KANSAS GEOLOGICAL SURVEY
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Seismic Reflection Survey of Faulting Near Charleston, South Carolina

Final Report
to
The University of South Carolina
Columbia, South Carolina 29208

by

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INTRODUCTION

The 1886 Charleston earthquake was the largest documented historical event known to have occurred in the eastern one-third of the United States (Bollinger, 1977). Smaller earthquakes have been either felt or recorded in the area since 1689 (Bollinger and Visvanathan, 1977, Tarr, 1977; Rhea, 1981). Only recently have attempts been made to define the cause of the intraplate seismicity as well as define the seismicity patterns based on data from small earthquakes (Talwani, 1982).

The Kansas Geological Survey (KGS) acquired and processed five CDP seismic reflection lines totalling 31.3 km in the Summerville, South Carolina, area for the University of South Carolina (USC). The seismic surveys included a combination of two different techniques/sources (miniSOSIE and explosive/projectile). The primary purpose of this survey was to map faulting present on the surface of the volcanic basement rocks with depth ranging from 500 to 1500 m. Secondary to that was the imaging of sedimentary units between the basement surface and bedrock.

Data Acquisition

Data for this study were acquired on a 24-channel Input/Output DHR-2400 seismograph and a 48-channel EG&G Geometrics 2401x. The data from the DHR were analog filtered, amplified, A/D converted (11 bits plus sign), and recorded on 9 track tape for future digital processing. The record length is 1000 ms with a sampling interval of 1 ms. The 1 ms sampling interval equates to a sampling frequency of 1000 Hz and therefore an alias or Nyquist frequency of 500 Hz. A 500 Hz high-cut filter with a 24 dB/octave rolloff acted as an anti-alias filter and to reduce wind and higher modes of 60 Hz power line noise. For the production portion of the survey 40 Hz analog low-cut filters were used to shape the pre-amplified spectra, enhancing the higher frequency components of the recorded energy. The Geometric's seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. The 25 Hz analog low-cut filters used during the production portion of this survey have a 18 dB/octave rolloff. The 1/2 ms sampling interval resulted in a 2000 Hz sampling frequency for a record length of 1024 msec. The Geometrics 2401x is a 48-channel floating point seismograph. Both seismographs and the associated field parameters for the individual lines were optimized for the conditions of each line and geologic target (Table 1).

The sources for the testing included the auger gun (Healey et al., 1991), and MiniSOSIE (Barbier et al., 1976, see Appendix A). The receivers for the entire study were Mark Products L-28E 40 Hz geophones wired three in series per string. The receivers were placed in a 3 m in-line array to help attenuate source-generated air coupled wave and some source-generated linear noise.

Data Processing

Data processing was done on an Intel 80486-based microcomputer using *Eavesdropper*, a set of commercially available algorithms. The processing flow was similar to those used in petroleum exploration (Figure 1). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, extra care during muting operations, and lack of deconvolution. Post-stack migration proved quite useful in improving the signal-to-noise ratio and coherency of the CDP stacked data.

In a general sense, the stacking velocities were relatively consistent for all the lines. Stacking velocities represent hyperbolic curves that best fit the apparent curvature of reflection arrivals. They are only a means to determine approximate depths and thicknesses. The velocity functions in general were 1650 m/sec from the surface to 250 msec, 1850 m/sec from 250 msec to about 600 msec, and 2050 m/sec from 600 msec to 1000 msec. Specific values (included in processing history format) need to be used with an understanding of the percent error associated with time depth conversions.

Statics included surface consistent, elevation, and to a lesser degree residual. The data only possessed minor indications of anomalies generally associated with statics. The very shallow water table contributed to the minimal problems encountered with statics.

The five processed sections possessed sufficient signal-to-noise to map significant basement as well as sedimentary features of interest (Figures 2, 3, 4, 5, and 6).

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TABLE 1
Field Parameters Used

LINE 1: The northernmost line.

Parameter	Description
Source type	8-gauge Auger
Source array	1 shot per station
Source point interval	16.7 m (55 ft)
Geophone array	Three 40 Hz natural frequency geophones, 3 m in-line array
Geophone spacing	16.7 m (55 ft)
Recording channels	48
Field filters	High cuts 500 Hz, Low cuts 25 Hz, Notch 60 Hz
Recording system	EG&G ES-2401
Sampling rate	0.5 ms
Trace length	1024 ms
Velocity info	Migration velocity 2000 m/s

LINE 2: Highway I-26

Parameter	Description
Source type	3 Wackers
Source array	16 m spacing parallel to reflection line
Source duration	1500 impulses per vibration point
Source point interval	16.7 m (55 ft)
Geophone array	Three 40 Hz natural frequency geophones, 3 m in-line array
Geophone spacing	16.7 m (55 ft)
Recording channels	24
Field filters	High cuts 500 Hz, Low cuts 40 Hz, Notch 60 Hz
Recording system	I/O DHR 2400
Sampling rate	1 ms
Trace length	1000 ms
Velocity info	Migration velocity 2000 m/s

LINE 3: Line through town

Parameter	Description
Source type	3 Wackers
Source array	16 m spacing parallel to reflection line
Source duration	1500 impulses per vibration point
Source point interval	16.7 m (55 ft)
Geophone array	Three 40 Hz natural frequency geophones, 3 m in-line array
Geophone spacing	16.7 m (55 ft)
Recording channels	24
Field filters	High cuts 500 Hz, Low cuts 40 Hz, Notch 60 Hz
Recording system	I/O DHR 2400
Sampling rate	1 ms
Trace length	1000 ms
Velocity info	Migration velocity 2000 m/s

Table 1 (continued)

LINE 4: The 2-mile line

Parameter	Description
Source type	8-gauge Auger
Source array	1 shot per station
Source point interval	16.7 m (55 ft)
Geophone array	Three 40 Hz natural frequency geophones, 3 m in-line array
Geophone spacing	16.7 m (55 ft)
Recording channels	48
Field filters	High cuts 500 Hz, Low cuts 25 Hz, Notch 60 Hz
Recording system	EG&G ES-2401
Sampling rate	0.5 ms
Trace length	1024 ms
Velocity info	Migration velocity 2000 m/s

LINE 5: The southernmost line

Parameter	Description
Source type	8-gauge Auger
Source array	1 shot per station
Source point interval	16.7 m (55 ft)
Geophone array	Three 40 Hz natural frequency geophones, 3 m in-line array
Geophone spacing	16.7 m (55 ft)
Recording channels	48
Field filters	High cuts 500 Hz, Low cuts 25 Hz, Notch 60 Hz
Recording system	EG&G ES-2401
Sampling rate	0.5 ms
Trace length	1024 ms
Velocity info	Migration velocity 1900 m/s

APPENDIX A

Introduction to the MiniSOSIE Recording Technique

The MiniSOSIE technique is an excellent approach to seismic reflection surveying in a noisy environment with lots of utility problems. The SOSIE technique was originally developed as a marine seismic source (Barbier and Viallix, 1973) and MiniSOSIE is its land adaptation. Most seismologists who see the technique in operation for the first time in the field don't immediately and intuitively understand how it can work, and we were also skeptical. Because MiniSOSIE is a relatively new (Barbier et al., 1976) and somewhat mysterious technique, we discuss it here. Understanding the MiniSOSIE method is important because of its unique application of fundamental geophysical principles and because it is a creative means of enhancing signal from a weak source. MiniSOSIE, or an adaptation of it, is a potential means of substantially improving shallow high resolution reflection seismology. Its weakness to date is related to limitations of the hardware that is licensed to use the method.

In the field, MiniSOSIE recording is done by summing signals from about 10 to 40 impacts per second from one or more civil engineering earth compactors known as Wackers (after the manufacturer of the most common earth compactors used). Typically, signals from 1000 to 2000 impacts are stacked at each shotpoint. The impacts are usually made along the seismic line over a linear segment equal to geophone group interval (i.e., a source array) rather than at a single point, and one to four Wackers are run simultaneously. Each Wacker has a transducer attached to its base plate and the transducer sends a time-break pulse by radio or wireline to the recording truck each time the Wacker base plate strikes the ground.

The mystery about MiniSOSIE is that typical seismic records are about one second in duration, while the time between successive Wacker impacts is of the order of one-tenth of a second or less. Intuitively we know that the signals from successive impacts should interfere in an unpredictable and possibly noisy, if not destructive, manner. The key to the MiniSOSIE technique is overcoming this intuitive difficulty by having the seismograph perform a simple processing step in the recording truck during recording.

Real-time processing is done according to the following scheme:

Signal from a single impact = (source)*(earth function)

Signal from multiple impacts = (single impact)*(source input time series)
= (source)*(earth function)*(source input time series)

Recorded signal = (source)*(earth function)*(ACF time series) (1)

where "source" is the shape of an impulse pulse of energy transmitted into the Earth by an earth compactor impact, "earth function" is the reflection coefficient series of the earth and varies with geology, "source input time series" is the function defining the impact pattern of the impulses, "ACF time series" is the auto-correlation function of the time series of impulses from the Wacker base plate, and * is the convolution operator. This compares with conventional techniques (i.e., dynamite) where

Recorded signal = (source)*(earth function) (2)

Note that if "ACF time series" in equation (1) is a spike (i.e., an impulse or Dirac delta function), the recorded signals, equations (1) and (2), will be the same. MiniSOSIE acknowledges the fact that the auto-correlation function of a "random time series" is a spike and that convolution with a spike is essentially multiplication by unity. In essence, this is why MiniSOSIE works. The "random time series" is generated by randomly varying the engine speed (and, hence, the impact rate) of the Wackers. Correlation of the "signal from multiple impacts" and the "source input time series" is performed by the seismograph using a real-time processing procedure using a 20-bit microprocessor. The results are MiniSOSIE field data, equation (1), that look very much like dynamic field data, equation (2). Except for the unique energy source and the auto-correlation processing during recording, MiniSOSIE seismic recording is identical to conventional dynamite recording.

MiniSOSIE surveys have provided good high-resolution results at depths between 100 and 1000 m in most localities (for example, Steeples et al., 1986; Miller et al., 1988). It is an especially good technique in areas of high ambient noise because most noise tends to cancel during the tens of seconds required to stack coherent signal from 1000 or more Wacker impacts. This is particularly true for random noise (i.e., traffic and wind), but is also true for any noise type that does not correlate with the source input function (i.e., 60 Hz highline hum). Because the source input function is random, it is unlikely that any ambient noise source would synchronize with it.

Theory

SOSIE is a fascinating concept which bridges the idea of an impulsive source with the ideas of an impulse-encoded source such as VIBROSEIS. SOSIE has typically been applied as a marine system, but MiniSOSIE is a land-based application of the technique used for shallow reflectors.

With typical impulsive sources the shot is set off once and the recorders listen for the duration of the record, stop and recycle for the next shot. With the SOSIE method an impulsive source is used, but rather than setting off one impulse and then listening, the impulsive source is set off in a continuous, but random, fashion and the listening phase continues for the duration of the source input function and a short time thereafter. For instance, at a single station the listening period might be several minutes rather than the few seconds required for a single impulse. In the time frame of several minutes a few thousand impulses can be put into the earth. The average impulse rate can be 30 to 40 impulses per second. (This is a limitation of the hardware currently being used for MiniSOSIE and does not represent any sort of theoretical limit.)

The final record section (of perhaps a half second in length) is obtained by cross correlating the input source function (random pattern) with the recorded seismogram. Several points:

(1) The recorded seismogram of several seconds is collapsed into a seismic trace of only a second or even a fraction of a second by the correlation procedure, and

(2) Although the source function, which goes off several times per second, would seem to interfere with the reflections being returned by earlier impulses, it does not because several thousand impulses are constructively reduced to one big impulse by the correlation process. Because the source impulses are random, the interference influence of one impulse becomes negligible. It is improbable that two or more interfering impulses will occur at the same time. The signal-to-noise ratio is therefore 60 dB for one thousand random impulses (theoretically).

The astute reader might worry that several minutes of record represents an oppressively long trace and that the correlation is consequently an awesome computer problem. With SOSIE and marine applications this is not the case because the ship is constantly in motion and recording is done on a continuous basis. The records are broken down into manageable sizes prior to correlation. Actual shot-point distribution is manufactured artificially after the data are recorded. For Mini-SOSIE the correlation process is accomplished on a real-time basis using computer RAM (random access memory) to accumulate the results and, in fact, a record length of 0.25 to 4 seconds is all that is ever produced and recorded to tape.

Discussing the method mathematically, if s(t) is the source impulse response and e(t) is the earth reflectivity series, then the seismogram that will be recorded from a single impulse will be:

$$x(t) = s(t)^{*}e(t).$$

This is the ideal seismogram to be obtained.

If y(t) is the source sequence function (ideally random) then over the course of several minutes of listening the seismogram will be:

$$x(t) = s(t)^{*}e(t)^{*}y(t).$$

Correlating x(t) with y(t) we get:

$$x(t) \oplus y(t) = s(t)^{*}e(t)^{*}y(t) \oplus y(t).$$

$$x'(t) = s(t)^{*}e(t)^{*}\mathrm{acf}[y(t)],$$

$$\mathrm{acf}[y(t)] = y(t) \oplus y(t).$$

Finally, if y(t) is truly random, then:

$$x'(t) = K\, s(t)^{*}e(t),$$

because then acf[y(t)] is an impulse (amplitude equal to K) at $t = 0$ and is everywhere else equal to zero. Random functions correlate only at time lags of zero, by definition. Neglecting the scaling constant K, the results are identical to the results from a single impulse.

After 1000 or more pops with a random source input function, the amplitudes of the primary reflections is substantially enhanced, and the amplitudes of the interfering reflections is not. Ideally, the primary reflectors might be 1000 times larger (60 dB) than the interfering signal. In practice, the enhancement is according to the square root of the number of pops, so that the correlation noise is -30 dB of the signal with 1000 pops. That is, the signal-to-noise ratio is 316:1. Uncorrelated noise, however, will also attenuate according to the square root of the number of pops (-30 dB/1000 pops) which when coupled with the signal enhancement of 30 dB/1000 pops means that signal-to-uncorrelated noise will be 60 dB or 1000:1. This is the ideal case. In practice, MiniSOSIE has other factors which add noise to the system and which will be discussed later.

One caveat of the stacking of 1000 to 2000 records needs to be mentioned here. If the seismograph doesn't have sufficient dynamic range to have *at least* the least significant bit set by reflection data once in a while, the method will not work. In other words, if part of the digital word of the stack is not made up of reflection information, the seismologist is out of luck.

The advantages of MiniSOSIE in a noisy environment should now be obvious. Uncorrelated noise tends to disappear when averaged over the several minutes that it takes to do a shotpoint, and the signal, although generated from a weak surface source, is rapidly enhanced. There are many examples of excellent MiniSOSIE data that were gathered in noisy settings such as down the median strips of busy interstate highways with traffic in progress, or through urban areas. One can sometimes even wonder if MiniSOSIE works better with extreme background noise! (There is no theoretical basis for this thought, but certainly, relative to other source types, MiniSOSIE does not tend to degrade under noisy conditions.) MiniSOSIE uses small non-damaging sources (assuming it misses the toes of the operator). Typically one-man earth compactors are used. Therefore, MiniSOSIE is clearly the best technique we know of for working with reflectors in the 0.2 to 1.0 range under noisy conditions or in an urban setting. (VIBROSEIS may have the same signal-to-noise advantages when a long sweep is employed, but it is not generally practiced for very shallow work.)

Disadvantages of MiniSOSIE are that correlation noise is in practice larger than theoretical expectations because truly random sources are not used and because the system does not function with theoretical perfection. Earth compactors have a tendency to run at a fixed rate of 8 to 12 pops/second and have a maximum rate of about 18-20 pops/second. Consequently, the "random" rate required is in fact distributed between about 4 to 18 pops/second. Using more than one source at a time increases randomness dramatically, however. If nothing else can be said about earth compactors, it is probably impossible to synchronize them! The MiniSOSIE system is limited to a certain maximum number of pops per second. This number is 46 pops/second as of this date and according to the specifications of the equipment that is licensed to do MiniSOSIE. The MiniSOSIE source is also inherently noisy, in part because the Wacker is a loud machine.

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Figure 1. Processing Flow

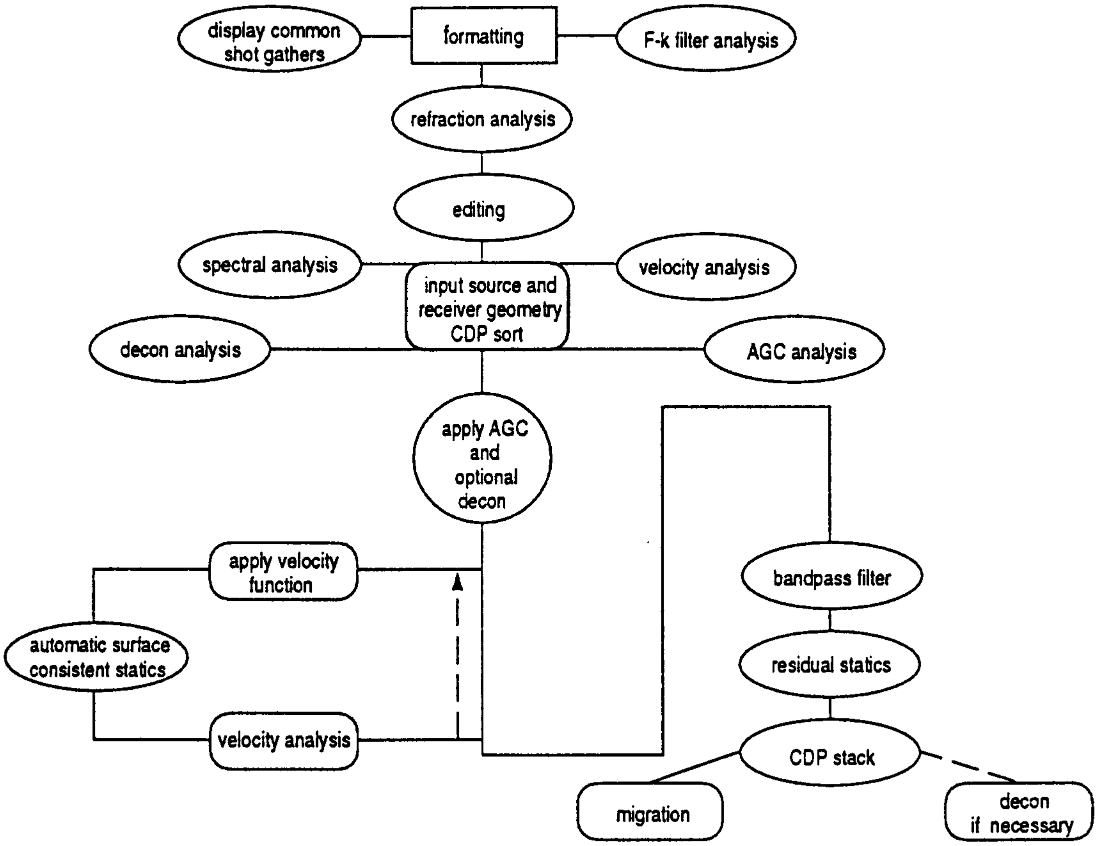

Figure 2. CDP processed section for Line 1.

Figure 3. CDP processed section for Line 2.

Figure 4. CDP processed section for Line 3.

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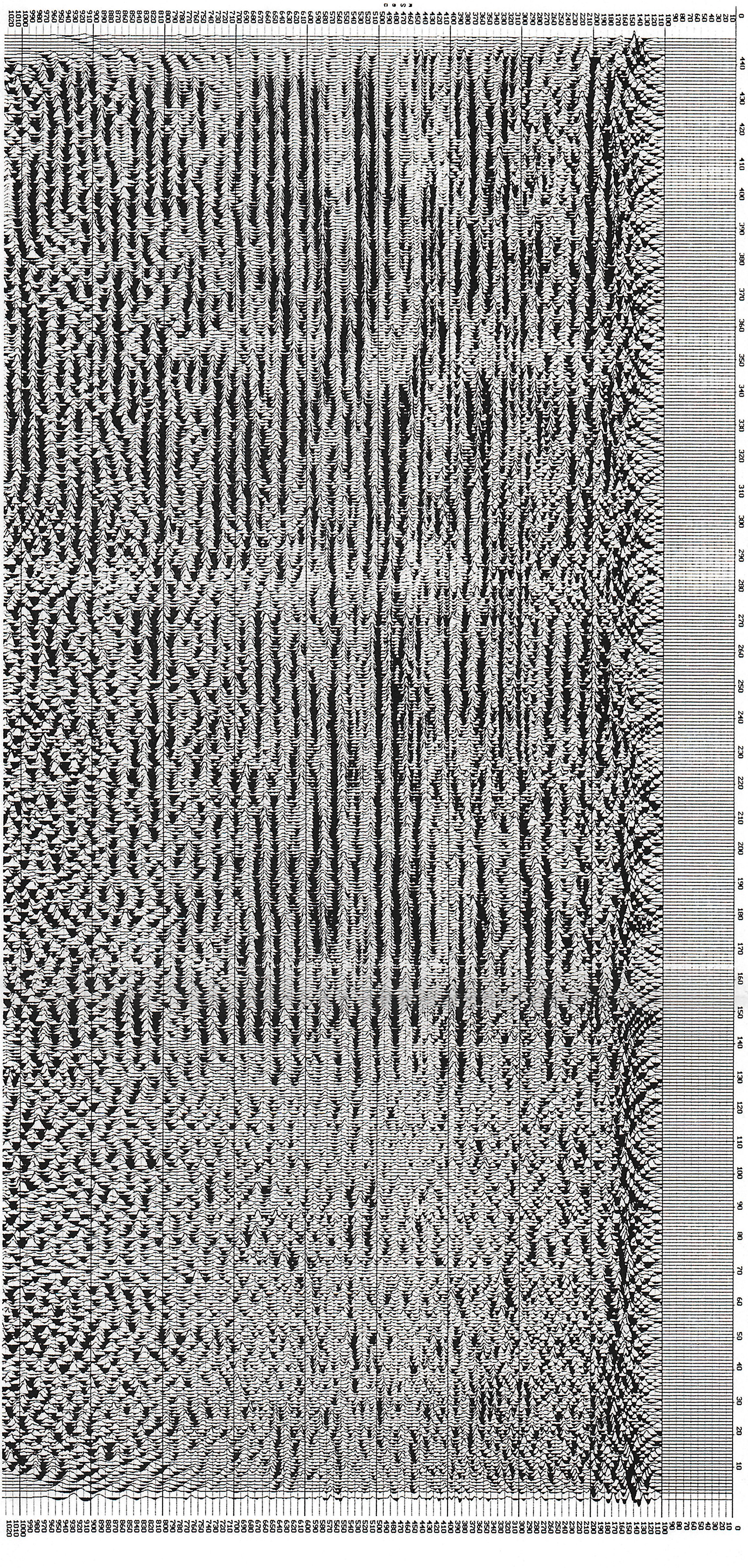

Figure 5. CDP processed section for Line 4.

Figure 6. CDP processed section for Line 5.