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Interim Report to

Burns & McDonnell WCI
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Introduction

Shallow seismic techniques could complement and enhance the effectiveness of a drilling program designed to locate dissolution features large enough to risk the integrity of equipment or environment at Alabama Electric Cooperative's proposed Damascus site (Figure 1). Dissolution features could directly impact engineering design specifications and future plant safety. Feasibility testing of high resolution seismic reflection and surface wave imaging techniques on December 13 and 14, 1998, focused on the capabilities of these techniques in this area (Appendix A). The primary goals and objectives of this feasibility study were to: 1) identify any acoustic characteristic unique to voids, subsurface subsidence, and/or karst features, 2) evaluate the potential of acoustic methods to enhance drill assisted mapping of major stratigraphic units and structural features at this site, 3) identify the maximum and minimum depths of seismic investigation, 4) estimate resolution potential (vertical and horizontal features detectable and resolvable), 5) define optimum geometries and equipment, 6) study near-surface variability and its effects on recorded data, 7) approximate near-surface static difficulties, 8) observe file-to-file consistency and determine the degree of QC necessary to insure no artifacts are present on stacked data while maximizing imaging potential, 9) evaluate the potential of coincident interpretation of 2½-D reflection and surface wave profiles, 10) determine if a shear wave velocity map from bedrock to the ground surface is a potential product, and 11) determine the feasibility of incorporating production 2½-D reflection and shear wave profiles with exploratory drilling.

Information about the local geologic setting, accompanied by physical examination of surface expressions and exposures of geologic features and anomalies similar to those targeted by this seismic imaging program, provided the necessary background for evaluating the feasibility and optimizing these techniques. Dissolution caverns in the Glendon and Marianna Limestone are postulated to be the origin of voids and collapse features within the Bucatunna Clay and river terrace deposits throughout this part of southern Alabama and nearby northern Florida

(Figure 2). Present at depth (about 100 ft) is the Ocala Limestone, the geologic unit proposed to be responsible for many of the karst-related sinkholes in Florida. The Glendon, Marianna, and Ocala limestones, all present within the upper 150 ft at this site, have a history of dissolution. Critical to safe construction and operation of the proposed power station is the presence of an intact geologic section between the top of the river terrace deposits (ground surface) down to the base of the Ocala Limestone.

A swarm of sinkholes in the Conecuh National Forest less than 5 miles from the proposed site provides an ideal setting to study the acoustic characteristics of pre-subsidence earth. Tests designed to identify acoustic signatures associated with developing sinkholes targeted areas near these sinkholes with no apparent surface expression. Since drilling in the national forest was not possible, survey lines were located in close proximity to sinkholes, with receiver stations adjacent to the sinkholes classified as subsidence prone areas. Results of seismic testing permitted estimation of the detectability of cavities, minimum resolvable dimensions of subsurface features, and depth ranges affected by dissolution.

Testing Procedure

Evaluating the feasibility of seismic techniques and necessary considerations for optimizing the methodologies at this site required testing a variety of parameters and equipment (Steeple and Miller, 1990; Park et al., in press). These techniques will be useful to characterization and engineering at this site if the resolution and detection potential of processed data can be established and is sufficient to allow the largest subsidence feature tolerable by the proposed construction and future operations.

Walkaway tests were instrumental in evaluating shallow seismic reflection at the proposed Damascus (AEC) site (Figure 1). A total of 206 strings of triple, 40 Hz geophones were deployed at 2 ft spacing along line 1 located near borehole B-9. Data from five sources (two projectile, two explosive, and one impact) were recorded with a 240-channel Geometrics StrataView seismograph (Appendix A). End-on and split-spread data provided two unique surface locations and an opportunity to observe all the significant acoustic properties of the wavefield. Walkaway testing was designed to evaluate the utility of state-of-the-art shallow high-resolution seismic reflection techniques in detecting, delineating, and imaging local stratigraphy and karst/dissolution features.

In addition to high resolution seismic reflection, a newly developed surface wave imaging technique sensitive to abrupt changes in shear wave velocity was evaluated (Xia et al., 1998). Abrupt and distinct changes in the shear wave velocity are expected at the contacts between the Bucatunna Clay and Glendon Limestone (bedrock). It is unlikely the pinnacled topography of the bedrock surface (as observed in outcrop) will be completely resolved with the shear wave velocity profile, but the unique pinnacle geometries should provide a distinctive signature. The potential of surface wave imaging was evaluated at three different locations in this study area. A 60-station spread of single, 4.5 Hz geophones was deployed with 4 ft geophone spacings along line 2, near boring B-13, to measure the dispersive nature of this near surface and to quantify the frequency content of surface wave energy (Figure 1). Data were recorded by a 60-channel Geometrics StrataView seismograph. Two shear wave profiles were acquired during this study: one at the AEC site (coincident with the reflection walkaway along line 1) and one in a sinkhole area of the Conecuh National Forest (Figure 1). Both shear wave profiles were recorded with a nominal 30 ft source offset from forty-eight 4.5 Hz geophones separated by 4 ft.

Seismic Reflection Data

Seismic reflection testing was conducted along a single 400 ft long profile (Figure 1). Source and receiver testing focused on resolution and signal-to-noise ratio. Based on comparisons of the five sources tested it appears the 50 cal downhole has the greatest potential to image features from 50 to over 600 ft of depth at this site (Figure 5). This suggestion is based on shallowest discernable reflection, overall frequency content, depth of penetration, number of shots necessary to properly condition the hole, and percentage of noise (ground roll, air-coupled wave, and guided waves).

It is difficult to conclusively determine whether the 30.06 downhole or 50 cal downhole is the optimum source for this site and target depth range. The 50 cal was selected as the optimum source based on its depth of penetration, signal-to-noise ratio, and single shot per station requirement. It is evident after studying the test data that while the 30.06 and 50 cal have similar spectral properties, the 30.06 has slightly better bandwidth and provides the most discernable shallowest reflection (from 35 ft). The 50 cal, on the other hand, has a better signal-to-noise ratio and requires fewer shots to optimize recorded data. If the subtle improvement in either

recording the 35 ft reflector or in resolution potential possible with the 30.06 becomes significant to the survey success, similarity in waveforms make changing sources possible without adversely impacting the interpretability of the data.

Maximizing the economics of the proposed survey requires balancing data redundancy with signal-to-noise and trace-to-trace event coherency. All walkaway testing was performed using 2 ft receiver spacing, which optimized the trace-to-trace coherency of the shallowest reflecting events. Increasing trace spacing reduces the number of sample points along a reflection curve and increases the difficulty distinguishing a unique reflection arrival from coherent noise arrivals. A minimum of four to six unique sample points along a reflection hyperbola should be maintained to provide sufficient confidence interpreting reflection events. Decimating the 2 ft trace spacing on walkaway data to 4 ft and duplicating in reversed trace order allowed simulation of a split-spread geometry with 4 ft receiver spacing (Figure 4c). This configuration will provide acceptable sampling and confident identification of reflections as shallow as 65 ft, and for most records events as shallow as 35 ft might be interpretable.

Hole conditioning has long been known to improve the coupling of high frequency seismic reflection data (Miller et al., 1986). The benefits of hole conditioning are extremely evident on walkaway data from this site (Figure 3). It would be necessary to record at least two and likely three 30.06 shots into each hole at each location if it was chosen as the optimum source at this site. With each shot fired into the same hole the frequency content, signal-to-noise, and depth of penetration increases. Data from the 50 cal downhole does not appear to benefit from multiple shots in a single hole. The first shot is nearly equivalent to all successive shots into the same hole.

Explosive and projectile sources provided superior data at this site. Unique characteristics of each non-impact source are obvious (Figure 5). The most striking difference is the complete lack of air-coupled wave on the 50 cal data (Figure 5b). All three: 30.06 (Figure 5a), 50 cal (Figure 5b), and 8 gauge auger gun (Figure 5c) have dominant reflection frequencies in excess of 250 Hz for the shallower events and 200 Hz for deeper reflections. It is also interesting to note that the 50 cal appears to produce significantly less ground roll than the other two sources. Data from the 50 cal also includes around 50 % more interpretable reflecting events than the other sources under equivalent conditioning. When comparing spectrally balanced shot

gathers from all sources tested at this site, the 50 cal has the greatest potential to meet the project objectives.

Data conditioning proved highly effective and critical to optimizing the recorded data from this site. A technique called spectral balancing was applied to all shot gathers prior to establishing characteristics and comparisons (Figure 6). This process simply quantifies the amplitude of each spectral component of the data and then attempts to increase the amplitude (strength or volume) of each frequency component equivalent to the highest amplitude value. The effect of this process is to bring up or enhance lower amplitude components of the spectra (which are usually higher frequency body wave arrivals) without cutting or removing the high amplitude portions (usually ground roll, however some body wave energy is present at lower frequencies). It is evident that reflection data from this site needs to undergo spectral balancing as a matter of practice.

Based on the properties of these test data, shallow high-resolution seismic reflection should work quite well at this site. Questions of resolution are all that remain in evaluating the feasibility of seismic reflection at this site for the stated goals and objectives. The empirically derived $\frac{1}{2}$ -wavelength criteria for vertical resolution (Miller et al., 1995) suggests 8 ft of vertical resolution is reasonable for the shallower part of the section (35 ft to 100 ft) and 15 ft vertical resolution for the deeper part of the section (250 ft to 650 ft). If the $\frac{1}{4}$ -wavelength axiom is used (Widess, 1974), the minimum vertical resolution numbers drop by 50%, making the vertical limit around 4 ft for the shallower depths and 8 ft or so for the deeper features. Horizontal resolution is a much more difficult property to confidently define. It has been suggested that the horizontal resolution of a reflection data set is about one-half the radius of the first Fresnel zone (Sheriff, 1988). Using this axiom, the horizontal resolution at 65 ft of depth is about 12 ft and at 630 ft of depth it is around 50 ft. This suggests any feature less than 8 ft tall and 12 ft wide at 65 ft of depth and 15 ft tall and 50 ft wide at 630 ft of depth will not be resolvable with a shallow reflection survey at this site. It is, of course, possible to detect features much smaller, but only through wavelet interference or indirect methods (Gochioco, 1992). The rule of thumb for detecting voids stipulates the void be no smaller than an order of magnitude down from the depth of burial (i.e., 8 ft tall void detectable at 80 ft of depth).

Surface Wave Imaging

Surface waves, when used to image the earth, provide a rapid and relatively straightforward method of examining the shallow subsurface. Unfortunately, interpretations of the two-dimensional shear wave velocity field derived from the inversion of the surface wave dispersion curve are much lower resolution than seismic reflection sections. However, the shear wave velocity field derived in this fashion is quite sensitive to abrupt changes in shear wave velocity. In this setting, it is reasonable to expect voids, caverns, or collapse features to be associated with an abrupt change in shear wave velocity.

Seismic reflection surveys are generally designed to image structural and stratigraphic features with a high degree of resolution and accuracy. On such surveys, surface waves are considered noise. For our application, however, it is possible to exploit the sensitivity of the surface wave to changes in material velocities that make up the half-space it travels through. Surface wave propagation depends on frequency (depth of penetration), phase velocity (compressional and shear), and density. Each of these properties will affect the surface wave dispersion curve (phase velocity vs. frequency) in a predictable fashion (Figure 7). Since shear wave velocity has the greatest impact on the properties of a surface wave, it is possible to invert the dispersion curve in such a way as to obtain the shear wave velocity as a function of depth (Xia et al., in press). Disturbances in the shear wave velocity field will show up as anomalies in the otherwise uniform contours of the shear wave velocity field for a layered earth.

Surface wave data were studied at three locations with unique near-surface and/or subsurface features of interest (Figure 1). A short spread was acquired south of boring B-13 (line 2) to establish the dispersive properties of the near-surface material and to select optimum source offsets and receiver spacing. A second profile was acquired using a continuous acquisition method in the Conecuh National Forest in an area where surface expression of subsurface dissolution features was evident (Figure 2). This line was collected so that about half the profile was over what was thought to be undisturbed material and half over an area thought to be riddled with dissolution caverns and voids. This presumption was based on the number and orientation of sinkholes evident in the immediate area. The third and final surface wave profile was acquired coincident with the reflection walkaway identified as profile 1 (Figure 1).

Continuously acquired surface wave data along a line coincident with the reflection walkaway data (Figure 1, line 1) possess several noteworthy features (Figure 8). The high

gradient area between 20 and 35 ft is likely representative of the bedrock surface. Between 30 and 40 ft deep are a series of undulating contours that are remarkably similar to the geometries expected for the pinnacle structures observed in outcrop about one mile east of this site. There appears to be a decreasing average velocity of sub-bedrock materials to the south (toward the higher station numbers). This trend can be traced in general by the violet and purple velocity intervals that get deeper toward the right of the profile (Figure 8). Probably most noteworthy is the relatively uniform contours above 40 ft. Uniformity in these shallower contours suggests laterally continuous, undisturbed sediments.

Discerning the acoustic characteristics of subsurface voids on shear wave velocity profiles in this geologic setting required a surface wave profile in an area with known voids. A group of sinkholes in the Conecuh National Forest that align generally along an east/west trend provided the appropriate density and distribution for the acquisition of a single profile traversing an area without sinkholes into an area with sinkholes. It must be kept in mind that without ground truth drilling it is not possible to unequivocally say dissolution voids similar to the ones responsible for the observable sinkholes are only present at stations adjacent to the observable sinkholes.

Several questions concerning the processed section from the Conecuh Nation Forest need to be addressed. First, do subsurface anomalies associated with sinkholes have a unique acoustic expression in the shear wave velocity field as measured using surface waves? Based on preliminary analysis of these data (Figure 9), subsurface anomalies associated with sinkholes have a characteristic high velocity “bulls eye” or contour closure directly over a low velocity “bulls eye” or closure. This unique combination is interpretable between station 3055 and 3060 as well as between 3090 and 3100 on both sections. Unique to the right-to-left section (lower section in Figure 9) is the high over low velocity closure over station 3080. This is likely related to a sinkhole evident adjacent to station 3080, which is only interpretable on the lower section due to the higher apparent resolution of the lower section. Both sections were recorded using geophones planted in the same locations but with different source locations. All source locations for the upper section were left of center point of the spread and for the lower sections all source locations were right of spread center. For this particular line the overall data resolution seems better when the source was on the right half of the line.

The apparent difference in shear wave velocity between the left-to-right and right-to-left sections below the interpreted bedrock (1000 ft/sec contour at about 50 ft) is likely related to averaging effects of the longer wavelength surface waves sampling below bedrock (Figure 9). The apparent trend toward decreased shear wave velocity from station 3030 toward 3100 is consistent on both versions of this profile. The difference is in degree and location of highest velocity areas. These differences are likely related to both smearing or averaging of the longer wavelengths as the depth of investigation increases and directionality of source to nearest receiver. The general velocity trend and absolute shear wave velocities are similar on both sections. Unique high velocity anomalies on both sections appear to be representative of the same subsurface feature just skewed in the direction of the source and at a distance approximately equal to the source offset. It is easiest to quantify this skew by locating the center of the high velocity (1600 ft/sec) closure located below bedrock on the right-to-left section (3040) and comparing it to the center on the left-to-right section (3020). If the contours below bedrock were shifted 10 stations to the right on the left-to-right section and 10 stations to the left on the right-to-left section, the contours below 60 ft would match extremely well.

Correlation between the sinkholes identified near the survey line (Figure 1) and the high velocity over low velocity closures on the shear wave velocity sections (Figure 9) is likely the unique acoustic characteristic necessary for this technique to guide an exploratory drilling program. Longer lines would be necessary to truly evaluate the correlation between high over low velocity closures and sinkholes. However, based on all three profiles acquired as part of this feasibility study, surface wave imaging is sensitive to subsurface features related to sinkholes and can be used to identify areas susceptible to subsidence.

Conclusions

Shallow seismic reflection and surface wave profiling in conjunction with a focused drilling program will dramatically reduce the size of a subsurface feature potentially undetected by pattern drilling alone. Most of the primary goals and objectives of the feasibility study were met. A unique acoustic signature interpreted on shear wave velocity field data can be indirectly (proximity of recently developed sinkholes) correlated to sinkhole development. Reflection imaging successfully detected reflectors from 35 ft to over 630 ft while surface wave imaging

provided a reasonable representation of the first 100 ft of the earth. Both data sets can be correlated to borehole geology.

Defining resolution and detection limits is critical to this study. Voids or cavities have a common characteristic on shear wave velocity profiles derived from surface wave data. A high velocity halo appears to correlate to voids/cavities and is likely related to shear stress built up on the void roof. The minimum size of a void detectable using surface waves cannot be established without confirmation drilling at this site. It could be suggested that the minimum vertical dimension is not a factor (i.e., the void can be less than a few inches in height) as long as shear stress from bridging is present at or above the roof rock. The larger the open expanse the greater the shear stress (for equivalent load) and therefore the larger the velocity gradient. It would be reasonable to assert that a cavity at 35 ft of depth with as little as 10 ft of horizontal expanse would be detectable if enough shear stress is present above the cavity. Defining the resolution limits of reflection data has the benefit of years of research and modeling of resolution potential. Based on those studies, features 4 ft tall and 12 ft wide are resolvable at a depth of 65 ft with seismic reflection. Detection through direct or indirect methods could be on the order of one-quarter of a wavelength (2 ft) or less.

Optimizing the seismic program relies heavily on apparent reflection velocities, frequency content of body and surface waves, and coupling. Reflection data acquisition will be optimized with 4 ft receiver spacing, 8 ft source spacing, downhole 50 cal source, 40 Hz geophones, a minimum source offset of 6 ft, and a maximum source offset of around 300 ft. Surface wave data should be collected with a source offset of 30 ft, receiver spacing of 4 ft, source spacing 8 ft, and a maximum offset of around 240 ft. Based on the walkaway shot gathers, static variability on the order of 2 to 3 msec will not be uncommon on CMP data. This much near-surface static will present a challenge but should not dramatically inhibit the overall accuracy of stacked data from this site. Comparisons of end-on and split spread data using the same 206-channel spread provides some insight into the degree of variability from shot to shot if CMP data are recorded at this site.

Subtle differences in reflection data characteristics should not adversely affect event identification across this site. Surface wave data on files collected at each site appears very consistent, dispersive, and relatively broad banded. QC will be necessary with occasional checks (every fifth shotpoint or so) of data characteristics. Reflection and surface wave data have

overlapping depths of investigation. Interpretations of both types of seismic data from this site should combine to provide higher confidence and better results than either seismic method individually. The bedrock surface on shear wave profiles manifests itself as a high gradient, with the 1000 ft/sec contour line grossly representative of that interface. Considering the size of the dissolution features, depths dissolution is or has been active, and redundancy of sampling between the surface wave and reflection data, a seismic program could enhance the effectiveness of characterization based on drilling only. Reducing the chances a subsidence hazard large enough to jeopardize the environment or facility could go undetected will be the objective of a seismic program at this site.

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Figure Captions

Figure 1. Site map of study areas in southern Alabama. The feasibility study was conducted at two sites (A and B) located between Andalusia and Brewton, Alabama (modified from Rand-MacNally, 1995). Site A was about 1.5 miles from the Conecuh River and is the location of the proposed AEC power facility. The conceptual overlay of the proposed plant onto existing surface features and relief provides a measure of scale and orientation. Two locations (1 and 2) were used to perform walkaway noise tests for the reflection and surface wave techniques. Site B is located in an area of the Conecuh National Forest with several sizeable sinkholes. Surface wave test data at this sinkhole site were acquired along an existing road that was flanked by several sinkholes but had no evidence of surface subsidence.

Figure 2. This cartoon of the generalized site geology was modified from a cross-section developed by Burns & McDonnell Waste Consultants, Inc. Burns & McDonnell used information from drilling, surface mapping, and sinkhole/karst studies to produce the original conceptual cross-section. It is reasonable to suggest that the Bucatunna Clay, Glendon Limestone, Red Bluff Clay, and the Ocala Limestone possess sufficiently thickness in this area to produce uniquely distinguishable reflection arrivals on processed shot gathers.

Figure 3. Downhole 30.06 data clearly show the advantage of hole conditioning at this site. A 12-inch hole was poked into the ground with a bar and the barrel of a specially modified 30.06 with a protective sheath was lowered into the hole. A steel plate attached to the gun barrel provided a ground seal and protection for the operator. One shot into the hole (a) produces a record with good reflection and refraction arrivals and a strong air-coupled wave component. Firing a second shot (b) into the same hole produces a higher signal-to-noise record than the first shot. The best data recorded was by the third projectile fired into the same hole. Changes in hole compaction at this shallow depth (12 inches) clearly influences the data quality. It is also possible that as each successive projectile deepens the hole, more component material is made available for energy transfer to the ground. A late zero-time trigger is evident on the first two shots. The trigger sensitivity was adjusted for the third shot. This triggering error had no effect on the data quality since these data were not vertically stacked.

Figure 4. A single shot from a downhole 50 cal source provided the best signal-to-noise ratio and resolution potential at this site. After spectral balancing, reflection events clearly dominate the shot gather (a). Trace separation is 2 ft. This shot gather was recorded by 206 triple 40 Hz geophones. The shallowest reflection is interpreted to be from a depth of around 35 ft (b). No less than a dozen unique reflecting events are evident between 35 ft and 200 ft. Dominant frequency of most of the shallower reflection events is around 300 Hz. Production data should be acquired using a nominal split-spread geometry with a receiver spacing of 4 ft. To simulate such a shot gather, every other trace has been removed from (b) and the remaining traces have been reversed in order and gathered all together. The resulting pseudo 206-channel, split-spread shot gather possesses highly interpretable reflections from depths of 65 to over 600 ft of depth. Reducing the trace spacing to 4 ft has reduced the potential of recording reflection from the 35 ft deep interface consistently across the site.

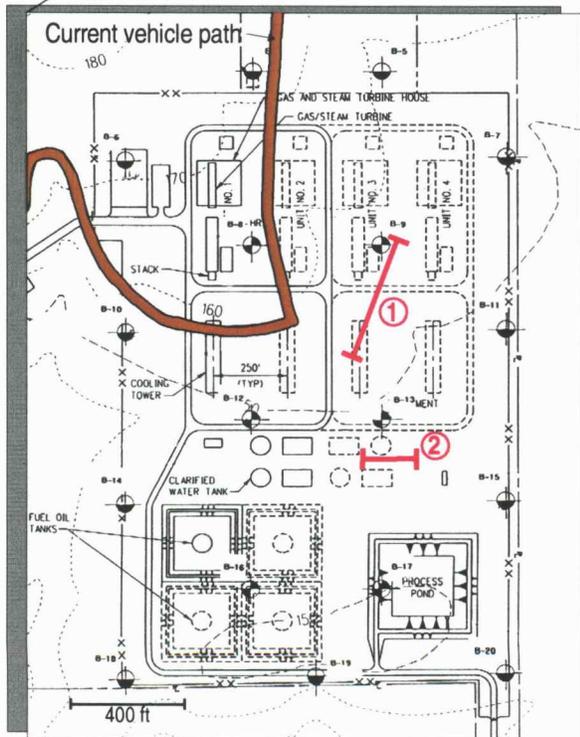
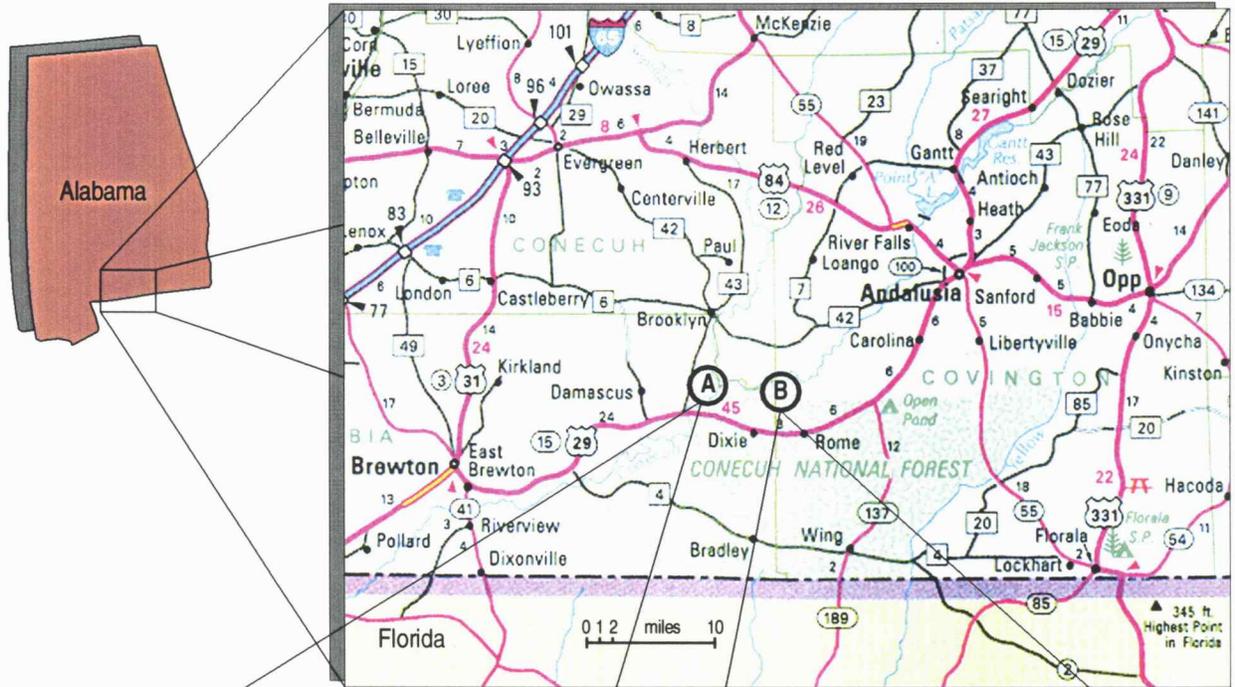
Figure 5. Explosive/projectile sources produced data with the greatest resolution and structural mapping potential. The third shot in a hole with the downhole 30.06 (a) and the downhole 50 cal (b) produced reflections with similar dominant frequencies, but the 50 cal clearly excelled in the category of signal-to-noise ratio and nearest-to-vertical offset reflections. The 8 gauge auger gun (c) data have good spectral properties as well, but also rival the 50 cal with respect to signal-to-noise ratio and nearest-to-vertical incidence reflections. An interesting observation is the lack of an air-coupled wave on the downhole 50 cal in comparison to the 30.06 and the 8 gauge auger gun. It is also interesting to note the more prominent ground roll arrivals present directly after the air-coupled wave on the 30.06 and 8 gauge auger gun in comparison to the 50 cal.

Figure 6. Spectral balancing compensated these data for amplitude variation within critical portions of their spectra. This technique simply amplitude adjusts all frequency components of a shot gather to approximate a spike in time or a trapezoid in the frequency domain. Since reflected body wave energy is generally very low amplitude relative to guided waves, refractions, ground roll, and air-coupled wave, in effect this process acts to increase the apparent signal-to-noise ratio. Raw shot gathers (a) have a strong ground roll component, complemented by high amplitude refractions and associated guided waves. Reflection arrivals as shallow as 20 msec and covered by ground roll are easily interpretable on the spectral balanced downhole 50 cal data (b).

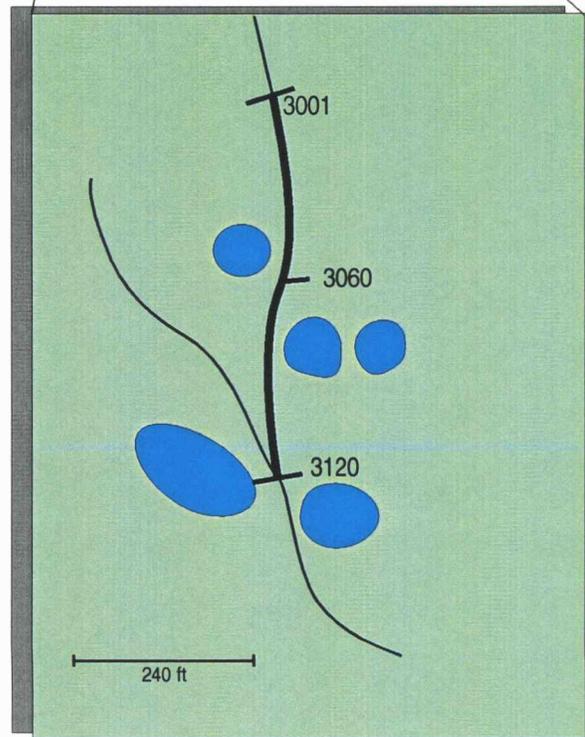
Figure 7. Surface wave data from these test sites were very dispersive and possessed a broad frequency band. These characteristics are conducive to the generation of shear wave velocity cross-sections. The shot gathers are transformed from time-offset domain to frequency-phase velocity domain with the resulting curve representative of the dispersive properties of the near surface. Data from these two sites have different dispersive properties, but both have very well behaved dispersion curves consistent with model data and depths of penetration (imaging depths) in excess of 75 ft.

Figure 8. Contouring the shear wave velocity field provides the most diagnostic way of locating anomalous areas in the subsurface. A "normal" earth will produce flat contour lines gradually increasing in velocity with depth. At the AEC proposed site shallow contours (less than 35 ft) are relatively uniform with an apparent change in near-surface materials near the low station numbers (north end) of the cross-section. The data below 35 ft has the most variability at this site and seems somewhat consistent with the conceptual geologic cross-section (Figure 2) at the bedrock surface. The undulations between 40 and 50 ft of depth could be related and grossly representative of a pinnacled bedrock surface. The changes in velocity between 60 and 100 ft of depth are on the order of 200 ft/sec (10% to 15%). It is unlikely that changes of this magnitude are representative of missing material/voids. It is more likely these changes are material composition.

Figure 9. Ground truthing the surface wave technique is critical for its reliable use. These data were collected at a site within the Conecuh National Forest where sinkholes were present in close proximity to the dirt access road the data were acquired on (Figure 1). Sinkholes were evident adjacent to station 3055 and for a large portion of the high number side of the line (from around 3080 to 3100 with smaller sinkholes between 3100 and the end of the line). It is interesting to note that approximately adjacent to sinkholes are high velocity over low velocity anomalies. Breaking down these higher over lower velocity signatures, it is not unreasonable to suggest the high velocity is related to increased shear stress over voids with the lower velocity anomalies representative of the voids themselves. Lower velocity anomalies would not be sufficient alone to uniquely characterize or identify voids, but the combination of higher over lower in the form of a very localized anomaly should be unique enough to provide the necessary interpretation confidence.



Proposed AEC Site



Sinkhole Test Site

Figure 1

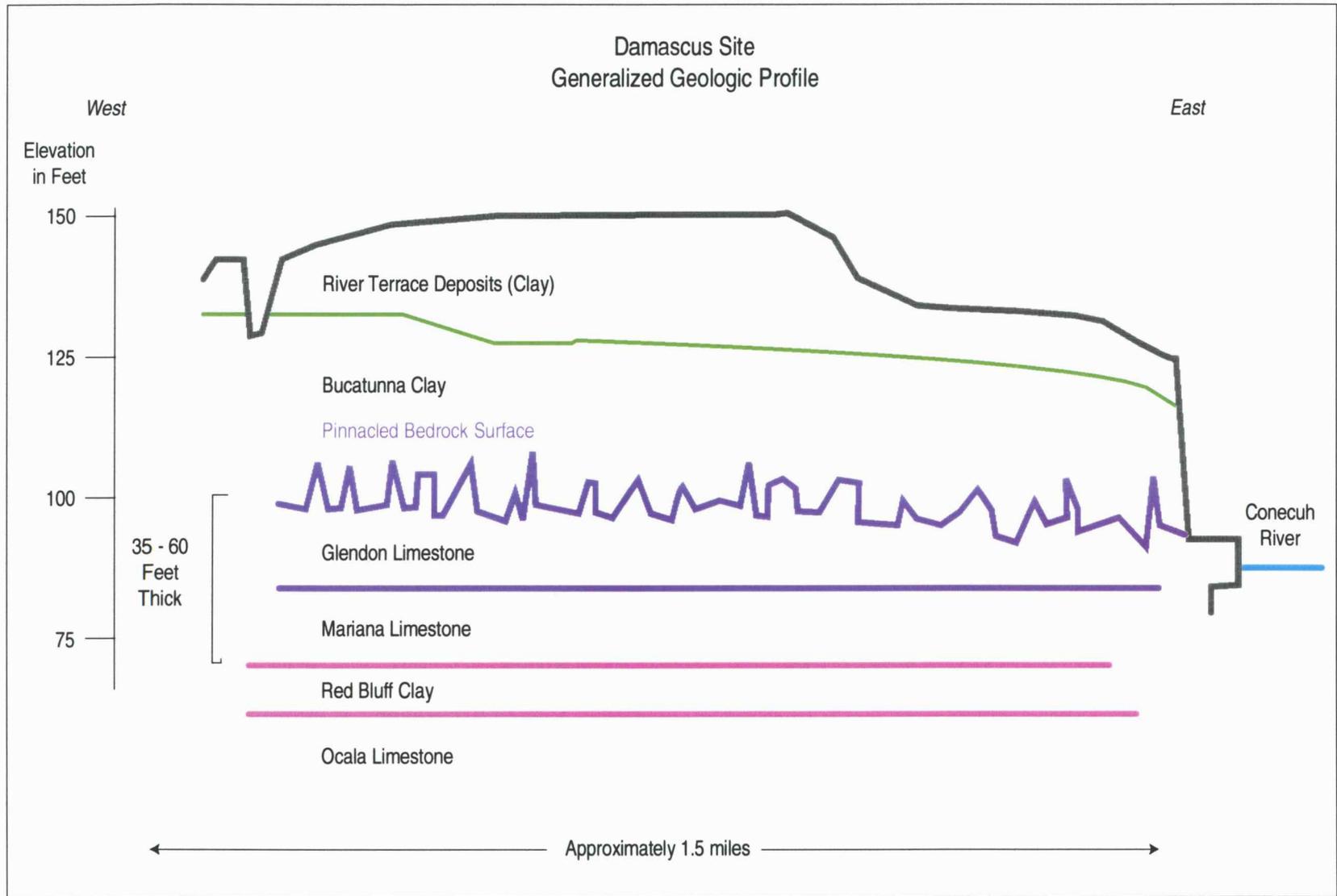


Figure 2

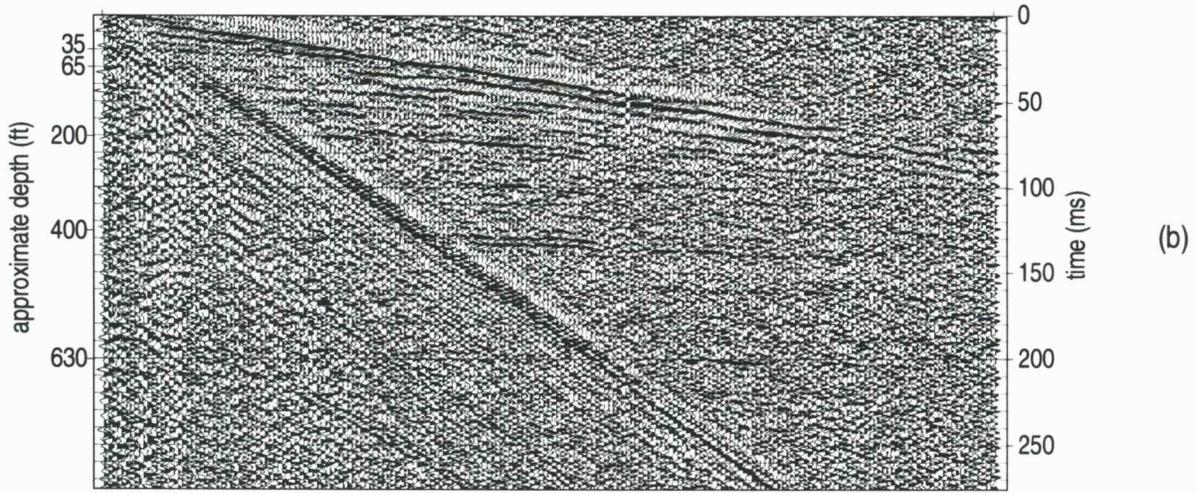
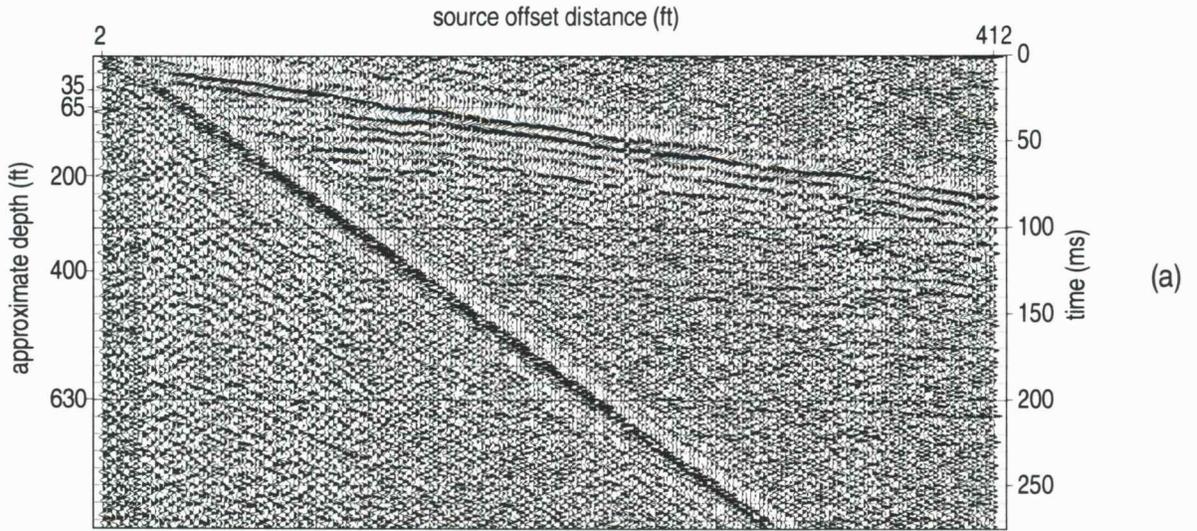


Figure 3

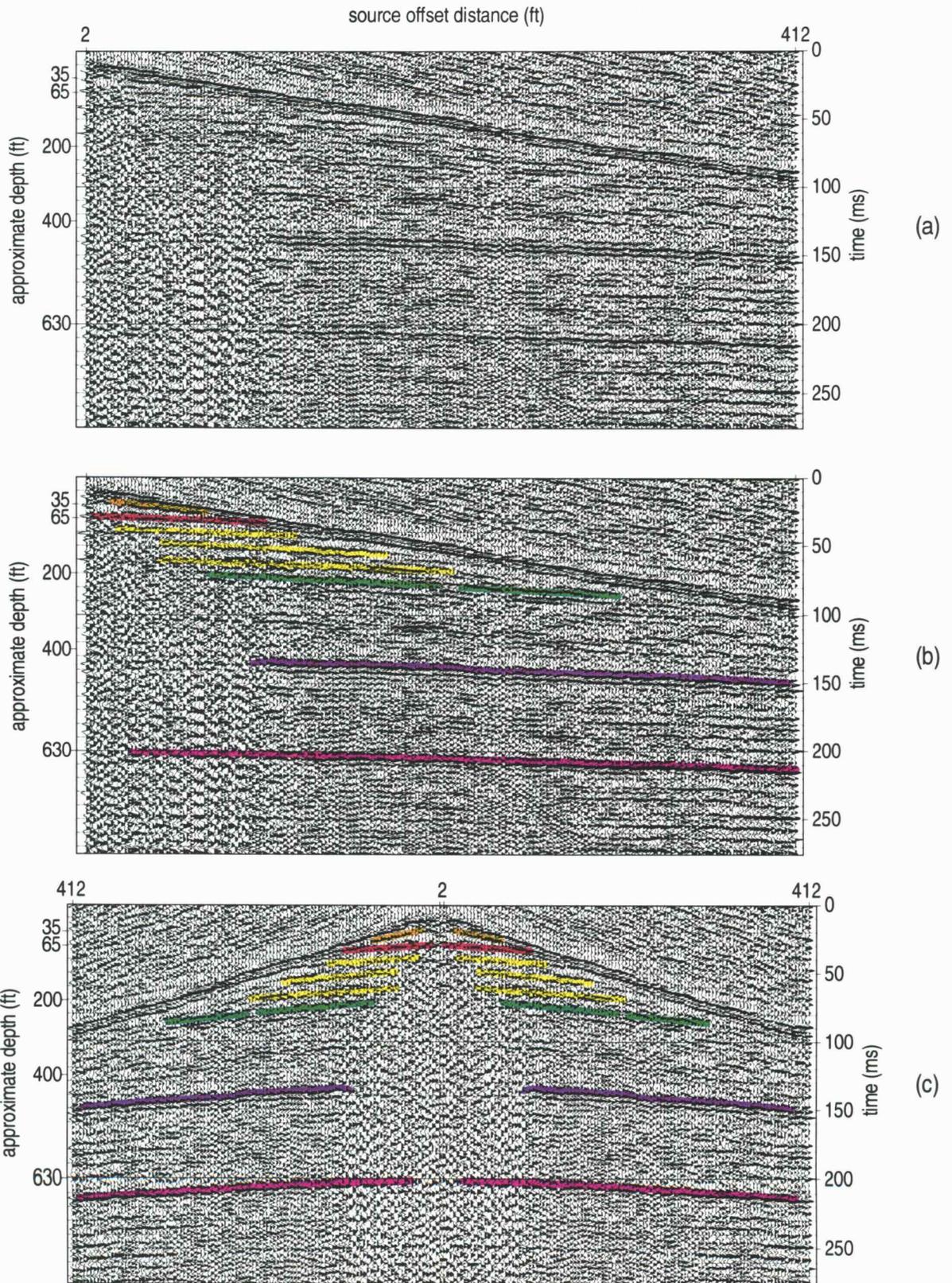


Figure 4

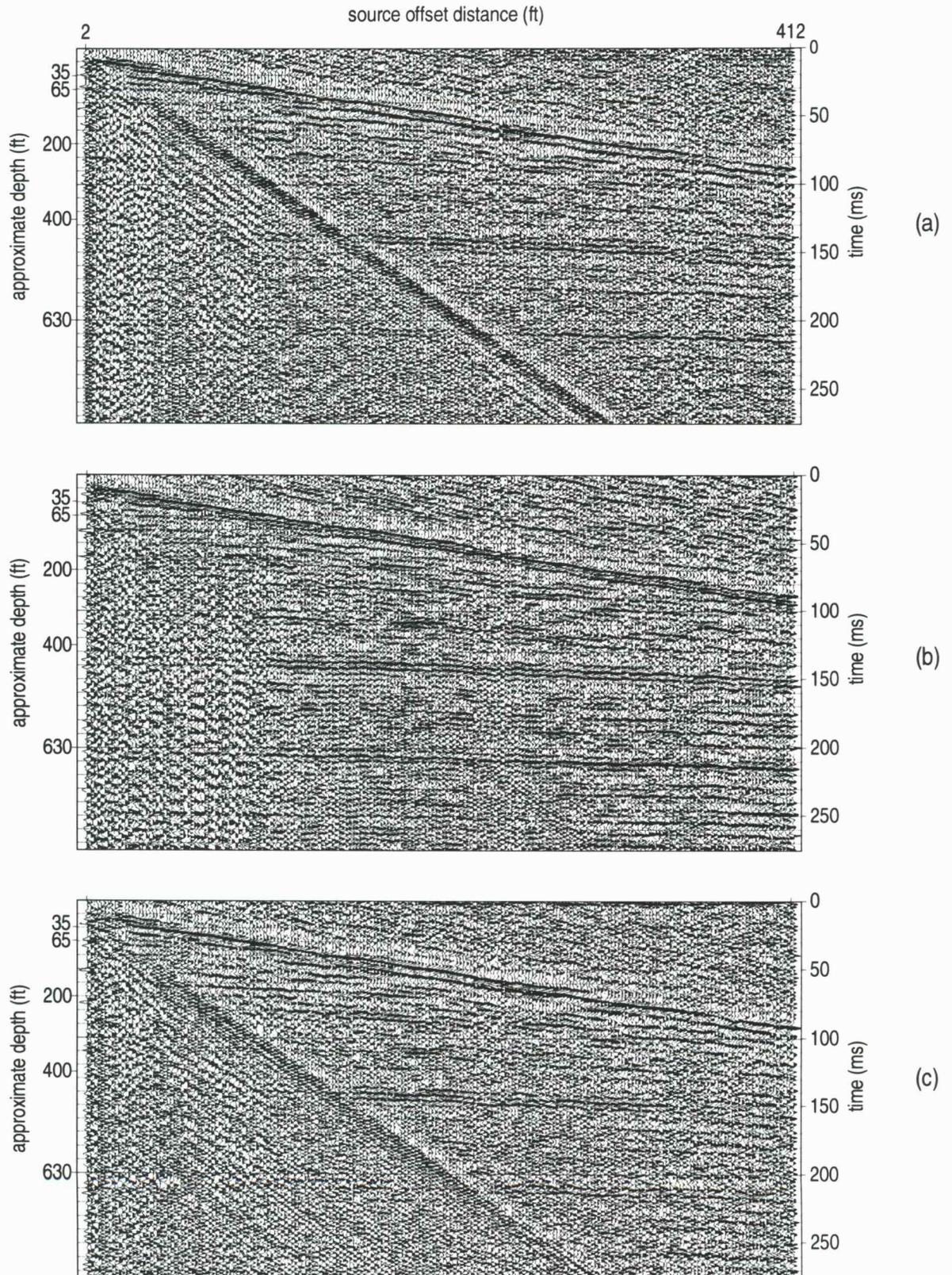


Figure 5

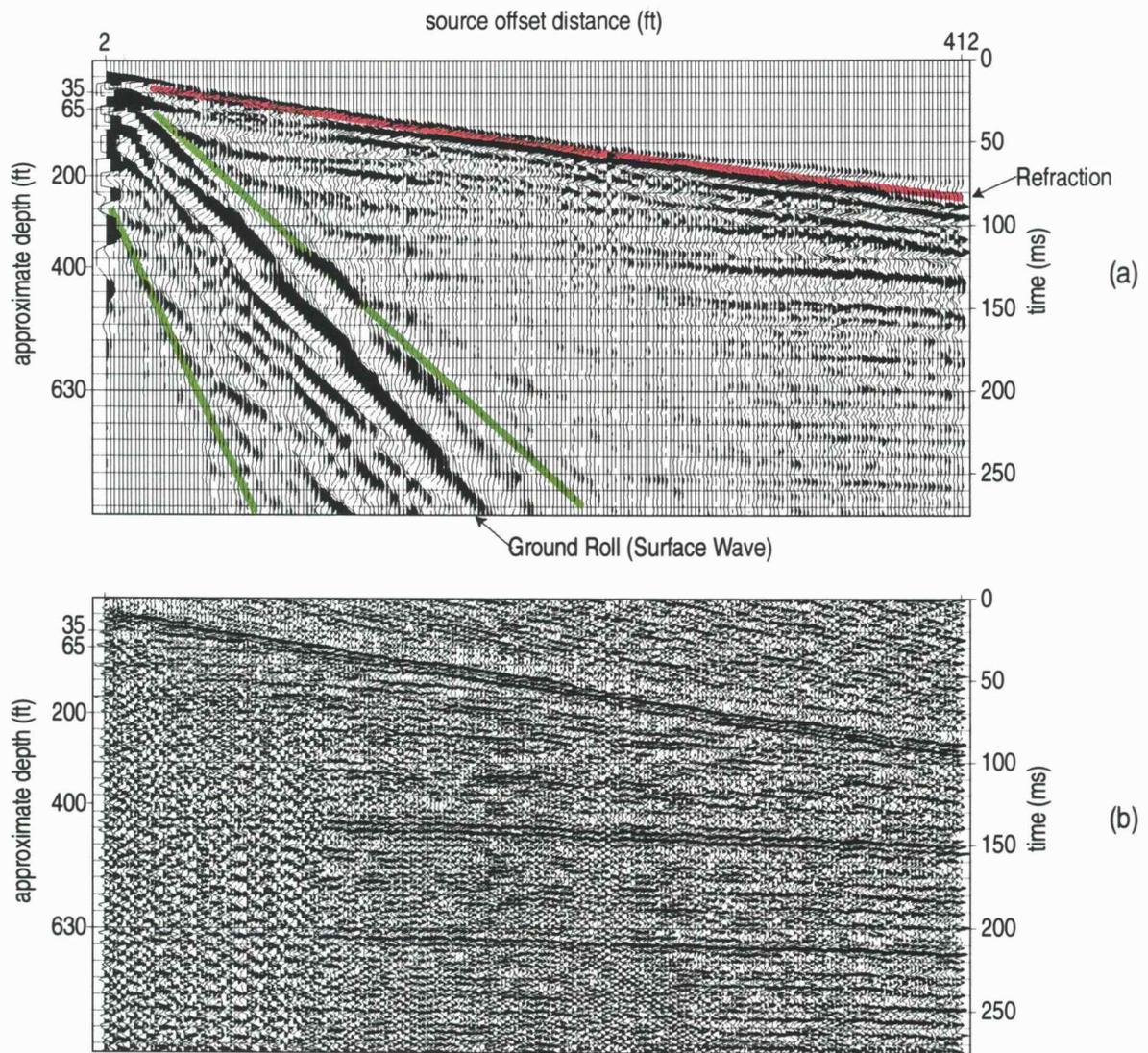
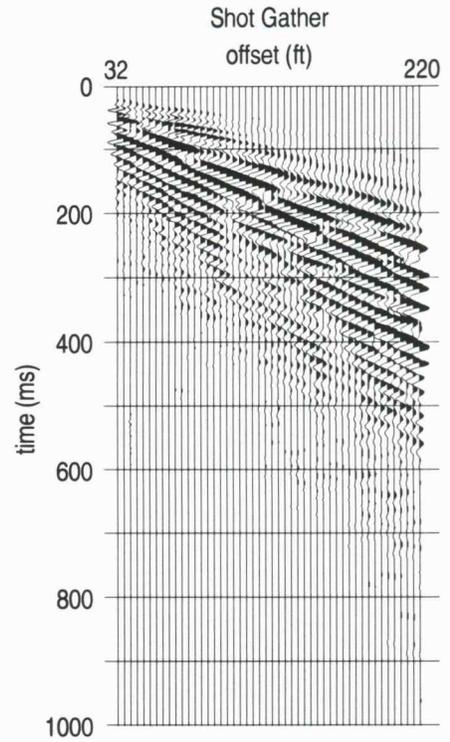
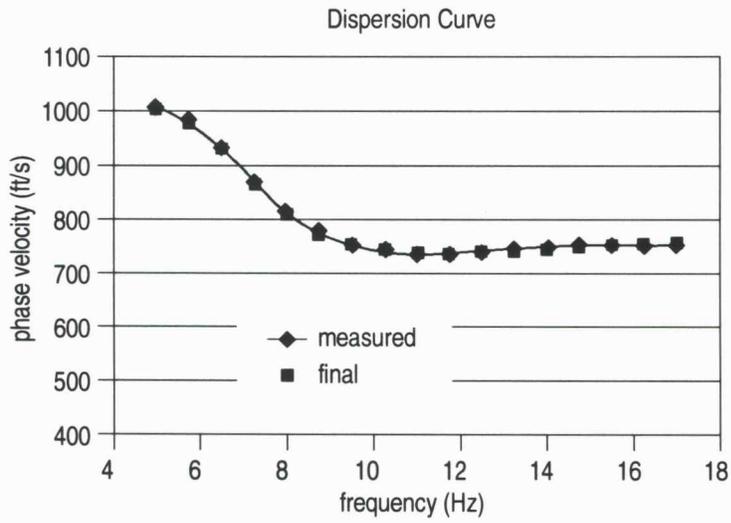


Figure 6

Surface Wave Data

Proposed AEC Site



Sinkhole Test Site

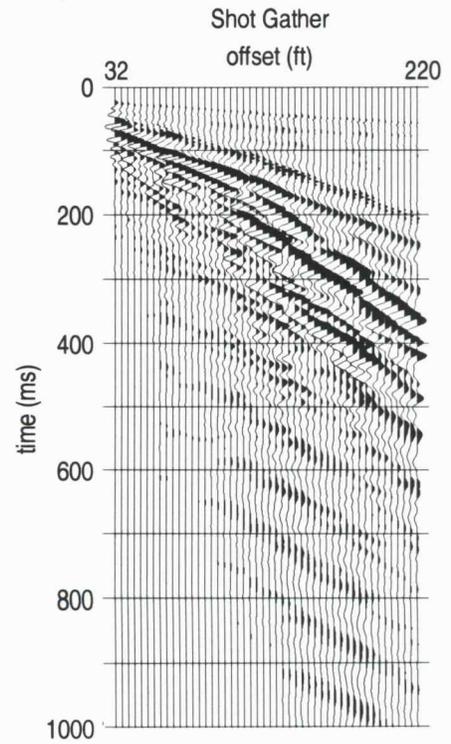
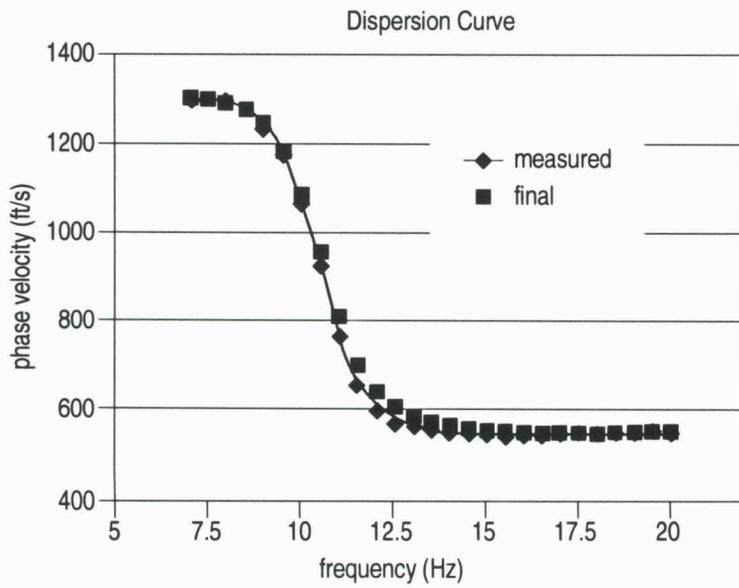


Figure 7

S-wave Velocity Field from Surface Wave Inversion
Proposed AEC Site near Andalusia, AL

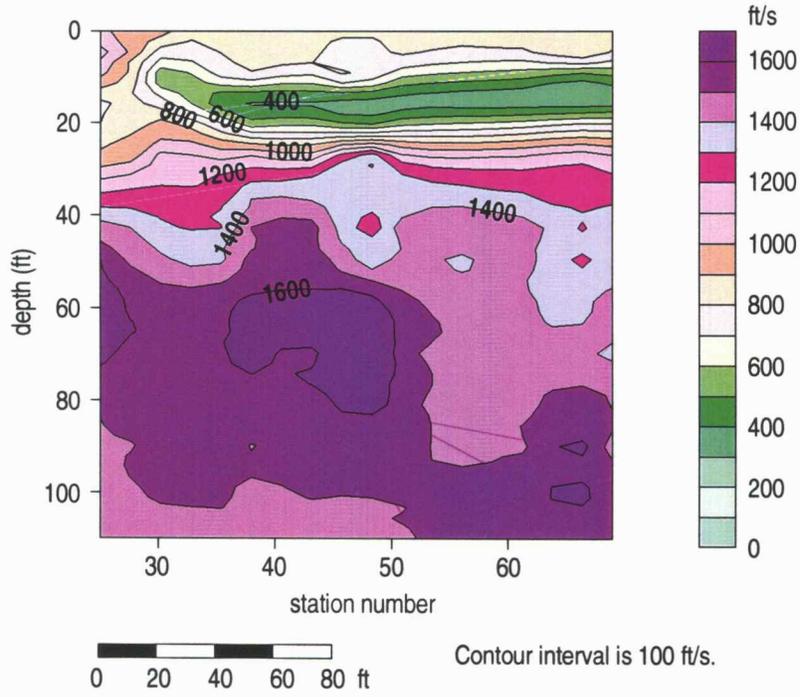


Figure 8

S-wave Velocity Field From Surface Wave Inversion
Sinkhole Test Site near Andalusia, AL

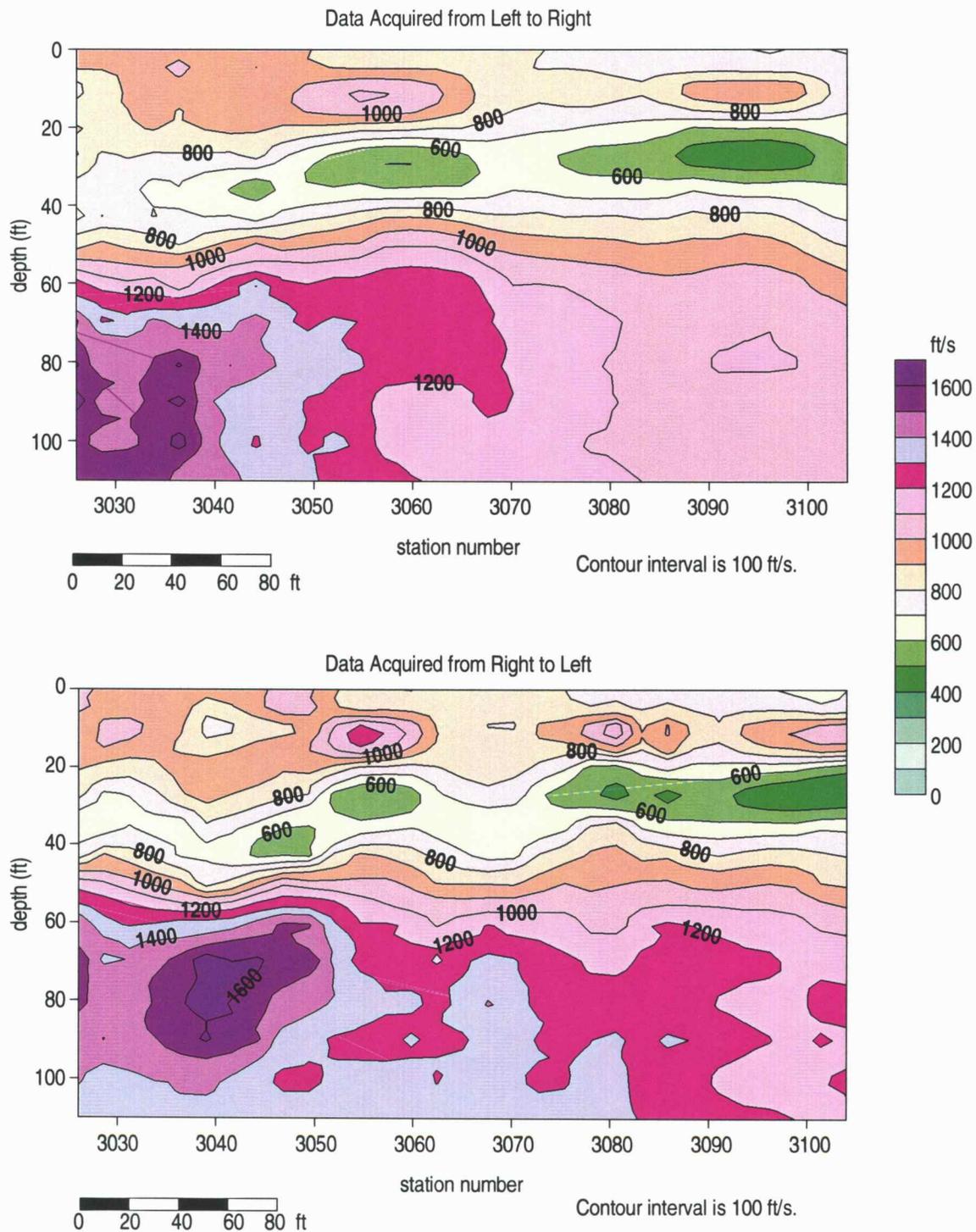


Figure 9

Appendix A

Test Data

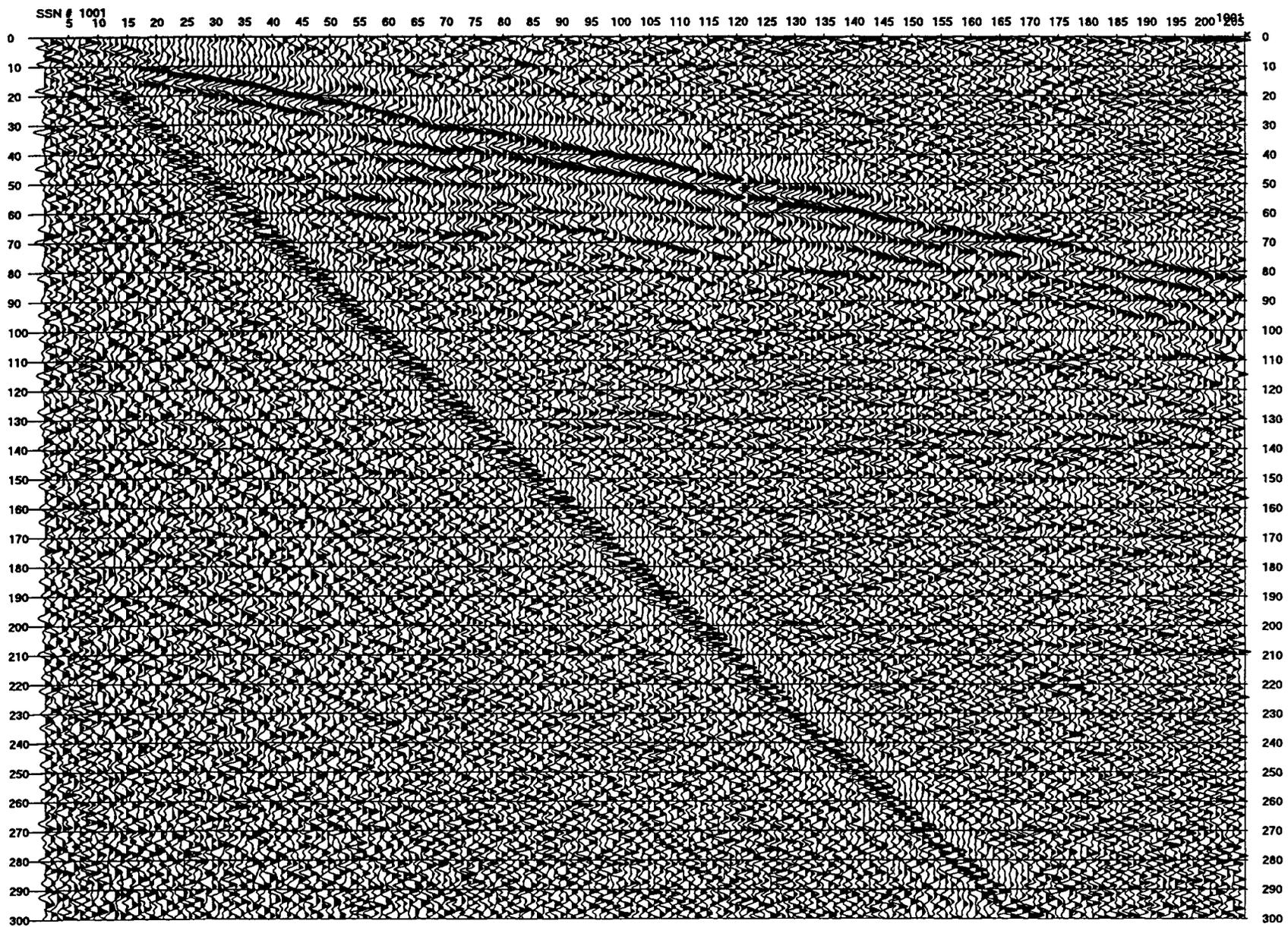


Figure A1. 30.06, shot 1, end-on.

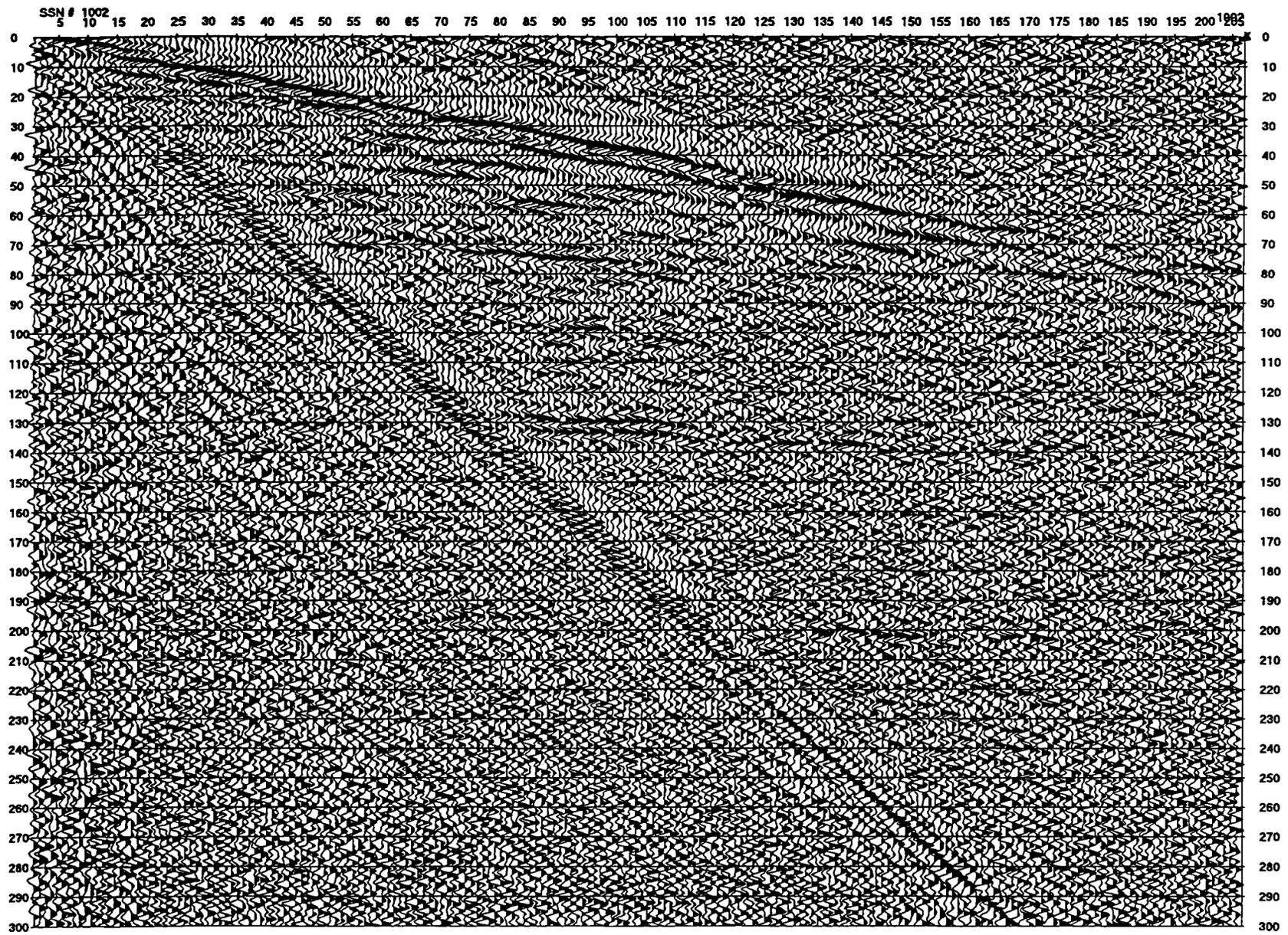


Figure A2. 30.06, shot 2, end-on.

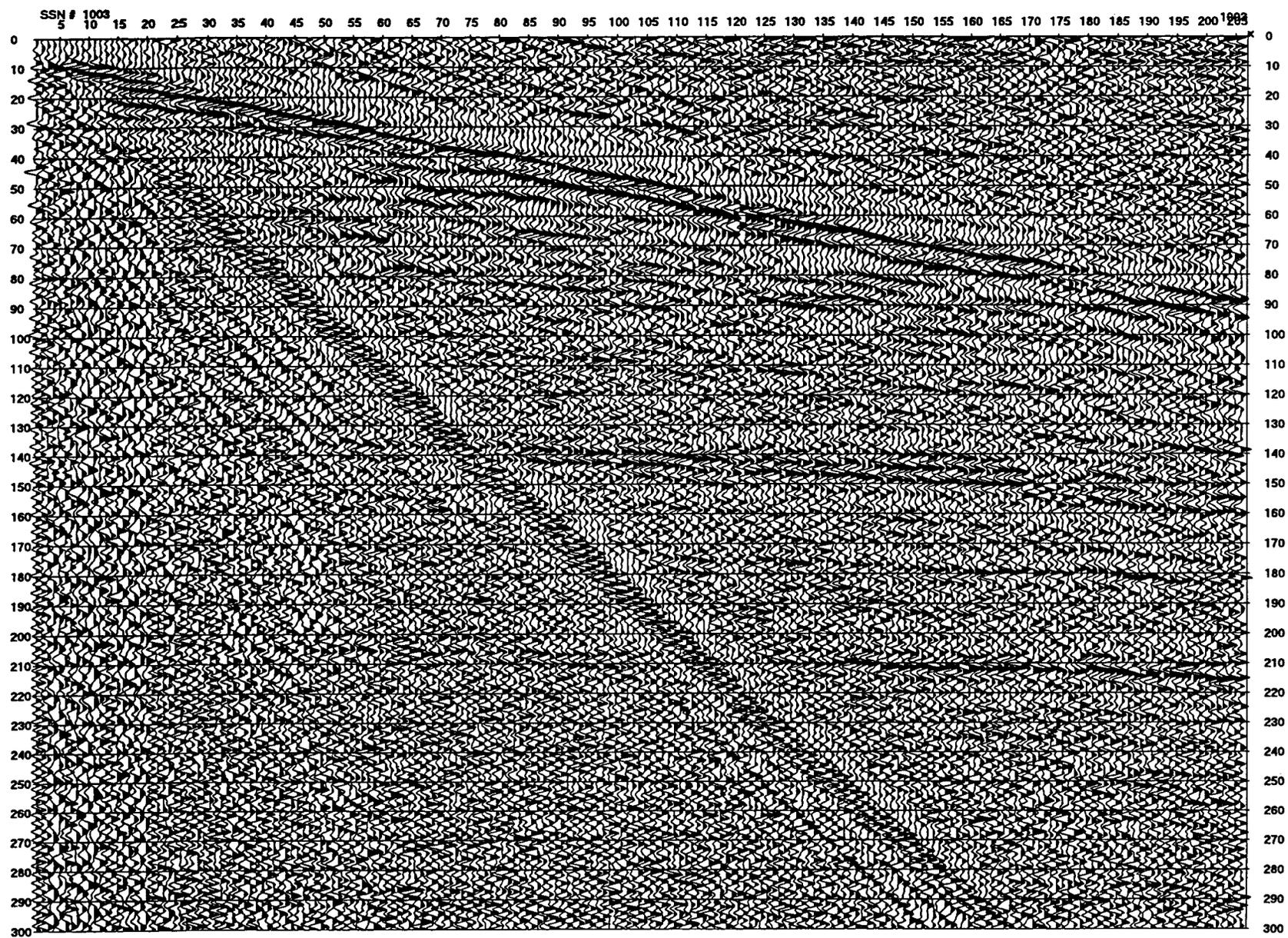


Figure A3. 30.06, shot 3, end-on.

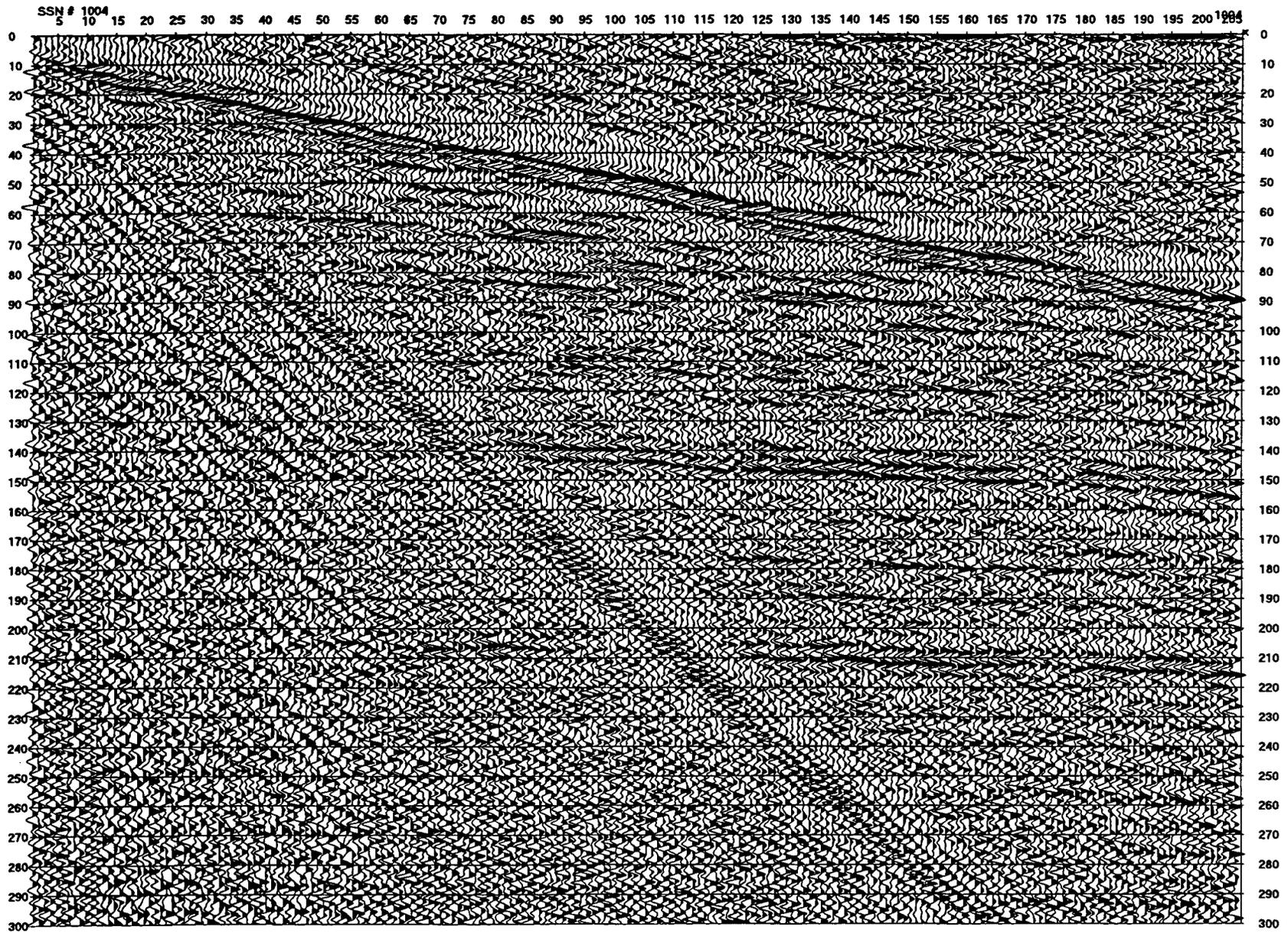


Figure A4. 50 cal., shot 1, end-on.

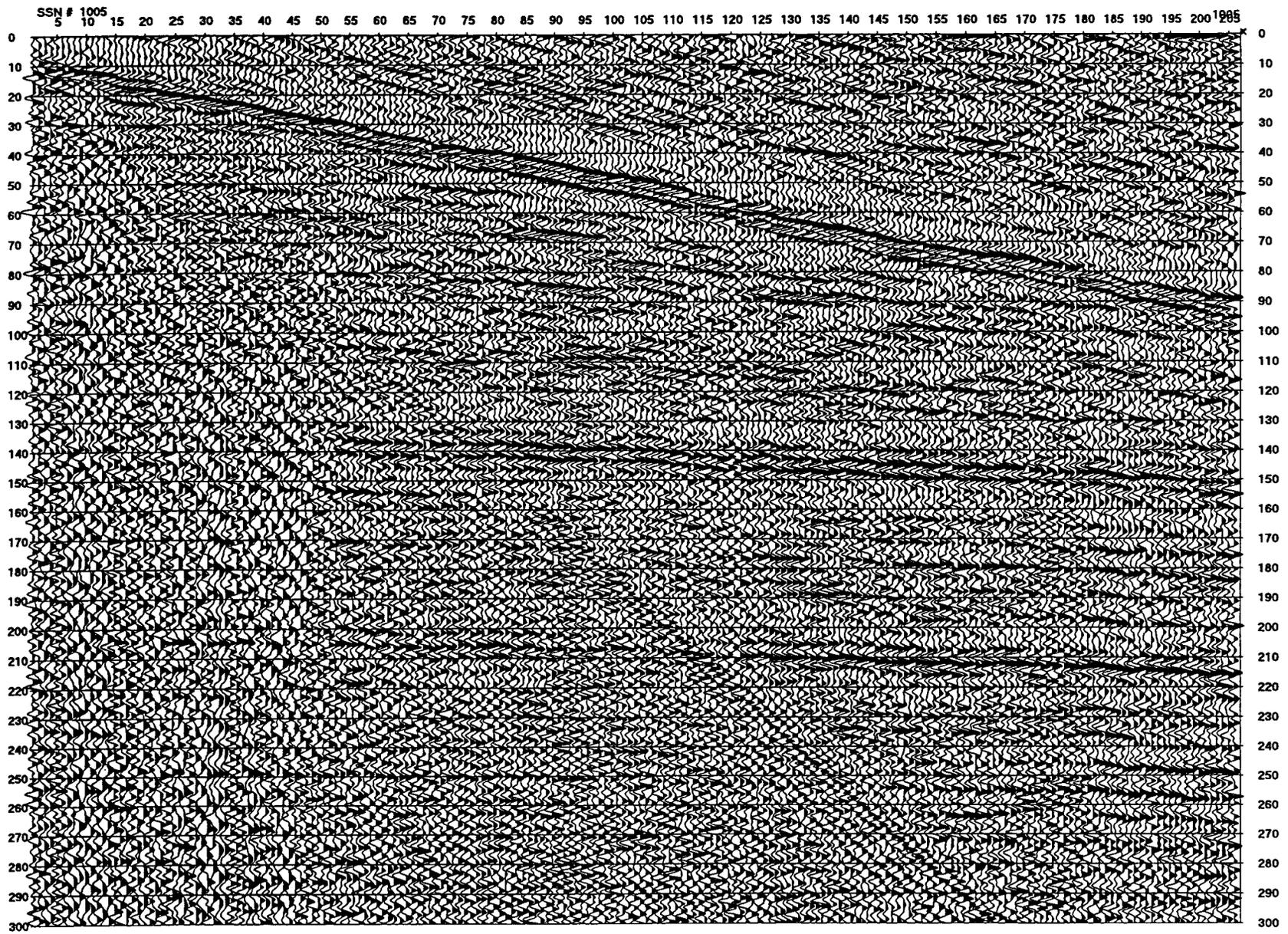


Figure A5. 50 cal., shot 2, end-on.

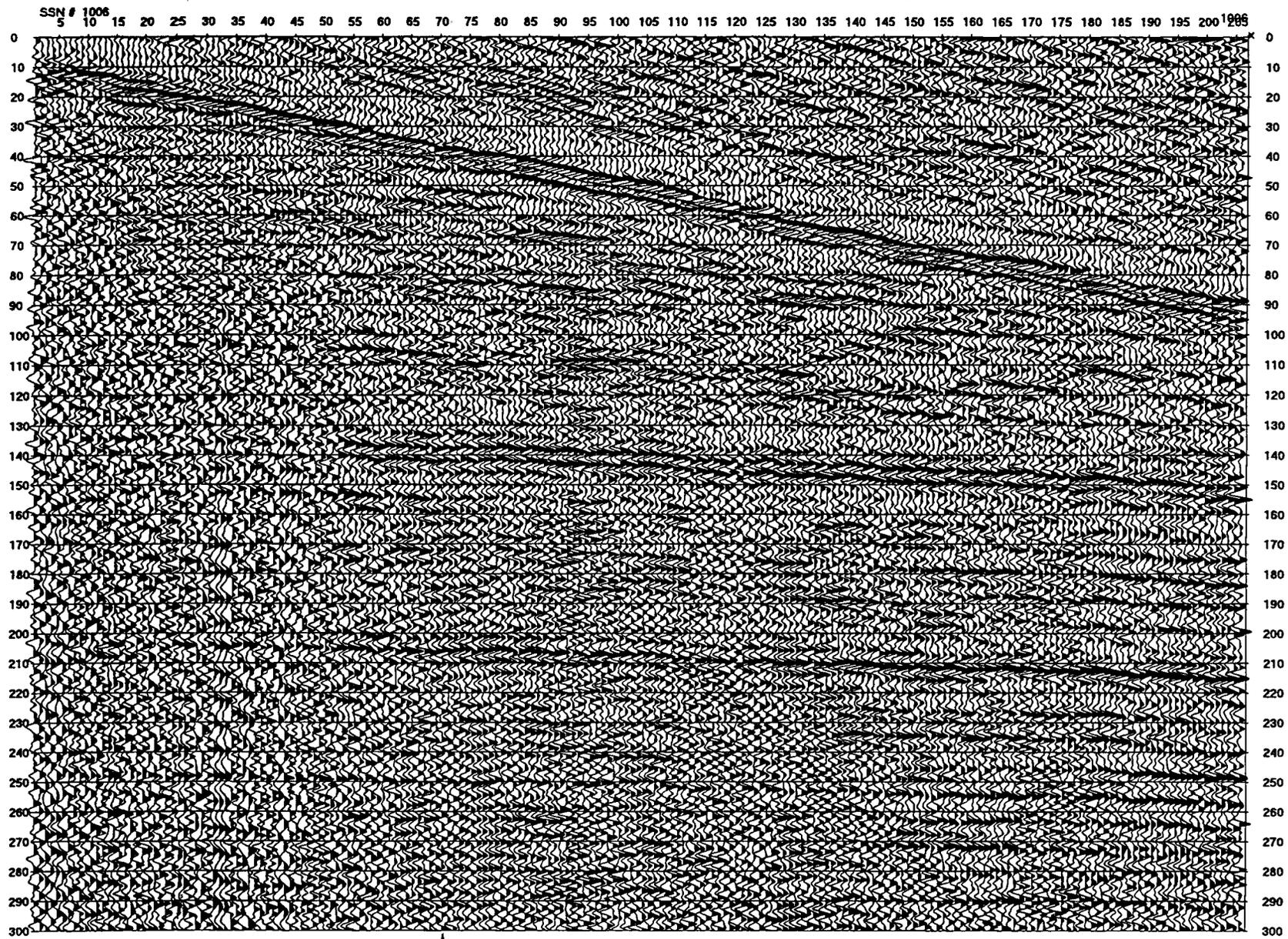


Figure A6. 50 cal., shot 3, end-on.

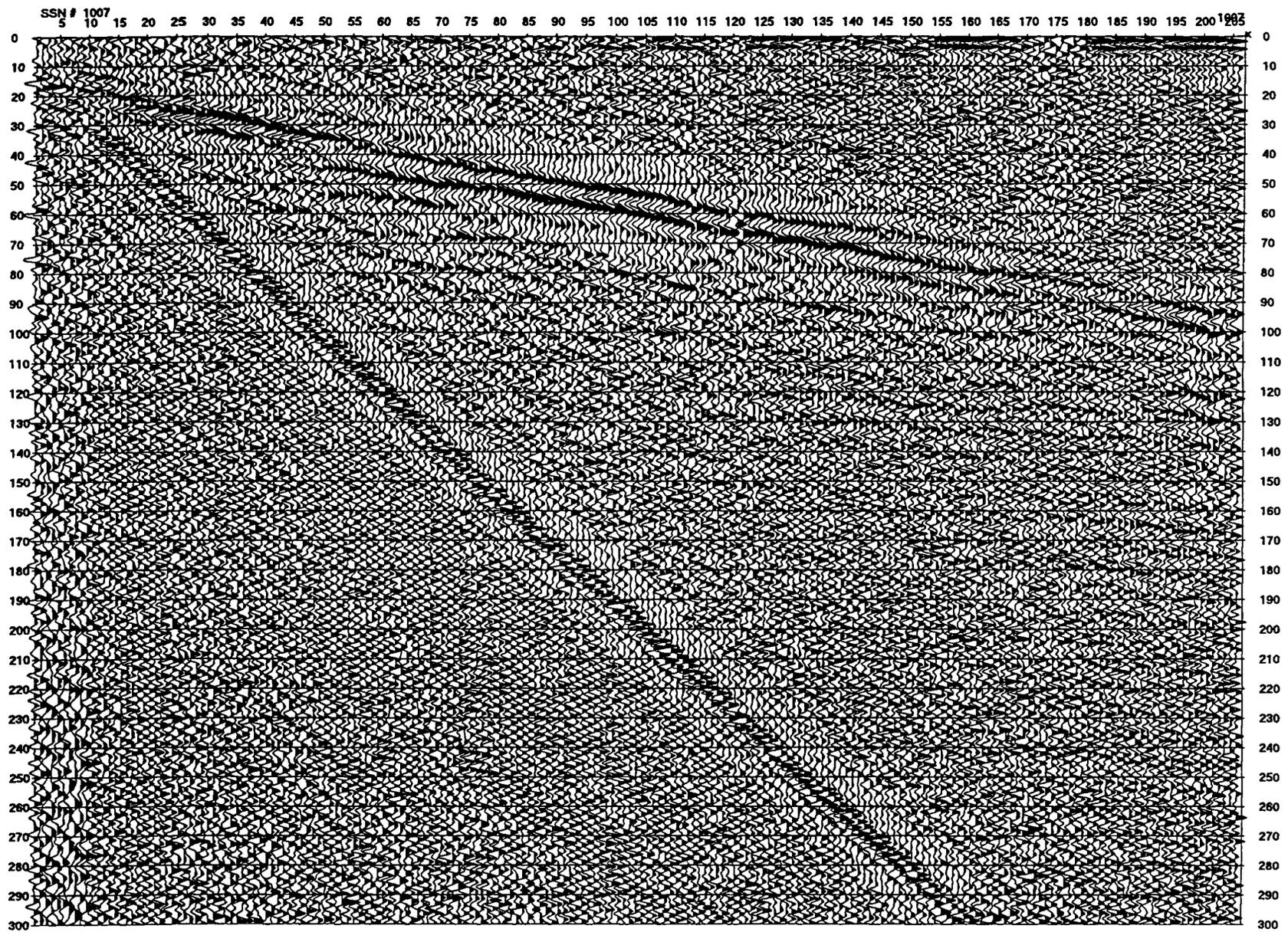


Figure A7. 12 ga. auger gun, shot 1, end-on.

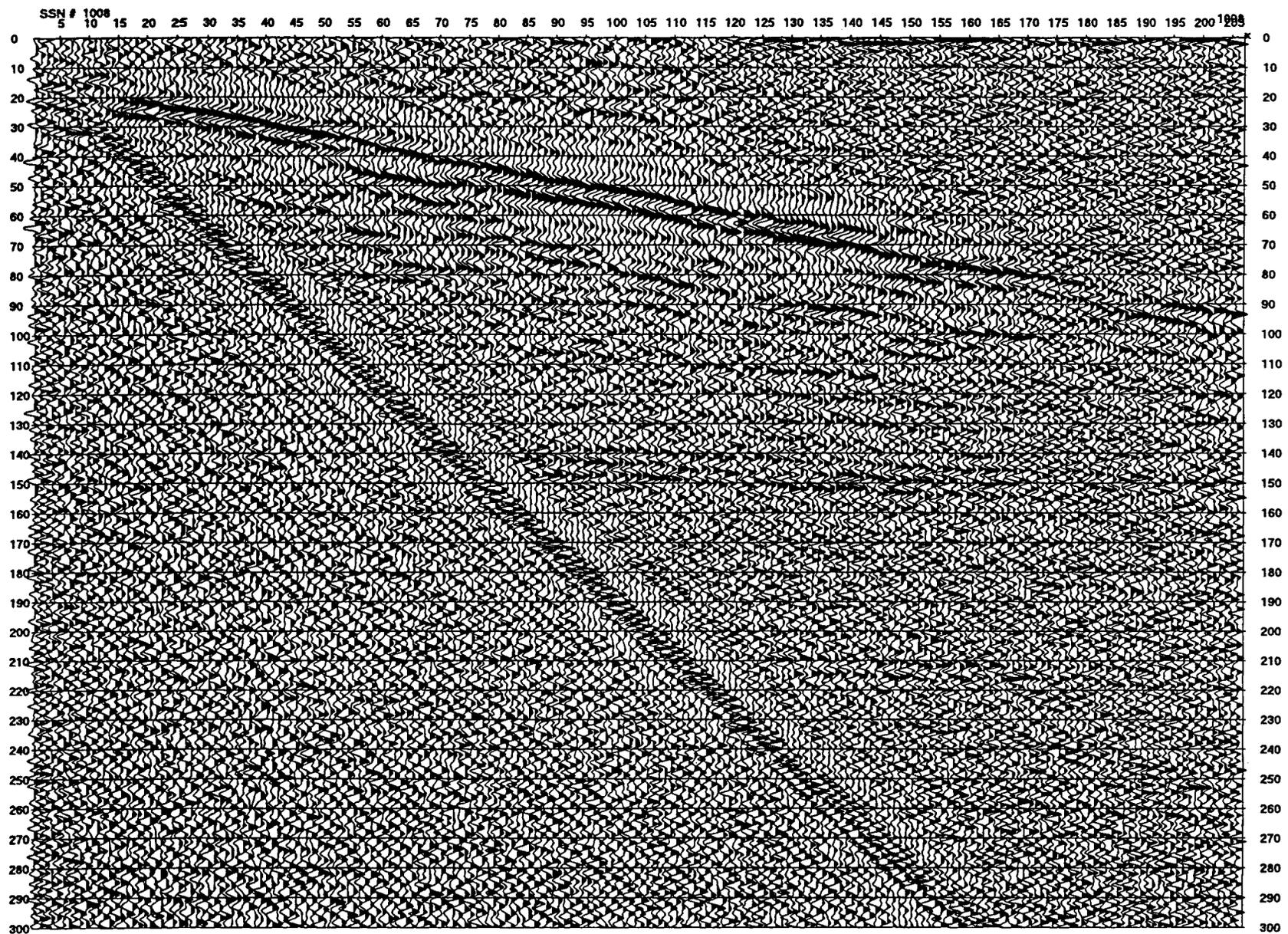


Figure A8. 12 ga. auger gun, shot 2, end-on.

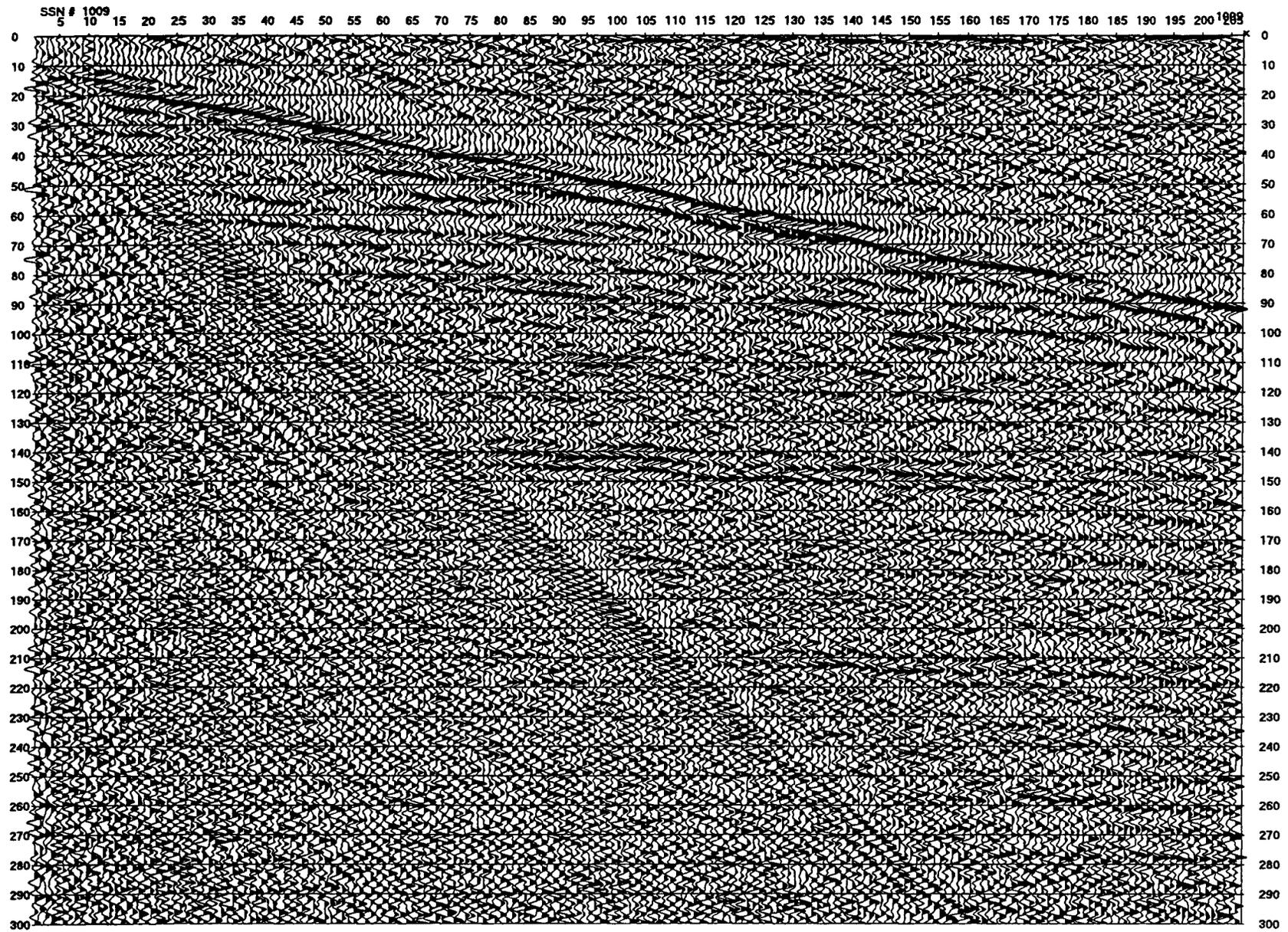


Figure A9. 8 ga. auger gun, shot 1, end-on.

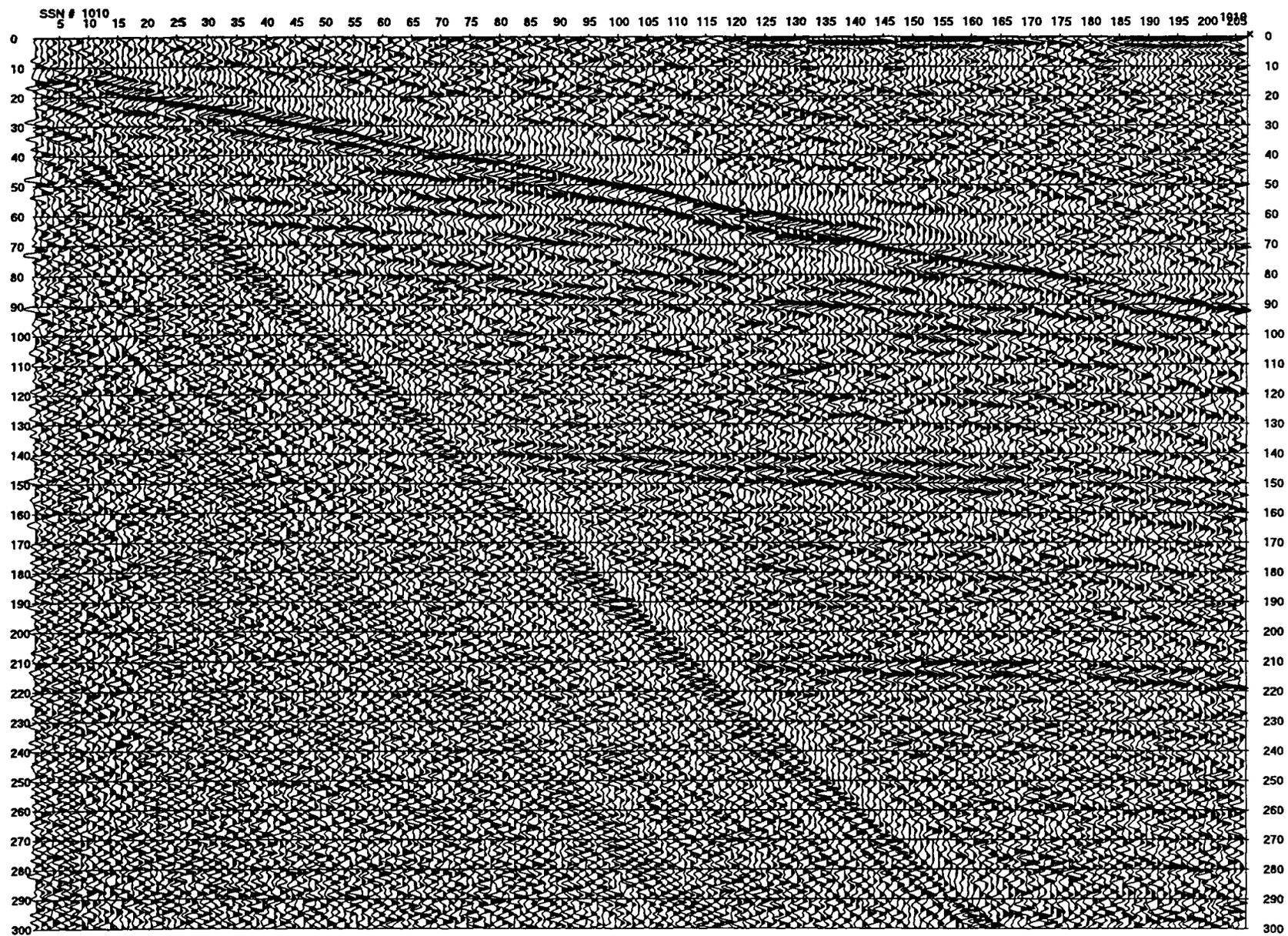


Figure A10. 8 ga. auger gun, shot 2, end-on.

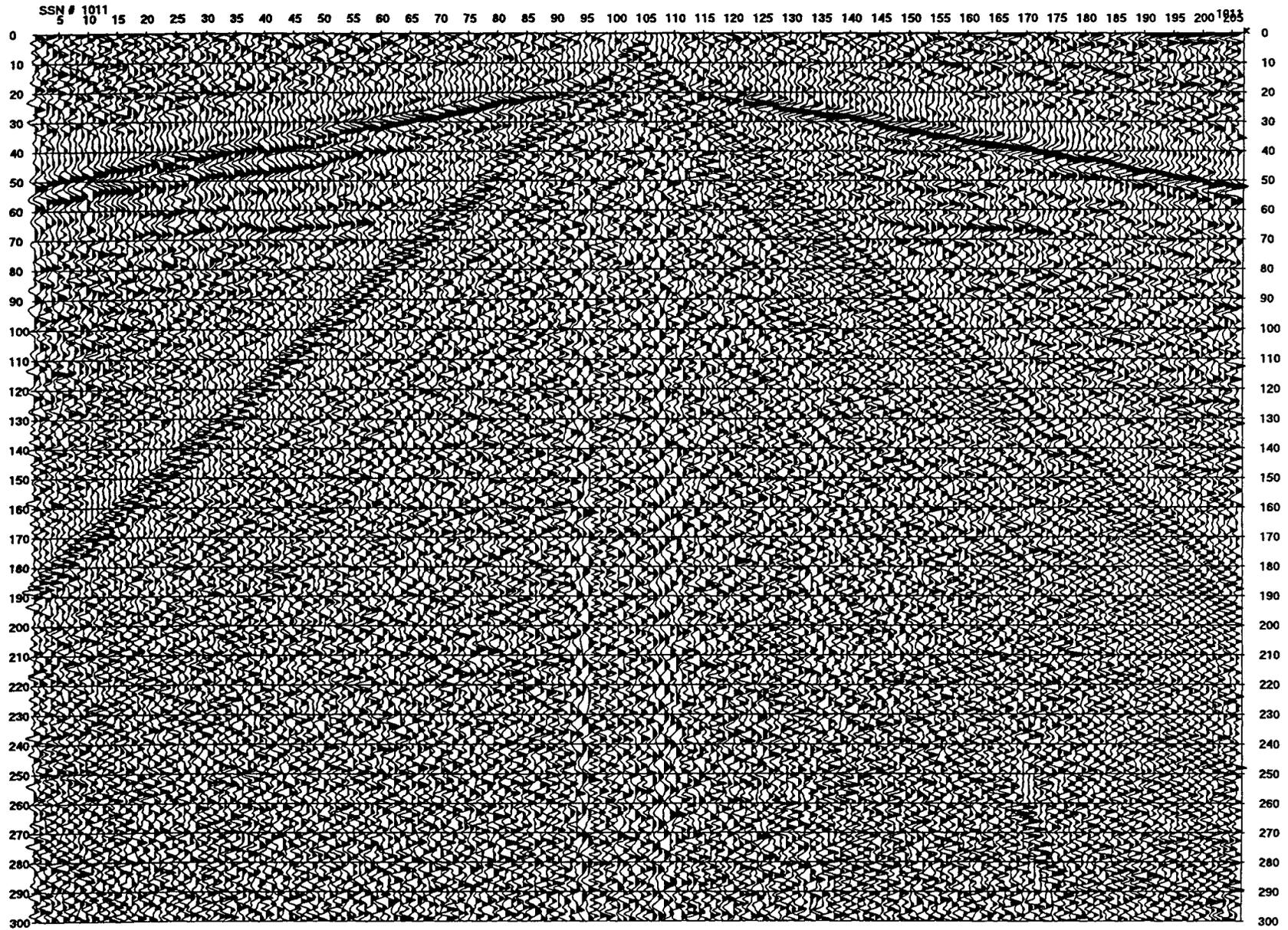


Figure A11. 30.06, shot 1, split spread.

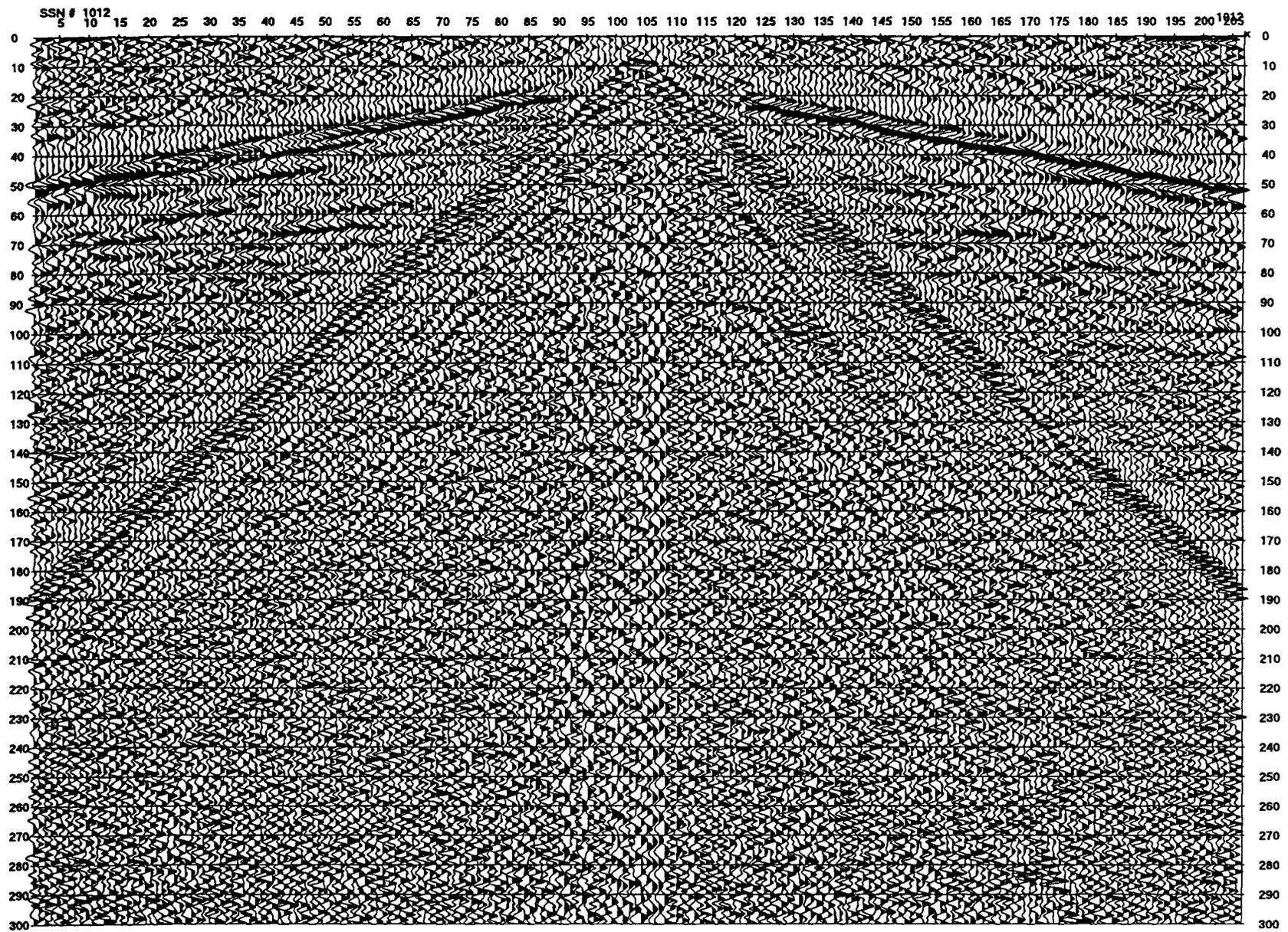


Figure A12. 30.06, shot 2, split spread.

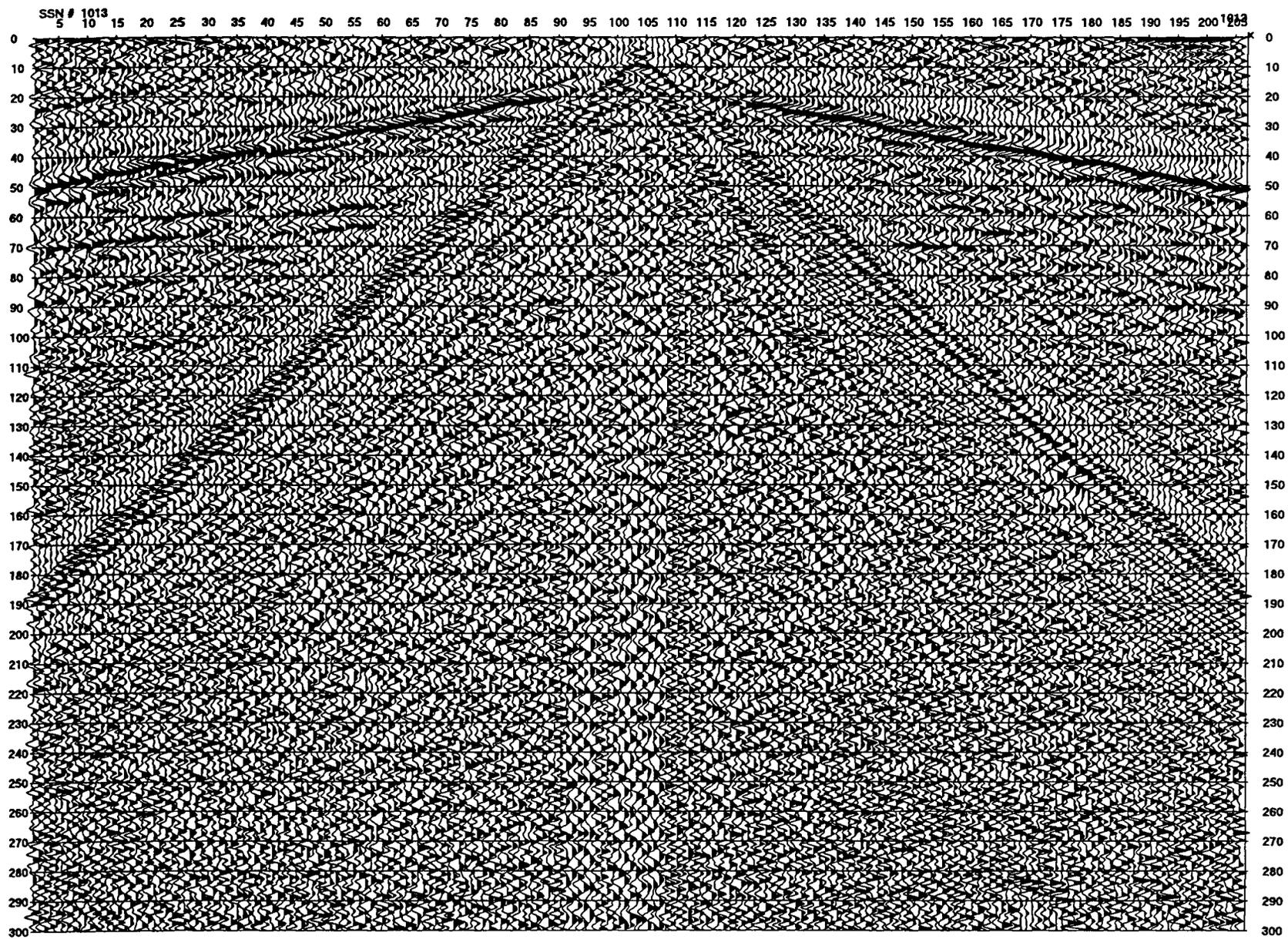


Figure A13. 30.06, shot 3, split spread.

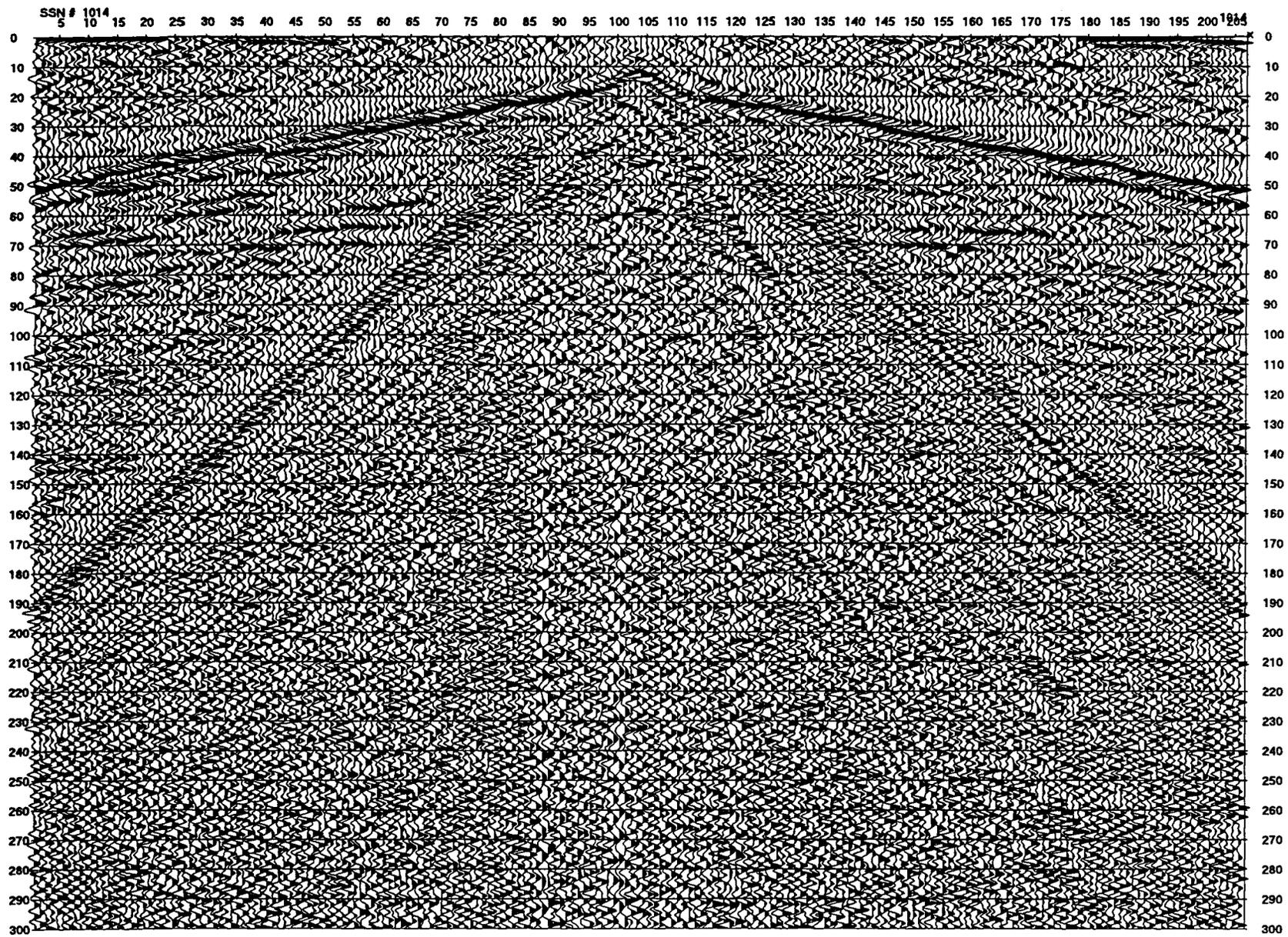


Figure A14. 50 cal., shot 1, split spread.

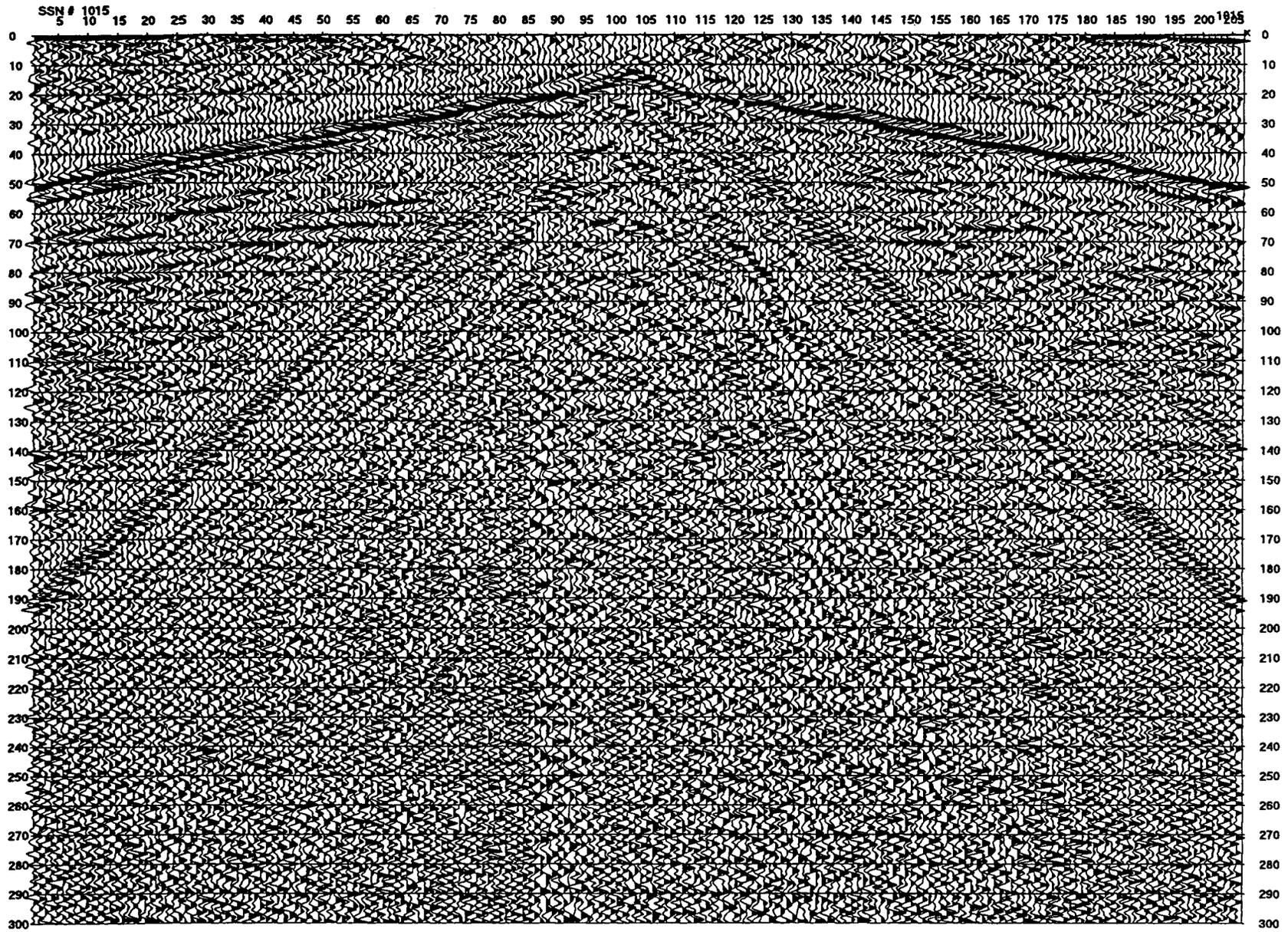


Figure A15. 50 cal., shot 2, split spread.

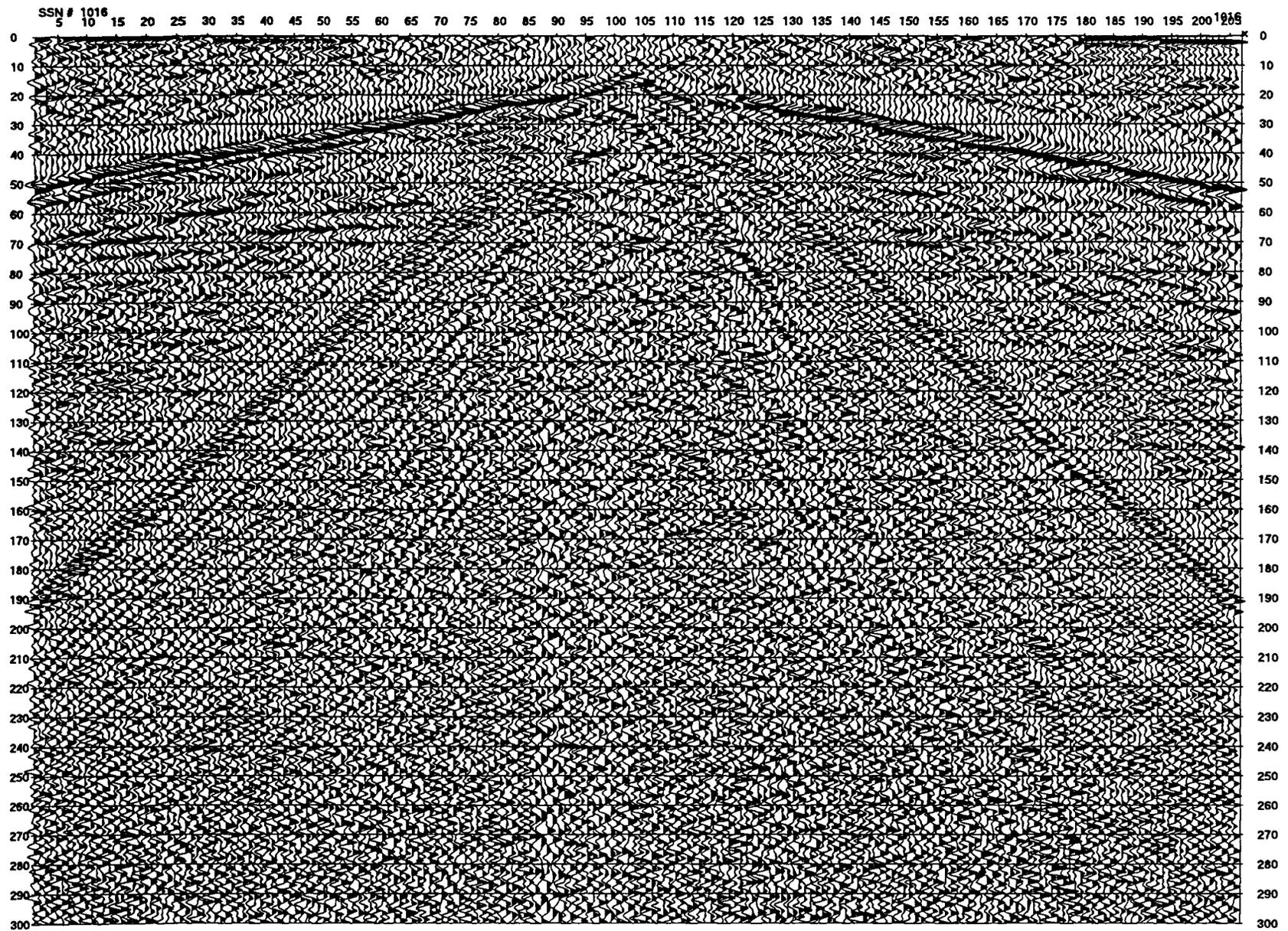


Figure A16. 50 cal., shot 3, split spread.

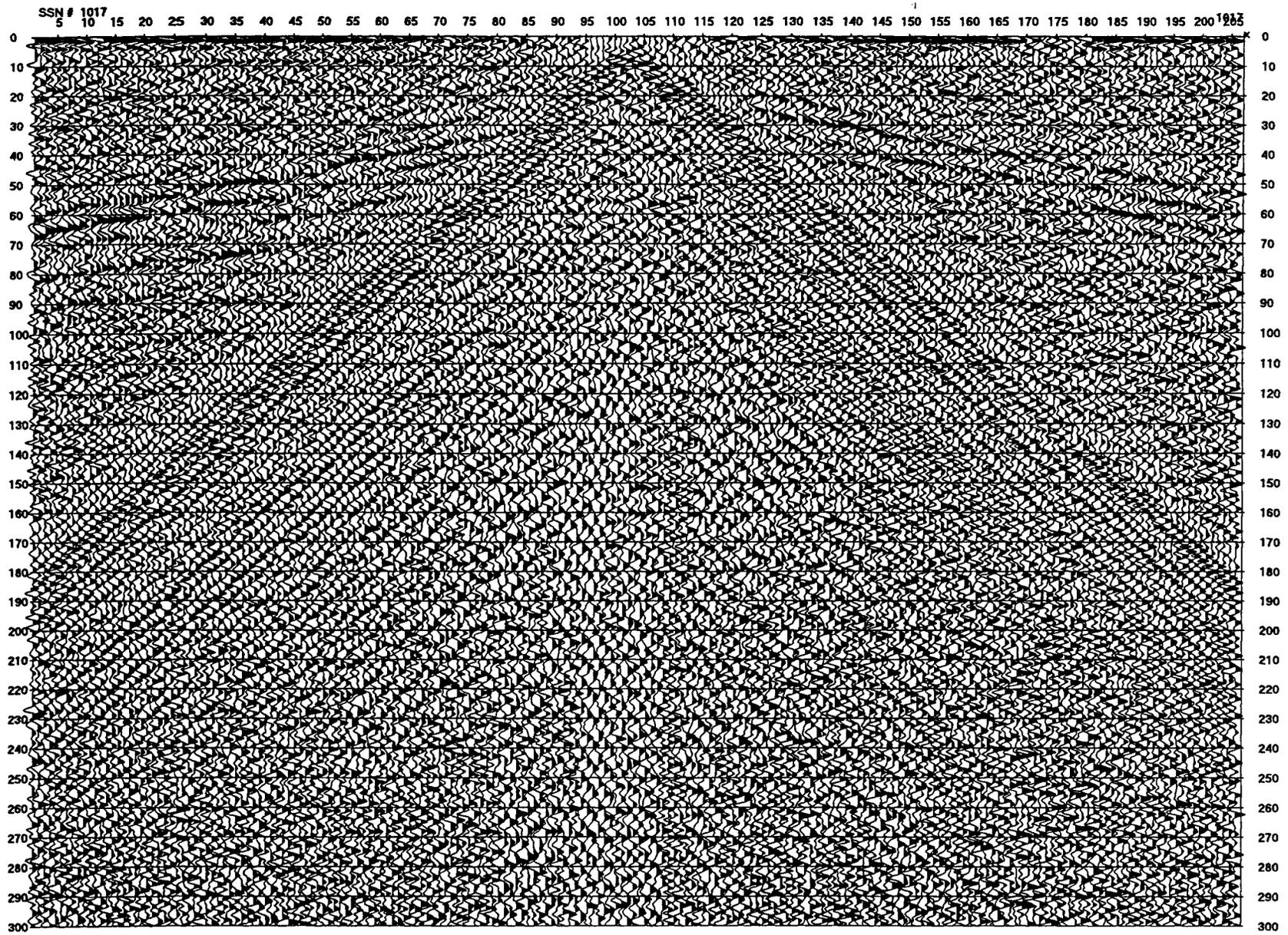


Figure A17. Small hammer, one impact, split spread.

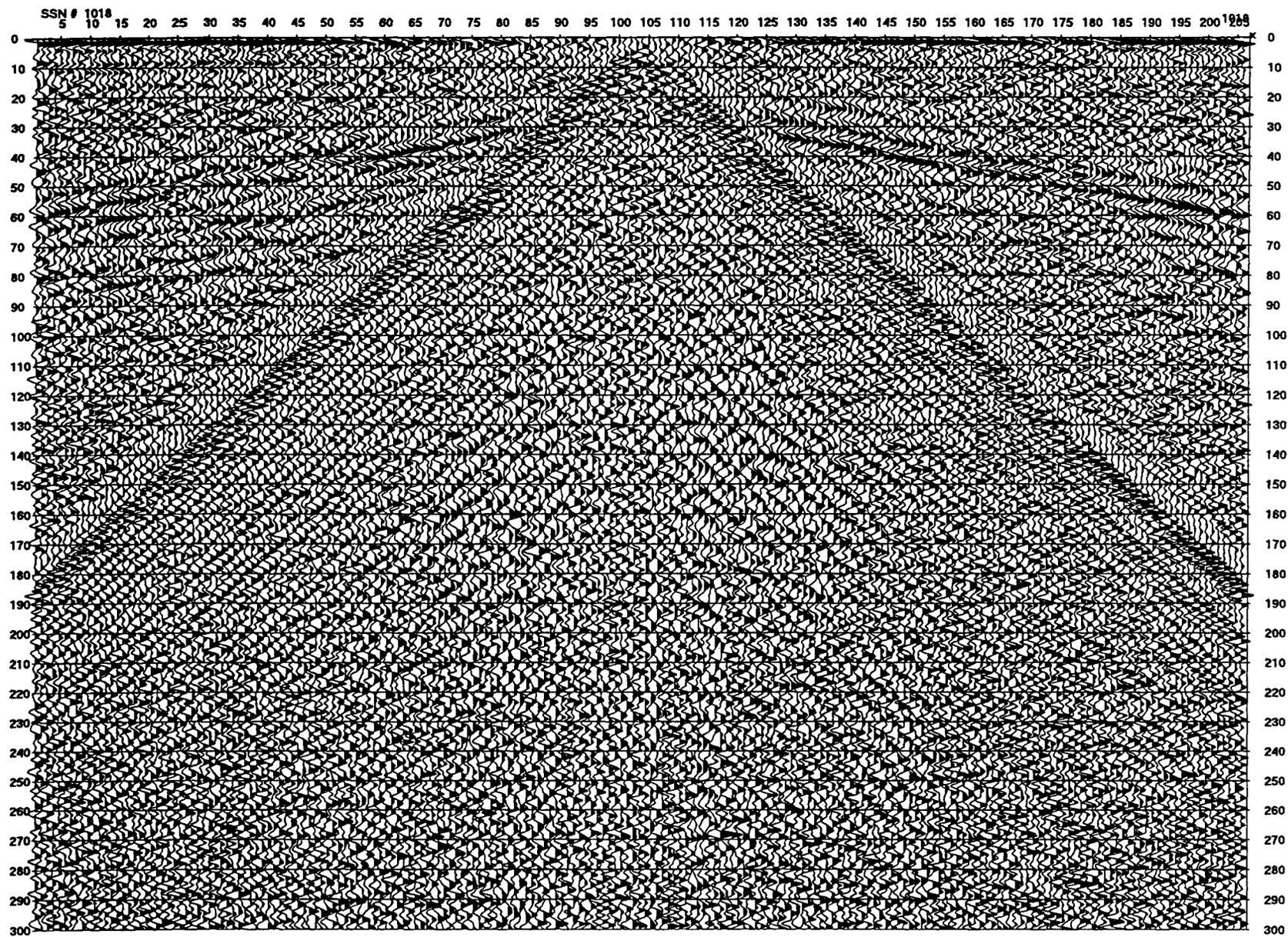


Figure A18. Small hammer, five impacts, split spread.

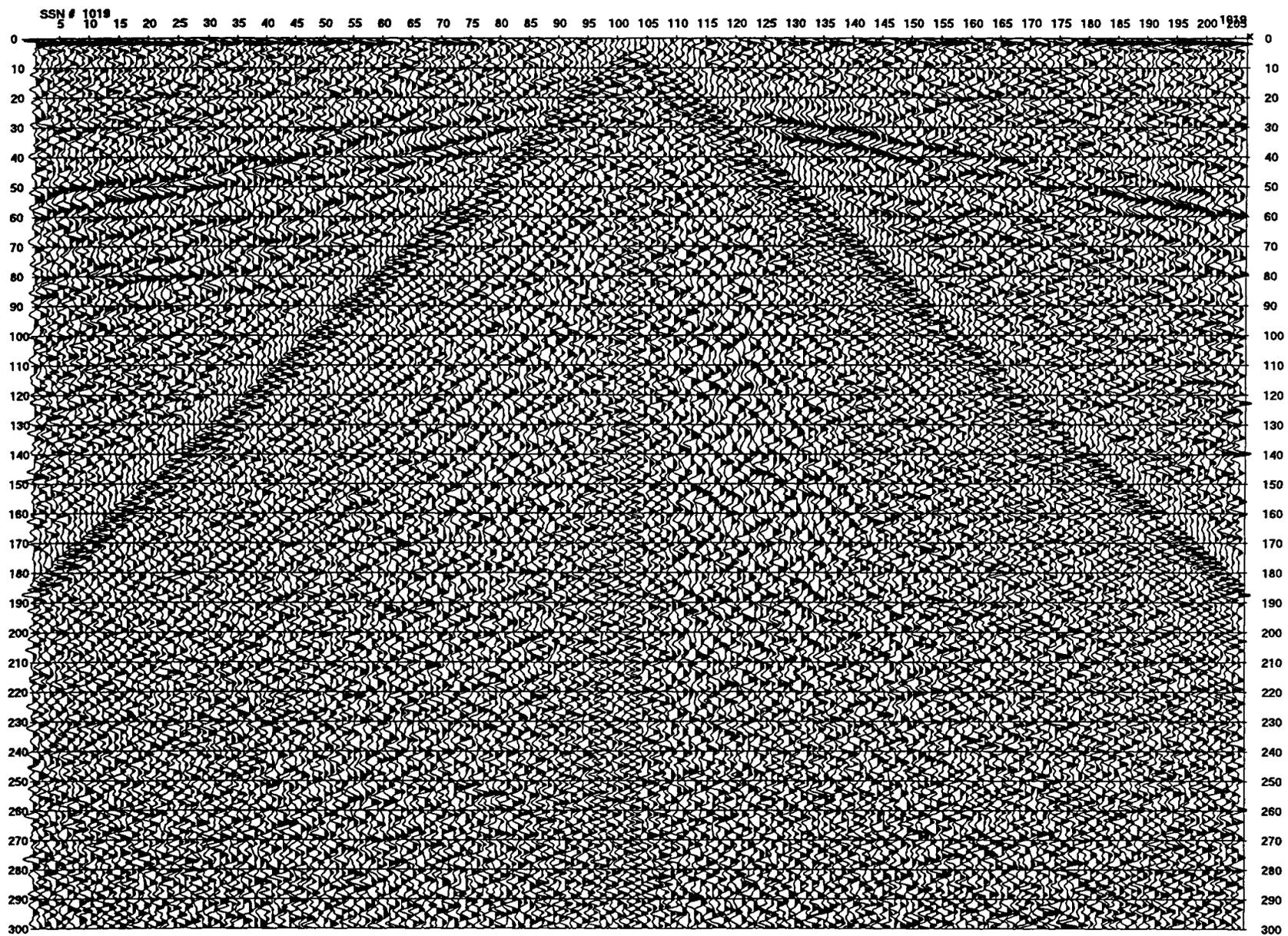


Figure A19. Small hammer, ten impacts, split spread.

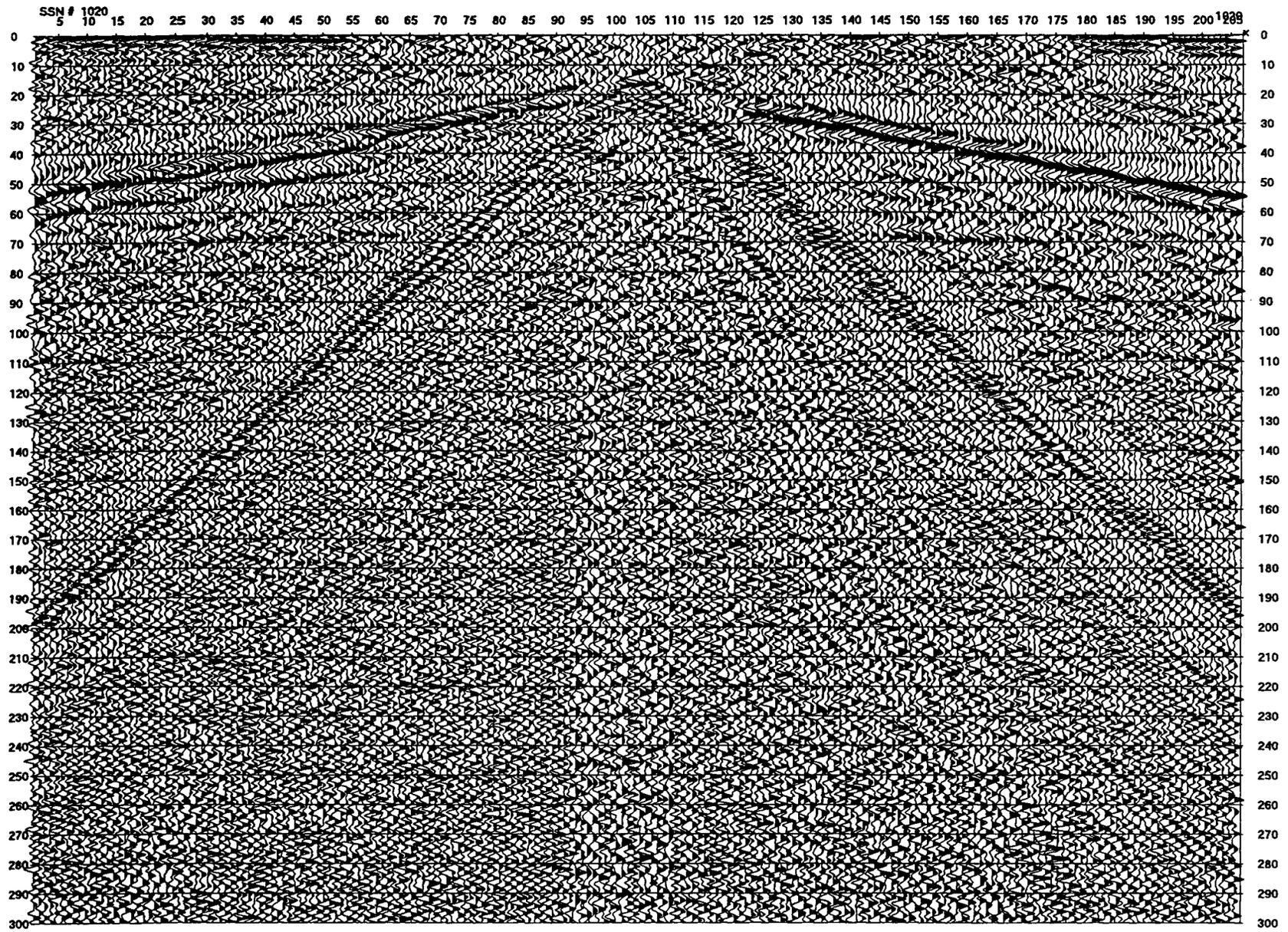


Figure A20. 12 ga. auger gun, shot 1, split spread.

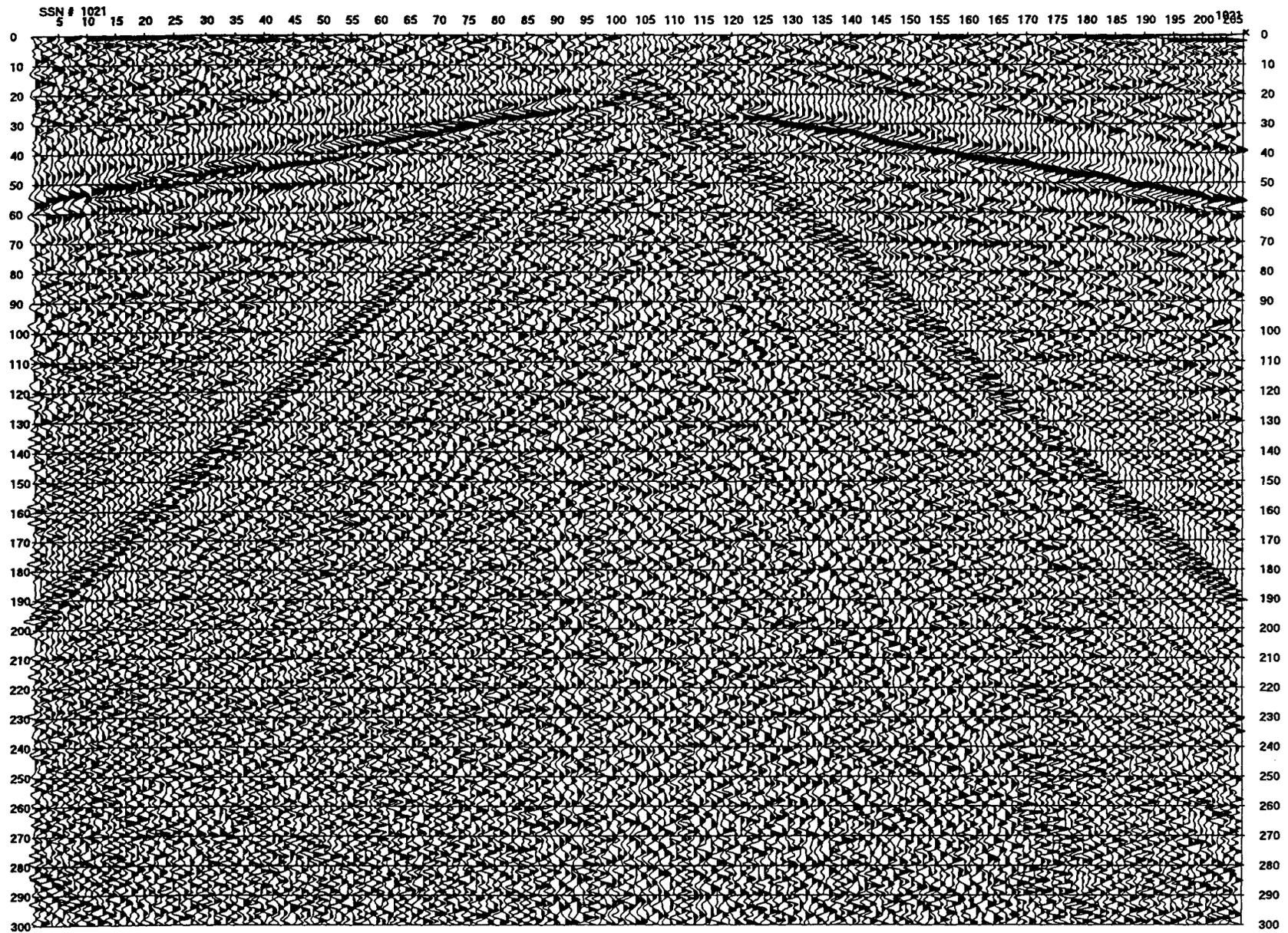


Figure A21. 12 ga. auger gun, shot 2, split spread.

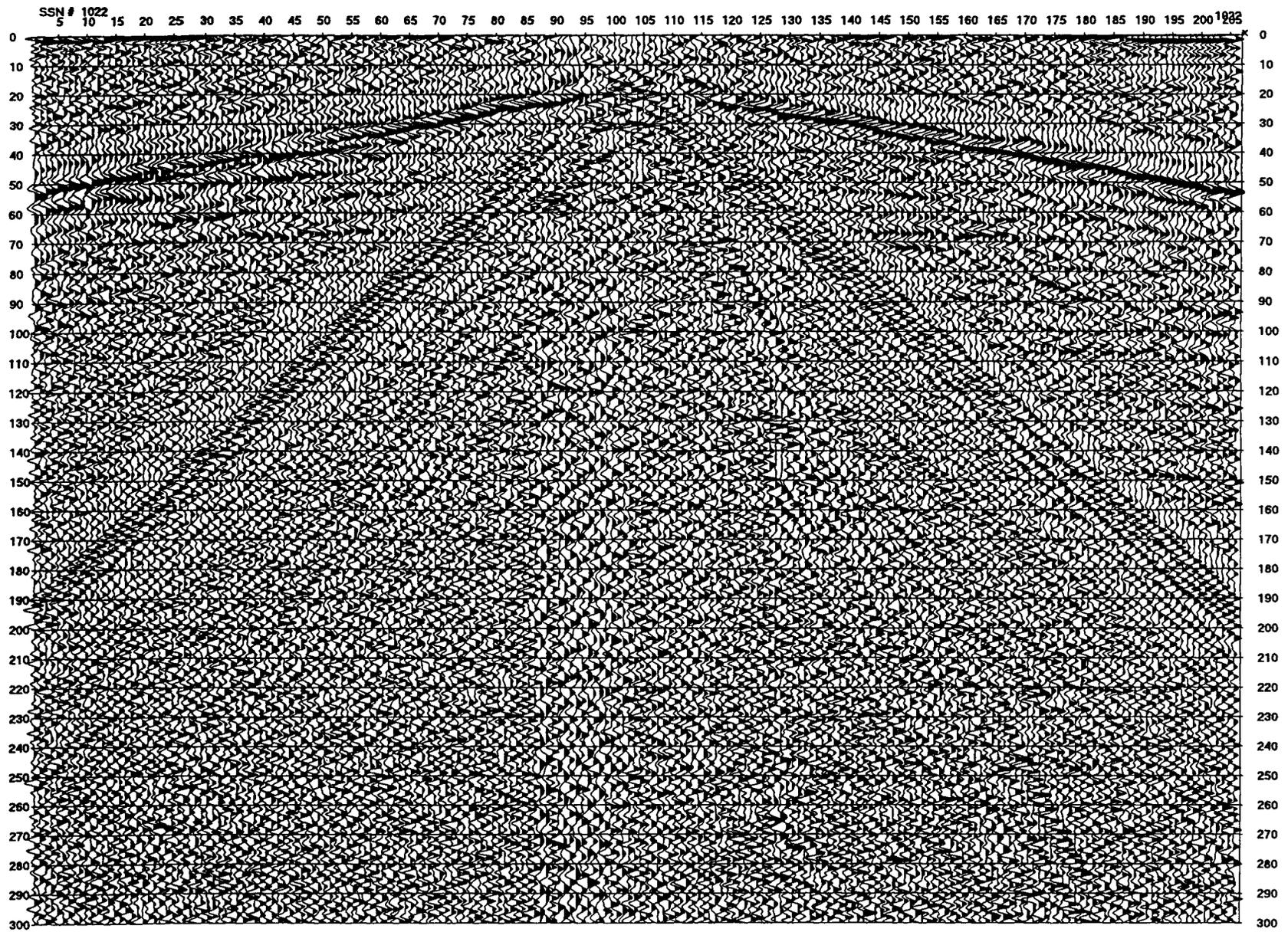


Figure A22. 8 ga. auger gun, shot 1, split spread.

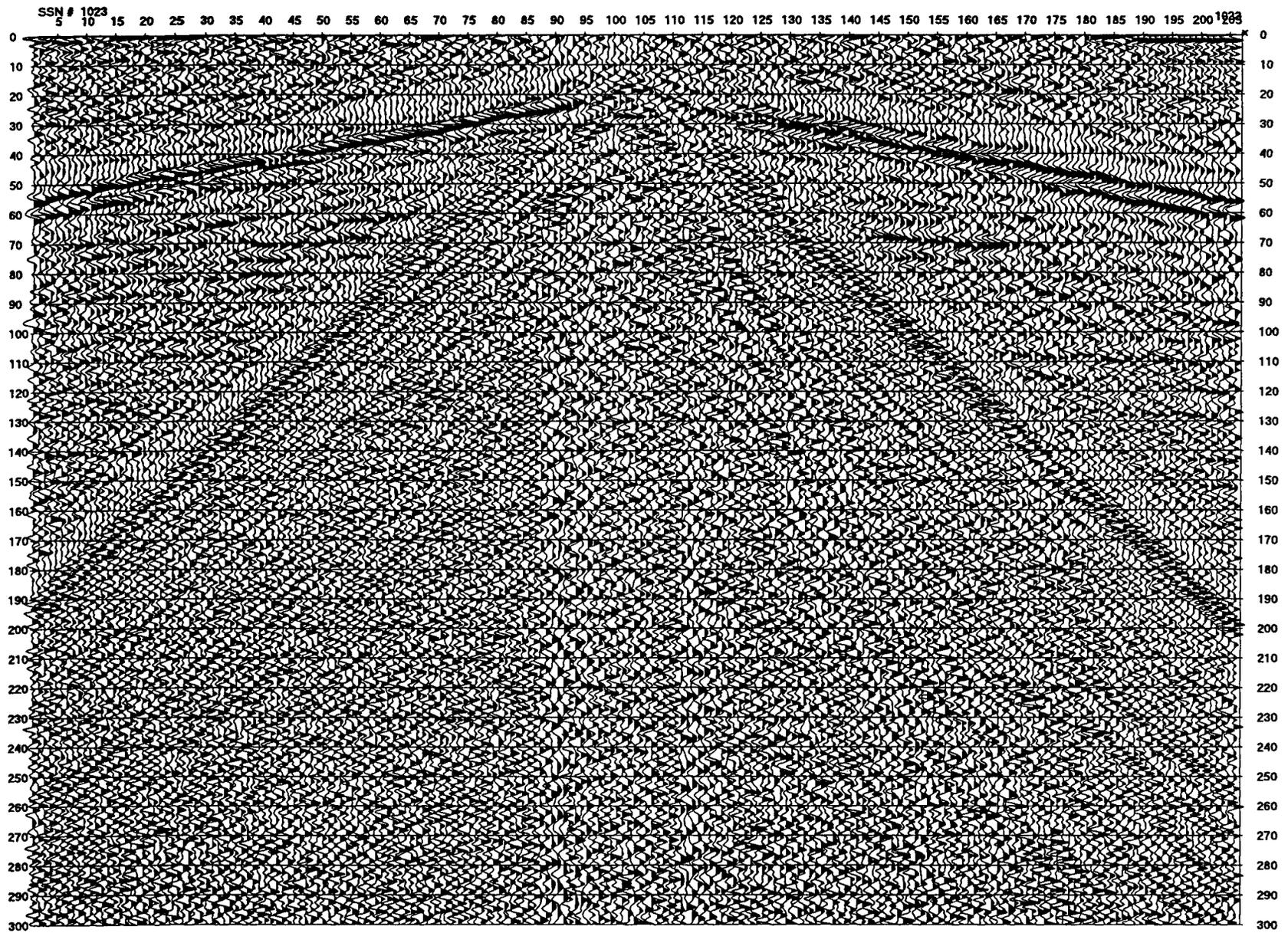


Figure A23. 8 ga. auger gun, shot 2, split spread.

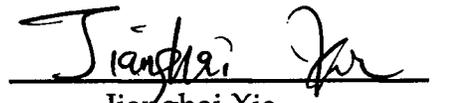
Appendix B
Project Proposal

**Feasibility of High Resolution 2 1/2-D Seismic Reflection
And Surface Wave Imaging to Delineate Dissolution
Features Within the Upper 200 m in Escambia County,
Alabama**

Proposal to
William T. Shefchik
Burns & McDonnell Waste Consultants, Inc.
9400 Ward Parkway
Kansas City, Missouri 64114

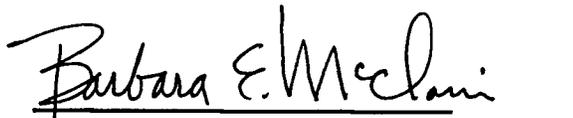
by
The University of Kansas
Kansas Geological Survey
1930 Constant Avenue, Campus West
Lawrence, Kansas 66047-3726


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The University of Kansas
Center for Research, Inc

12/10/98

Date

Feasibility of High Resolution 2 1/2-D Seismic Reflection and Surface Wave Imaging to Delineate Dissolution Features Within the Upper 300 ft in Escambia County, Alabama

Introduction

A properly designed and executed high resolution seismic reflection and surface wave surveys should be capable of identifying and delineating dissolution features of size within the upper 300 ft in Escambia County, Alabama. This seismic study will focus on the following goals and objectives: 1) identifying anomalous subsurface features with the characteristics of voids, subsurface subsidence, and/or karst, 2) stratigraphic and structural (delineate pinnacle bedrock topography) characteristics of this site, 3) feasibility of the technique to delineate subsurface voids and subsidence potential in the upper 300 ft, 4) resolution potential (vertical and horizontal features detectable and resolvable), 5) optimum geometries and equipment, 6) near-surface variability and its effects on recorded data, 7) near-surface static effects, 8) necessary QC to eliminate artifacts and maximize data, 9) potential of coincident interpretations of 2 1/2-D reflection and surface wave profiling, 10) evaluation of effective depth of imaging, 11) generation of a bedrock surface map including shear wave velocity field between bedrock and ground surface and 12) produce a 2 1/2 -D reflection and shear wave profile.

Proven high resolution techniques will be used to design the data acquisition and processing parameters and determine optimum equipment and methodologies for the reflection survey (Steeple and Miller, 1990). Maximizing the resolution potential and signal-to-noise ratio will be an emphasis of this survey. The continuous CDP profile lines will be acquired using a fixed spread consisting of up to 200 live stations. The seismic source, geophone type, spread geometry, shots/point, and acquisition philosophy used to acquire the CMP profile lines will be based on the results of walkaway noise tests. One goal of this study will be to determine the utility of state-of-the-art shallow high resolution seismic reflection techniques to detect, delineate, and evaluate local stratigraphy and likelihood of karst features at this site.

A newly developed surface wave imaging technique will be used to explore for abrupt changes in shear wave velocity expected where karst features are present (Xia et al 1998). Abrupt and distinct changes in the shear wave velocity are expected at the contacts between the Bucatunna Clay and Glendon Limestone representing bedrock. It is unlikely the pinnacled surface of bedrock will be completely resolved with the shear wave velocity profile but the unique geometries should provide a distinctive wave

pattern. This study will be designed to both develop an accurate shallow subsurface image and study optimization and limitations of delineating lateral changes in shear wave velocity using surface waves.

Dissolution caverns in the Glendon and Marianna Limestone are postulated to be the origin of voids and collapse features within the Bucatunna Clay and river terrace deposits in portions of southern Alabama and northern Florida. Sinkholes have been identified within the Conecuh National Forest less than 2 miles from the proposed site. If dissolution related features with the potential to form sinkholes exist on the proposed site of this power plant in extreme southern Alabama, appropriate site modifications or locally specific engineering design compensation would be critical during the early stages of construction. Present at depth (about 100 ft) is the Ocala Limestone which has been responsible for karst related sinkholes in Florida. Critical to the safe construction and operation of the presently proposed power station is an intact geologic section between the river terrace deposits at the ground surface down to the base of the Ocala Limestone over 150 ft below ground surface. At the proposed site, three different limestone units are present in the upper 150 ft with a history of karsting in the region. This seismic reflection effort will emphasize identification of anomalous subsurface features to be drilled for confirmation of existence, lithology, material characteristics, and dimensions.

The project will consist of two major phases: testing and production. The testing phase will commence as soon as a mutually agreed time can be arranged between the Kansas Geological Survey (KGS) and Burns & McDonnell (BM). A start date of December 13, 1998, has been proposed and tentatively agreed upon, forgoing any unforeseen mobilization delays. The testing phase will consist of walkaway tests near planned survey lines and a 2-D surface wave survey in an area with a known sinkhole. Reflection walkaways will focus on resolution potential and signal-to-noise necessary to image the depth of interest. Surface wave testing will consist of a profile traversing an area with a known dissolution feature and into an area with intact limestones. Quality judgements and the practical potential of the test data will dictate if the production phase is undertaken and the approach. If both KGS and BM agree that the test data warrants continuation of the project, the production phase will commence at a mutually agreed upon time.

The production data will require about 3 weeks (depending on field conditions) following well established shallow high resolution data acquisition procedures (Hunter et al., 1984; Knapp and Steeples, 1986; Steeples and Miller, 1990) and surface wave imaging guidelines (Xia et al 1998, Park et al in press). Data acquisition will be roughly

structured and designed around the findings of the preliminary testing. Ideally, an uphole or check shot and VSP survey should be acquired in monitor wells along survey lines to enhance confidence, preliminary event identification, and eventual correlation to the processed data. Step-by-step analysis during the acquisition and processing phases of the survey will be continuous with appropriate modifications made to ensure the quality of the final product.

Outline of Proposed Program

1) An extensive series of walkaway noise tests for the reflection portion and a shear wave velocity field test profile for the surface wave method will be conducted during phase 1 (initial site visit). The reflection portion will include walkaways at two different locations with testing to include: several low energy, high frequency seismic sources; a pseudo-continuous spread with 2 ft receiver spacing spanning source-to-receiver offsets from 2 ft to over 400 ft; and an analysis of shot gathers incorporating geologic and any borehole information available. Surface wave method will consist of a shear wave velocity profile traversing an area with a known dissolution feature and into an area with a relatively undisturbed subsurface.

2) Contingent on the walkaway noise tests and surface wave test line, a series of 2-D profiles will be acquired to image beneath the areas of primary interest for the proposed facility (figure 1 and 2). The data will be acquired on 200 recording channels for the reflection profiling and 60 channels for the surface wave. Nominal 90-fold and 24-fold redundancy is anticipated for the reflection and surface wave sections, respectively.

3) The walkaway noise survey data, CMP reflection profiles, and shear wave velocity field lines will be analyzed and brute processed as part of the preliminary report. The processing flows will be optimized to insure accurate, high resolution images of the subsurface. On-site processing and analysis will be done to ensure project objectives can be met with acquired data. If uphole data are collected they will be used to correlate time with depth for layers of particular interest.

4) All data will be processed into final display format at the Kansas Geological Survey in Lawrence, Kansas. Included in the preliminary report will be justification for acquisition methods, parameters, and equipment as well as processing flows and preliminary interpretations.

5) Final report materials will be provided after review and considerable interaction between KGS geophysicists and BM geologist/hydrologists. It will require around one month to bring together all the materials and profiles into final format.

Table 1 – Summary of Proposed Survey

- 1) Seismic system to be used – 240-channel R60 StrataView from Geometrics

- 2) Equipment and Testing Parameters
 - triple 40 Hz L28E Mark Products Geophones (210 strings)
 - single 4.5 Hz Geospace Geophones (60 strings)
 - downhole 30.06 projectile source
 - downhole 50 cal projectile source
 - hammer source
 - hammer (12 lb, 8 lb, 2 lb) and
 - plate (1 sq ft x 1")
 - 12- and 8-gauge auger gun
 - RAWD (Rubber band Assisted Weight Drop)
 - Geostuff three-component downhole geophone
 - Single Mark Products borehole hydrophone

 - optimum vertical stacking
 - 2 ft receiver station spacing
 - 0.25 msec sampling interval
 - 200-trace, pseudo-continuous walkaway w/source offsets from 0.2 ft to 400 ft
 - digital filtering

 - a) Surface Wave
nominal 24-fold, 60-channel non-uniform roll-along recording
 - b) Reflection Profiles
nominal 90-fold, 200-channel non-uniform roll-along recording

- 3) VSP
 - 3-component hole lock geophone or single hydrophone
 - 200 ft maximum vertical profile
 - 5 ft vertical station spacing*
 - as many as 3 source offset positions*
 - source consistent with production survey

- 4) Planned Field Schedule:

	<u>Approx. Dates</u>
Mobilization	Dec. 8-11
Travel	Dec. 11-12
Walkaway noise testing	Dec. 13-14
Travel	Dec. 15-16
Demobilization	Dec. 17-20
Mobilization	Jan. 13-17
Travel	Jan. 19-20
Production Data Acquisition #1	Jan. 21-30
Travel	Jan. 31

Travel	Feb. 7
Production Data Acquisition #2	Feb. 8-18
Travel	Feb. 19-20
Demobilization	Feb. 19-22

- 5) Preliminary Report (including all walkaway tests, brute processed data, initial interpretations, and field safety report) approximately March 15, 1999.
Final Report after review and comment by BM (April 15, 1999 at the earliest).

* Depending on results of testing.

Seismic Reflection

Philosophy

Unequivocal identification and verification of reflections on shot gathers is not only necessary, it is mandatory for meaningful interpretations of shallow seismic data. Matching modeled NMO curves based on borehole velocity information with reflection hyperbola interpreted on shot gathers is the most conclusive means to both verify and analyze reflections. This combination incorporates ground truth (borehole velocity), geometric curve fitting (forward and inverse modeling), and event identification directly from single-fold shot gather data. Data from this project will go through rigorous verification techniques that include modeling, event verification, and cross comparisons of borehole and surface seismic. Modeling reflection arrivals as interpreted on shot gathers is not only critical, it should be required by law.

Quality Control (QC)

QC is critical and will be continuous throughout acquisition. Near-surface inconsistencies, vehicle noise, an extremely narrow and changing optimum recording window, and poor receiver coupling conditions will require strict compliance with QC guidelines and meticulous monitoring of data, an absolutely essential aspect of the data acquisition. Based on subtle changes in the near-surface, minor adjustments to some parameters (e.g., source-to-near offset) may be necessary to maintain the optimum recording window (Hunter et al., 1984). The seismograph CRT display, nearly real-time digital filtering, and real-time graphical display of noise levels will permit instantaneous monitoring of cultural, air traffic, vehicle traffic noise, cable-to-ground leakage, and geophone plant quality. After each geophone is planted, it will be tested to insure a cable-to-ground resistance greater than 1000K ohms and individual geophone continuity within 5% of nominal string impedance (including consideration

for cable offset). As well, each geophone will undergo a modified tap and twist test. No shot will be recorded if background noise voltage levels on active geophones is greater than 0.05 mV. The ability of the seismograph to real-time monitor noise levels, signal quality (through digital filtering), and unacceptable geophone plants as well as the roll-switch's built-in earth leakage and continuity meters minimizes the chances a recorded shot is not maximized for the site and equipment.

Phase 1

Walkaway Testing

Unique shallow data characteristics expected to be evident during the walkaway testing will exemplify the utility of a good testing program and demonstrate the need to have a sizable repertoire of acquisition equipment available for testing. A shallow seismic reflection program needs to be tuned for the acoustic and logistical conditions at a particular site. As previously stated, identification and confirmation of reflection hyperbola on walkaway noise tests is essential and best accomplished through mathematical curve fitting, matching to borehole-derived velocity structure, and observation of file-to-file consistency. Walkaway noise tests will be designed so the subsurface is over-sampled horizontally and the source-to-farthest-receiver-offset is at least equivalent to the primary depth of interest. This allows all aspects of the complete wave field (especially the reflections) to be thoroughly appraised.

The primary intent of a walkaway noise test is to allow the comparison of various source, receiver, and instrument settings and configurations as they relate to overall improvements in the signal-to-noise ratio and frequency content. Walkaway tests are ideally suited to the identification of individual events within the full wave field. Phase velocity and wave types are a couple of the most important pieces of information extractable from walkaways. The relationship of velocity and wave type to spread geometries and offsets needs to be completely analyzed and understood for acquisition parameters and equipment to be optimized (Pullan and Hunter, 1990). Assumptions or partial analysis of these key properties could result in artifacts or improperly recorded data. Processing of walkaway data for this study will be limited to trace organizing, gain balancing, and digital filtering. Walkaway data from each source configuration or comparison parameter will be displayed in a source-to-receiver offset order.

The evaluation/feasibility portion of the study is designed to allow analysis of acoustic characteristics and, more generally, the reflection method, which in turn permits accurate estimations of resolution and optimization of acquisition equipment

and parameters. The walkaways will consist of source-to-receiver offsets ranging from 2 ft to approximately 400 ft or more if necessary. The receiver interval will be 2 ft. The 12- and 8-gauge auger gun (Healey et al., 1991) (requiring only class C explosives), an accelerated weight drop (Bison EWG or equivalent), various hammer and plate combinations, and 30.06 downhole will be evaluated (if conditions permit) so the optimum source for the near-surface conditions, target depth, resolution requirements, and environmental constraints can be determined. Each source will be evaluated with as near equivalent conditions and parameters as possible. Experience with source testing (Miller et al., 1986; Miller et al., 1992; Miller et al., 1994; Doll et al., 1994) will greatly enhance both the quality and the efficiency of source evaluations at this site.

The receivers available for testing be triple 40 Hz Mark Product L-28E geophones wired in series. From previous experience the 40 Hz geophones will probably produce the best response. The need for a strong signal from geophones with a high spurious noise threshold is paramount and from previous experience, lower quality geophones will not produce the desired output within the desired frequency band. If at any point during the noise testing an optimum parameter or component is identified, the affected portions of the remaining tests at that site could be by-passed.

In summary, the walkaway noise testing will be designed and executed to allow evaluation of acoustic signature, optimum acquisition equipment and parameters, near-surface velocity structure, horizontal consistency in reflection character, general resolution potential, signal-to-noise ratio, and impact of cultural noise (i.e., jet aircraft, industrial facility, vehicle traffic, etc.). Walkaway noise tests will guide the definitive selection of equipment and parameters as well as optimum station spacing and recording geometries for the production profiles.

Phase 2

Production Phase

The production acquisition phase of this project will begin as soon after the testing phase is completed and both BM and KGS are satisfied with the parameter design. A total of 20 field days will be necessary for data acquisition. Source and receiver selection will be a qualitative choice based on frequency, potential penetration depths, quantity of ground roll relative to body waves, and physical site and near-surface constraints.

The equipment and parameters used to acquire the production lines will be based on the results of the individual walkaway tests performed at the site during the testing phase of the survey. Data will be acquired on a 240-channel (Quad 60-channel

machines networked), R60 Geometrics StrataView floating-point seismograph. Parameters such as sampling interval and record length will be determined after careful examination of the dominant frequency and usable bandwidth of reflection energy recorded during the walkaway noise tests. The sampling interval will be chosen to insure at least 5 samples/wavelength of the upper corner frequency and 10 samples/wavelength of the dominant reflection energy. The total number of samples will be chosen based on maximum time (depth) of interest as determined by both the sampling interval and the uphole survey (if possible). Once the seismograph's variable settings are selected, the settings will not change for the duration of the particular line being acquired. This is to insure consistency in phase and to avoid confusion relating to plotting scales, alias values, and system response.

Based on experience at sites with a similar near-surface and target interval, the most probable source used for production will be either the downhole 50 cal or the 8 gauge auger gun. Triple L-28E 40 Hz geophones will likely be the preferred choice for the receivers on the production line. Equipment parameters chosen to record the CDP lines will incorporate the results of both walkaway noise tests and uphole survey.

Data will be acquired using a standard CMP roll technique with a variable nearest source-to-receiver offset, resulting in a 90-fold variable offset section. Geophone station spacing will be confirmed by computations and qualitative judgments made from data acquired during the testing phase. The most probable geophone spacing is 4 ft. The data will probably be acquired using an asymmetric split-spread source/receiver geometry. The source-to-nearest receiver offset will be 2 ft with a maximum source-to-receiver offset ranging between 200 ft and 400 ft. Modifications to the source/ receiver geometries and offsets will likely be necessary after analysis of the data acquired during the testing phase.

Fine tuning of the field geometries and equipment will be based on analysis of potential (using physical properties derived from the test data) versus required resolution (Miller et al., 1995), balanced with maximum signal-to-noise ratio. The 1/4 wavelength criteria of Widess (1973) will be used to determine the best vertical resolution with equipment and near-surface conditions present during the acquisition of the test data. The potential versus actual horizontal resolution of the production lines will be based on the radius of the theoretical Fresnel zone. Oversampling of the first Fresnel zone will not exceed 15 times (Miller et al., 1990) while a minimum of four times will be maintained throughout the survey (Knapp and Steeples, 1986).

In-hole seismic studies should provide improved correlation between the borehole defined geology and events on the seismic sections. Uphole surveys will be

designed to complement and appraise walkaways and high resolution seismic reflection data, providing information for correlation to geophysical and lithologic logs. This uphole survey will likely involve both a hole lock geophone and a hydrophone sampling every 5 ft with a source offset around 10 ft. The two measurements will be incorporated into and hopefully used to improve the interpretation of the seismic reflection data through more accurate time-to-depth conversions, correlation with existing electric and geologic logs, and horizontal extrapolation of geologic information from the borehole.

Data Processing

Shallow seismic reflection is a method that lends itself to over-processing, inappropriate processing, and minimal involvement processing. Interpretations must take into consideration not only the geologic information available but also each step of the processing flow and the presence of reflection events on raw unprocessed data. During this study, the only operations or processes that will be used are those that enhance the signal-to-noise ratio and/or resolution potential as determined through evaluation of high confidence reflections identified directly on field files.

For most basic shallow high-resolution seismic reflection data, CDP processing steps are a simple scaled-down version of established petroleum-based processing techniques and methods (Yilmaz, 1987; Steeples and Miller, 1990) (Figure 2). CDP data processed as part of this survey will follow a processing flow similar to those used for routine petroleum exploration (Table 2). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, and the accuracy of the muting operations. A very low (by conventional standards) allowable NMO stretch (< 20%) will likely be extremely critical in minimizing contributions from the very shallow reflected energy at offsets significantly beyond the critical angle. Limiting wavelet stretch

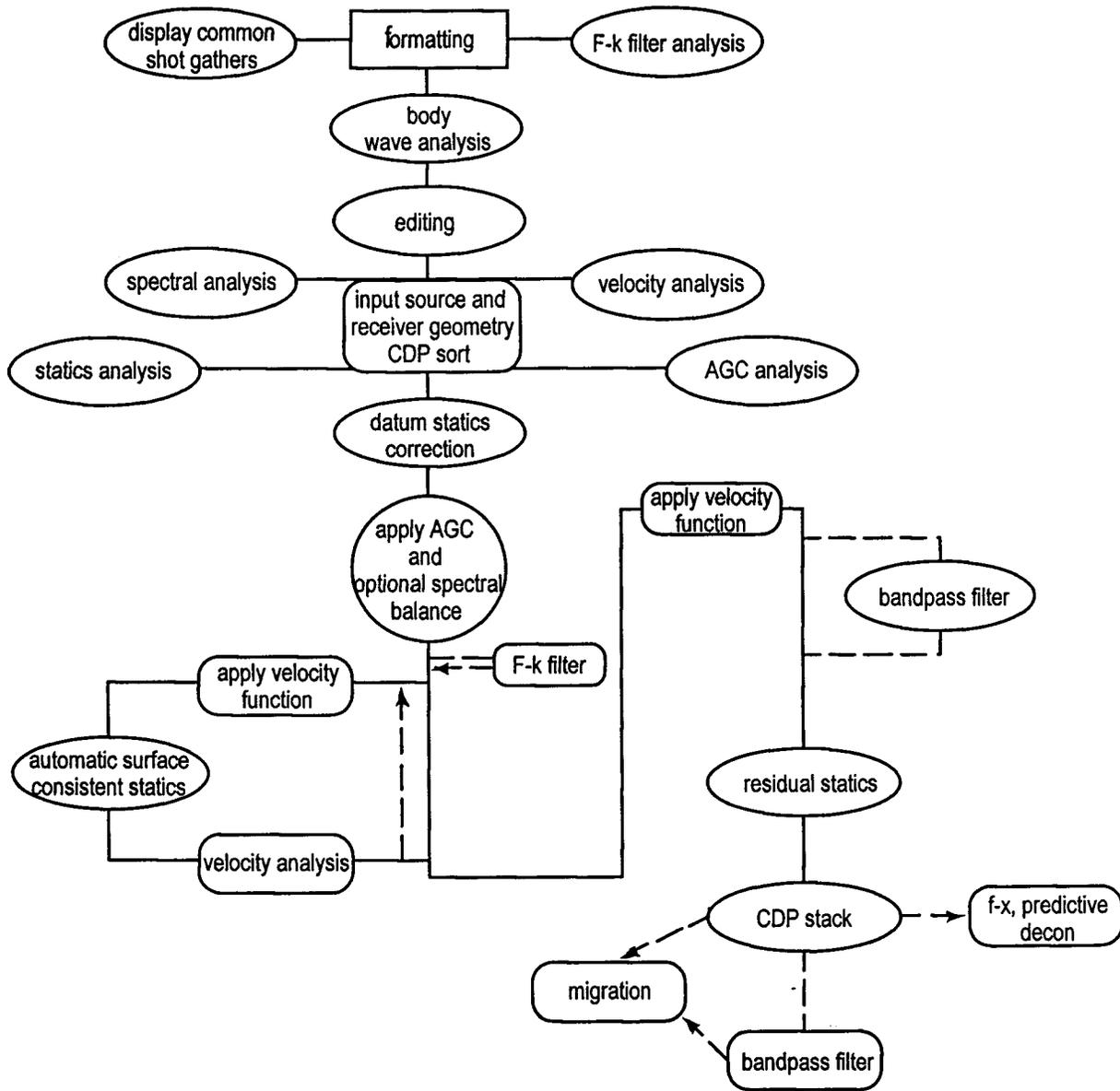


Figure 2

through muting maximizes resolution potential and minimizes distortion in the stacked wavelets (Miller, 1992). Processing/processes used on this data will be executed with no *a priori* assumptions. Extreme care will be taken to enhance through processing only what can be identified on shot gathers and not to create coherency on stacked sections.

Some basic petroleum processing techniques make assumptions that are violated by most shallow reflection data sets. Applying these processes could dramatically reduce data quality or worse, generate artifacts. Particular processes,

Table 2
Basic Processing Flow

Primary Processing

format
preliminary editing
trace balancing
digital filtering
spectral balance
first arrival muting (remove direct wave and refraction)
surgical muting (removal of ground roll based on trace-by-trace arrival)
assign geometries (input source and receiver locations)
elevation correction to multiple, floating datums
sort into CDPs (re-order traces in common midpoints)
velocity analysis (whole data set analysis on 100 ft/sec increments)
spectral analysis (frequency vs amplitude plots)
NMO correction
surface consistent correlation statics
secondary editing
residual correlation statics
CDP stack
amplitude normalization
correct to flat datum
display

Secondary Processing

f-k filtering
f-k migration
deconvolution (spiking and second zero crossing)
f-x deconvolution

such as deconvolution and some forms of trim statics, assume large numbers of reflections with a random reflectivity sequence and a broad range of reflection frequencies (Yilmaz, 1987). Migration is another process that, due to non-conventional scaling, many times appears to be necessary when in actuality geometric distortion may be a simple scale exaggeration (Black et al., 1994). Consistency in arrival and apparent orientation of individual reflections after each process is critical to ensuring the authenticity of final interpretations.

Final Sections

The principal CDP lines will be processed with commercial processing software into CDP stacked format at the KGS's Lawrence, Kansas facility. The basic architecture and sequence of steps to be followed during the generation of the stacked sections will be similar to conventional petroleum exploration processing flows with exceptions relating to the step-by-step QC necessary for the generation of a stacked section allowing a reasonably confident interpretation of shallow features (Miller et al., 1989; 1990; Miller and Steeples, 1991).

Each analysis step in the brute processing flow will be available to BM for critique. Any additional information requested by BM during the processing flow will be generated within a reasonable amount of time (amount of time determined jointly). All digital information requested by BM will be delivered by KGS on the requested magnetic or optical media (if available at the KGS). All hardcopy printouts of analysis steps as well as any special request data will be delivered to BM as 300 dpi continuous plots and in SEG-Y format, if requested. Horizontal and vertical scale on hardcopy printouts will be set to maximize the analysis potential and will be discussed and agreeable with BM staff.

Reflection Survey Project Goal

The goal of the reflection portion of this study is to determine the feasibility of and optimize the technique to image and resolve anomalous structures and characteristics within the upper 200 ft at this site possibly related to karst. The results of this study will include a thorough comparison of several high resolution seismic sources, an empirically based estimation of horizontal and vertical resolution potential, stacked and interpreted CDP section focusing on enhancing dissolution structures beneath the proposed power plant, produce a 2 1/2-D interpretation of the study area, and determination of optimum recording parameters.

Surface Waves

Introduction

Surface waves have traditionally been viewed as noise on multichannel seismic data designed to image targets significant to shallow engineering, environmental, and groundwater studies (Steeples and Miller, 1990). Recent advances in the use of surface waves for near-surface imaging have incorporated spectral analysis techniques (SASW), developed for civil engineering applications (Nazarian et al., 1983) with multi-trace reflection technologies (CDP) developed for petroleum applications (Mayne, 1962).

Combining these two uniquely different approaches to acoustic imaging of the subsurface allows high confidence, non-invasive delineation of horizontal and vertical variations in near-surface material properties (MASW) (Park et al., 1996; Xia et al., 1998; Park et al., in press).

Surface wave imaging has shown great promise detecting shallow tunnels (Figures 3 and 3a), bedrock surface (Figure 4), remnants of underground mining (Figure 5), and fracture systems. Extending this imaging technology to include lateral variations in lithology has required a unique approach incorporating SASW, MASW, and CDP methods. Integrating these techniques provides a 2-D continuous shear wave velocity profile of the subsurface. Signal enhancement resulting from determination of a dispersion curve using upwards of 60 closely spaced receiving channels and the calculation of a dispersion curve every 4 ft or so along the ground surface provides a unique, relatively continuous view of the shallow subsurface. This highly redundant method enhances the accuracy of the calculated shear wave velocity and minimizes the likelihood of irregularities associated with an occasional erratic dispersion curve corrupting the data analysis.

The objective of this research program is to determine the feasibility of this new technology to delineate lateral variations in shear wave velocity within consolidated as well as unconsolidated sediments. This site study will be divided into two individual phases: 1) testing and evaluation and 2) sitewide mapping to delineate the three-dimensionality of the feature. The testing stage will involve forward modeling and on-site acoustic wavefield studies as well as acquisition and processing of a surface wave line to study the shear wave velocity field when traversing an area with a known dissolution feature and into an area with a relatively undisturbed subsurface. This testing stage will fully appraise the test data and determine penetration depths, a generalized velocity model, and feasibility of distinguishing anomalous velocity changes below, at, and above the bedrock surface. The second phase will attempt to delineate the entire area of interest in a pseudo three-dimensional sense ($2\frac{1}{2}$ -D). This phase will require the deployment of an extensive series of profile lines designed (based on available drill data and the results of the phase one) to optimize line orientation to map the areal and volumetric expression of the bedrock and any suspected anomalous zones.

Current Procedure

The current operational procedure requires the generation and analysis of an extremely broadband acoustic signal. The primary waveform of interest will be the

Rayleigh wave. The dispersive nature of this wave is related to the shear wave velocity structure of the subsurface. By calculating the dispersion curve (phase velocity as a function of frequency) and then inverting that curve, a shear wave velocity profile can be determined for the area directly beneath the acquisition spread. Acquiring data by progressively moving the source from one station to the next while maintaining a consistent number of receivers and source-to-receiver separation permits the generation of a two-dimensional profile showing the shear wave velocity structure as a function of depth and station location. This shear wave profile can then be analyzed to identify significant changes in shear wave velocity likely indicative of abrupt and large changes in material properties. The laterally non-uniform portions of the velocity profile can be seen most prominently as large variations in the gradient of the velocity field.

Once the anomalous velocity zones can be confirmed, a grid of profiles can be laid out and data collected along each profile. This two-dimensional grid provides a 2 1/2-dimensional fence diagram that readily allows interpretation of both shape and trend of meandering or spatially extensive features.

Final Products

It is the intent of this survey to provide a final report that includes all the data processed into an appropriate display/interpretation format with significant documentation. Initial interpretations will be based on model studies, drilling, correlation to other data, and experience. A fence style diagram for the site will be attempted to allow a single pseudo three dimensional view of the subsurface. At a minimum all profiles will be displayed as two dimensional section with anomalous zones interpreted and some discussion of possible significance of each. All acquisition, processing, and interpretation discussion and annotations will be complete and appropriate for the data and research objectives.

Surface Wave Study Project Goal

The goal of the surface wave portion of this study to determine the feasibility of the technique to image and resolve dissolution features and geologic characteristics immediately beneath, at, and above bedrock (upper 75 ft at this site). The results of this study will include a thorough analysis of the feasibility of and confidence in this technique and resulting interpretations, an empirically based estimation of horizontal and vertical resolution potential, and a pseudo three dimensional representation of the subsurface beneath the critical portions of the power plant.

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This is will be a fixed unit-price contract. The budget assumes all site access, permits, scheduling, brush clearing, and utility clearances are the responsibility of BM. Depth of source penetration should not exceed 4 ft, most likely < 3 ft.

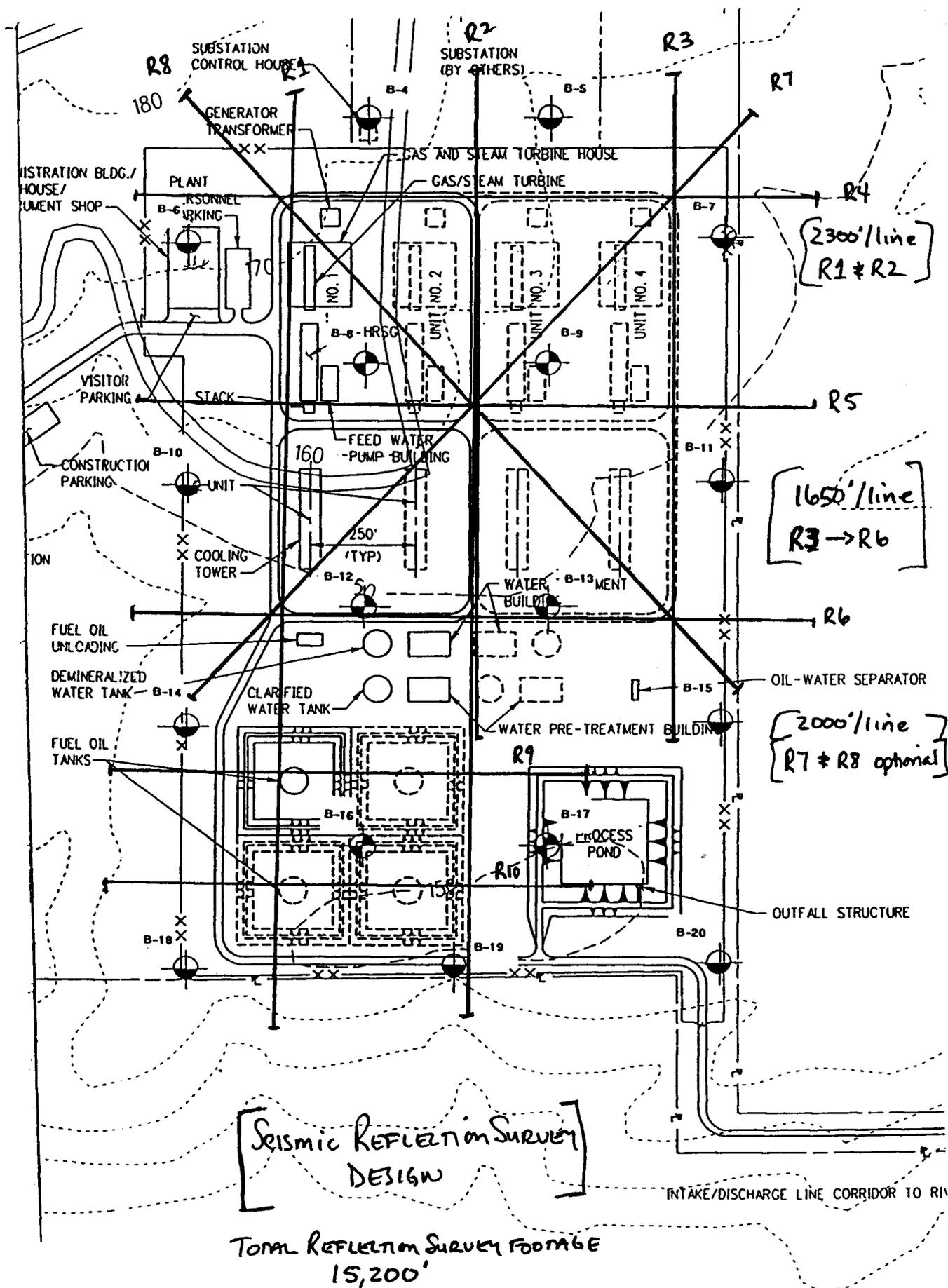


Figure 1

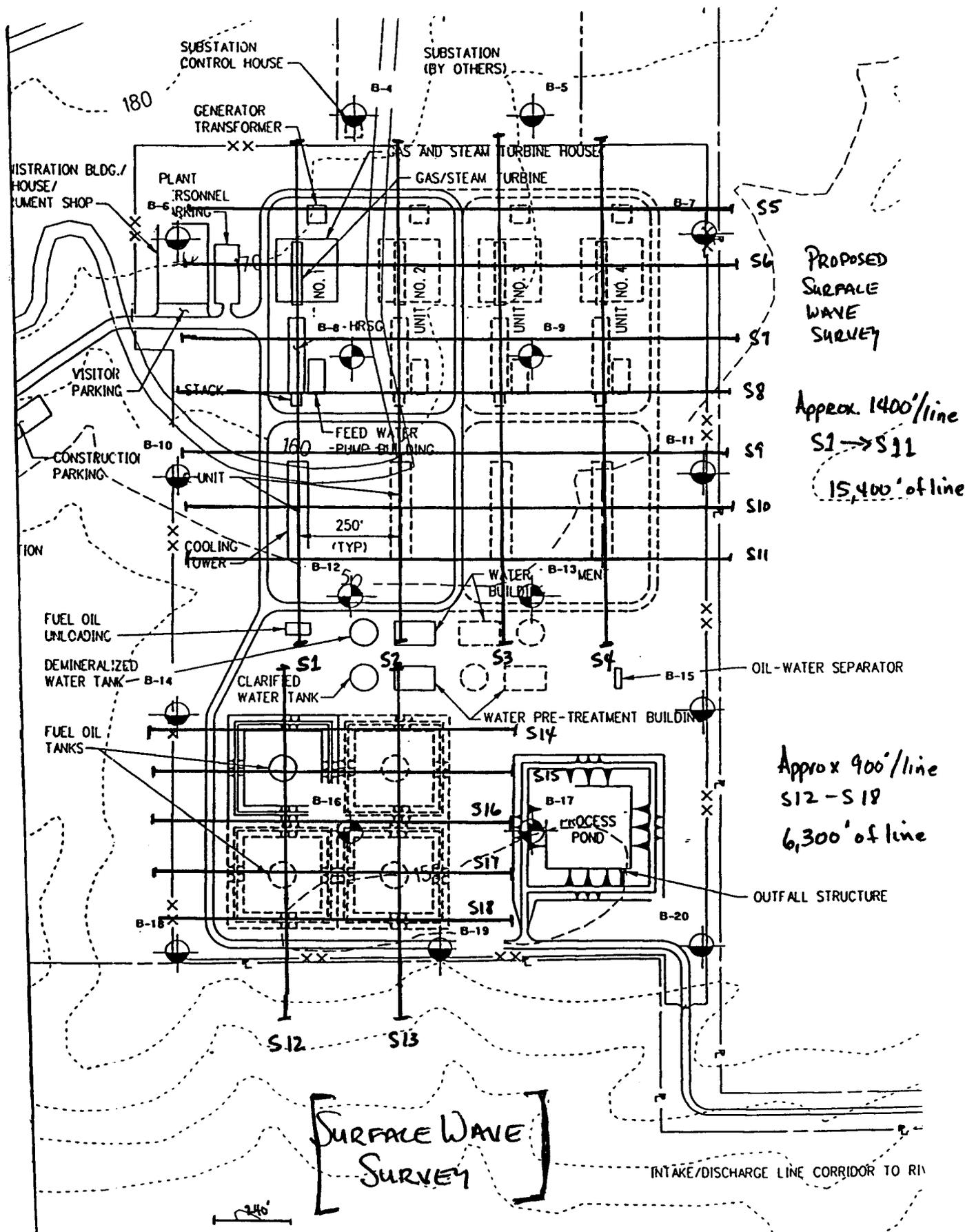


Figure 2

CASE STUDY 1

IMAGING STEAM TUNNEL

University of Kansas, Lawrence, KS

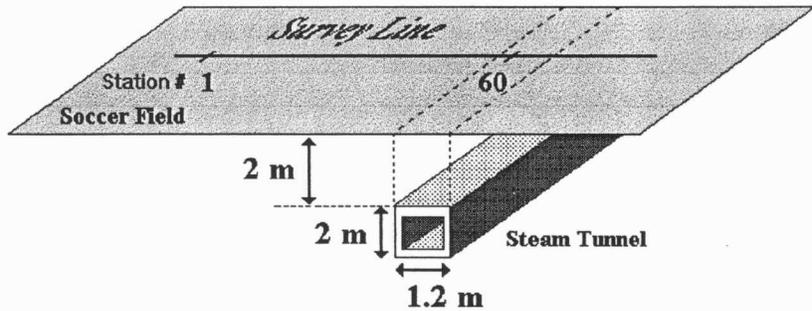
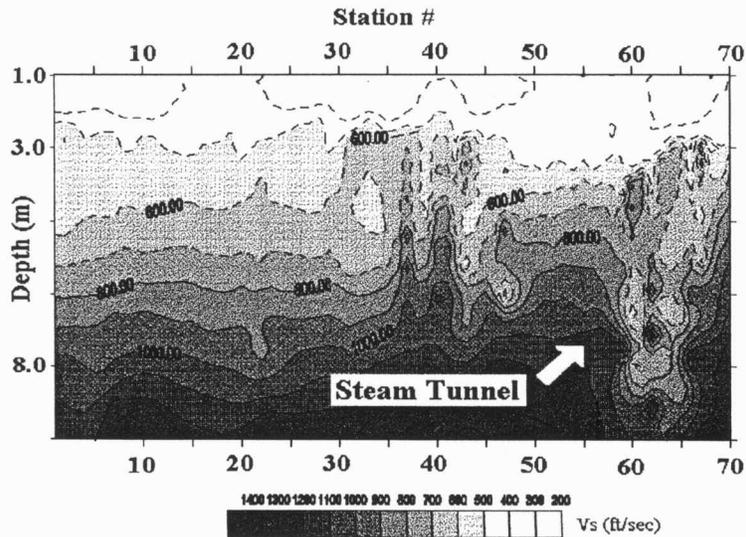


Image by Contouring



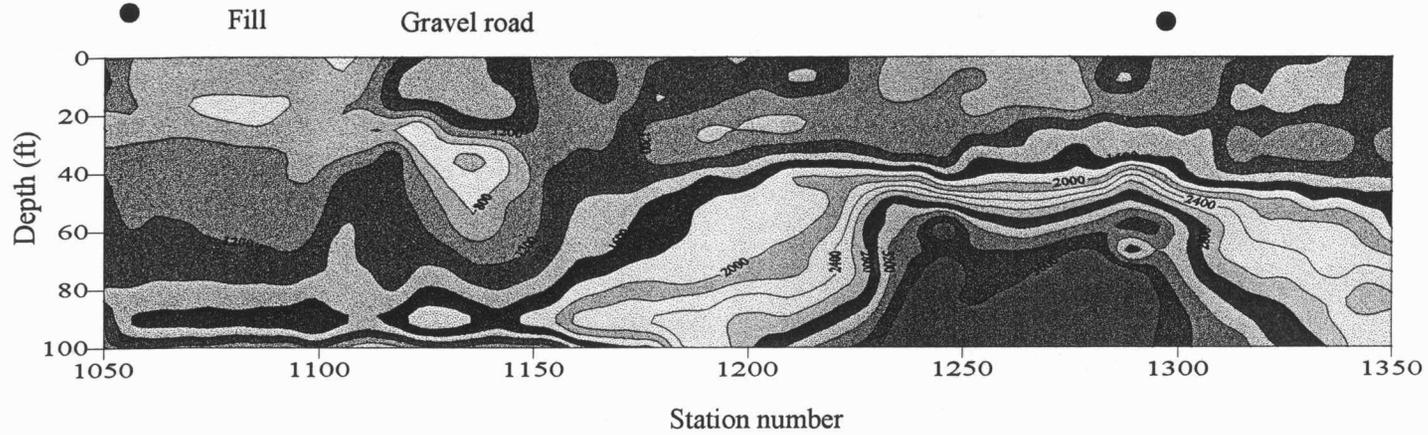
*Patent Pending on This Technique

Figure 3

S-wave velocity of line 1, Joplin, MO

Well, 70 ft to bedrock

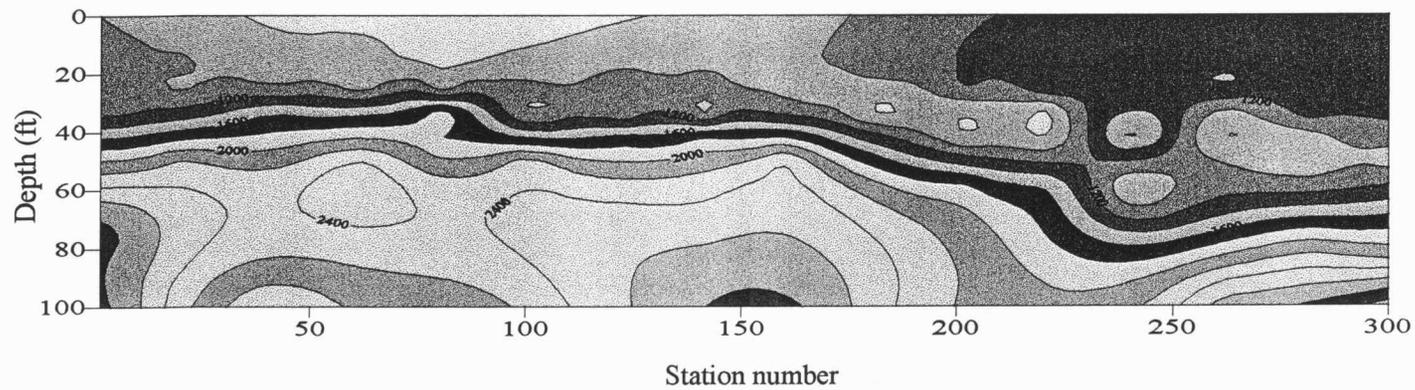
Well, 40 ft to bedrock



S-wave velocity of line 2, Joplin, MO

Well, 36 ft to bedrock

Well, 51 ft to bedrock



0 50 100 150 200 Feet

The vertical scale is exaggerated 1.3 times comparing the horizontal scale. Contouring interval is 200 ft/s.

Figure 4

S-wave Velocity of Line 1, Ione, CA, Motohammer

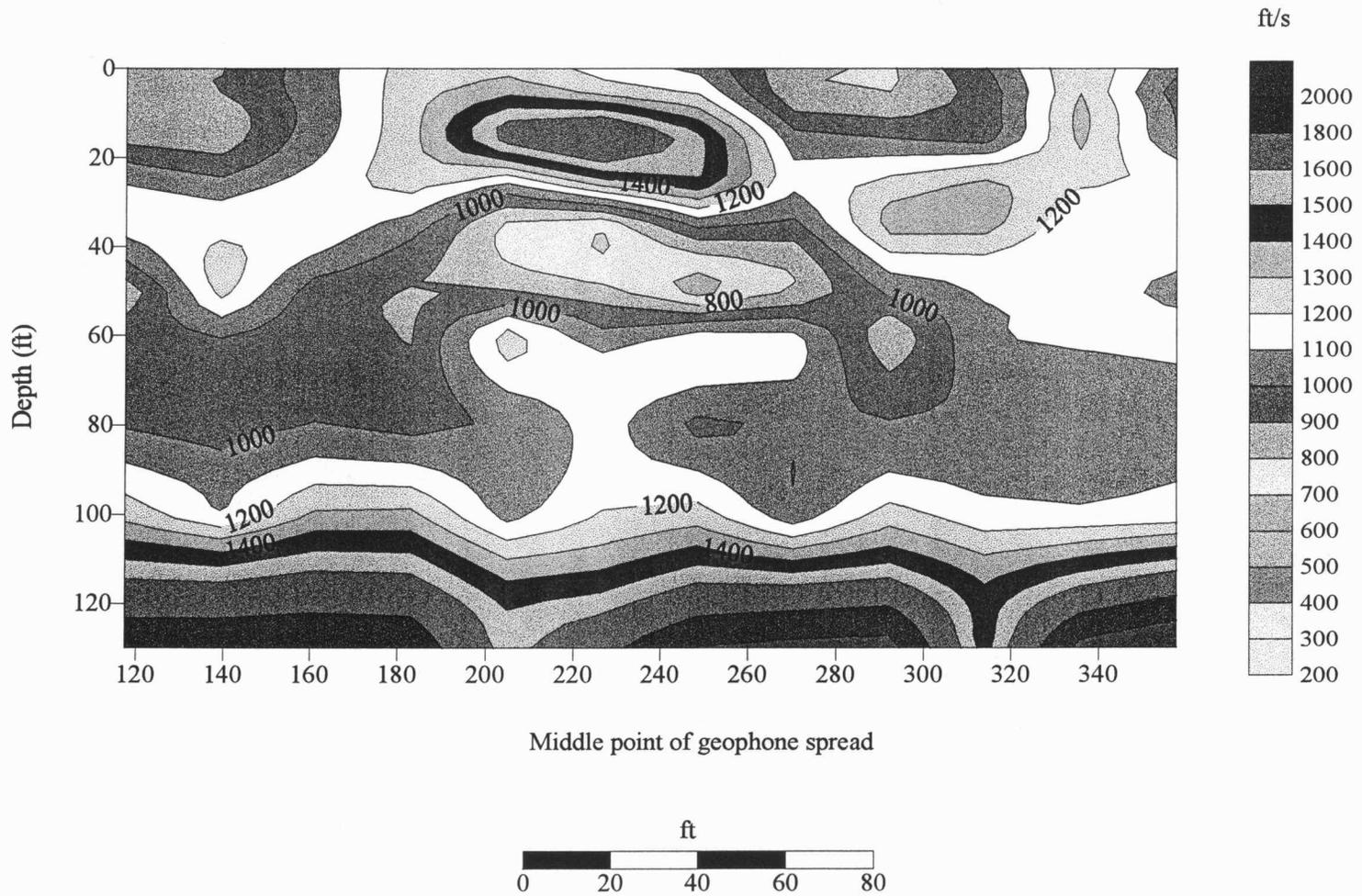


Figure 5