# High Resolution 2-D Seismic Reflection Survey Targeting Faults and Stratigraphic Features Within the Upper 200 m Near Katemcy in Mason County, Texas

*by*
Richard D. Miller
Jianghai Xia

*technical assistance by*
David R. Laflen
John Siceloff
Joshua Steinlage
Diedra Kim Begay

Preliminary Report to

Conoco, Inc.
Ponca City, Oklahoma

September 8, 1998

Open-file Report No. 98-36

Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047

**High Resolution 2-D Seismic Reflection Survey Targeting Faults and Stratigraphic Features Within the Upper 200 m Near Katemcy in Mason County, Texas**

## Introduction

High resolution seismic reflection data were acquired between July 18 and 22, 1998, near Katemcy, Texas, targeting faults and fault-associated structures as well as any acoustic contrasts/geologic contact within the upper 200 m. Five days of field work (two days of testing [walkaway noise testing, walkaway analysis, and two VSPs] and three days of CMP data acquisition [four lines forming a polygon totaling around 640 shotpoints]) were necessary to complete the program scope. This seismic reflection study focused on: 1) stratigraphic and structural characteristics of this site, 2) feasibility of the technique to delineate faults and other structural features in the upper 140 m, 3) resolution potential (vertical and horizontal), 4) optimum geometries and equipment, 5) near-surface variability and its effects on recorded data, 6) near-surface static effects, and 7) necessary QC to eliminate artifacts and maximize data quality. Proven high resolution techniques were used to design the data acquisition parameters and determine optimum equipment and methodologies (Steeples and Miller, 1990). Maximizing the resolution potential and signal-to-noise ratio was emphasized during this survey. The continuous CDP profile lines were acquired using fixed spreads consisting of 209, 180, 150, and 60 live stations. The seismic source, geophone type, spread geometry, shots/point, and acquisition philosophy used to acquire the CDP profile lines were based on the results of walkaway noise tests and VSP. The primary goal of this study was to determine the utility of state-of-the-art shallow high resolution seismic reflection techniques in detecting, delineating, and evaluating local stratigraphy and structural features at this site.

Localized faulting and the shallow depth of the Hickory Sandstone at a site in Mason County, Texas, provides an ideal setting for field studies of how faulting influences fluid behavior for the University of Texas A&M. The aquifer system present in this 140 m thick sandstone unit is strongly influenced by both normal and slip faulting. Provided fluid characteristics of aquifer/aquiclude systems are analogous to petroleum reservoirs, this faulted sandstone unit provides a low-cost analog for performing a large number and diversity of in-situ measurements. Secondary, but still significant, is the potential this site possesses for developing and testing a variety of characterization techniques. Shallow, high resolution seismic represents a non-invasive method of imaging faults in two and/or three dimensions. Shallow seismic reflection has been effective in extending the geometries and characteristics of faulted rock away from boreholes and surface exposures in previous applied research efforts (Miller et al., 1990; Treadway et al., 1988). Enhancing vertical and horizontal resolution and signal-to-noise ratio has become an overwhelming area for research and technique development (Steeples et al., 1997). This applied research effort emphasized effective and accurate imaging of faults evident in surface exposure and optimizing resolution and signal-to-noise ratio.

The project consisted of two major acquisition phases: testing and production. The testing began on July 18 (following a short delay due to equipment malfunction) and consisted of a walkaway test along the proposed north/south line, NNL-1. The walkaway noise test data were separated into common source gathers and spectral balanced. Each source gather was then analyzed for spectral properties, coherent energy arrivals, wavelet characteristics, and total source energy. A two-offset VSP acquired in borehole NNR-3 provided an estimate of the average velocity as a function of depth throughout the approximately 100 m cased interval. Four continuous profile lines filled the remaining three days on-site. Data were acquired following well-established shallow high resolution data acquisition procedures (Hunter et al., 1984; Knapp and Steeples, 1986; Steeples and Miller, 1990). The CDP profiles were designed around the findings of the walkaway tests and VSP. Based on preliminary analysis, reflection data from this survey should possess at least three reflecting events (at approximately 25, 40, and 90 msec) with a dominant frequency around 150 Hz and an upper corner at over 250 Hz.

**Program Overview**

1) An extensive series of walkaway noise tests were conducted using several low energy, high frequency seismic sources and a pseudo-continuous spread with 0.25 m receiver spacing spanning source-to-receiver offsets from 0.5 m to over 180 m. Analysis of shot gathers incorporated geologic with spectral analysis, NMO curve fitting, and wavelet characteristics.

2) Based on the walkaway noise tests, four 2-D profiles were acquired approximately along lines designed by Conoco. The data were acquired using 209-station, 180-station, 150-station, and 60-station fixed spreads. The resulting maximum fold at the center of the spreads ranged from 30 to over 200.

3) Walkaway noise test data and uphole data were processed into display format in the field and then accompanied with descriptions of acquisition methods,

parameters, and equipment at the Kansas Geological Survey in Lawrence, Kansas, for this field report.

4) A VSP was acquired NNR-3 on 3 m spacing from 100 m to 3 m.

**Table 1**
**Summary of Proposed Survey**

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

2) Equipment and Parameters Tested
- triple 40 Hz L28E Mark Products Geophones (210 strings)
- downhole 30.06 projectile source
- variety of hammer and plate combinations:
  hammer (16 lb, 8 lb, 2 lb)
  plate (1 sq ft x 1", 0.25 sq ft x 1", 2" shaft, 1" shaft, _" shaft)
- slide hammer impact source
- 12 gauge auger gun
- RAWD (Rubber band Assisted Weight Drop)
- Geostuff three component downhole geophone
- IVI Minivib (20 to 400 Hz), ~8,000 lbs peak force
- several linear up-sweeps 20-400 Hz
- optimum vertical stack count
- 0.25 m receiver station spacing
- 0.25 msec sampling interval
- 900 and 720 trace, pseudo continuous walkaway with source offsets from 0.5 m to 180.5 m
- digital filtering

3) VSP
- 3-component hole lock geophone
- 100 m vertical profile
- 3 m vertical station spacing
- 2 source offset positions (3 m and 15 m)
- source consistent with production survey

4) Field Schedule:

| | Approx. Dates |
|---|---|
| Mobilization | July 6 - 15 |
| Travel | July 16-17 |
| Walkaway noise testing | July 18 |
| Walkaway noise testing/VSP | July 19 |
| Production Data Acquisition | July 20-22 |
| Travel | July 23 |
| Demobilization | July 24-31 |

5) Data shipped from KGS in 240, 180, and 60 channel SEG-Y format on/by July 31.
Preliminary report (incl. all walkaway tests and safety report) approx. September 8, 1998.
Final report after review and comment by Conoco.

**Seismic Reflection Philosophy**

Unequivocal identification and verification of reflections on shot gathers was a primary criteria during the design and implementation of this survey. Model NMO curves were matched with reflection hyperbola interpreted on shot gathers as a means to confirm and analyze reflections. NMO velocities were then compared to one-way velocities derived from first-arrival times on VSP data to correlate and verify the reflection events interpreted on walkaways. This combination incorporates ground truth (borehole velocity) and geometric curve fitting (forward and inverse modeling) with event identification directly on single-fold shot gather data. Data from this project was closely monitored throughout acquisition to insure events with reflection properties could be identified on each line. Matching reflection events interpreted on shot gathers with modeled reflection curves is essential to avoid incorrectly collected data.

**Quality Control (QC)**

QC is critical and was continuous throughout acquisition. Near-surface inconsistencies, vehicle noise, an extremely narrow and changing optimum recording window, and poor receiver coupling conditions required strict compliance with QC guidelines and meticulous monitoring of data. Since a fixed spread was deployed, each shot record contained 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 permitted instantaneous monitoring of cultural, air traffic, vehicle traffic noise, cable-to-ground leakage, and geophone plant quality. After each geophone is planted it was tested to insure a cable-to-ground resistance greater than 1000K ohms and individual geophone continuity within 5% of coil impedance (including consideration for cable offset). As well, each geophone underwent a modified tap and twist test. No shot was recorded when background noise levels (measured as output voltage) on active geophones exceeded 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 help insure each recorded shot was maximized for the site and equipment.

**Walkaway Testing**

Unique shallow data characteristics evident during the walkaway testing exemplify the utility of a good testing program and demonstrated the need to have a sizable repertoire of acquisition equipment available for testing. The reflection program was tuned for the acoustic and logistic conditions and constraints of this particular site by identifying and confirming reflection hyperbola on walkaway noise tests using mathematical curve fitting (matched to the borehole-derived velocity structure) and spectral analysis of the various source configurations. The walkaway noise tests were deployed to horizontally oversample the subsurface and so the source-to-farthest-receiver-offset was at least equivalent to the maximum depth of interest. These steps were taken to allow all aspects of the complete wave field (especially the reflections) to be thoroughly appraised.

The primary goal of the walkaway noise test was to study how the various sources and geometries effected the overall signal-to-noise ratio and frequency content of the recorded data. Walkaway tests are ideally suited for identifying individual events within the full wavefield. Phase velocity and wave types were two of the most important pieces of information extractable from the walkaways collected at this site. Each walkaway section is trace balanced and displayed in a variable-area wiggle trace format. Spectral analysis of each walkaway is displayed and provides insight into the general frequency response of the ground to the various source configurations and a relative measure of source energy.

The evaluation/feasibility portion of the study allowed analysis of acoustic characteristics, and more generally, the reflection method, permitting accurate estimation of resolution potential and optimum selection of acquisition equipment and parameters. The walkaways included source-to-receiver offsets ranging from 0.5 m to approximately 180 m with a receiver interval of 0.25 m. Sources tested included:

12-gauge Auger Gun (Healey et al., 1991) (requiring only class C explosives),
RAWD (an accelerated weight drop, Bison EWG equivalent),
various hammer and plate combinations,
slide hammer,
30.06 downhole, and
IVI Minivib.

These sources were evaluated to determine the optimum source for the near-surface conditions, target depth, resolution requirements, and environmental constraints. Each source was evaluated with as near equivalent conditions and parameters as possible.

Hammer sources proved the best overall source for this site under the conditions at the time the data were collected. The 16 lb sledge and one foot square plate provided energy to the longest offset with hyperbolic arrivals interpretable at various offsets (Figure 2). Six shots stacked provided the cleanest data while still retaining single shot spectral properties (Figure 3). The usable bandwidth extends from about 40 to almost 400 Hz (Figure 3). To evaluate both improvements in recorded energy and changes in the spectral properties of a shot gather by vertically stacking, during the walkaway testing a file was saved after stacking one shot (Figure 4), two shots (Figure 6), four shots (Figure 8), and six shots (Figure 10). After comparing improvements and degradation from each additional shot (Figure 5, 7, 9, 11) it was determined that little improvement was evident after about four shots, but that no deterioration in the data properties were evident throughout the stacking process.

Data from a six-shot stack using a 12 lb hammer and one foot square plate proved to be optimum for this site after a study of the waveform and apparent hyperbolic arrivals (Figure 10) and spectral properties (Figure 11). Only minor differences were evident with decreasing sledge hammer weight. An 8 lb sledge impacting a 1/4 square foot steel plate produced a shot gather that possessed all the arrivals interpretable on the heavier sledge with some decay in the amplitude of energy at longer offsets (Figure 12). The spectral properties (with the exception of maybe the air-coupled wave) of the 8 lb sledge changed little when the hammer weight and plate area were decreased (Figure 13). Longer offset energy is noticeably affected when the hammer weight is decreased to 2 lbs (Figure 14). The spectrum seems flatter with less air-coupled wave with this configuration (Figure 15).

Tests with shafts (punch) as a ground couple proved interesting, but data quality was clearly not as good as when a plate was used. At least some of this difference can be attributed to the vertical movement of the shaft with each hammer impact. The 1/2 inch shaft was only used at the near three offsets due to a drop in amplitude at the longer offsets (Figure 16). The spectra of the 1/2 inch shaft impacted with an 8 lb hammer seems to roll off from about 200 to 250 Hz, which is noticeably lower than when a plate is used for the ground coupling (Figure 17). It is evident, however, that as the diameter of the shaft increased the total energy delivered to ground also increased (Figure 18). A one-inch shaft had a slower vertical component than the 1/2 inch, but had spectral properties similar to the 1/2 inch shaft (Figure 19). When the hammer weight was reduced, the amplitude at longer offsets decreased as well (Figure 20). Using a 2 lb hammer did little to improve the upper corner of the bandwidth (Figure 21). A center punch purchased at a hardware store and the 2 lb hammer provided a section very similar to the 2 lb hammer and the 1-inch shaft (Figure 22). The spectra possesses a sizable hole around 100 to 150

Hz that was not present on any of the other hammer shaft/punch combinations (Figure 23).

In moving to the various other sources tested during this study, it was apparent that none of these possessed the optimum characteristics for this site. A downhole 30.06 projectile source was fired into an 18-inch hole at the nearest three offsets (Figure 24). The 30.06 seems to possess a high amplitude spike at around 80 Hz that is unique to this source (Figure 25). In general, the spectra do not seem to be as rich as from the hammer sources. The slide hammer provided a shot gather that was quite comparable with the best hammer impacts (Figure 26). The frequency content was comparable and maybe just a little better than the hammer/plate configuration (Figure 27). It was the waveforms and apparent reflection-looking events that swayed the decision to the hammer/plate source. The 12-gauge black powder source clearly does not possess the broad bandwidth of the hammer sources (Figure 29). This single shot record has a high concentration of cyclic events that seem to parallel (in general) the first arrivals (Figure 28). This may suggest the energy is not coupling to the ground very well when using this explosive source.

A mechanical accelerated weight drop source was tested and provided a very uninspiring shot gather (Figure 30). Clearly the spectra is narrow in comparison to some of the hammer/plate spectra (Figure 31). If reflections are present from shallower events on the vibrator shot gather, they are not evident on these spectrally balanced plots (Figure 32). The spectra of the vibrator is consistent with the weight drop, but not nearly as uniform in amplitude through the primary band of interest (Figure 33). The difference between a four-second and a six-second sweep is nearly impossible to tell from the shot gathers (Figure 34). It maybe even more difficult to distinguish the two when comparing the spectra (Figure 35). From a general comparison perspective the accelerated weight drop and vibrator are very similar in both spectra and general seismic characteristics.

Triple 40 Hz Mark Product L-28E geophones wired in series provided a strong signal with no evidence of spurious noise or resonance within the frequency band of interest. On-site evaluation of these phones in comparison to the output (based on previous experience) of the other geophones available for testing (L40A 100 Hz) concluded in the use of the 40 Hz geophones for the entire project.

All tests were 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.).

**Production Phase**

The production acquisition phase of this project began immediately after the collection of the walkaway VSP. Data were acquired on four lines using fixed spreads equal to the total length of each line. The resulting fold varied from 1 to over 200, depending on line and relative station location on the line. The 1 m geophone station interval was optimal for identifying coherent reflection events through a relatively large depth window. A half-integer style source-receiver configuration was used in which the source was located half way between adjacent receivers and off-line about 1 to 3/4 of a meter. The source-to-nearest receiver offset was about 1 m, with the maximum offset varying with each shot, dependent on line length and station location. A total of three field days were necessary for production data acquisition.

Parameters such as sampling interval and record length were selected after careful examination of the dominant frequency and usable bandwidth of reflection energy recorded during the walkaway noise tests. The sampling interval was 0.25 msec, providing 27 samples/wavelength of the dominant frequency (~150 Hz) and 16 samples/wavelength of the upper (usable) corner frequency (250 Hz). The total number of samples (2048) were chosen based on maximum time (depth) of interest of primary reflections as well as multiples and diffractions.

Based on the 1/4 wavelength theoretical (Widess, 1973) and the 1/2 wavelength empirical (Miller et al. 1995) the best vertical resolution possible on this survey is 3 and 6 m, respectively. Considering a dominant frequency of around 150 Hz and an average velocity of 1750 m/sec, layers separated by 6 m or more should be resolvable. Horizontal resolution, based on the radius of the first Fresnel zone, is about 30 m at 140 m of depth, 20 m at 70 m of depth, and 15 m at 40 m of depth. Since the subsurface sampling is 1/2 the receiver interval, oversampling of the first Fresnel zone exceeded 15 times at depths over 20 m, setting up the potential to laterally smear some subtle features (Miller and Steeples, 1990). The closer geophone spacing was necessary to enhance event identification and to allow the recording of reflections returning from depths less than about 20 m. This is a situation where compromises had to be made and it was determined that recording events with sufficient traces to confidently identify them as reflections throughout the depth interval of interest was more important than minimizing the oversampling of the subsurface. It is also noted that, through processing, the subsurface sampling can be reduced for the deeper events to minimize any oversampling artifacts.

In-hole seismic studies were designed to complement, enhance, and confirm the walkaway tests and the high resolution seismic reflection data. Normal move-out (NMO) velocities were calculated through curve fitting on walkaway data at about 1250 m/sec at depths of around 15 m and 1700 m/sec at about 30 m deep. Once the uphole data are gathered according to source location and borehole depth the average velocity from surface to each 3 m depth interval down the hole was easily established (Figure 36). Average velocity and depth estimations from uphole data were within 10% of the NMO velocities calculated from curve fitting on walkaway data. Considering the NMO curve fitting was done prior to collection of the borehole survey, no bias was involved with the picking of the reflection hyperbola on common shot gathers.

The four reflection lines and several boreholes involved with the cross-hole tomography were elevation surveyed with a hand level which carried manufacturer's specifications suggesting relative elevation accuracy better than ±15 cm at a distance of 10 m. This level of accuracy was appropriate considering the accuracy with which the near-surface velocities, necessary for depth-to-to time correction, can be determined. Unfortunately, due to the high heat, the level and eye piece optics were misaligned. This misalignment resulted in nonsystematic errors that could not be corrected in the data. The elevation survey cannot be used to for datum corrections on these data.

A high frequency spike observed on all seismograms is evident near time zero on some records. This series of spikes was thought to be related to the time break pulse due to the proximity of the spike to time zero (Figure 37). Attempts were made to improve grounding by saturating the grounding spike, in the off chance it was a grounding problem, as well as the time break cable was relocated several meters away from the cable and geophones in the off chance it was a cross-talk problem. The spike persisted, seeming unchanged throughout all these changes. After field discussions between the participants the data were collected under the notion that a top mute would remove the noise. The noise was only evident when a high low-cut filter and AGC scale were used during data display. Continued efforts to find the source of this problem led to grounding the power sources (batteries). During that process a connection between the negative post of one battery and the frame of the battery cart was discovered. Once the connection was terminated, data did not possess the noise spikes. The consistent and horizontal nature of the spikes makes distinguishing and separating them from the seismic energy a straightforward process.

The fault is quite evident on many of the shot gathers. The diffraction pattern possesses the classic moveout pattern associated with point source re-radiation (Figure 37). Based on the high amplitude nature of the diffraction pattern centered at about 90 msec it is very likely this hyperbola is indicative of the basement offset. The apparent reflection event at about 90 msec is also likely from the basement at 140 m. If this is the case, the average velocity to basement would be about 3000 msec. Considering the average velocity to 100 m is about 2700 m/sec (from uphole data), this interpretation is quite reasonable and likely correct.

During the acquisition of the surface seismic data, some experimenting was carried out on the crosshole tomography study. Based on field QC it was determined necessary to minimize the running of a power generator while the reflection survey was in progress. Based on the observed noise levels, it was a good decision to keep the generator off while seismic reflection data was being recorded (Figure 38). The noise from the generator manifests itself on line 2 as a series of lower frequency hyperbolas with an apex around channel 135 (Figure 38). As inconvenient as it was to require downtime for the tomography crew, it will greatly improve the signal-to-noise on the final stacked sections.

**Final Products**

The raw data was transferred from computer hard drives to CD-ROM and 8 mm tape at the KGS's Lawrence, Kansas, facility. Data recorded using this configuration of the StrataView seismograph is natively stored as four separate 60-channel files, each in a SEG2 format. Each recorded field file was appropriately grouped (into 60, 180, or 240 depending on line length) and converted to a SEGY format (Figures 39-43). Standard archival procedures at KGS involve burning the data to a CD. At Conoco's request, the data were written to an 8 mm Exabyte tape drive currently integrated into a SGI workstation running ProMax. All field notes (OB and survey) were scanned and loaded onto CD. The KGS shipped the raw digital data in SEGY format on 8 mm tape with all field notes to Conoco within 6 working days after leaving the field area.

This acquisition report provides a chronological and technical accounting of field activities associated with design and collection of these data. Discussions in this report include dialog and associated figures covering the following topics:

walkaway tests, testing procedures, decisions regarding optimization, data acquisition observations, and the full safety plan/report. Walkaway data are gathered according to unique equipment and/or parameters. The completed safety plan (with daily signatures) will be consistent with OSHA and DOE standards with copies of all MSDS and a detailed description of Health/Safety risks associated with the environment and equipment. This report will be considered final when review comments and questions provided by Conoco have been full addressed.

### Overall Project Goal

The goal of this study was to determine the feasibility of the technique to image and resolve structural and stratigraphic features and characteristics within the upper 140 m at this site. The results of this study include a thorough comparison of several high resolution seismic sources, an empirically based estimation of horizontal and vertical resolution potential, evaluation of acquisition effort, determination of optimum recording parameters, and over 600 meters of shallow seismic reflection data with a 1/2 m subsurface sampling interval.

## REFERENCES


Healey, J., J. Anderson, R.D. Miller, D. Keiswetter, D.W. Steeples, and B. Bennett, 1991, Improved shallow seismic-reflection source: Building a better Buffalo [Exp. Abs.]: Soc. of Explor. Geophys. v. 1, p. 588-591.

Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.S. Good, 1984, Shallow seismic-reflection mapping of the overburden-bedrock interface with the engineering seismograph—Some simple techniques: *Geophysics*, v. 49, p. 1381-1385.

Knapp, R.W., and D.W. Steeples, 1986, High-resolution common depth point seismic reflection profiling: Field acquisition parameter design: *Geophysics*, v. 51, p. 283-294.

Miller, R.D., N.L. Anderson, H.R. Feldman, and E.K. Franseen, 1995, Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in Southeastern Kansas: *Geophysics*, v. 60, p. 423-430.

Miller, R.D., and D.W. Steeples, 1990, A shallow seismic reflection survey in basalts of the Snake River Plain, Idaho: *Geophysics*, v. 55, p. 761-768.

Miller, R.D., D.W. Steeples, and P.B, Myers, 1990, Shallow seismic-reflection survey across the Meers fault, Oklahoma: *GSA Bulletin*, v. 102, p. 18-25.

Steeples, D.W., A.G. Green, T.V. McEvilly, R.D. Miller, W.E. Doll, and J.W. Rector, 1997, A workshop examination of shallow seismic reflection surveying: *Leading Edge*, v. 16, n. 11, p. 1641-1647.

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. Investigations in Geophysics, Investigations in Geophysics no. 5, Stan H. Ward, ed., Volume 1: Review and Tutorial, p. 1-30.

Treadway, J.A., D.W. Steeples, and R.D. Miller, 1988, Shallow seismic study of a fault scarp near Borah Peak, Idaho: *Journal of Geophysical Research*, v. 93, no. B6, p. 6325-6337.

Widess, M.D., 1973, How thin is a thin bed: *Geophysics*, v. 38, p. 1176-1180.

# Conoco - Mason County, Texas

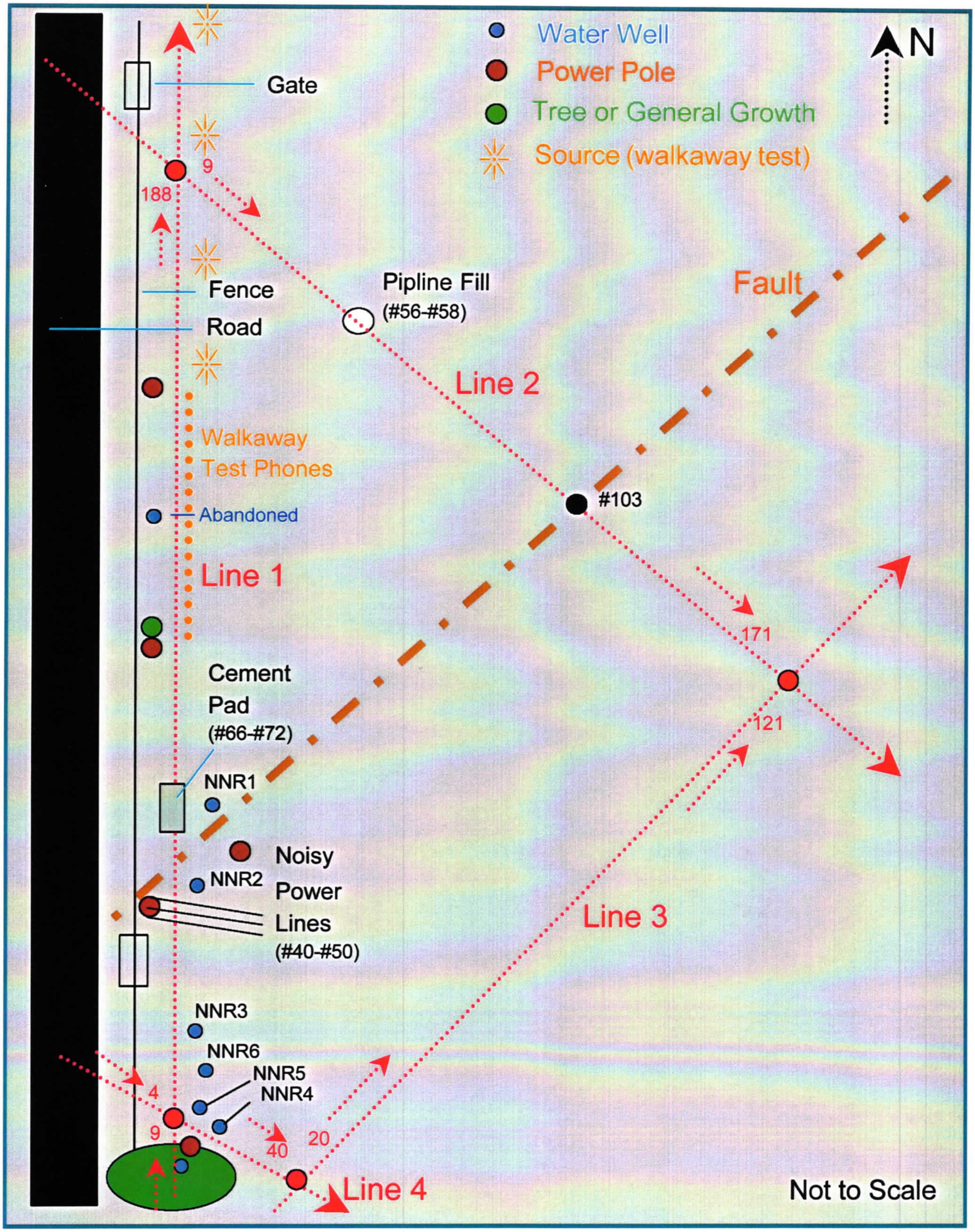


Figure 1. Site map detailing relative location of all significant surface landmarks and tie points.

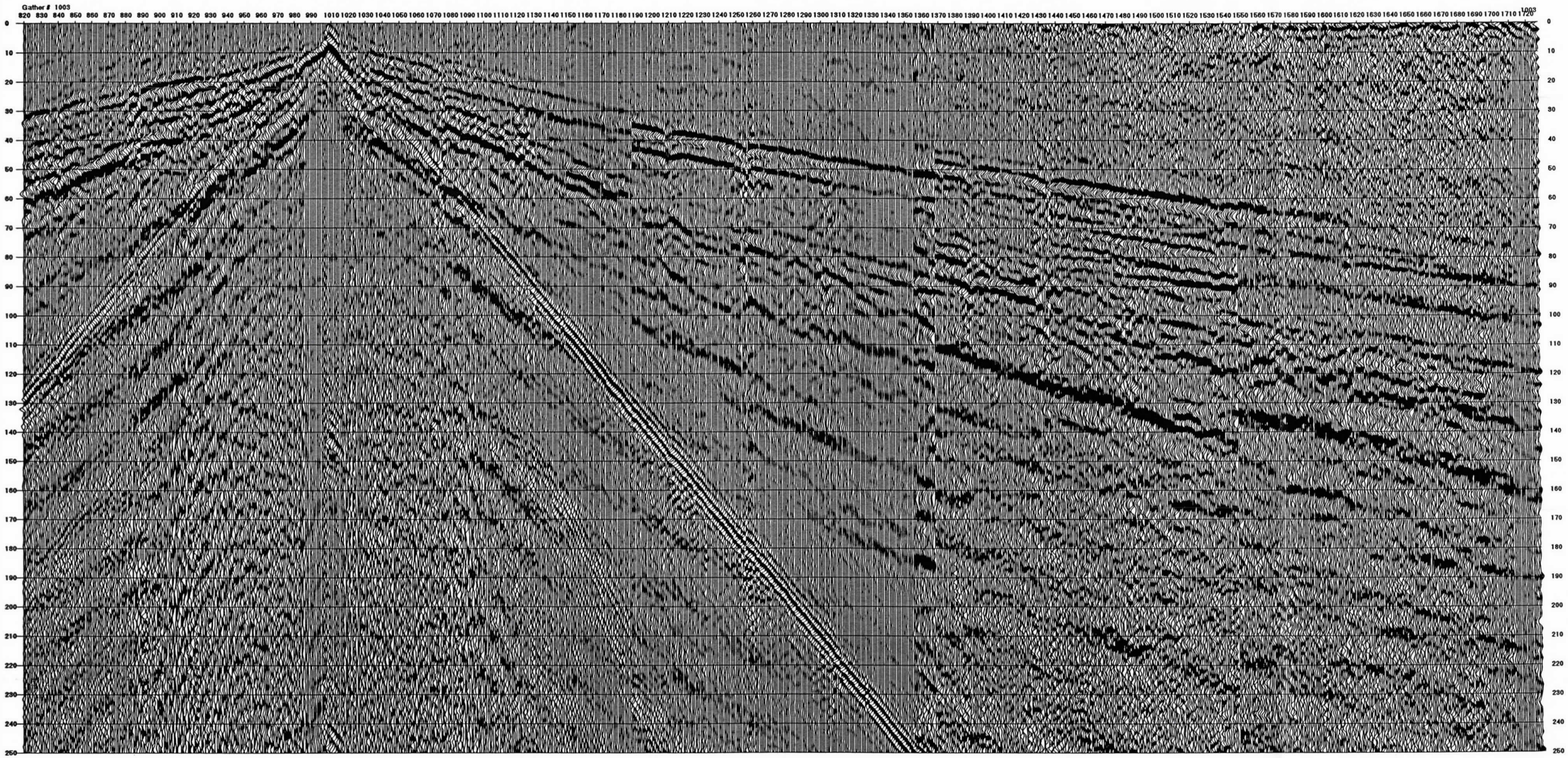

Figure 2. 16 lb sledge and one square foot plate provided energy to the longest offset with hyperbolic arrivals interpretable at various offsets.

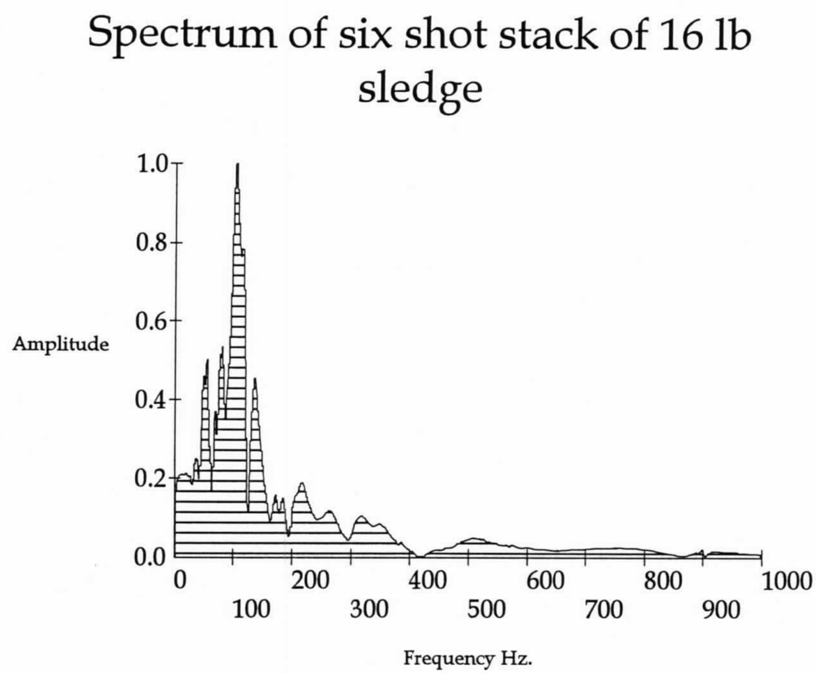


Figure 3. Six shots stacked provided the cleanest data while still retaining single shot spectral properties. The usable bandwidth extends from about 40 to almost 400 Hz.

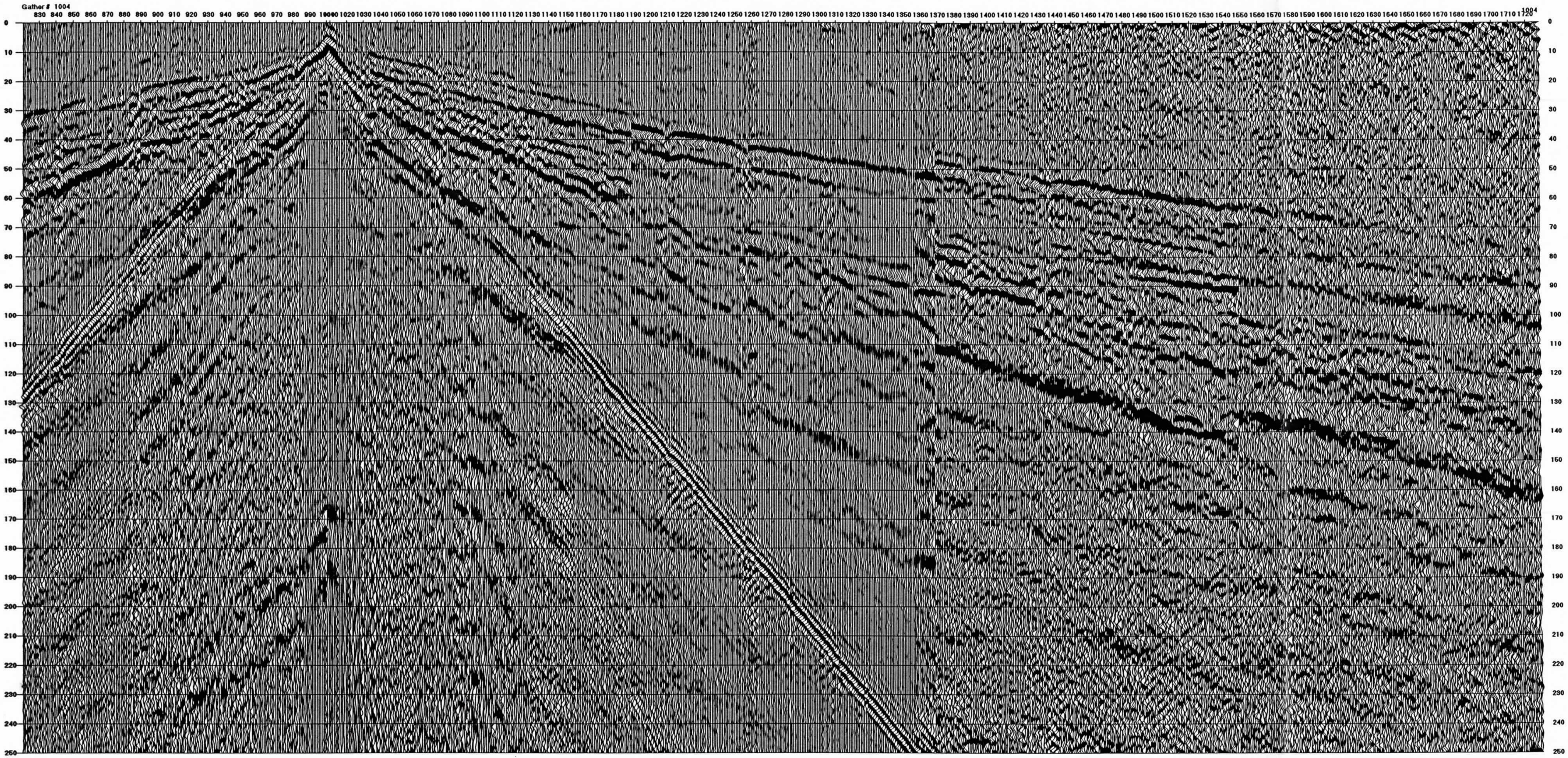

Figure 4. To evaluate both improvements in recorded energy and changes in the spectral properties of a shot gather by vertically stacking, during the walkaway testing a file was saved after stacking 1 shot.

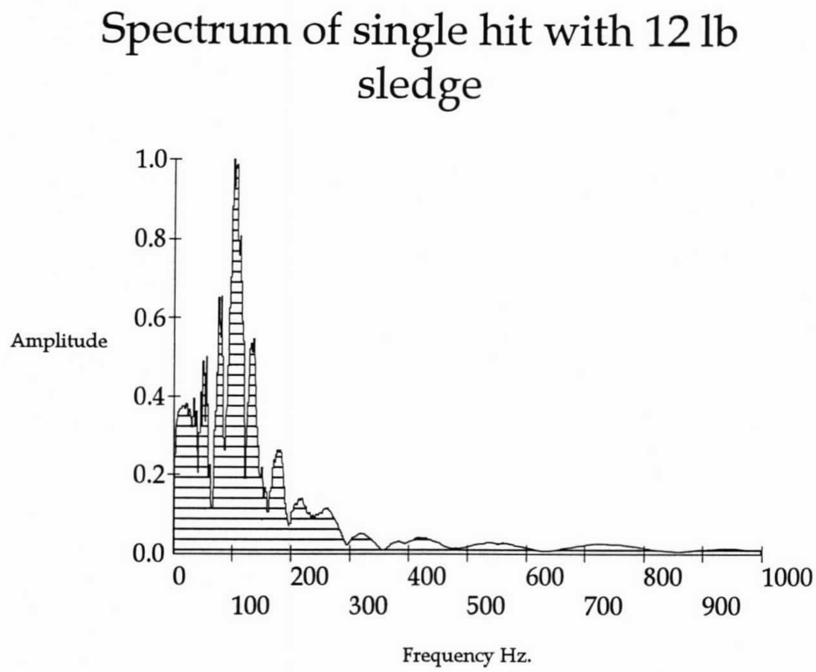


Figure 5. Little change is evident in the spectral properties between 1, 2, 4, or 6 vertically stacked shots.

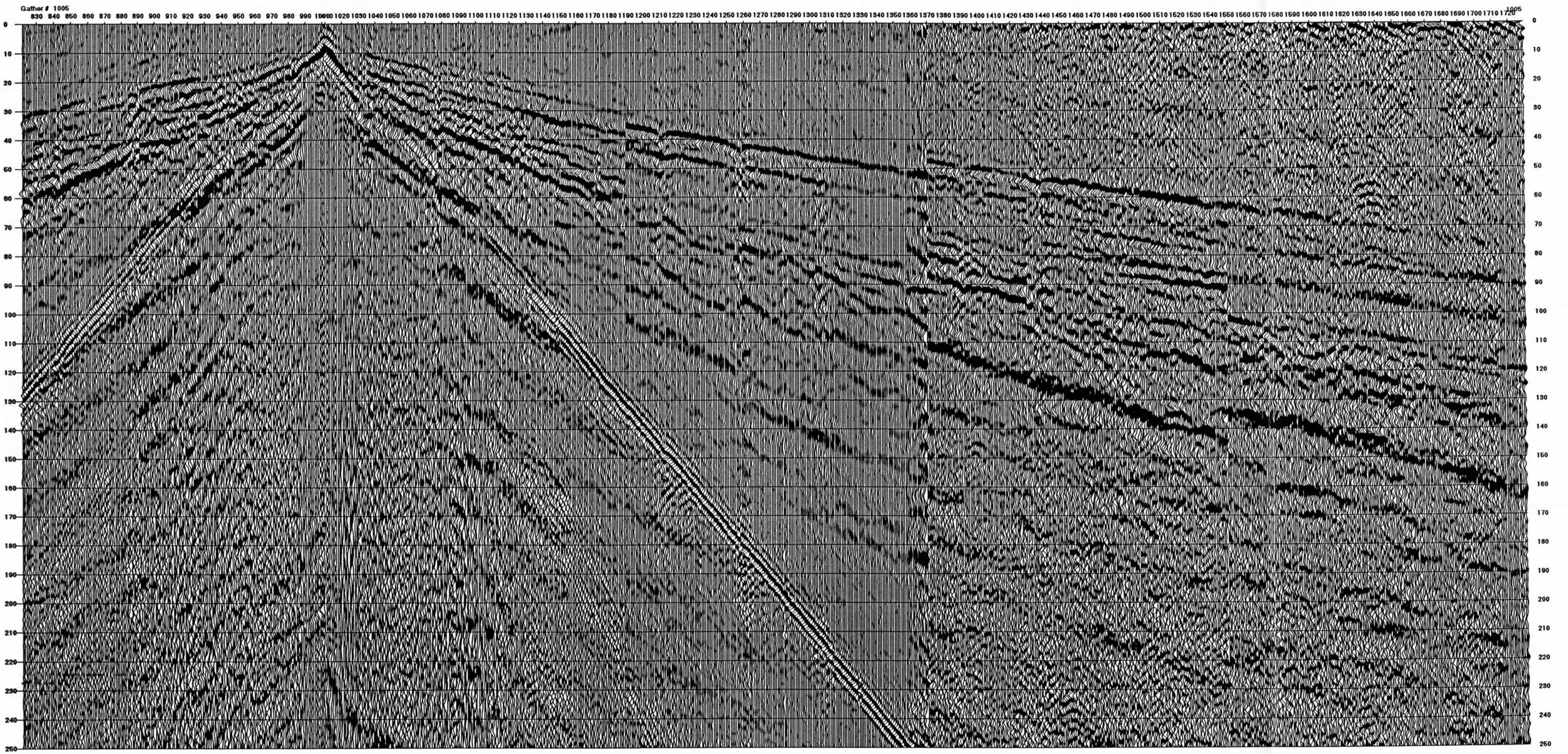

Figure 6. To evaluate both improvements in recorded energy and changes in the spectral properties of a shot gather by vertically stacking, during the walkaway testing a file was saved after stacking 2 shots.

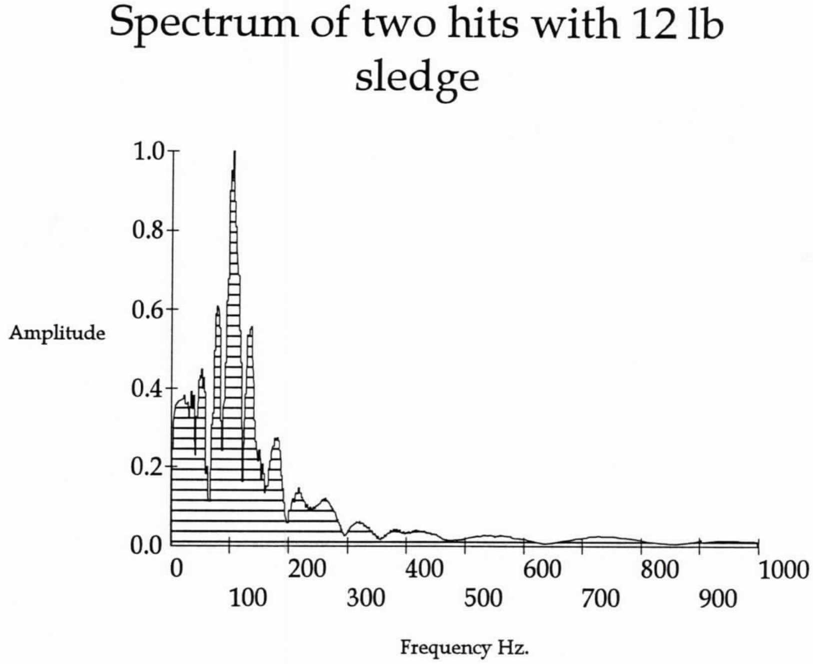


Figure 7. Little change is evident in the spectral properties between 1, 2, 4, or 6 vertically stacked shots.

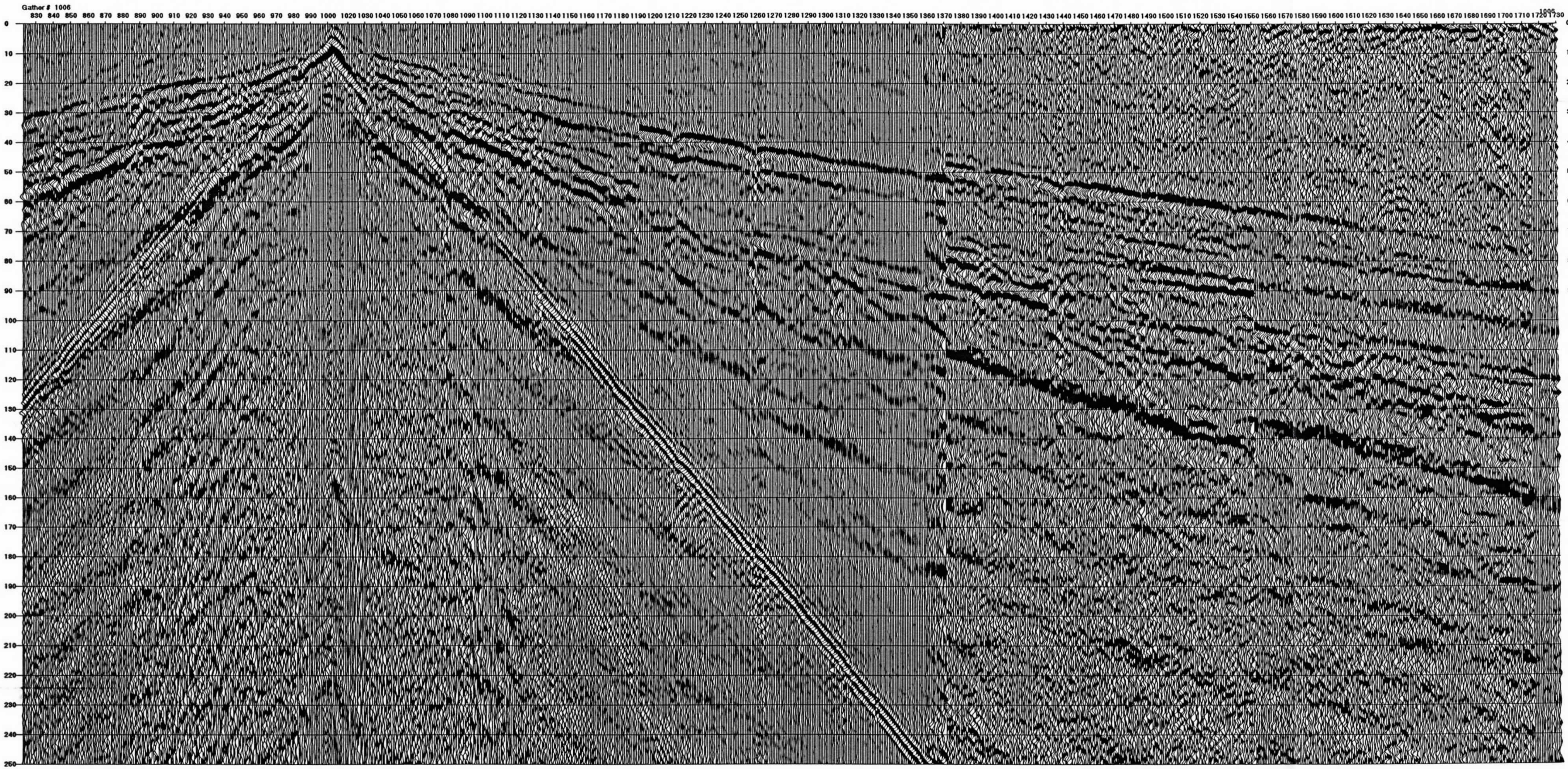

Figure 8. To evaluate both improvements in recorded energy and changes in the spectral properties of a shot gather by vertically stacking, during the walkaway testing a file was saved after stacking 4 shots.

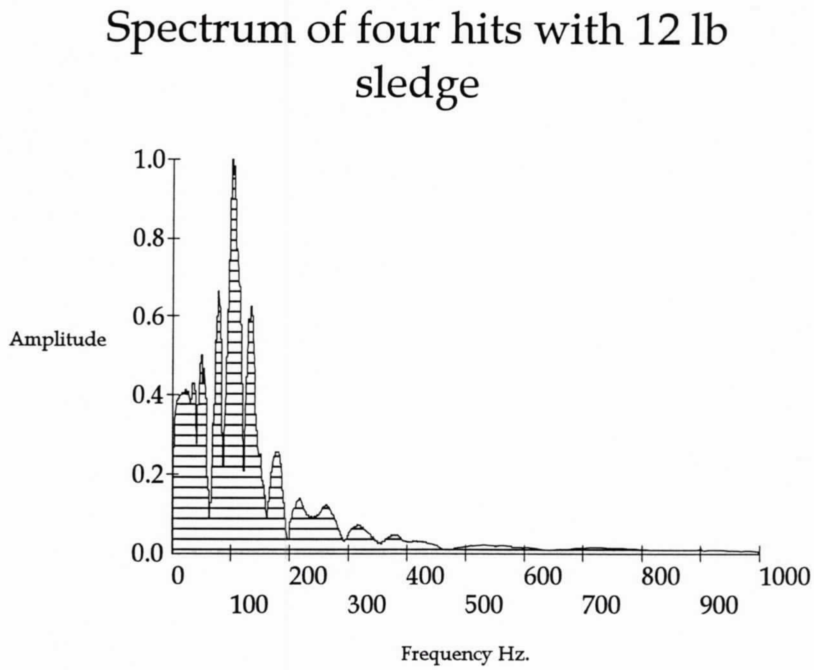


Figure 9. Little change is evident in the spectral properties between 1, 2, 4, or 6 vertically stacked shots.

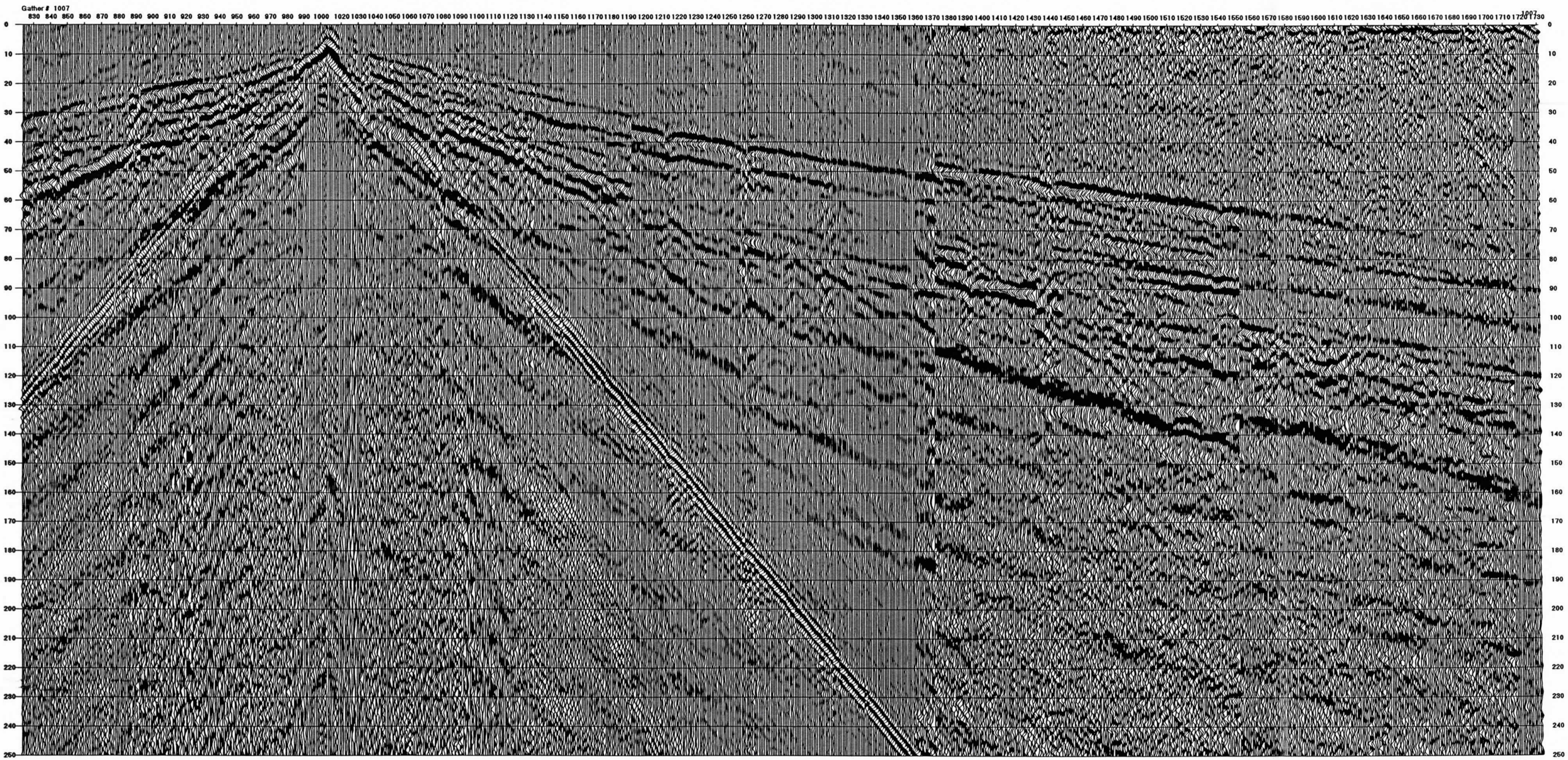


Figure 10. To evaluate both improvements in recorded energy and changes in the spectral properties of a shot gather by vertically stacking, during the walkaway testing a file was saved after stacking 6 shots. Data from a six-shot stack using a 12 lb hammer and one square foot plate proved to be optimum for this site after study of the waveform and apparent hyperbolic arrivals.

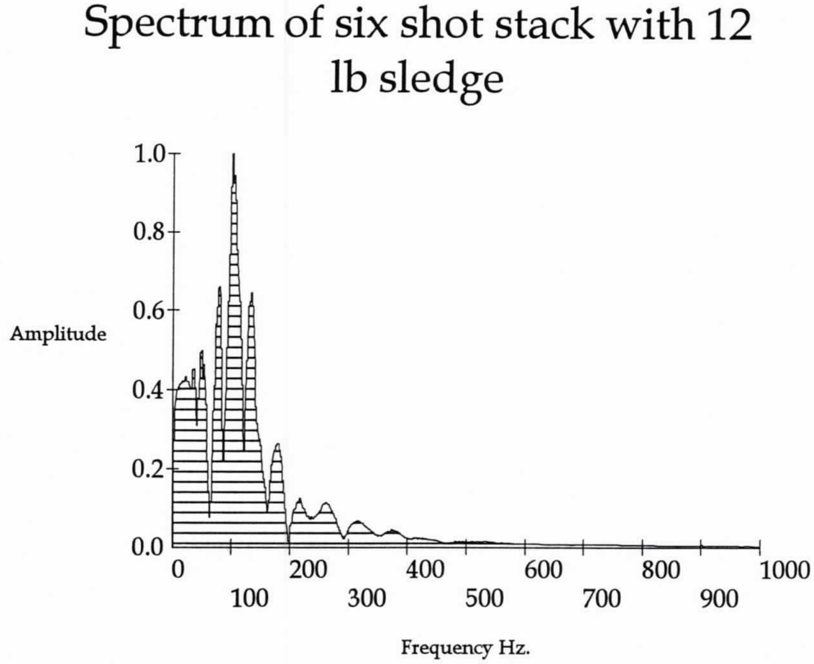


Figure 11. Little change is evident in the spectral properties between 1, 2, 4, or 6 vertically stacked shots.

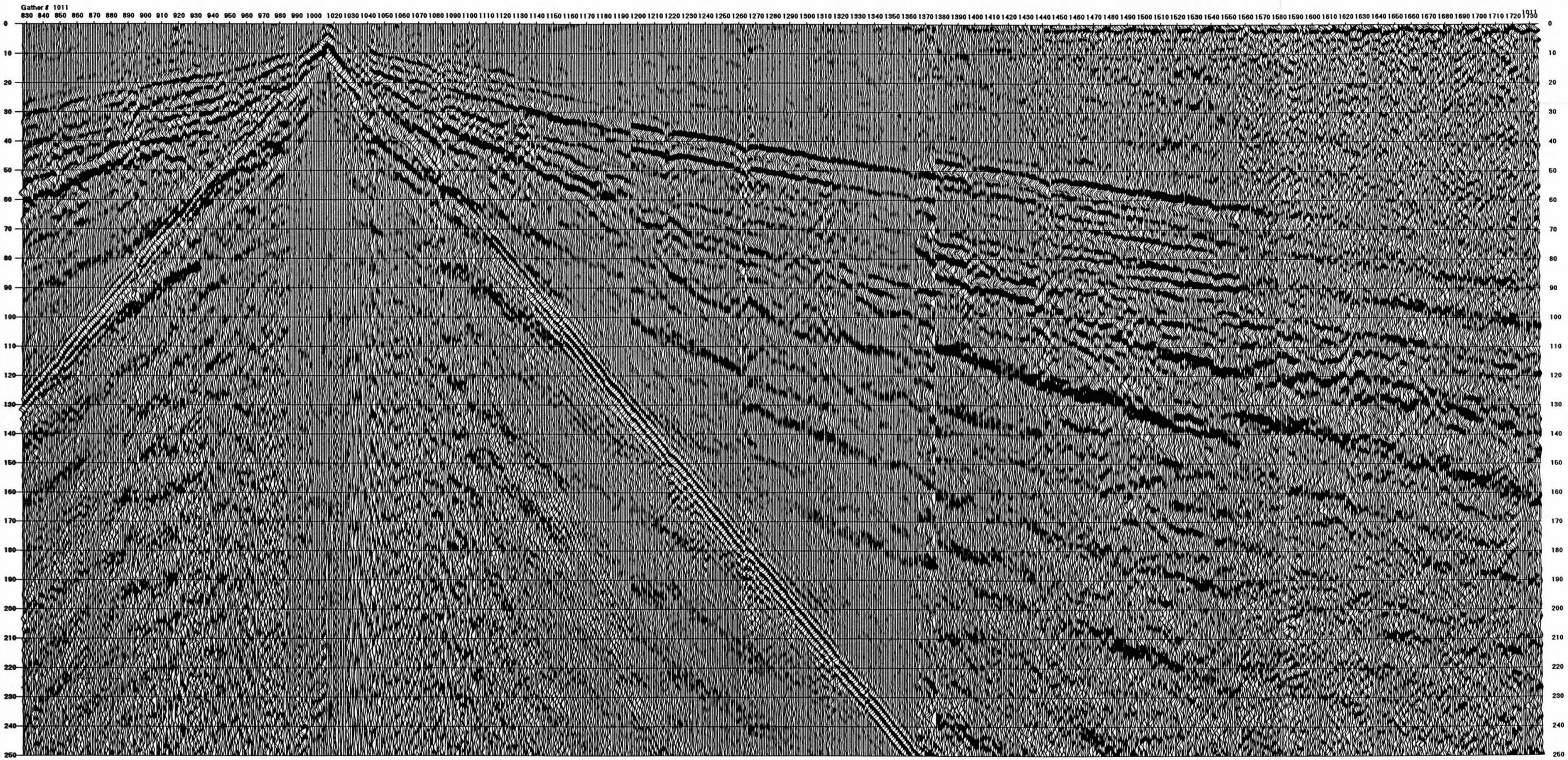


Figure 12. An 8 lb sledge impacting a 1/4 square foot steel plate produced a shot gather that possessed all the arrivals interpretable with the heavier sledge with some decay in the amplitude of energy at longer offsets.

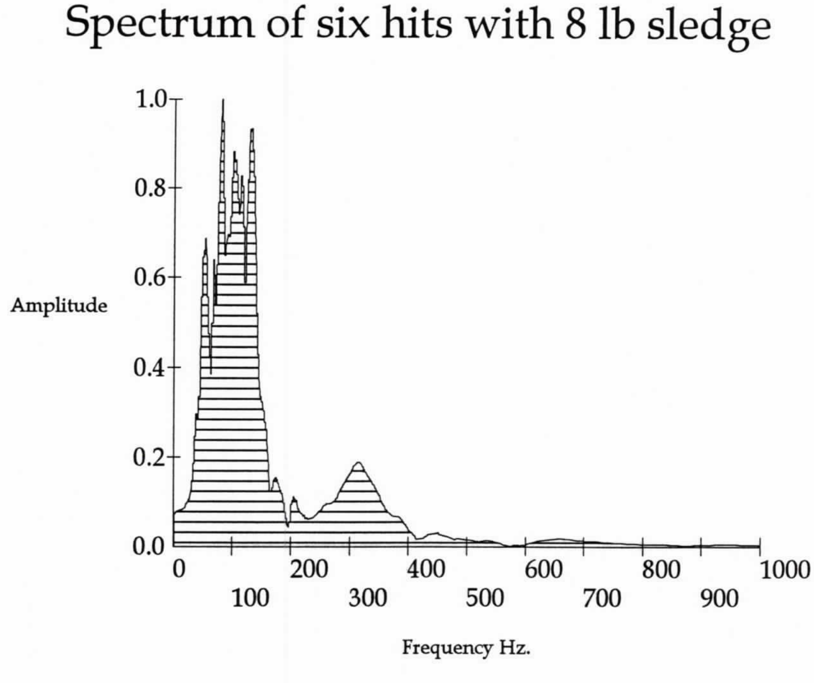


Figure 13. Spectral properties (with the exception of maybe the air-coupled wave) of the 8 lb sledge changed little when the hammer weight and plate area were decreased.

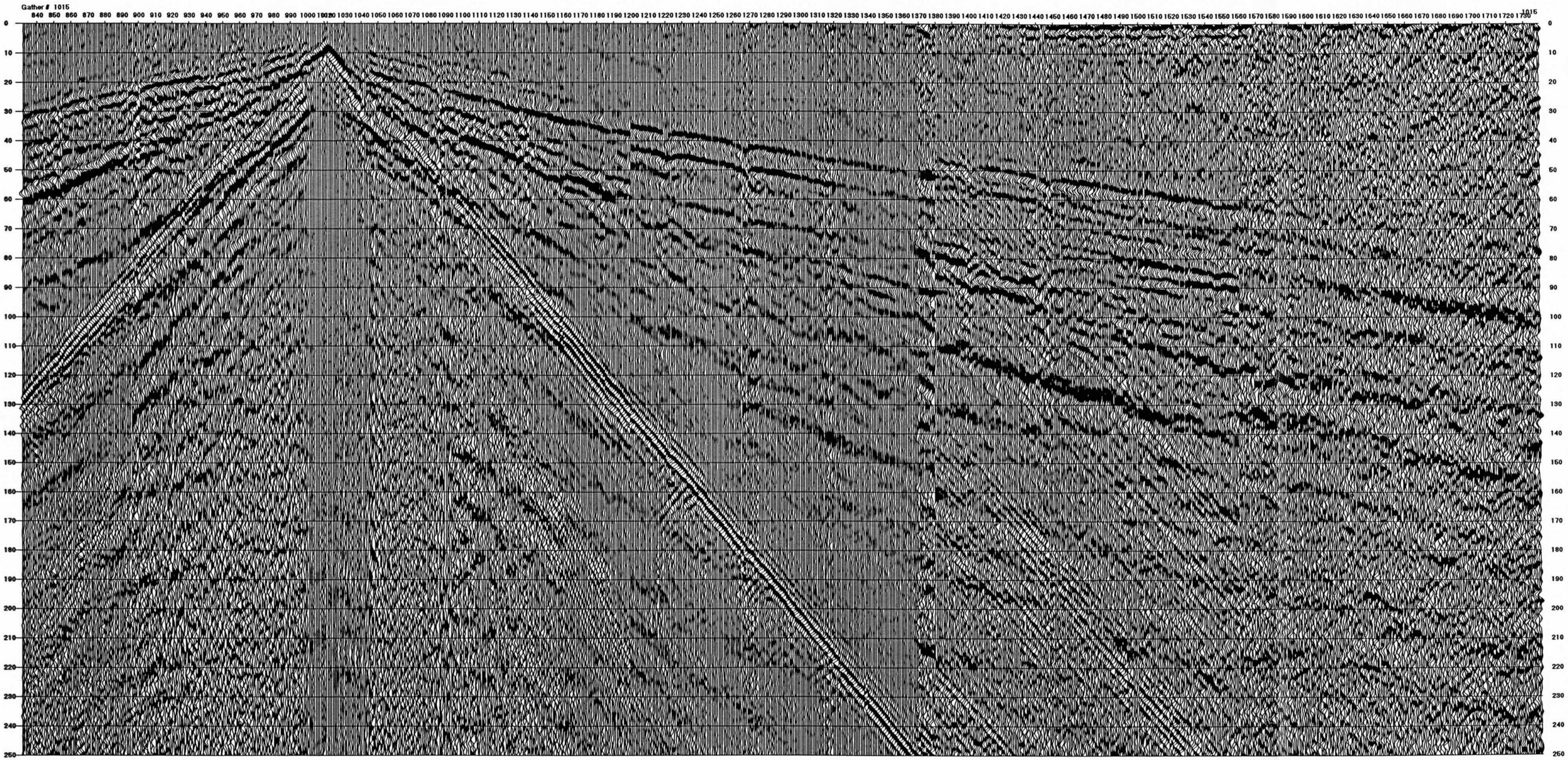


Figure 14. Longer offset energy is noticeably affected when the hammer weight is decreased to 2 lbs.

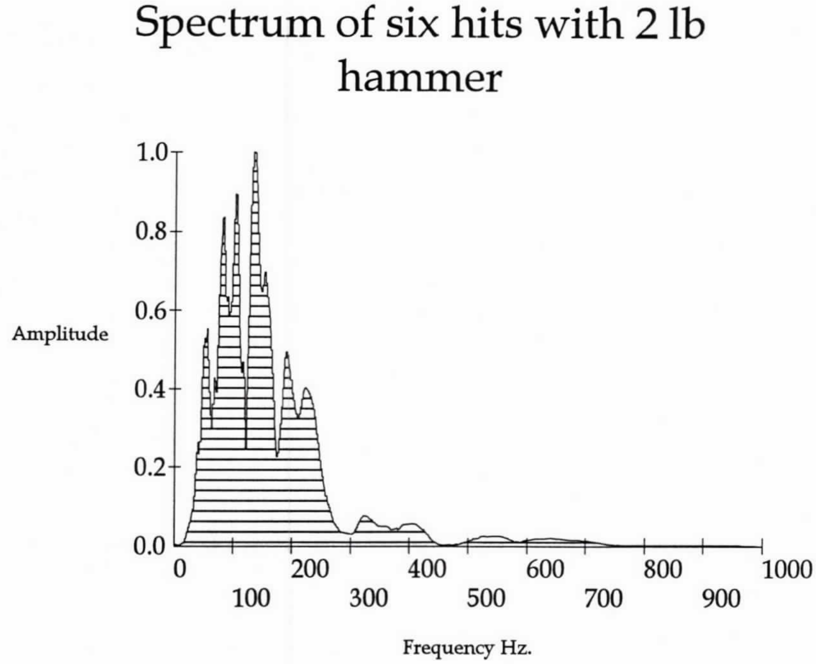


Figure 15. The spectrum seems flatter with less air-coupled wave with this configuration.

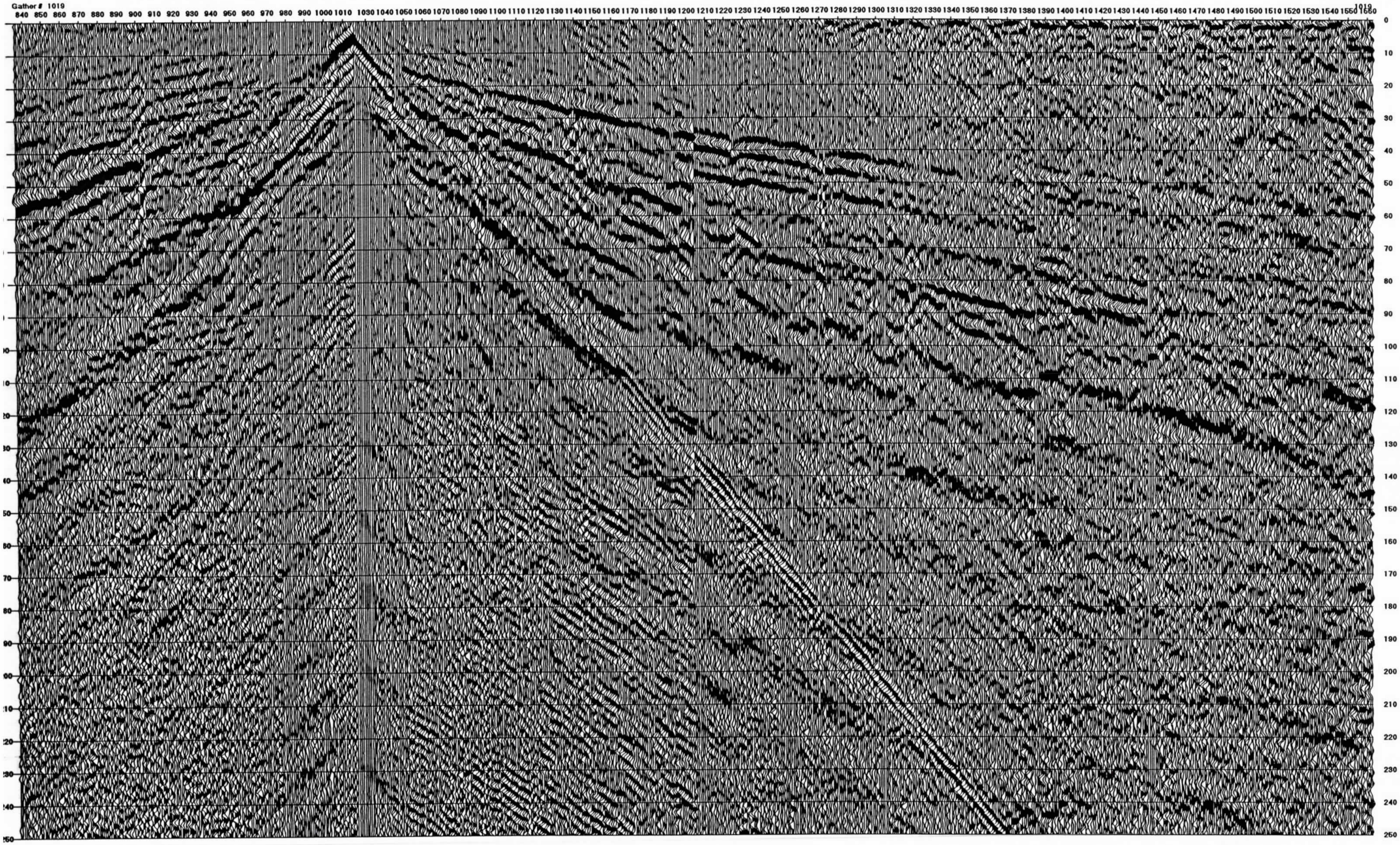


Figure 16. The 1/2 inch shaft was only used at the near three offsets due to a drop in amplitude at the longer offsets.

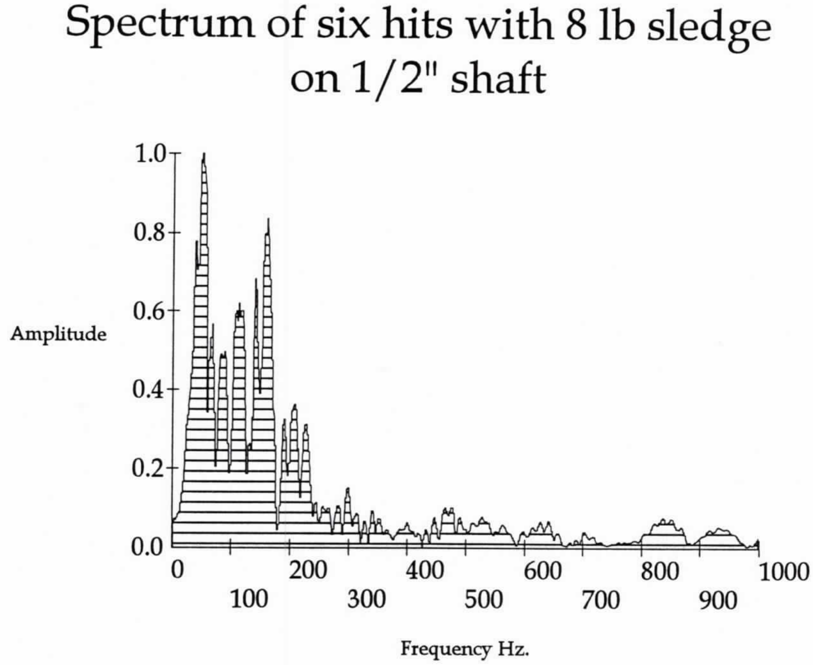


Figure 17. The spectra of the 1/2 inch shaft impacted with an 8 lb hammer seems to roll off from about 200 to 250 Hz, which is noticeably lower than when a plate is used for the ground coupling.

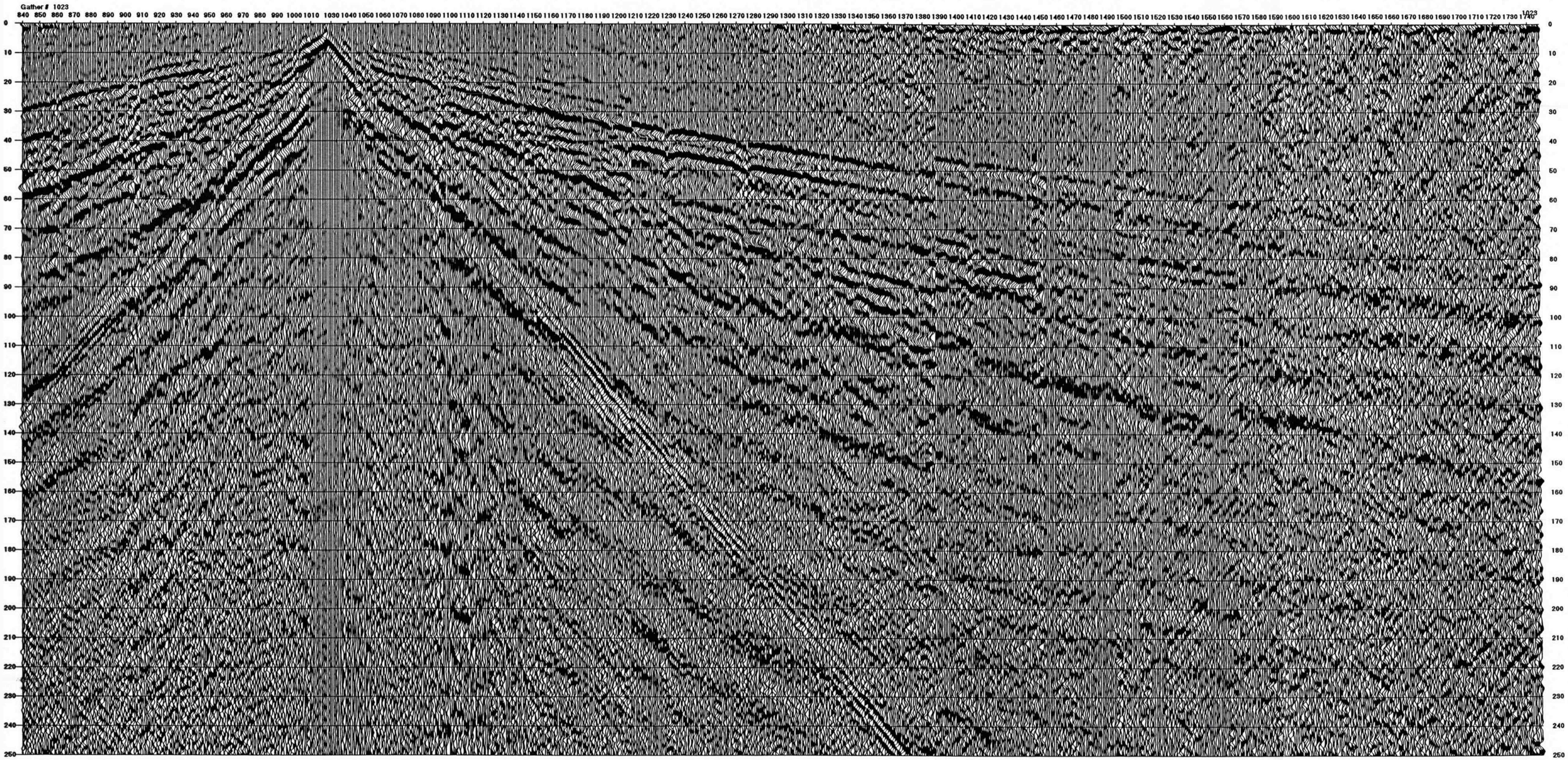

Figure 18. It is evident that as the diameter of the shaft increased the total energy delivered to ground also increased.

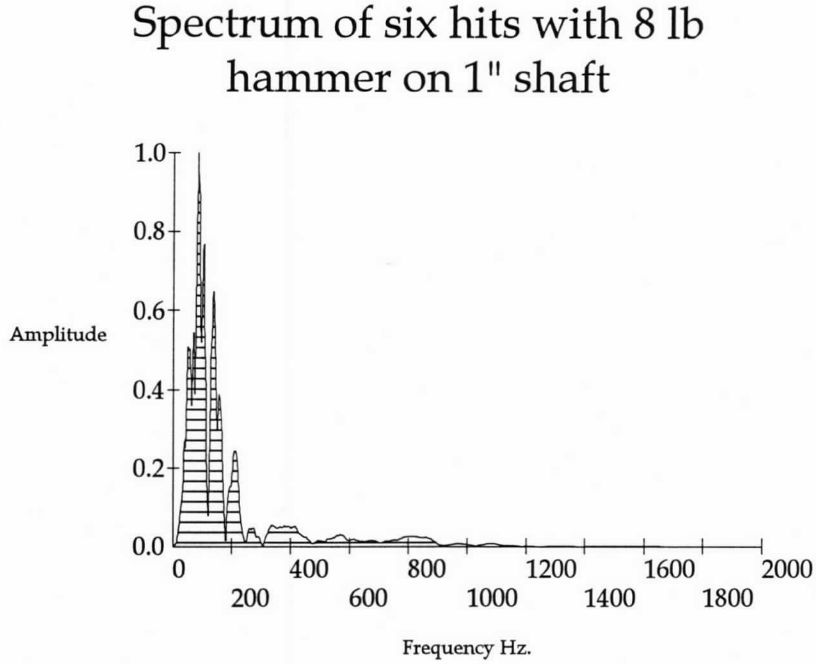


Figure 19. A one-inch shaft had a slower vertical component than the 1/2 inch, but had spectral properties similar to the 1/2 inch shaft.

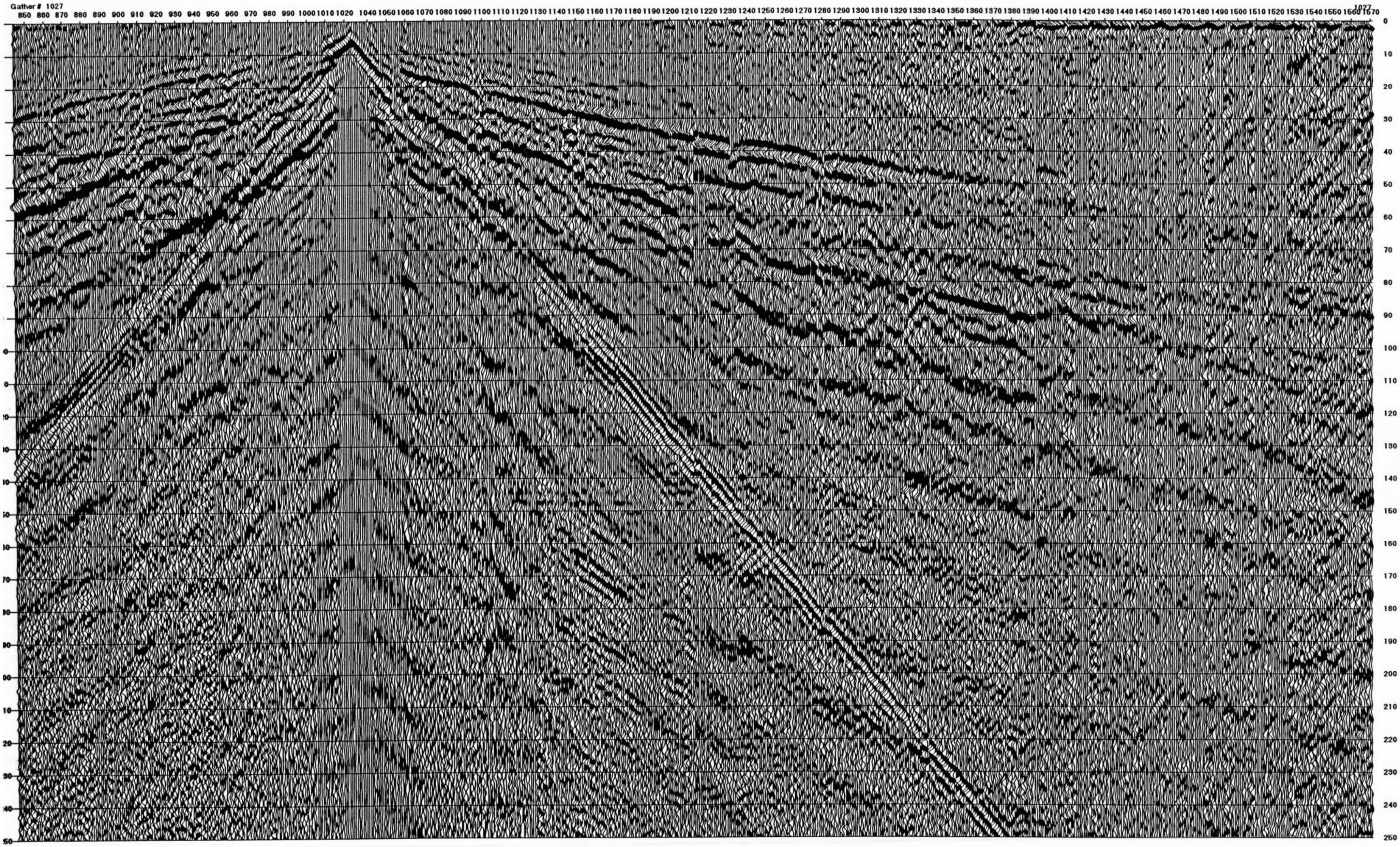


Figure 20. When the hammer weight was reduced, the amplitude at longer offsets decreased as well.

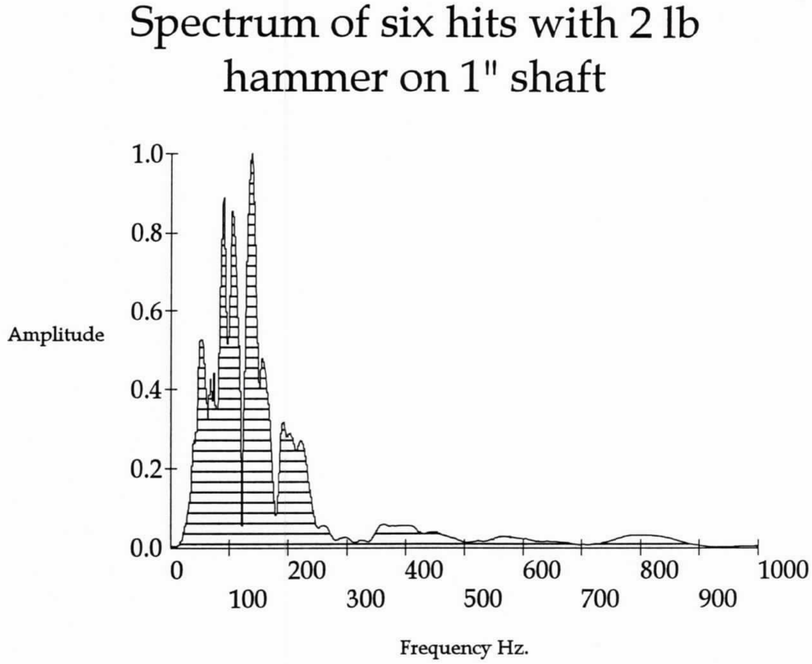


Figure 21. Using a 2 lb hammer did little to improve the upper corner of the bandwidth.

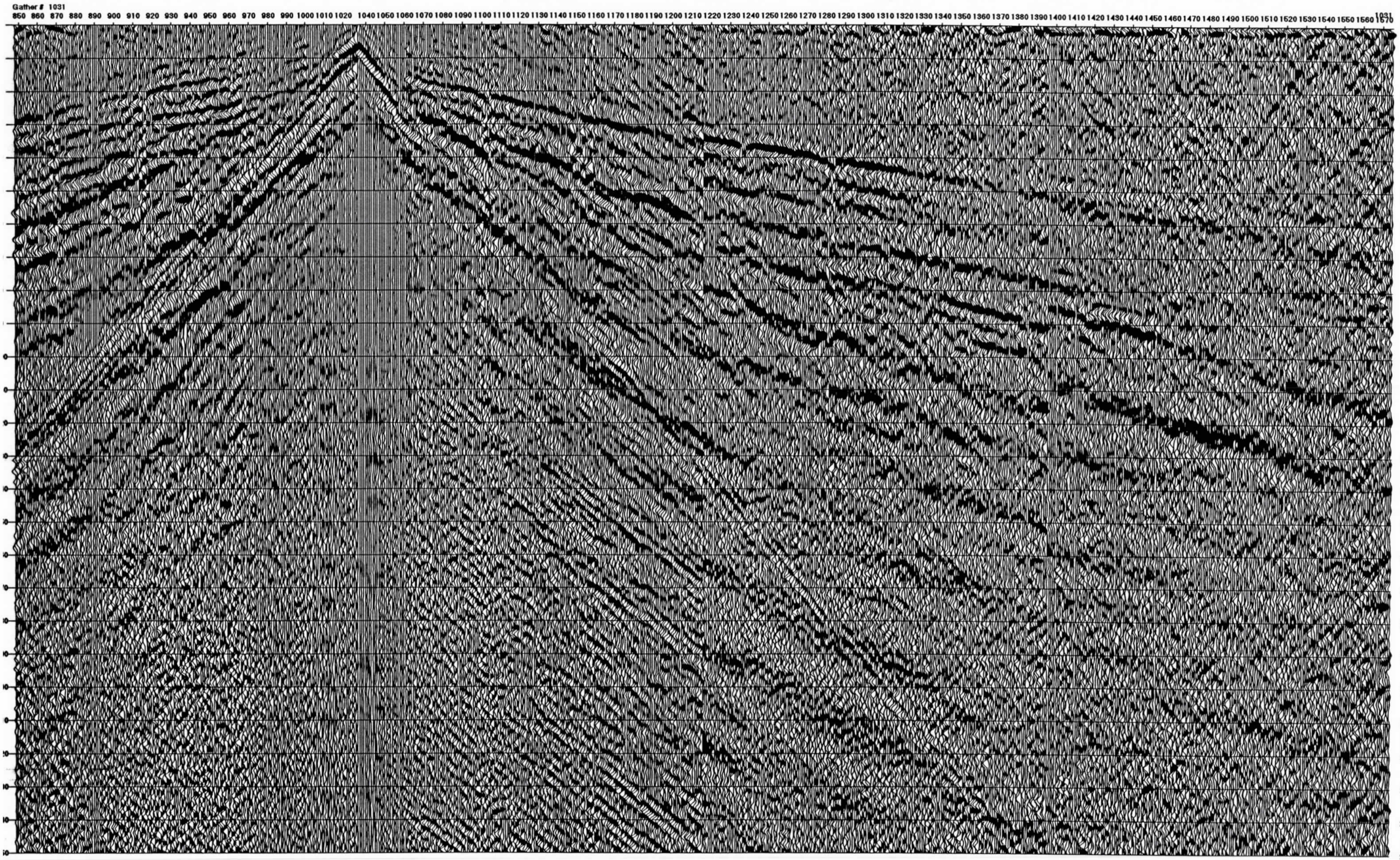


Figure 22. Moving down in size to a center punch purchased at a hardware store and the 2 lb hammer provided a section very similar to the 2 lb hammer and the 1 inch shaft.

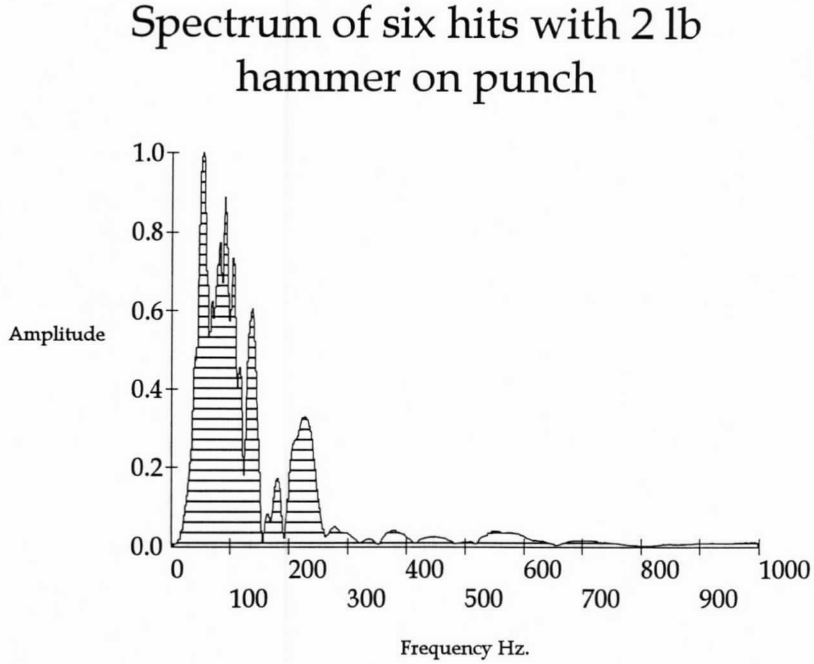


Figure 23. The spectra possesses a sizable hole around 100 to 150 Hz that was not present on any of the other hammer shaft/punch combinations.

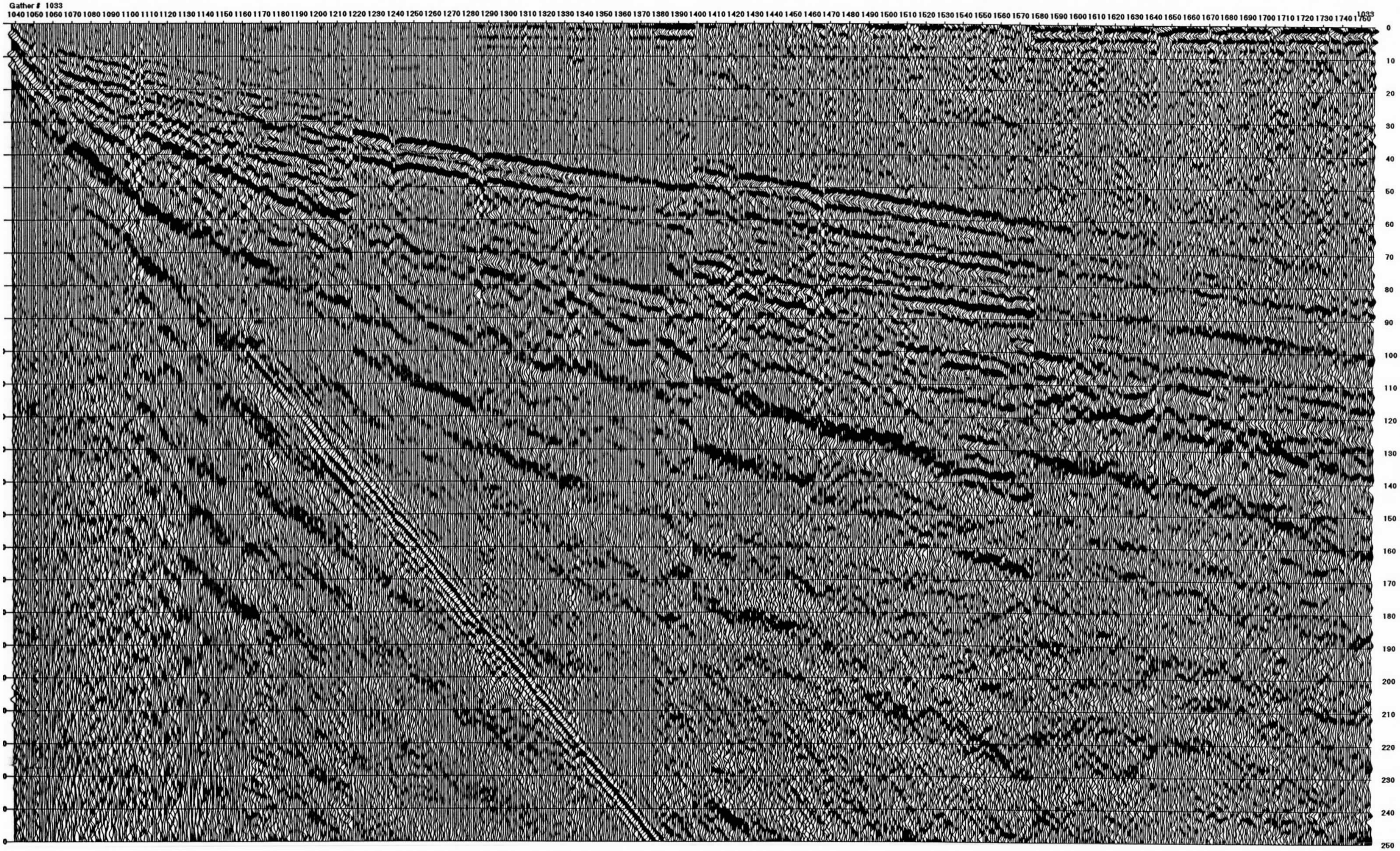

Figure 24. A downhole 30.06 projectile source was fired into an 18 inch hole at the nearest three offsets.

# Spectrum of single shot from 30.06 downhole

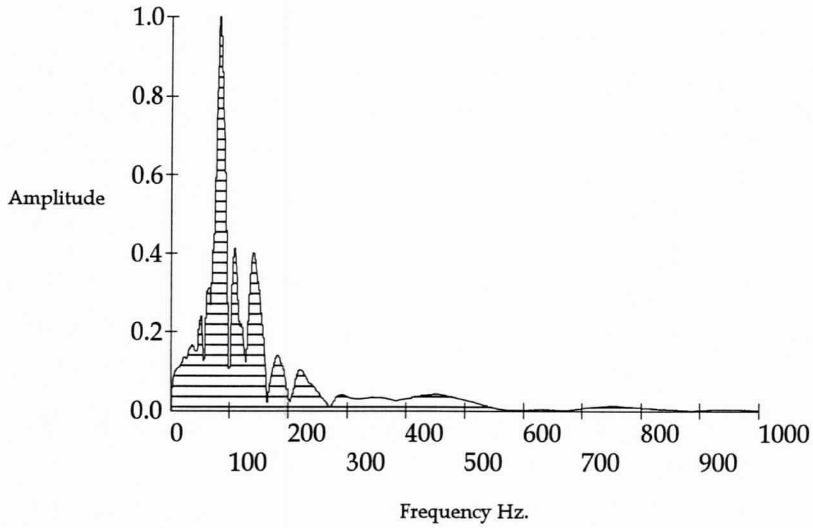


Figure 25. The 30.06 seems to possess a high amplitude spike at around 80 Hz that is unique to this source. In general the spectra does not seem to be as rich as the hammer sources.

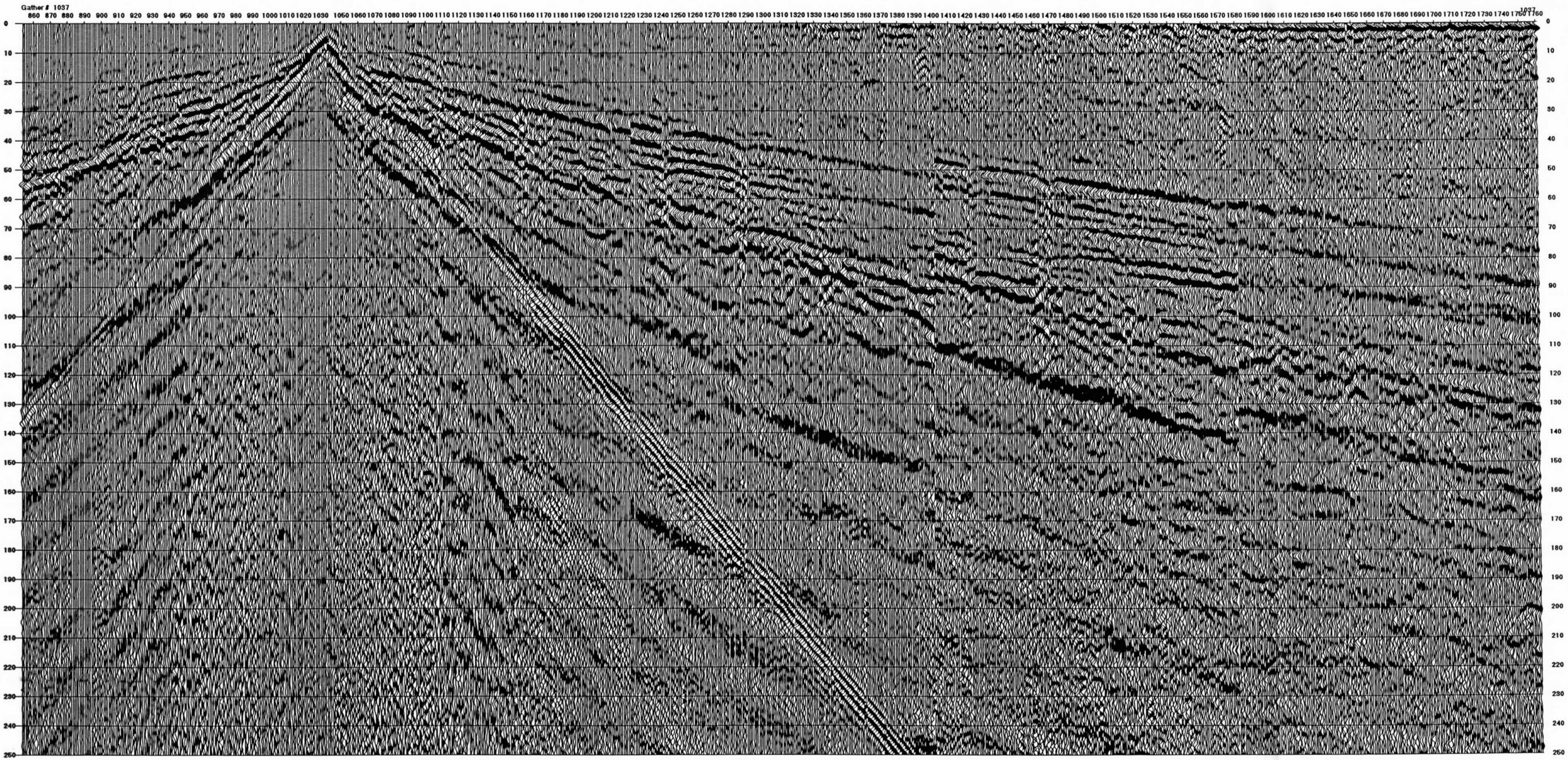


Figure 26. The slide hammer provided a shot gather that was quite comparable with the best hammer impacts.

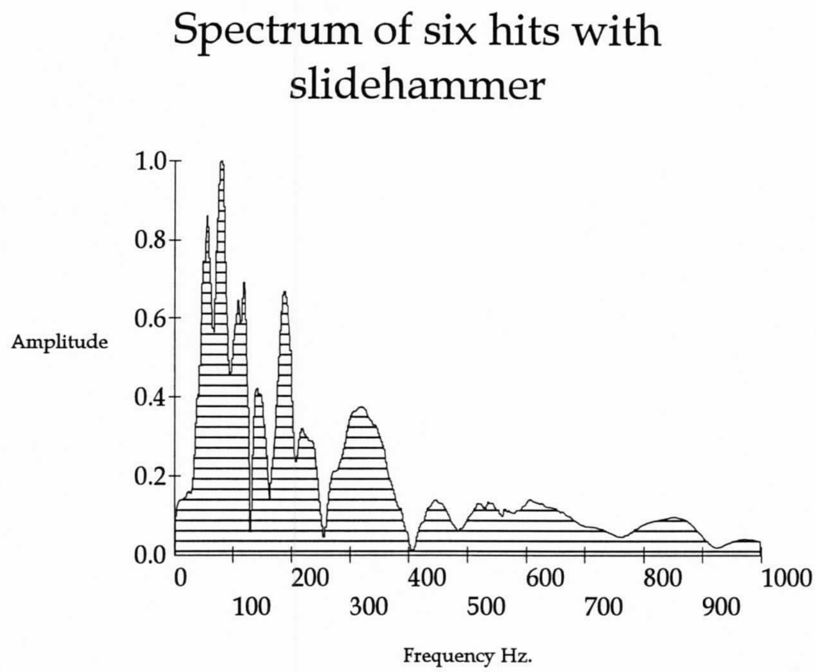


Figure 27. The frequency content was comparable and maybe just a little better than the hammer/plate configuration.

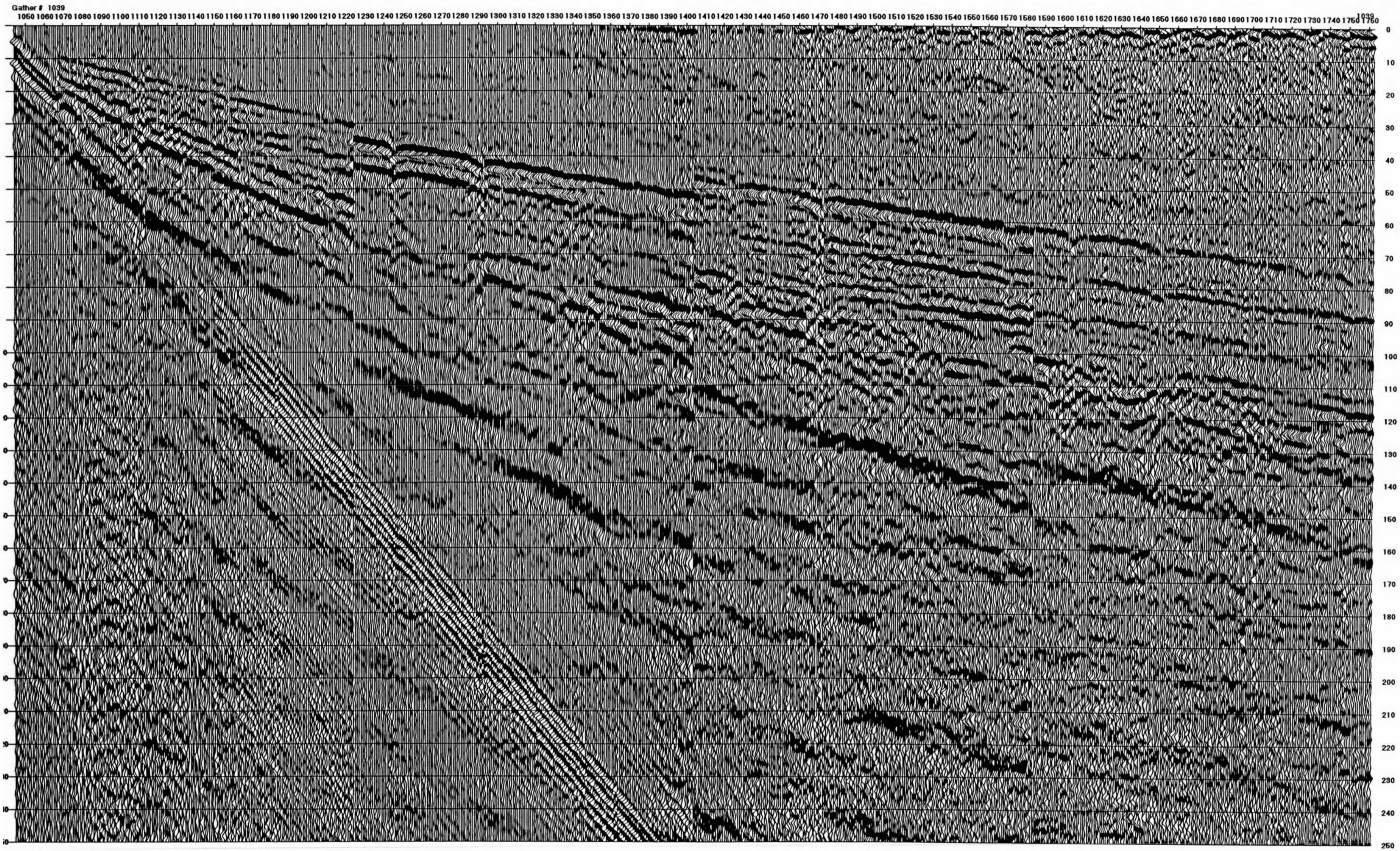


Figure 28. This single shot record has a high concentration of cyclic events that seem to parallel (in general) the first arrivals.

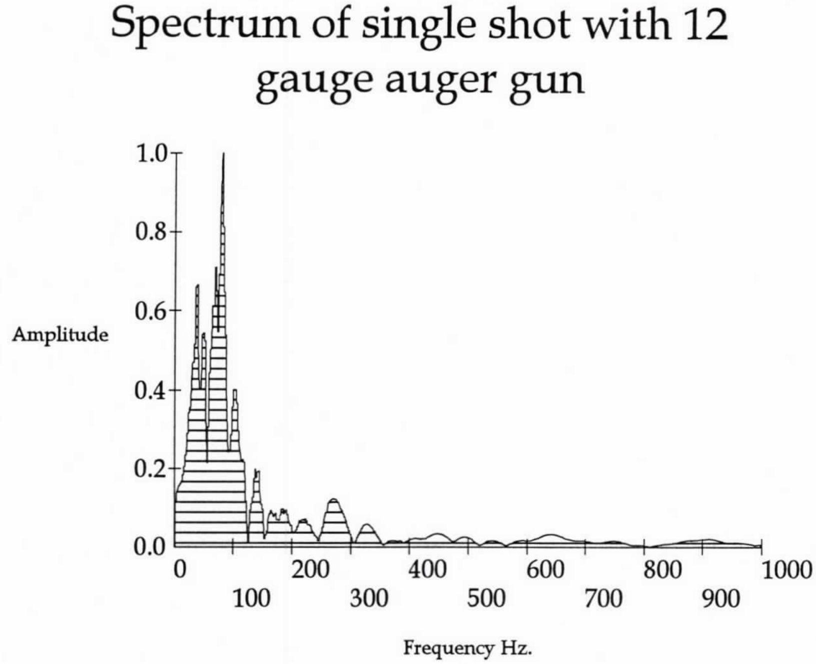


Figure 29. The 12 gauge black powder source clearly does not possess the broad bandwidth of the hammer sources.

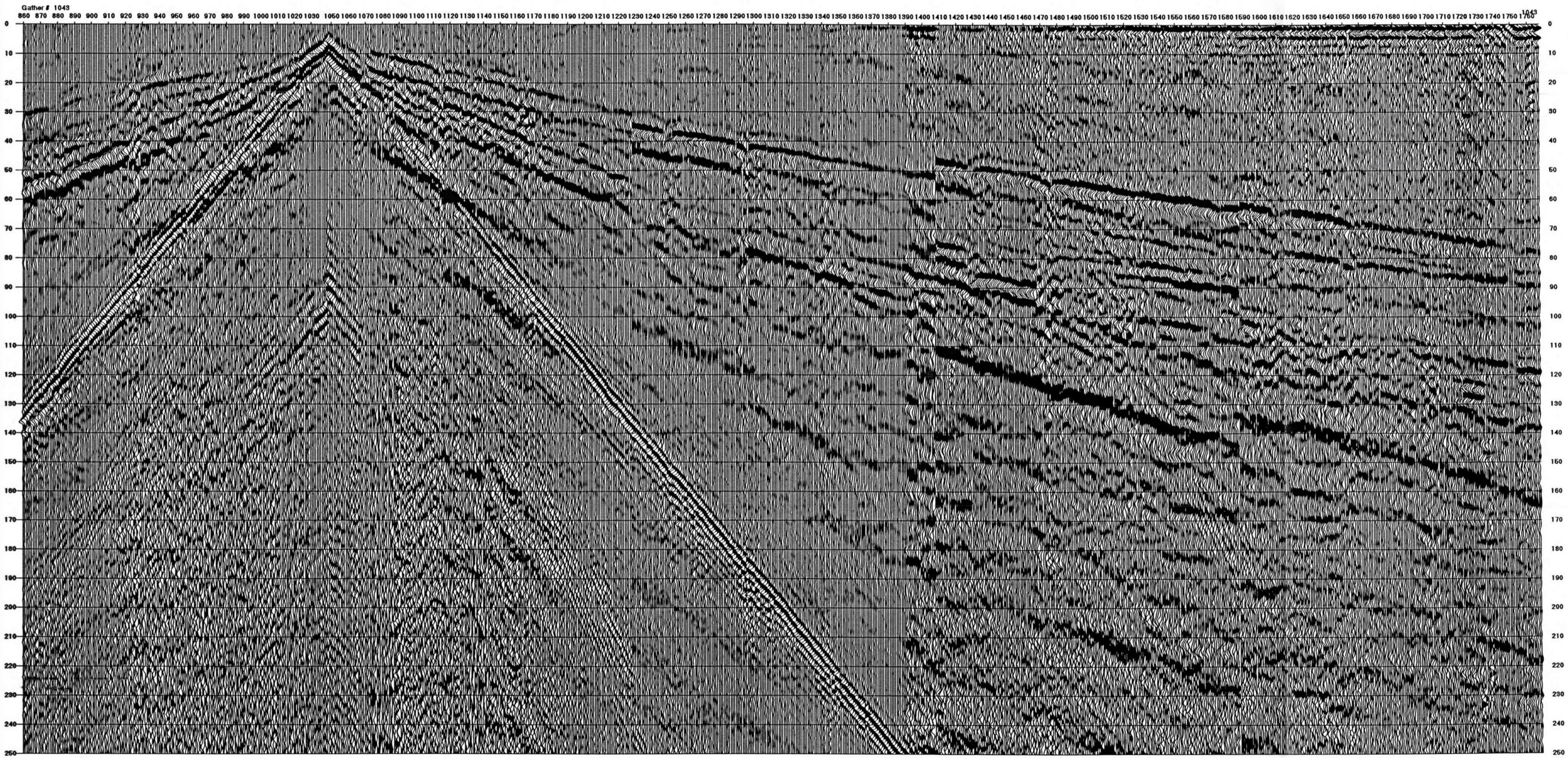

Figure 30. A mechanical accelerated weight drop source was tested and provided a very uninspiring shot gather.

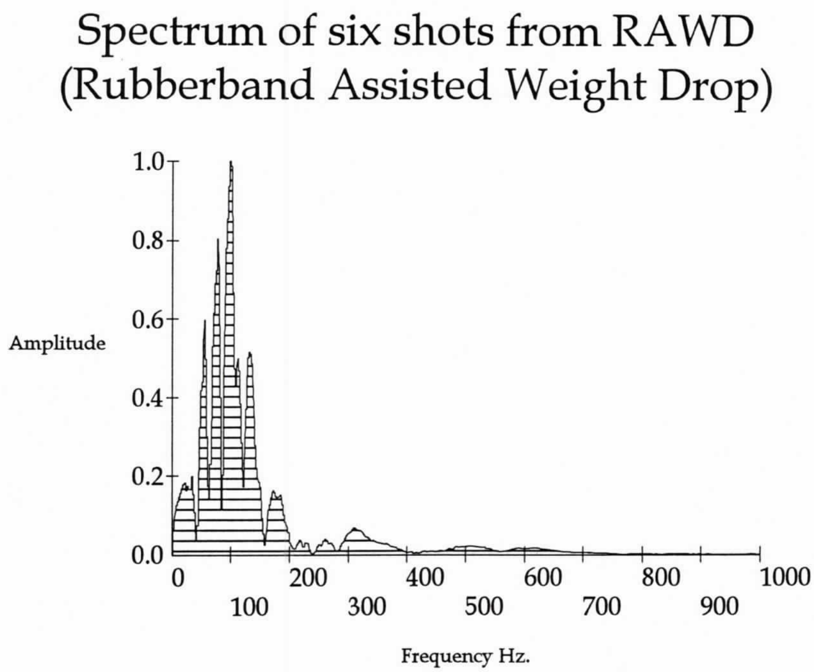


Figure 31. Clearly the spectra is narrow in comparison to some of the hammer/plate spectra.

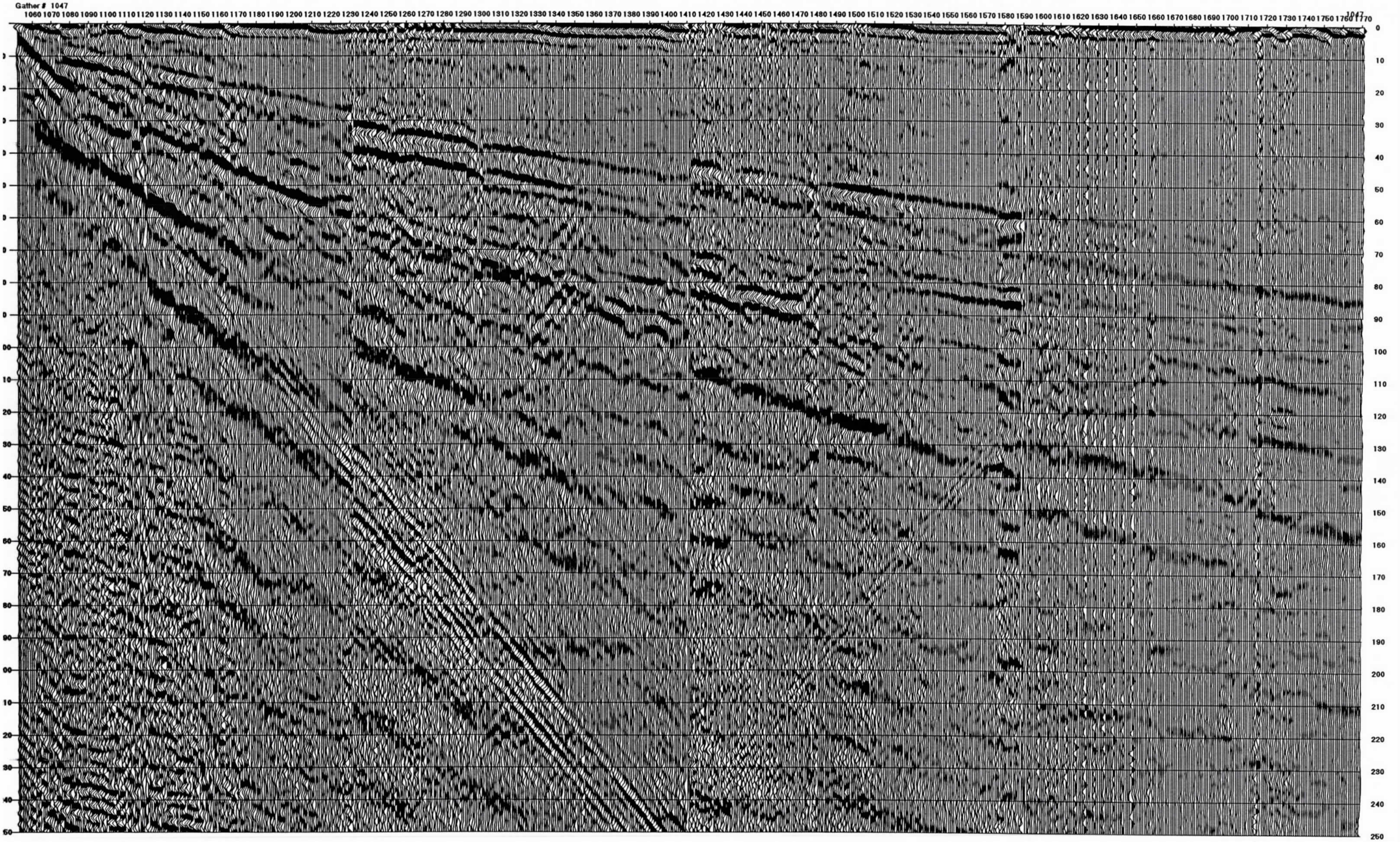

Figure 32. If reflections are present from shallower events on the vibrator shot gather, they are not evident on these spectrally balanced plots.

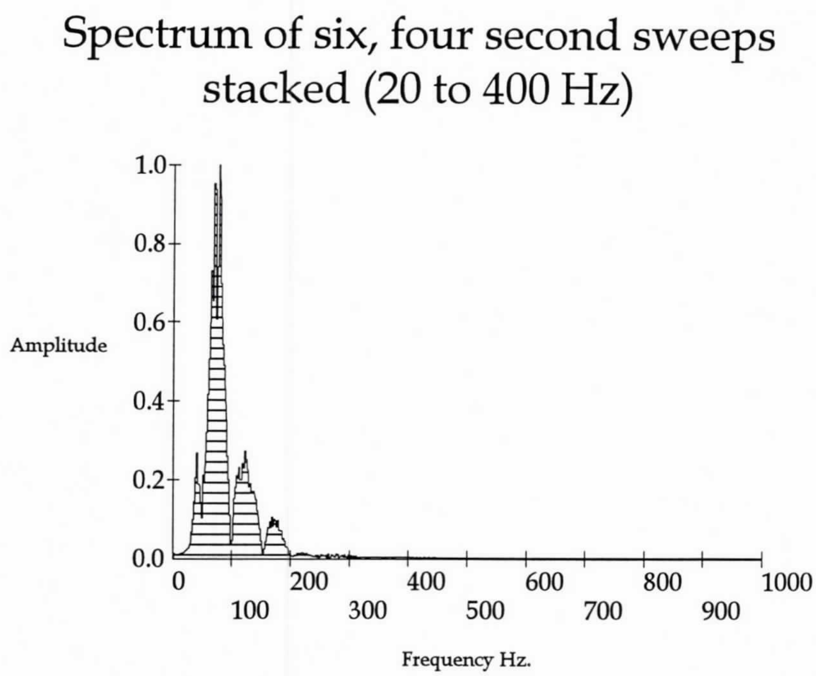


Figure 33. The spectra of the vibrator is consistent with the weight drop, but not nearly as uniform in amplitude through the primary band of interest.

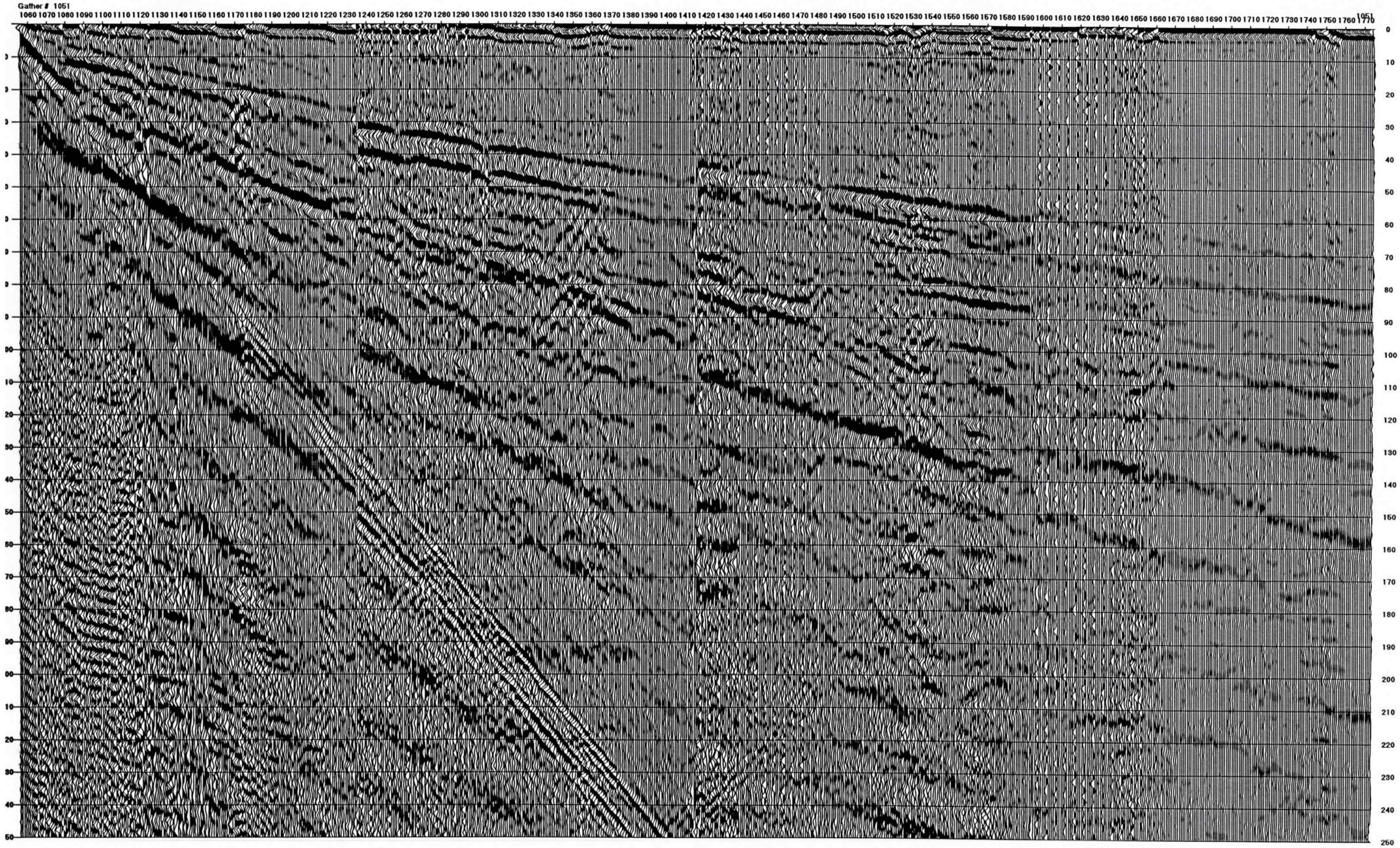

Figure 34. The difference between a four second and a six second sweep is nearly impossible to tell from the shot gathers.

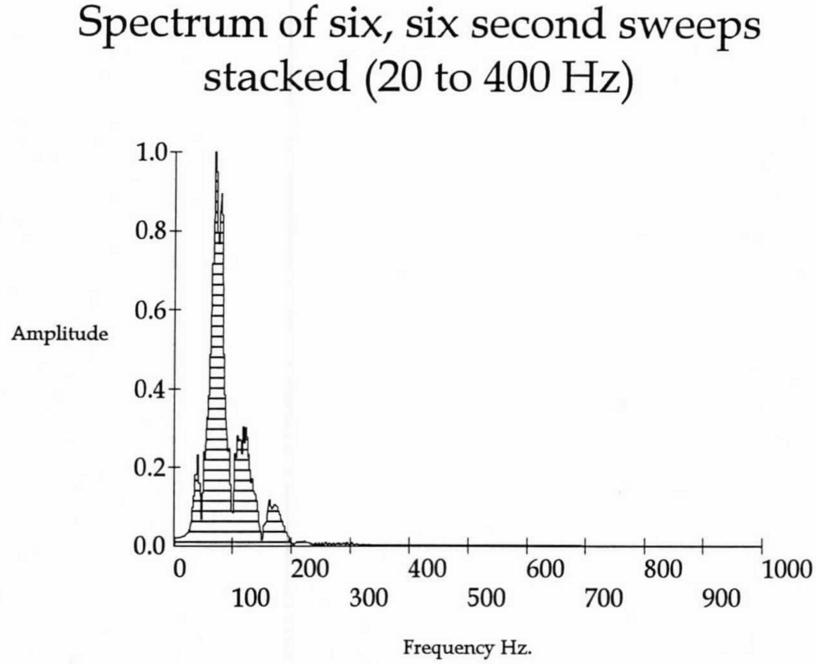


Figure 35. It maybe even more difficult to distinguish the two when comparing the spectra.

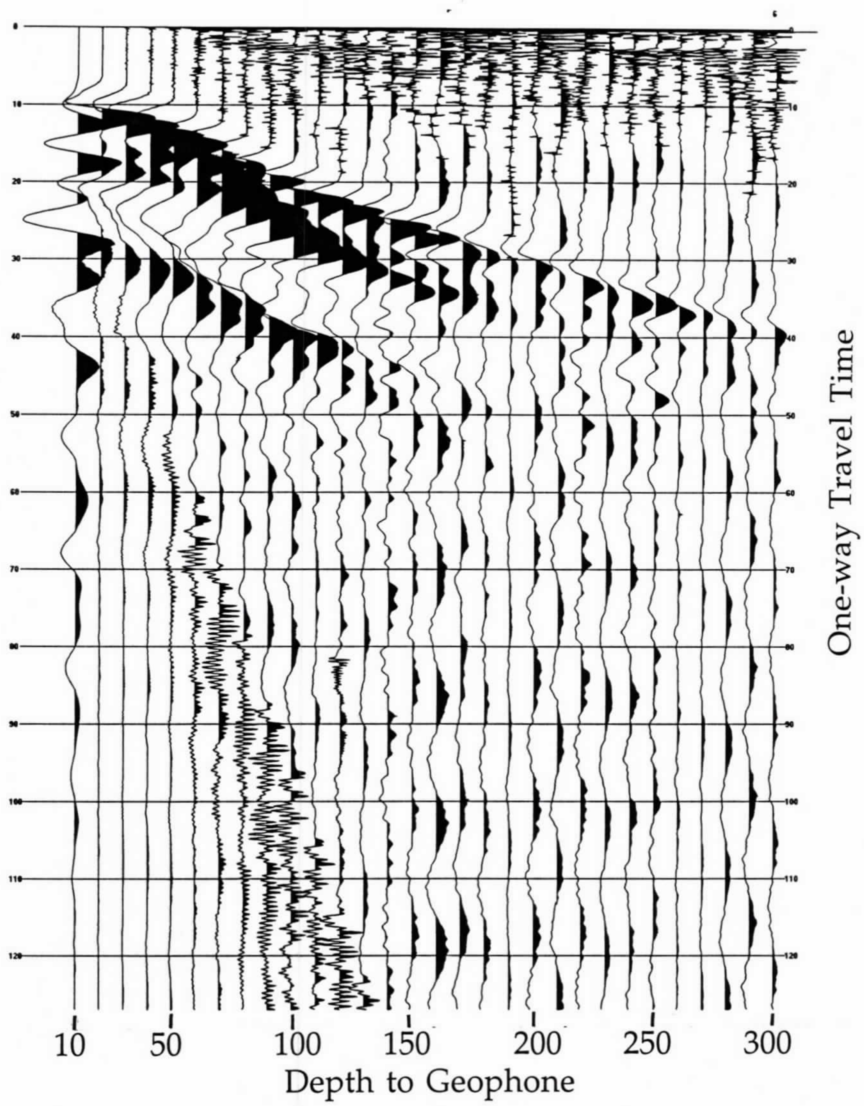


Figure 36. Uphole data gathered according to source location and borehole depth with each trace separated by 3 m in depth.

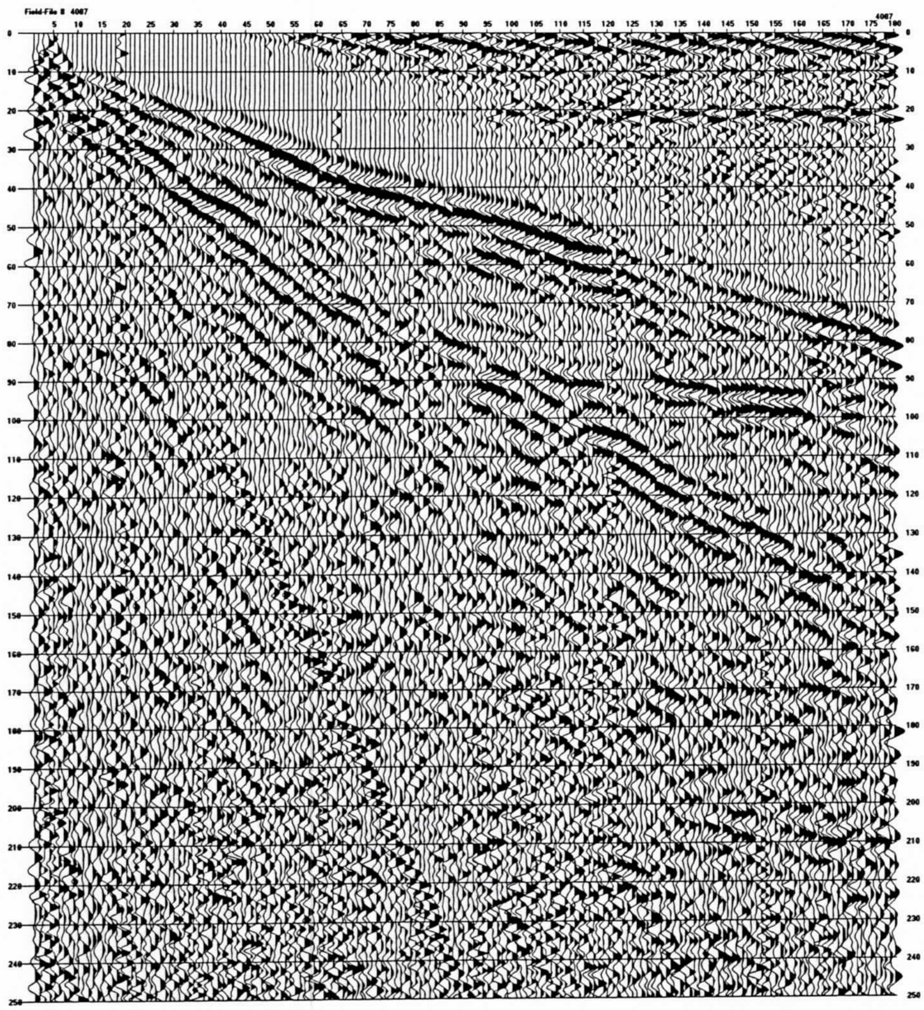


Figure 37. A series of spikes was thought to be related to the time break pulse due to the proximity of the spike to time zero, when in actuality it was found to be related to a ground loop in the 12 volt batteries supplying power to the seismograph.

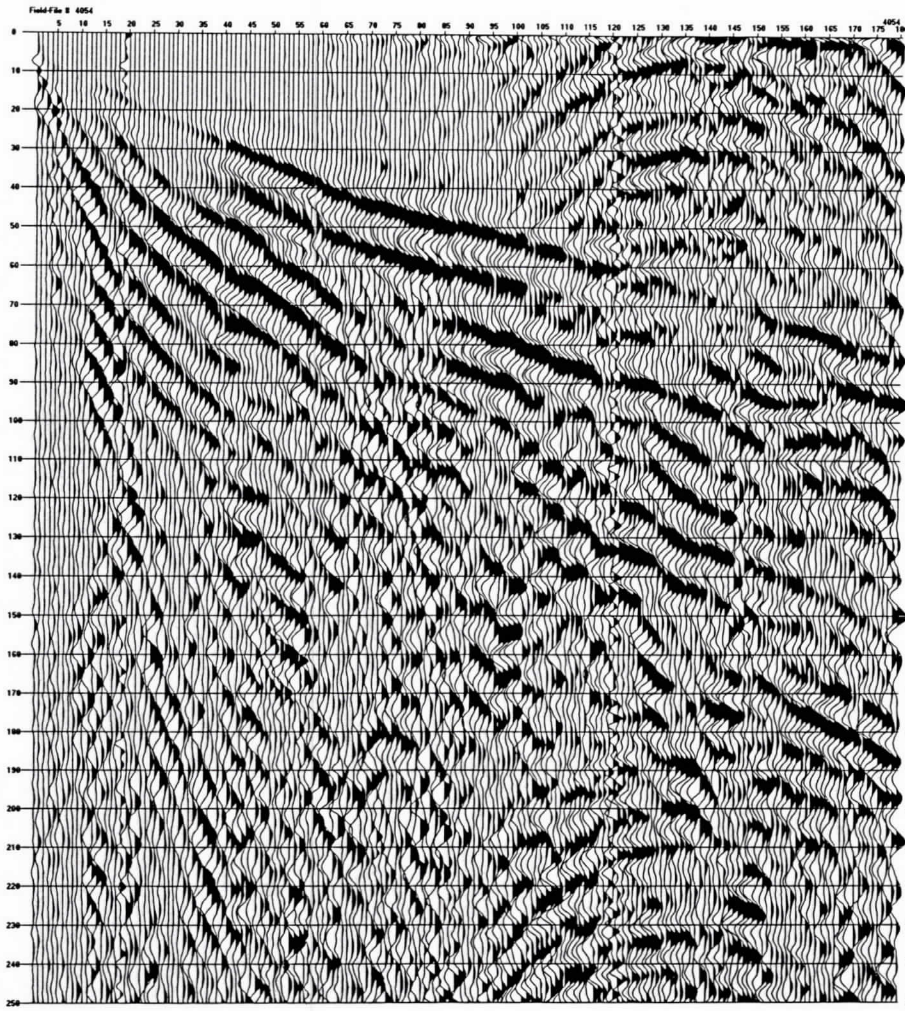

Figure 38. Based on the noise levels recorded, it was a good decision to keep the generator off while seismic reflection data was being recorded. The noise from the generator manifests itself on line 2 as a series of lower frequency hyperbolas with an apex around channel 135.

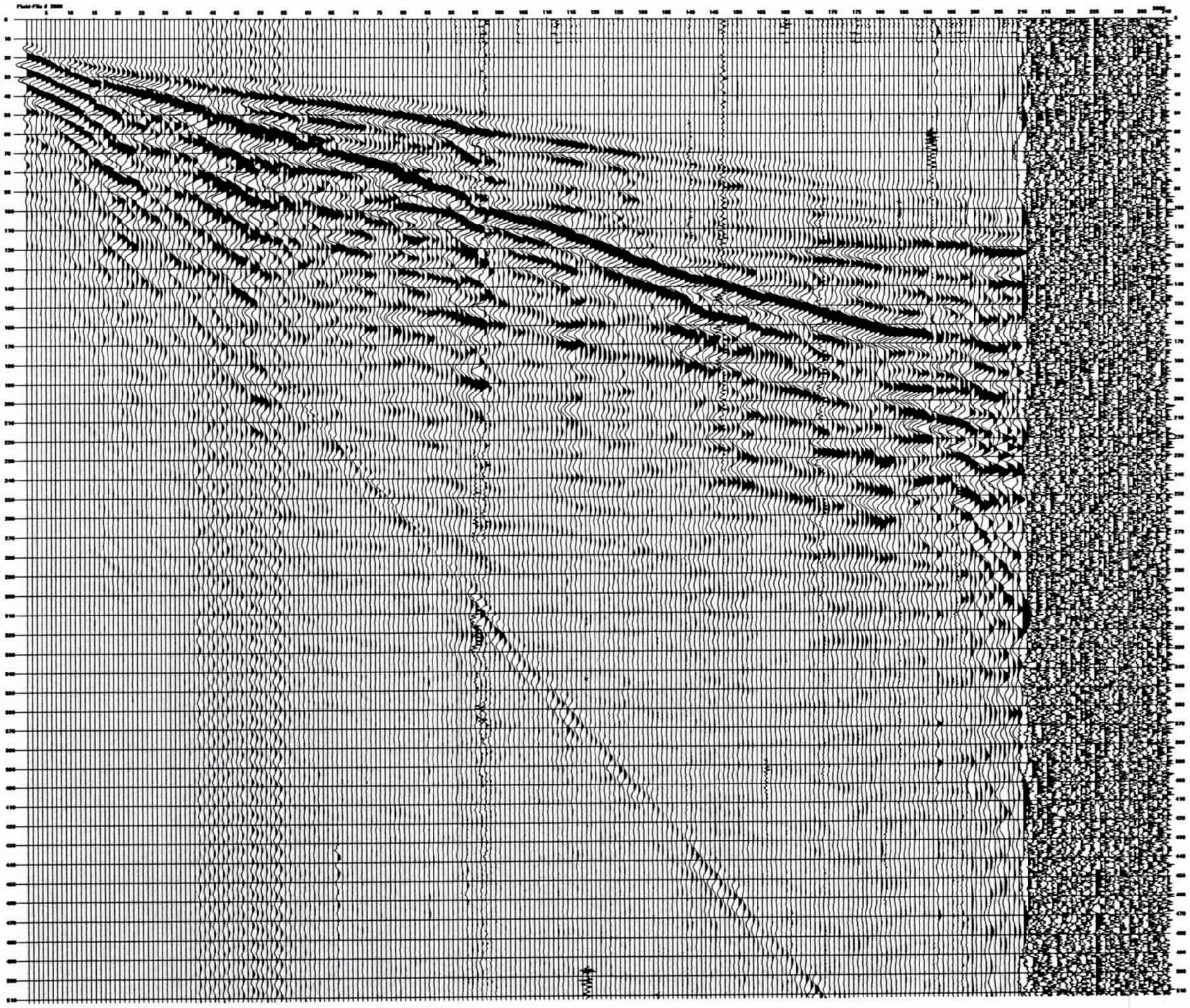

Figure 39.  Sample shot gather from line NNL-1.

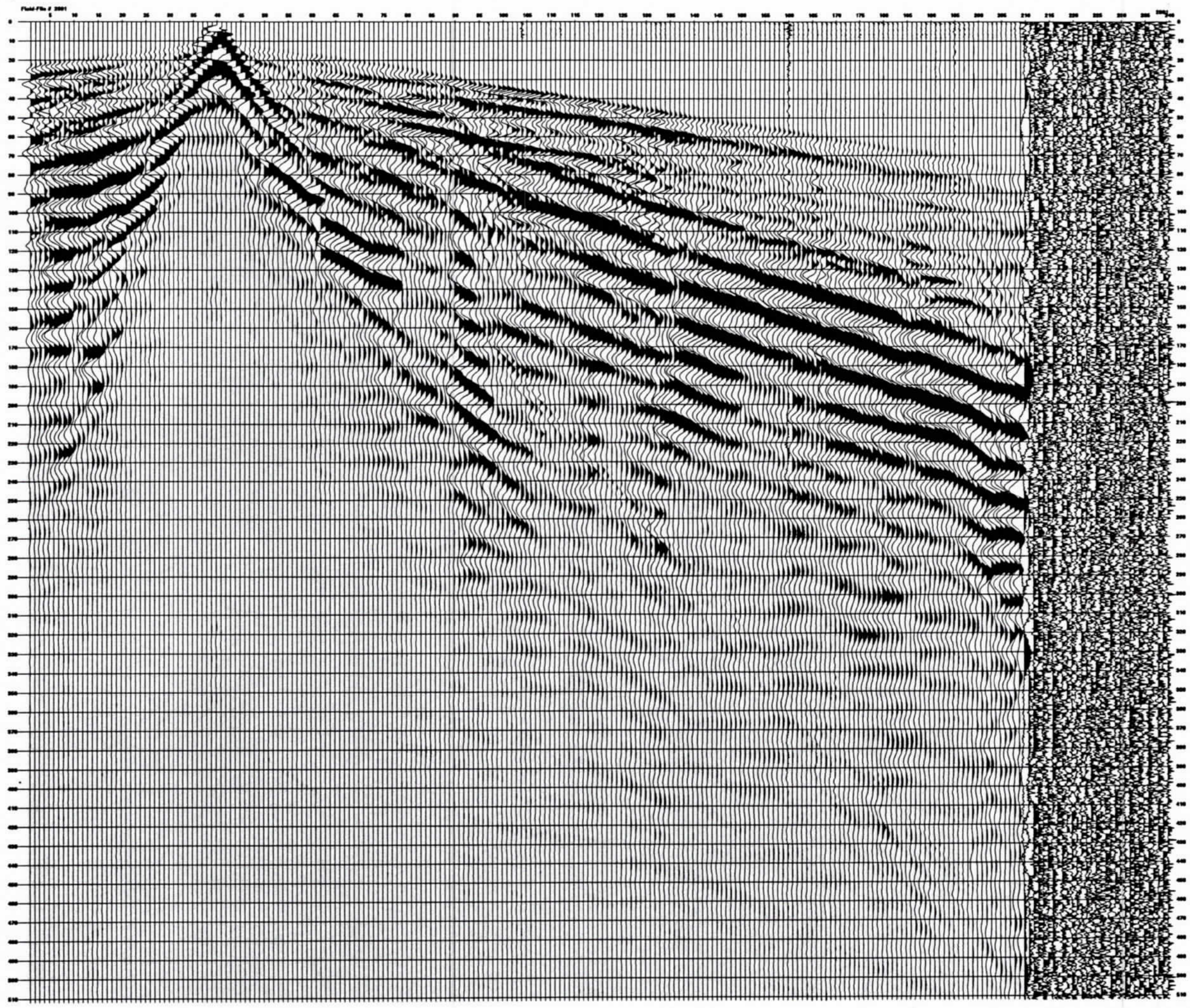

Figure 40. Sample shot gather from line NNL-1.

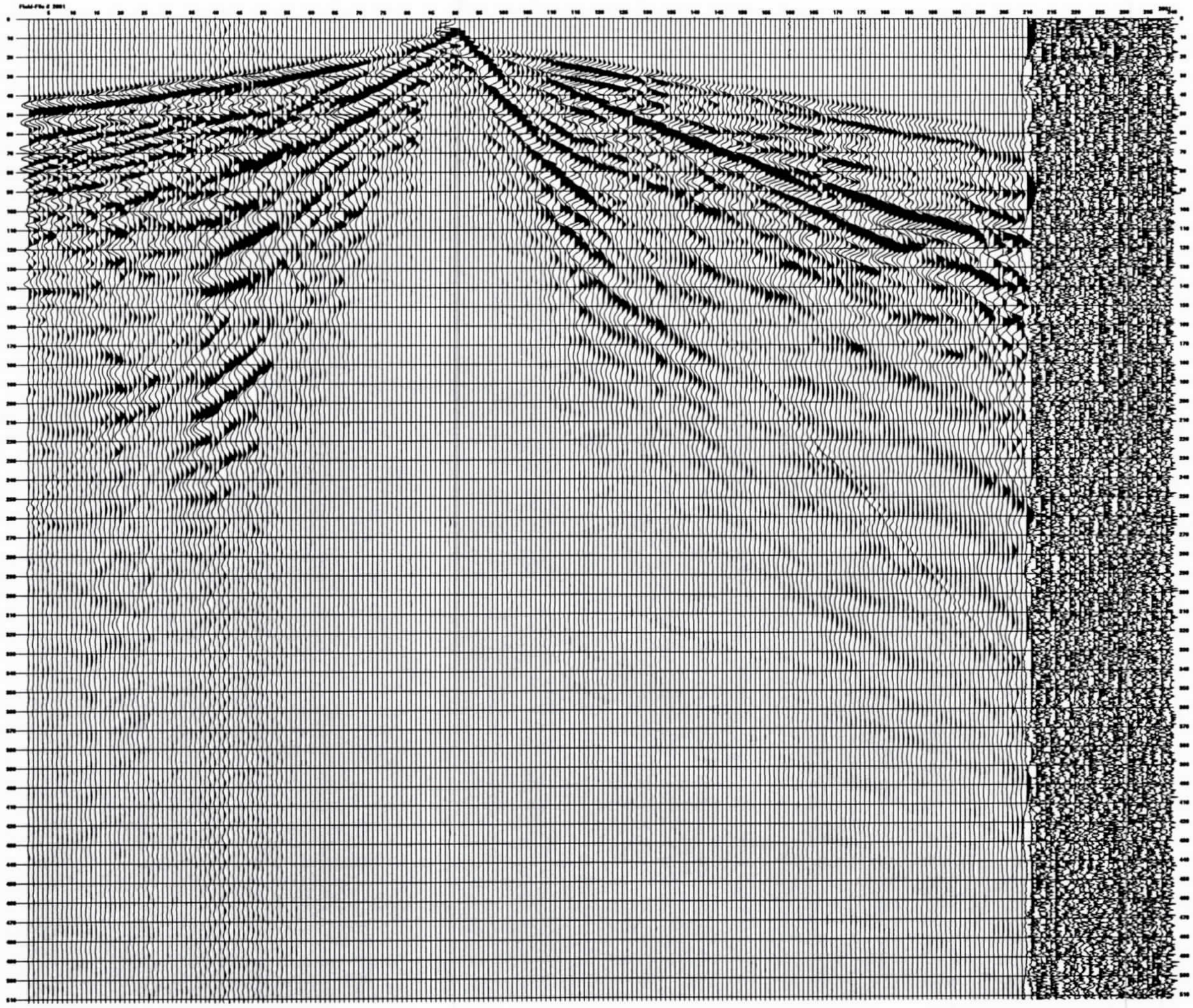

Figure 41. Sample shot gather from line NNL-1.

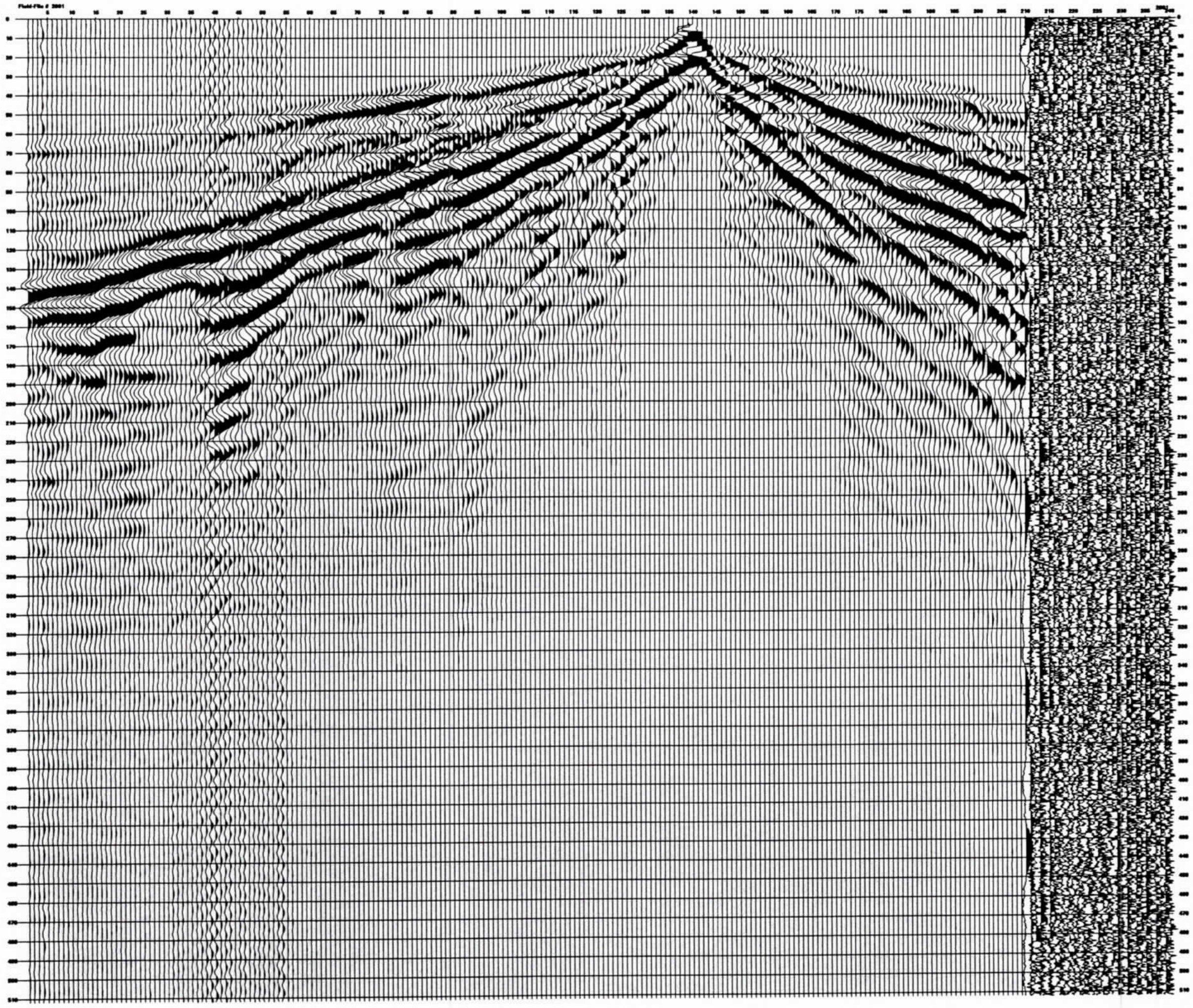

Figure 42. Sample shot gather from line NNL-1.

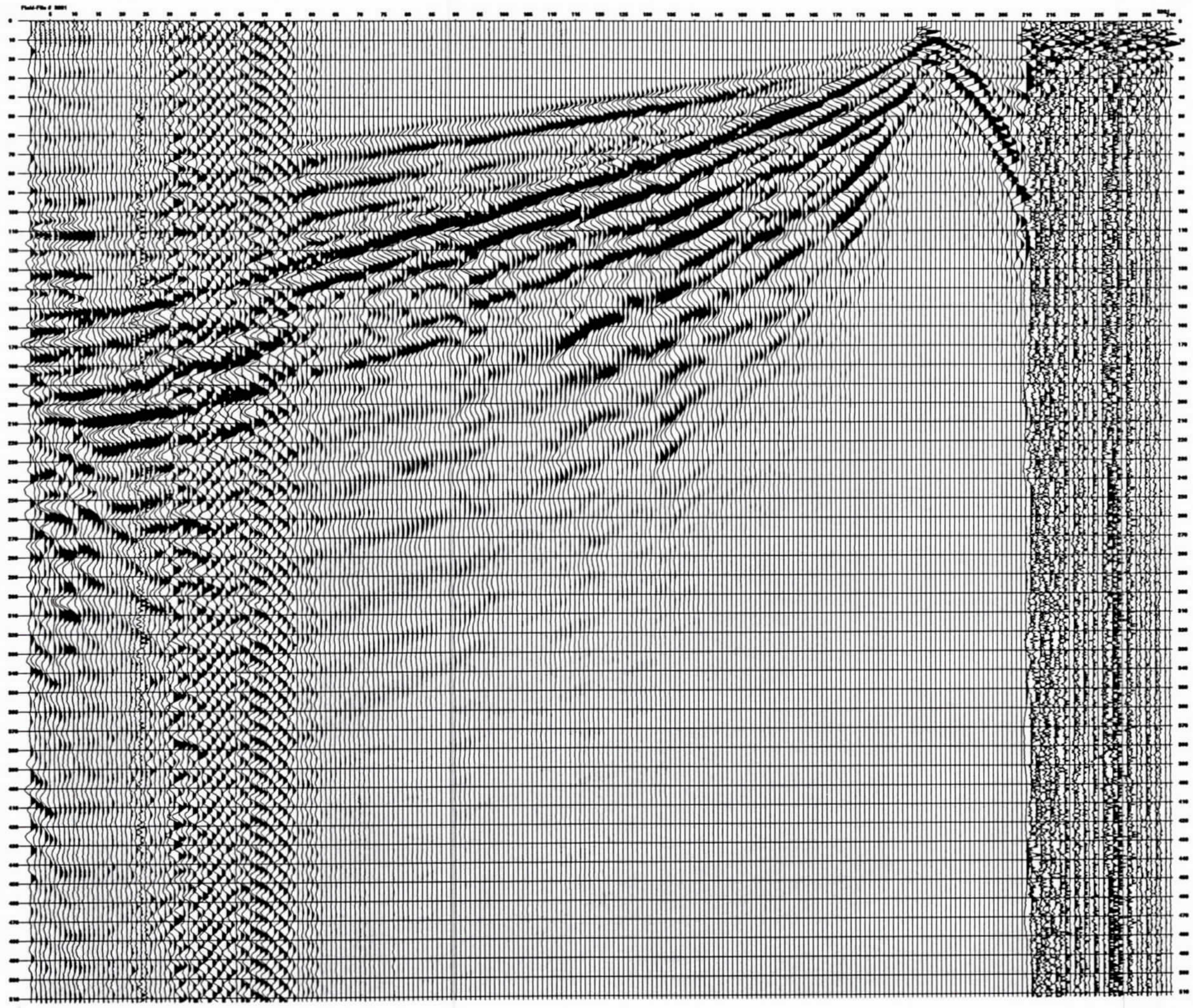

Figure 43.  Sample shot gather from line NNL-1.