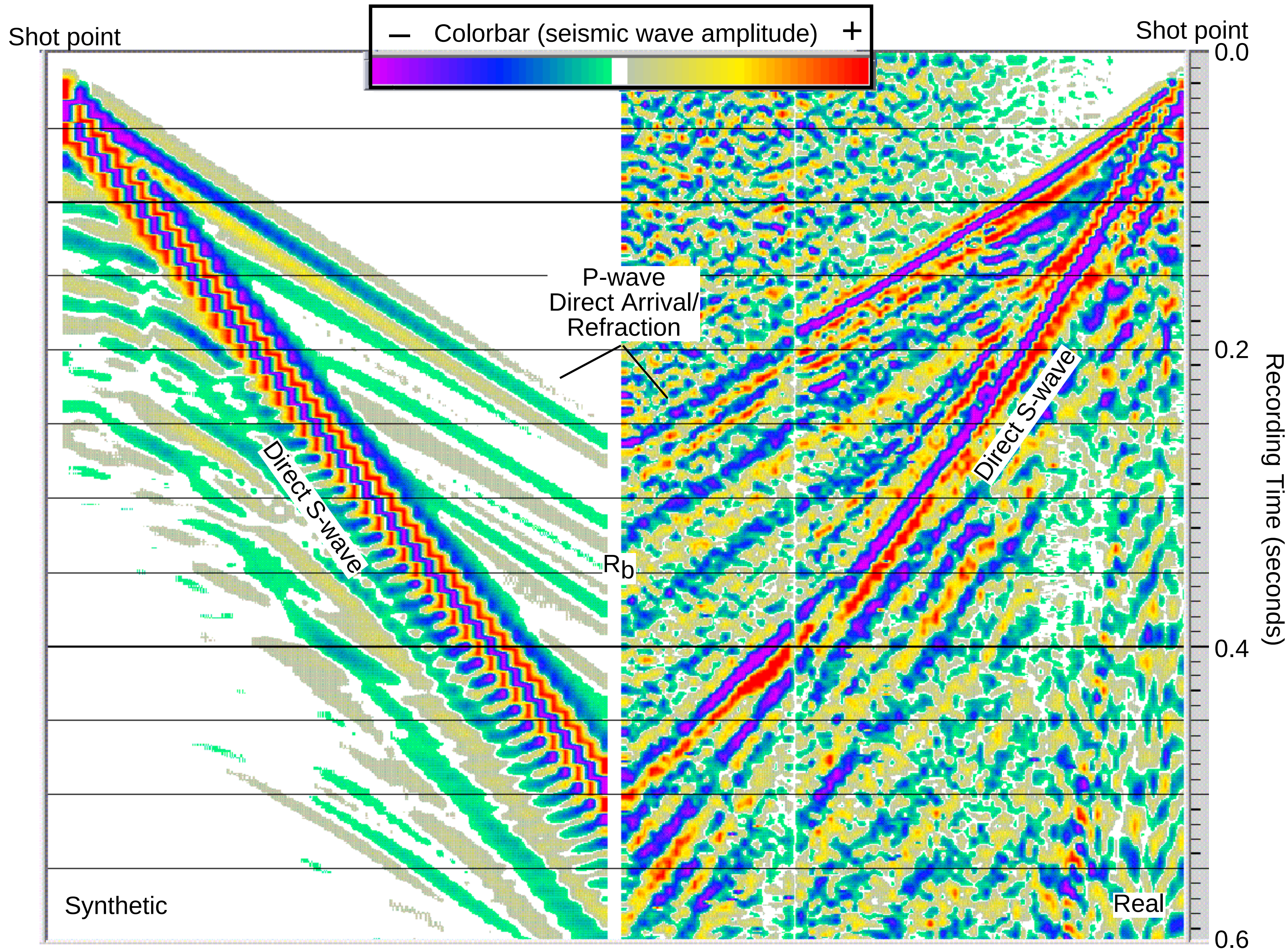

Figure 11. Comparison between a synthetic shot and half of data acquired at Profile 4 location. Synthetic model consisted of 450 ft of permafrost over 150 ft of sediment underlain by bedrock. Both P- and S-wave direct arrival/refractions match reasonable well, as does a bedrock reflection (Rb). This give us some confidence that permafrost is thicker at this site and model bedrock depth is reasonable.

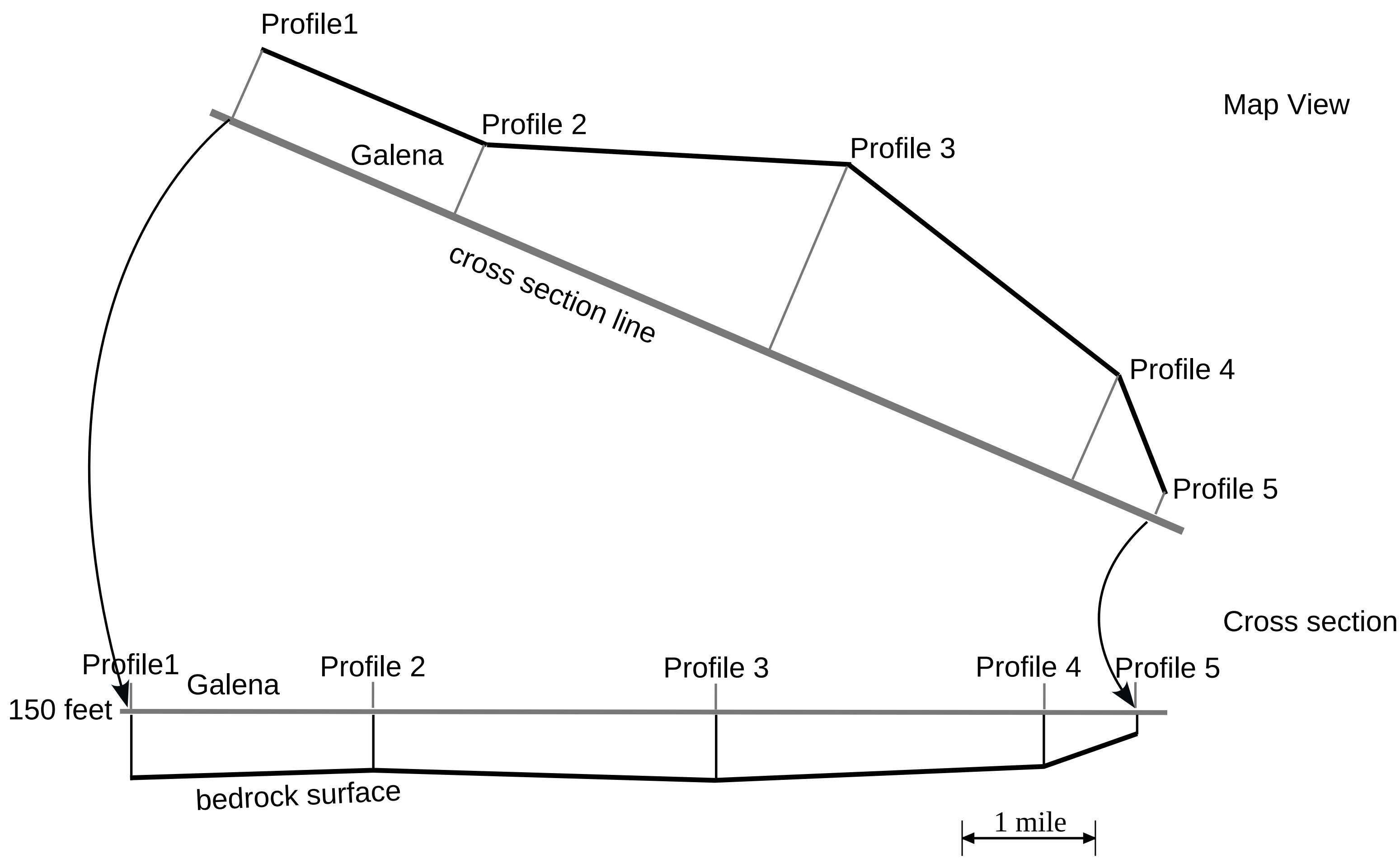

Figure 12. Cross section showing depth to interpreted bedrock surface projected from midpoint for receiver arrays of profiles 1 through 5. Cross section has vertical exaggeration of 4:1 and elevations are projected on to a datum of 150 feet elevation.

permafrost and saturated sediment layers), as well as the unknown contrast between the sediments and the Tertiary or Cretaceous bedrock, we believe an oil-industry-style seismic reflection survey would be an appropriate method to image the necessary targets to answer the problem. However, its cost might be prohibitive given that several 1000-foot holes could probably be drilled for the cost of an industry reflection survey.

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APPENDIX

Shot records from six seismic profile locations near the City of Galena, Alaska

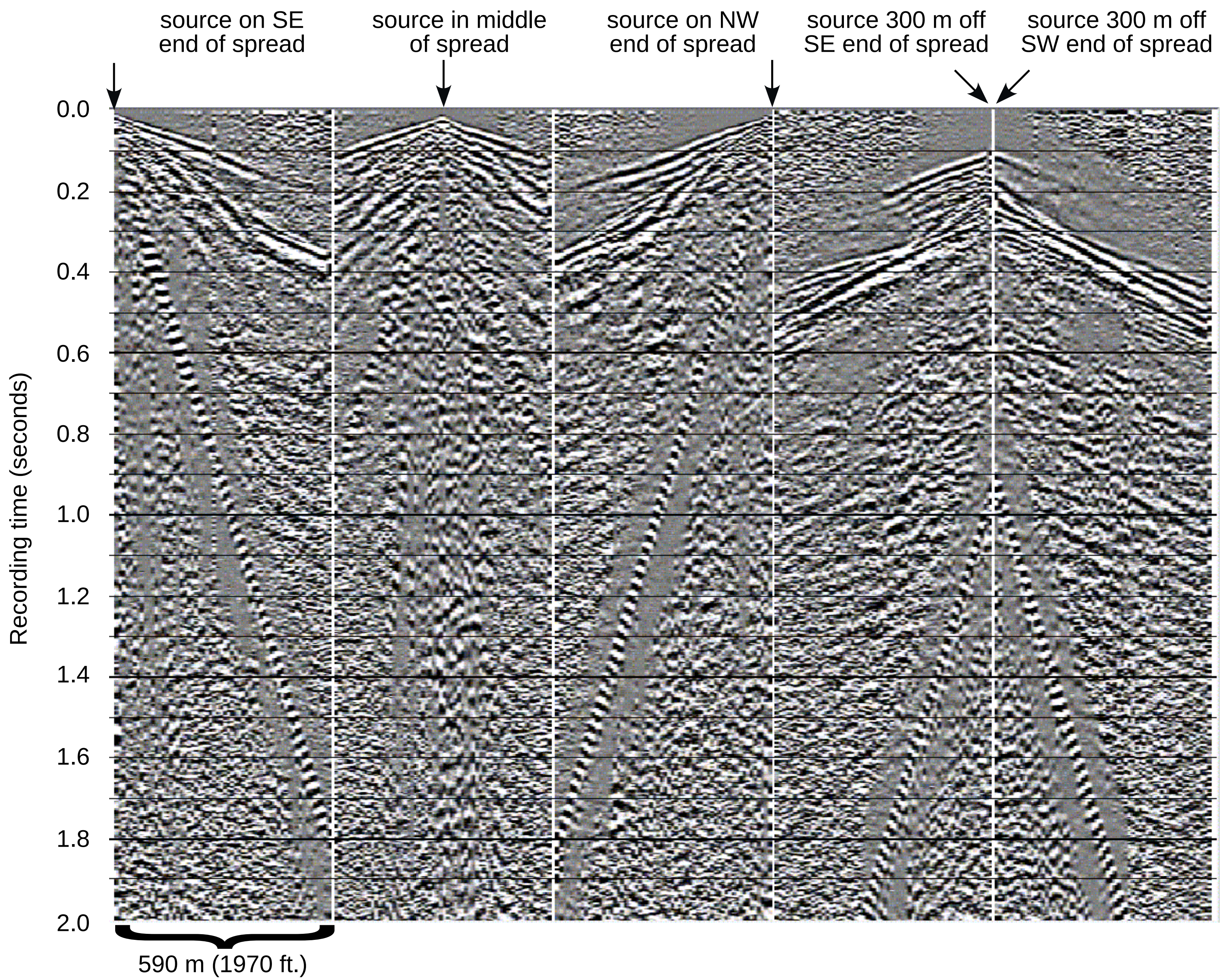

Figure A1. Shot records from Profile 1, north of the Galena Airport. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).

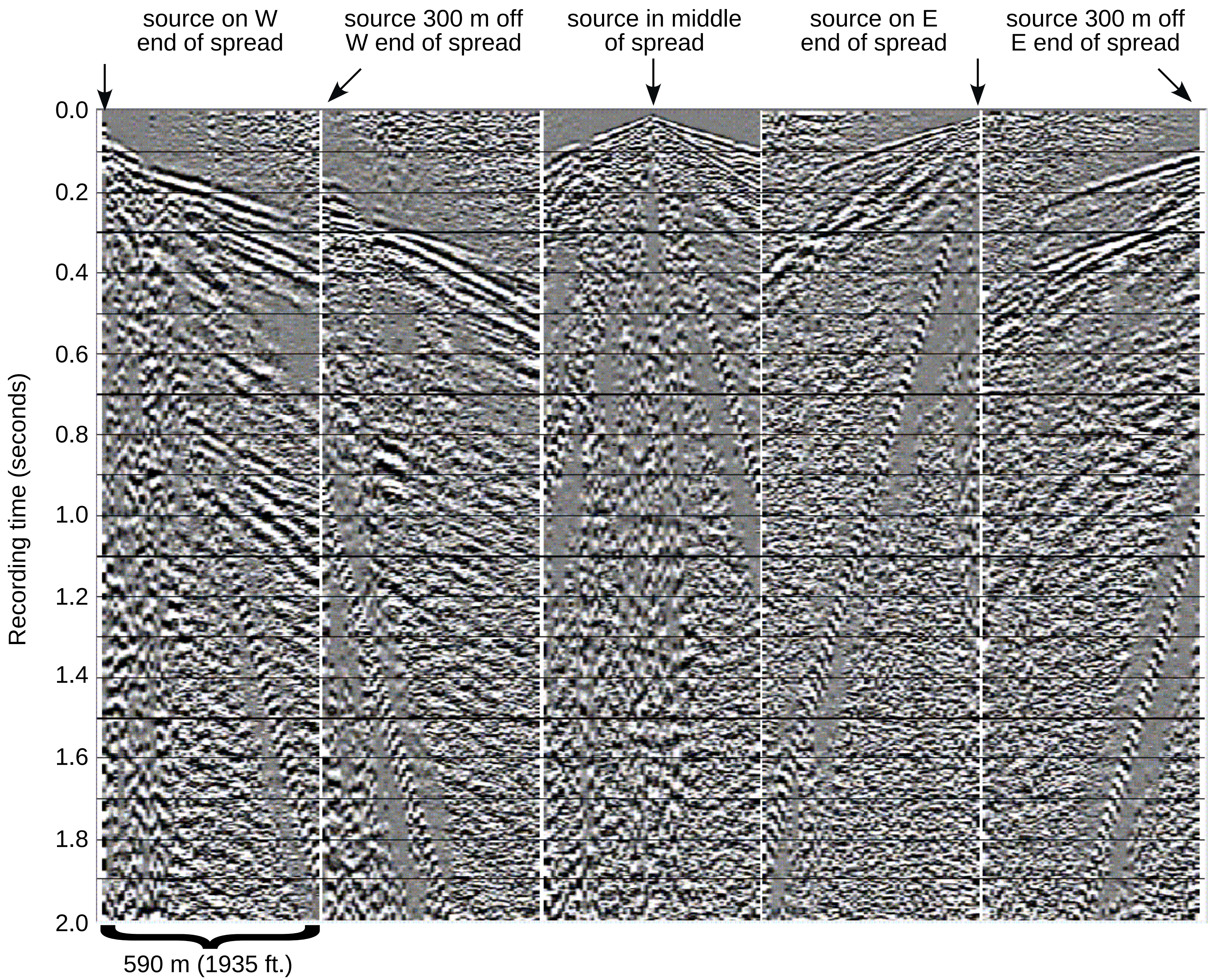

Figure A2. Shot records from Profile 2, along bike path in Galena. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).

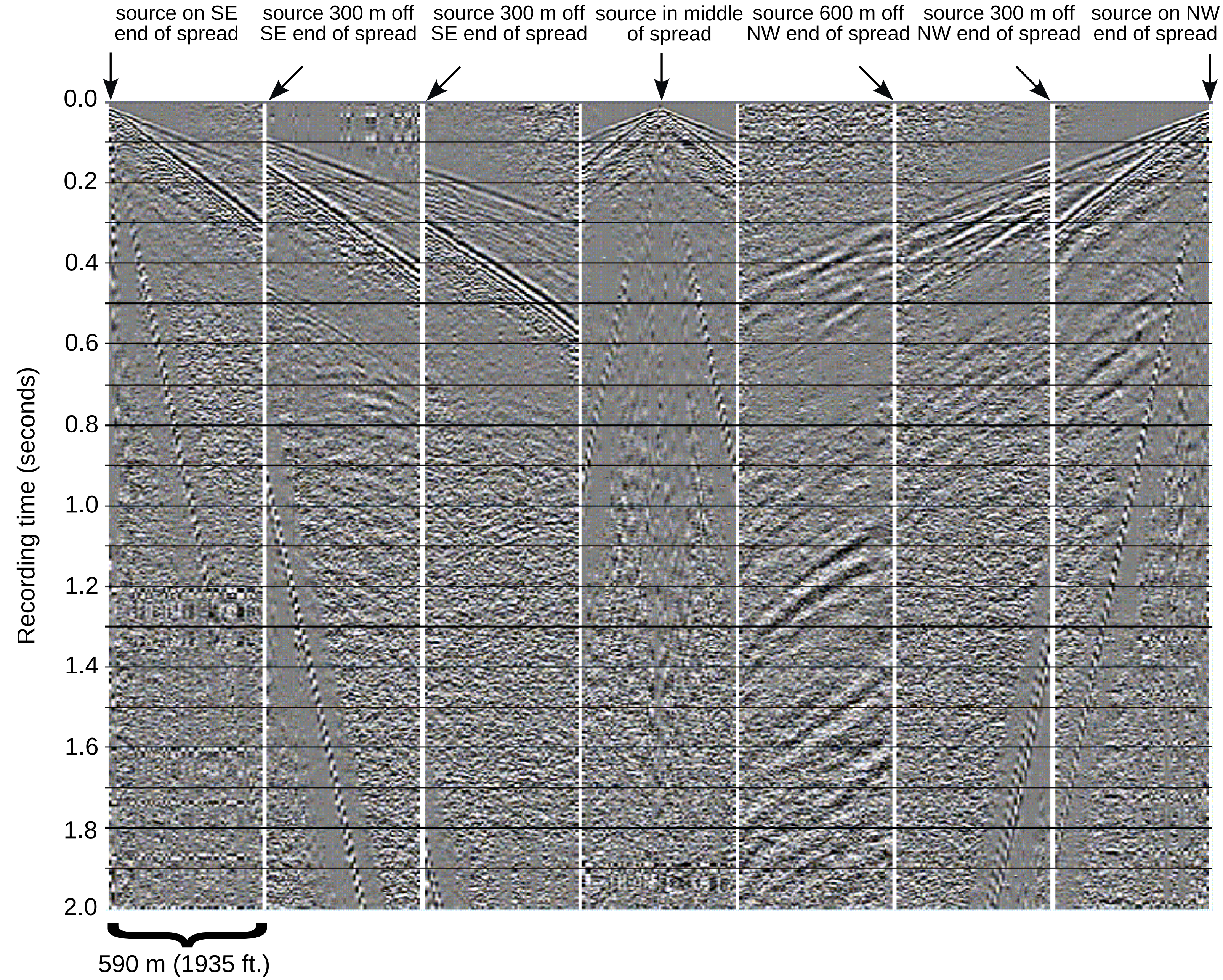

Figure A3. Shot records from Profile 3, roughly midway between profiles 2 and 5. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).

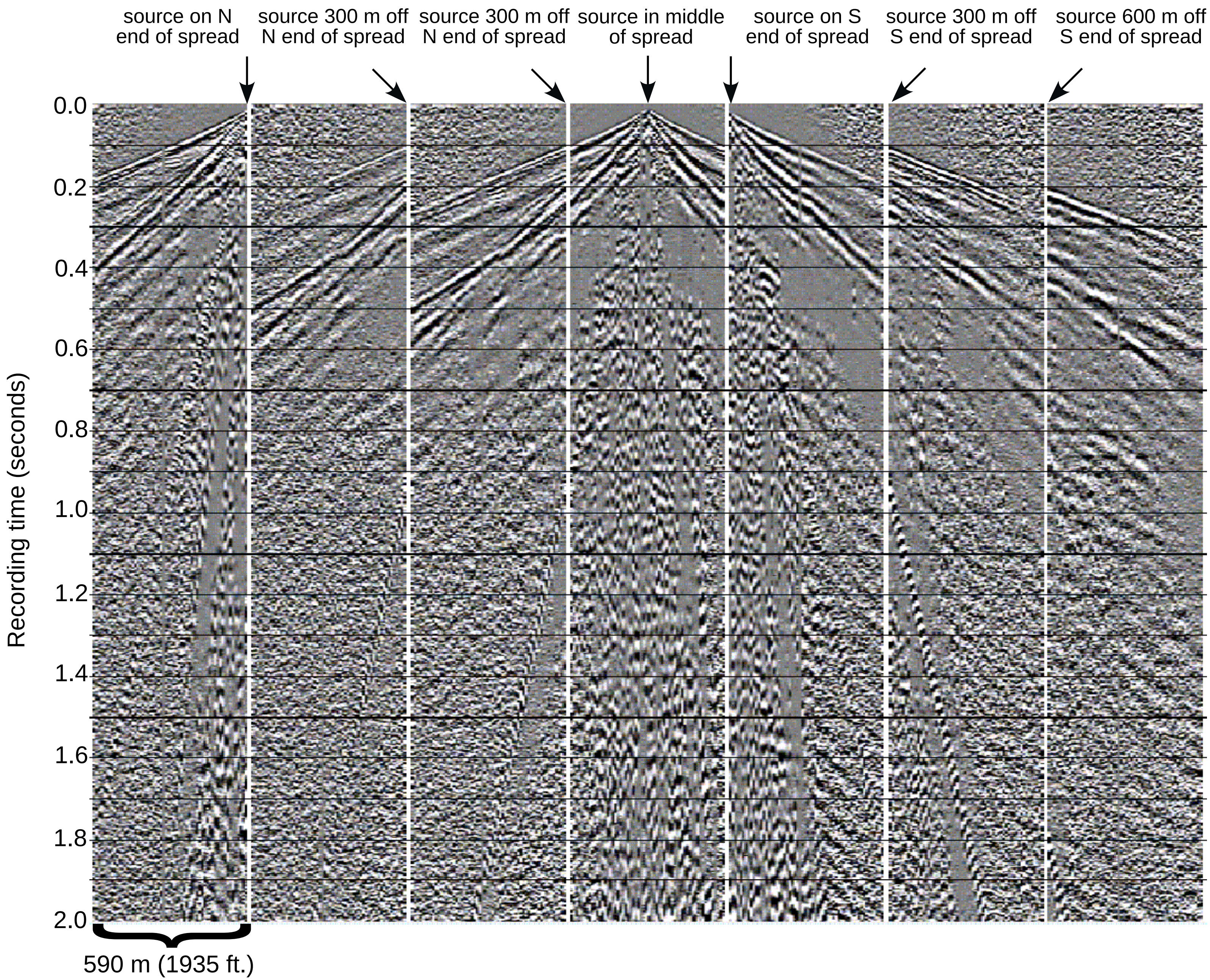

Figure A4. Shot records from Profile 4, at Campion air strip. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).

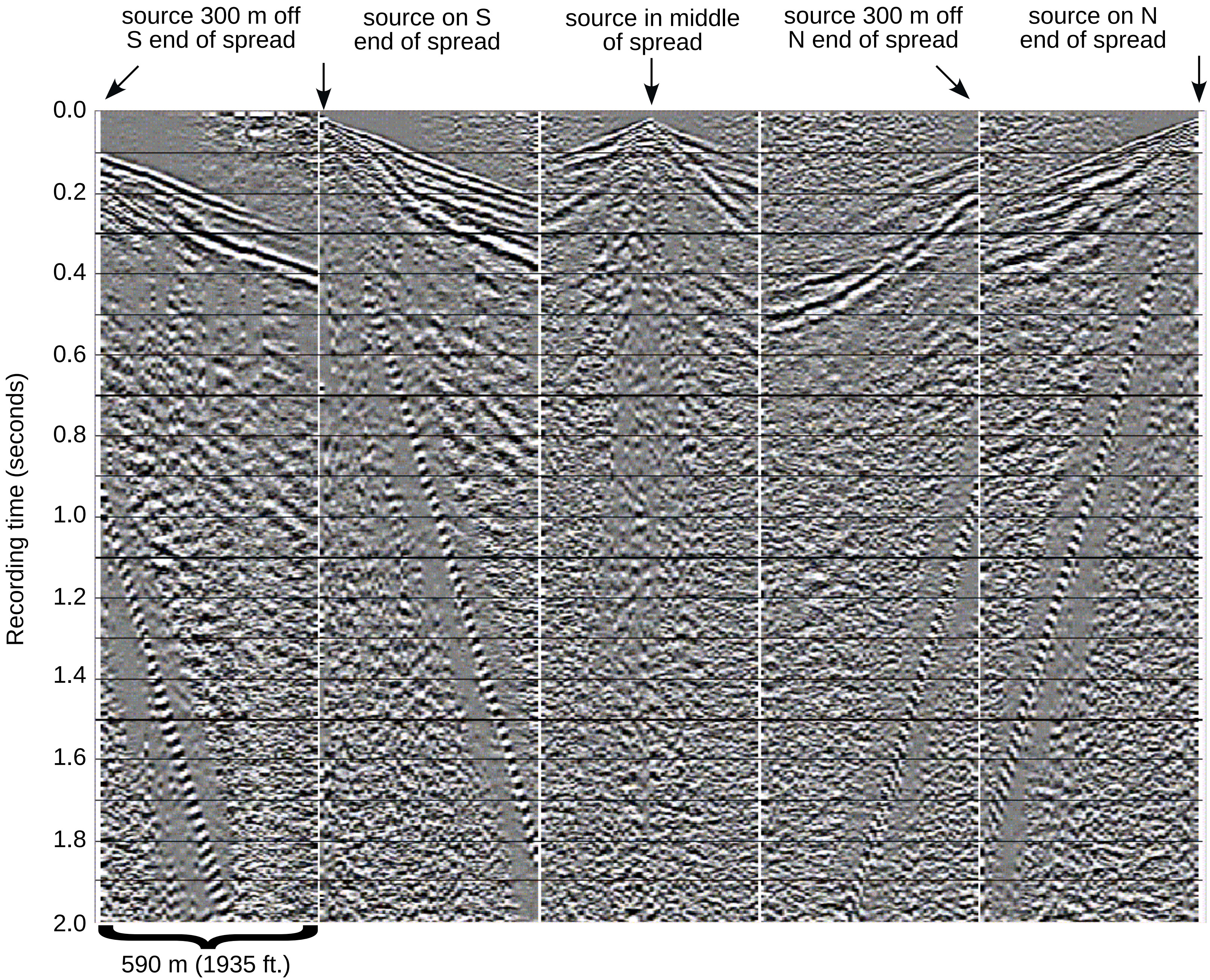

Figure A5. Shot records from Profile 5, south of Profile 4. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).

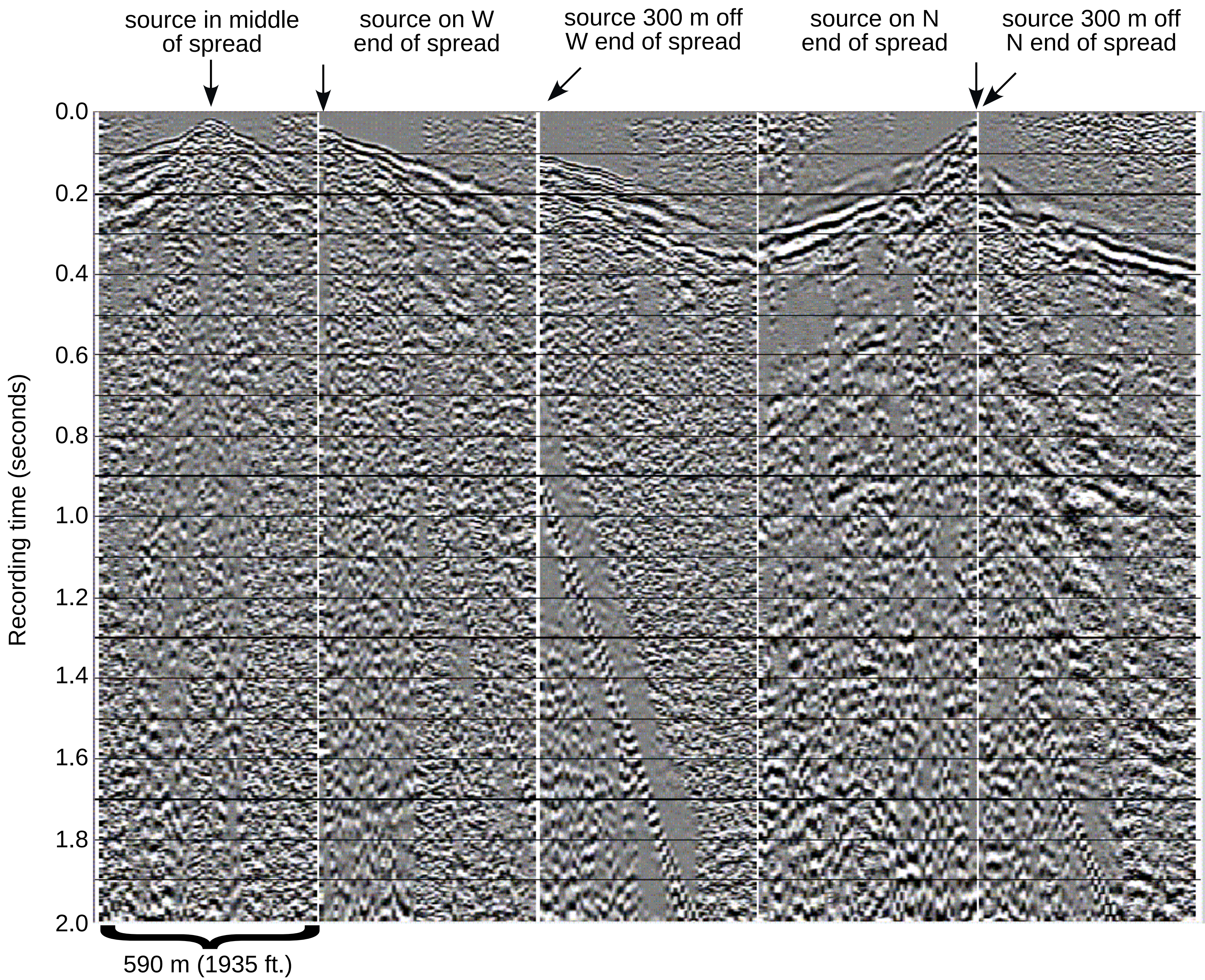

Figure A6. Shot records from Profile 6, southwest of Profile 5. Arrow indicates source location for each record. Sixty receivers were spaced every 10 m over 590-m-long profile. Black represents upward ground motions, white are downward ground motions, and gray are motions at or near zero displacement. Data have been filtered and gain-corrected (see Table 2).