Phase II Geologic Characterization Data Acquisition

Task 2 Deep Seismic

Revised Final Report

U.S. Department of Energy
Rocky Flats Plant
Golden, Colorado

April 1993

EG&G Rocky Flats, Incorporated

ADMIN RECORD

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PHASE II GEOLOGIC CHARACTERIZATION DATA ACQUISITION
DEEP SEISMIC DATA ACQUISITION
FROM COAL CREEK CANYON TO GREAT WESTERN RESERVOIR

Revised Final Report

April, 1993

Prepared by

THE EBASCO TEAM

Ebasco Services Incorporated

Dames & Moore

Science Applications International Corporation

S.M. Stoller Corporation

Prepared for

EG&G ROCKY FLATS, INC.

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BY G. T. Ostdiek
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LIST OF ACRONYMS AND ABBREVIATIONS

ASI	Advanced Sciences Incorporated
bgs	Below ground surface
CDP	Common depth point
CSM	Colorado School of Mines
db	Decibel
EBASCO	Ebasco Services Incorporated
EG&G	EG&G Rocky Flats, Inc.
ft	Feet
g/cm^3	Grams per cubic centimeter
HR	High-Resolution
Hz	Hertz
ms	Millisecond
RFP	Rocky Flats Plant

EXECUTIVE SUMMARY

EG&G Rocky Flats, Inc. is performing remedial investigations, feasibility studies, and remedial/corrective actions at the Rocky Flats Plant under the U.S. Department of Energy's Environmental Restoration Program. As part of the Environmental Restoration Program, a seismic reflection survey was conducted to provide information on geologic structures and features between depths of 500 and 12,000 feet. The survey was conducted along one 11-mile line and was designed to cross a number of postulated faults. Gravity and magnetic data were also collected along the western portion of the seismic line by the Colorado School of Mines.

The processed seismic data reveal complex structures that are interpreted to be the result of compressional forces. A major thrust fault with approximately 5,000 feet of displacement originates in the Precambrian basement and cuts the sedimentary section from the Fountain Formation through the Niobrara Formation. Above the Niobrara Formation this fault turns parallel to bedding and becomes a sole thrust fault that produces a series of smaller imbricate thrust and backthrust faults. On the west end of the seismic line, two additional thrust faults moved older sedimentary rocks and Precambrian material to the east over younger sedimentary strata.

Post-acquisition seismic modeling was performed on the geologic interpretation of the seismic data. The modeled seismic response closely matched the deep seismic profile. Post-acquisition gravity modeling was also applied to the geologic interpretation. The modeled gravity responses matched the acquired gravity data on the west end of the seismic line with less than 1 percent error. Based on modeling, the geologic interpretation is valid.

1.0 INTRODUCTION

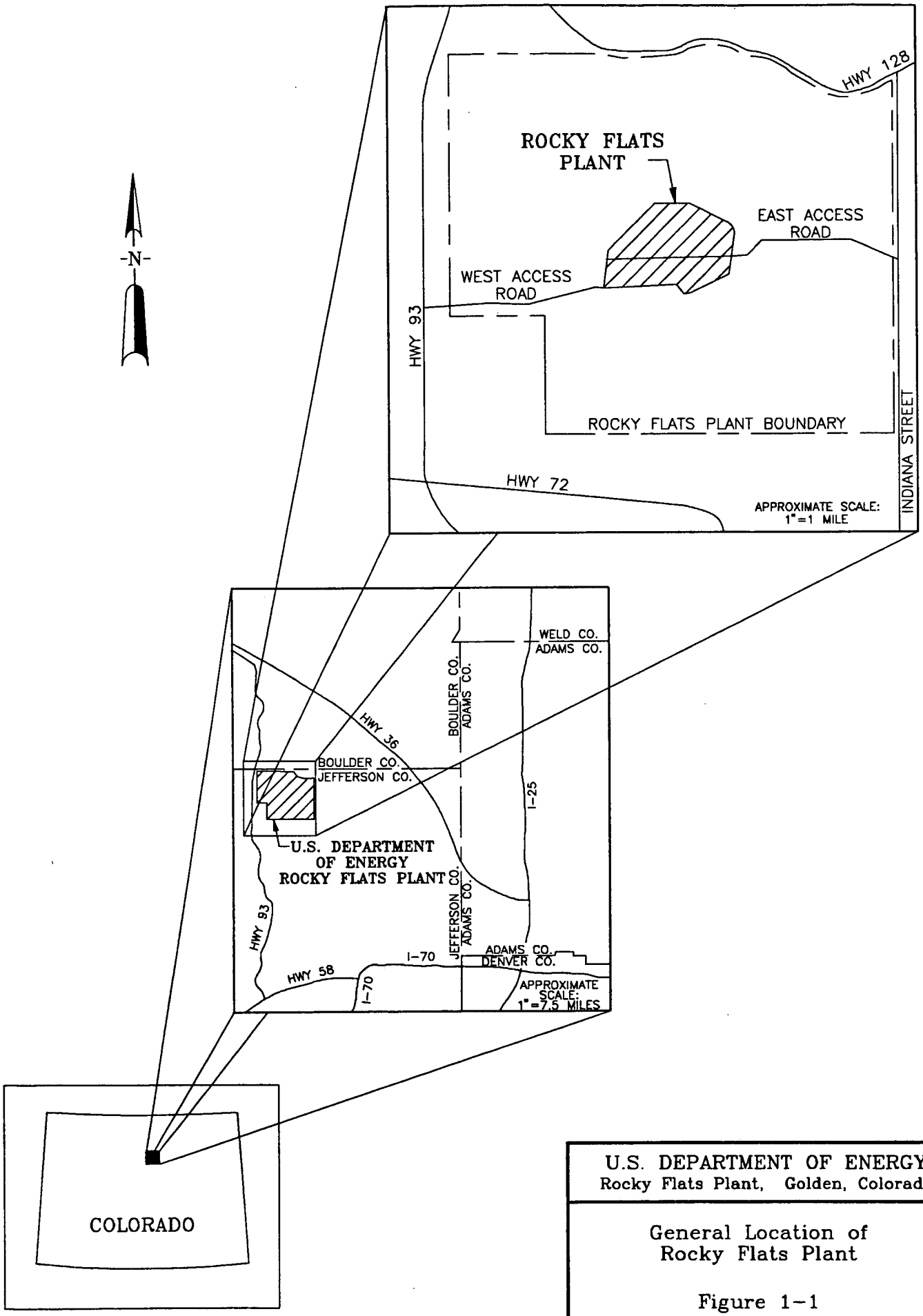
1.1 PURPOSE AND SCOPE

EG&G Rocky Flats, Inc. (EG&G) is performing remedial investigations, feasibility studies, and remedial/corrective actions at the Rocky Flats Plant (RFP) under the Department of Energy's Environmental Restoration Program. RFP is located approximately 11 miles northwest of Denver in northern Jefferson County, Colorado (Figure 1-1). RFP is close to known geologic structural features and faults that may provide conduits or act as barriers to vertical migration of contaminated groundwater into deeper aquifers. The proper remediation or monitoring of groundwater contamination depends on locating and delineating these features and faults in the RFP area.

EG&G is in the process of combining the deep seismic reflection data with the shallow high-resolution (HR) seismic reflection, geologic, and hydrogeologic data to complete the Phase II Geologic Characterization at RFP. The seismic program (Task 2 of the Phase II Geologic Characterization) involves acquiring, processing, and interpreting deep seismic reflection data. The objectives of the program are to identify major stratigraphic horizons, define subsurface structures, and determine the locations and types of faults near RFP. To satisfy these objectives, approximately 11 miles of deep seismic data were acquired from 3 miles west of the Livingston Fault in Coal Creek Canyon to 1 mile east of Great Western Reservoir (Figure 1-2). Two miles on the west end of the seismic line were acquired with a shothole dynamite source, and the rest of the seismic line was acquired with a vibrator source. Gravity and magnetic data were also collected along the western portion of the seismic line (station 1001 to station 1217) by Colorado School of Mines (CSM).

When complete, the geologic characterization will be used to accomplish the following:

- Resolve prominent hydrogeological problems (map geologic structure and stratigraphy)
- Provide hydrogeologic data for the design of efficient monitoring and correction systems
- Optimize boring and monitoring well placement



U.S. DEPARTMENT OF ENERGY
Rocky Flats Plant, Golden, Colorado

General Location of Rocky Flats Plant

Figure 1-1

- Select hydrostratigraphic units for future studies such as aquifer testing and water quality testing
- Evaluate the effectiveness of corrective action design options for the remediation of contamination

1.2 PREVIOUS SEISMIC INVESTIGATIONS

Several previous strudies have included seismic reflection data acquired at RFP. Different structural features have been defined by these studies. The following sections briefly summarize information from previous seismic investigations. Each subheading lists the author's name and the date the paper was published (see Section 7.0 for references). More information and maps can be found in the individual publications.

1.2.1 Davis (1976)

In late 1975 and early 1976, Rockwell International arranged for CSM to acquire approximately 13 miles of seismic reflection data on 11 seismic lines in the vicinity of RFP and Eggleston Reservoir. The data cover approximately 10 miles (eight seismic lines) on plant property and 3 miles (three seismic lines) near Eggleston Reservoir. Davis of CSM interpreted these data to represent two different types of fault systems. One fault system, located north of RFP, was interpreted to affect only the upper sediments and was thought to be depositional in nature (growth faulting). The second fault system was interpreted to consist of basement-controlled faults that placed RFP "on the stable, upthrown, horst block south of the graben area north of Highway 128." RFP was thought to be flanked 1 mile to the west by a north-south trending vertical basement-controlled fault that moved the west block up relative to the east. No faults were mapped on RFP property.

1.2.2 Davis and Weimer (1976)

The 13 miles of seismic data acquired by CSM at RFP (Davis 1976) were included in a study consisting of 250 total miles of seismic data. Davis and Weimer theorized the existence of Cretaceous growth faults in the Boulder-Weld Fault Zone. This theory was advanced in part

to explain abnormally thick Fox Hills section in the Boulder-Weld Fault Zone. However, it has recently been suggested that increased geologic section in the Upper Cretaceous rocks was due to repetition of the section by high angle reverse and decollement faulting (Kittleson 1992).

1.2.3 Davis and Young (1977)

The 13 miles of CSM data acquired at RFP (Davis 1976) were combined with 27 miles of reflection data acquired by CSM between Golden and RFP and 10 miles of data provided by Shell Oil Company to define the Laramide structure along the Rocky Mountain Front Range. Davis and Young interpreted the Golden Fault set as two near vertical convex-upward faults with combined displacement of approximately 8,000 feet (ft). The northern extent of this fault set was interpreted on a seismic line acquired parallel to Highway 72, south of RFP. This study also introduced the concept of the Basin Margin Fault Set, which consists of two and possibly three north-south trending vertical faults. The Basin Margin Fault Set was mapped west of RFP and parallel to Highway 93. Motion on these faults was interpreted to be down to the east.

1.2.4 Advanced Sciences Incorporated (1989)

In 1989, Ebasco Services Incorporated (EBASCO) was contracted by Advanced Science Incorporated (ASI) to reprocess the 13 miles of CSM seismic data acquired at RFP (Davis 1976) in an attempt to characterize the hydrogeology beneath the plant. Raw data for approximately 3 miles (two lines) of the original data were reprocessed. The remaining 10 miles of data were not reprocessed because raw data and field observer notes on the lines were not available. Reprocessing of the two lines revealed possible ramp thrusts in the Pierre Shale under RFP.

1.2.5 Shallow High-Resolution Seismic Reflection (Rockwell 1989; EG&G 1991; EG&G 1992a; EG&G 1993)

Approximately 3.7 miles of shallow HR seismic reflection data were acquired on the plant property to aid in the hydrologic characterization of RFP (Rockwell 1989; EG&G 1991; EG&G 1992a). EBASCO designed the HR seismic reflection survey to collect data at depths between approximately 25 ft and 500 ft. The HR seismic data were used to identify and map channel zones in the Arapahoe and Laramie Formations that could be potential conduits for groundwater flow and to identify potential geologic structures on some of the HR seismic lines. A structural fold was recognized in the West Spray Field, and three reverse faults were identified on the Indiana Street seismic lines (EG&G 1992; EG&G 1993)

2.0 GEOLOGY

RFP lies 4 miles east of the Rocky Mountain Front Range in the western portion of the Denver Basin. The Denver Basin contains more than 10,000 feet (ft) of Pennsylvanian to Upper Cretaceous sedimentary rocks that have been locally folded and faulted. Figure 2-1 shows a generalized stratigraphic section of the bedrock in the vicinity of RFP. Sedimentary bedrock is conformably overlain by Quaternary alluvial gravels. The seismic survey was designed to acquire data between depths of 500 to 12,000 ft, encompassing the stratigraphic section from the Laramie Formation to Precambrian basement. Seismic information was not collected on the alluvial material and uppermost Cretaceous rocks (at depths less than 500 ft); therefore, these units are not discussed in this report.

2.1 STRATIGRAPHY

The following discussion describes the geologic section along the deep seismic line (Figure 1-2). Descriptions are adapted from Romero (1976) and LeRoy and Weimer (1971) unless otherwise noted.

The Laramie Formation is Upper Cretaceous in age and is comprised of sandstones, siltstones, claystones, and coals deposited in fluvial-deltaic and lacustrine environments (Weimer 1973). The Laramie Formation can be subdivided into a lower (predominantly sandstone) unit with abundant thin coal seams and an upper (predominantly claystone) unit. Both of these units are exposed in outcrops west of RFP (Rockwell 1987). The Laramie Formation comformably overlies the Fox Hills Sandstone and is approximately 600 to 800 ft thick (EG&G 1992b).

The Upper Cretaceous Fox Hills Sandstone is approximately 90 to 140 ft thick (EG&G 1992b). The lower portion of the formation consists of sequences of sandy shale interbedded with thick layers of limey sandstone at its base. The upper portion of the formation consists of medium-bedded to massive, soft to medium-hard sandstone interbedded

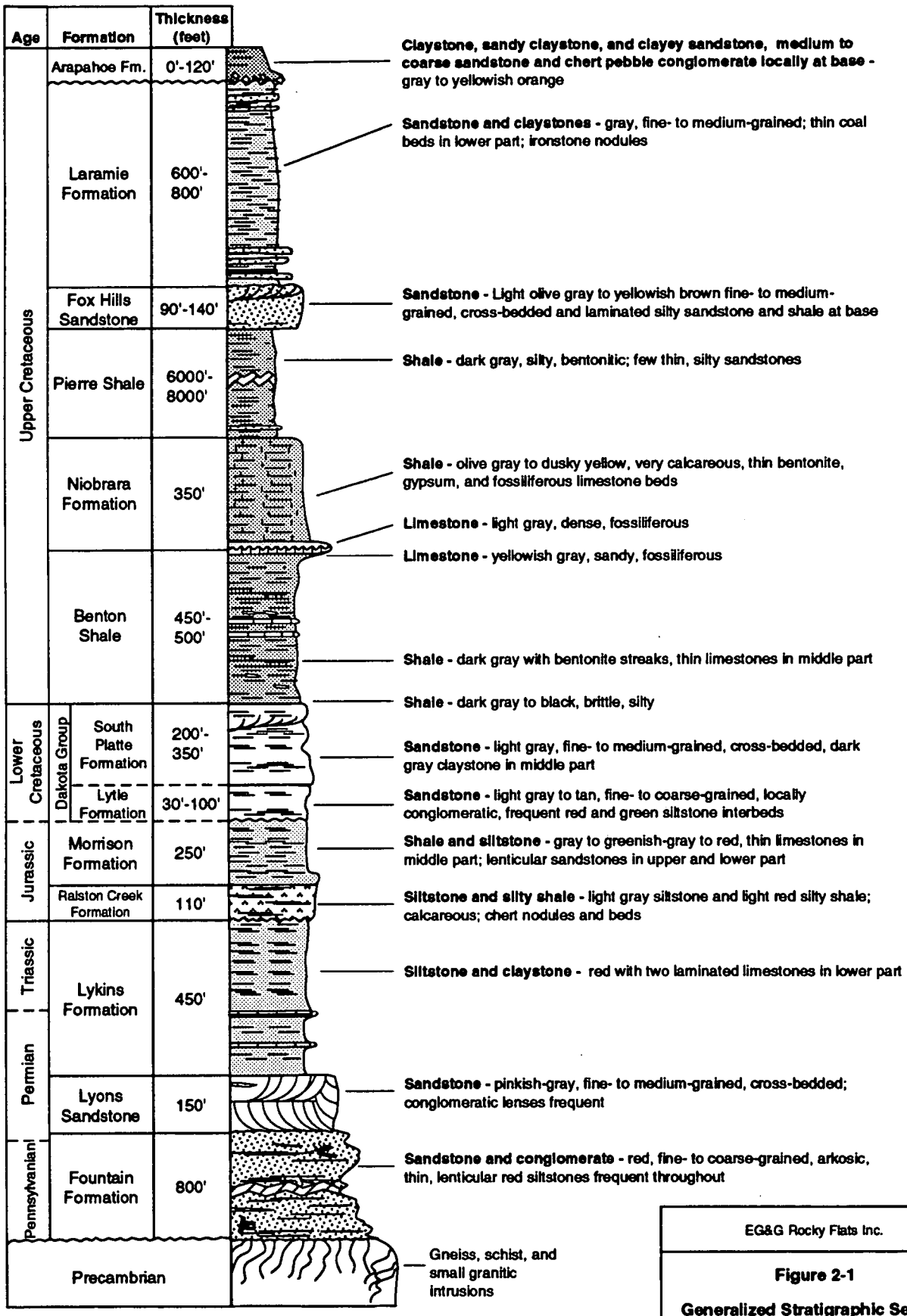


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Figure 2-1

Generalized Stratigraphic Section for the Rocky Flats Plant Vicinity

After LeRoy and Weimer 1971

with a few very thin layers of silty shale. The Fox Hills Sandstone exhibits a transitional contact with the underlying Pierre Shale.

The Cretaceous age Pierre Shale consists of 6,000 to 8,000 ft of clayey, marine shale. The lower portion of the formation is composed of massive to thin-bedded silty bentonitic claystone with a few very thin, noncalcareous siltstone beds. The upper portion of the formation is composed of thin-bedded to massive, silty, bentonitic shale with a few limestone concretions and thin, poorly cemented sandstone beds (Wells 1967). The Pierre Shale conformably overlies the Niobrara Formation.

The Upper Cretaceous Niobrara Formation is approximately 350 ft thick. The Fort Hayes Limestone Member comprises the lower portion of the Niobrara Formation and is composed of thick-bedded medium crystalline limestone with calcareous shale. The upper portion, the Smokey Hill Shale Member, is composed primarily of calcareous shale with a few thin beds of bentonite, gypsum, and limestone (Van Horn 1967; Wells 1967). The Niobrara Formation unconformably overlies the Benton Shale.

The Upper Cretaceous Benton Shale consists of a series of thin-bedded, fissile marine shales interbedded with bentonite and shaley limestone. The Benton Shale is approximately 450 to 500 ft thick and exhibits a transitional contact with the underlying Dakota Group.

The Lower Cretaceous Dakota Group is divided into two formations. The Lytle Formation occupies the lower 30 to 100 ft of the Dakota Group and is composed of lenticular, locally conglomeratic sandstone interbedded with claystone. The South Platte Formation overlies the Lytle Formation and ranges from 200 to 350 ft in thickness. The South Platte Formation is composed of fine-grained, locally ripple-marked sandstone interlayered with claystone and siltstone. The Dakota Group unconformably overlies the Morrison Formation.

The Morrison Formation is Jurassic in age. The base of this formation is marked by a light gray, cross-bedded, fine- to medium-grained sandstone that is 10 to 40 ft thick. The overlying sequence consists of claystones and mudstones interbedded with siltstones (Van Horn 1967). The thickness of the Morrison Formation is approximately 250 ft (EG&G 1992b). The Morrison Formation conformably overlies the Ralston Creek Formation.

The Jurassic Ralston Creek Formation is composed of limestone, shale, and thin beds of fine calcareous siltstone. The Ralston Creek Formation is approximately 110 ft thick and unconformably overlies the Lykins Formation.

The Permian and Triassic age Lykins Formation is predominantly thin-bedded shale and siltstone with minor sandstone and limestone beds. The Lykins Formation averages 450 ft in thickness and conformably overlies the Lyons Sandstone.

The Permian age Lyons Sandstone consists of fine- to medium-grained, thin-bedded to massive quartzose sandstone. The Lyons Sandstone is approximately 150 ft thick. Claystone, siltstone, and conglomerate interbeds occur in the upper 50 ft of the formation. The Lyons Sandstone unconformably overlies the Fountain Formation.

The Fountain Formation is approximately 800 ft thick and consists of cross-bedded, poorly sorted micaceous and arkosic sandstones and conglomerates. The upper 30 ft of the Fountain Formation contains a few lenticular beds of fine-grained, cross-bedded, quartzose sandstone that resemble beds in the overlying Lyons Sandstone (EG&G 1992b). The Pennsylvanian and Permian age Fountain Formation unconformably overlies the Precambrian basement complex.

The Precambrian basement complex contains both igneous and metamorphic rocks and consists primarily of microcline gneiss with varying amounts of amphibolite, hornblende gneiss, and schistose rocks with occasional pegmatite dikes.

2.2 SURFACE GEOLOGY

The deep seismic program was designed to help resolve the subsurface stratigraphy and structure and to identify faults from 3 miles west of the Livingston Fault to 1 mile east of Great Western Reservoir. Figure 1-2 is a geologic map showing the location of the seismic line. This geologic map was assembled using the following five sources:

- Sheridan et al. (1958) mapped bedrock geology of the Ralston Buttes Quadrangle.
- Spencer (1961) mapped bedrock geology of the Louisville Quadrangle.
- Wells (1967) mapped surficial geology of the Eldorado Springs Quadrangle.
- Van Horn (1972) mapped surficial and bedrock geology of the Golden Quadrangle.
- EG&G (1992b) mapped surficial and bedrock geology of RFP and the vicinity

Some of the bedrock contacts shown on the map are not continuous. Unmapped bedrock contacts covered by alluvium have been inferred for projection onto the seismic profile.

2.3 GEOLOGIC STRUCTURE

RFP is close to known geologic faults and shear zones; however, neither the presence nor the extent of faulting at RFP has been conclusively determined. The Idaho Springs-Ralston Shear Zone extends from between Georgetown and Idaho Springs, Colorado to the mouth of Coal Creek Canyon (Sheridan et al. 1967). The structural history of this zone is long and complex, with deformation beginning in the Precambrian. This ancient structural system is highly mineralized and comprises a major part of the Colorado mineral belt. North of the Idaho Springs-Ralston Shear Zone is the northwest-southeast trending Livingston Fault. The Livingston Fault is one of the largest faults in the region, with approximately 5,000 ft of strike slip movement and 2,300 ft of vertical displacement. It is postulated to be a continuation of the Golden Fault (Wells 1967). Approximately 5 miles north of RFP is the Boulder-Weld Fault Zone. This zone consists of a series of faults trending northeast-southwest. Spencer (1961) mapped the Boulder-Weld Fault Zone as a series of horsts and grabens. Weimer (1973) and Davis and Weimer (1976) attributed the faulting in this area to Upper Cretaceous growth faulting in a deltaic environment. A more recent study by Kittleson (1992) interpreted the fault zone to be a product of high-angle reverse and decollement

faulting. Kittleson (1992) speculated that the Boulder-Weld Fault Zone could extend southwest beneath RFP. Seismic lines acquired by CSM that were recently reprocessed show thrust faulting in the Pierre Shale under RFP (ASI 1989). The deep seismic line was designed to determine whether faults extend beneath the plant site.

3.0 SEISMIC REFLECTION

Seismic reflection profiling consists of producing an acoustic wave that propagates through the earth and recording the waves that are reflected back to the surface from subsurface rock layers and fault planes. A seismograph records the acoustic vibrations detected by geophones. Using the common depth point (CDP) method of seismic reflection profiling, lithologic beds and structural features (e.g., folds and faults) can be identified and mapped. Appendix I presents seismic reflection techniques, including the CDP method.

To develop a seismic program that would meet the data objectives (identify major stratigraphic horizons and characterize the subsurface structure and the locations and types of faults near RFP), seismic reflection modeling, a noise analysis test and a vibrator source test were performed prior to data acquisition.

3.1 PRE-ACQUISITION SEISMIC MODELING

The purpose of conducting seismic reflection modeling was to optimize seismic data acquisition parameters and techniques by identifying possible acquisition, processing, or interpretation problems before acquiring actual field data. Steps used in the seismic reflection modeling process were as follows:

1. Construct a geologic cross section showing the geology anticipated in the area of proposed seismic data acquisition.

2. Estimate the physical properties of the subsurface lithology.

3. Simulate the collection of the seismic reflection data across the geologic cross section using various field parameters.

4. Determine any parameters that need to be tested in the field to ensure optimum results.

5. Identify potential problems regarding data acquisition and processing (i.e., steeply dipping geologic beds and fault planes) and recommend possible solutions.

Source and receiver spacing, data frequency content, and noise content were varied in the model until the most effective data acquisition parameters were determined.

Figure 3-1 shows the digitized geologic cross section used for the seismic reflection modeling. This cross section was constructed using surficial geologic data collected along the proposed seismic line and using a cross section of Coal Creek Canyon published by Boos and Boos (1957). Velocities used in the modeling were estimated from a sonic log. The U.S. Army Corps of Engineers Rocky Mountain Arsenal Well #1 P. I. D. W. located in NW NE Section 26, Township 2 South, Range 67 West was used because this well penetrated the Precambrian basement rocks and has the most complete sonic log of any well in the RFP vicinity.

Surficial geology at the mouth of Coal Creek Canyon near the seismic line indicates faulting and vertical and overturned beds. One objective of this seismic program was to image beds dipping as much as 50 to 60 degrees. Seismic modeling tested the ability of seismic reflection to image steeply dipping beds and fault planes. The synthetic seismic section of the model (Figure 3-2) illustrates that beds dipping greater than 70 degrees are difficult to image. Figure 3-2 shows that very few reflections from the upper faulted block exist due to the extreme dips. Three different receiver intervals were modeled: 55-ft, 110-ft, and 220-ft. Horizons dipping greater than 70 degrees were not imaged using a 220-ft receiver interval, but were marginally imaged using the 55-ft and 110-ft receiver intervals. The horizons dipping less than 70 degrees were imaged best with 55-ft and 110-ft receiver intervals. A 110-ft receiver interval was chosen for the seismic field program because modeling indicated this interval would be able to image dipping beds as well as deep reflectors.

Seismic modeling indicated that individual horizons could be distinguished at frequencies as low as 50 hertz (Hz). Field testing of the vibrator source later showed that 120 Hz was the maximum frequency of signal that could be generated. A 2 millisecond (ms) sample rate was chosen because it allows recording of this frequency. Appendix I presents a more detailed discussion on the modeling performed.

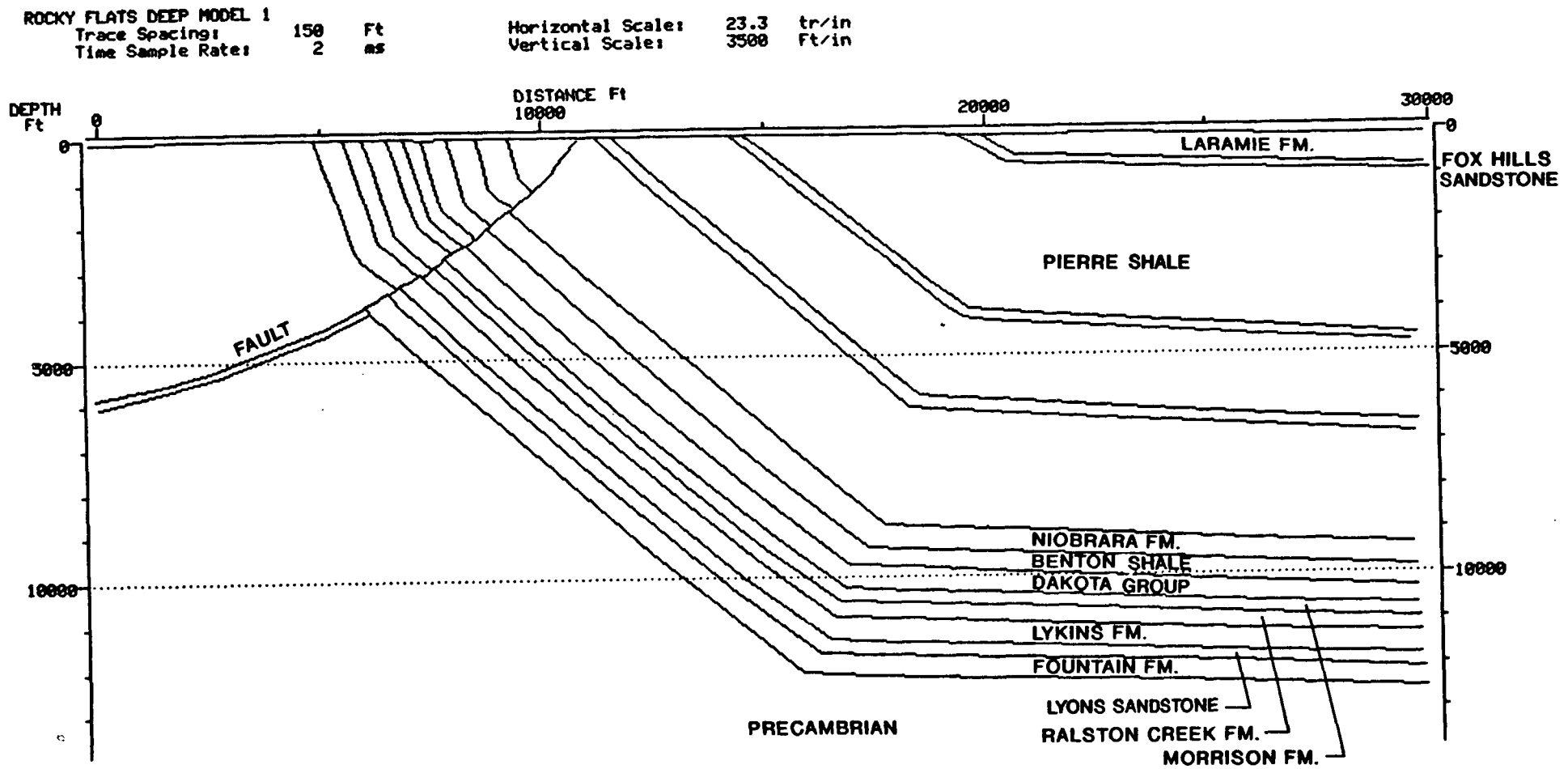

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Figure 3-1
Digitized Geologic Model

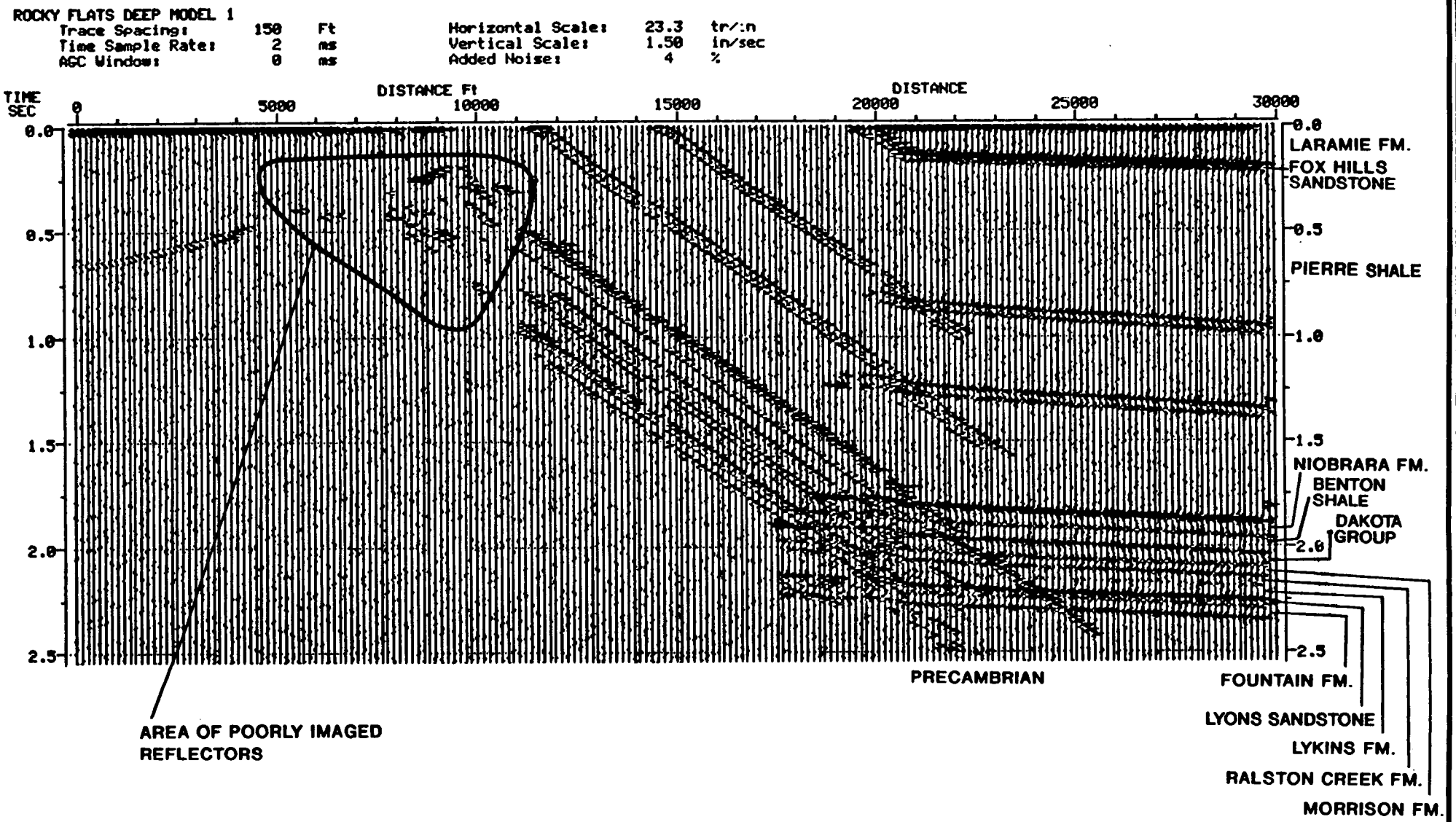

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Figure 3-2
Synthetic Seismic Section
Using A 10/20-60/80 Hz Wavelet

3.2 FIELD TESTS

Prior to seismic data acquisition, some of the parameters determined by modeling were field tested. Two tests were conducted: a noise analysis test and a vibrator source test.

In seismic reflection surveying, surface waves represent unwanted events. To minimize the effects of surface waves on seismic data, a noise analysis test, often called a "walkaway" is performed. A walkaway consists of activating the seismic source and recording the vibrations detected by a spread of geophones. The walkaway field records are analyzed to identify the velocities, frequencies, and amplitudes of any surface waves. Knowing the characteristics of the surface waves, the geophysicist modifies recording parameters, such as the near offset (distance from a source point to the closest geophone station), seismograph filter settings, and source and receiver arrays, that will help cancel out surface waves.

A vibrator source test was also performed to determine the synchronicity between vibrators, vibrator sweep frequencies, length of each vibrator sweep, and number of vibrator sweeps per source point. Appendix II presents the results of these tests.

3.3 FIELD PROCEDURES AND DATA ACQUISITION

In August 1991, approximately 11 miles of deep seismic reflection data were acquired. Figure 3-3 shows the location of the deep seismic line in relation to the reprocessed CSM seismic lines and the shallow HR seismic reflection lines. The depth range for deep seismic data resolution was 500 to 12,000 ft below ground surface. Data acquisition consisted of activating the seismic source (dynamite or vibrator), detecting the reflected energy with a spread of geophones, and recording the energy with a seismograph.

A dynamite source was used for the 2 miles of rough terrain in Coal Creek Canyon. Shot hole drilling and data acquisition on this portion of the seismic line required helicopter support for the movement of equipment and supplies. There were approximately 48 shot holes i.e., one shot hole per source point. Each shot hole was approximately 50 ft deep, and

less than 10 pounds of dynamite were loaded down hole. Figure 3-4 presents the dynamite source array configuration.

For the remaining 9 miles of seismic line that were relatively flat, truck-mounted vibrators were used. Vibrators are relatively inexpensive sources that allow for quick data acquisition and cause minimal damage to the environment. When several vibrators are used in a source array, they cancel undesired source-generated surface waves. Figure 3-5 shows how the vibrator source array was configured.

The seismograph used for the seismic survey was a Geosource MDS-10. The seismograph was configured for 120 channels per spread at a 2 ms sample rate and had a string of geophones connected to each channel. Mark LRS-1000 geophones were used to minimize the low-frequency, source-generated surface waves. The geophone string was laid out on the ground in an array that enhanced reflected energy from the subsurface and canceled undesired source-generated surface waves (Figure 3-6). The parameters (Table 3-1) of the geophone array were determined from field tests. Based on modeling of the anticipated geologic structure (50 to 60 degree dips) and desired depths of interest, a 110-ft geophone station interval was used. A 110-ft station interval was necessary to properly record reflections from steeply dipping beds. With a 110-ft station interval and a 120-channel recording system, the resulting geophone spread was 13,200 ft long, which was sufficient to record reflectors as deep as 12,000 ft below the surface.

As shooting progressed forward the spread geometry was maintained by using a roll-along switch. As the source points advance forward, the roll-along switch activates channels at the front of the spread and deactivates channels at the rear of the spread.

To enhance the reflection data, a shooting sequence was designed to provide CDP data along the spread (see Appendix I for an explanation of the CDP technique). For this program, a

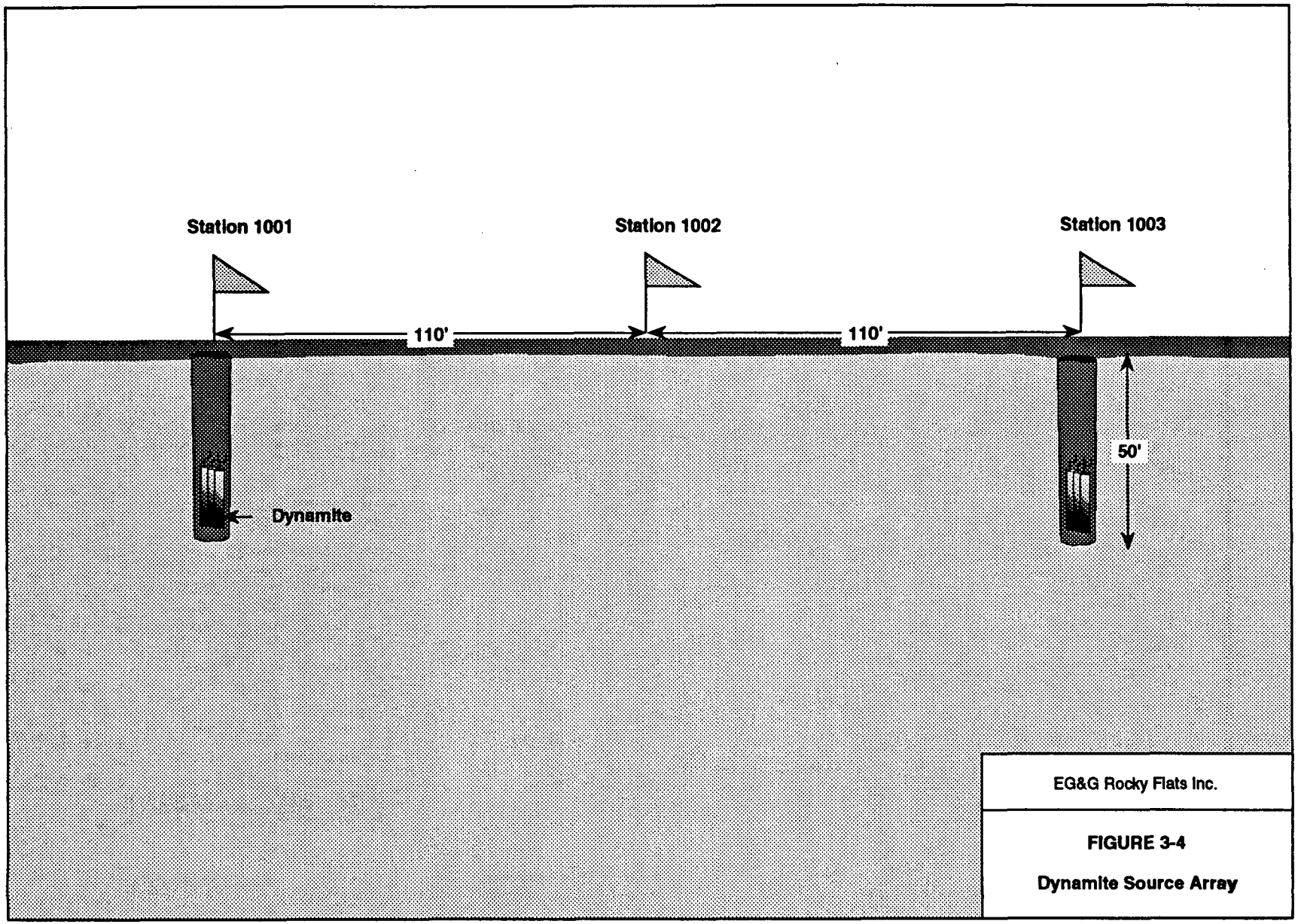

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FIGURE 3-4

Dynamite Source Array

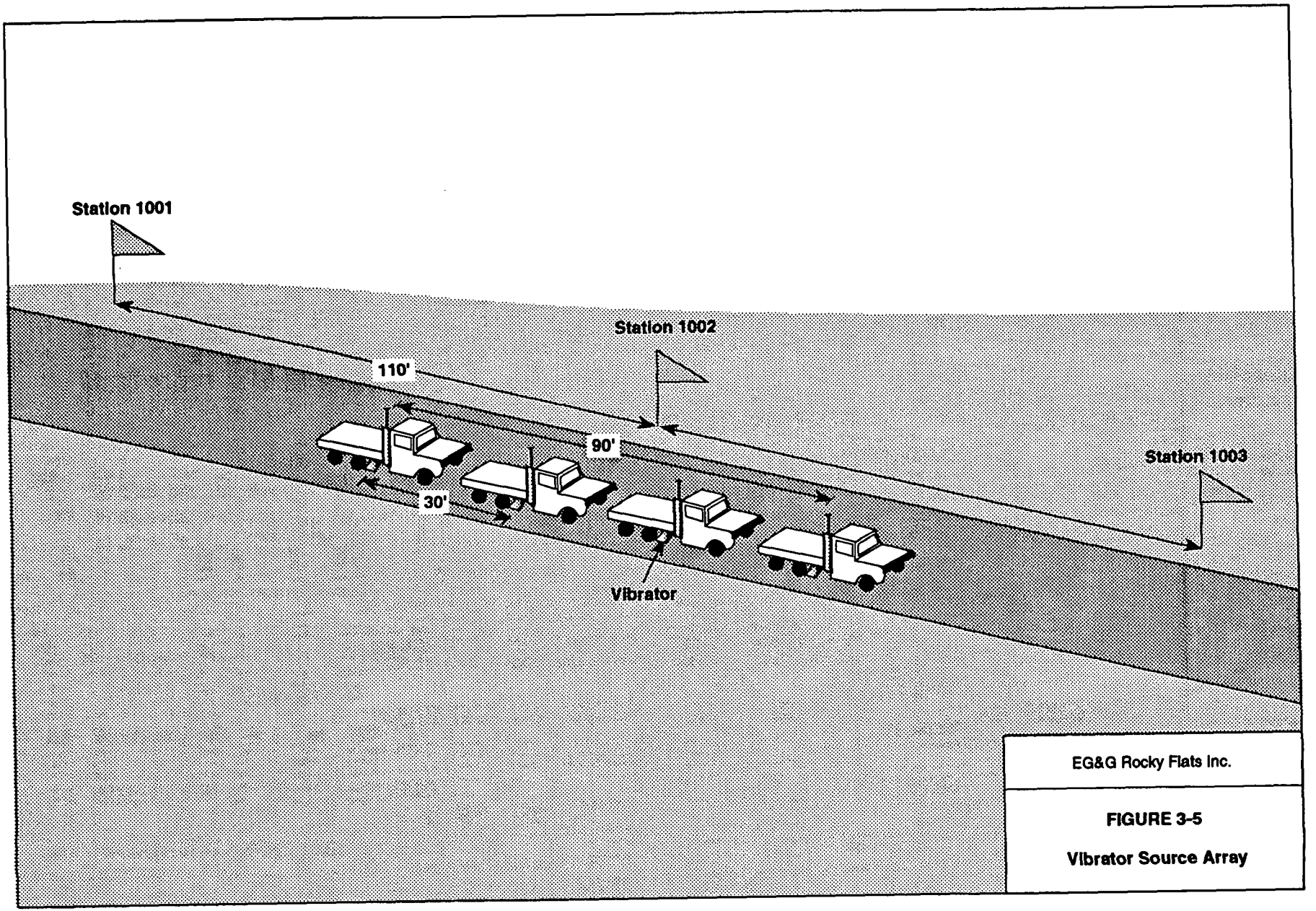

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FIGURE 3-5

Vibrator Source Array

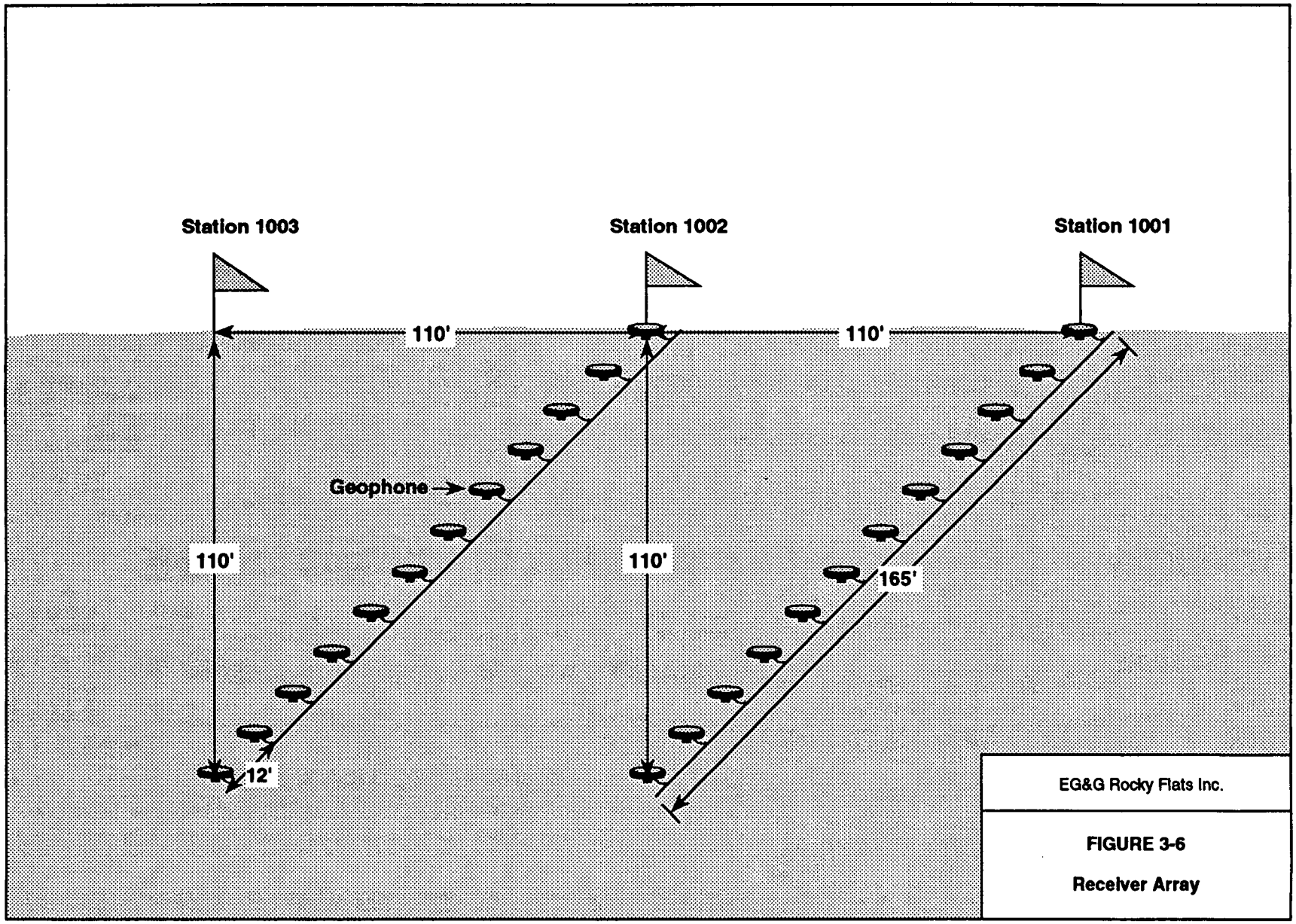

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FIGURE 3-6

Receiver Array

Table 3-1 Data Acquisition Parameters for the Seismic Survey

Geophone Station Spacing	110 ft
Source Spacing	220 ft
Geophones per Station	12
Geophone Frequency	28 Hz
Spread Length	13,540 ft
Far Offset	9,020 ft
Cable Geometry	unbalanced split spread
Number of Recording Channels	120
Sample Rate	2 ms
Field Record Length	16 seconds
Vibroseis Correlation Record Length	4 seconds
Low Cut Filter	12 Hz
Low Cut Filter Slope	18 db/octave
Alias Filter	125 Hz
Alias Filter Slope	72 db/octave
Notch Filter	60 Hz
CDP Fold	30
Number of Vibrators per Source Point	4
Number of Sweeps per Source Point	10
Sweep Frequencies	10 Hz ---> 120 Hz
Sweep Length	12 seconds
Shothole Depth	50 ft
Pounds of Dynamite per Shothole	< 10 pounds

db decibel
ft foot
Hz Hertz
ms milliseconds

spread of 120 geophone stations was used; every other geophone station served as a source point. The resulting CDP coverage for each geophone station was 30 fold.

All reflection seismic data were recorded to a 9-track computer tape in SEG B format (SEG 1980). Field tapes and survey data were sent to the seismic data processing center at the end of data acquisition.

3.4 DATA PROCESSING

The basic objective of all seismic data processing is to convert the data recorded in the field into a form that can be used for geological interpretation. This conversion process consists of several steps. One of these steps eliminates or reduces all noise (i.e., energy not associated with primary reflections, especially energy that interferes with primary reflections). This step in data processing is known as filtering. Closely associated with filtering is signal enhancement, which involves increasing the frequency bandwidth and amplitudes of the primary reflections. Another step, known as migration, presents the reflections on the seismic profile in the proper geometrical relationship to each other. Seismic data are displayed in time; a computer process called depth conversion converts seismic data from time to depth using stacking velocities. The depths calculated are approximate because the velocities used are estimates of the interval acoustic velocities of the geologic horizons.

Figure 3-7 shows a general processing sequence. The processing sequence used for the deep seismic line included a variety of computer programs that are designed to enhance data presentation. These programs have many functions including adding signal gain; adding static and velocity functions; editing, reducing, and removing unwanted noise; enhancing signal frequency content; sorting data traces into CDP format; migrating the data to its proper geometric location; and scaling the data for presentation. Appendix III describes the processing sequence used for the deep seismic program.

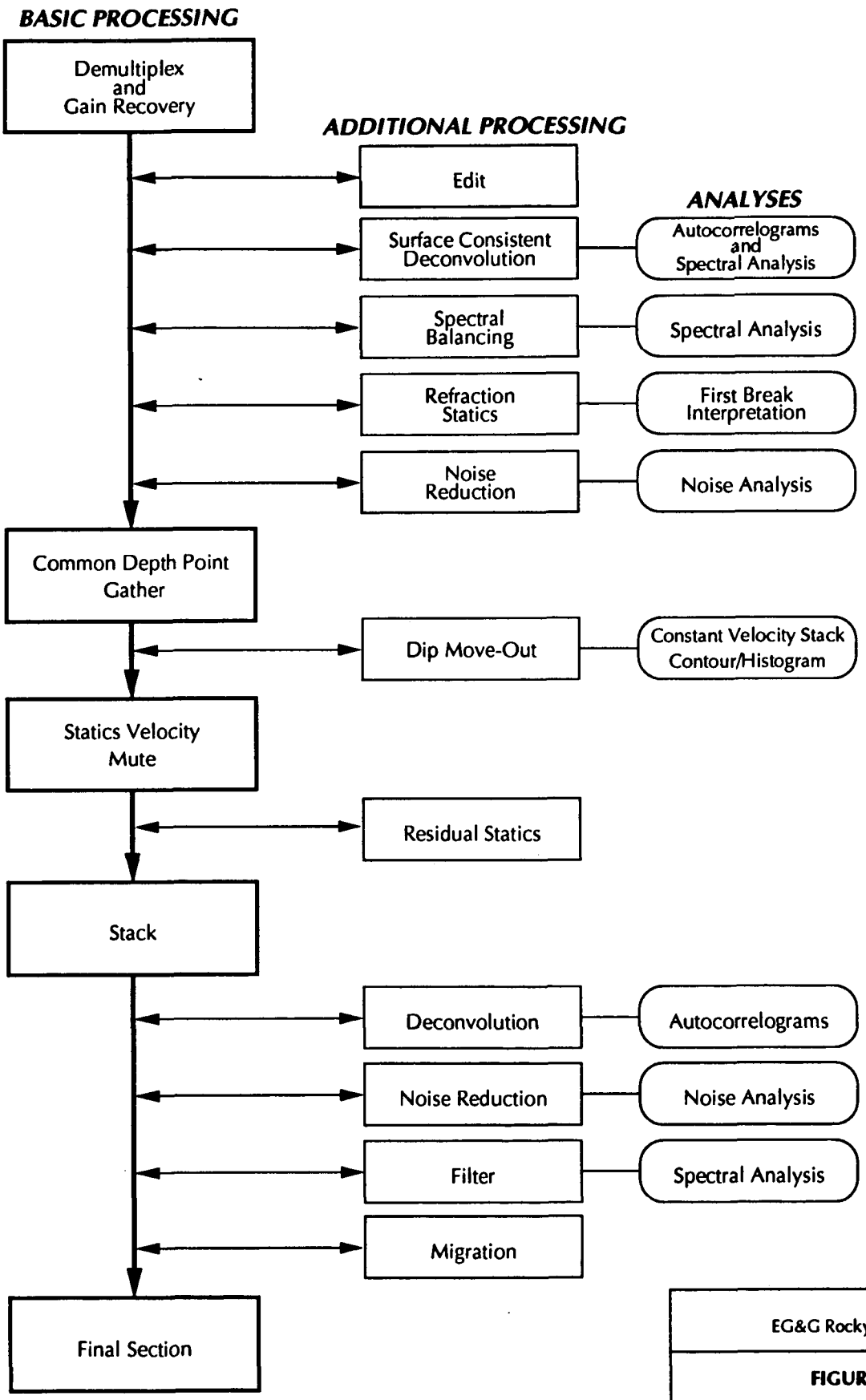

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FIGURE 3-7

SEISMIC DATA PROCESSING ROUTINES

After Sheriff, 1984

Computer processing flow decisions were made by the processing geophysicist after consultation with the project geophysicist at various steps to ensure and improve data quality. The end result of the data processing operation was the generation of a two-dimensional seismic profile representing a geologic cross section through the earth.

4.0 DATA INTERPRETATION

Seismic data interpretation is a complex process that involves relating seismic events on a profile to geologic units and structure. Deep well data, one tie line (CSM Line 5), and surface geology (i.e., strike, dip, and lithology of outcrops) were correlated to the deep seismic data to identify subsurface geologic horizons on the deep seismic profile.

Approximate depths to geologic horizons can be estimated on a seismic profile using borehole lithologic logs. The interpretation can be enhanced if sonic logs, which provide velocities necessary to convert time to depth, are available. Sonic logs are also used to make synthetic seismograms that correlate geologic horizons directly to the seismic profile. Only two sonic logs exist for this part of the Denver Basin. These logs are from the following boreholes:

- U.S. Army Corps of Engineers
  Rocky Mountain Arsenal #1 P. I. D. W.
  NW NE Section 26, Township 2 South, Range 67 West
  Approximately 15 miles east of the deep seismic line

- Tom Jordan
  #1 Sam Rudd
  SE NE Section 22, Township 1 South, Range 70 West
  Approximately 3-1/2 miles north of the deep seismic line

In addition, an induction log was used to create a pseudosonic log. This log was from the following borehole:

- Teton Energy
  26-1 Teton Superior
  NE NE Section 26, Township 1 South, Range 70 West
  Approximately 2-1/2 miles north of the deep seismic line

Synthetic seismograms were constructed for each of the sonic logs and the pseudosonic log. The synthetic seismograms were correlated to the deep seismic line (RFD-1). Individual seismic reflection events correlated well. Regional stratigraphic thickening and thinning is evident between the borehole locations and the seismic line. Thicknesses between reflection

events were different on the synthetic seismograms and the profile due to lateral thickness changes.

The deep seismic reflection data were also correlated with seismic line CSM-5. Figure 4-1 shows how line CSM-5 ties with the deep seismic line. The time scales on the two lines are different because the seismic datum on the deep seismic line is at a higher elevation. The two lines correlate well. Reflections from the Pierre Shale correlate from line to line as does the package of reflections representing the Niobrara Formation to the Dakota Group. The higher frequency content of the deep seismic line data results in more reflections than on the line CSM-5.

Figure 1-2 presents the deep seismic line location. The seismic line crosses Colorado Highway 93 at stations 1219. RFP lies south of the line between stations 1296 and 1351. The seismic line crosses Indiana Street at station 1421. Great Western Reservoir is south of the line between station 1432 and 1465. The western edge of the deep seismic line begins just south of the Idaho Springs-Ralston Shear Zone. At station 1115, the deep seismic line crosses the western branch of the Livingston Fault. Located between station 1115 and 1142 are a series of overturned Paleozoic and Mesozoic sediments that comprise the geologic section from the Fountain Formation to the Niobrara Formation. At station 1142, the inferred eastern branch of the Livingston Fault is projected to emerge at the surface. Spencer (1961) mapped the probable location of this fault and suggested that it connected the Livingston Fault with the Golden Fault. From station 1142 to 1243, the Pierre Shale is mapped at the surface. From station 1243 to 1245, the Fox Hills Sandstone is projected to subcrop beneath the alluvium. From station 1245 to the end of the seismic line at station 1515, the Laramie and Arapahoe Formations form bedrock.

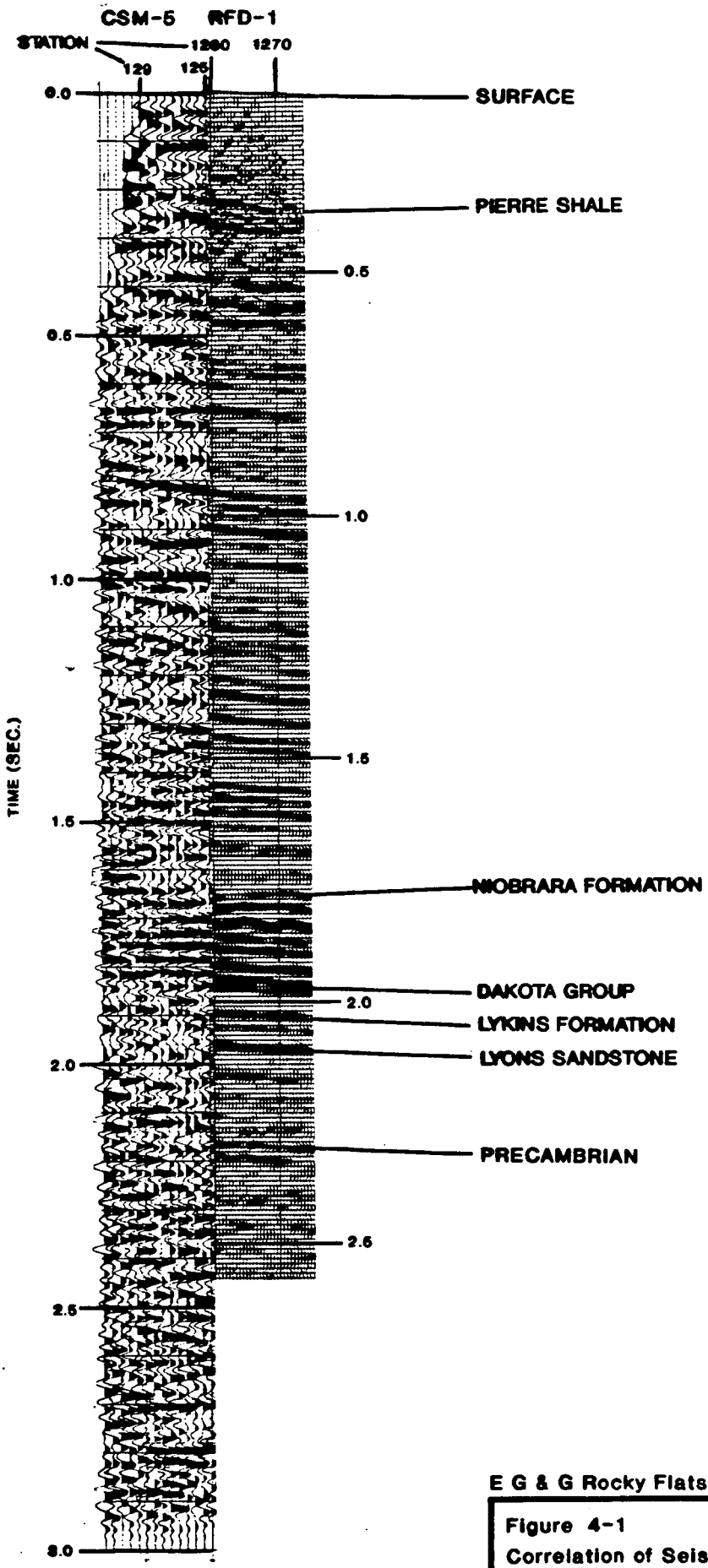

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Figure 4-1
Correlation of Seismic Line RFD-1 to Seismic Line CSM-5

The acquisition parameters were designed to collect seismic data between 500 and 12,000 ft below ground surface (bgs). Seismic data outside of this depth range are not of sufficient quality nor are they of sufficient quantity to allow for an accurate geologic interpretation. Specifically, the location and nature of shallow faulting cannot be determined.

Seismic profiles are displayed in reference to a seismic datum, which is an arbitrary reference elevation usually beneath the weathering layer. Appendix I provides a discussion of the seismic datum. A time scale is presented on the side of each seismic profile.

Because seismic data are recorded in time, the approximate depth to a seismic event is computed using estimated seismic velocities. Seismic velocities were used to covert the tops of geologic horizons from time bgs to depth bgs. Because the velocities are estimated, and actual seismic velocities vary both laterally and vertically, these depths are only approximate.

4.1 DEEP SEISMIC LINE RFD-1

Plate 1 shows the interpreted seismic profile for line RFD-1. Major stratigraphic horizons are identified on the seismic profile in addition to major structural features. The time scale represents the time it takes for energy from the source to reflect off acoustic boundaries and return to the geophones. Dashed isopleths on the seismic profile represent levels of equal depth. Generally seismic velocities are higher on the west end of the profile, causing the equal depth lines to become shallower on the time profile.

The east portion of the seismic profile (between stations 1260 and 1513) is characterized by generally flat reflections between 0.3 and 2.4 seconds. On this portion of the line, the Laramie Formation reflections occur between 0.3 and 0.43 seconds (0 to 800 ft bgs), the Fox Hills Sandstone reflections occur between 0.43 and 0.46 seconds (800 to 900 ft bgs), and the Pierre Shale reflections occur between 0.46 and 1.9 seconds (900 to 8,400 ft bgs). The Niobrara Formation and Benton Shale are characterized by a high-amplitude positive reflection at 1.9 seconds (8,400 ft bgs), and by three to four smaller reflections to 2.01

seconds (9,000 ft bgs). The Dakota Group and Morrison Formation are characterized by a high-amplitude positive reflection at 2.01 seconds (9,000 ft bgs) followed by a generally flat response (indicating little acoustic contrast). The Lykins Formation, Lyons Sandstone, and Fountain Formation are characterized by generally low-amplitude reflections, which also indicates little acoustic contrast. The high-amplitude Precambrian basement reflection occurs at 2.4 seconds (12,300 ft bgs) on the east side of the seismic line.

Figure 4-2 shows the geologic interpretation of the deep seismic profile. The interpretation was developed using the seismic data. The structural features shown on the interpretation are the product of compressional forces and crustal shortening that probably occurred during the Laramide Orogeny. Similar type features have been described to the north of RFP by Erslev et al. (1988). Figure 4-2 shows a complex set of thrust faults and back thrust faults that are described below.

4.2 THRUST FAULT 1

Thrust Fault 1 originates in the Precambrian basement, cuts the sedimentary section from the Fountain Formation to just above the Niobrara Formation, and turns into a bedding plane sole thrust fault in the base of the Pierre Shale. Estimated displacement along Thrust Fault 1 is approximately 5,000 ft at the Niobrara horizon. The sole thrust fault loses slip to the east by a series of blind imbricate thrust faults in the fashion described by Boyer and Elliot (1982). The blind imbricate thrust faults originate on the sole thrust fault and extend up through the Pierre Shale. Displacements on the imbricate thrust faults are on the order of 150 to 200 ft in the lower Pierre Shale. Although displacement on the faults decreases near the top of the Pierre Shale, the upper extent of these fault is unknown. Back-thrust faults occasionally occur in association with the imbricate thrust faults. The sole thrust fault in the base of the Pierre Shale and additional small imbricate thrust faults probably continue out into the basin beyond the eastern extent of the seismic line.

Between the Precambrian Basement/Fountain Formation contact and the claypits (near the West Spray Field) the sedimentary section dips to the east at approximately 45 degrees. In addition to slipping along Thrust Fault 1, the sedimentary section has been hinged up by a wedge of Precambrian material. The wedging of Precambrian basement material may have produced a back-thrust fault parallel to bedding above the Precambrian wedge.

4.3 THRUST FAULTS 2 AND 3

Thrust Fault 2 was interpreted on RFD-1 based on surface geology and subtle seismic features. It is inferred to come to surface between the Dakota Formation outcrop and the Fox Hills Sandstone outcrop south of Coal Creek Canyon. North of Coal Creek Canyon, the Pierre Shale section is approximately 8,000 ft in thickness and appears to be complete. South of the canyon, the mapped Pierre Shale section diminishes from approximately 8,000 ft near the canyon entrance to a few hundred feet near North Table Mountain. Thrust Fault 2 has thrust the section from the Precambrian through the Lower Cretaceous over the dipping Pierre Shale.

Thrust Fault 3 appears to truncate the Paleozoic section at the base of the Fountain Formation at station 1113. Wells (1967) suggested the location of this fault when he mapped the Eldorado Springs Quadrangle. This thrust fault moved Precambrian material to the east over the Paleozoic section, giving the map view appearance of a truncated Paleozoic section.

It was suggested by Wells (1976) that the presence of these faults indicate the connection of the Livingston Fault to the Golden Fault. Based on the deep seismic line, the displacement on Thrust Faults 2 and 3 are much less than either the Livingston Fault or the Golden Fault. It is possible that Thrust Faults 2 and 3 are smaller imbricate thrusts off of Thrust Fault 1.

4.4 OTHER FEATURES

No evidence of the Basin Margin Fault Set or the Golden Fault Set as described by Davis and Young (1977) can be found on the deep seismic line. Davis and Young introduced the

concept of the Basin Margin Fault Set. Movement along these faults was interpreted to be down to the basin with displacements varying from a few hundreds of feet at the basement to a few tens of feet near the surface. The basin margin faults were interpreted to exist approximately 1 mile west of RFP and parallel to Highway 93 (Davis and Young 1977). The Golden Fault Set just south of RFP was interpreted to be a convex upward fault system with up to 8,000 ft of displacement. Convex upward faulting is not apparent on the deep seismic profile, although the profile does show a low angle thrust with approximately 5,000 ft of displacement.

Growth faults were proposed by Davis and Weimer (1976) as an alternative method of producing the structural features observed to the north of RFP in the Boulder-Weld Fault Zone. No growth faults are seen in the Upper Cretaceous section of the deep seismic line RFD-1.

Kittleson (1992) suggests the decollement faulting in the Boulder-Weld Fault Zone was produced by gravity sliding, i.e., sediments were redeposited in response to Laramie uplift. The deep seismic line indicates that reverse offset in the Upper Cretaceous section is due to thrusting directly associated with the Laramide Orogeny. The thrust faulting observed in the Upper Cretaceous on the deep seismic line shows displacements similar to those described in the Boulder-Weld Fault Zone (approximately 150 to 200 ft). It is possible that the decollement faulting Kittleson observed in the Boulder-Weld Fault Zone was also produced by thrust faulting and not by gravity sliding.

4.5 POST-ACQUISITION SEISMIC MODELING

A simplified version of the geologic cross section (Figure 4-2) was digitized and a synthetic seismic section created. Figure 4-3 shows the digitized geologic cross section and Figure 4-4 the synthetic seismic section. The synthetic seismic section is similar to the unmigrated seismic profile, indicating that the geologic interpretation fits the seismic data. The most obvious similarities are a velocity pull-up under the dipping reflectors, the discontinuous

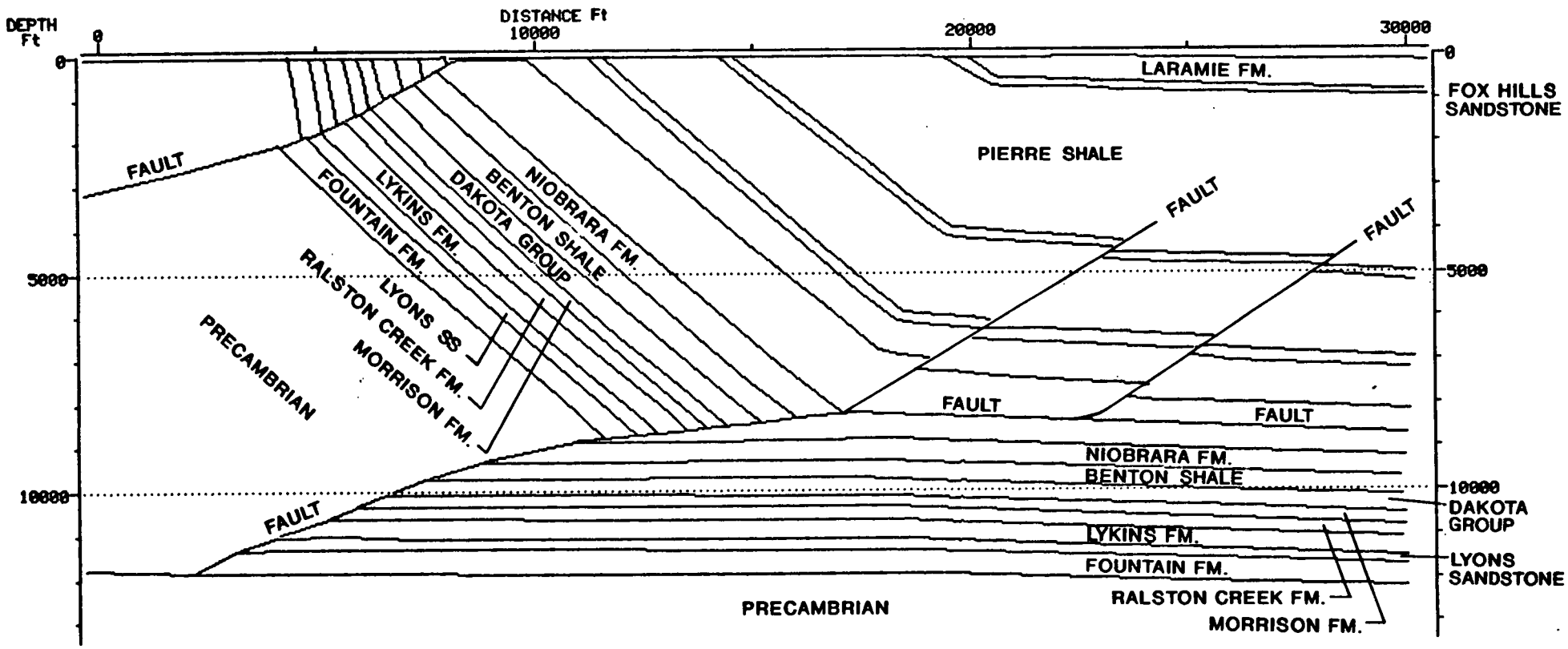

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Figure 4-3
Digitized Computer Model
of Interpreted Geology

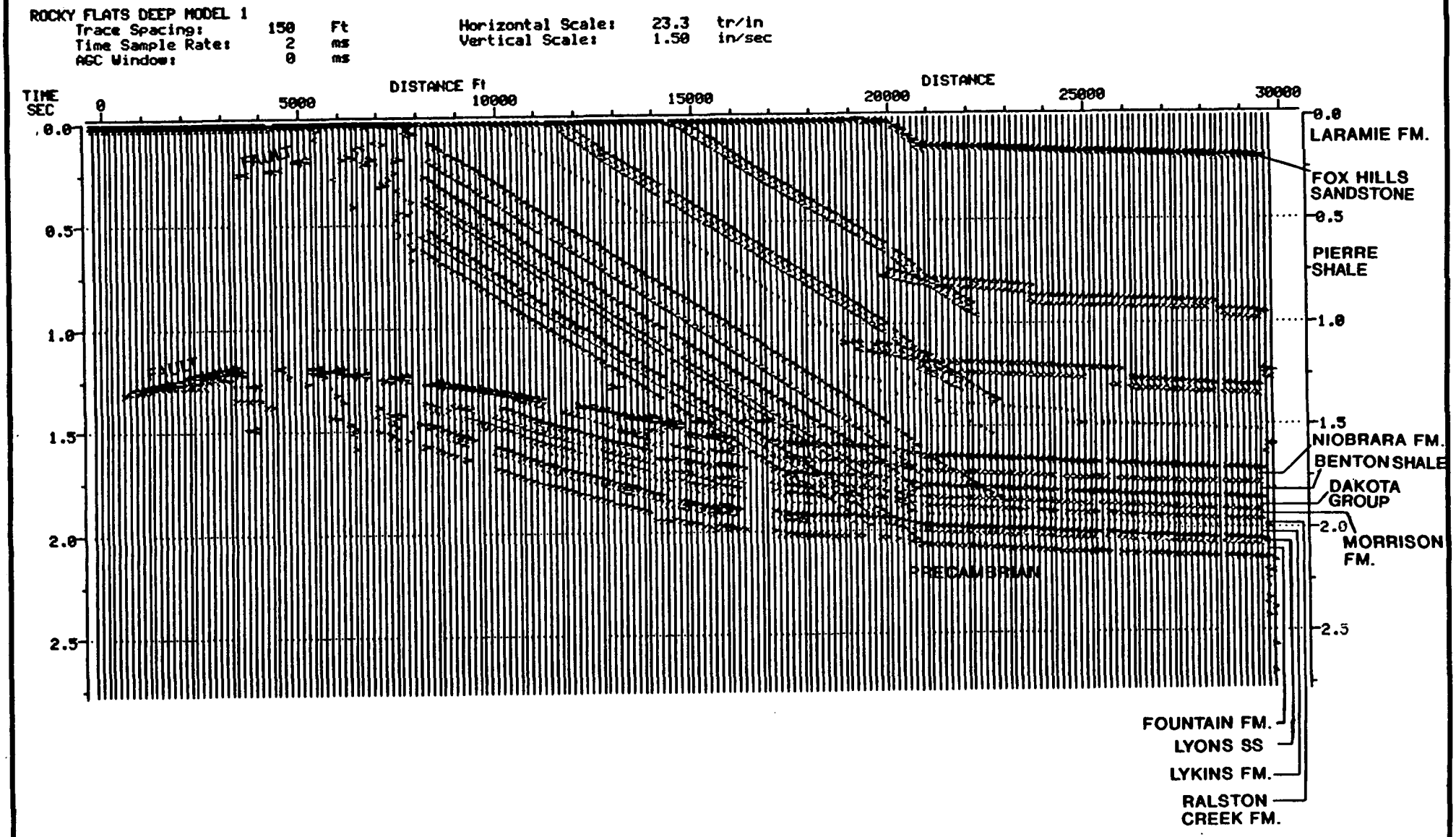

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Figure 4-4
Synthetic Seismic Section of Interpreted Geology

nature of the reflectors in the velocity pull-up zone, and the inability to image steeply dipping and overturned beds near the surface on the west end of the profile. The velocity pull-up occurs on the reflections from the Niobrara Formation through the Precambrian horizons underneath the thrusted wedge of Precambrian material and tilted sedimentary rocks. These pulled up reflections occur between 1.2 and 2.0 seconds (0 to 0.5 seconds or 4,000 and 8,000 ft on the synthetic section shown on Figure 4-4, 0.1 and 0.6 seconds and between stations 1110 and 1140 on line RFD-1 unmigrated seismic profile).

4.6 GRAVITY DATA

Gravity data were collected and processed by CSM along seismic line RFD-1 to assist in the interpretation of the seismic line. These data were collected from stations 1001 (western end of RFD-1) through 1217 (at Colorado Highway 93). Appendix IV presents the raw and reduced gravity data. It is beneficial to acquire and integrate gravity data with seismic data since gravity data provide information on lateral contrasts in density and since density is directly related to the propagation velocity of seismic waves.

A gravity model was constructed using the gravity data acquired along the deep seismic line. The objective of the gravity modeling was to delineate the large-scale structural regime along the deep seismic line. The gravity data were modeled using a widely accepted and efficient two-dimensional forward modeling algorithm that is based on the work of Talwani (Talwani, 1959).

In general, a two-dimensional gravity model represents the earth as a cross section containing discrete geologic units. Each geologic unit is characterized by a density distribution, and the geometry of each unit is assumed to extend perpendicular to the direction of the gravity profile to plus and minus infinity.

Forward modeling is the technique of generating a reasonable geologic model of the subsurface geology that is consistent with the geologic data available in the area (e.g.,

seismic, borehole density logs). The model is improved by adjusting model parameters such as the density distribution and shape for selected geologic units and comparing the calculated gravity response for that particular model to the measured (or actual) gravity data. The end result is a model that realistically portrays the geologic units, their structural and stratigraphic features, and their corresponding density distributions.

A geological interpretation should not be based on gravity data alone. As is the case in most gravity modeling, the calculated response for an unlimited number of different geologic models may adequately fit the measured gravity data. This inherent property of the gravitational field is known as "nonuniqueness." Because of the nonuniqueness of the gravitational field, the interpreter of the data must rely on independent subsurface information such as seismic data and borehole density logs to reduce the ambiguity of the interpretation. The accuracy and reliability of the final gravity model is often directly proportional to the amount and quality of independent subsurface information and the proper incorporation of this information into the gravity model.

The structural and stratigraphic data used in the gravity model were obtained from the deep seismic line. These seismic data are a reliable indicator of subsurface geology from stations 1116 to 1217. Due to the lack of continuous reflectors, the structure within the Precambrian is difficult to determine using the seismic data from station 1116 westward. The geologic control for this portion of the seismic line was inferred by analyzing the United States Geological Survey surficial geology maps of the Ralston Buttes and Eldorado Springs Quadrangles (Sheridan et al. 1958; Wells 1967). In addition, the horizontal derivative of the gravity profile was computed. The horizontal derivative is an effective tool for delineating contacts between adjacent materials that possess different density distributions.

The densities for the sedimentary geologic units comprising the gravity model were acquired from borehole density logs in the immediate area of the gravity profile. Specifically, the following wells were analyzed for density information:

- Teton Energy, # 1 Cowdery Moore (NW SE Section 18, Township 1 South, Range 69 West)
- Teton Energy, # 1 Rocky Mountain Fuel (NW SW Section 24, Township 1 South, Range 70 West)
- Teton Energy, # 18-2 Minks (SW NW Section 18, Township 1 South, Range 69 West)

The densities for the igneous and metamorphic rocks comprising the gravity model were selected from Dobrin (1988), and Telford et al., (1976).

Figure 4-5 shows the observed and calculated gravity response for the model. The calculated gravity response corresponds with the observed gravity data; however, there are specific regions in the Precambrian rocks where the observed gravity data deviate from the calculated model curve. These regions are most likely representative of intrusive activities that have created intense alteration or deformation (i.e., fracturing and faulting) of the surrounding geologic materials.

For example, the geologic unit mapped on the surface between stations 1038 and 1043 is a microline quartz-epidote granulite schist. This metamorphic unit is an intrusive, and the presence of the mineral epidote may indicate that a relatively high degree of metamorphism occurred. In general, the deposition of minerals with high densities, such as epidote (grain density 3.3 to 3.6 grams per cubic centimeter), may account for some of the increased gravity response in this area, as well as other similar areas in the Precambrian rocks.

There are also isolated areas in the Precambrian rocks that exhibit low values of gravity at a single gravity station or that extend along the profile for a few gravity stations. These distinct gravity "lows" are most likely related to intense local faulting and fracturing of the rocks.

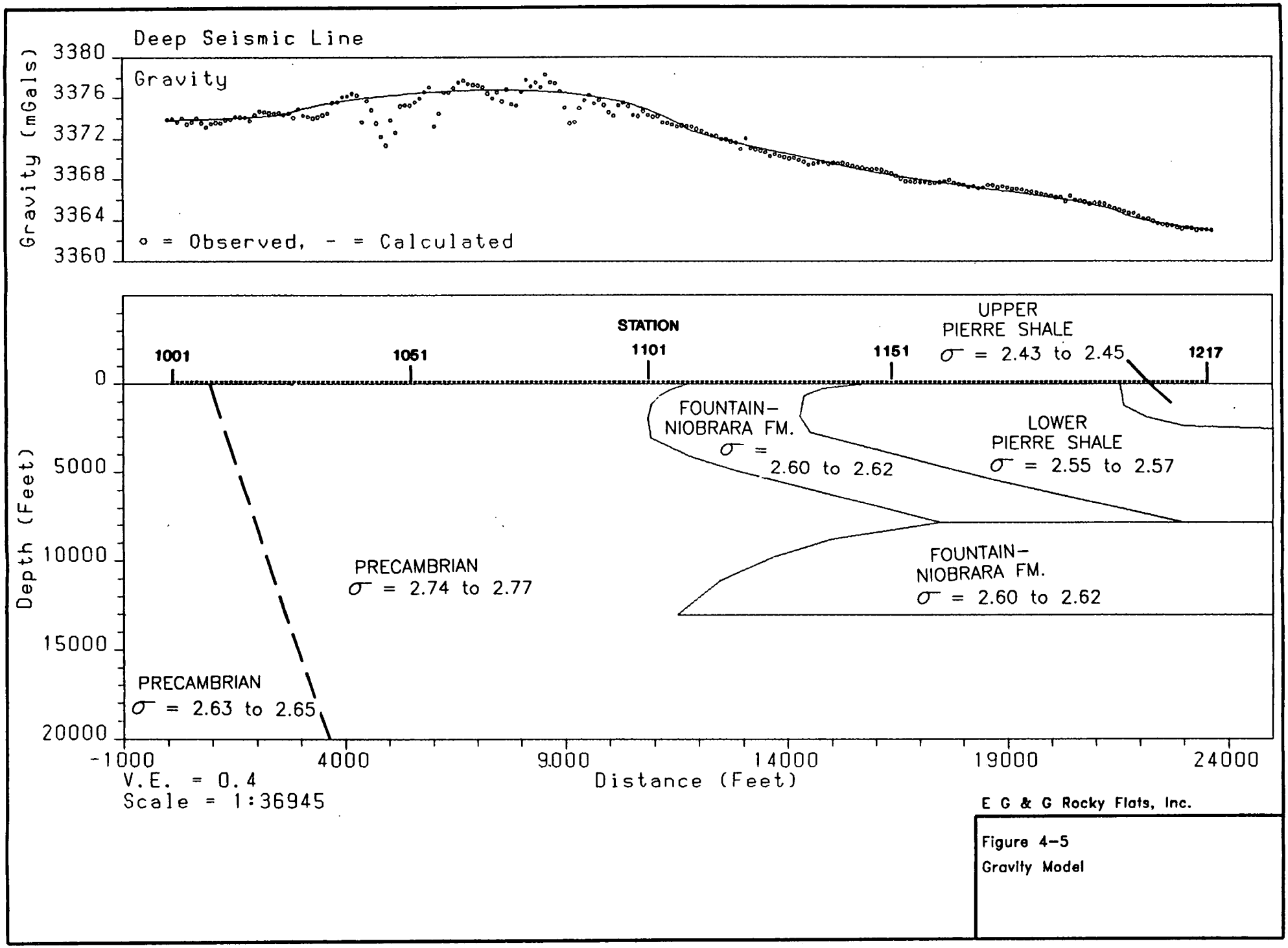

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Figure 4-5
Gravity Model

The objective the gravity modeling was to produce a simple, two-dimensional model of the large-scale geological features along the deep seismic line. Localized areas in the Precambrian rocks that are characterized by large changes in the amplitude of the gravity field over small horizontal distances (i.e., high-frequency anomalies) were not accurately modeled at this time; however, they can be incorporated into the model in the future if there is a necessity. The analysis of the high-frequency anomalies can provide useful information such as the maximum depth for isolated intrusive sources, for the geologic model.

The modeled gravity response matches the acquired gravity data with a calculated error of less than one percent (Figure 4-5). This indicates that the modeled geologic interpretation fits the measured gravity data.

4.7 MAGNETIC DATA

Magnetic data were collected and processed by CSM from stations 1001 (western end of RFD-1) through 1217 (at Colorado Highway 93) (see Appendix IV). As seen from Figure IV-1 in Appendix IV, the magnetic profile is similar in character, with a few exceptions, to the gravity profile. The difference in character between the gravity and magnetic profile may be related to ferrous cultural features that are proximate to the magnetic data acquisition stations.

The magnetic data were analyzed in an attempt to provide knowledge on the depth to some of the intrusive sources in the Precambrian rocks. A useful technique for estimating the depth to intrusive sources is the Werner method, which utilizes magnetic data and computes the depth to intrusive sources for simplistic geologic models. The Werner technique indicates that the maximum depth to the top of many of the intrusive sources is less than several hundred feet. This conclusion is in agreement with the high-frequency content of the gravity data in the Precambrian rocks and the presence of several faults that are indicated on the geologic quadrangle map.

5.0 CONCLUSIONS

Under Task 2 of Phase II of the Geologic Characterization, approximately 11 miles of deep seismic reflection data were acquired, processed, and interpreted. To ensure quality data, seismic modeling was performed prior to acquisition. The results of modeling determined that a 110-ft receiver interval would be able to image beds dipping up to 70 degrees and image deep reflectors, and that beds dipping at an angle greater than 70 degrees would be difficult to image.

The complex structure shown on the deep seismic line is interpreted to be the product of compressional forces during the Laramide Orogeny. Three major thrust faults are shown on the line. Thrust Fault 1 originates in the Precambrian basement and cuts upward through the sedimentary section from the Fountain Formation to just above the Niobrara Formation. Displacement on this thrust fault is approximately 5,000 ft at the Niobrara Formation. In the Pierre Shale, this fault slides along bedding planes and becomes a sole thrust fault. The sole thrust fault loses slip to the east in a series of imbricate thrust faults. Displacements on the imbricate thrust faults are approximately 150 to 200 ft. The sole thrust fault probably continues eastward into the basin beyond the eastern end of the seismic line.

Thrust Faults 2 and 3 occur above the sole thrust fault. Thrust Fault 2 thrust the section from the Precambrian through the Lower Cretaceous over the dipping Pierre Shale. Thrust Fault 3 moved Precambrian material to the east over the Fountain Formation. It is possible that Thrust Faults 2 and 3 are smaller imbricate thrusts associated with Thrust Fault 1.

Neither the Basin Margin Fault Set as described by Davis and Young (1977), or the Cretaceous growth faults as described by Davis and Weimer (1976) were observed on the deep seismic profile.

The Boulder-Weld Fault Zone was interpreted by Kittleson (1992) to be a series of decollement faults that were produced by sediments sliding in response to the Laramide uplift.

The thrust faulting of the Upper Cretaceous section that is visible on the deep seismic profile is similar to faults mapped in the Boulder-Weld Fault Zone. It is possible that decollement faulting of the type described by Kittleson was produced by thrust faulting and not by gravity sliding.

Post-acquisition seismic modeling was performed on the geologic interpretation of seismic line RFD-1. Seismic responses predicted by the modeling closely match the unmigrated profile of the deep seismic line, indicating that the geologic interpretation is representative of the seismic data acquired.

Post-acquisition gravity modeling was also performed on the geologic interpretation. Densities observed in nearby oil and gas wells were assigned to the sedimentary section, and average densities for metamorphic rock as published by Dobrin and Savit (1988), and Telford et al. (1976) were assigned to the Precambrian section. The modeled response matched the gravity data acquired by CSM on the western portion of the Seismic line RFD-1 with less than 1 percent error, indicating that the geologic interpretation fits the observed data.

6.0 RECOMMENDATIONS

It is recommended that data be acquired on a north-south line through the Boulder-Weld Fault Zone and across RFP by tying into the deep seismic line RFD-1 (Figure 6-1). This line should be designed to collect data in the 70- to 2,000-ft depth interval. A line of this orientation would help determine whether the Boulder-Weld Fault Zone extends beneath RFP as suggested by Kittleson (1992) and should image possible faulting in the Pierre Shale and Laramie-Fox Hills Aquifer. A north-south line combined with line RFD-1 may show the lateral extent of faulting in the Pierre Shale under RFP.

If a more accurate gravity model is desired, it is recommended that samples be acquired from different units within the Precambrian rocks and analyzed for their bulk density, or that a borehole density log be acquired in a well in the area that intersects the Precambrian rocks. It is difficult to accurately determine the densities of the igneous and metamorphic rocks in this area from their classification designation alone. If the densities of the igneous and metamorphic rocks in the area were known with a high degree of certainty, the gravity model could become more accurate in terms of the structural history and density distribution within the Precambrian rocks.

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Appendix I

Theory of Seismic Reflection Techniques

SEISMIC REFLECTION TECHNIQUE

A seismic source generates energy that manifests itself as seismic waves. Seismic waves propagate within solids as disturbances traveling through the materials with velocities dependant upon the elastic properties and densities of the materials. Typical commercial seismic sources include explosives and vibrating machinery. These sources generate two types of seismic waves; body and surface waves. Body waves consist of compressional (p) and shear (s) waves. Since most of the energy generated by a seismic source is in the form of p-waves, these waves are of primary interest.

Seismic wave energy attenuates with distance partly due to frictional heat loss through absorption of energy by the host material. Absorption is dependent on the seismic medium; shales have the highest absorption rates, and granites have the lowest. Since seismic waves propagate as spherical wave fronts, the wave spreads out over a spherical area. Thus, the energy per unit area varies inversely as the square of the distance from the source.

A seismic wave will travel through a medium along a ray path until a discontinuity is encountered. A discontinuity can be caused by a change in lithology or fluid content of a porous medium. At a discontinuity, part of the wave will be reflected and another part refracted in accordance with Snell's Law as illustrated in Figure I-1.

The relative amplitude of a reflected wave from the boundary of two layers, Layer 1 and Layer 2, can be expressed in the form

$$R = \frac{d_2V_2 - d_1V_1}{d_2V_2 + d_1V_1}$$

where:

R = reflection coefficient
d = density in grams per cubic centimeter of medium
V = velocity of p-wave through medium

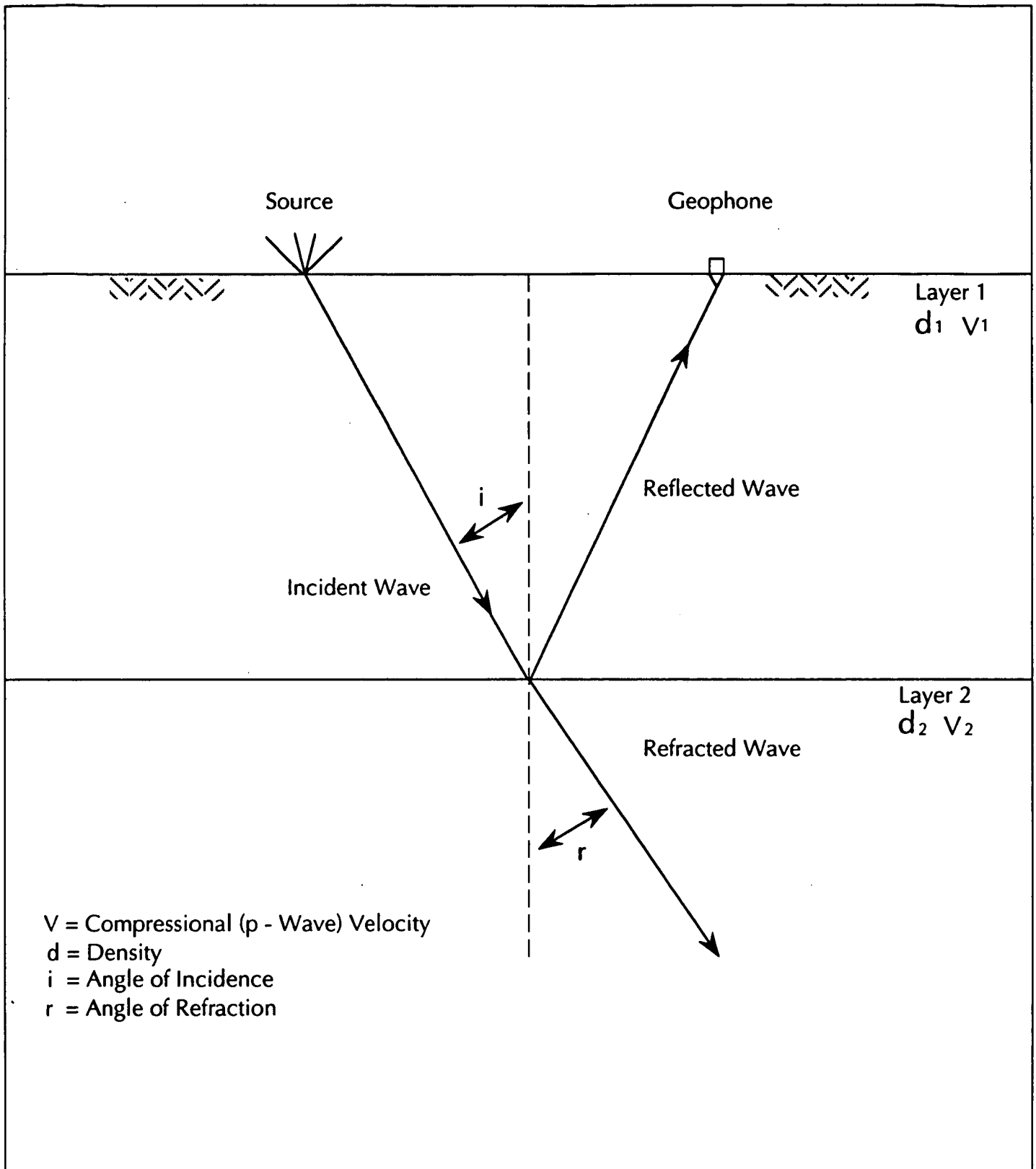

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FIGURE I-1

Illustration of Snell's Law

The product of the density and velocity is known as the acoustic impedance. If the acoustic impedance increases across an interface, then the reflected wave has a positive amplitude. Conversely, if the acoustic impedance decreases across an interface, the reflected wave has a negative amplitude.

The refracted p-wave makes an angle, r, expressed by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where:

i = angle of incidence
r = angle of refraction
V_1 = velocity of p-wave through Layer 1
V_2 = velocity of p-wave through Layer 2

When sin i = V_1/V_2, sin r becomes unity and r becomes 90°. The refracted wave does not penetrate the medium, but travels along the interface between the two materials. Angles i and r are measured relative to the normal at the intersection of the interface and the incident wave.

Where seismic waves strike any irregularity along a surface such as a corner or a point where there is a sudden change of curvature, the irregular feature acts as a point source radiating waves in all directions. Such radiation is known as diffraction. The amplitude of a diffracted wave falls off rapidly with distance away from a source.

Another seismic phenomenon, the interbed multiple reflection is illustrated in Figure I-2. A wave reflects upward from the interface between Layer 2 and Layer 3. Returning to the surface, the wave reflects downward from the Layer 1 - Layer 2 interface, because any change in acoustic impedance at an interface boundary can cause a reflection. The wave again reflects from the top of Layer 3 and successfully returns to the surface.

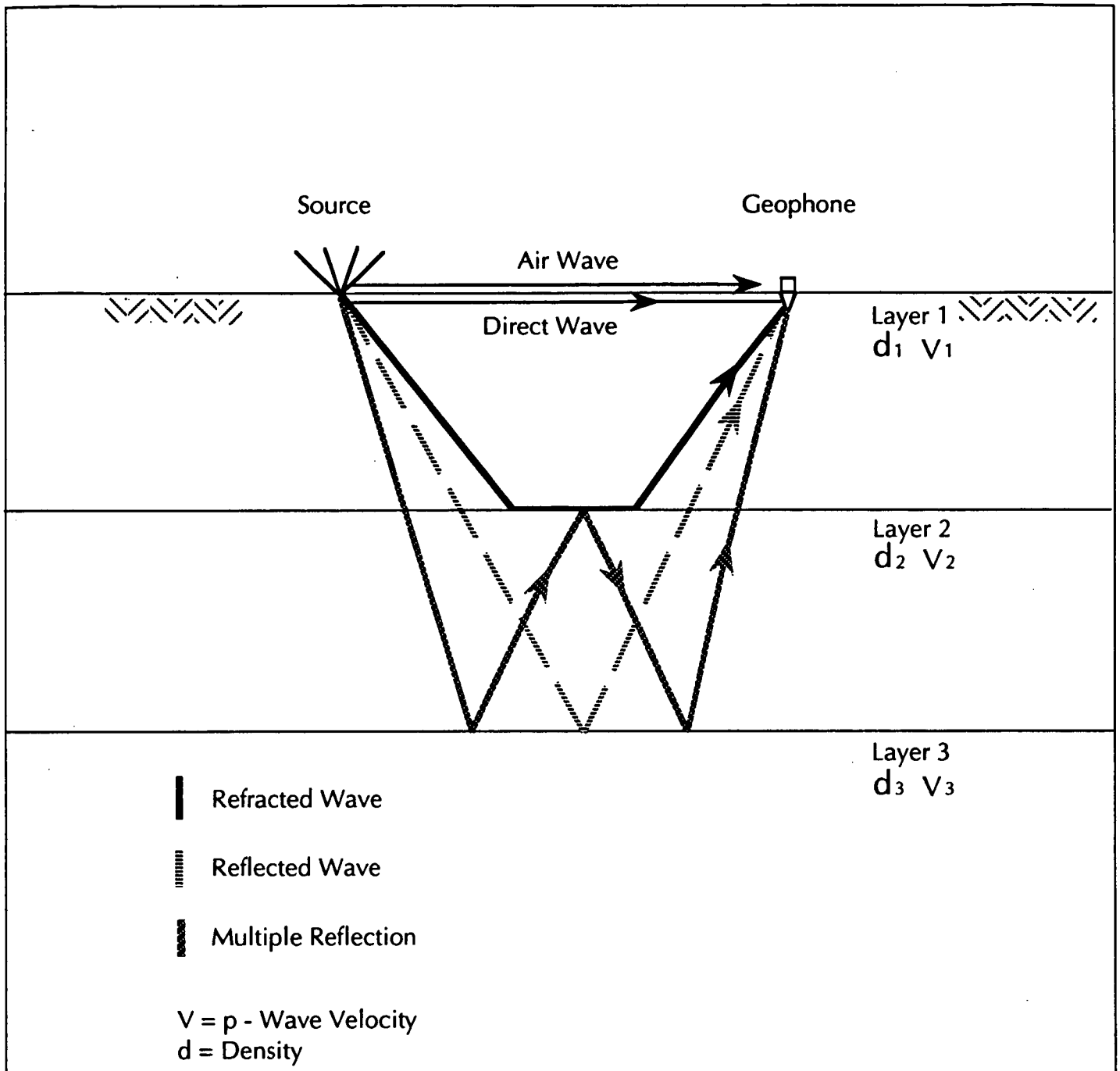

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FIGURE I-2

Types of Seismic Waves

Figure I-2 also shows the types of seismic waves generated by a surface source that will be detected by a geophone. The air wave travels at the speed of sound in air (approximately 1,100 feet/second (fps). The direct wave travels from the source to the geophone within the uppermost medium. This wave is normally faster than the air wave but slower than the other illustrated waves. The refracted wave has the earliest arrival time. The reflected wave is slower than the refracted wave. A multiple reflected wave has a longer arrival time than the reflected wave because of the greater distance traveled. Because of the varying velocities of the different waves it is possible to design seismic field parameters to record the waves of primary interest.

According to signal theory, the amount of information present in a seismic reflection signal is proportional to the bandwidth. The bandwidth of a seismic signal is the range of frequencies contained within. The maximum frequency that can be recorded reliably is equal to one-half of the sampling frequency or rate. This is known as the Nyquist frequency. At a 0.25-millisecond (ms) sampling rate, the Nyquist frequency is 2,000 hertz (Hz).

COMMON DEPTH POINT METHOD

Seismic reflection techniques build on basic seismic principles. Development of digital recording techniques in the 1960s catalyzed great advances in seismic reflection acquisition, processing, and interpretation. Seismic noise is any unwanted signal sometimes it is random and other times it is coherent (e.g., an operating water pump or a nearby electric powerline). To reliably interpret a seismic event, the signal-to-noise (S/N) ratio must be at least 1:1.

The Common Depth Point (CDP) technique has enabled the recording and display of reflection events that have S/N ratios less than unity. The CDP technique records reflections from multiple offsets at different source and receiver pairs as illustrated in Figure I-3. For each CDP the number of source and receiver pairs recorded is called the fold. Six fold data, also called

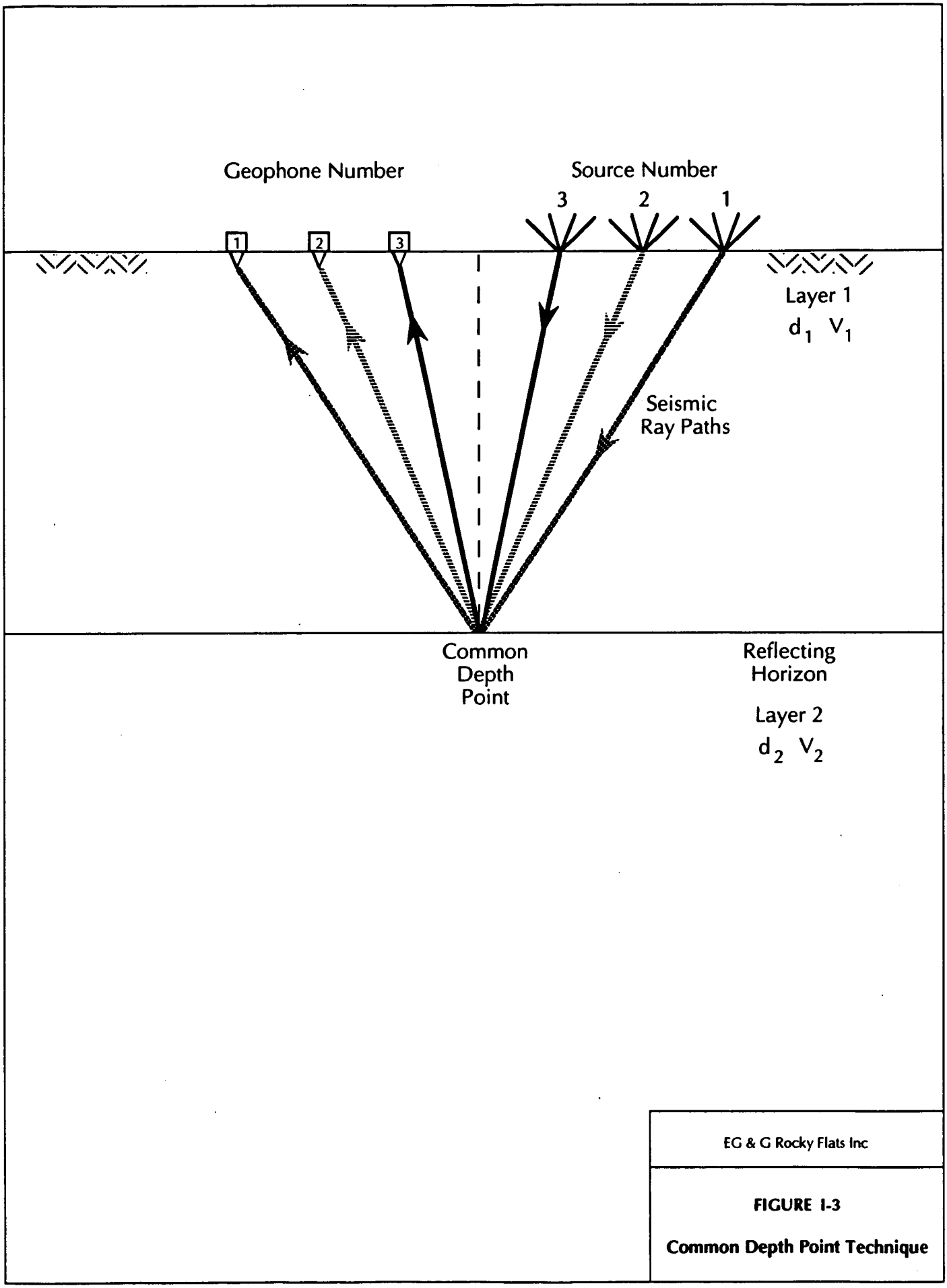

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FIGURE I-3

Common Depth Point Technique

600 percent stack, has six source and receiver pairs. The S/N ratio doubles for each quadruple increase in the CDP fold. The CDP fold can be calculated by:

$$CDP\ fold = \frac{receiver\ spacing}{2\ x\ source\ spacing}\ x\ number\ of\ recording\ channels$$

The processing of seismic reflection data is a statistically intensive procedure and requires human guidance at each step. After acquisition, the seismic reflection data are processed from source record format into CDP record format. Each CDP record will have the same number of traces equal to its fold. Because the distance between source and receiver is greater for the longer offsets of a reflection event (source-receiver 1 as opposed to source-receiver 3, Figure I-3), the recorded reflection event itself will record at a later time. The difference in time for a particular event on adjacent traces is termed normal moveout. Data are corrected for normal moveout during processing, and all traces in the CDP record are merged or summed together (stacked). This enhances the real events and cancels undesirable random noise, thus increasing the S/N ratio.

Before stacking, data are corrected for elevation variations, resulting in a static correction. After stacking, automatic statics are performed to correct for velocity variations in the near-surface weathered layer. Digital filters are applied at various steps in the processing to eliminate undesirable noise and enhance the reflection events. Post-stack filtering may include enhancing individual reflection events to improve the interpretation by statistically comparing adjacent seismic traces for continuous events versus random noise.

Seismic events recorded from a geophone appear to arrive from directly beneath the geophone. Where the reflecting horizon is dipping, the position of the event is incorrect. Dipping events migrate downdip. If necessary, these events can be migrated back to their true location. Depending on the data and objectives of the interpreter, this process can be done either before or after stacking (pre-stack or post-stack migration).

In standard seismic reflection techniques 12 or more geophones are grouped together as an array. Typical distances between groups are tens to hundreds of feet. The number of recording channels needed is dependent on the depth to the deepest target of interest and the geophone and source spacing. Vertical resolution is limited by the bandwidth of the recorded signal and the sampling frequency. Horizontal resolution is limited by the bandwidth of the recorded signal and the geophone spacings.

SEISMIC DATUM

The seismic datum is an arbitrary reference surface that corrects seismic data for local topographic variations. The start time of each record is corrected to the seismic datum. In general, if this reference datum is below the ground surface then some shallow data will be lost. If the datum is above the ground surface then the earliest seismic events are recorded and preserved on the seismic profile. Therefore, a seismic datum above the ground surface is used. For example, if a borehole has an elevation of 5,900 feet (ft), the seismic line intersecting the borehole might have a seismic datum elevation of 5,975 ft. If a sandstone was encountered in the borehole at a depth of 120 ft, the seismic depth of the sandstone would be 195 ft on the seismic profile because the seismic datum is 75 ft higher than the borehole ground surface elevation.

SEISMIC REFLECTION MODELING

High Resolution (HR) seismic computer modeling was performed to determine the parameters to be used in seismic data acquisition at the U.S. Department of Energy (DOE) Rocky Flats Plant (RFP) to determine to what degree the seismic reflection method may be effective in meeting specific objectives. Seismic reflection data will be used to aid in geologic characterization of the plant.

The seismic computer model designed for the RFP used existing data to ascertain the expected seismic response of the subsurface beneath the plant. Based on the results of the seismic computer modeling, the optimum configuration of receiver interval and source point

interval for a reflection field survey targeting depths from 500 to 12,000 feet (ft) below ground were determined.

The purpose of seismic reflection modeling is to optimize seismic data acquisition parameters and techniques by identifying possible acquisition, processing or interpretation problems that may interfere with obtaining the stated objectives of a program. In contrast to modeling, seismic data acquisition and processing are expensive operations. Pre-acquisition modeling is also useful in analyzing the actual seismic reflection responses.

Seismic modeling includes constructing a conceptual geologic cross section and generating the subsequent synthetic seismic data. The conceptual cross section is constructed using existing subsurface information to realistically portray the subsurface geology across an area of interest. The cross section includes certain specified geologic horizons that simulate seismic targets. Seismic velocity and density values are assigned to the various lithologic units after available geophysical data is reviewed. The cross section and geophysical properties are digitized and serve as the basis for the seismic model. Seismic field acquisition parameters such as source point and receiver intervals, sample rate, near receiver and far receiver offset distances, and amount of unwanted signal or noise are varied in the model to determine the optimum parameters for the actual data acquisition. The steps used to develop the RFP seismic reflection modeling process are as follows:

1. Construct a geologic cross section typical of the area proposed for seismic data acquisition.
2. Estimate the geophysical properties of the subsurface lithology.
3. Simulate the collection of the seismic reflection data across the geologic cross section using various seismic field parameters.
4. Determine the optimum set or sets of field parameters to collect seismic reflection data in the areas of interest.
5. Determine the field parameters that need to be field-tested to ensure optimum results.

6. Identify potential problems for data acquisition and processing and recommend possible solutions.
7. Estimate interpretive limitations of the seismic reflection technique and the potential vertical and horizontal resolution.
8. Present one or more synthetic seismic reflection profiles derived from the geologic cross section.

The conceptual geologic cross section was constructed using existing information. Subsurface information from wells on or around the RFP, were used to aid in the generation of the conceptual cross section (herein after referred to as the cross section) and seismic computer model. Borehole lithologic logs and downhole geophysical logs were compared to the cross sections to estimate unit thickness and extent of targeted horizons and produce a realistic, although simplified, subsurface picture. Figure I-4 shows the digitized geologic cross section.

Figure I-5 shows the simulation of the seismic reflection model data acquisition. The vertical lines represent the ray paths that energy wave fronts follow as they propagate down to a reflector (top of the Dakota Formation) and back up to the surface. This type of modeling is referred to as normal incidence modeling. The resulting synthetic section represents what would be measured if the data had been acquired as one receiver per shot with an offset of zero. Although this data acquisition method does not describe how multichannel Common Depth Point (CDP) seismic data is actually acquired (see section on Common Depth Point Method in Appendix I), it is representative of the CDP method.

Figure I-6 shows the resulting synthetic seismic section, using a 80-hertz (Hz) Ricker wavelet. Each wiggle trace deviates to the right for a positive amplitude reflection event and to the left for a negative amplitude reflection event. A positive amplitude reflection event occurs at a lithologic interface in which a slower, less dense layer overlies a faster, more dense layer. A negative amplitude reflection event occurs at a boundary where a faster,

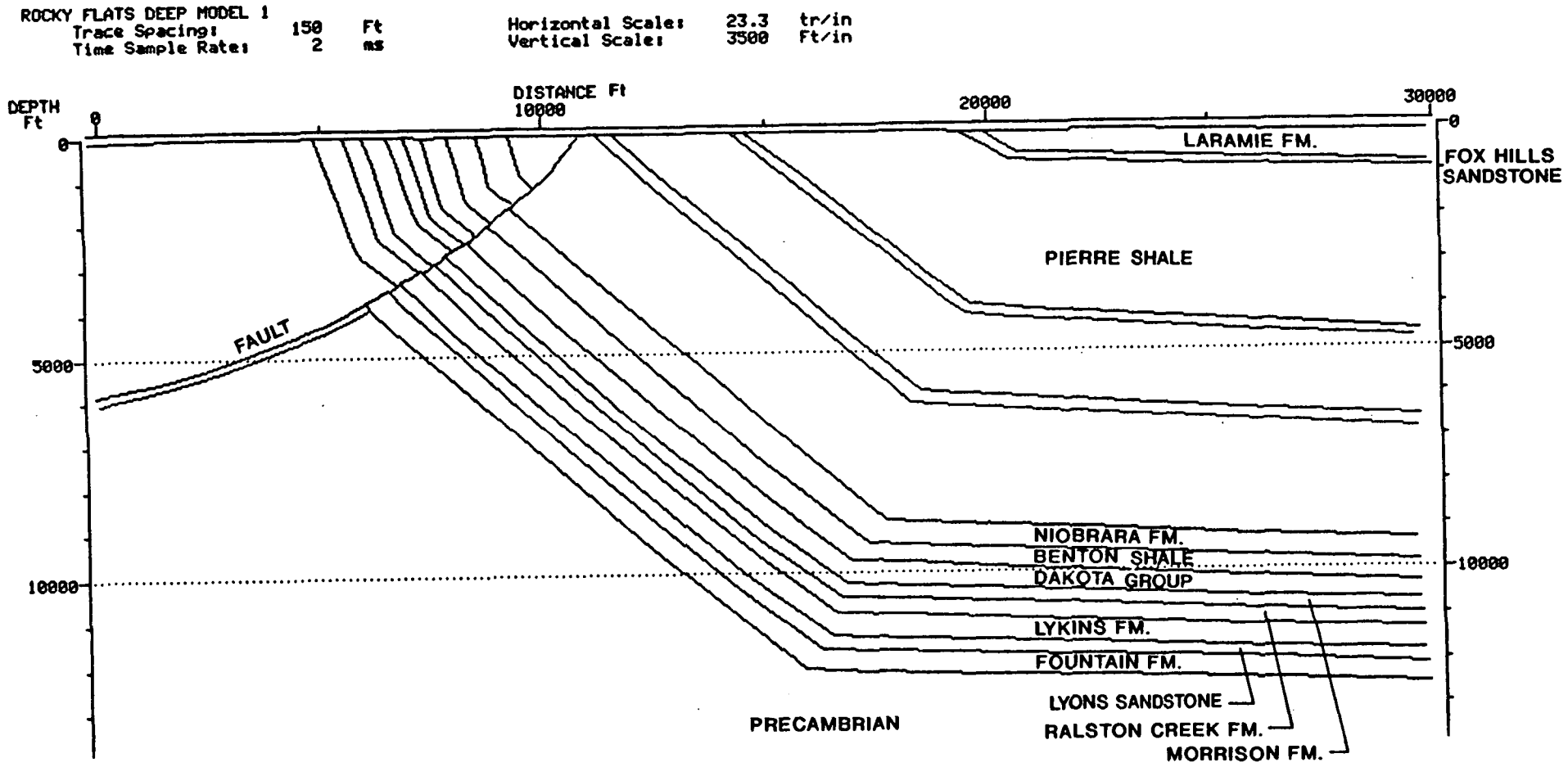

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Figure I-4

Digitized Geologic Model

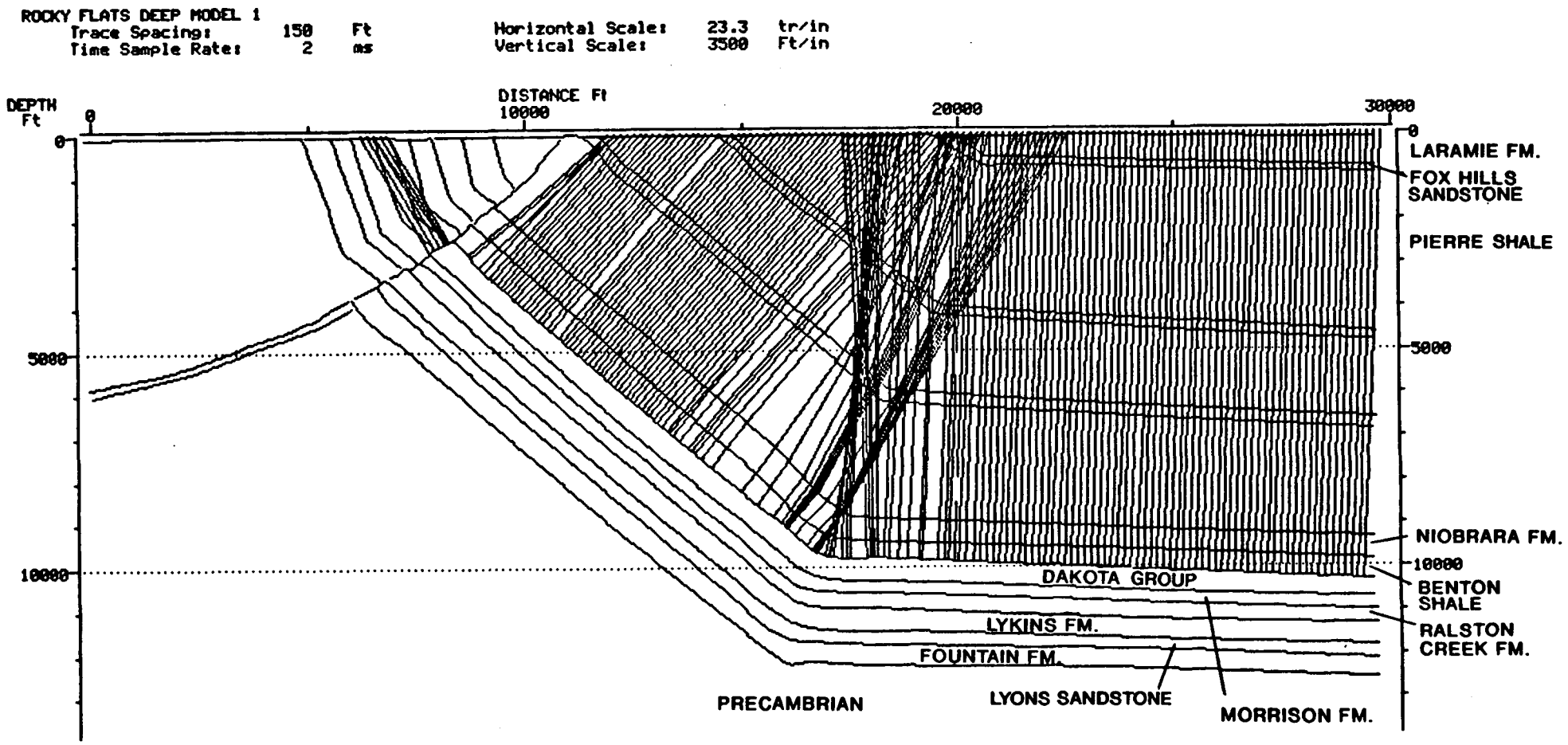

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Figure I-5
Simulated Seismic Energy Ray Paths - Dakota Formation Below Fault

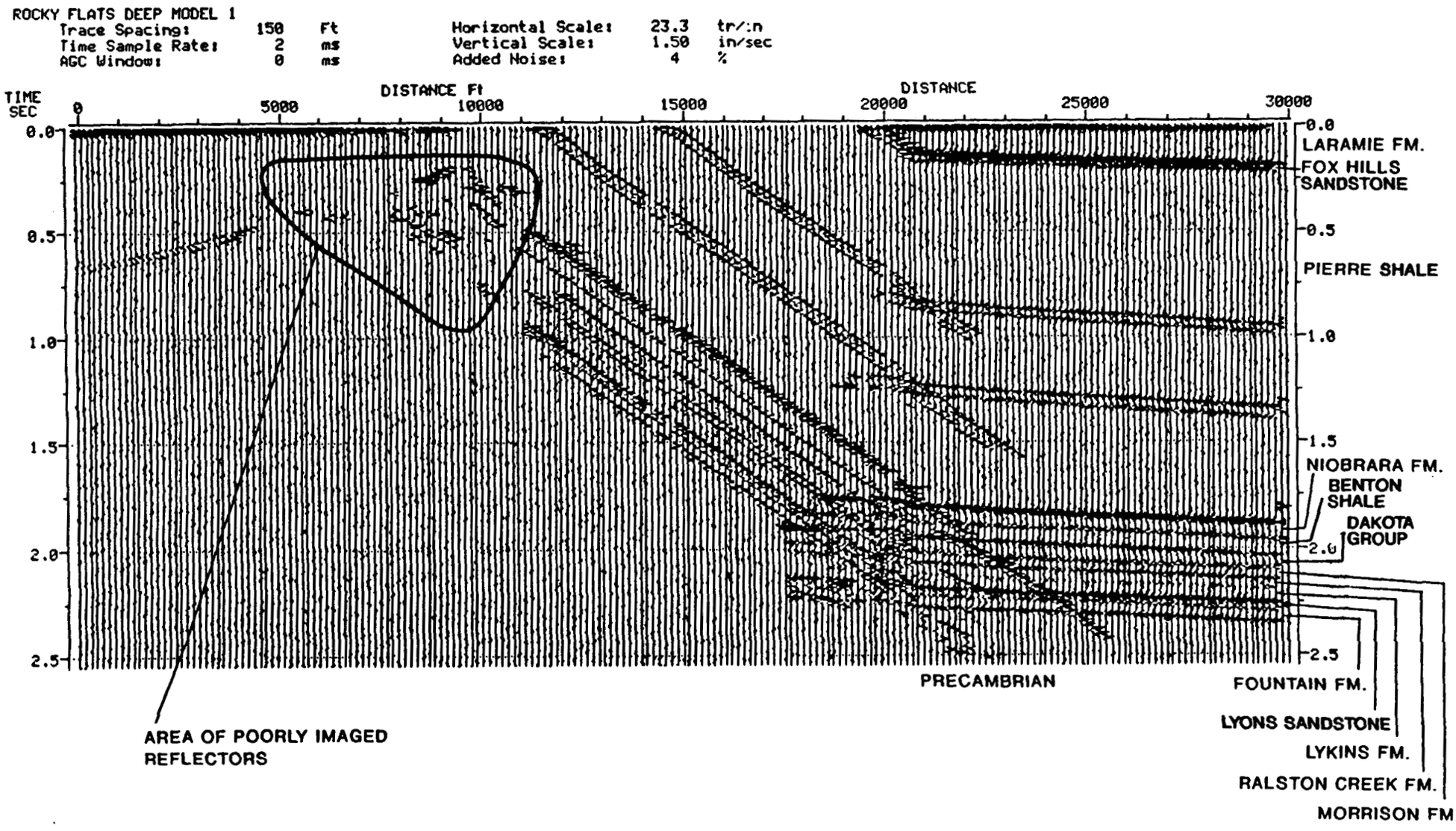

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Figure I-6
Synthetic Seismic Section
Using A 10/20-60/80 Hz Wavelet

more dense layer overlies a slower, less dense layer. The positive area of the wiggle trace is colored black to assist the interpreter in separating positive from negative events. The larger the contrast in seismic velocities and densities between layers, the higher the amplitude of the deflection.

Far receiver offset distance is based on the maximum depth of interest (approximately 12,000 ft to the Precambrian basement). To optimize the CDP data processing, the receiver spread length (the distance from the first receiver to the last receiver) should be equal to or greater than the maximum depth of interest. For a 120-channel system, a 110 ft receiver interval would yield a receiver spread length of 13,200 ft. A 55 ft receiver interval would yield a receiver spread length of 6,600 ft, and a 165 ft interval would yield a receiver spread length of 19,800 ft. The 55 ft receiver interval would be too short to record deep data; the 110 ft or 165 ft receiver intervals would be sufficient. The 165 ft receiver interval, however, would be to long to image steeply dipping beds (greater than 50-60 degrees). Figure I-7 shows the ray paths down to the steeply dipping Dakota Formation using a 150 ft receiver interval. There are an insufficient number of ray paths to properly image this horizon, therefore, a 110 ft receiver interval was recommended.

The source point interval is determined from the fold of the data that is necessary to cancel undesirable noise and enhance the signal. Figures I-8 through I-10 show the synthetic seismic section with varying degrees of noise. It is apparent that anything greater than 15 percent noise will make it difficult to image the deeper horizons. Random noise is reduced by the square root of the fold, i.e., 30 fold will increase the signal to noise ratio (S/N) by the square root of 30, or approximately 5.5 times. In addition, random noise can be reduced by using a repeatable source, and/or by filtering the data in the frequency domain during data acquisition. The proper filter settings are based on field tests to determine the frequency content of the most damaging noise. Care should be taken so that the desired signal is not also filtered out.

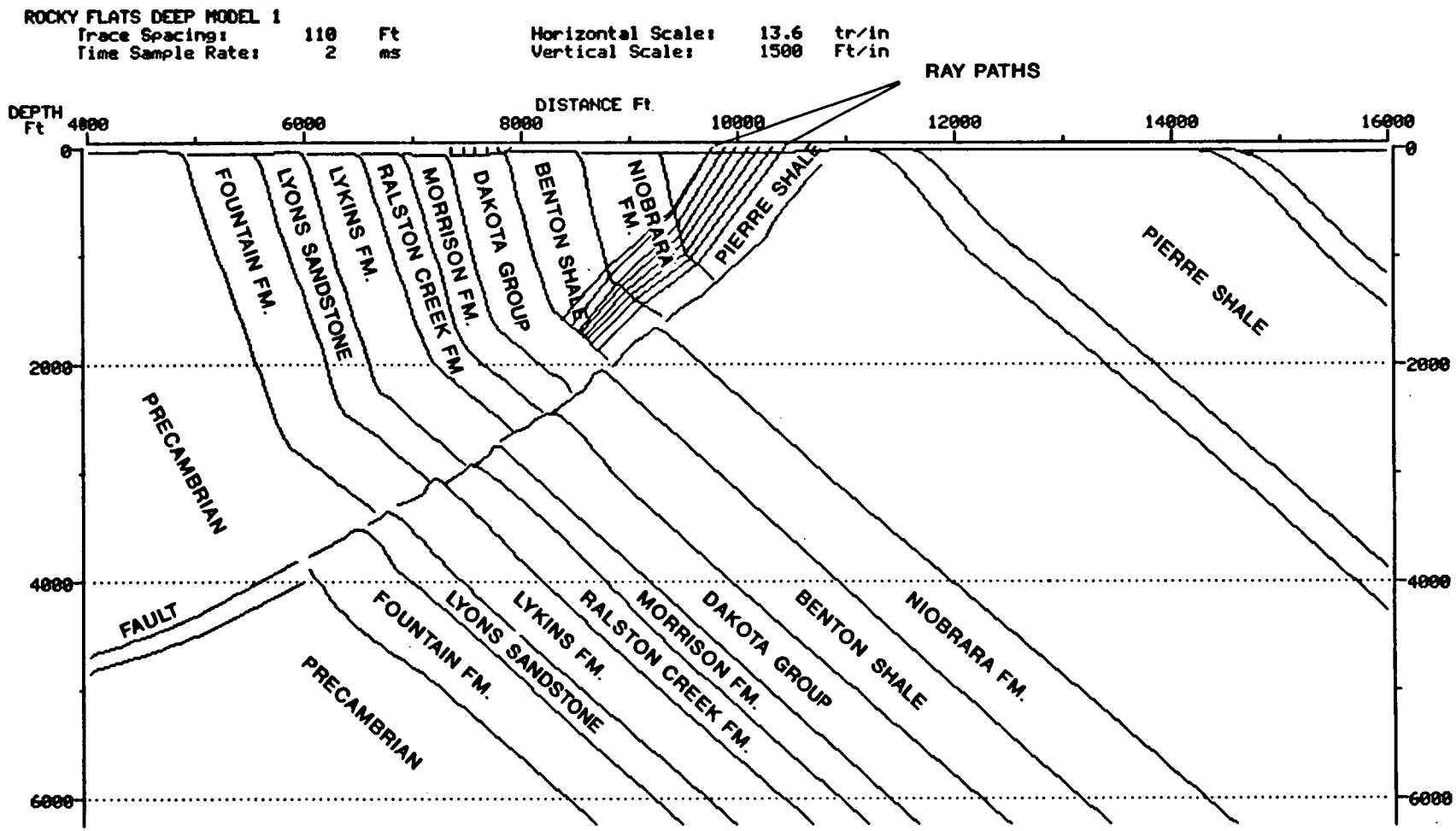

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Figure I-7
Simulated Seismic Energy
Ray Paths - Dakota Formation
Above Fault

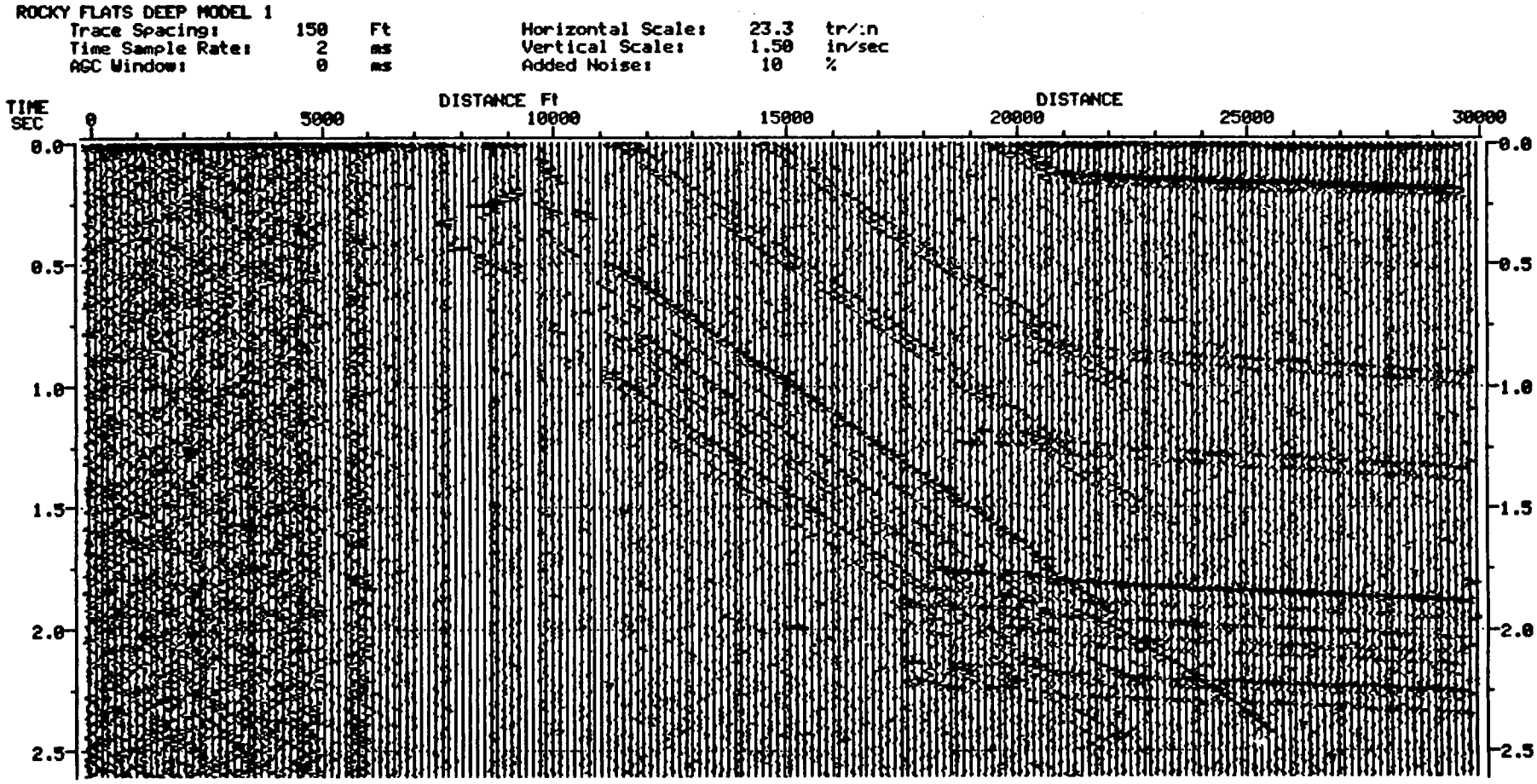

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Figure I-8
Synthetic Seismic Section
with 10% Noise

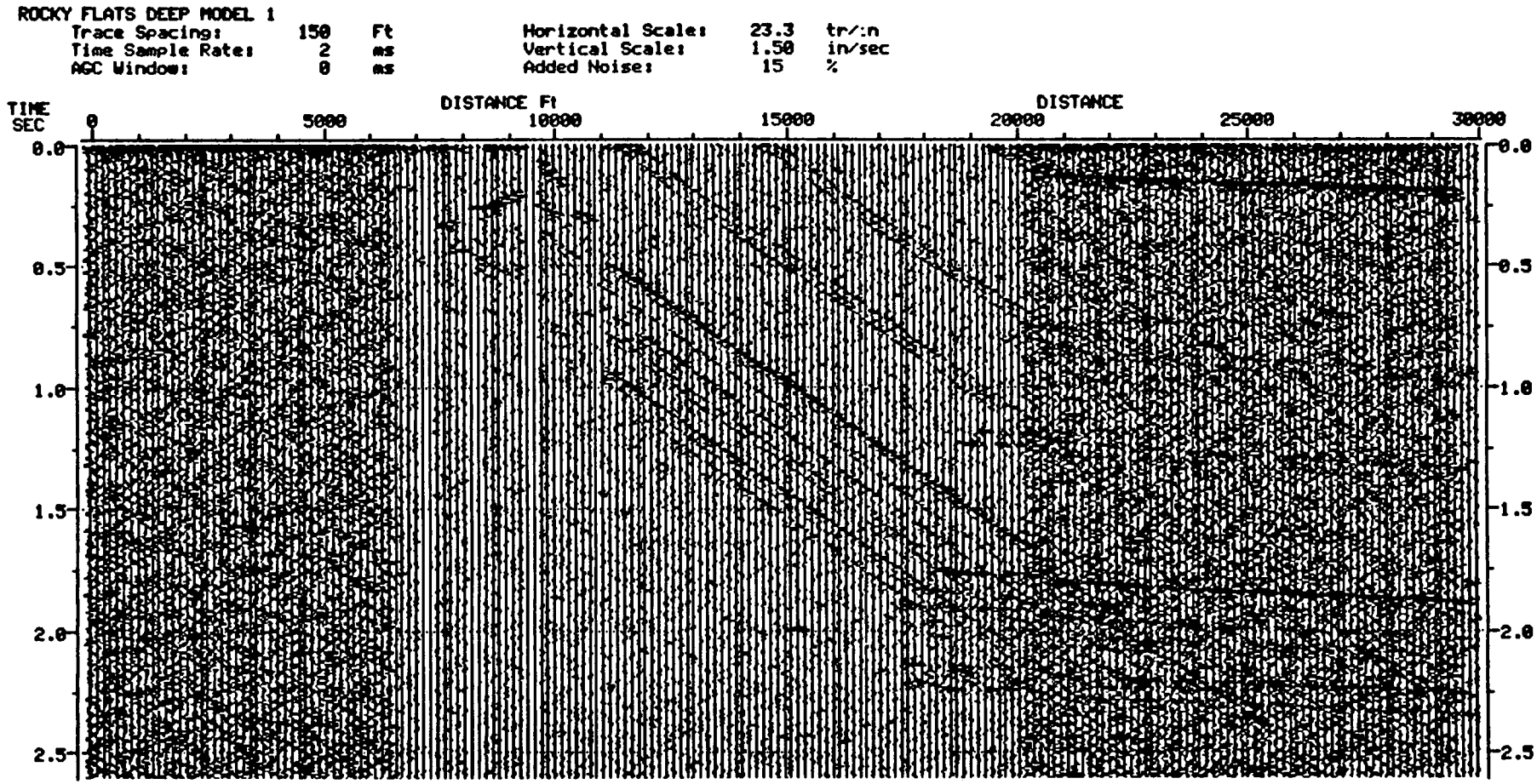

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Figure I-9

Synthetic Seismic Section with 15% Noise

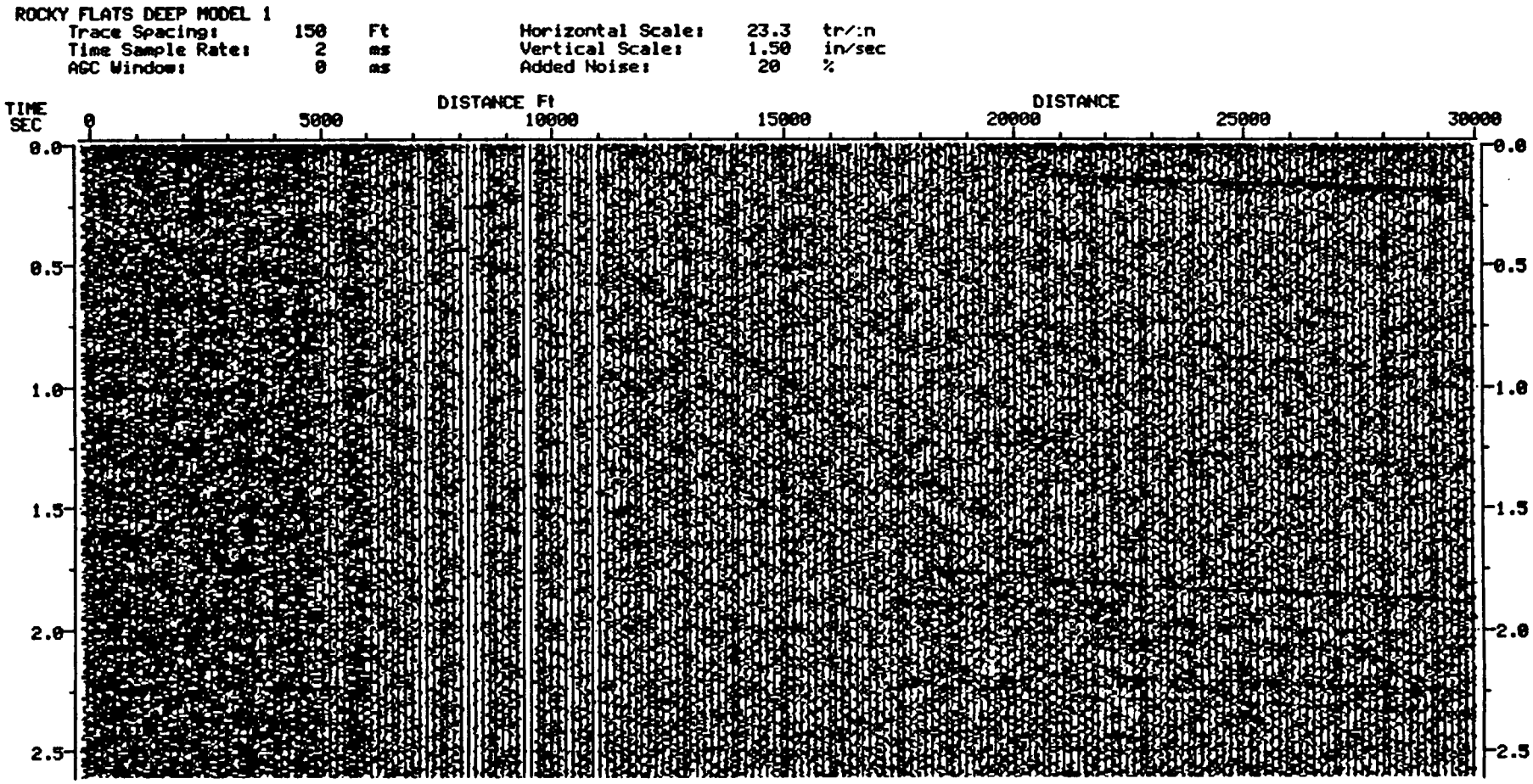

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Figure I-10

Synthetic Seismic Section with 20% Noise

The number of vibrators, sweeps per vibrator, and geophones per station will also have an effect on the reduction of random noise. The formula for the signal-to-noise ratio improvement is given by the square root of (number of vibrators*number of sweeps per vibrator*number of geophones per station). Therefore if 4 vibrators that sweep 10 times each are used in conjunction with 10 geophones per station, the S/N ratio will be improved by 20 times. These parameters will be determined during field tests.

The effect of the frequency content of the data on vertical resolution was tested to determine recording sample rate. Figure I-11 shows the seismic response of a 50-Hz Ricker wavelet, Figure I-12 a 80-Hz wavelet, and Figure I-13 a 125 Hz wavelet. Each of the modeled horizons was detectable with each of the wavelets. A 2 ms recording sample rate was recommended for data acquisition to allow for the recording of frequencies up to 125 Hz. To avoid aliasing of the data, seismographs have built-in, high-cut filters that are based on the recording sample rate. The high-cut corner frequency is the point at which all higher frequencies begin to be attenuated. For example, an EG&G Geometrics ES 2420 seismograph with a 1 ms sample rate has a high cut corner frequency of 180 Hz, for a 0.5 ms sample rate it is 360 Hz, and for a 0.25 ms sample rate it is 720 Hz. Although the maximum attainable frequency at the RFP is unknown, a sample rate of no greater than 2 ms is recommended. This will allow the recording of data above 125 Hz (high-cut for a 2 ms sample rate). If, during field testing, frequencies greater than 125 hz can be recorded, then a 1 ms sample rate may be necessary.

It was recommended that a recording time of 4 seconds be used. The seismic model indicates that the deepest layer of interest, the Precambrian basement, will be recorded at approximately 2.5 seconds. Considering that the velocities used to determine this arrival time are uncertain and that the model does not take into consideration extra travel time due to far receiver offsets, a minimum of an additional 1 second recording time beyond the 2.5 seconds is necessary.

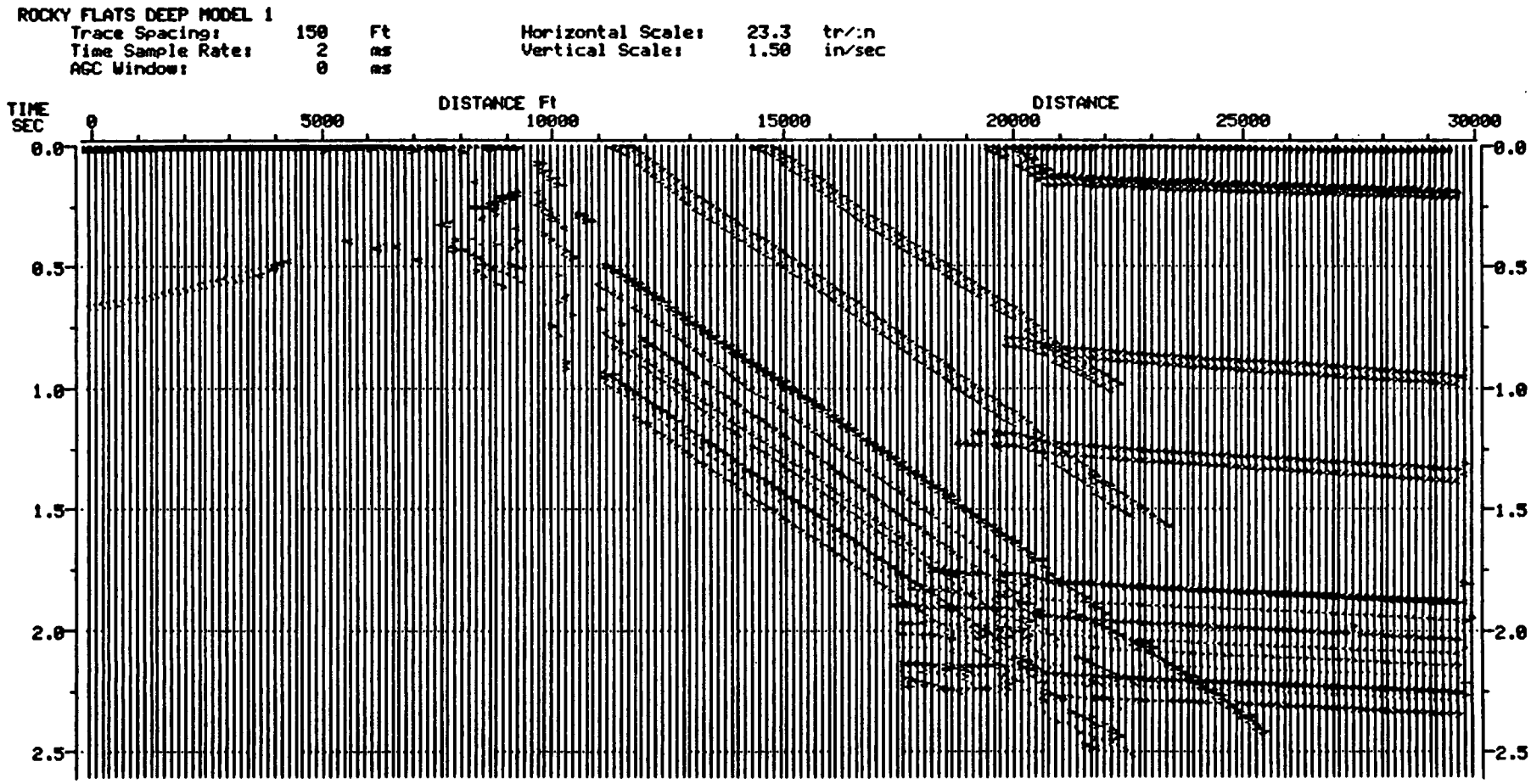

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Figure I-11

Synthetic Seismic Section with 50 Hz Wavelet

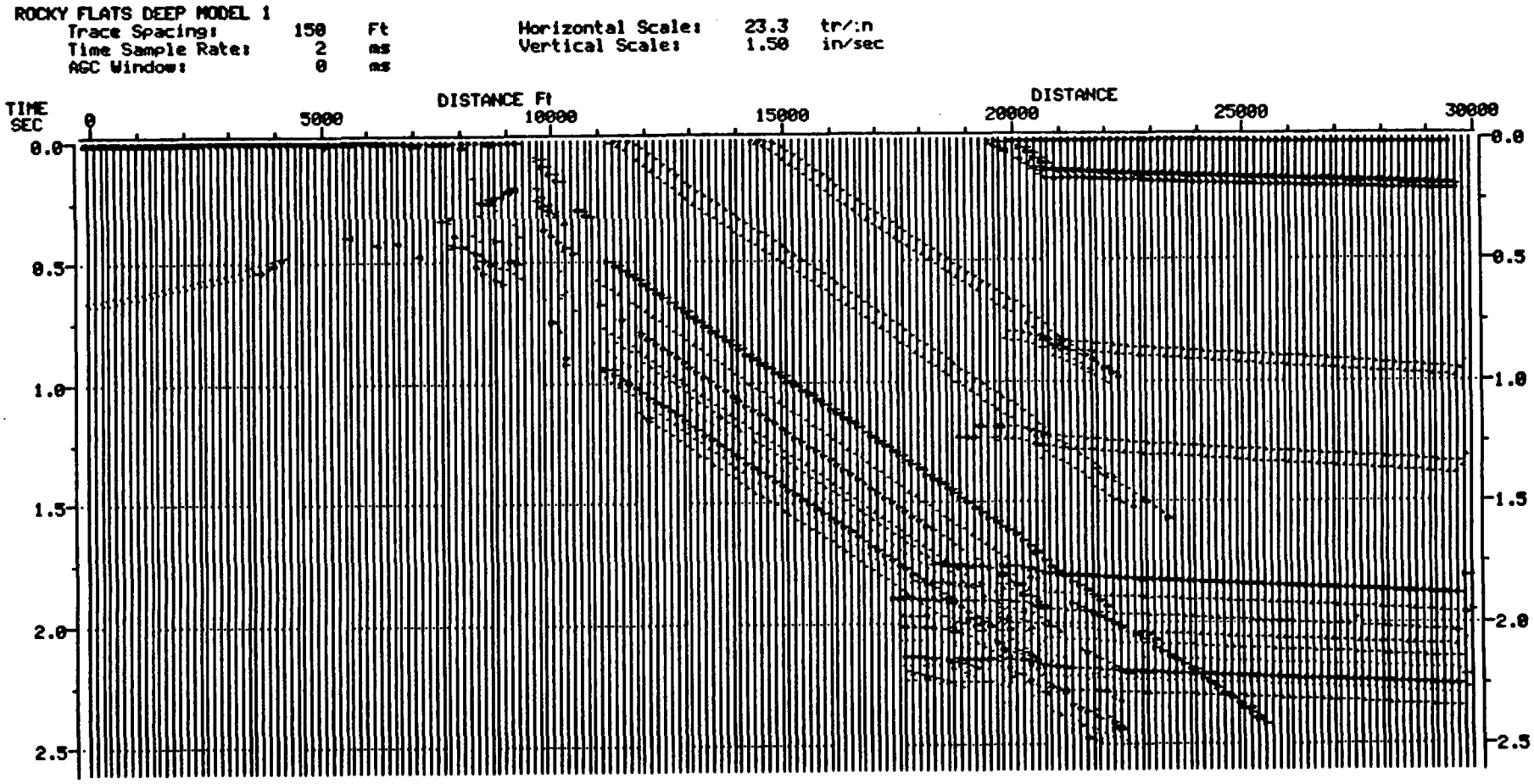

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Figure I-12

Synthetic Seismic Section with 80 Hz Wavelet

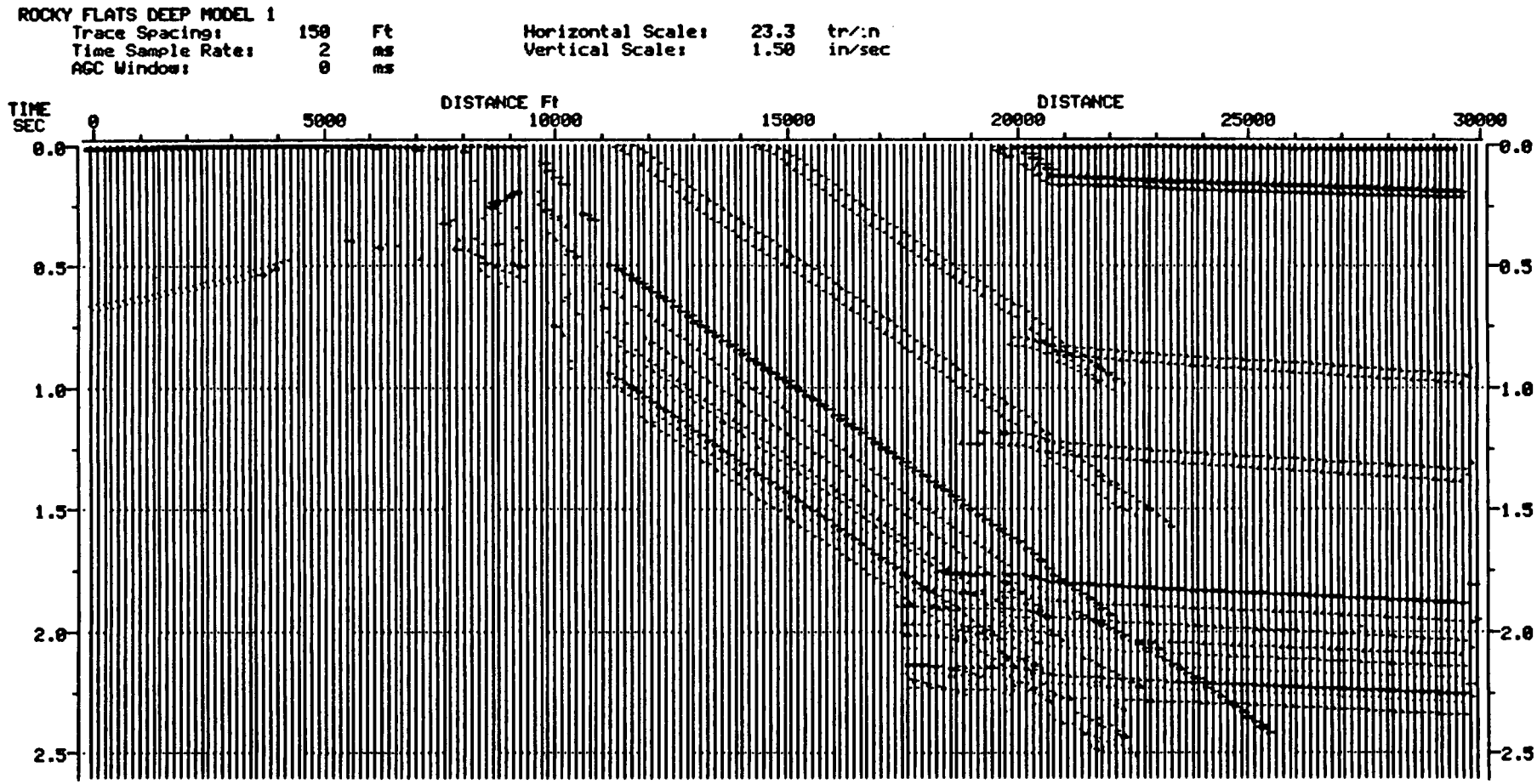

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Figure I-13

Synthetic Seismic Section with 125 Hz Wavelet

A 120-channel recording system, with a 110 ft receiver interval and a 220 ft source point interval was recommended. This will yield 30-fold coverage and improve the signal to noise ratio approximately 5 to 6 times. An unbalanced split spread configuration (the source point is located between the center of the receiver spread and the end of the receiver spread) will yield a far receiver offset of between 13,200 and 6,600 ft, which should be sufficient to record data down to the Precambrian basement (12,000 ft deep maximum). The actual spread geometry will be determined from field tests. The recommended 110 ft receiver interval is necessary to resolve the steeply dipping geology.

A noise analysis performed prior to data acquisition will determine the types, velocities, frequencies, and amplitudes of surface waves. A noise analysis (often called a walkaway) consists of shooting into a normal geophone spread, such as is used in refraction surveying, with recording filters turned off. The geophysicist can then determine what filter settings, and sources and receiver arrays should be used in actual data acquisition.

Appendix II

Field Tests

EBASCO SERVICES INC.
ROCKY FLATS PROJECT
JEFFERSON COUNTY
COLORADO
AUGUST 1991

Lookout Field Services
14142 Denver West Pkwy., Suite 180
Golden, Colorado 80401 USA
Tel: (303) 278-7557
Fax: (303) 278-7562

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REPORT SUMMARY

21 sets of sweep tests were run. Mike McGuire selected the following sweep for production: **10 - 120 Hz. , 12 seconds long, +3 db / octave emphasis, 110 foot long Vib array, 4 Vibs * 10 sweeps/VP (40 sweeps total).** Plots of raw records, filter panels, Signal to Noise analysis and Amplitude analysis of the filter panels were preformed on the test sweeps to aid in the parameter selection.

Instruments were in good calibration for all the standard monthly MDS 10 tests except that the Tape ID burst appears to tell my tape drive that it was 800 BPI. However, there were no problems reading the tape on any of the three different tape deck we had at the office.

All four Vibrators similarities were acceptable on the first set of hardwires performed. All four vibrators were within 15 degrees of phase error throughout the sweep.

Overall the crew was proficient and responsible. They worked well with the Lookout and Ebasco representatives.

INTRODUCTION

Lookout Geophysical Company was contracted by Ebasco Services Inc. to perform quality assurance and parameter testing on the Rocky Flats prospect near Golden, Colorado on 17 August and 18 August 1991. I took a SeiScope field processing computer system to the site. I processed instrument tests, Vibrator similarities, sweep tests and observed the crew's field procedures.

INSTRUMENT TESTING

The following tests were analyzed off tape for recorders #616 (Master) and #713 (Slave).

Equivalent Input Noise (EINT)
- DC Offset.
- RMS Levels.
- Noise to Reference RMS levels comparisons.

Dynamic Range Determination
- RMS Levels for each step.
- System Range.

Pulse
- High & Low Cut Filter Amplitude.
- High & Low Cut Filter Phase.
- High & Low Cut Filter Slope.
- Waterfall Analysis & Display.
  (See Appendix F Instrument Testing)

Crossfeed
- RMS Levels (in db) record to record.

Harmonic Distortion
- RMS Level.
- Phase.
- Individual Harmonics.
- Total Harmonic Distortion (THD).

Gain Accuracy
- Record to Record ratios of RMS levels.

Analog to Digital Linearity
- Record to Record ratios of DC levels.

Exponential Oscillator Decay
- Waterfall Analysis & Display.
- Amplitude Analysis Channel to channel.

INSTRUMENT TESTING cont.

The following problems were found during testing:

> The ID burst on the tapes may have some problem on it. One tape deck in our office IDs it as 800 BPI the other IDs it as 6250 BPI. The tapes are actually 1600 BPI.
>
> This is not a major problem and I had no problems reading the tapes from this recorder on three different decks in our office. It was just that you had to manually set the BPI rate.

Waterfall plots of the pulse, and Harmonic Distortion records are in Appendix H.

VIBRATOR TESTING

Hardwire Similarities were analyzed for phase, spectral and amplitude accuracy. Frequency vs. Time vs. Amplitude plots display levels harmonic distortion, resonances, and noise. Plots of vibrator QC are in appendix I.

PARAMETER TESTING

14 sets of sweep tests were run on the afternoon of Saturday, 17 August. I analyzed the test sweeps that evening on the SeiScope system.

I plotted raw records, filter panels, signal to noise, and Spectral comparisons of the different sweeps that evening.

The main sweep is No. 1. All the other sweeps vary from it only in a single way (the parameter underlined).

File ID	Sweep Range	Total Vib Length	Freq. Pre-Emphasis	No. Sweeps	Sweep Length	Vib -phone Gap [1]
001	10-120	110	Linear	3 * 12	12 sec	165'
002	10-120	220	Linear	3 * 12	12 sec	165'
003	10-120	330'	Linear	3 * 12	12 sec	165'
004	10-120	110'	Linear	3 * 8	12 sec	165'
005	10-120	110'	Linear	3 * 16	12 sec	165'
006	10-120	110'	Linear	3 * 12	12 sec	165'
007	10-120	110'	Linear	3 * 12	8 sec	165'
008	10-120	110'	Linear	3 * 12	6 sec	165'
009	10-96	110'	Linear	3 * 12	12 sec	165'
010	16-120	110'	Linear	3 * 12	12 sec	165'
011	10-80	110'	Linear	3 * 12	12 sec	165'
012	10-120	110'	+6 db/Oc	3 * 12	12 sec	165'
013	10-120	110'	+3 db/Oc	3 * 12	12 sec	165'
014	10-120	110'	+9 db/Oc	3 * 12	12 sec	165'

Footnotes:

1: This is the distance from array center to array center. Absolute distance from nearest vib to nearest phone is 110' less than the amount noted.

The basic idea with this collection of sweeps was to test five variables:

* Band Width
* Positive Frequency Pre-Emphasis
* Vibrator Array length.
* Near trace first breaks with respect to source noise.
* Sweep length.

On Sunday morning 18 August I met with Jim Applegate and Mike McGuire. We examined the AGC displays and the filter parameters carefully and noted the differences.

We narrowed down the desireable array sizes and band-widths but, we still had some questions about gap size, sweep length, and number of sweeps. I outlined a second series of tests to run to evaluate these items in more detail.

We returned to the test site and ran 7 more test sweeps. We waited several hours while Century tried to get all four Vibrators running. At 1:00 pm we decided to run the tests with only three Vibs. We than ran hardwire similarities.

I analyzed the test sweeps #2 that evening on the SeiScope system. I plotted raw records, filter panels, and Amplitude analysis of the different sweeps that evening.

Again for this second set of tests we picked a main sweep and every subsequent sweep is a derivation of that by only one factor.
The main sweep is No. 015. All the other sweeps vary from it only in a single way (the parameter underlined).

File ID	Sweep Range	Total Vib Length	Freq. Pre-Emphasis	No. Sweeps	Sweep Length	Vib -phone Gap [1]
015	10-120	110	-3 Db/Oct	3 * 12	12 sec	165'
016	10-120	110	+3 Db/Oct	3 * 12	12 sec	275'
017	10-120	110	+3 Db/Oct	3 * 12	12 sec	385'
018	10-120	110	+3 Db/Oct	3 * 14	12 sec	165'
019	10-120	110	+3 Db/Oct	3 * 10	12 sec	165'
020	10-120	110	+3 Db/Oct	3 * 12	14 sec	165'
021	10-120	110	+3 Db/Oct	3 * 12	12 sec	2590'

On Monday morning 19 August I again met with Jim Applegate and Mike McGuire and w examined the AGC displays and the filter panels from this second set of parameter tests.

FIELD PARAMETERS

Client	: EBASCO	Area	: Rocky Flats
County	: Jefferson	State	: Colorado
Contractor	: Century	Crew	:
Date	: 17 -18 August		
Lines	:		

Personal

Party manager: Andy Stamp Observer : Rick Boyd
Instr tech : Surveyor :
For Lookout Geophysical: Todd Fockler

==========

Spread Geometry

For Sweep tests

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                Ch.# 120                61
                     |----------------|
                     ----------------|
                Ch.#  1                 60    Vibs
Offsets:            6655'               165'  0'
```

Distances are all Array center to Array center In-line.

Group interval : 110 ft. Chs 1-60 are 110' arrays
V.P. interval : ft. Chs 61-120 are 55' arrays

==========

SOURCE

Type	: Vibroseis
Model	: Failing
Max Force	: lbs
Mass Weight	: lbs.
Base Plate Weight	: lbs.
Piston Area	: sq. in.
Total Vehicle Weight	: lbs.
Electronics	: Pelton Advance 1, Model 5

Source Array (for production)

Array type	: In-line
Max overall length	: 110 ft
Array width	: 0 ft
Lateral spacing	: 0 ft
Vib's on line	: 4
Spacing Basepl-Basepl	: 55 ft
Sweep/V.P	: 10
Move up/sweep	: 0 ft after each sweep
Drag (total move-up)	: 0 ft
Sweep freq.	: 10-120 hz.
Sweep length	: 12 sec.
Taper	: 300 ms.
Sweep Rate	: 9.16 Hz./sec
Sweep type	: Non-Linear
Emphasis	: +3 db
Dwell	: High

FIELD PARAMETERS

RECEIVER

Geophone type	:
Natural freq.	: Hz.
Coil resist.	: Ohm
Damping resist.	: Ohm
Damped	: %
String resist.	: Ohm
String Construction	: 12 per string wired in series parallel
String Geometry.	: 15 ft btwn phones with 15 ft lead on both sides
Case Construction	: Land, with 3" spike

Receiver Array

There were two arrays used in the parameter tests; a 110' length and a 55' length. They are noted here as two numbers separated by a slash.

Array type	:	Max In-line length	:110/55 ft
Array width	:110/55 ft	Max Cross-line lengt	:110/55 ft
Phones/Sta.	:12/12	In-line spacing	:10/5 ft
Array resist.	: Ohm	Cross-line spacing	:10/5 ft
Plants	: surface		

Recording Instruments

System	: MDS 10
Camera	: SIE ERC-10c
Correlator	:
Stacker	:
Vib Encoder	: Pelton Mod. 5 w/ Frequency Pre-Emphasis Option
Tape Drive	:

Field Recorded Data Specifications

Sampling Rate	: 2 ms.
Format	: SEG B
Density	: 1600 BPI
Gain Mode	: I.F.P.
Recording time	: 16.0 sec.
Encoder Pos.	: +90 Degrees
Record Length	: 4.0 sec. (after correlation & sum)
Data Word	: 11 Bit Mantissa
Data channels	: 120
Aux. channels	: #1 is Timing Word
	: #2 is True Reference Summed & Filtered
	: #3 is file I.D.
	: #4 is True Reference unFiltered

Filter settings

High Cut	: 125 hz.
High Cut Slope	: 72 db/ octave
Low Cut	: 12 Hz.
Low Cut Slope	: 18 db/ octave
Notch	: Out
Rejection 60 hz.	:

APPENDIX A
AGC'ed Raw Records of Test Sweeps #1

FILE NAMES
At the top of the test sweeps are the file names:
D:\data\Data_tst1\0004.gnd

The key number here is the 0004 or 0003 etc. These identify the data as sweep No. 3 or sweep No. 4 etc. The sweeps are numbered from 1 to 12 which corresponded to their file numbers.

File ID	Sweep Range	Total Vib Length	Freq. Pre-Emphasis	No. Sweeps	Sweep Length	Vib -phone Gap [1]
001	10-120	110	Linear	3 * 12	12 sec	165'
002	10-120	220	Linear	3 * 12	12 sec	165'
003	10-120	330'	Linear	3 * 12	12 sec	165'
004	10-120	110'	Linear	3 * 8	12 sec	165'
005	10-120	110'	Linear	3 * 16	12 sec	165'
006	10-120	110'	Linear	3 * 12	12 sec	165'
007	10-120	110'	Linear	3 * 12	8 sec	165'
008	10-120	110'	Linear	3 * 12	6 sec	165'
009	10-96	110'	Linear	3 * 12	12 sec	165'
010	16-120	110'	Linear	3 * 12	12 sec	165'
011	10-80	110'	Linear	3 * 12	12 sec	165'
012	10-120	110'	+6 db/Oc	3 * 12	12 sec	165'
013	10-120	110'	+3 db/Oc	3 * 12	12 sec	165'
014	10-120	110'	+9 db/Oc	3 * 12	12 sec	165'

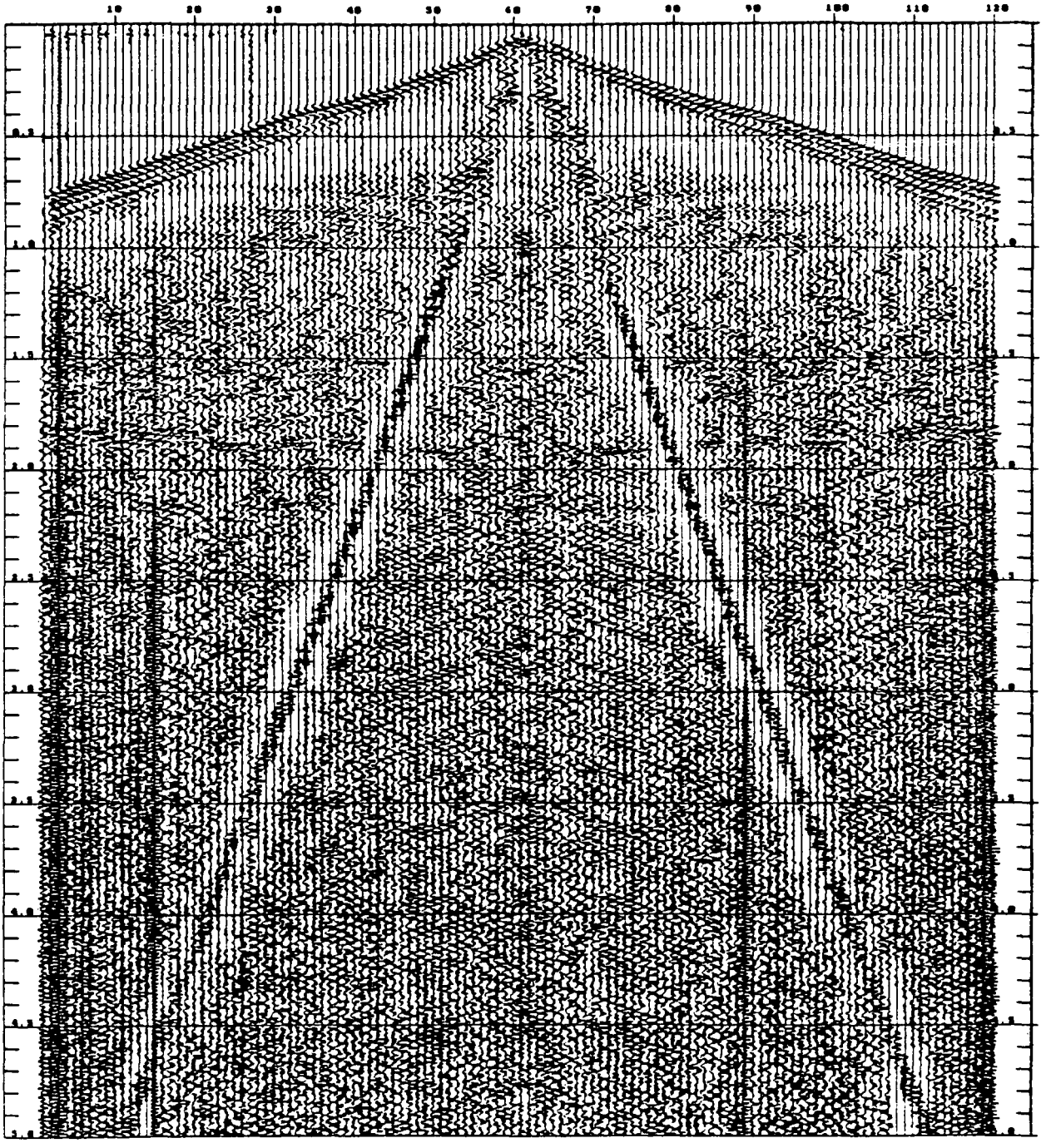
Footnotes:

1: This is the distance from array center to array center. Absolute distance from nearest vib to nearest phone is 110' less than the amount noted.

BASE SWEEP
5.0 SECONDS
FULL SPREAD

FILE: E:\data\DATA_TST\0001.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

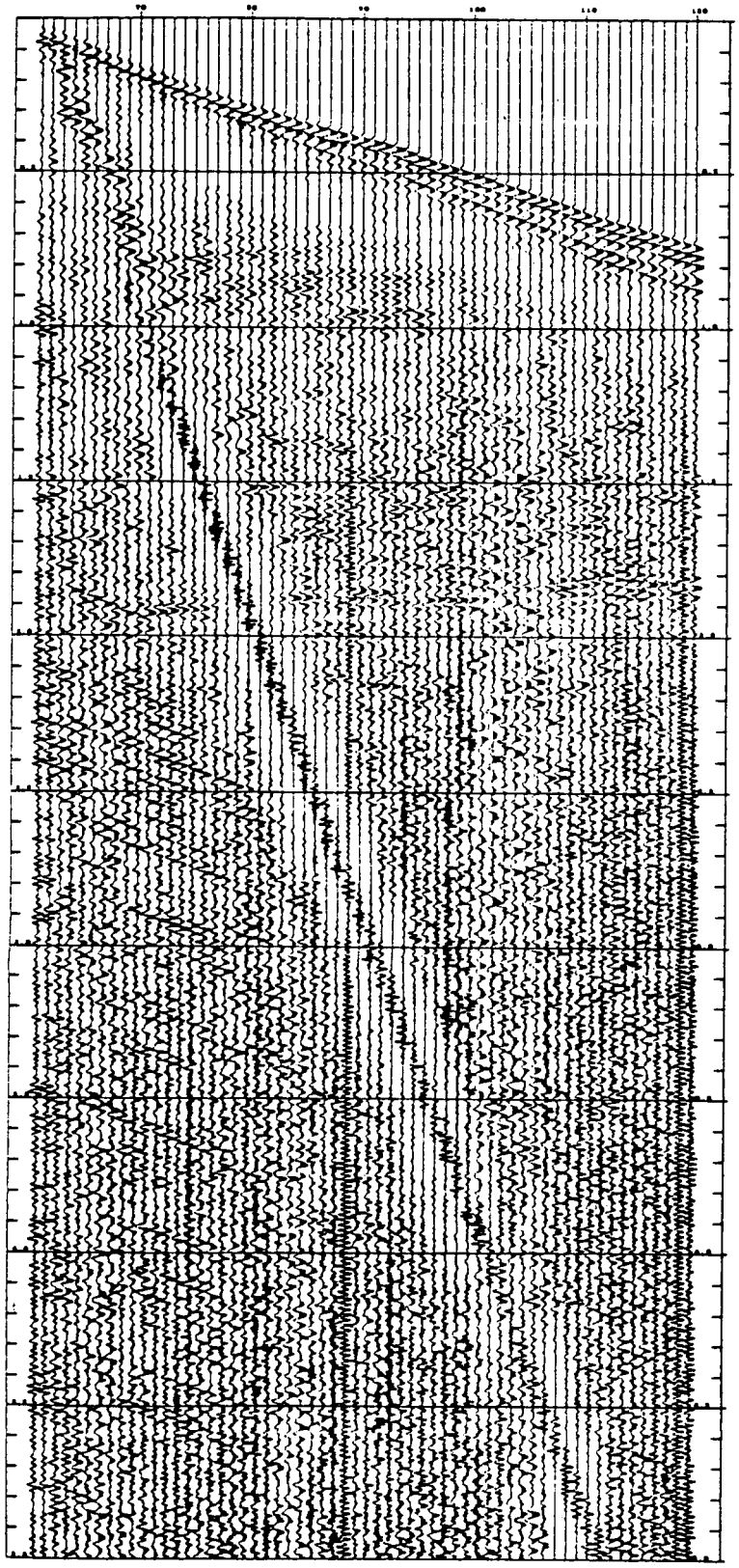
FFID: 0001
TIME: 19:02:40
DATE: Sat Aug 17



FILL 5.0 SECONDS
OF 55' HALF OF SPREAD

FILE: D:\DATA\DATA_TST\0001.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

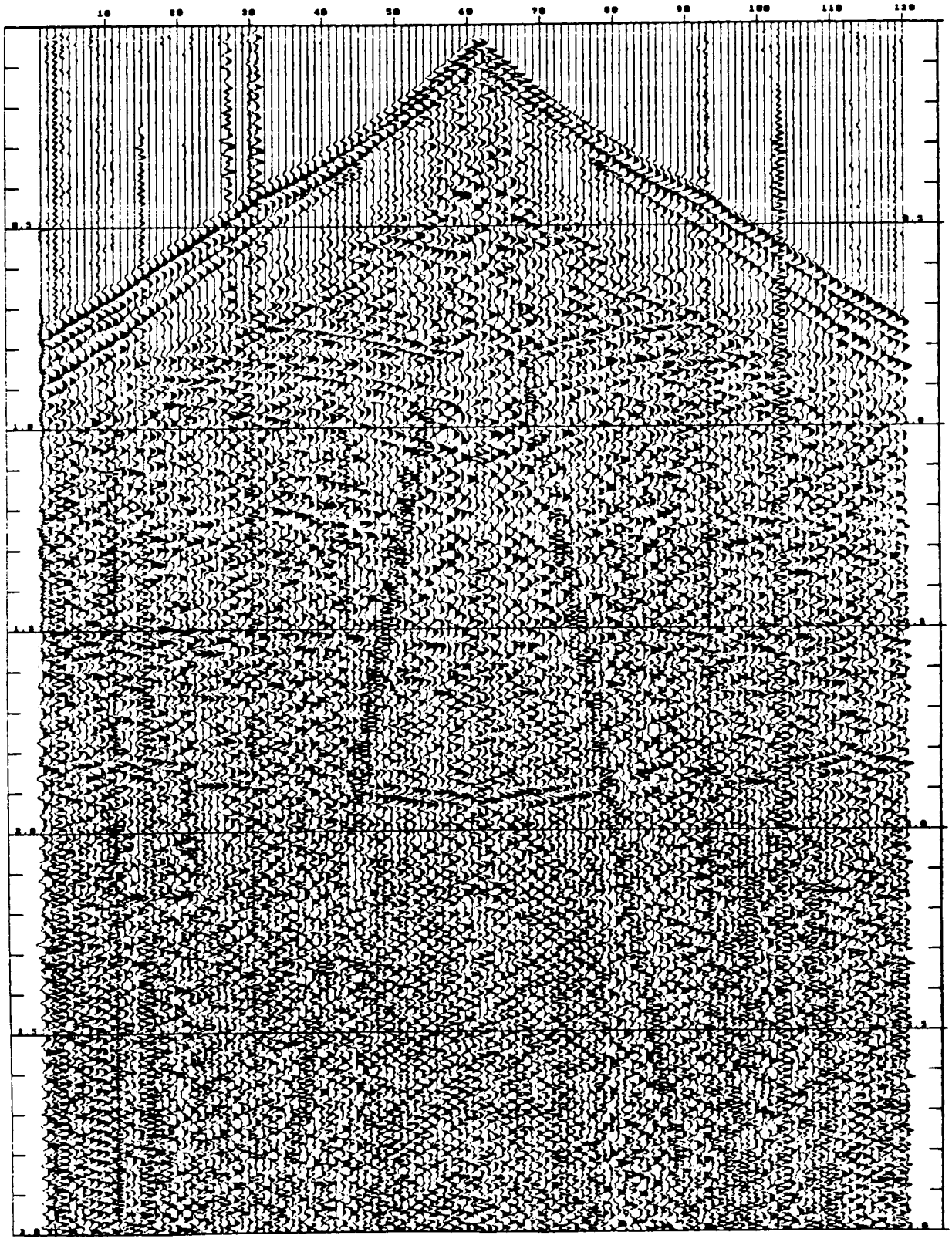
EFID: 0001
TIME: 19:15:10
DATE: Sat Aug 17



330' VIB
ARRAY

FILE: E:\data\DATA_TST\0003.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

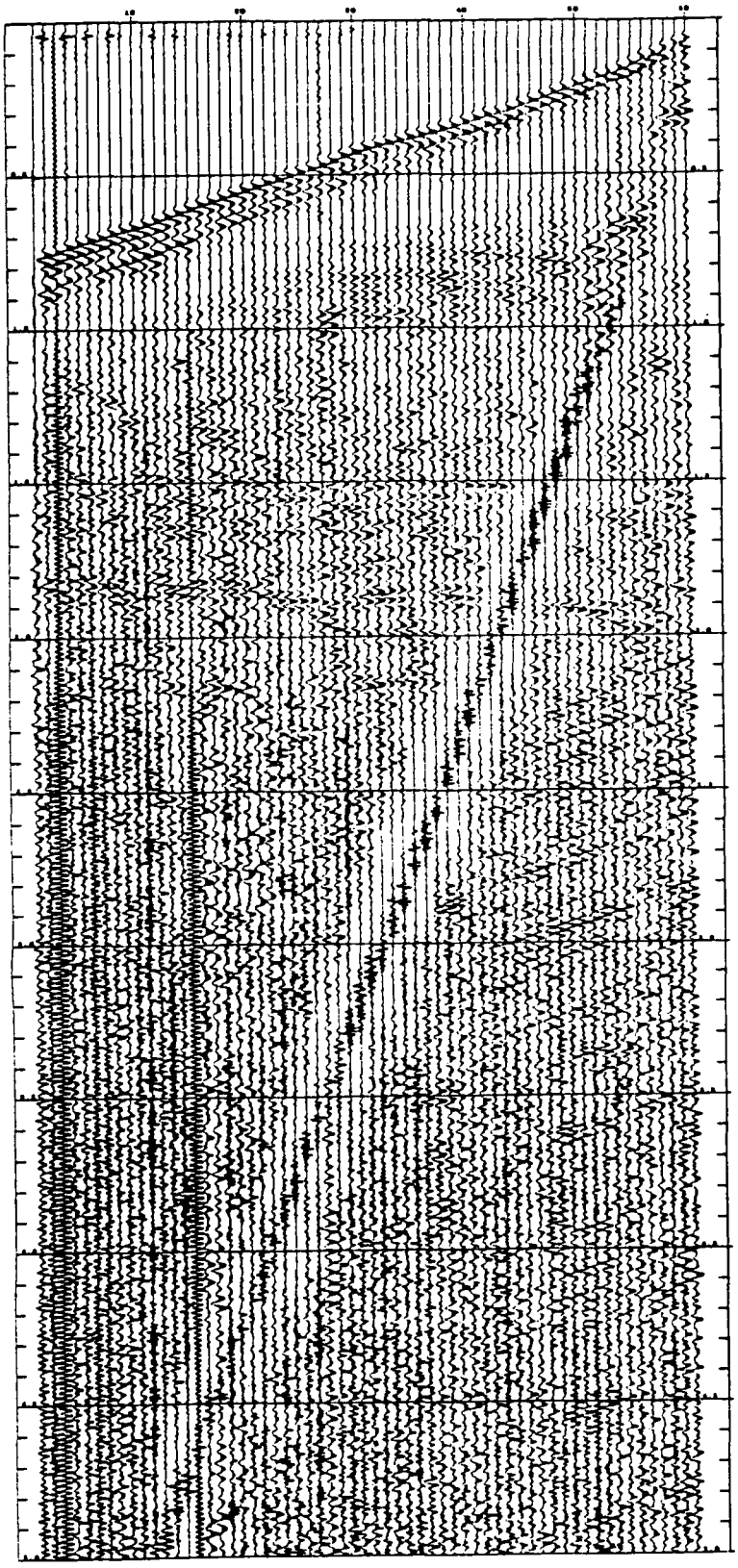
FFID: 0003
TIME: 19:30:47
DATE: Sat Aug 17



FULL 5.0 SECONDS OF
110' HALF OF SPREAD

FILE: D:\DATA\DATA_TST\0001.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

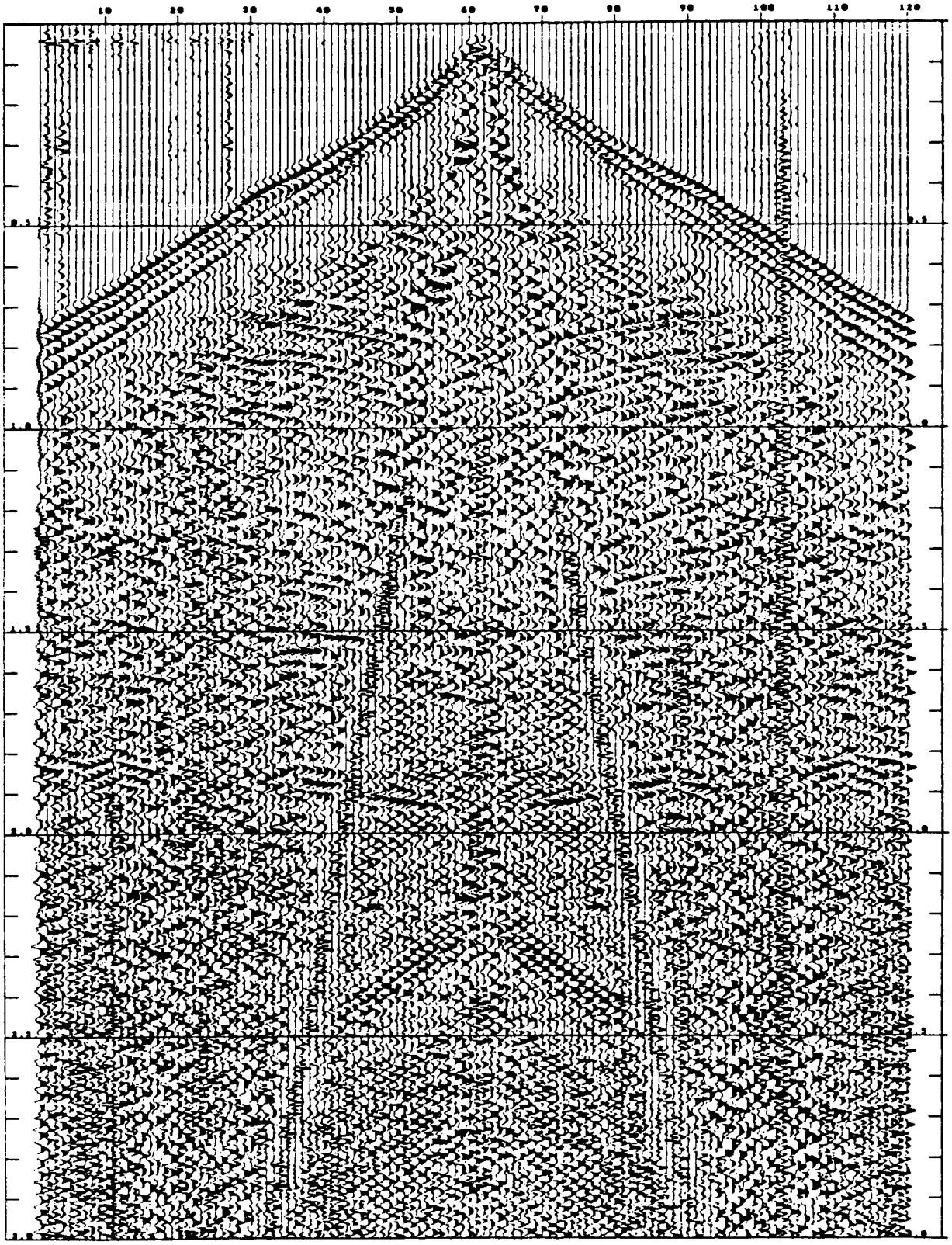
FFID: 0001
TIME: 19:12:45
DATE: Sat Aug 17



3* 8 SWEEPS

FILE: E:\data\DATA_TST\0004.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

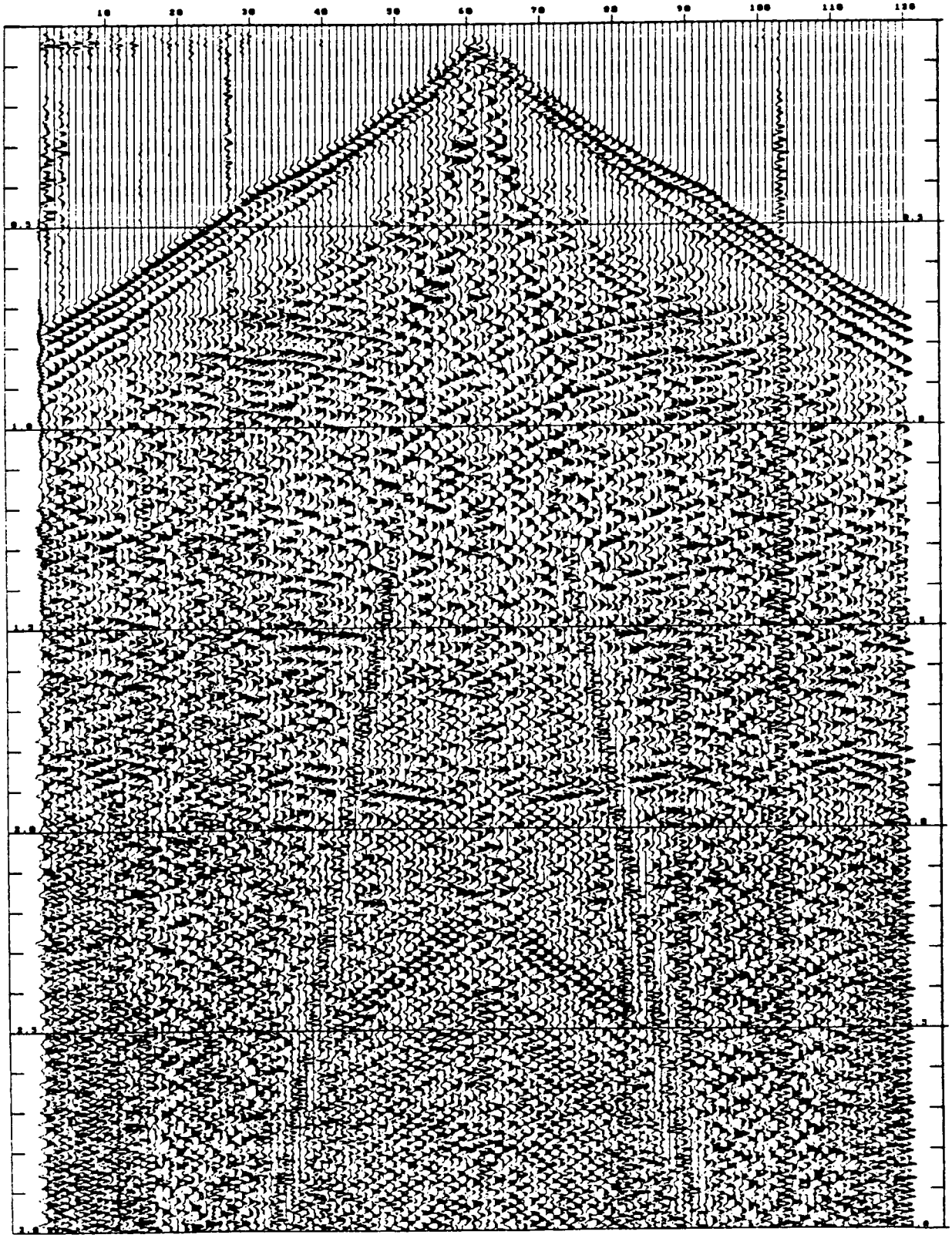
FFID: 0004
TIME: 19:36:34
DATE: Sat Aug 17



3 * 16
SWEEPS

FILE: E:\data\DATA_TST\0005.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

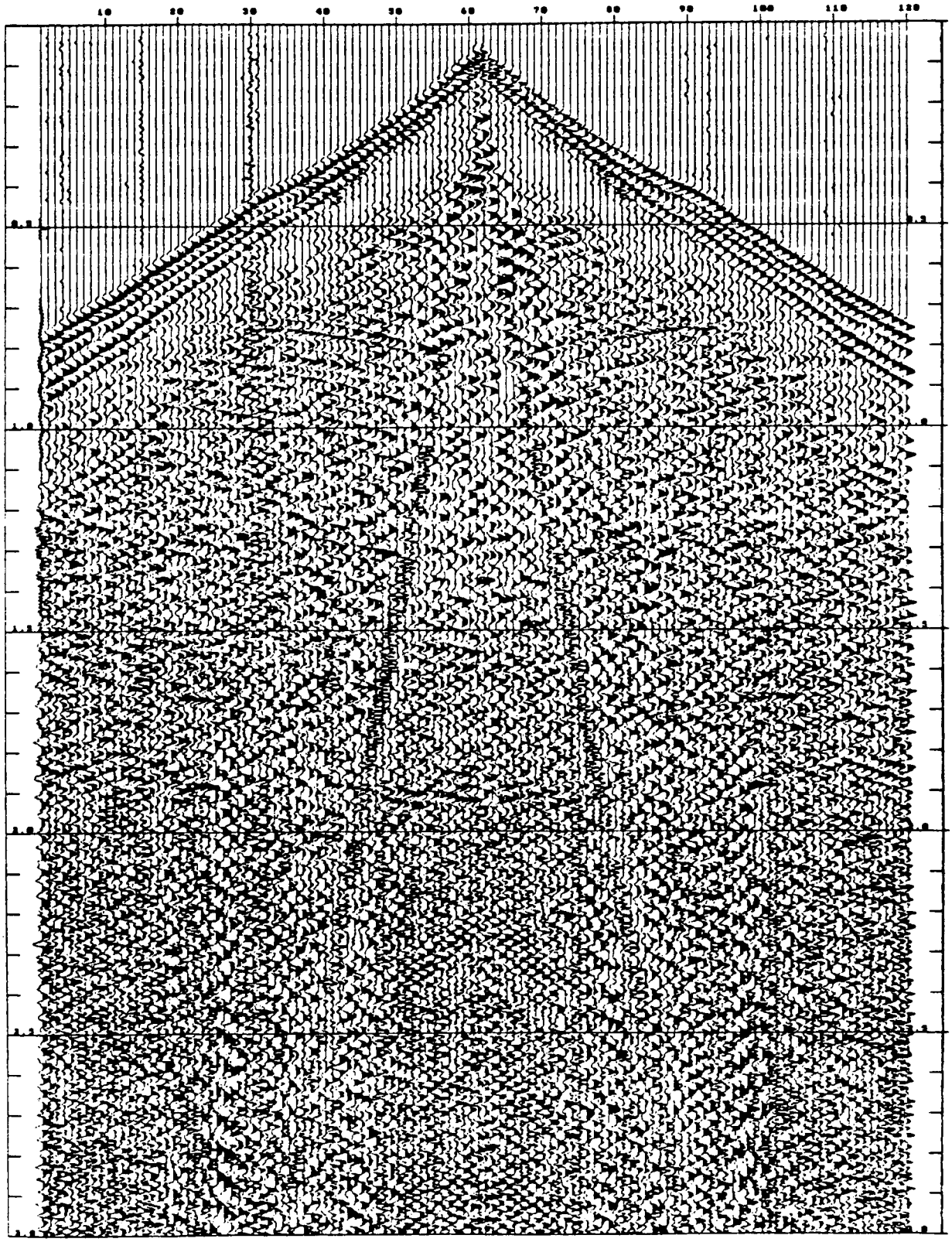
FFID: 0005
TIME: 19:42:22
DATE: Sat Aug 17



275' VIB TO 1ST
PHONE OFFSET

FILE: E:\data\DATA_TST\0006.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

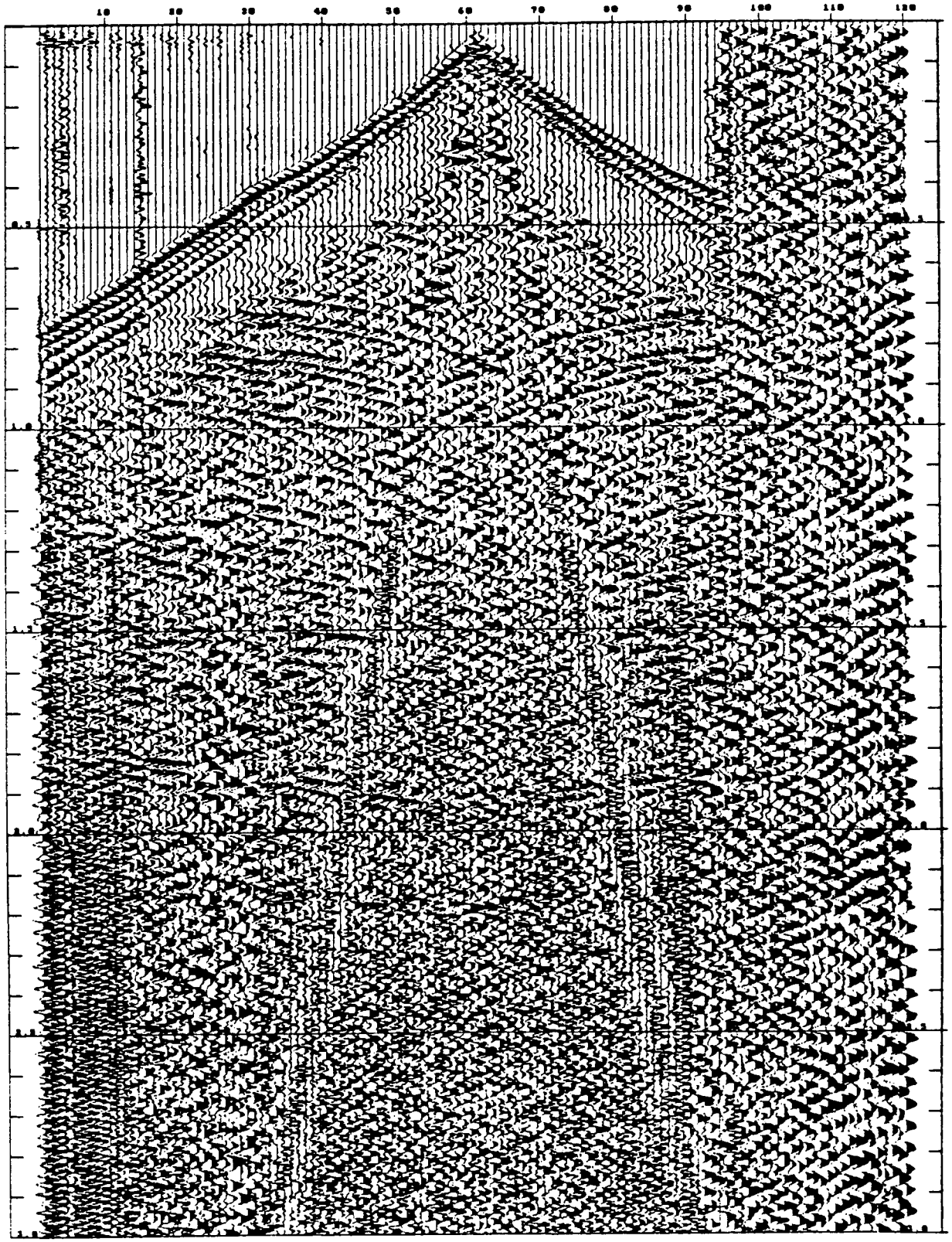
FFID: 0006
TIME: 19:48:09
DATE: Sat Aug 17



8 SECOND SWEEP
LENGTH

FILE: D:\DATA\DATA_TST\0007.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

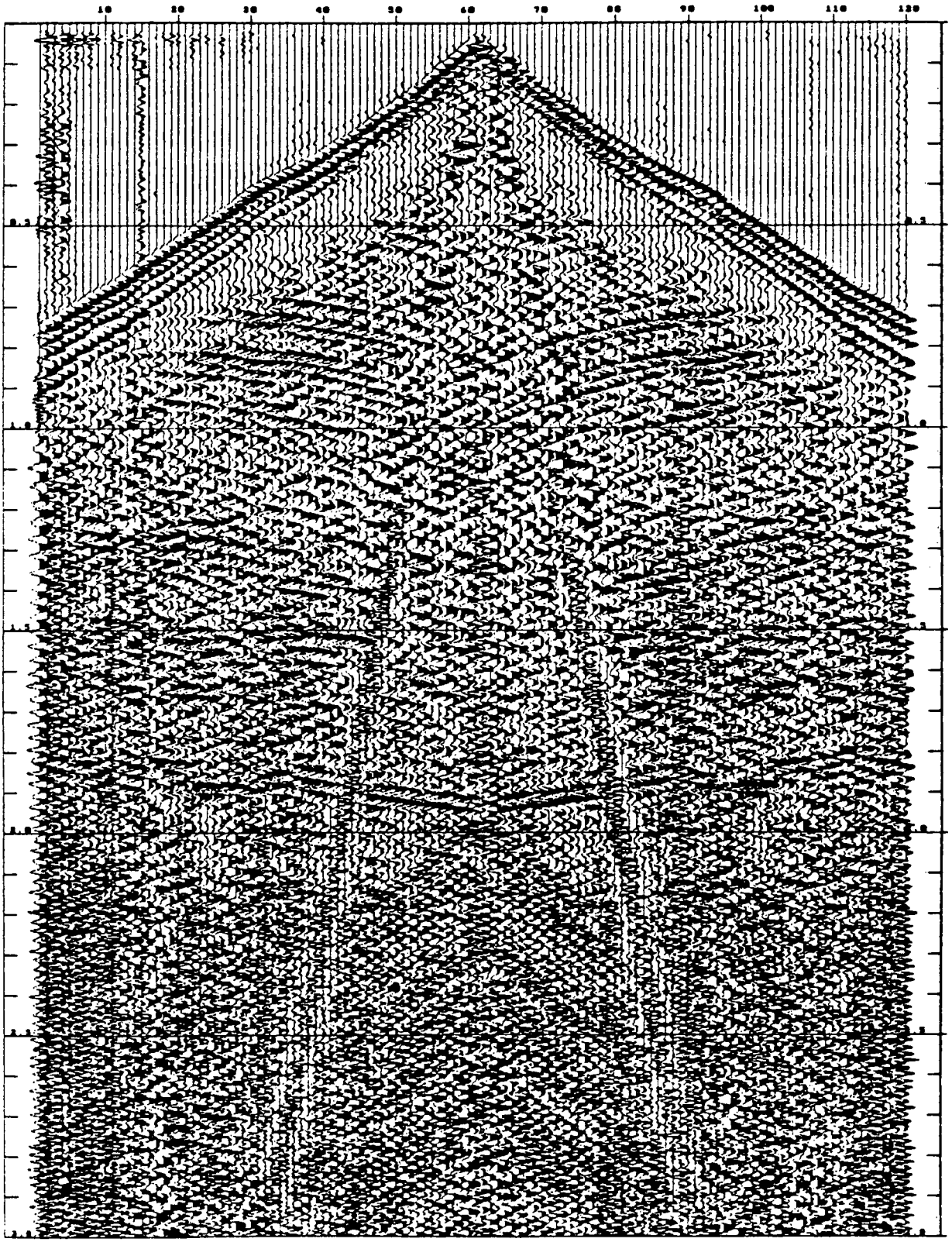
FFID: 0007
TIME: 21:43:15
DATE: Sat Aug 17



6 SECOND SWEEP LENGTH

FILE: D:\data\DATA_TST\0008.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

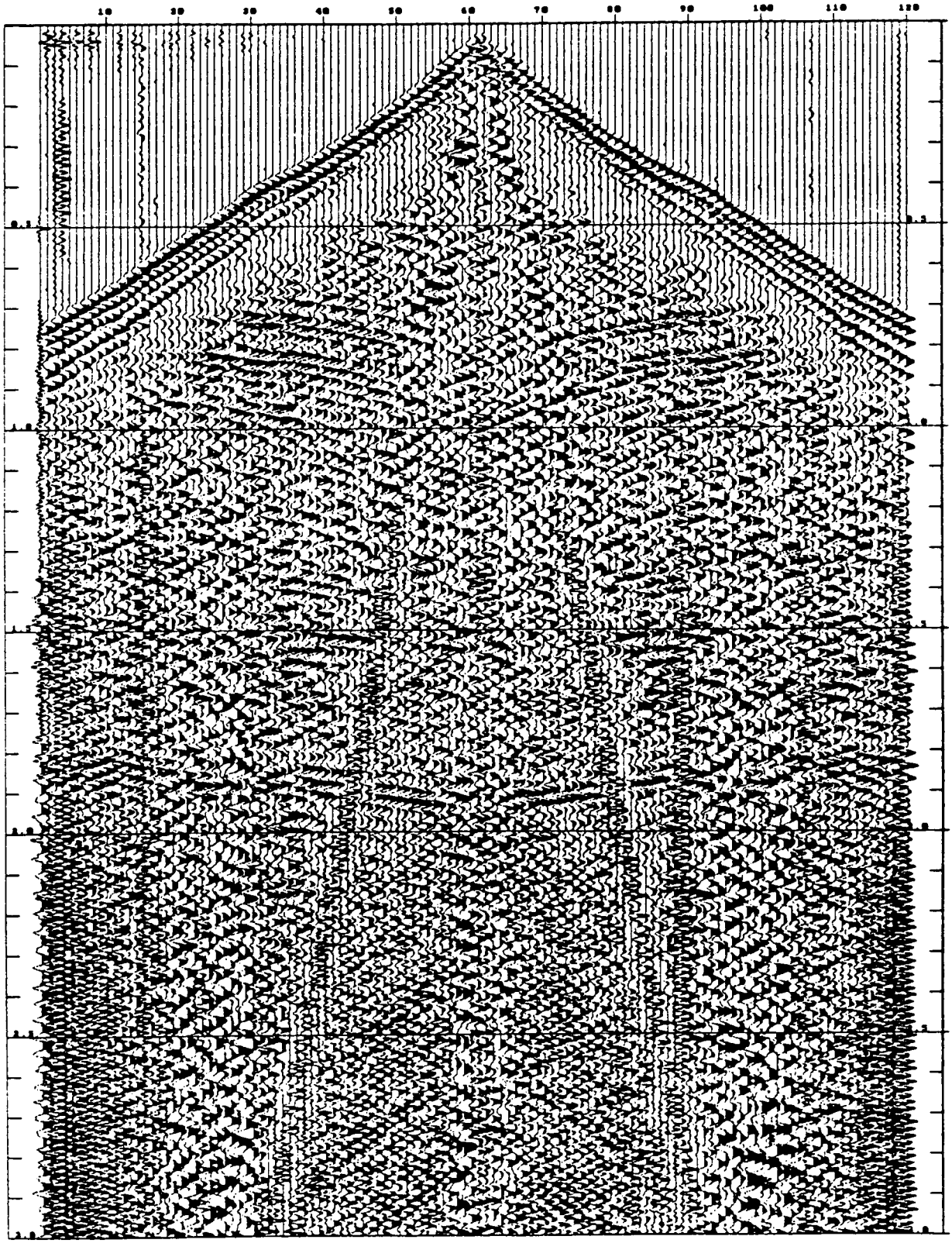
FFID: 0008
TIME: 21:30:23
DATE: Sat Aug 17



10-96 Hz.
BANDWIDTH

FILE: D:\DATA\DATA_TST\0009.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

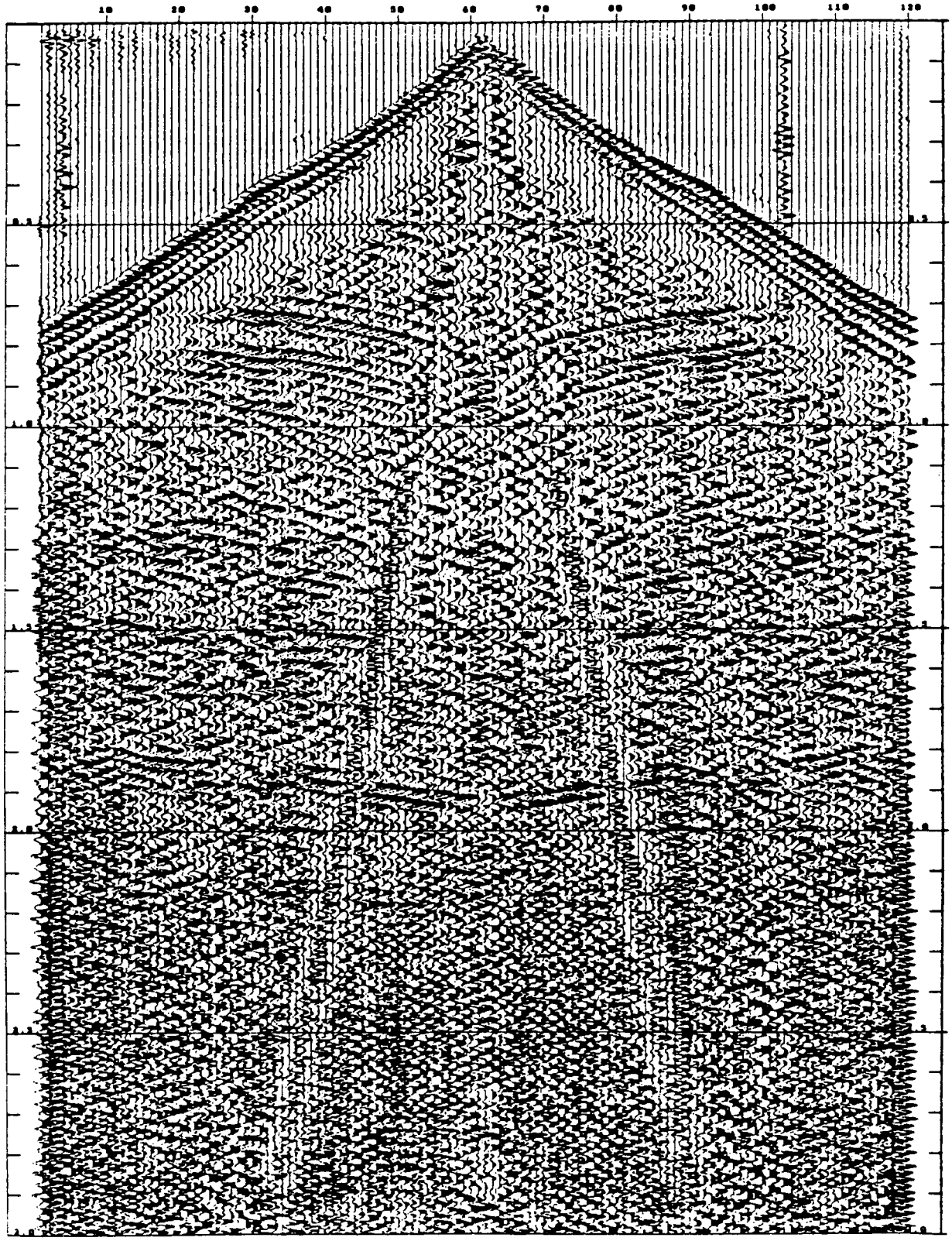
FFID: 0009
TIME: 21:44:50
DATE: Sat Aug 17



16-120 Hz
BANDWIDTH

FILE: D:\DATA\TEST\0010.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

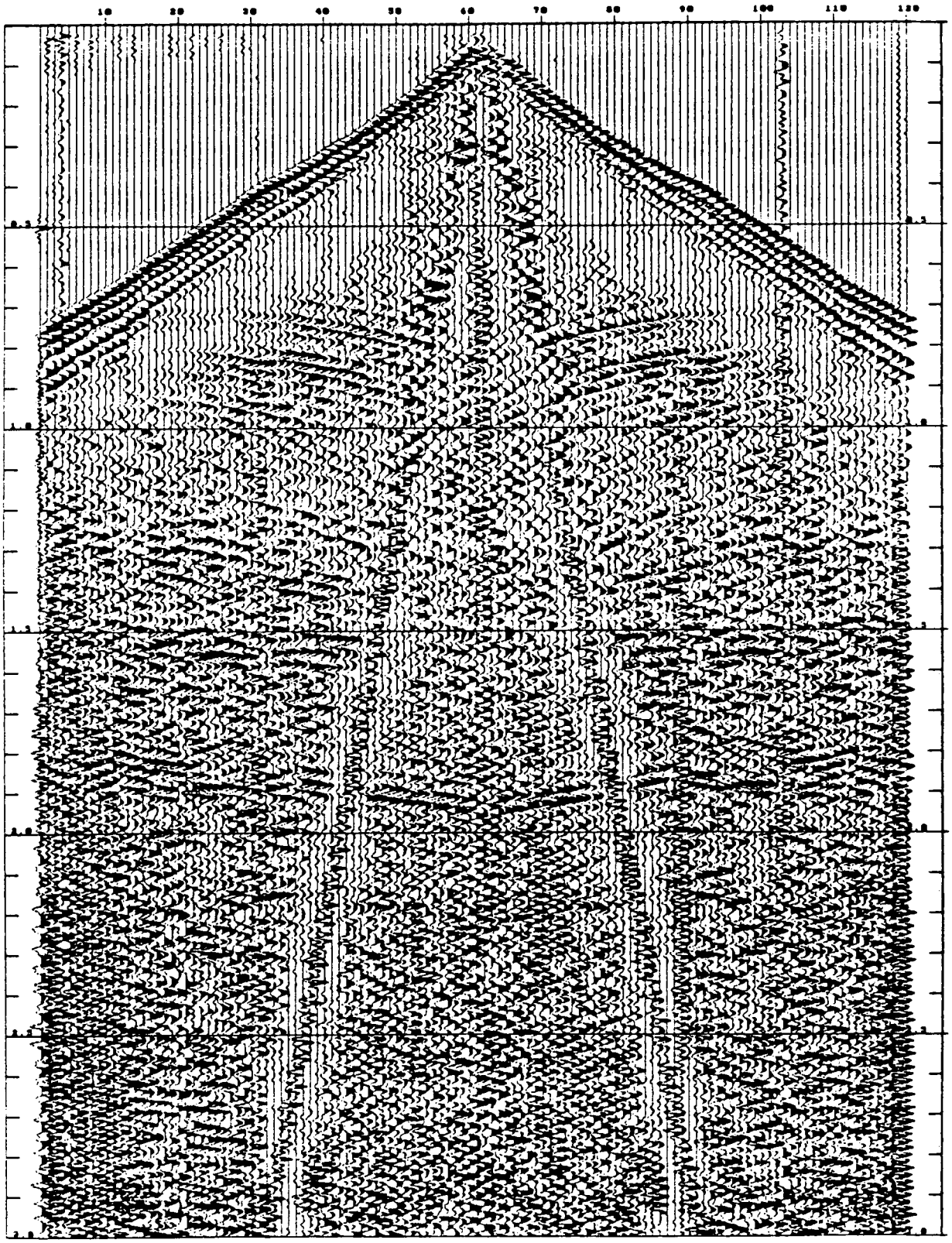
FFID: 0010
TIME: 23:06:03
DATE: Sat Aug 17



10-80 Hz.
BANDWIDTH

FILE: D:\DATA\DATA_TST\0011.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

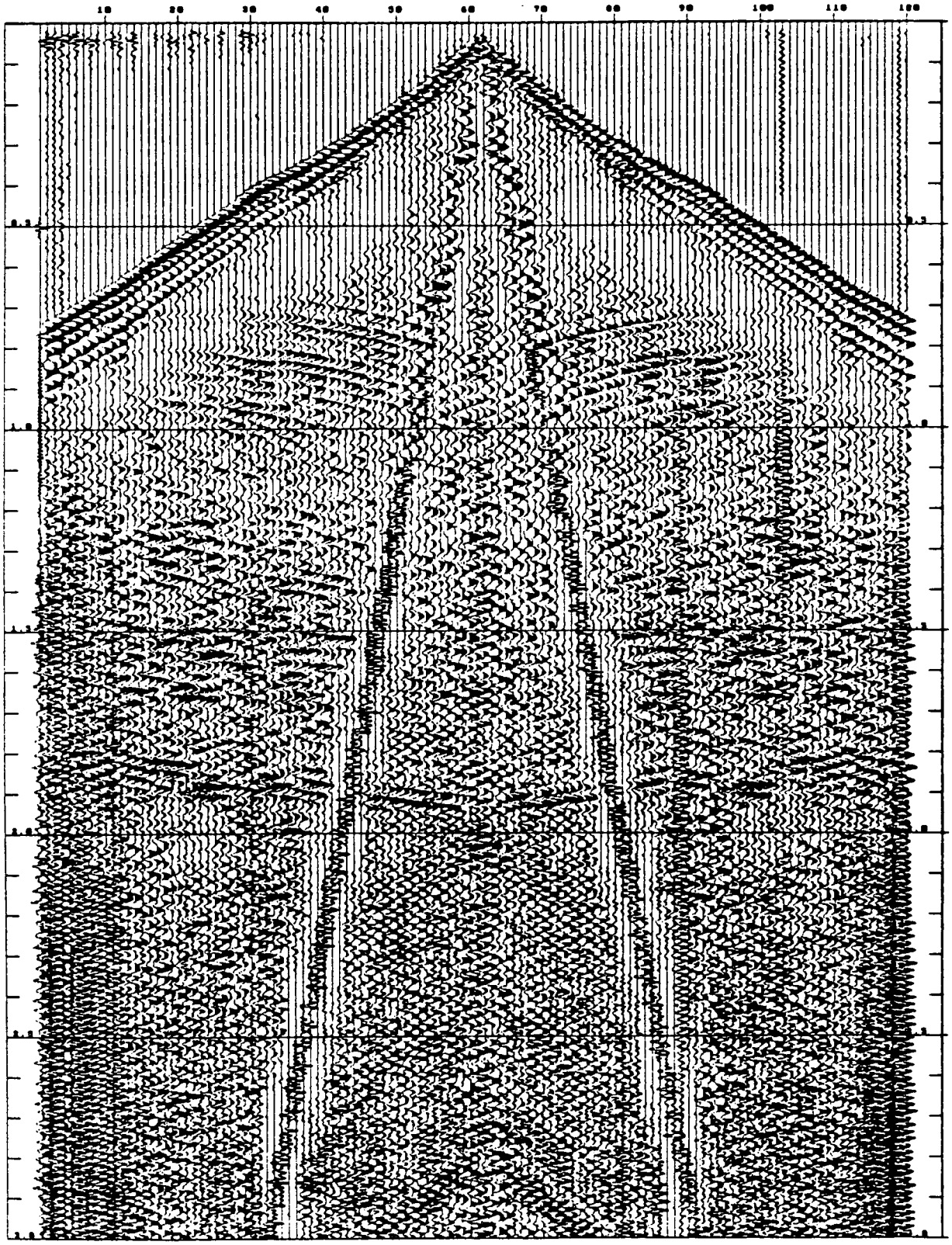
FFID: 0011
TIME: 23:13:11
DATE: Sat Aug 17



+3 db/OCT

FILE: D:\DATA\DATA_TST\0012.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

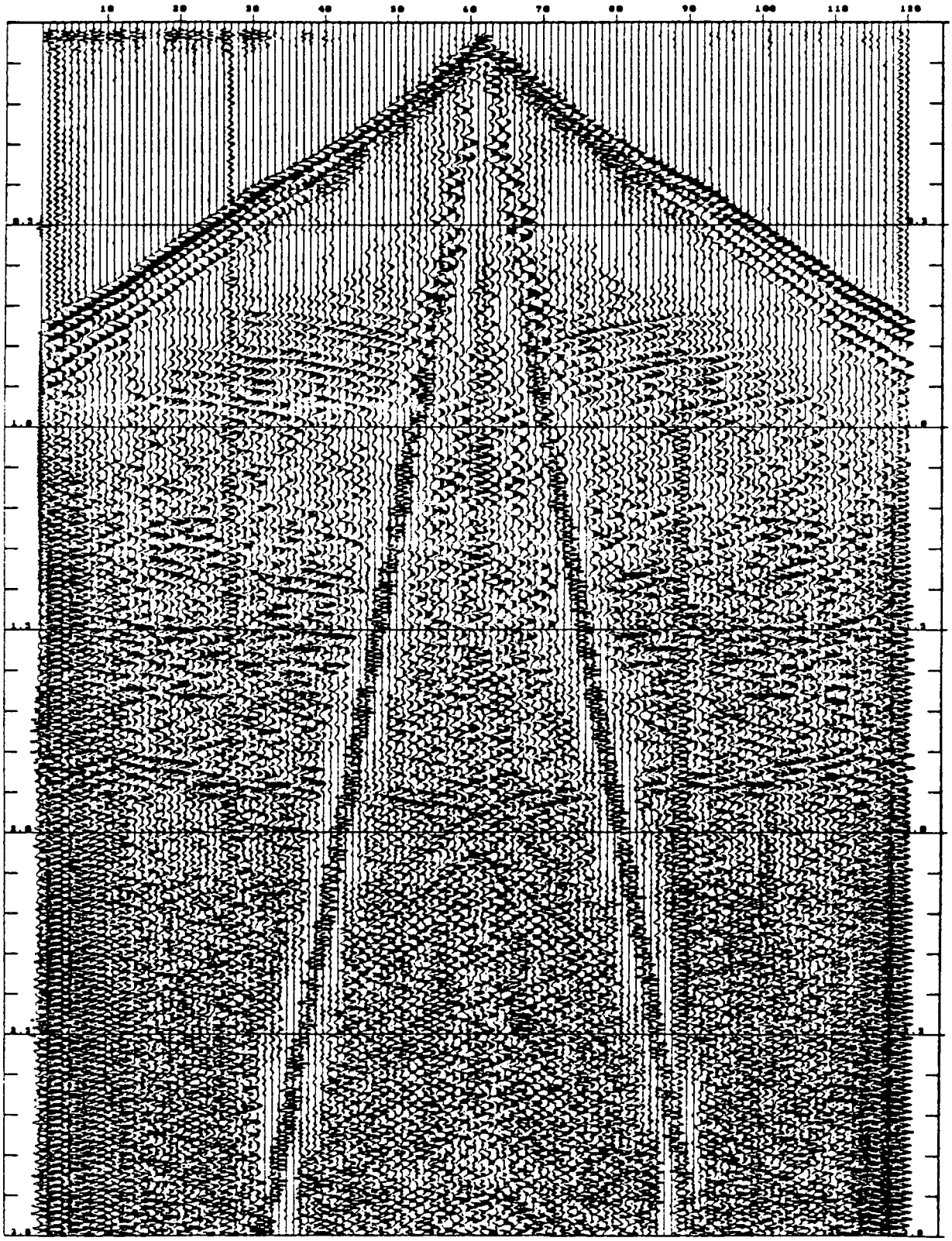
FFID: 0012
TIME: 23:14:23
DATE: Sat Aug 17



+6 db/OCT

FILE: D:\DATA\DATA_TST\0013.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

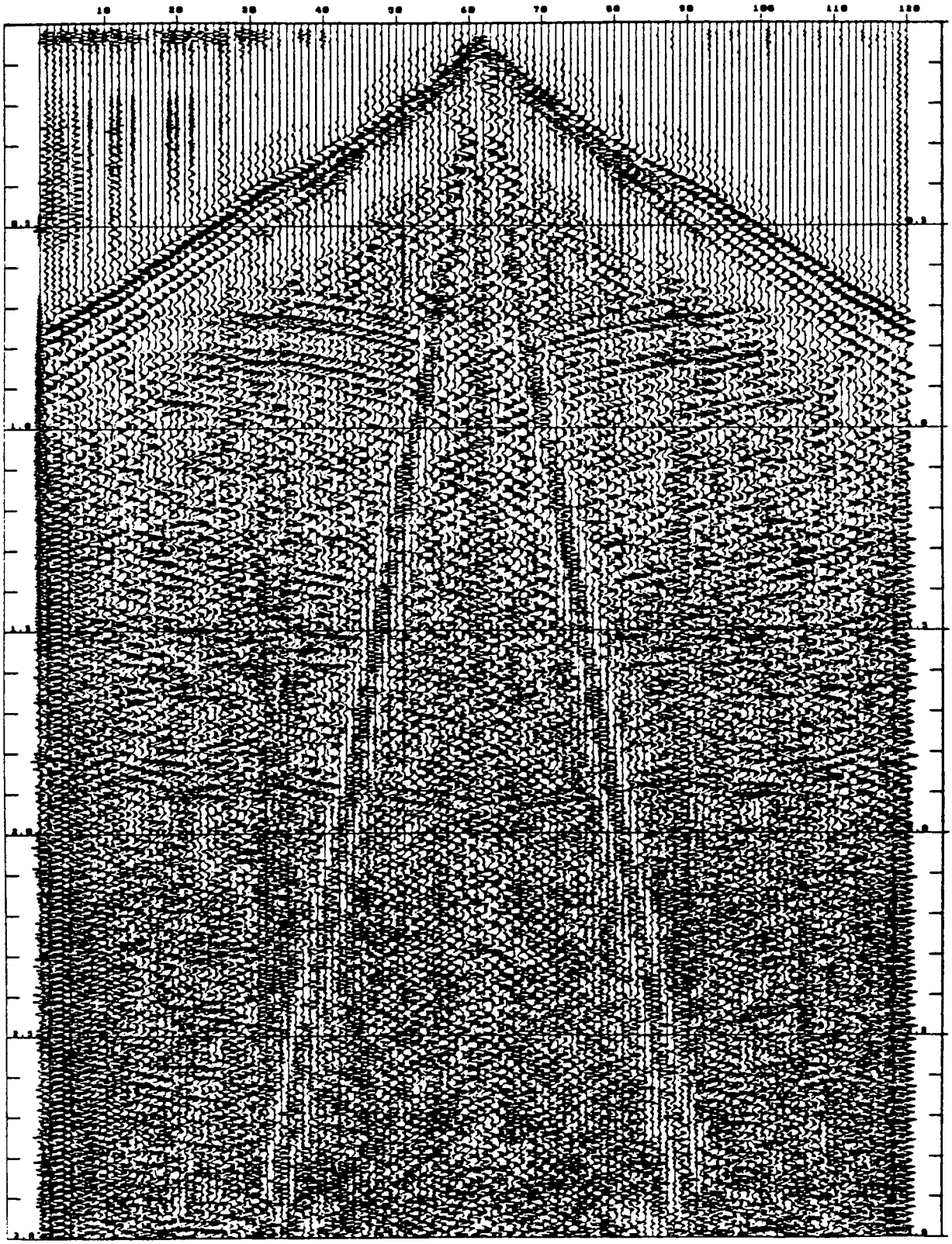
FFID: 0013
TIME: 23:15:35
DATE: Sat Aug 17



+ 9 dB/Oct.

FILE: D:\DATA\TEST\0014.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

FFID: 0014
TIME: 23:07:38
DATE: Sat Aug 17



APPENDIX B
Filter Panels of Test Sweeps #1

FILTER PANELS

There are two sets of filter panels. The first panel (far left) displays the input window. The next nine panels show the band pass filtered outputs of 10-20, 20-40, 30-60, 40-80 , 50-100, 60-120, 70-140, 80-140, and finally 90-140.

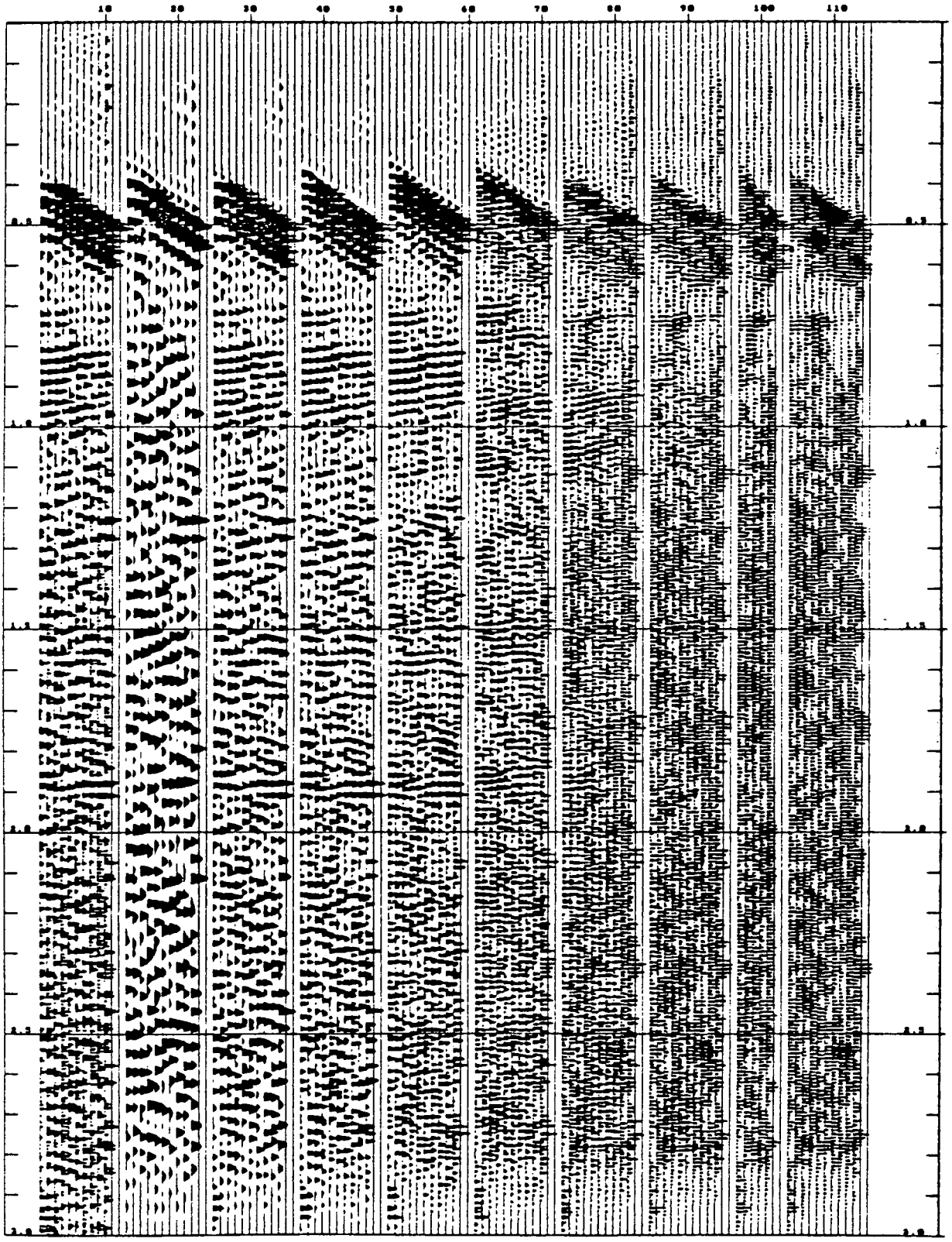
Basically the panels increment by 10 hz and they have a half octave bandwidth.

These panels were AGC'd. In some cases AGC of a filter panel will give erroneous results. There is the possibility to gain up the frequencies that were supposed to be filtered. It is fairly obvious when this occurs however. Note the 90-140 panel (farthest to the right) in sweep 011 (10-80 hz. band width).

BASE SWEEP 55' GEOPHONE ARRAY

FILE: D:\DATA\DATA_TST\0001.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

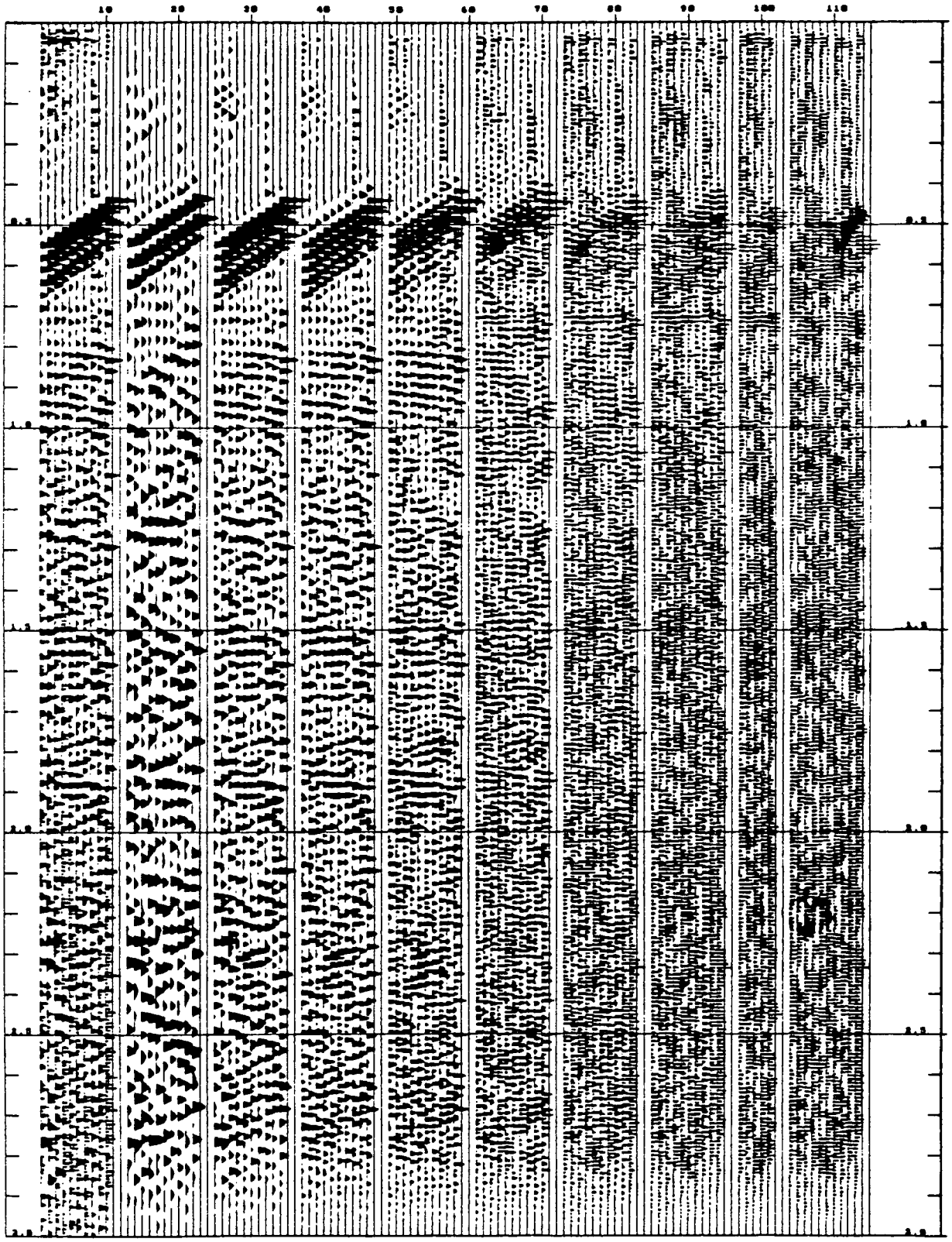
FFID: 0001
TIME: 23:44:16
DATE: Sat Aug 17



BASE SWEEP
110' GEOPHONE ARRAY

FILE: E:\DATA\DATA_TST\0001.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

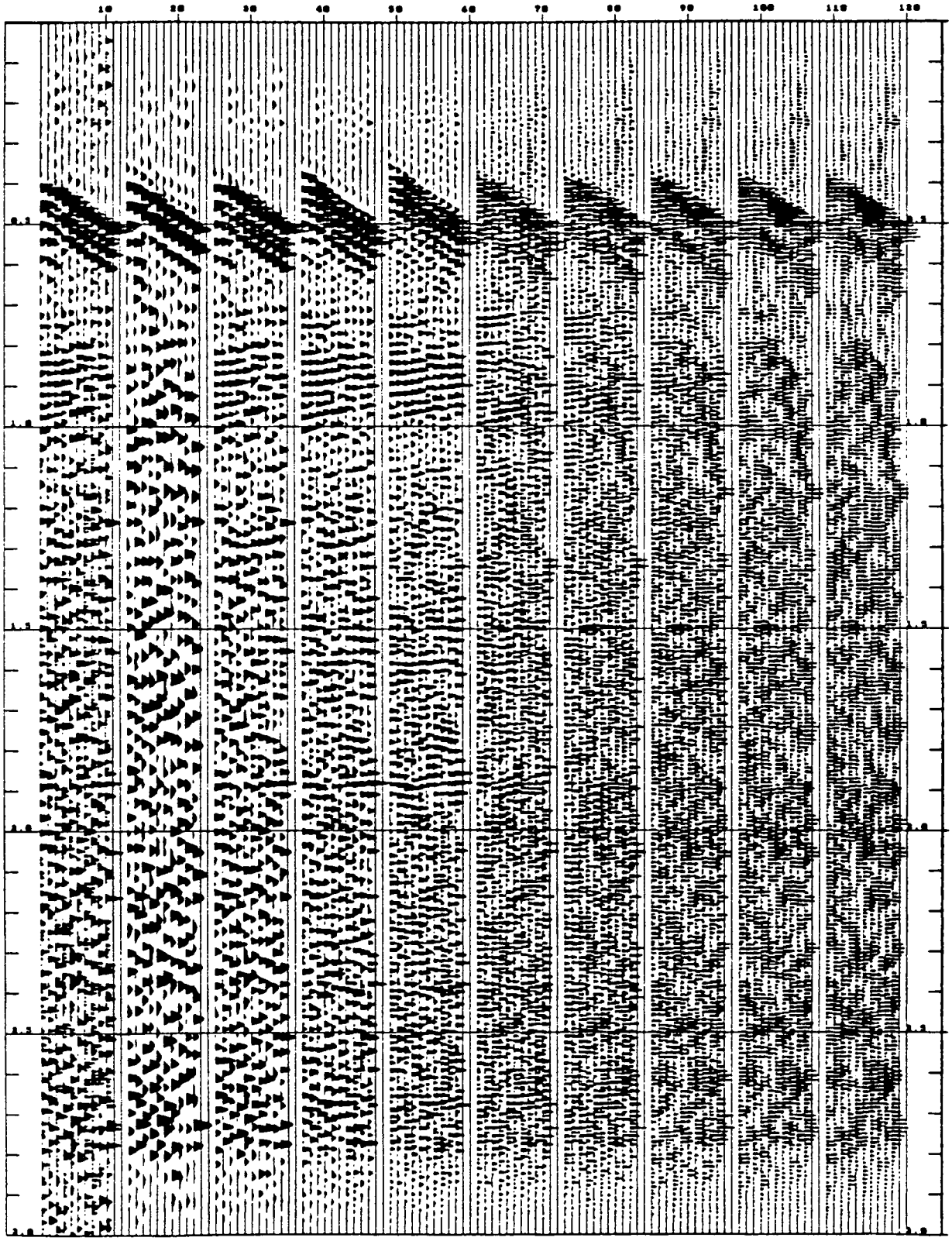
FFID: 0001
TIME: 23:37:37
DATE: Sat Aug 17



220' VIB ARRAY

FILE: D:\DATA\DATA_TST\0002.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

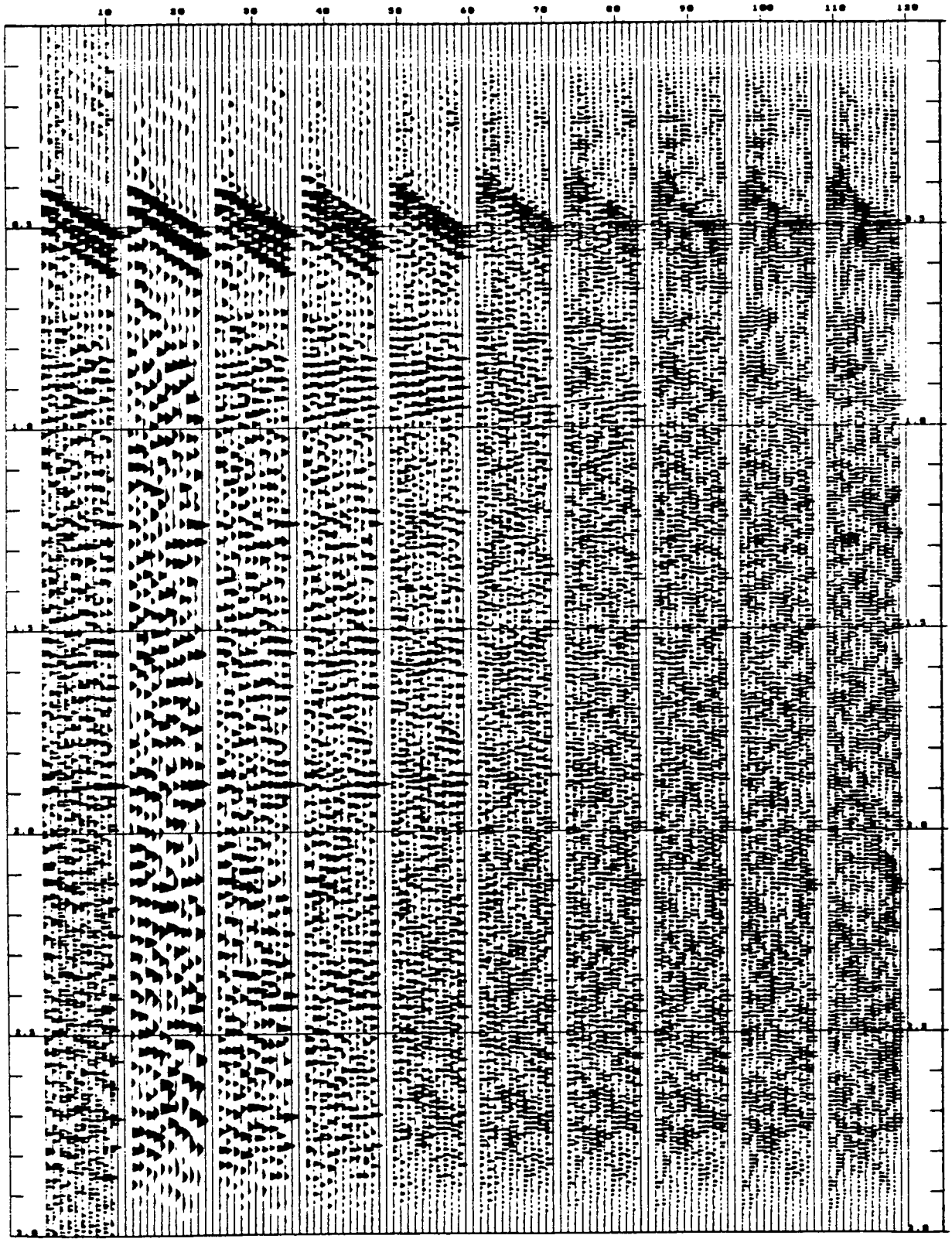
FFID: 0002
TIME: 23:52:11
DATE: Sat Aug 17



330' VIB ARRAY

FILE: D:\DATA\DATA_TST\0003.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

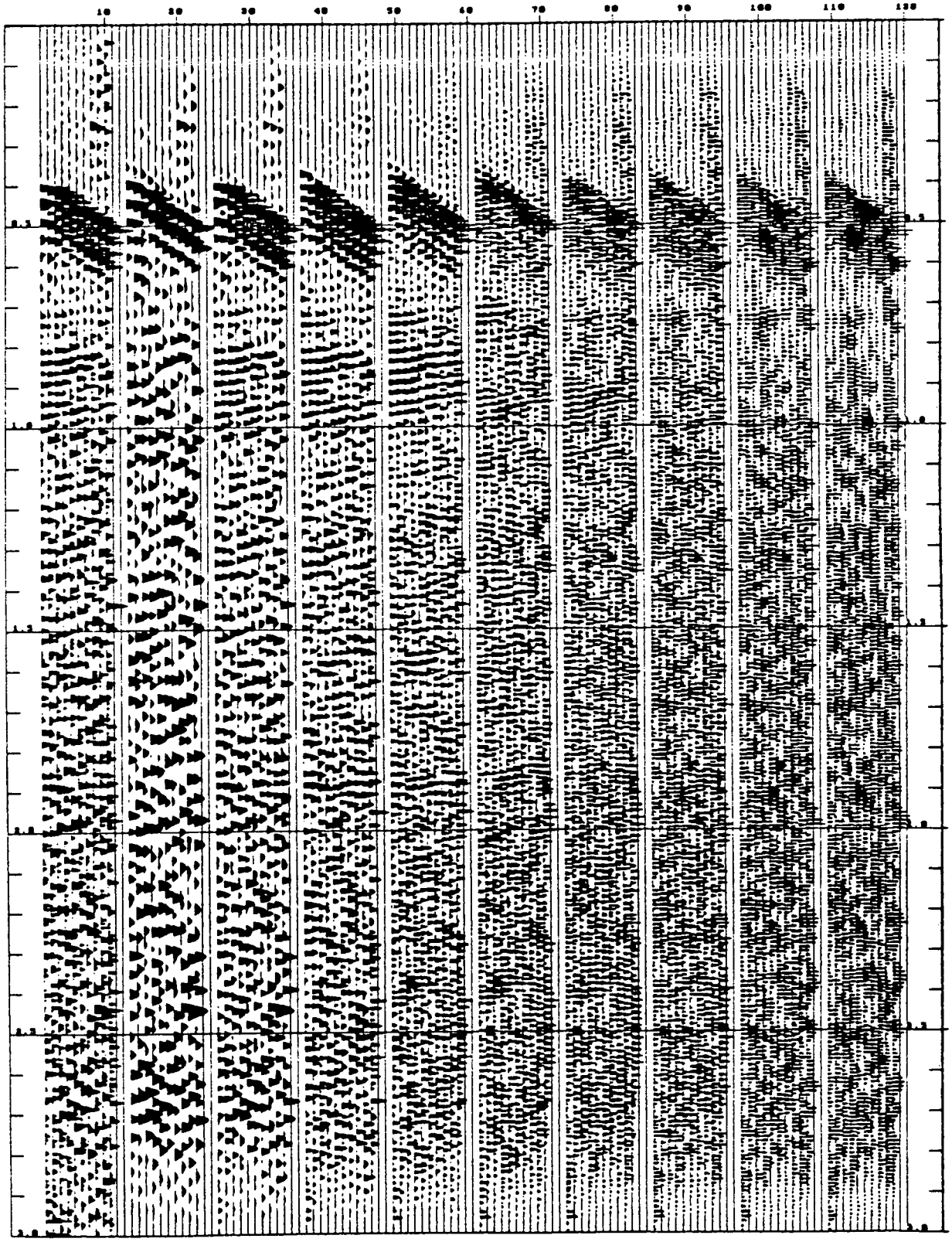
FFID: 0003
TIME: 23:55:51
DATE: Sat Aug 17



3 x 8 SWEEPS SUMMED

FILE: D:\DATA\DATA_TST\0004.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

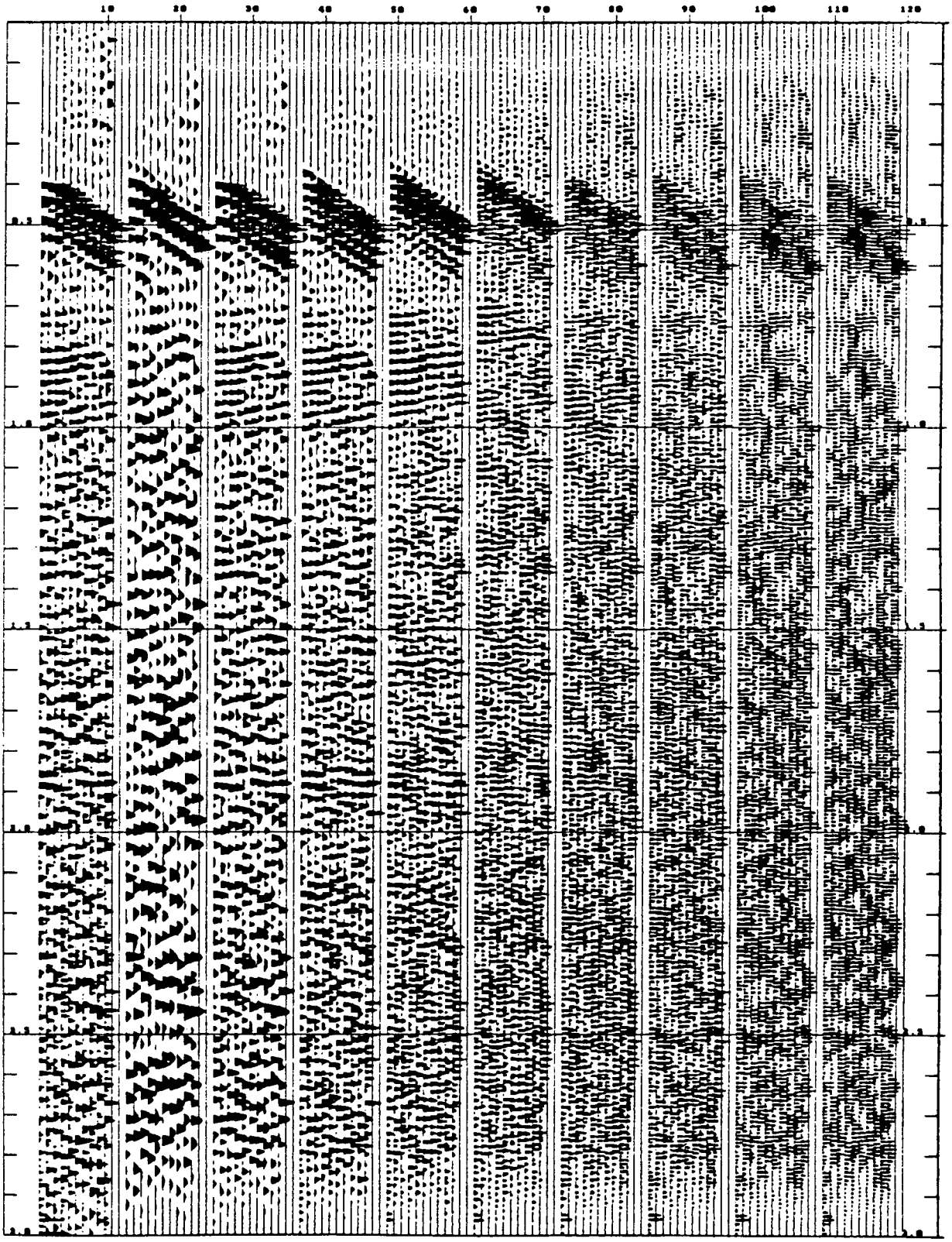
FFID: 0004
TIME: 23:59:30
DATE: Sat Aug 17



3 x 16 sweeps summed

FILE: D:\DATA\DATA_TST\0005.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

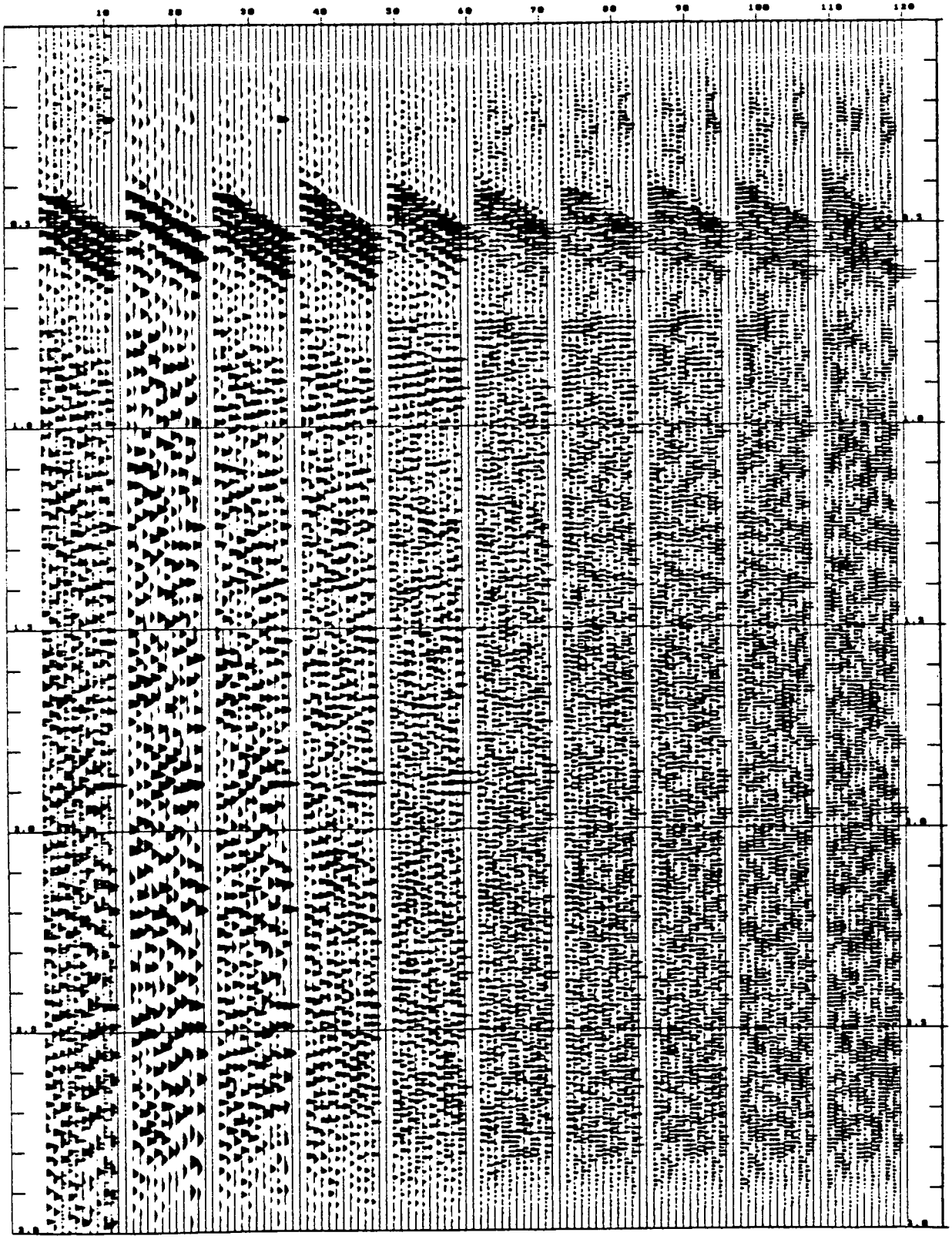
FFID: 0005
TIME: 00:03:11
DATE: Sun Aug 18



275' GAP: VIB TO 1ST PHONE

FILE: D:\DATA\DATA_TST\0006.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

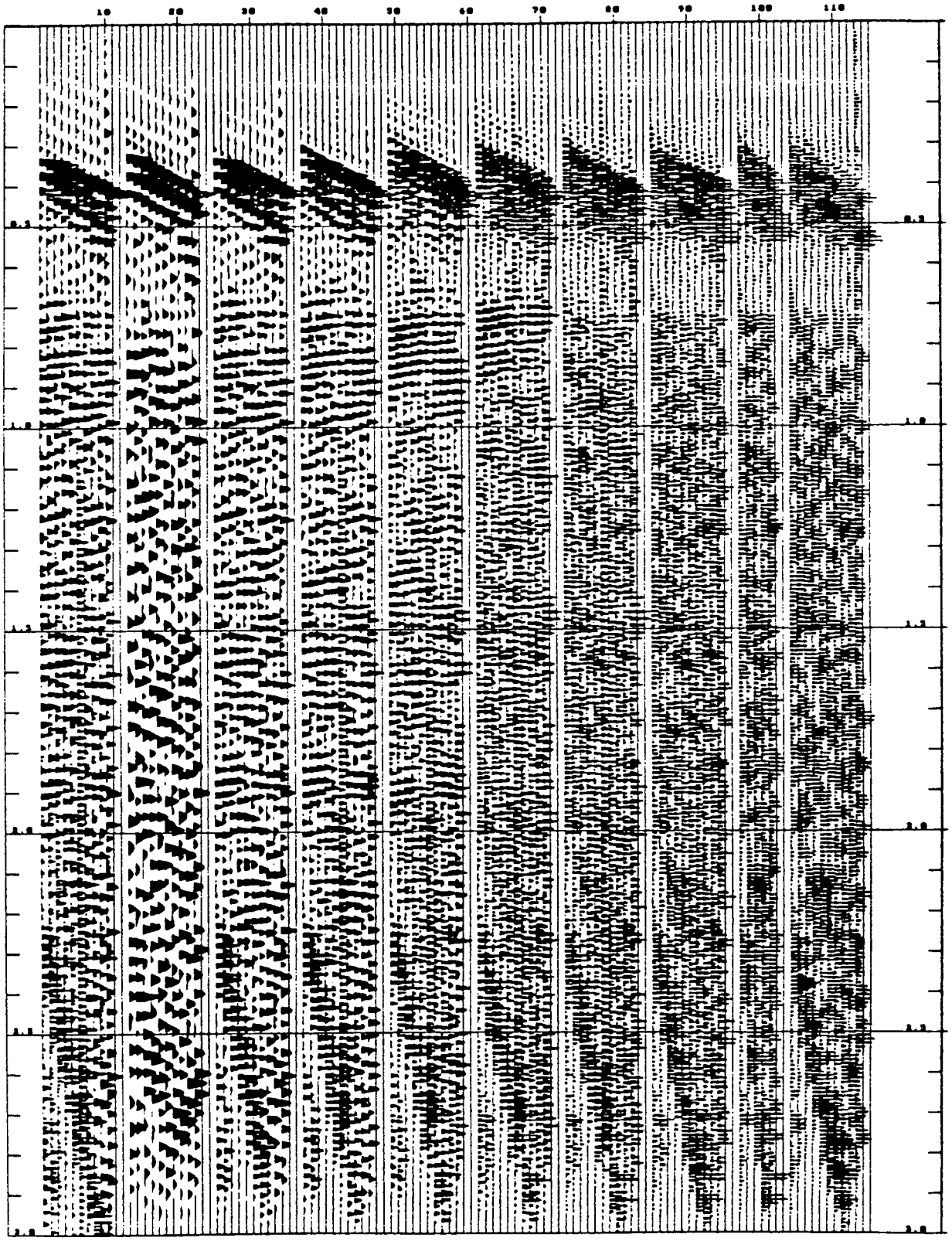
FFID: 0006
TIME: 00:06:50
DATE: Sun Aug 18



8 SECOND SWEEP LENGTH

FILE: D:\DATA\DATA_TST\0007.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

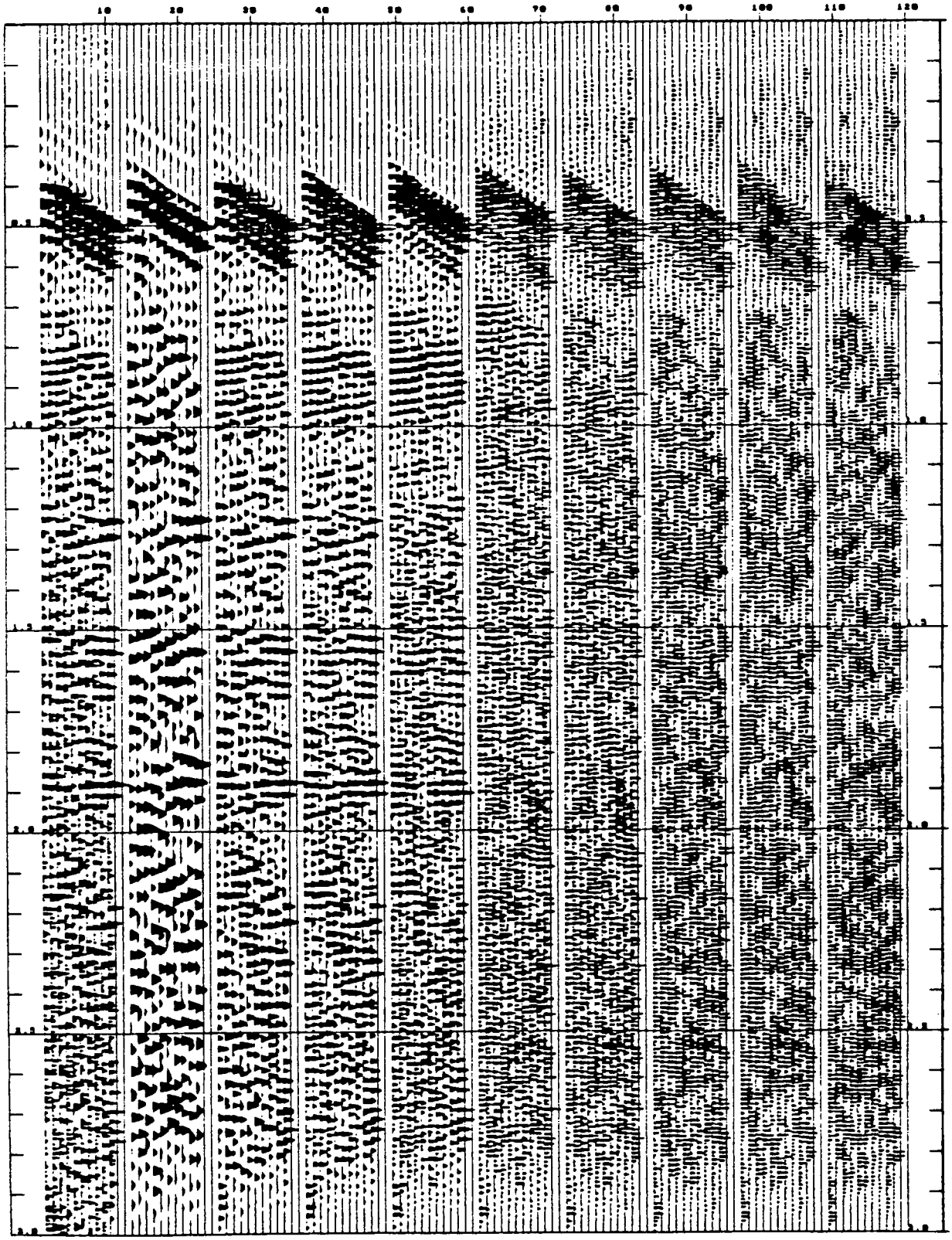
FFID: 0007
TIME: 01:26:40
DATE: Sun Aug 18



6 SEC SWEEP LENGTH

FILE: D:\DATA\DATA_TST\0008.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

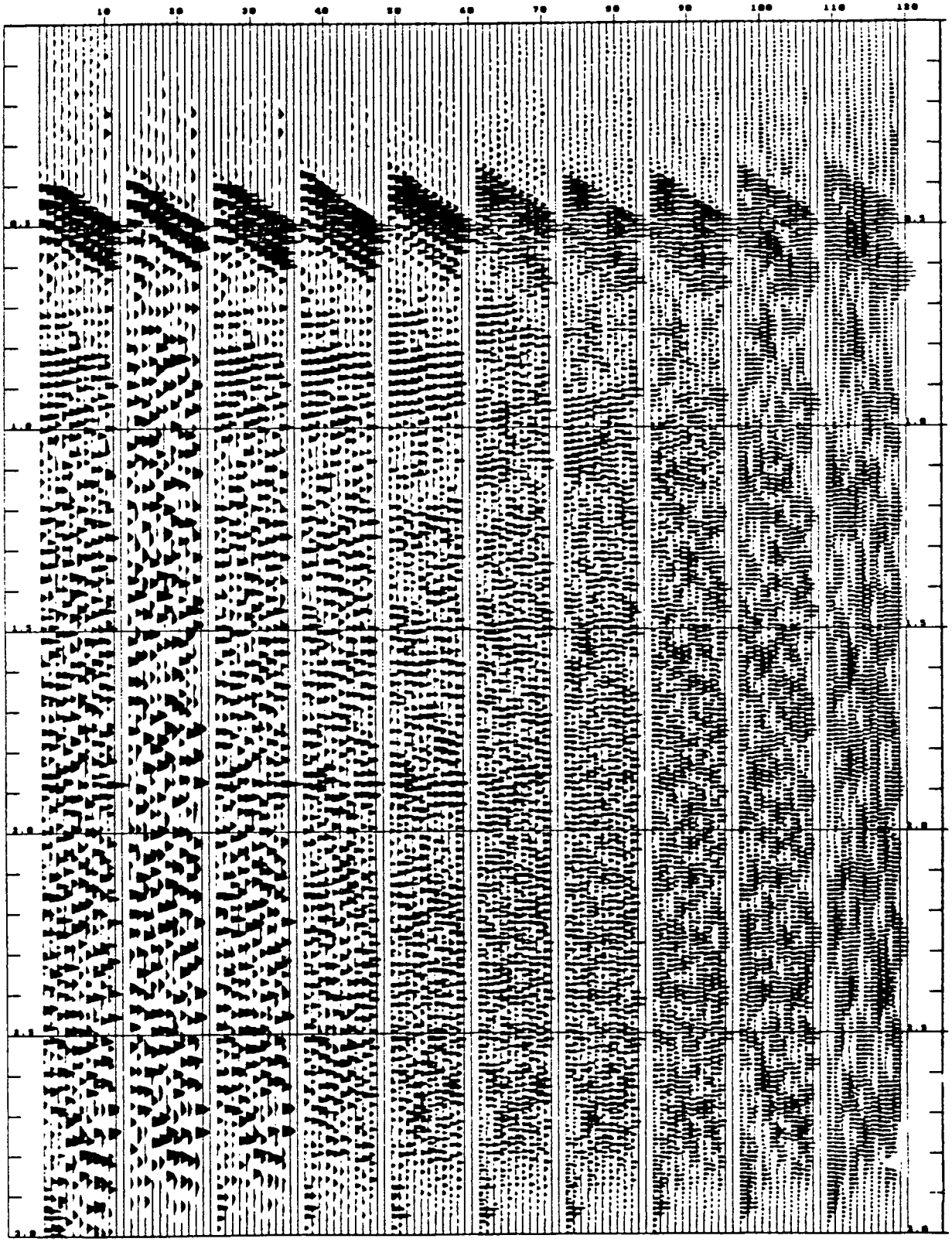
FFID: 0008
TIME: 00:14:09
DATE: Sun Aug 18



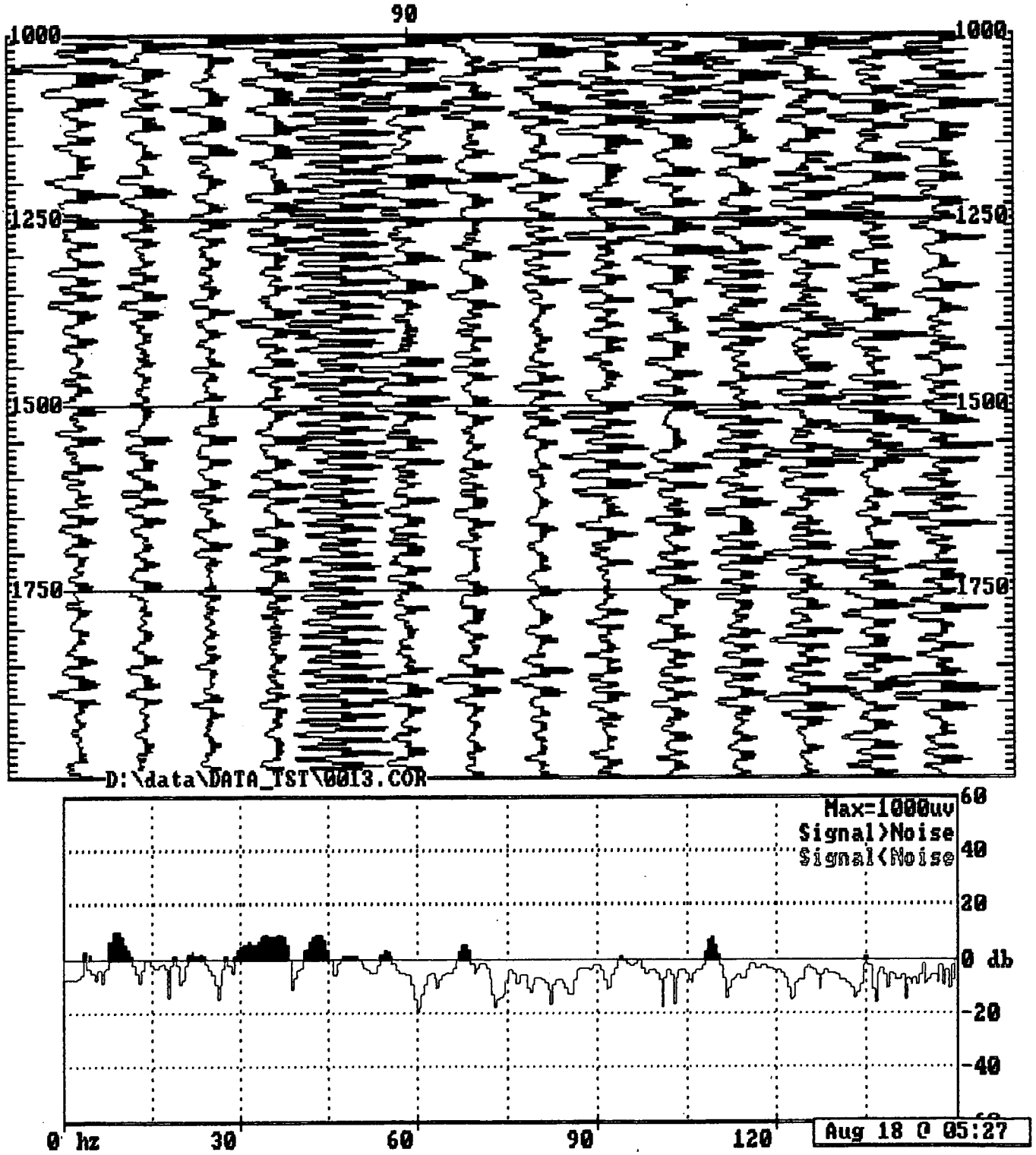
10-96 Hz. BANDWIDTH

FILE: D:\DATA\DATA_TST\0009.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

FFID: 0009
TIME: 00:17:48
DATE: Sun Aug 18



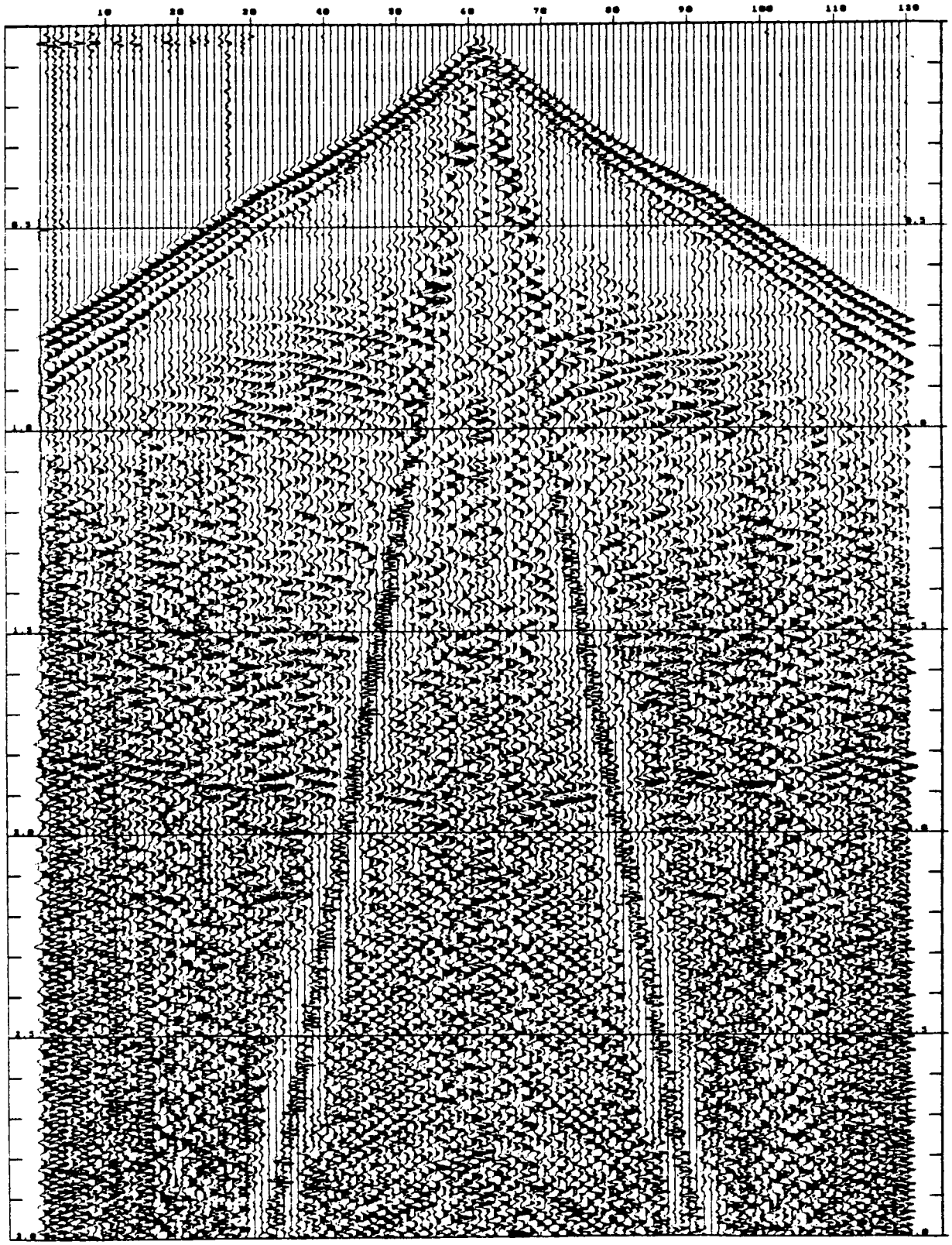
SIGNAL TO NOISE: +6 DB/OCT.



BASE SWEEP

FILE: D:\DATA\DATA_TST\0001.GNR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

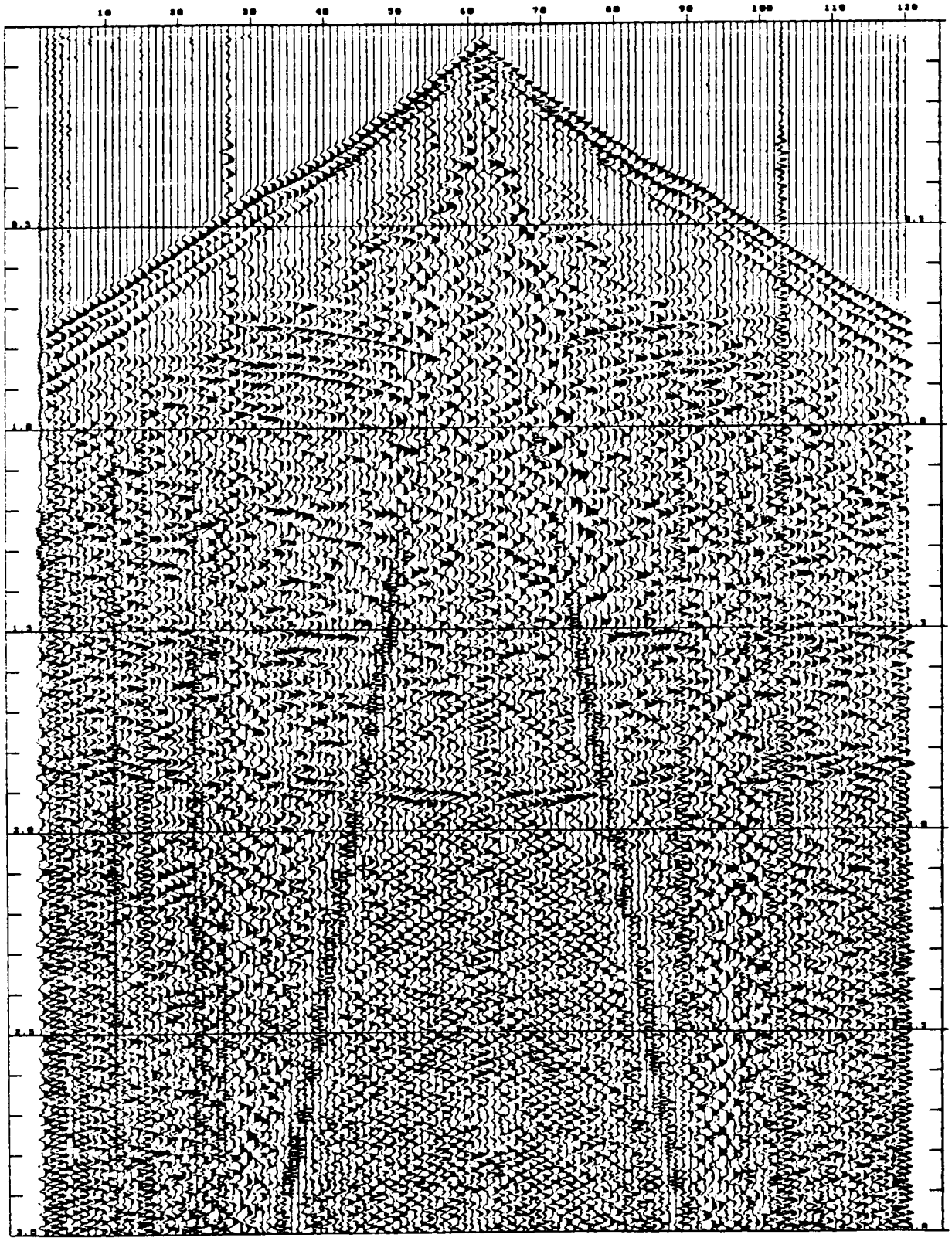
FFID: 0001
TIME: 19:08:21
DATE: Sat Aug 17



22.0' VIB
ARRAY

FILE: E:\data\DATA_TST\0002.GNr
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: WTVA

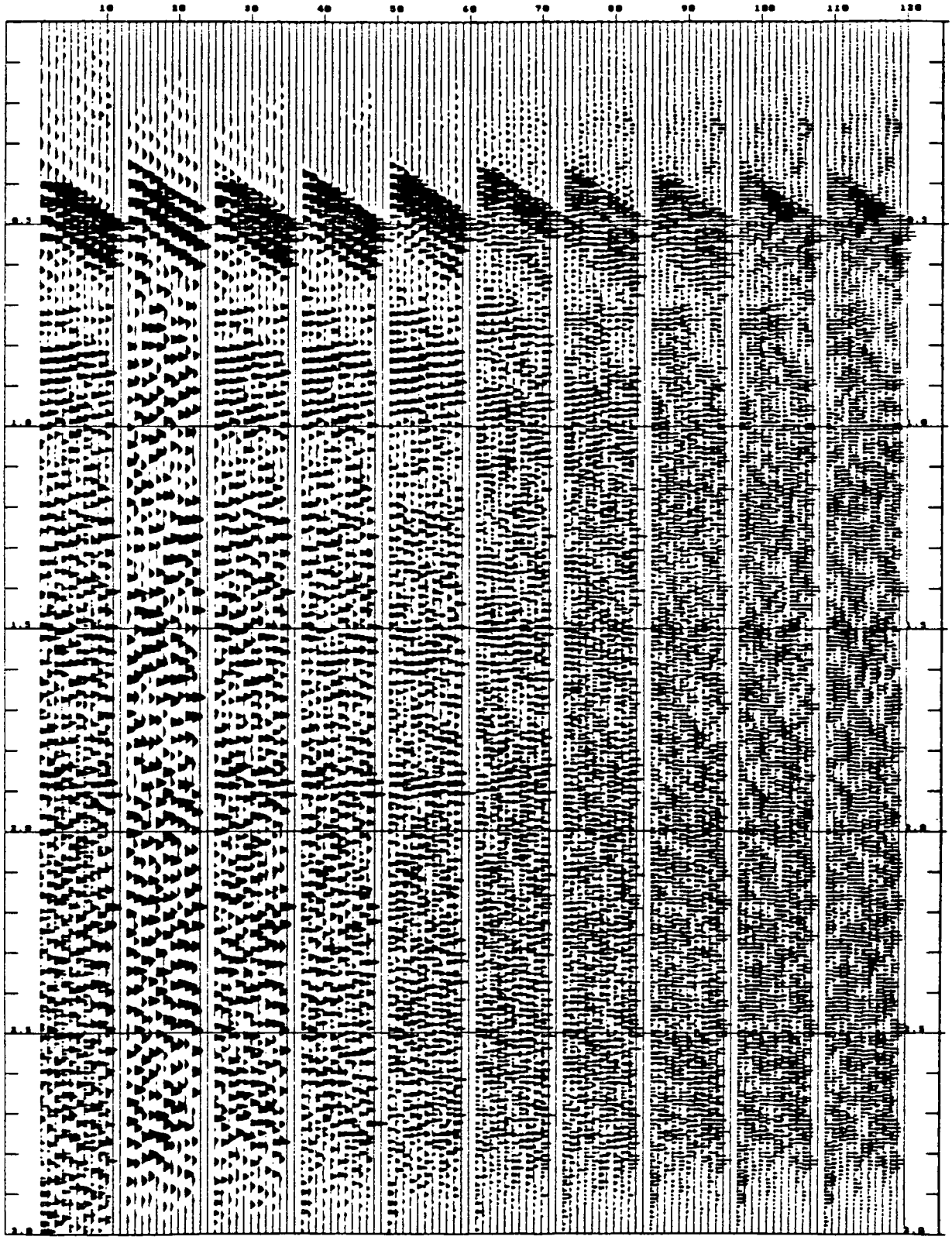
FFID: 0002
TIME: 19:24:59
DATE: Sat Aug 17



16-120 Hz. BANDWIDTH

FILE: D:\DATA\DATA_TST\0010.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

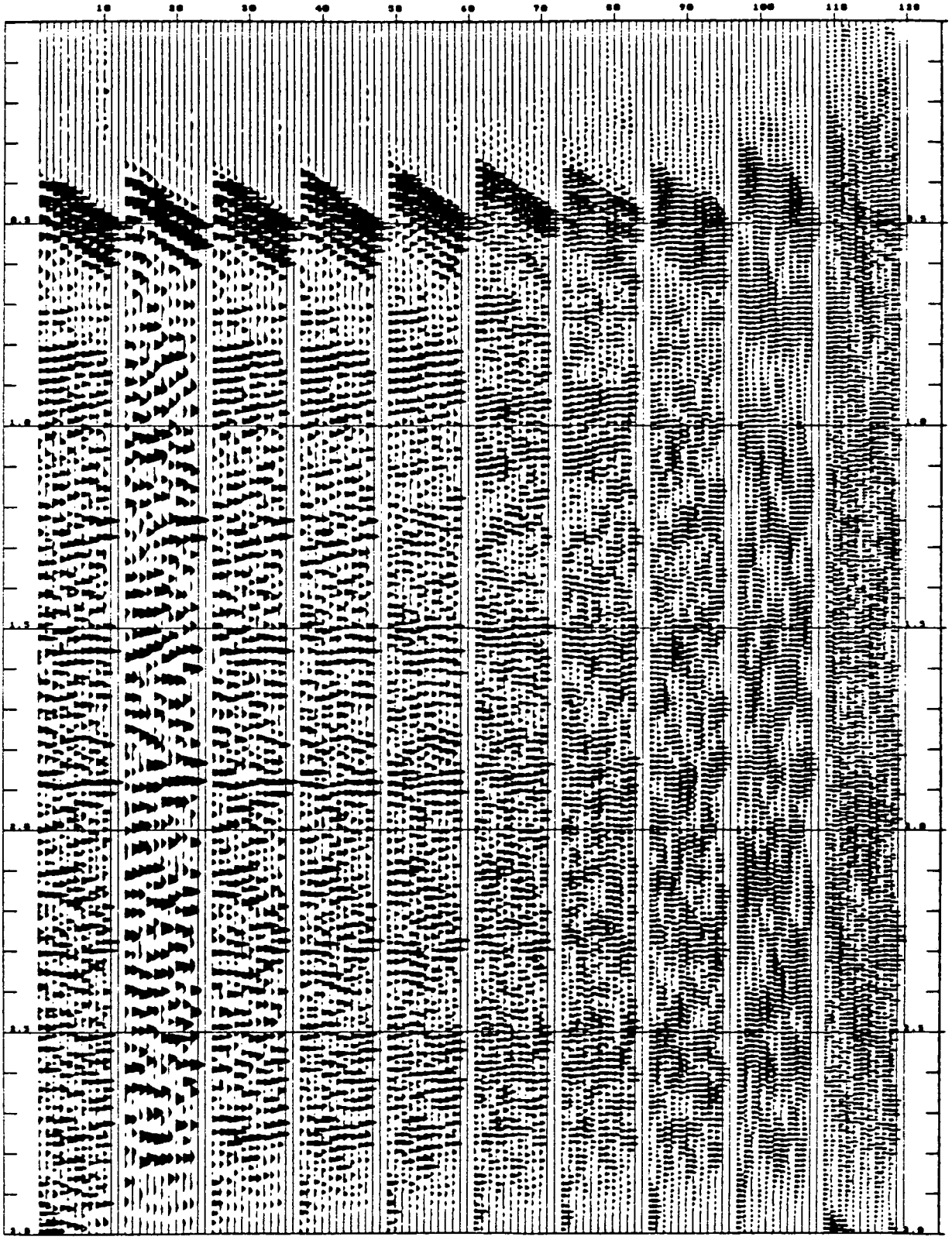
FFID: 0010
TIME: 00:21:28
DATE: Sun Aug 18



10-80 Hz
BANDWIDTH

FILE: D:\DATA\DATA_TST\0011.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

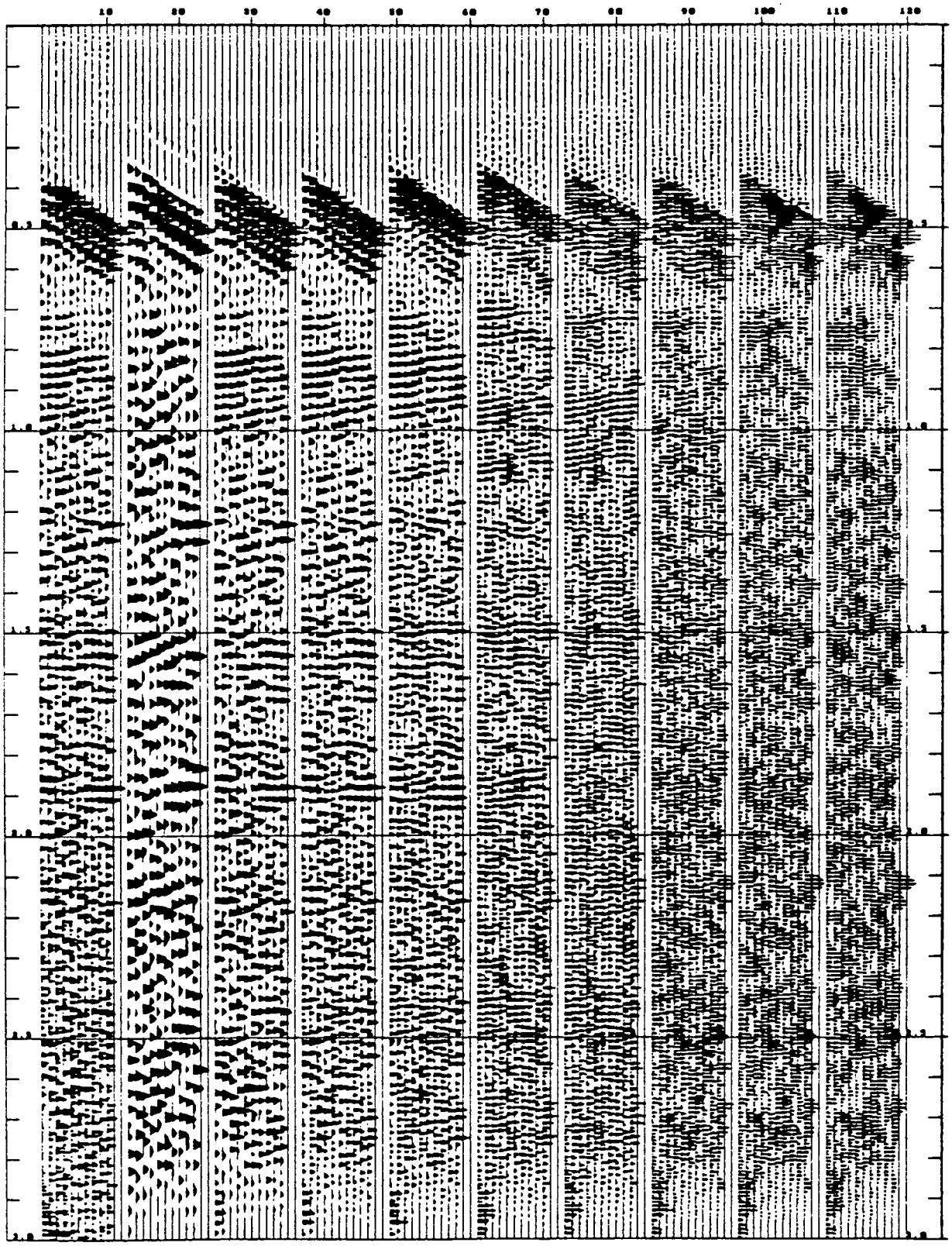
FFID: 0011
TIME: 00:25:07
DATE: Sun Aug 18



+3 db/oct.

FILE: D:\DATA\DATA_TST\0012.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

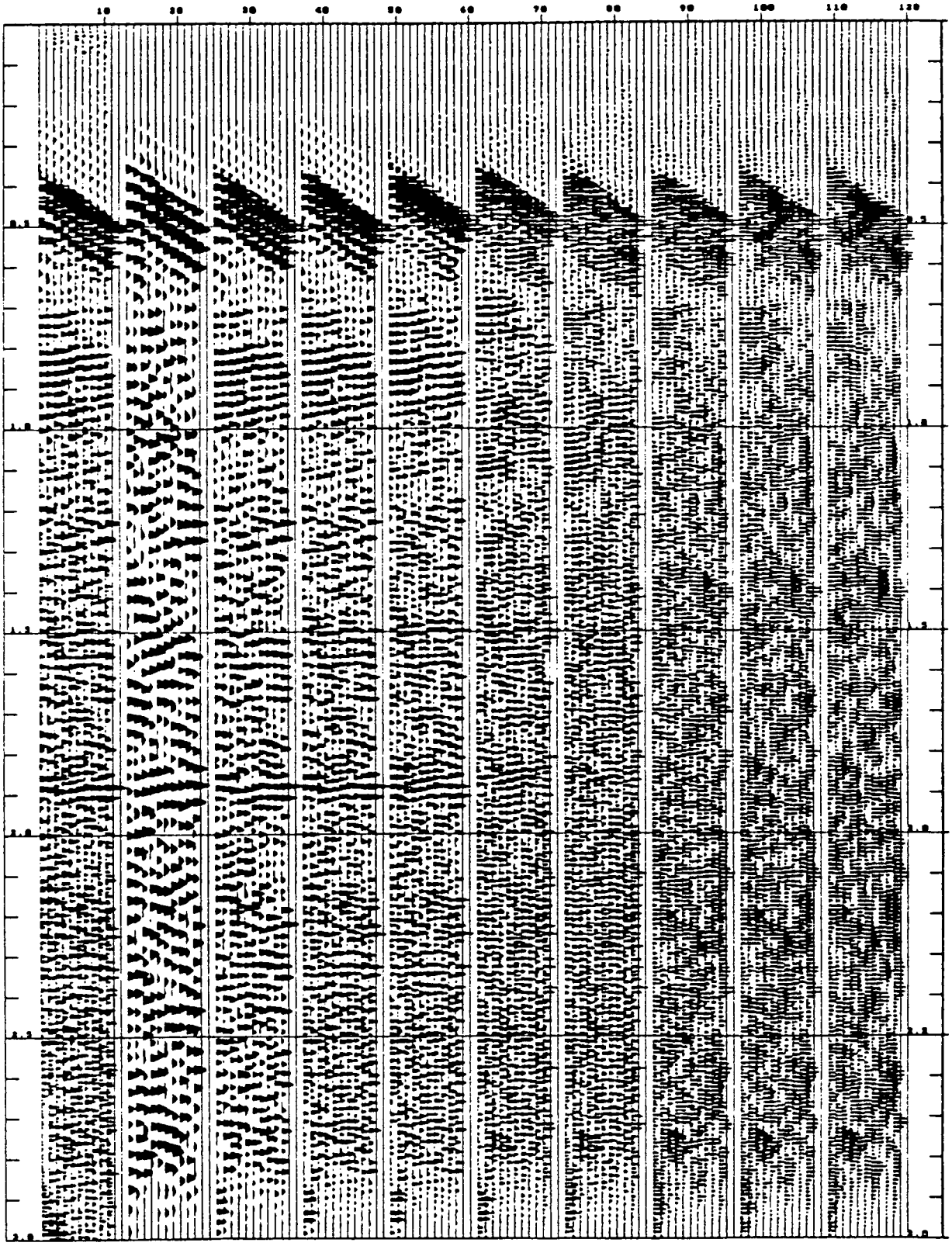
FFID: 0012
TIME: 00:28:46
DATE: Sun Aug 18



+6 db /OCT

FILE: D:\DATA\DATA_TST\0013.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

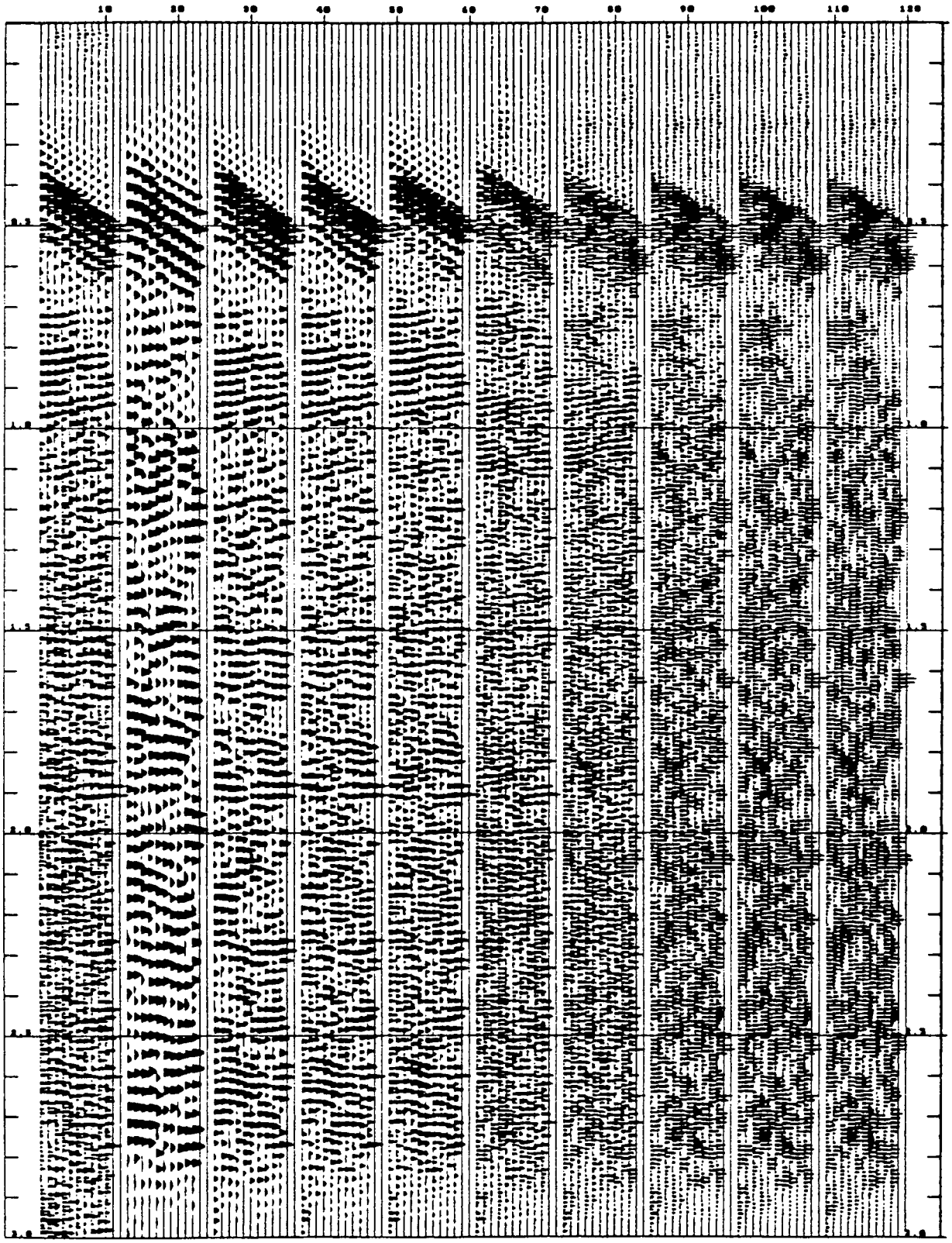
FFID: 0013
TIME: 00:32:26
DATE: Sun Aug 18



+ 9 db / oct

FILE: D:\DATA\DATA_TST\0014.gnR
AMPLITUDE: 0007.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

FFID: 0014
TIME: 00:36:04
DATE: Sun Aug 18

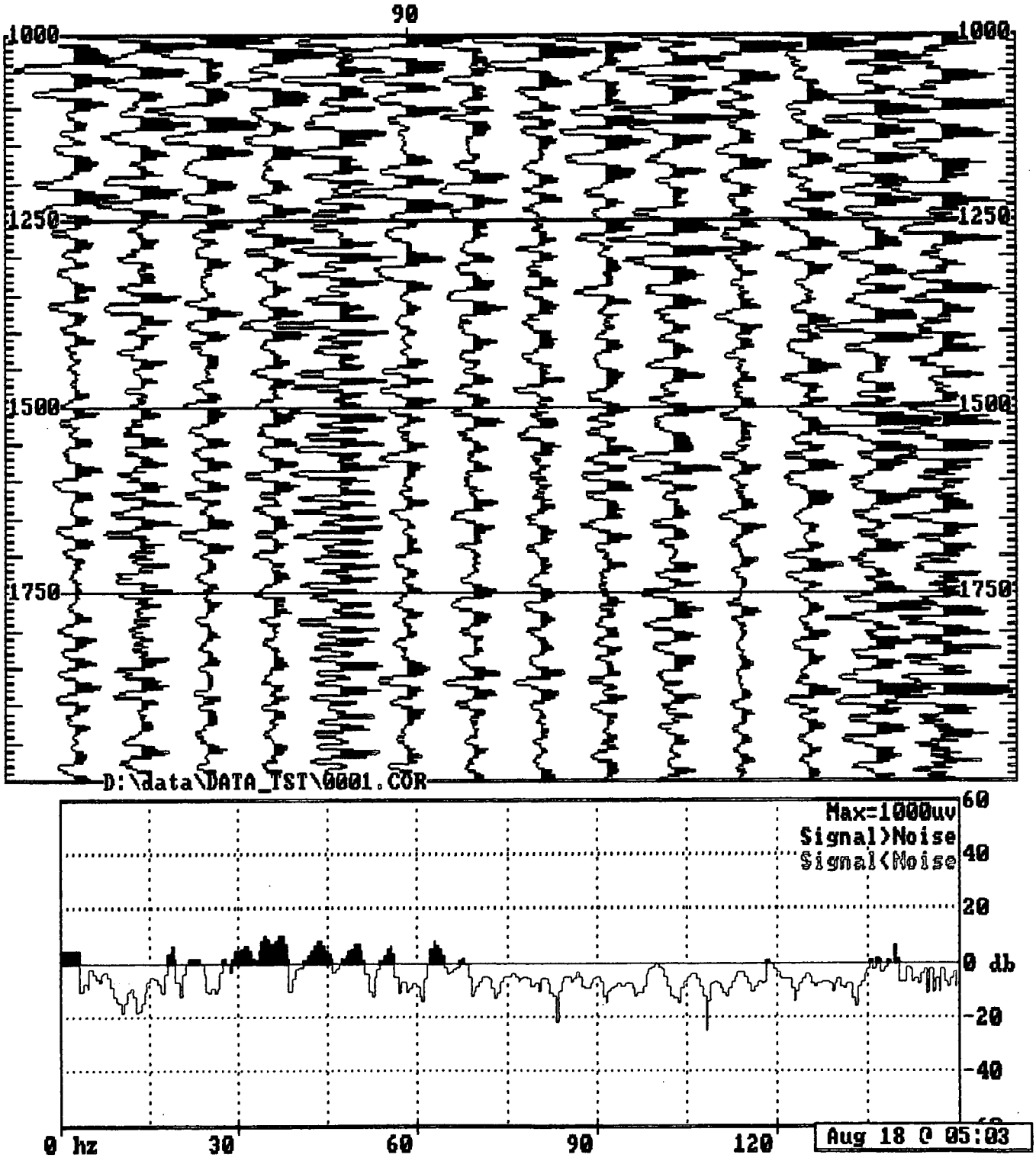


APPENDIX C

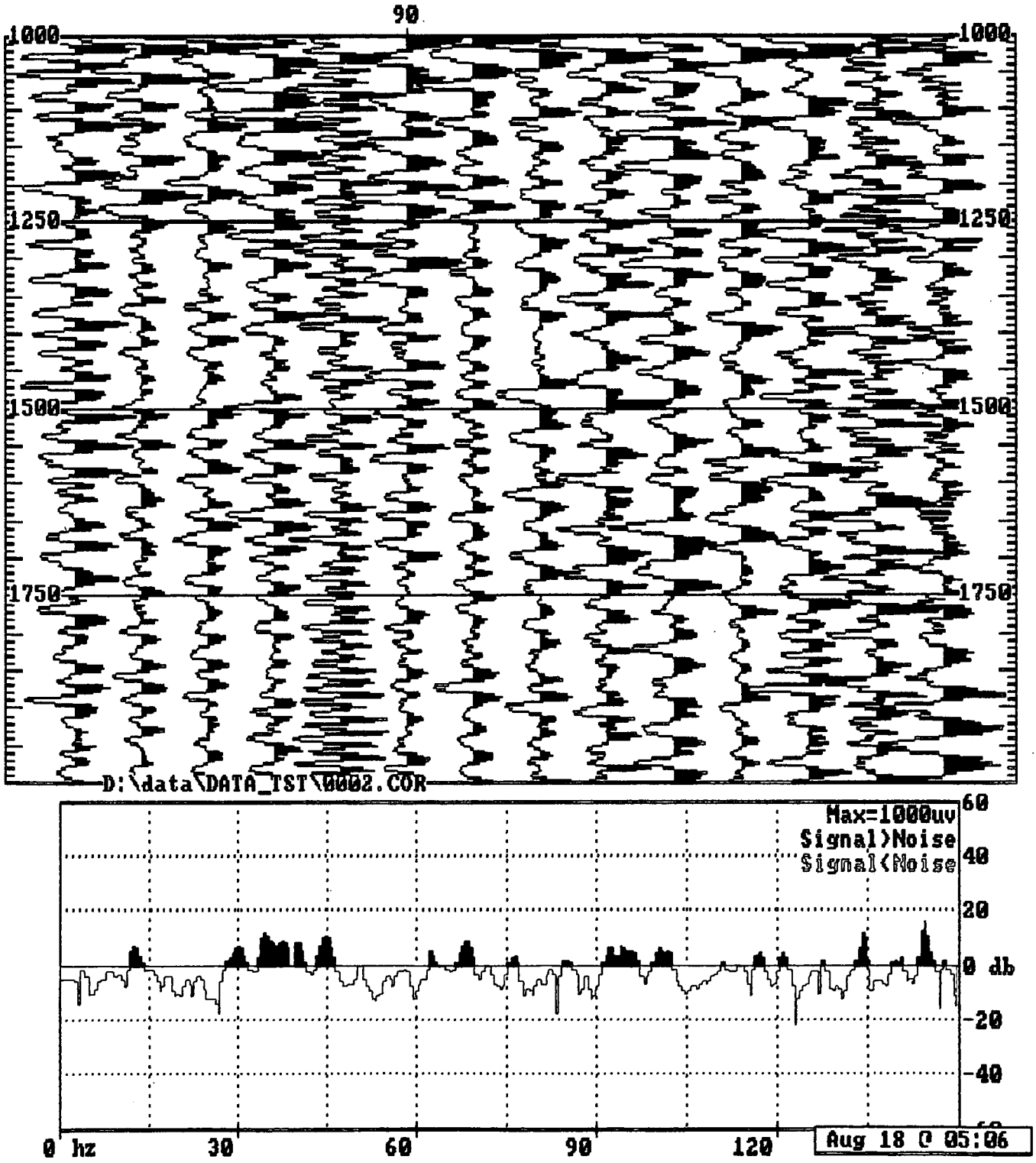
Signal to Noise Analysis of Sweep Test #1

These are open to interpretation but, we like to see the broadest tallest positive (black) area throughout the sweep.

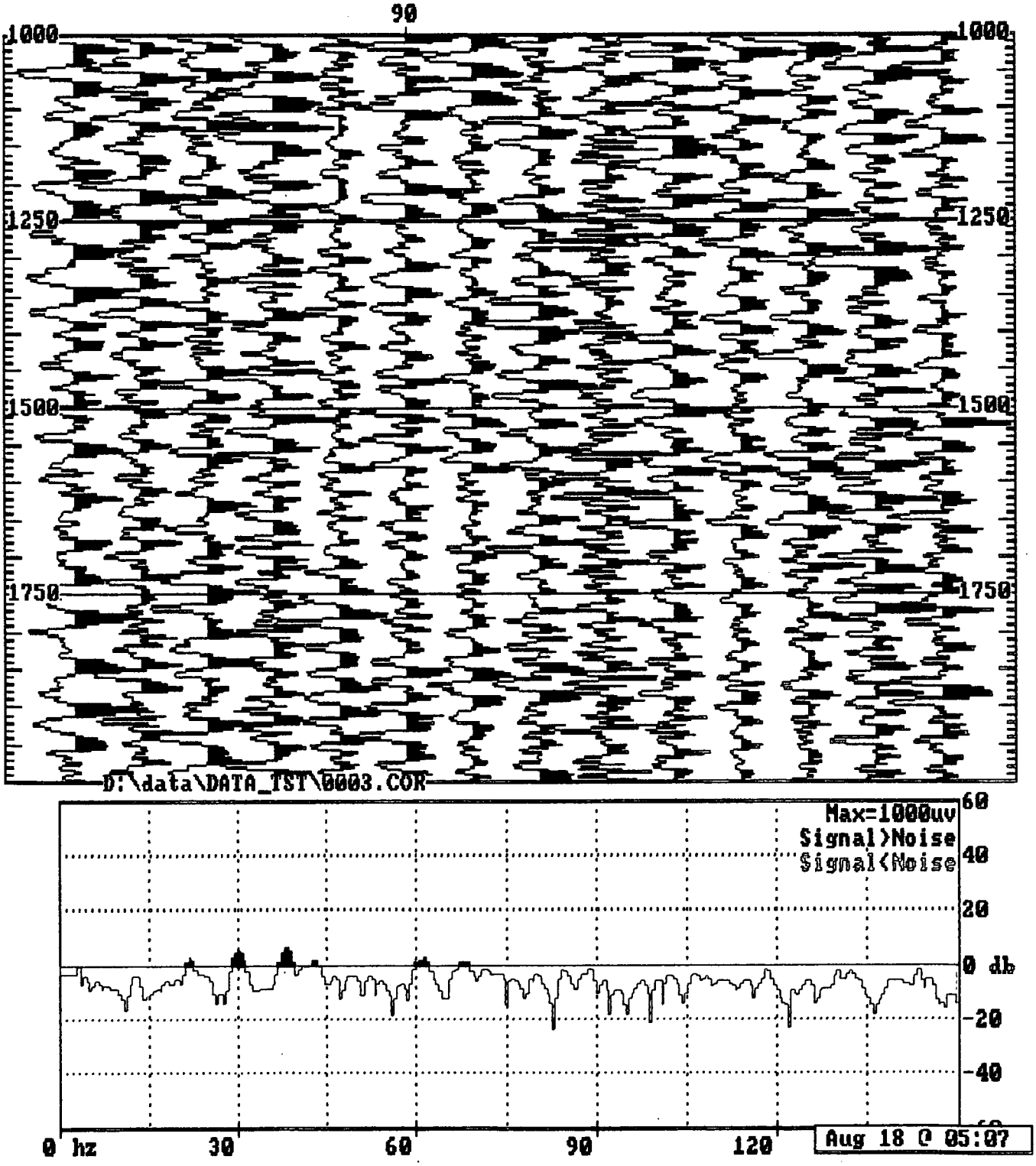
SIGNAL TO NOISE: BASE SWEEP



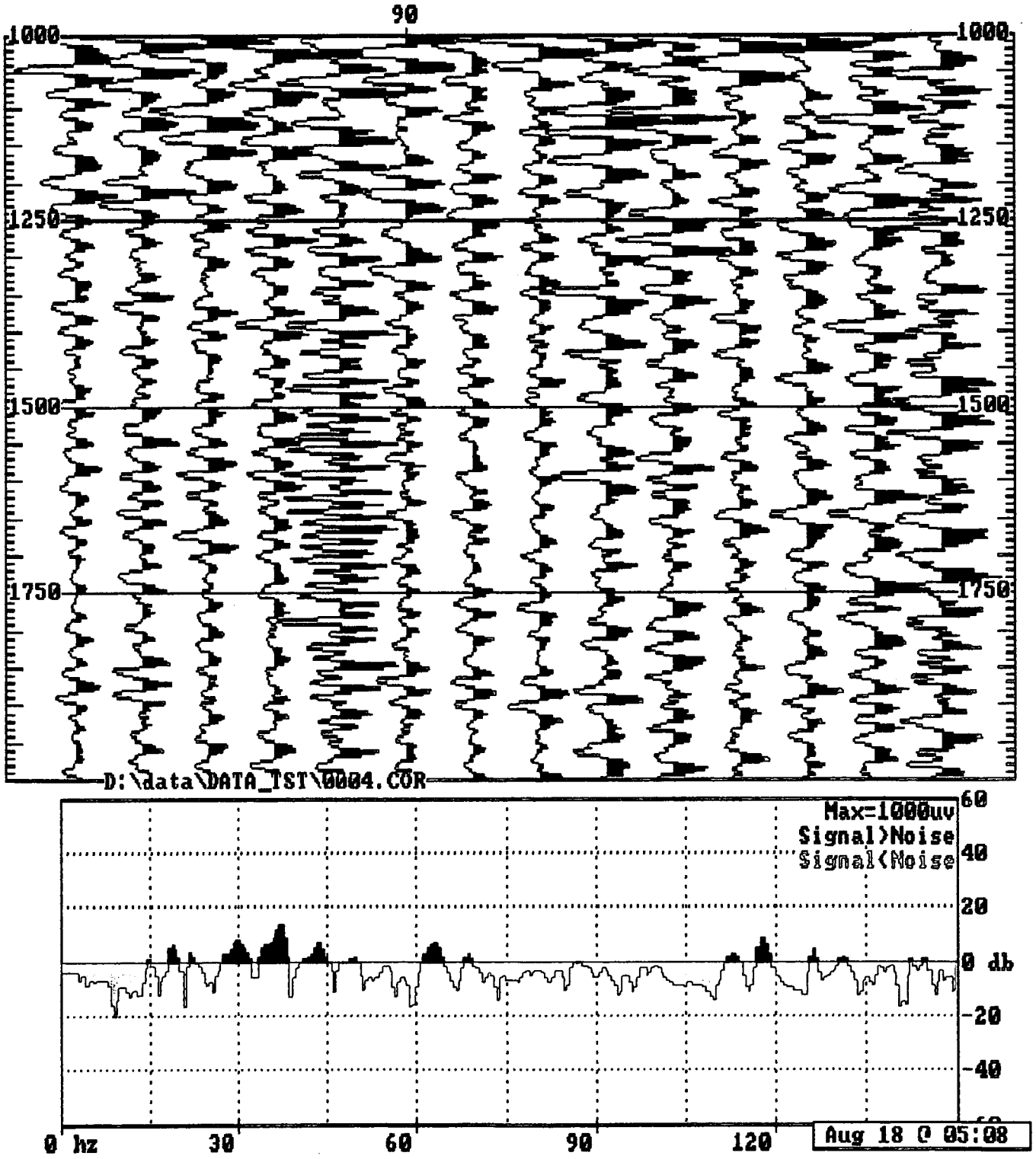
SIGNAL TO NOISE: 220 ' VIB ARRAY



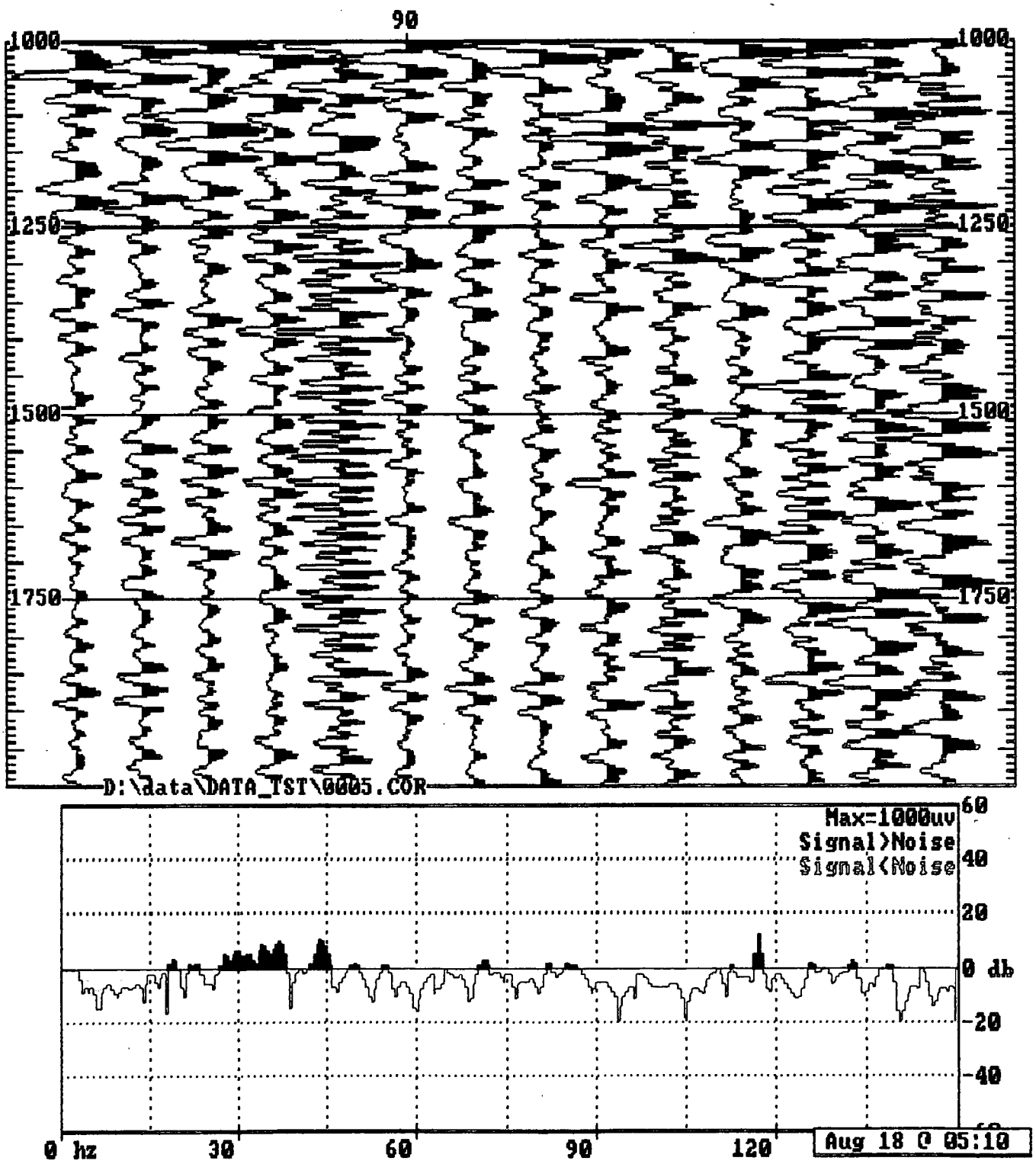
SIGNAL TO NOISE: 330' VIB ARRAY



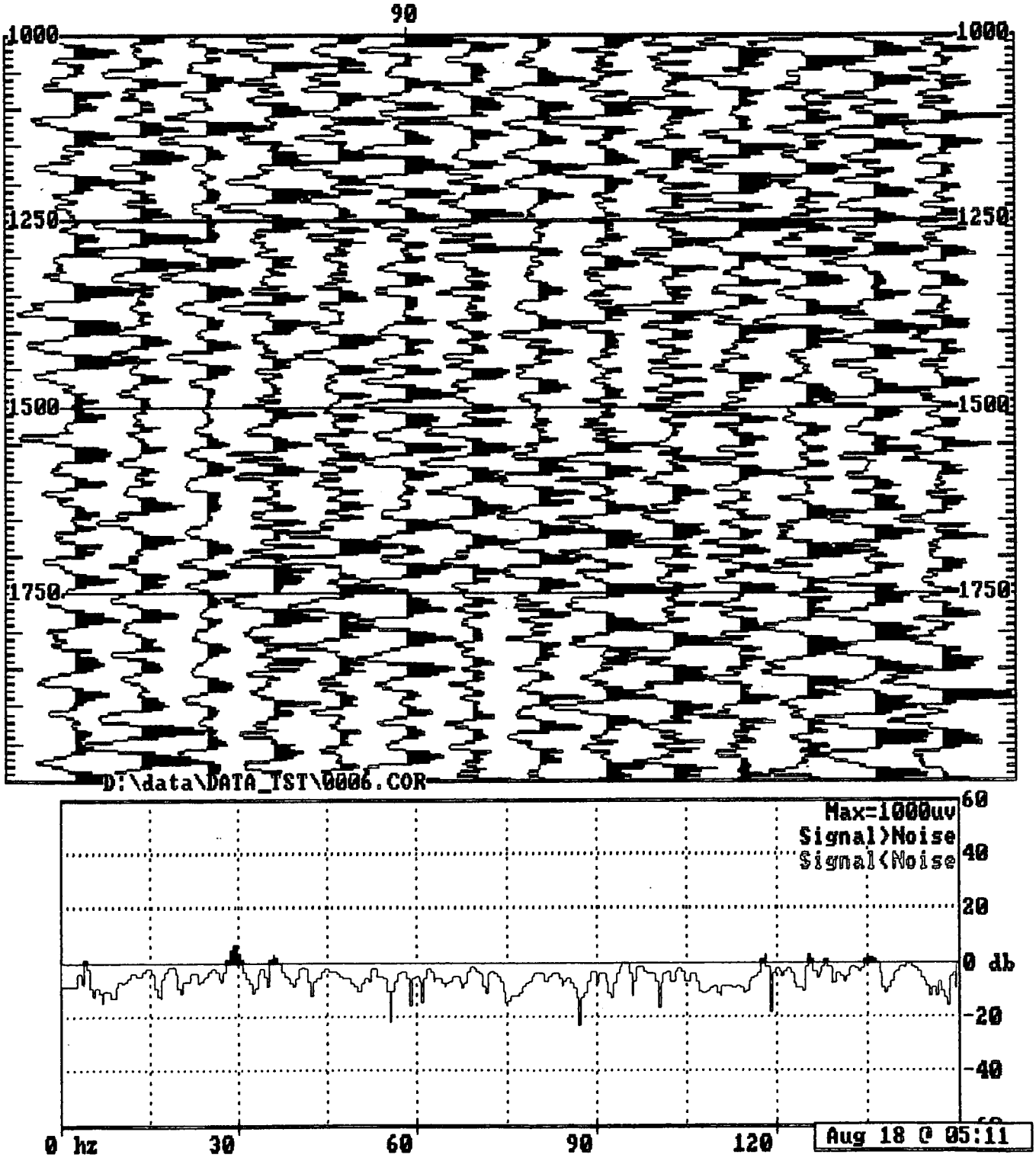
SIGNAL TO NOISE: 3 x 8 SWEEPS SUMMED



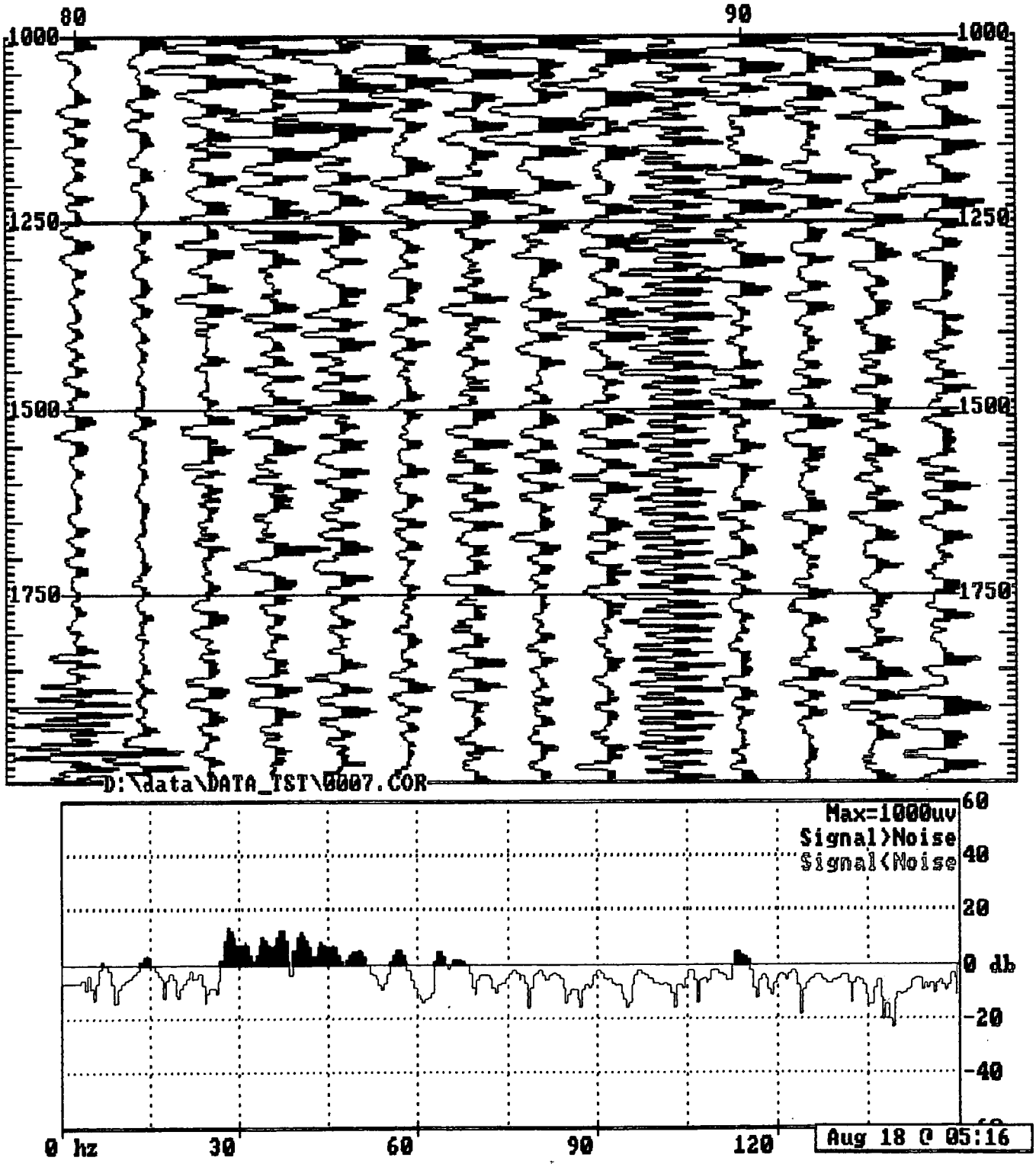
SIGNAL TO NOISE: 16 x 3 SWEEPS SUMMED



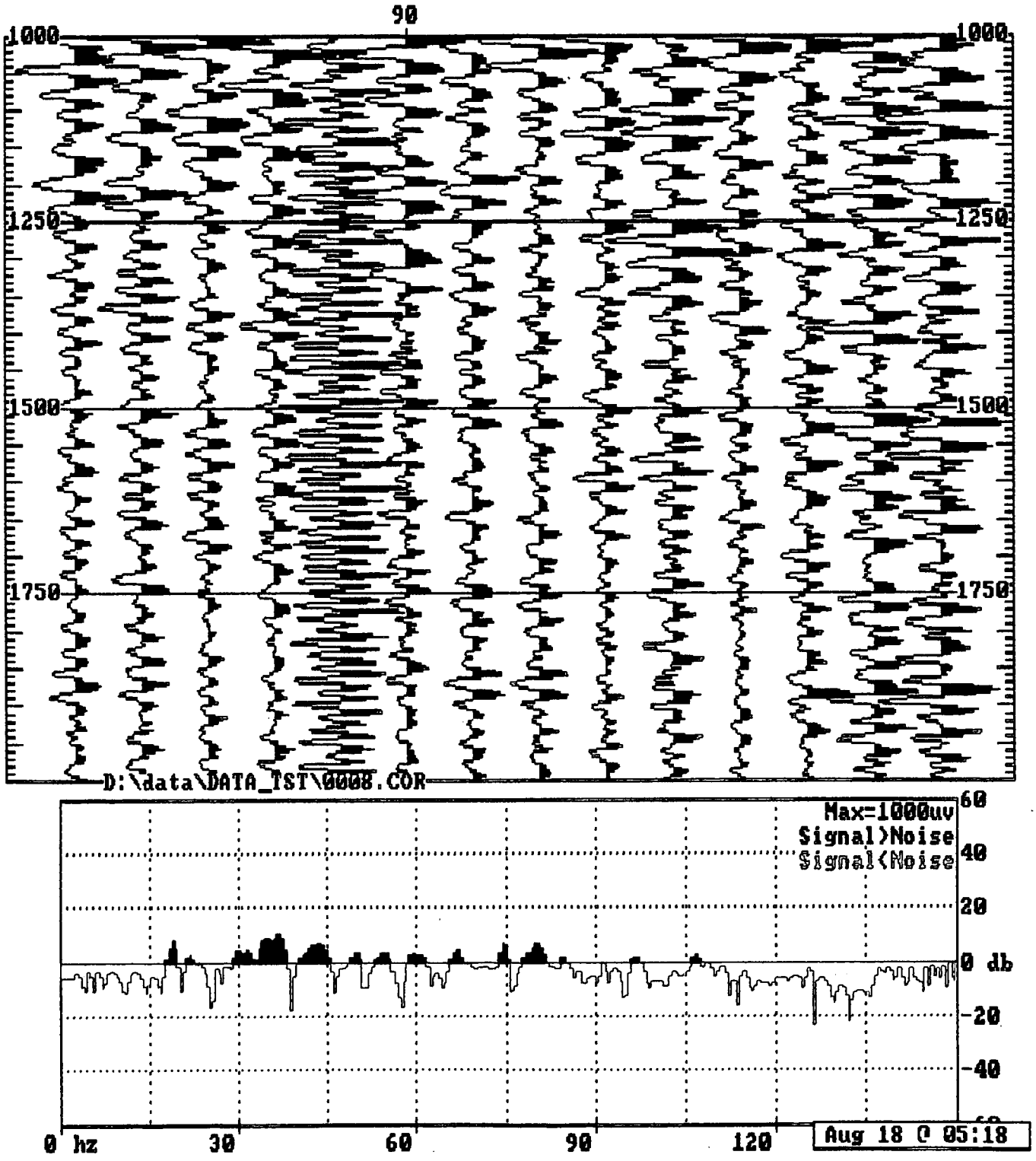
SIGNAL TO NOISE: 275' GAP FROM vIB TO 1ST LIVE PHONE.



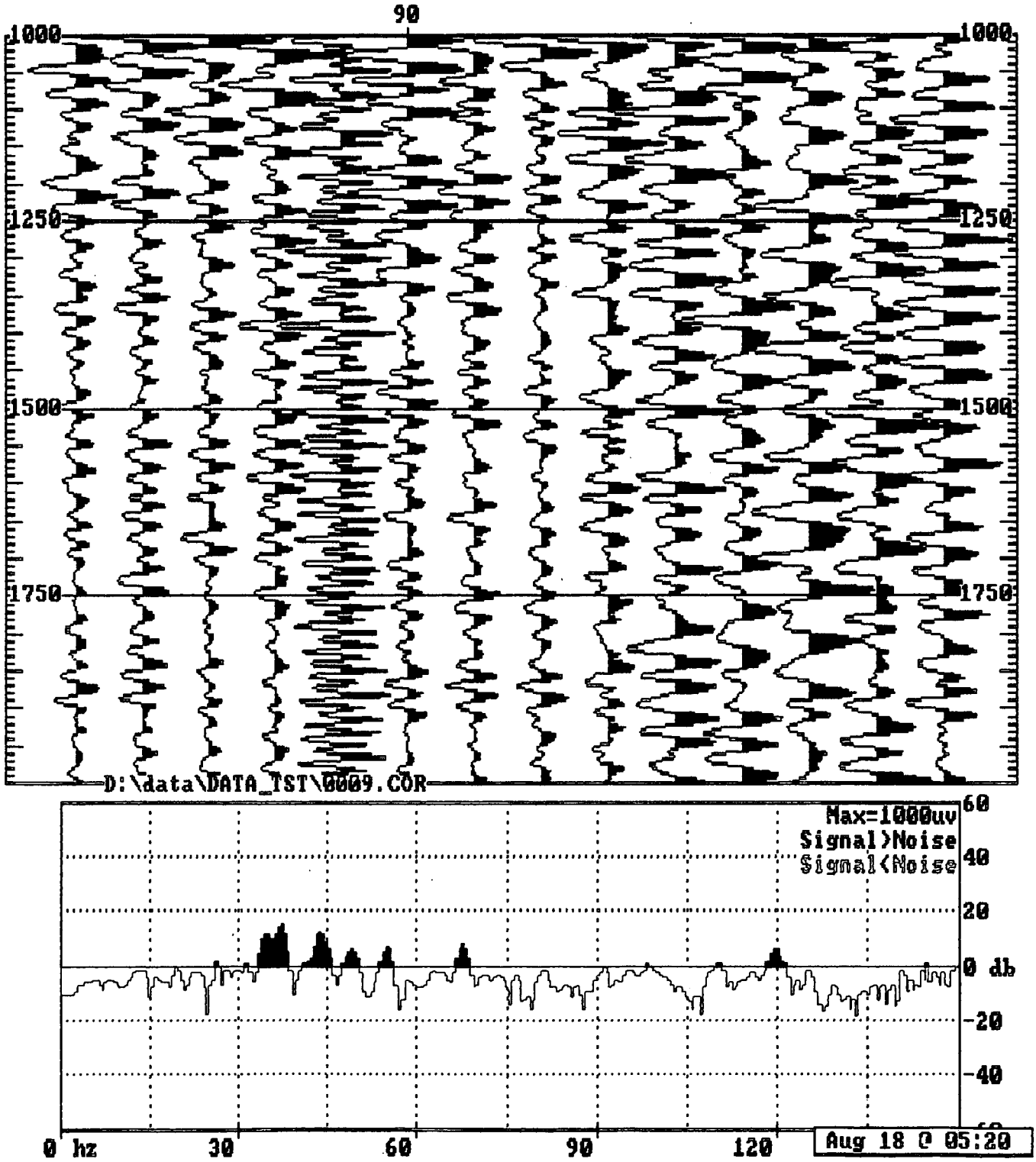
SIGNAL TO NOISE: 8 SECOND SWEEP LENGTH



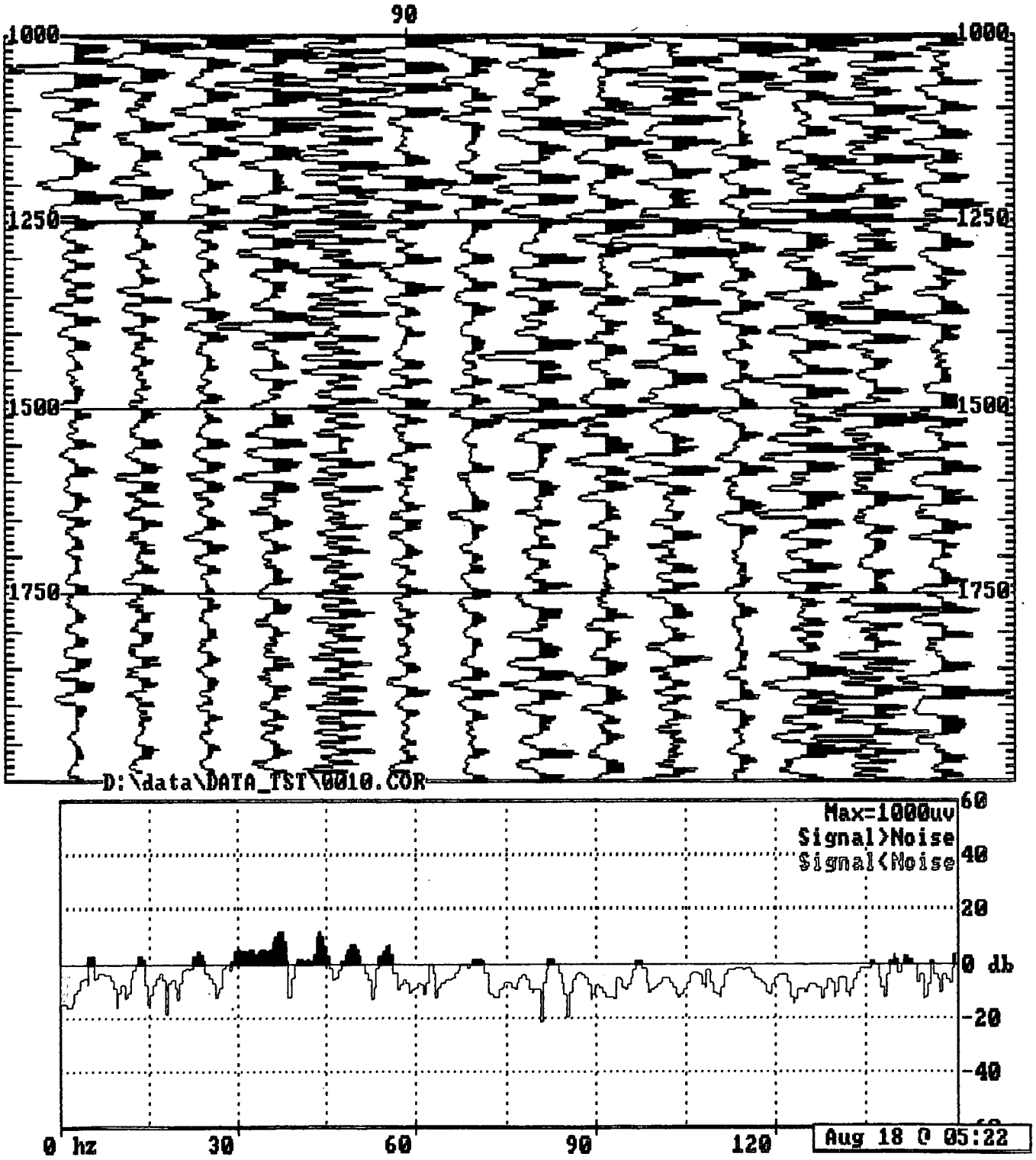
SIGNAL TO NOISE: 6 SECOND SWEEP LENGTH



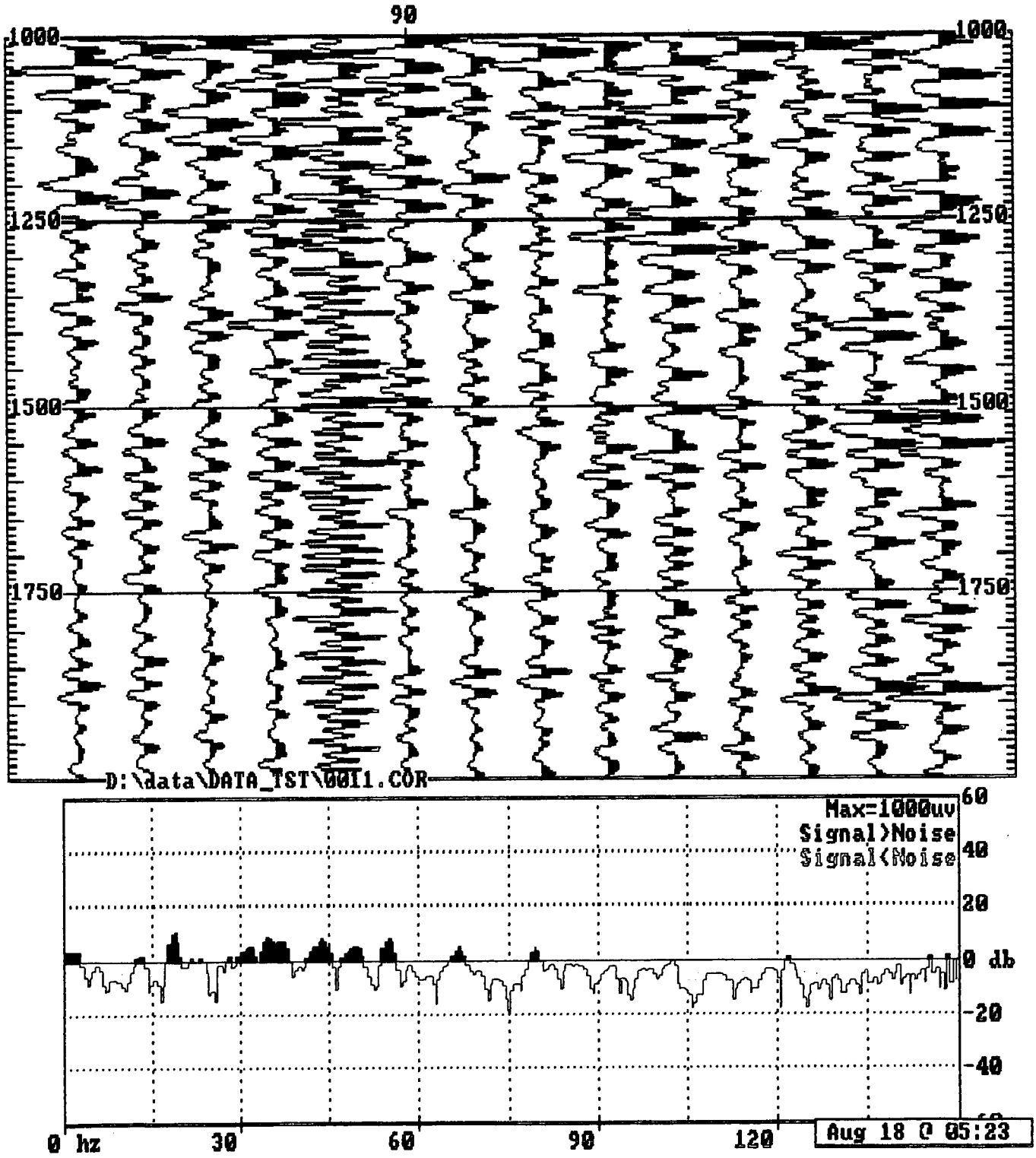
SIGNAL TO NOISE: 10 - 96 HZ. BANDWIDTH



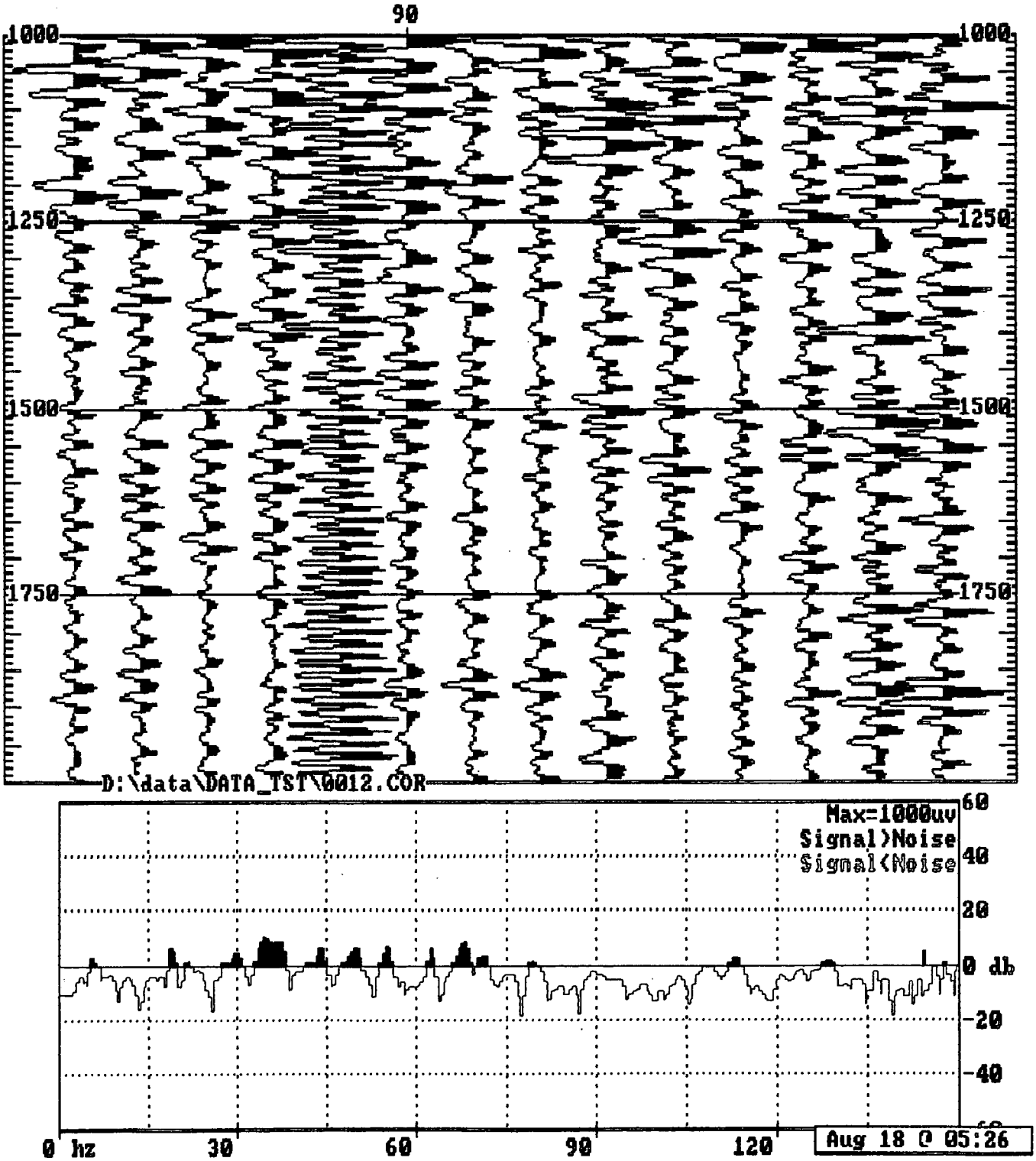
SIGNAL TO NOISE: 16 - 120 HZ. BANDWIDTH.



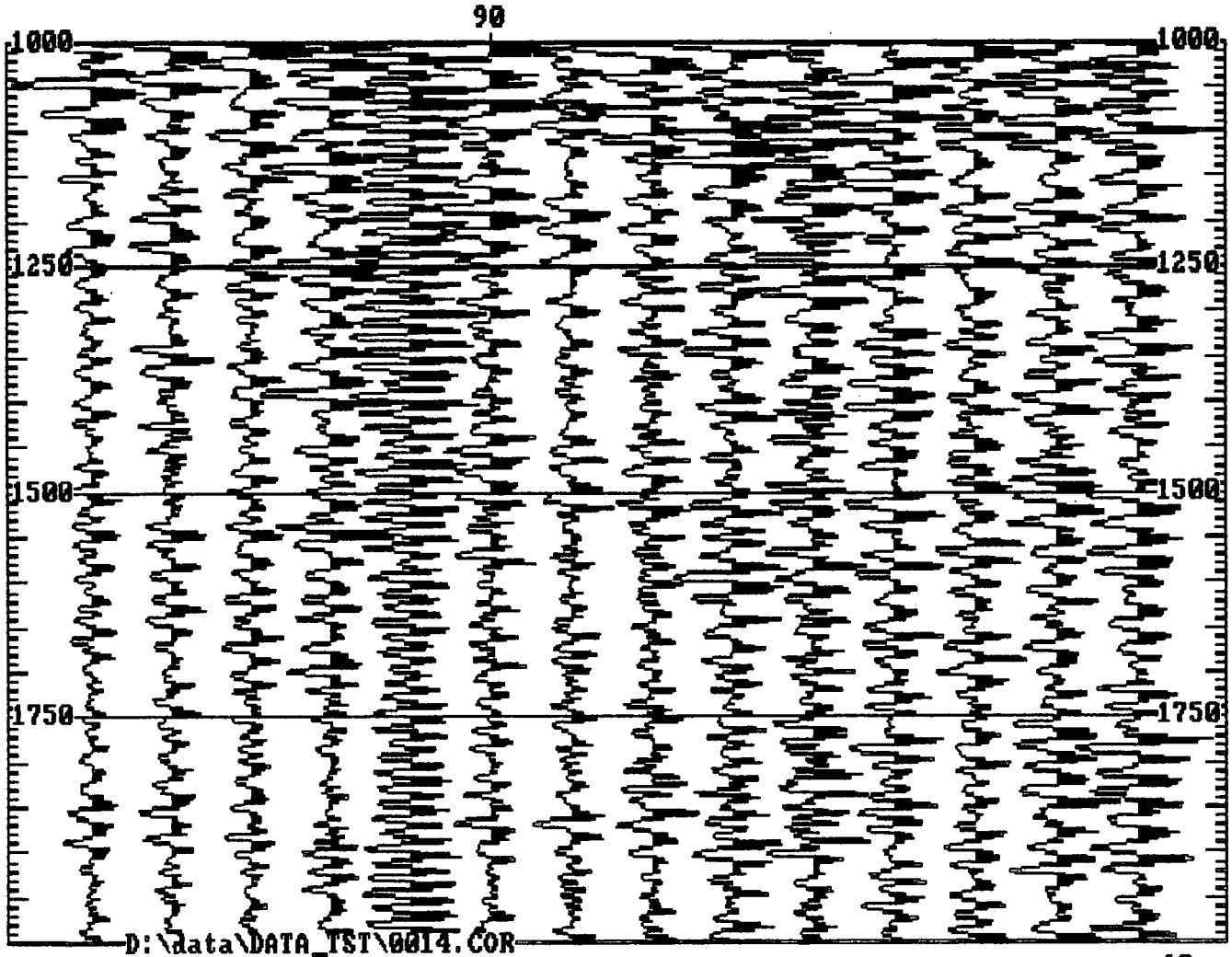
SIGNAL TO NOISE: 10 - 80 HZ BANDWIDTH

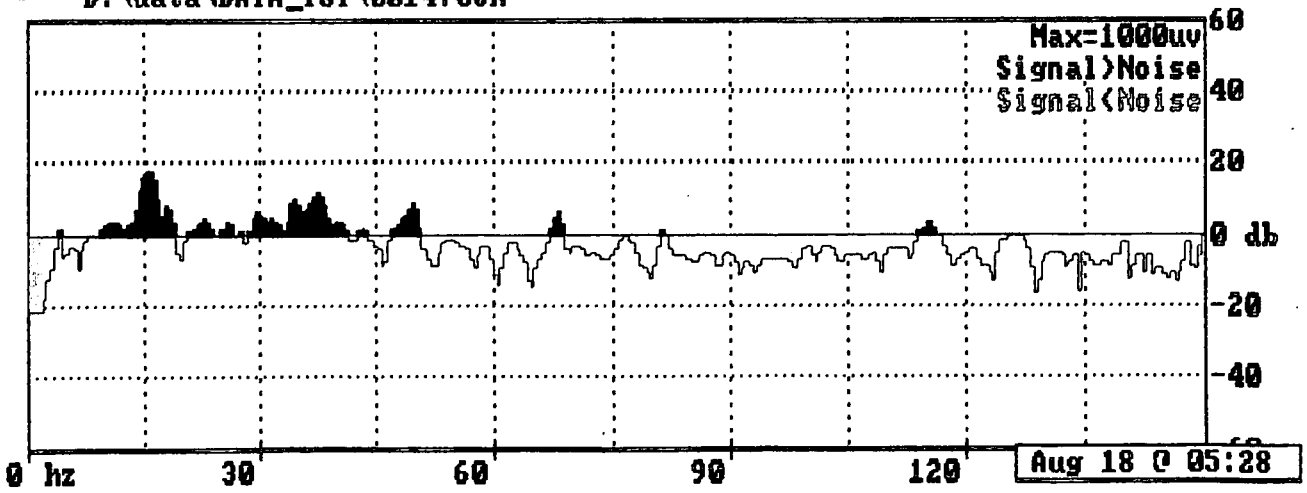


SIGNAL TO NOISE: +3 DB/OCT.



SIGNAL TO NOISE: +9 DB/OCT.





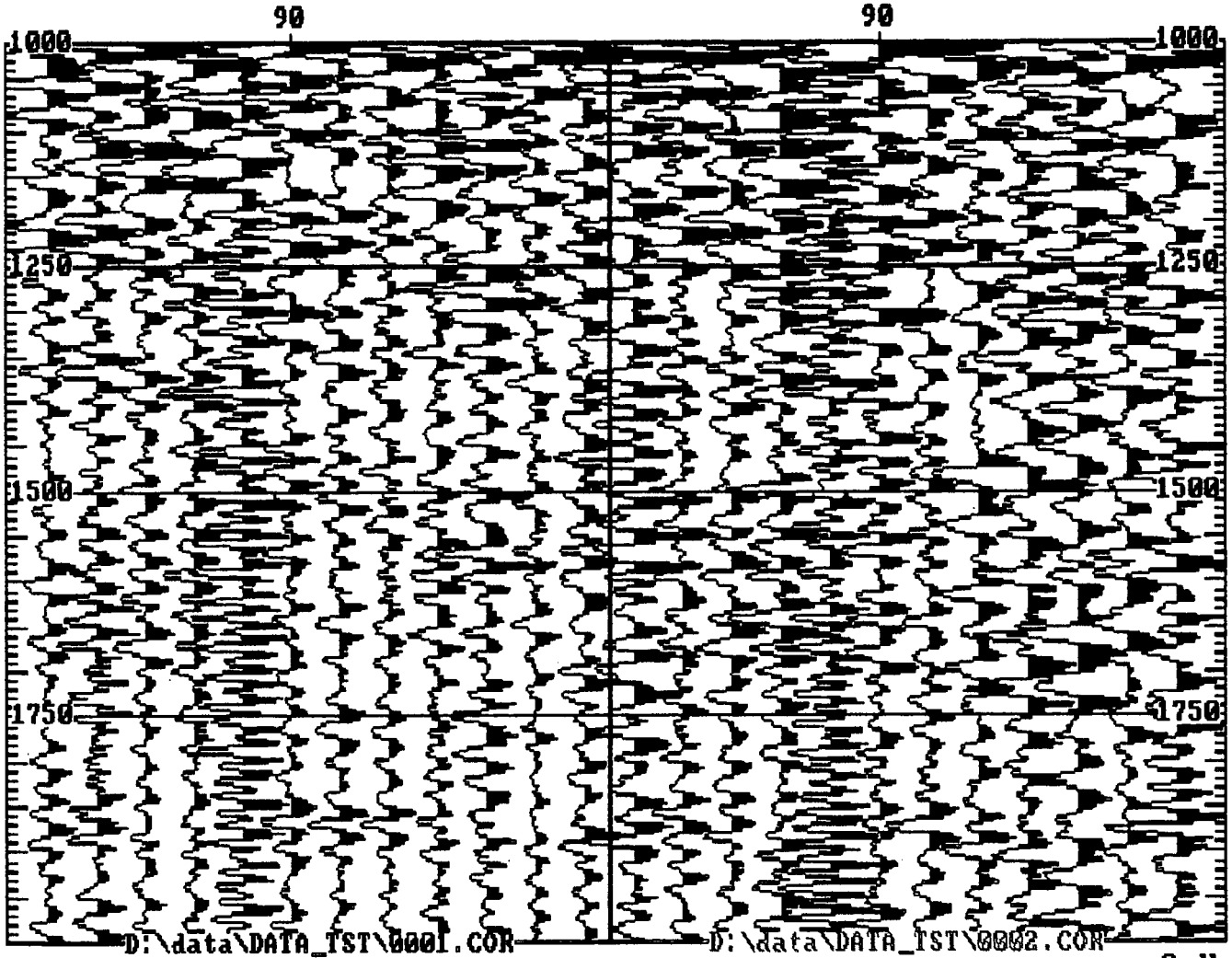
APPENDIX D

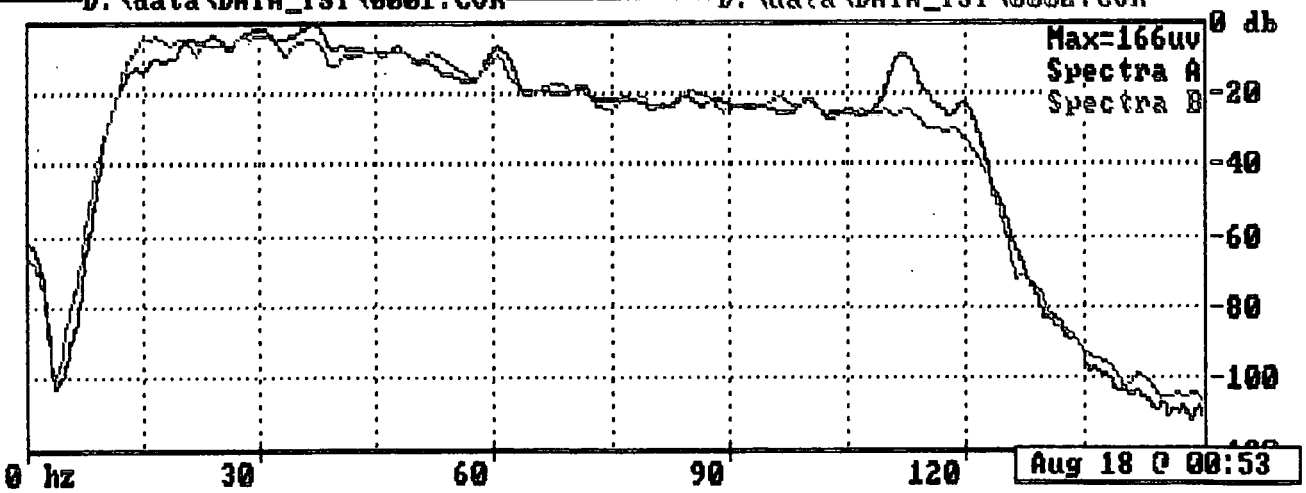
Spectral Comparisons Test #1

These displays compare the spectrums from the two different records. The window of analysis is : trace 90 to 98, (offset 3190-4290 ft.) 1.0 to 2.0 second. The blue spectra curve is for the file name in blue and likewise for the black spectra curve.

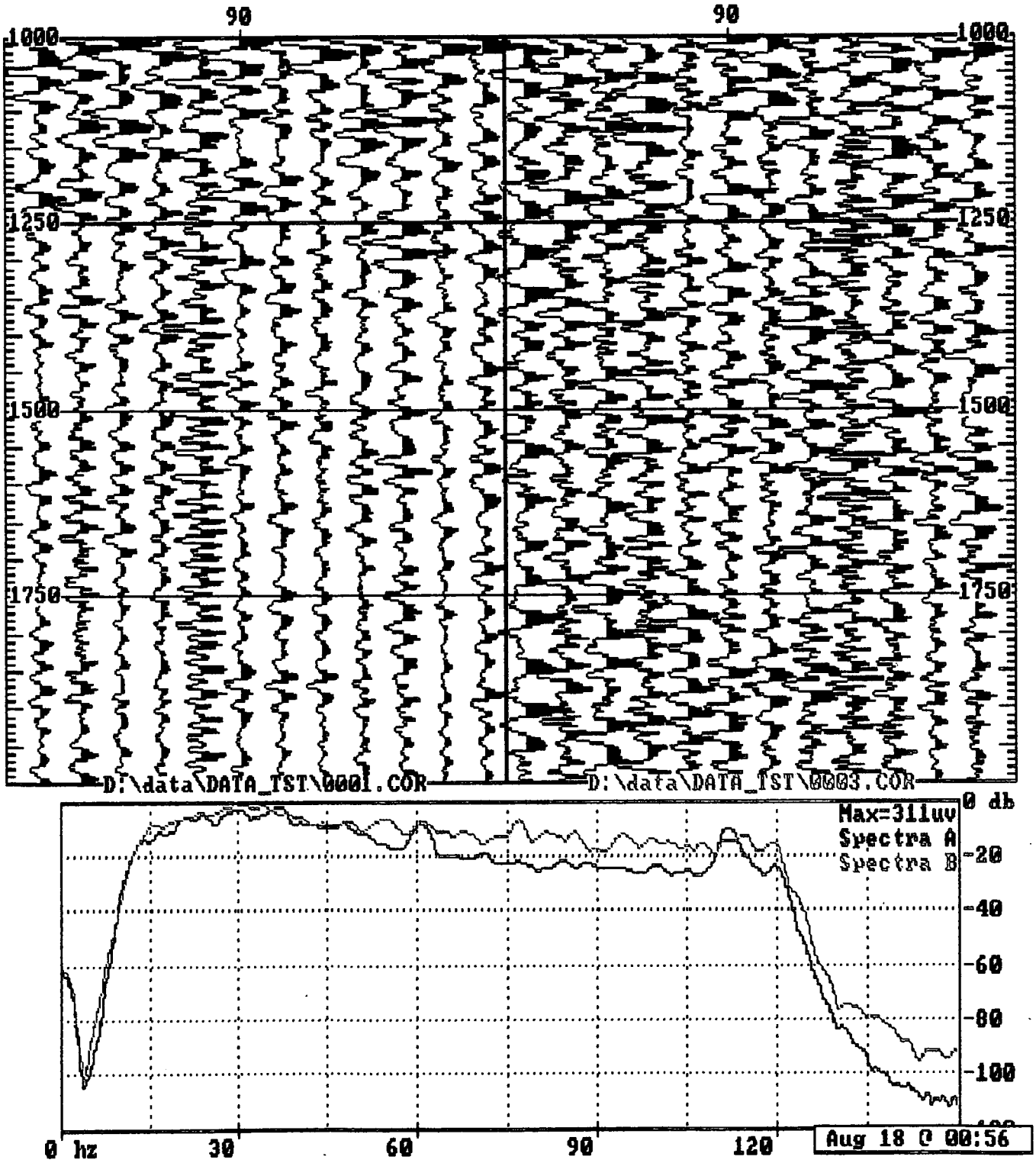
The spectrums don't necessarily tell us what we have, as much as what we don't. If the high frequencies taper off on these spectrums, it's a good bet you won't get anything back that high. On the other hand a clean flat spectrum up to the top of the sweep may be from either signal or noise.

SPECTRAL COMPARISON BASE VS 220' ARRAY

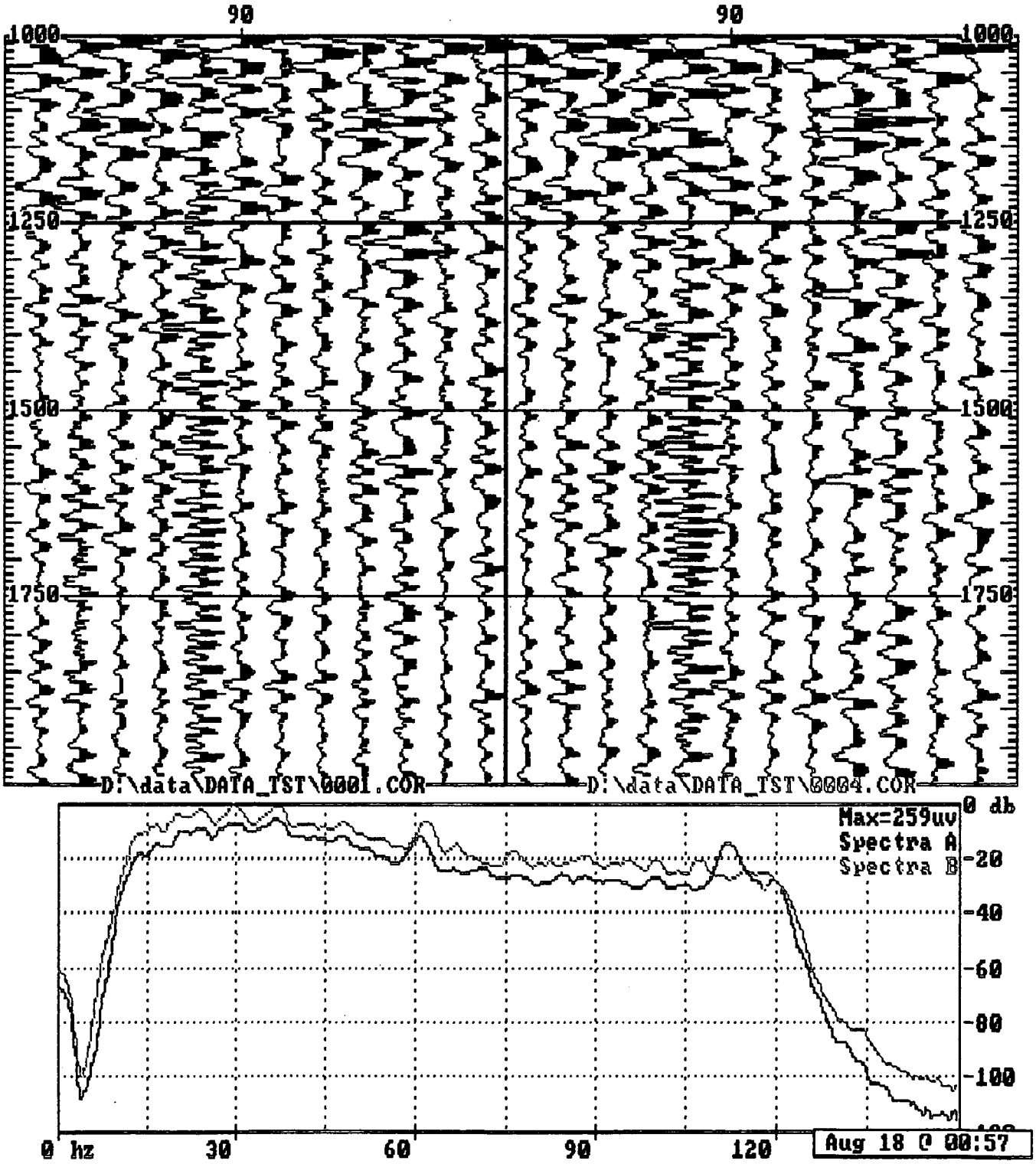




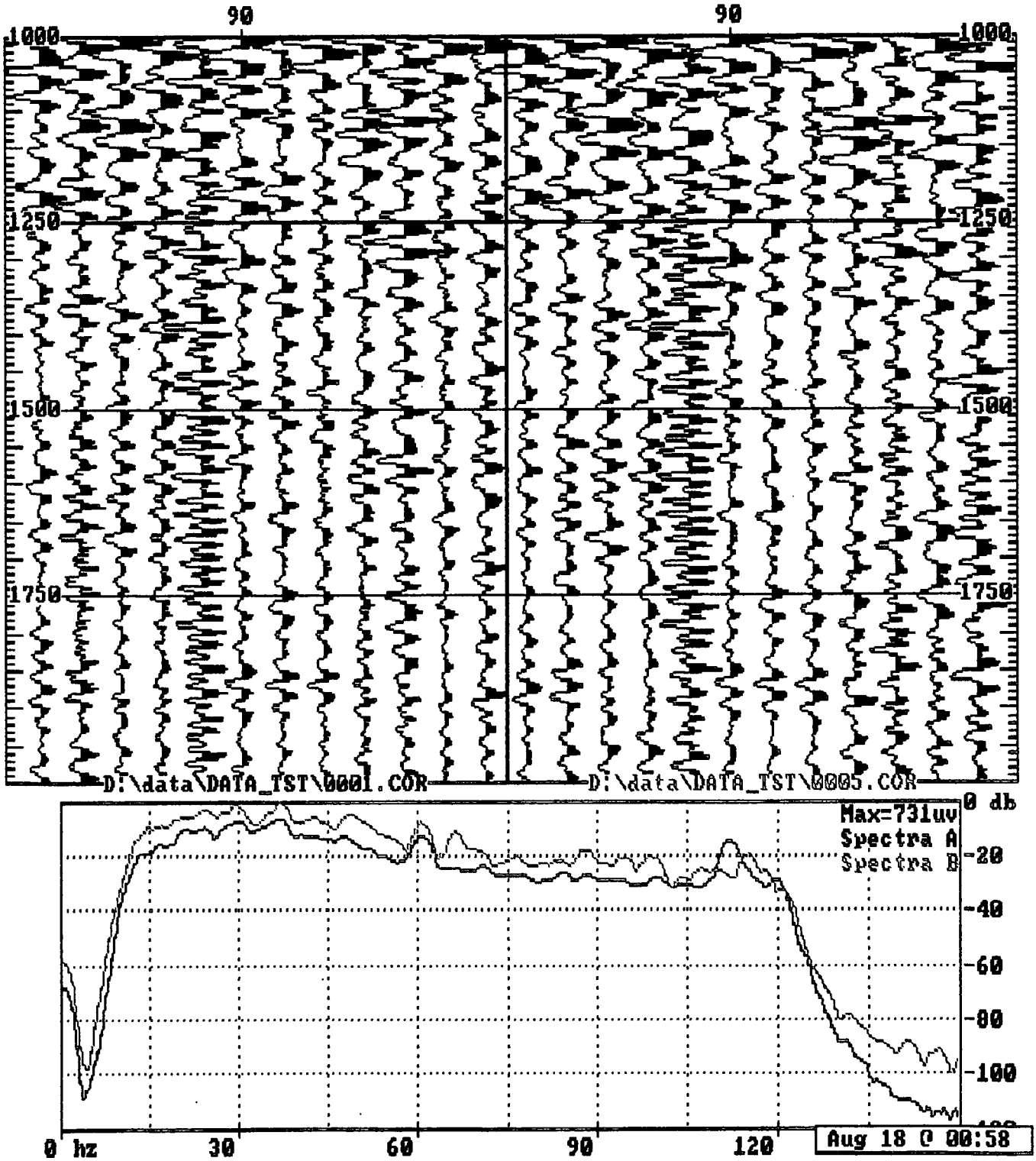
SPECTRAL COMPARISON, BASE VS 330' ARRAY



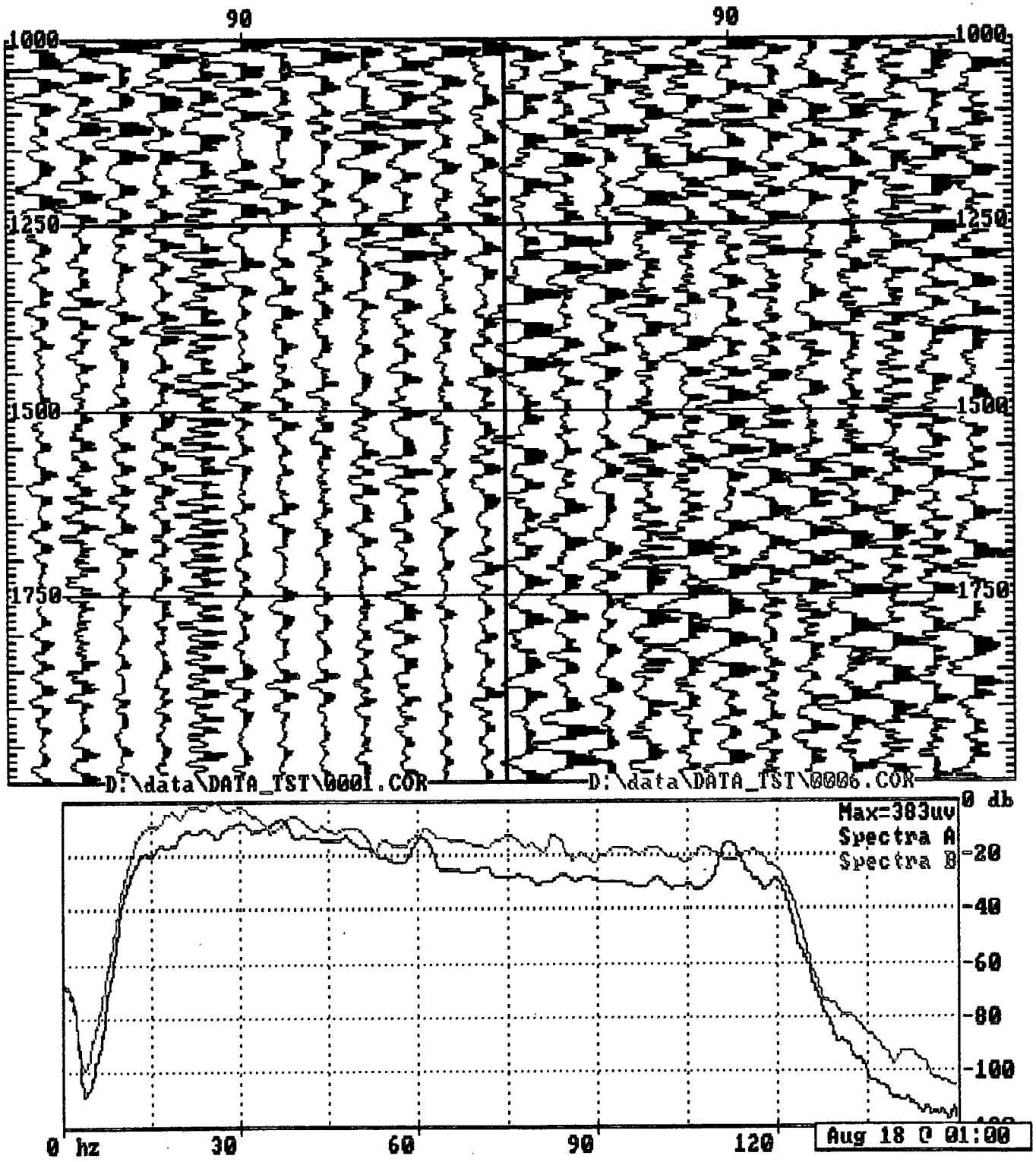
SPECRAL COMPARISON, BASE VS 3X8 SWEEPS.



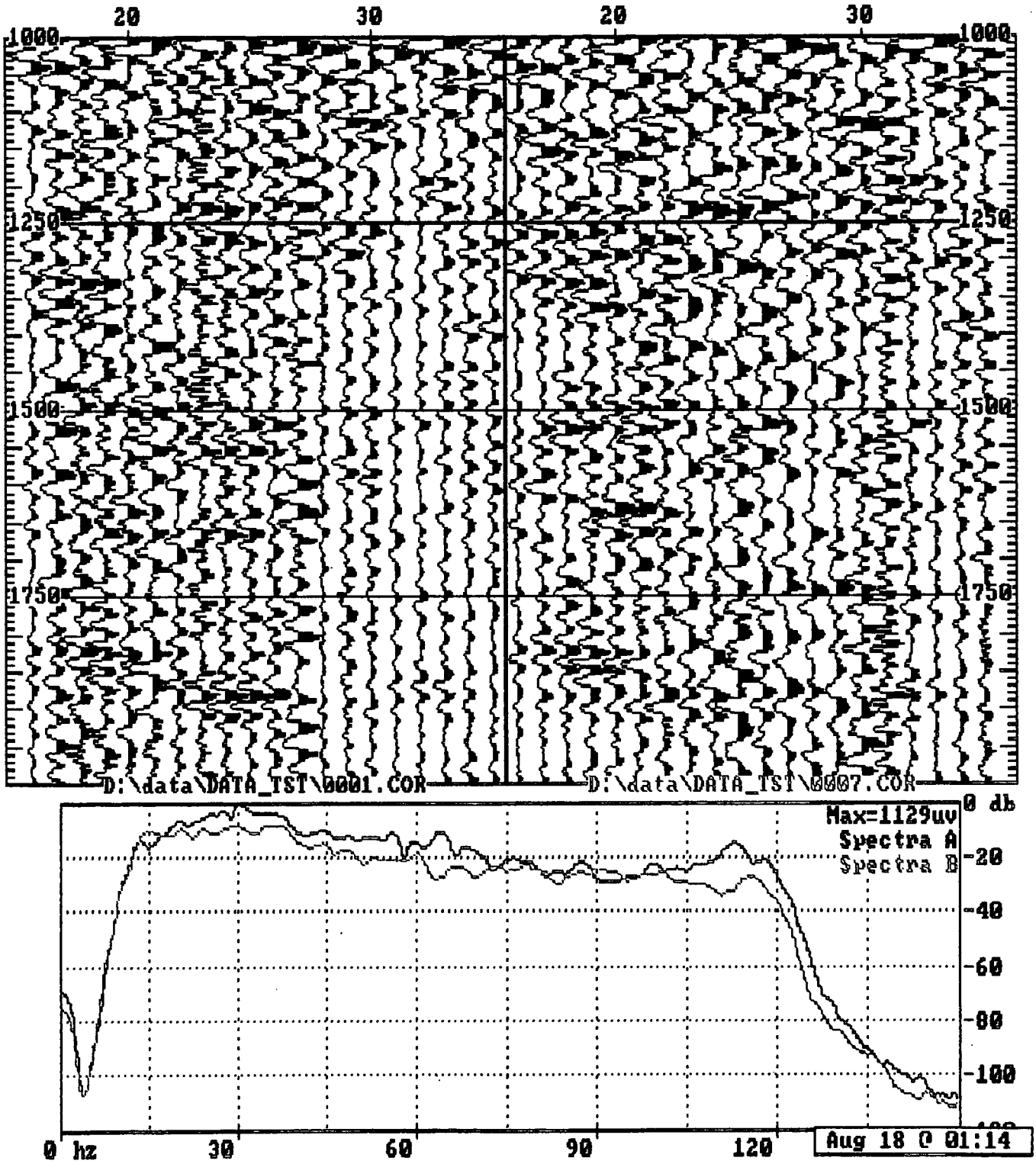
SPECTRAL COMPARISON, BASE VS 16x3 SWEEPS.



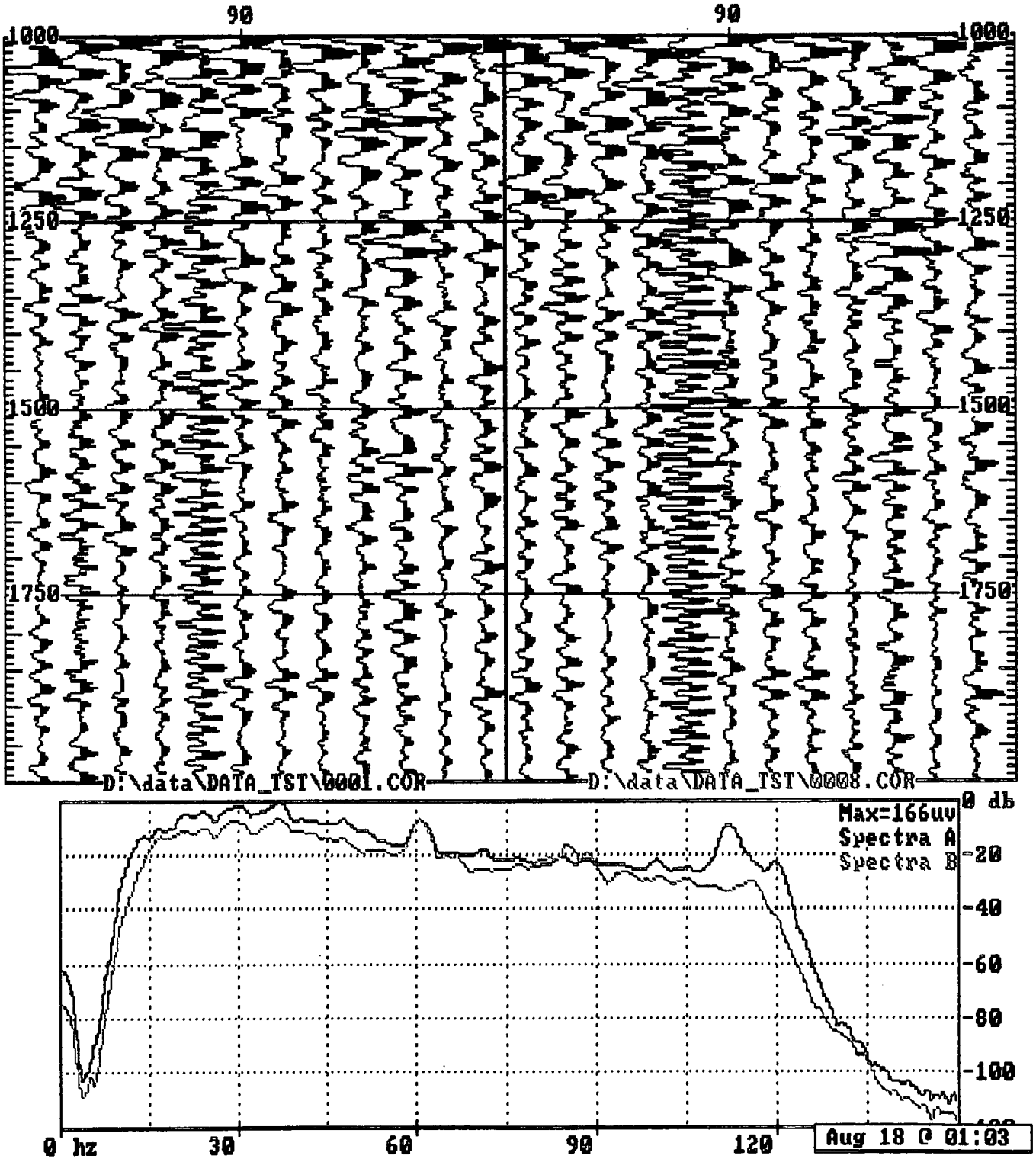
SPECTRAL COMPARISON, BASE VS 275' VIB TO 1ST PHONE OFFSET



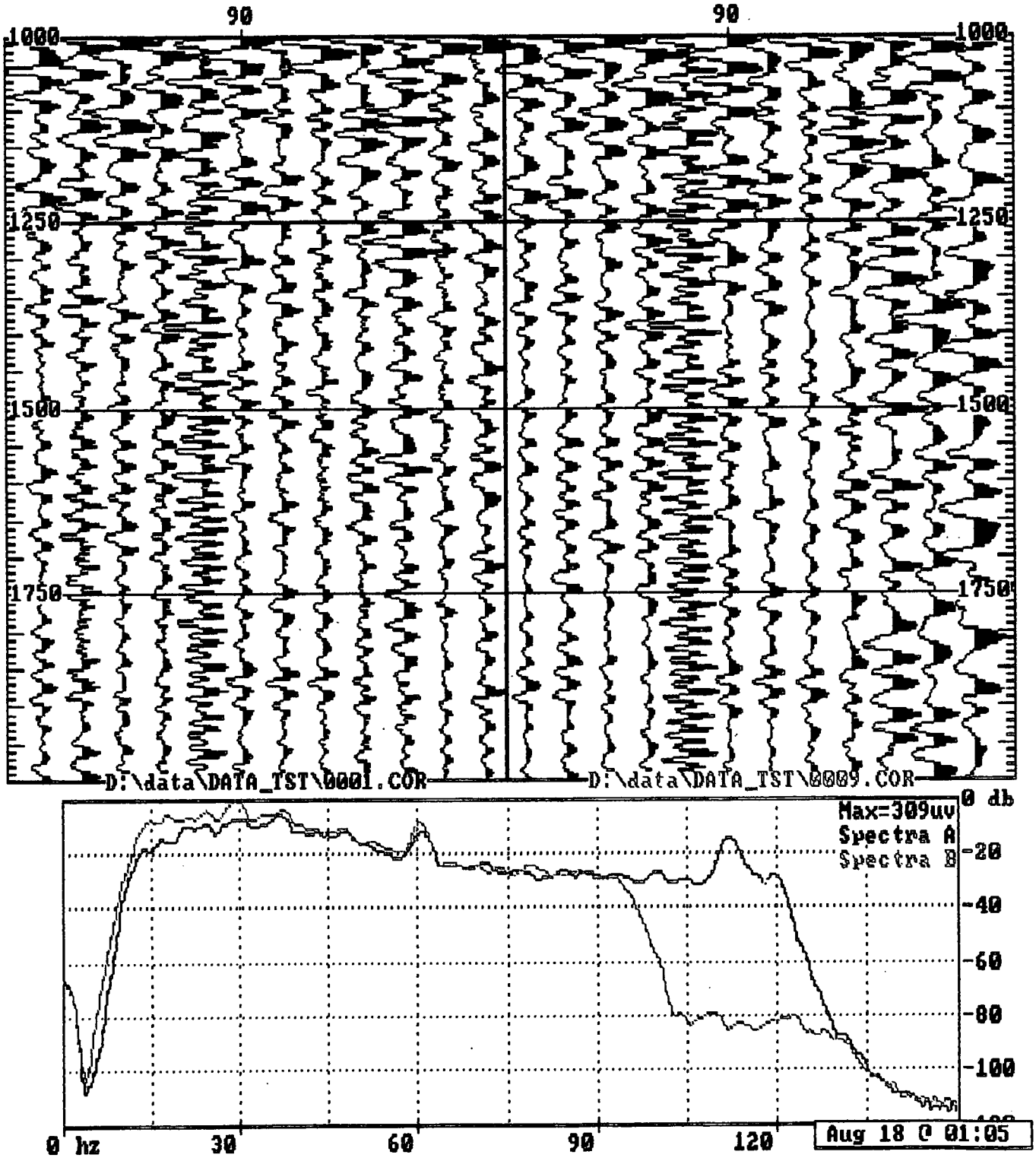
SPECTRAL COMPARISON; BASE VS 8 SECOND SWEEP



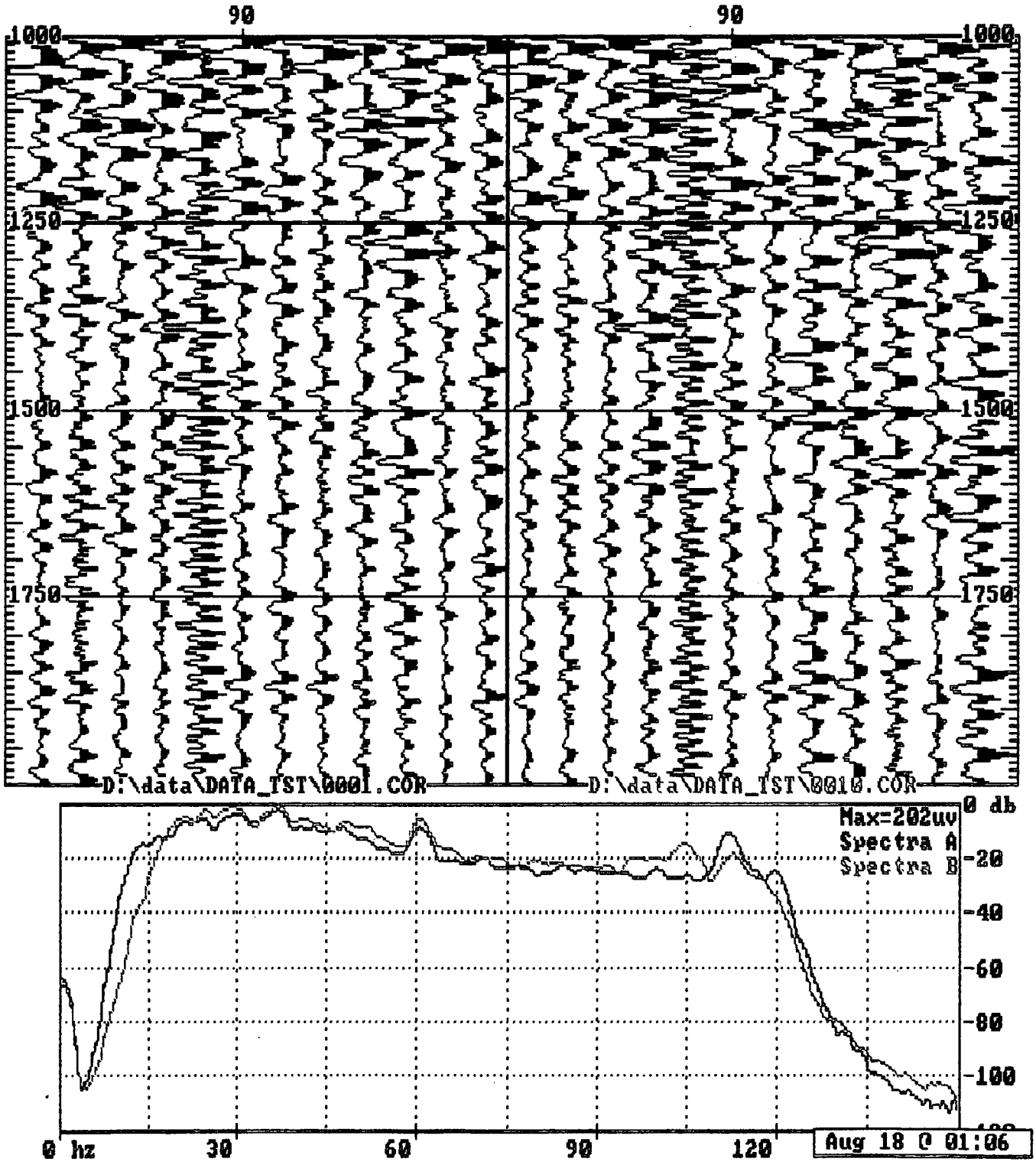
SPECTRAL COMPARISON: BASE VS 6 SECOND SWEEP



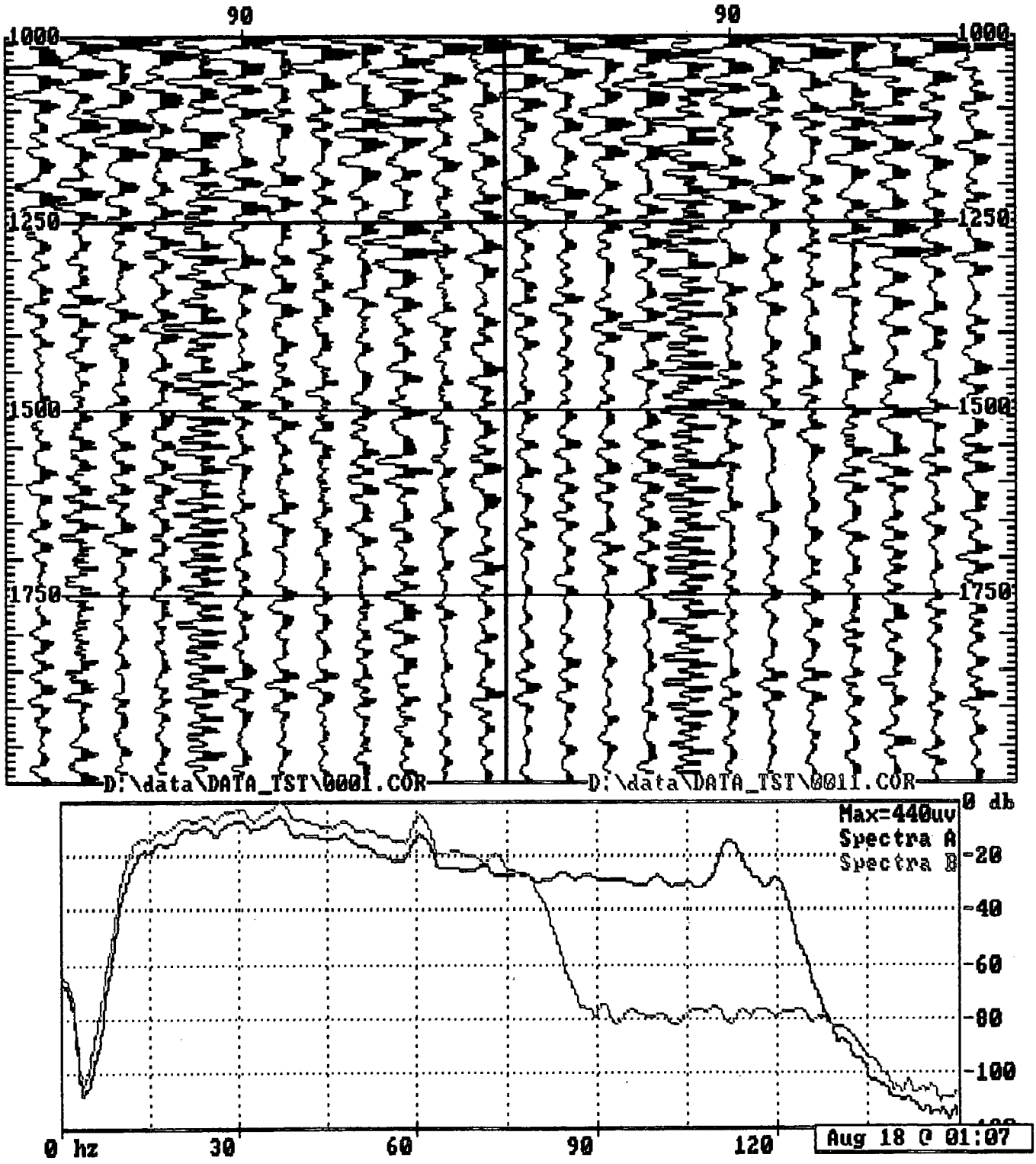
SPECTRAL COMPARISON: BASE VS 10-96 HZ SWEEP



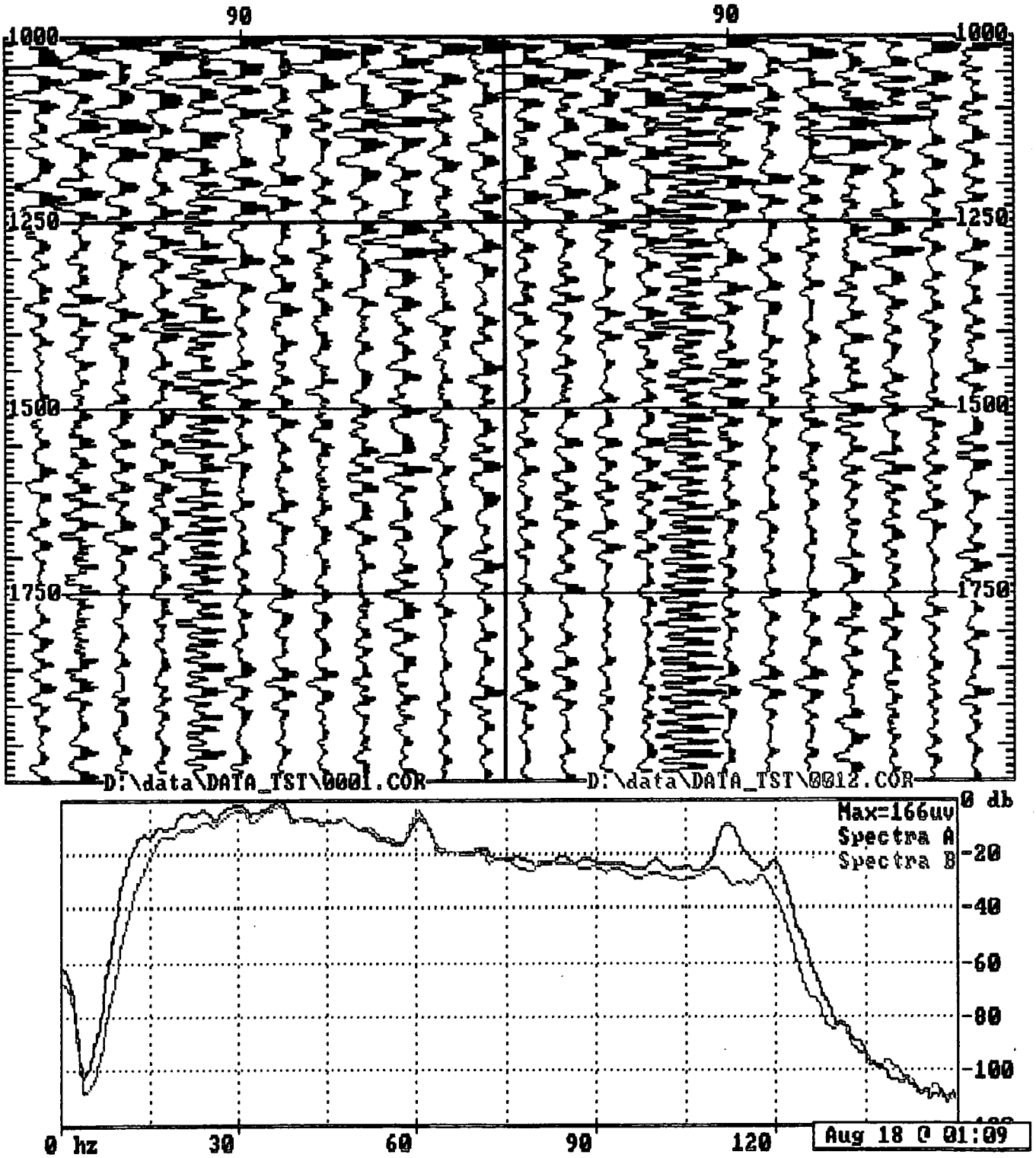
SPECTRAL COMPARISON, BASE VS 16-120 HZ SWEEP



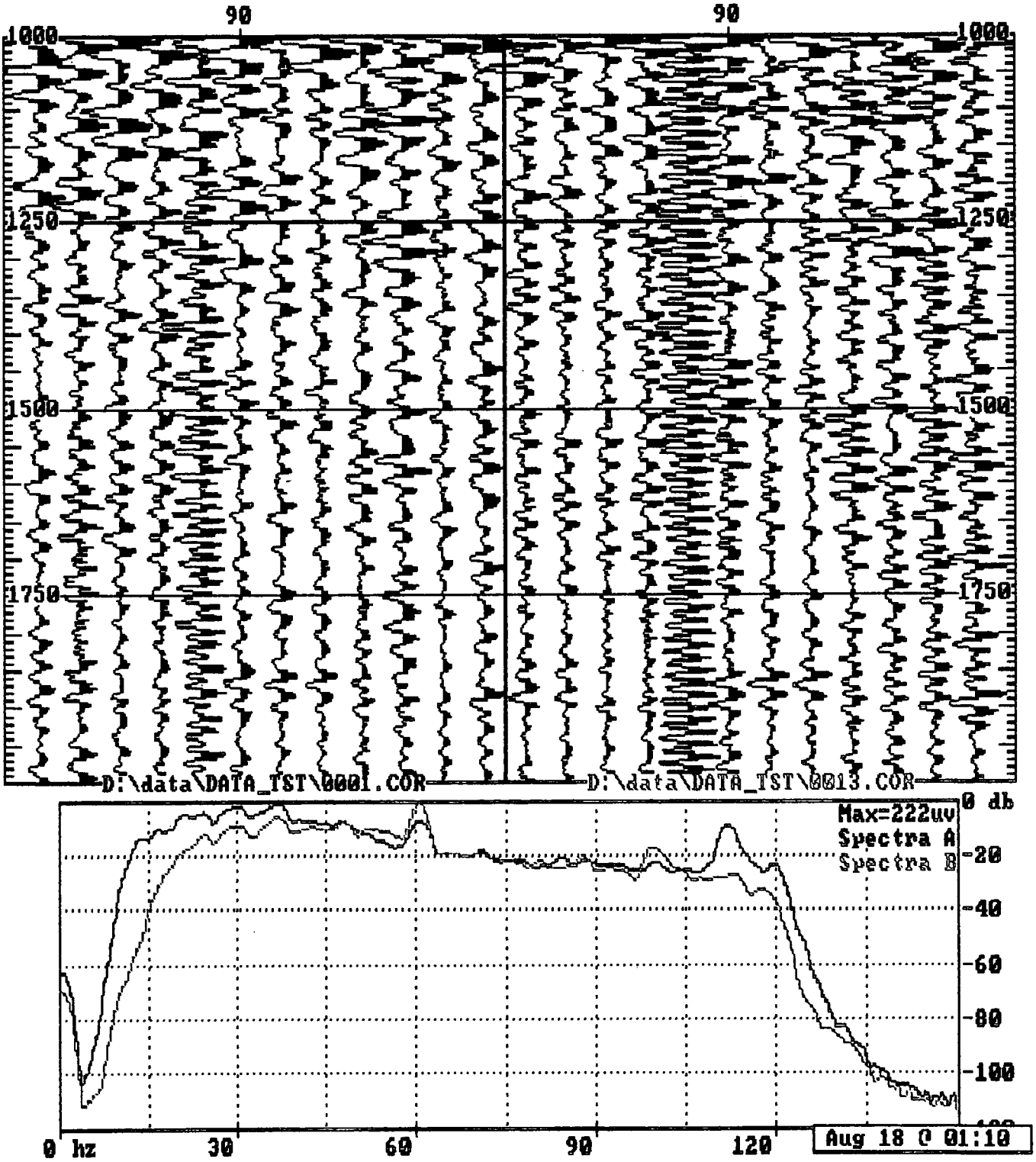
SPECTRAL COMPARISON, BASE VS 10-80 HZ. SWEEP



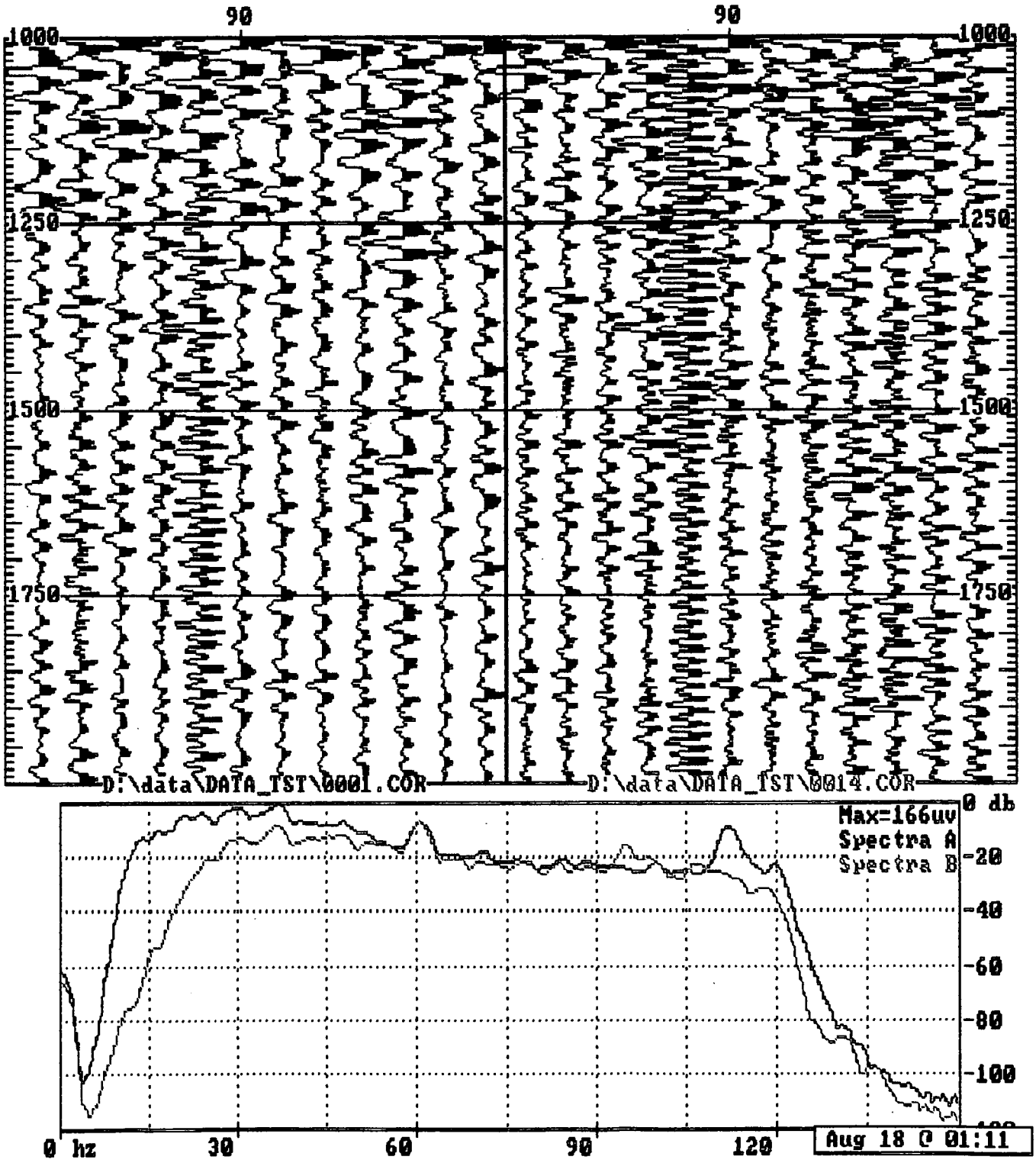
SPECTRAL COMPARISON, Base vs +3 db/oct.



SPECTRAL COMPARISON, BASE VS +6DB/OCT



SPECTRAL COMPARISON: BASE VS +9 DB/OCT



APPENDIX E
AGC'ed Raw Records of Test Sweeps #2

FILE NAMES
At the top of the test sweeps are the file names:
D:\data\Data_tst1\0004.gnd

The key number here is the 0004 or 0003 etc. These identify the data as sweep No. 3 or sweep No. 4 etc. The sweeps are numbered from 1 to 12 which corresponded to their file numbers.

File ID	Sweep Range	Total Vib Length	Freq. Pre-Emphasis	No. Sweeps	Sweep Length	Vib -phone Gap [1]
015	10-120	110	+3 Db/Oct	3 * 12	12 sec	165'
016	10-120	110	+3 Db/Oct	3 * 12	12 sec	275'
017	10-120	110	+3 Db Oct	3 * 12	12 sec	385'
018	10-120	110	+3 Db/Oct	3 * 14	12 sec	165'
019	10-120	110	+3 Db/Oct	3 * 10	12 sec	165'
020	10-120	110	-3 Db/Oct	3 * 12	14 sec	165'
021	10-120	110	+3 Db/Oct	3 * 12	12 sec	2590'

Footnotes:

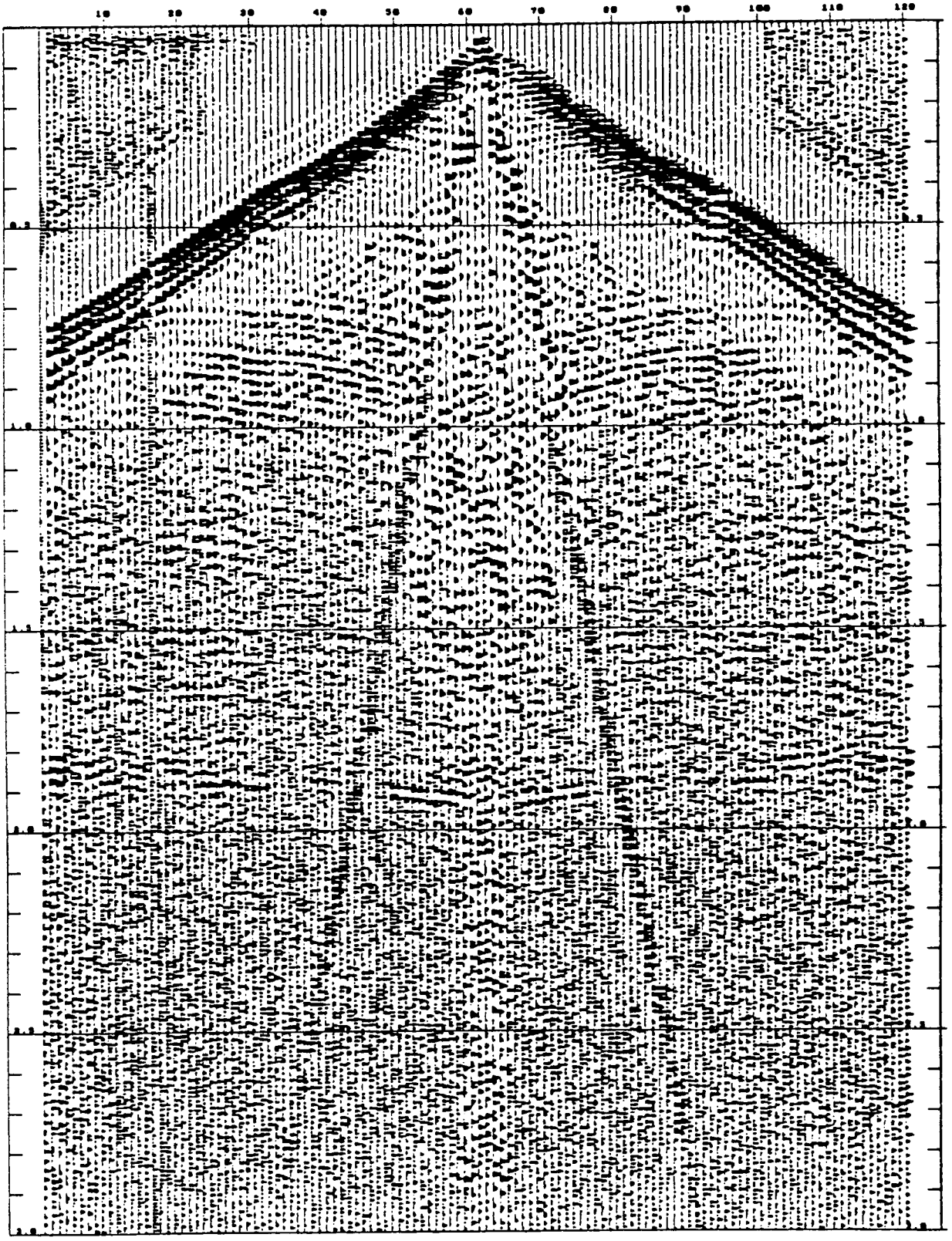
1: This is the distance from array center to array center. Absolute distance from nearest vib to nearest phone is 110' less than the amount noted.

BASE SWEEP #2

+3 db/OCT, 12 SEC, 3x12 SWEEPS, 110' VIB ARRAY, 55' GAP

FILE: D:\DATA\TEST2\0015.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

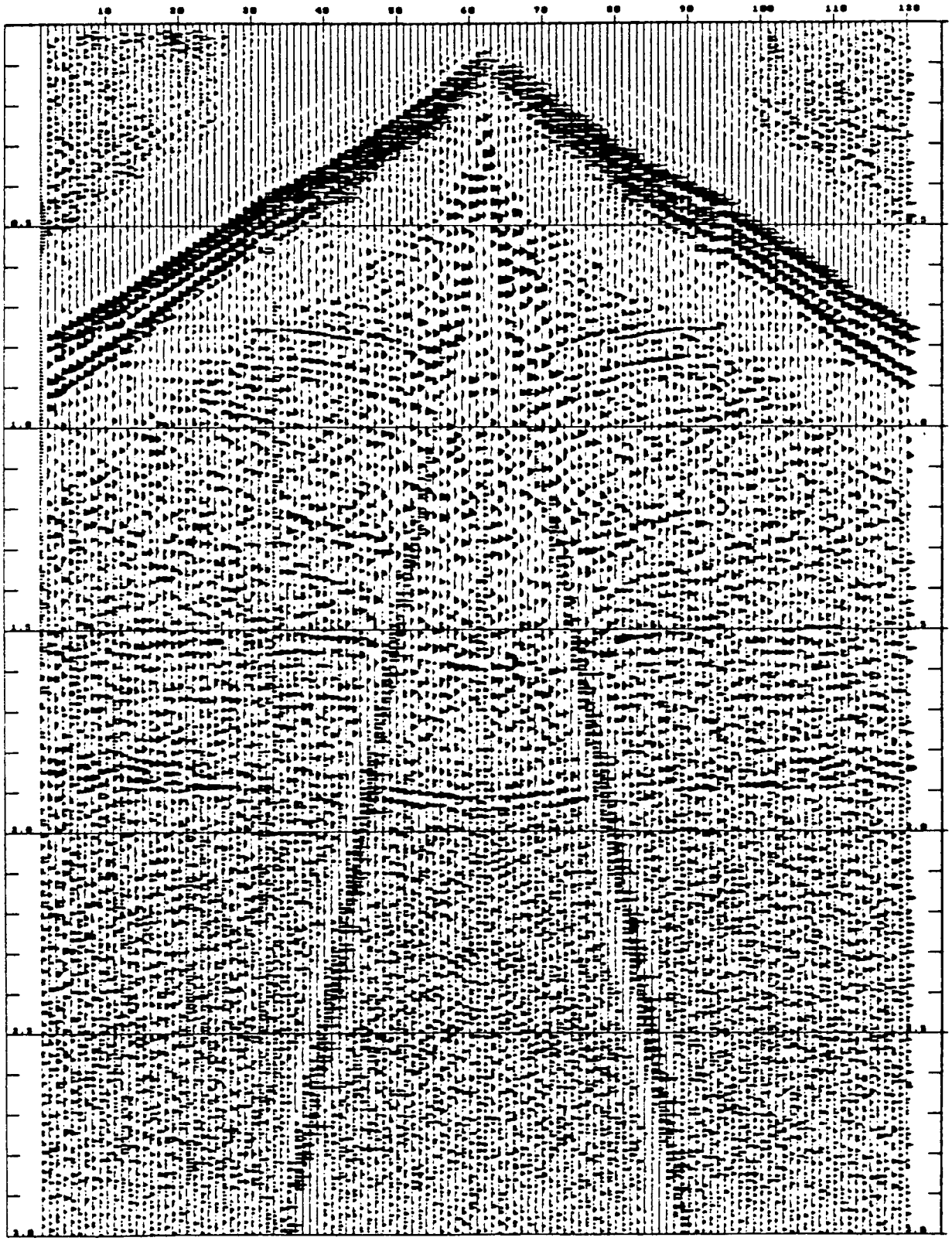
FFID: 0015
TIME: 19:34:53
DATE: Sun Aug 18



2.75' GAP

FILE: D:\DATA\TEST2\0017.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

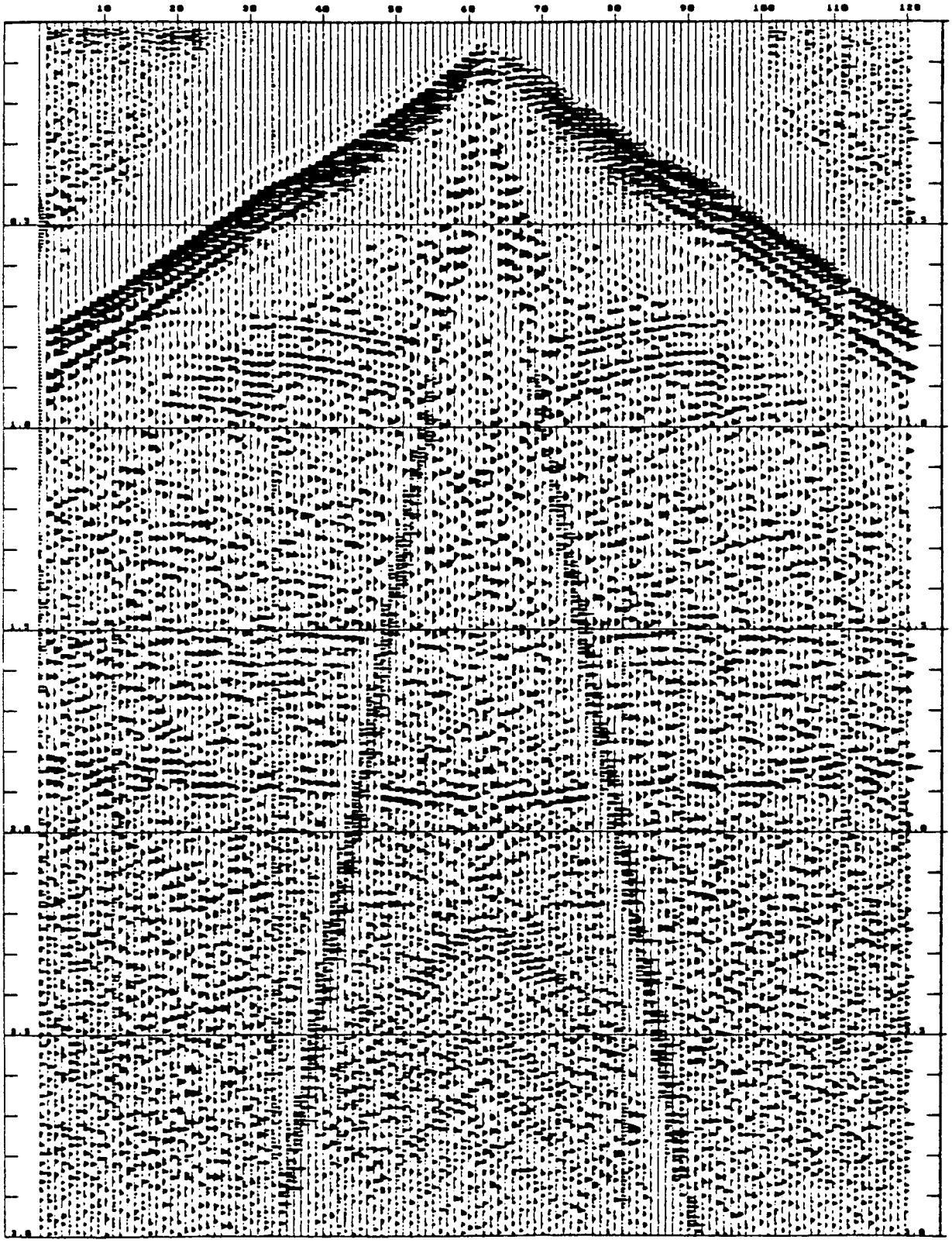
FFID: 0017
TIME: 19:39:35
DATE: Sun Aug 18



165' GAP

FILE: D:\DATA\TEST2\0016.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

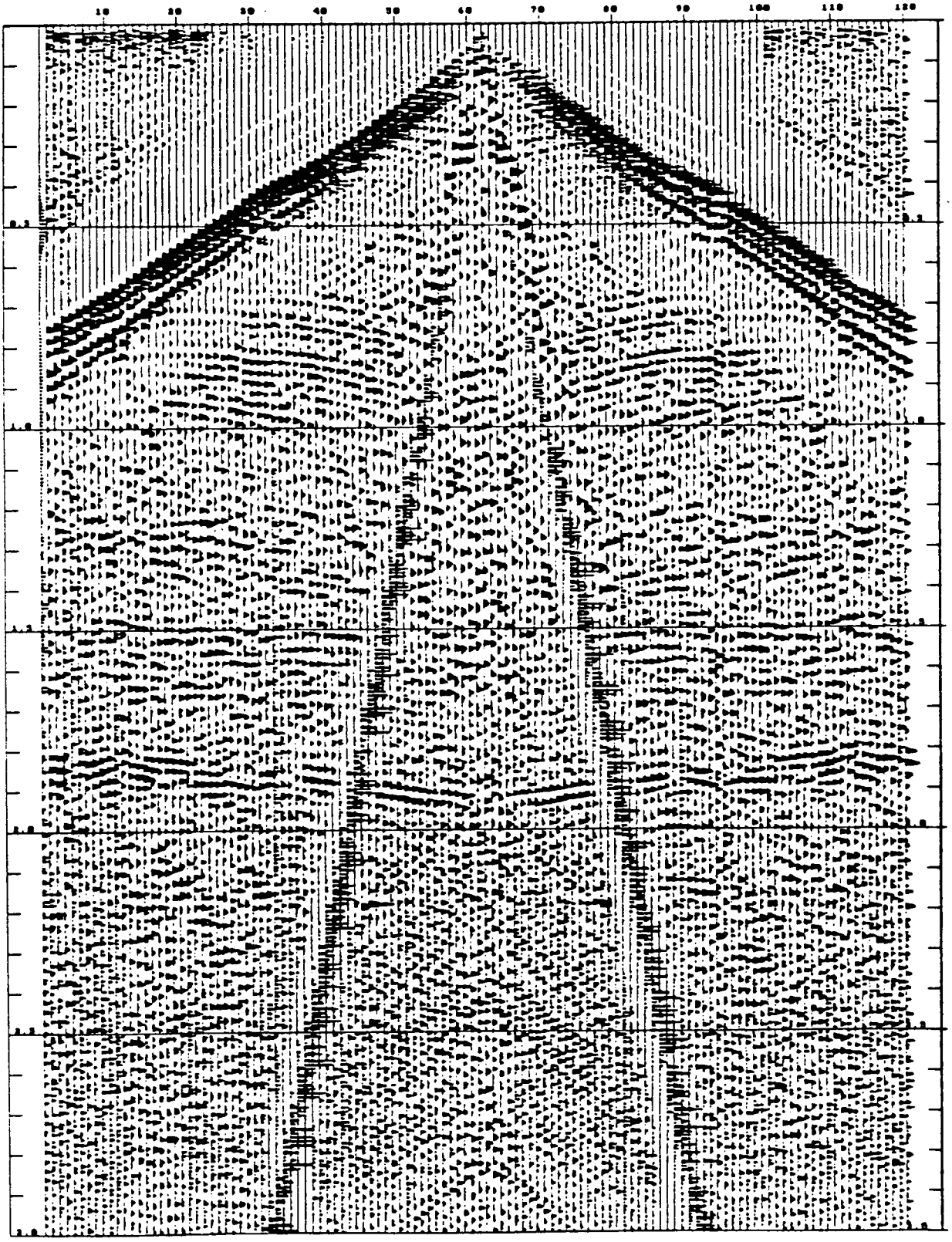
FFID: 0016
TIME: 19:37:14
DATE: Sun Aug 18



3 x 14 SWEEPS
SUMMED

FILE: D:\DATA\TEST2\0018.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

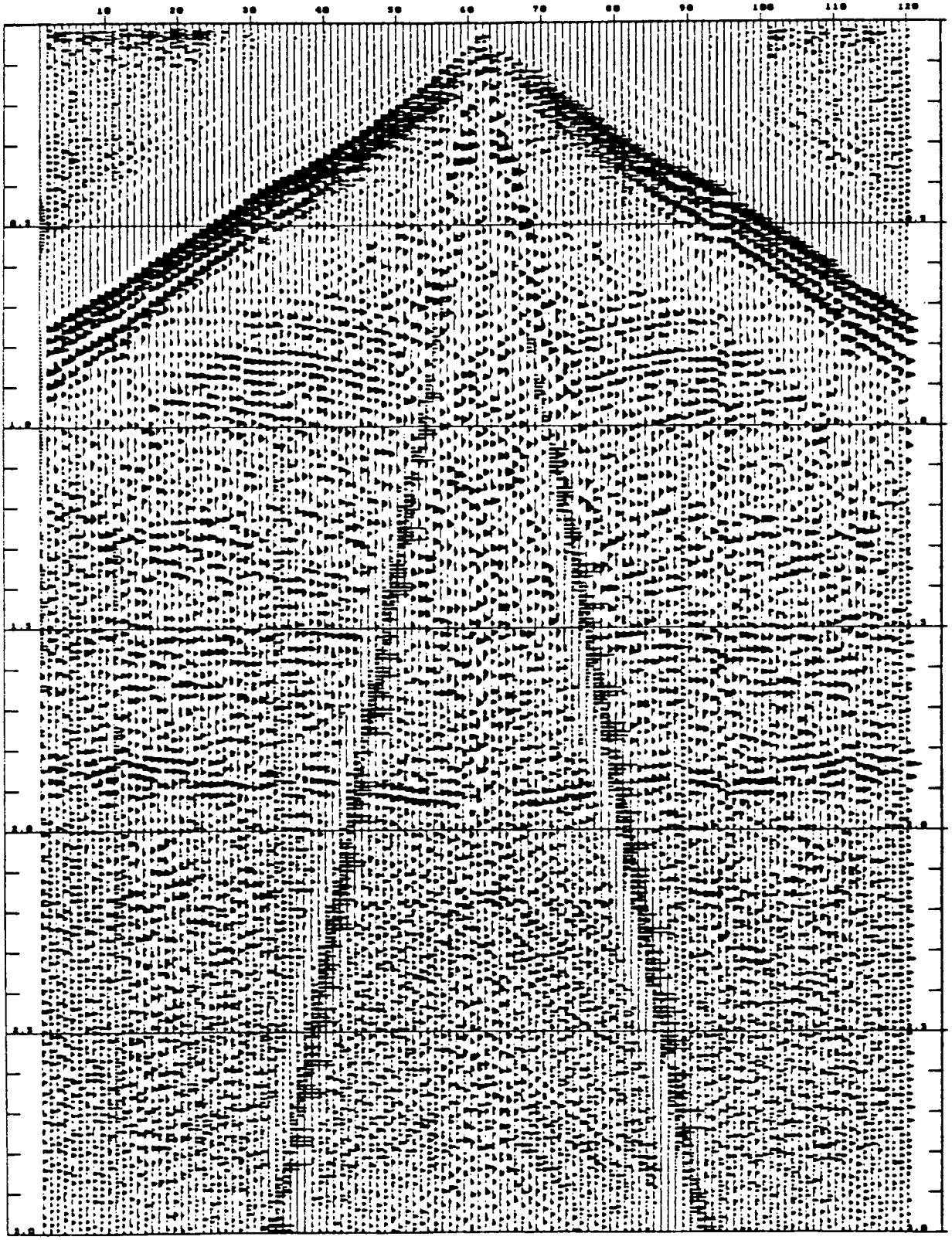
FFID: 0018
TIME: 19:41:58
DATE: Sun Aug 18



3x10 SWEEPS
SUMMED

FILE: D:\DATA\TEST2\0019.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

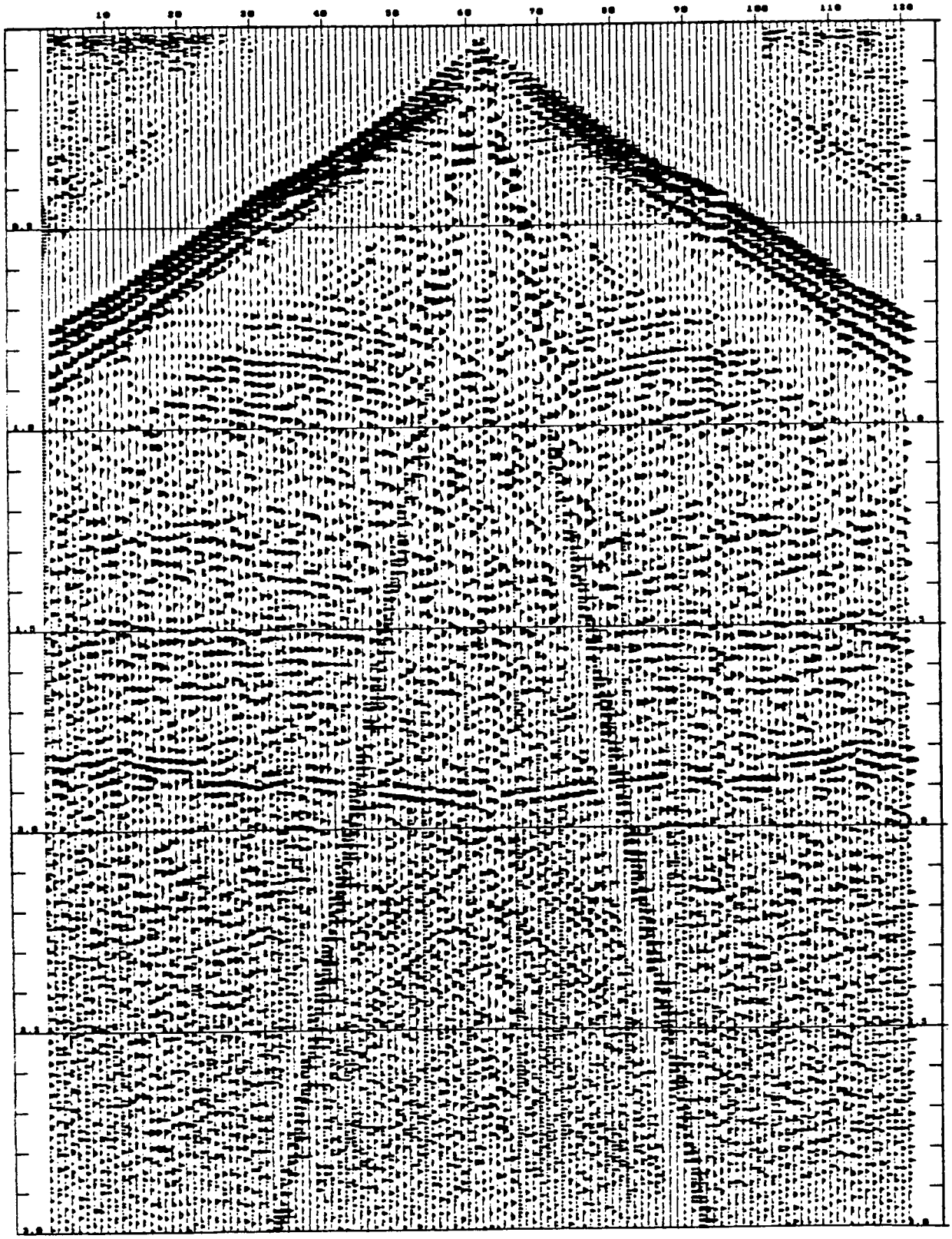
FFID: 0019
TIME: 19:44:20
DATE: Sun Aug 18



14 SECOND SWEEP LENGTH

FILE: D:\DATA\TEST2\0020.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

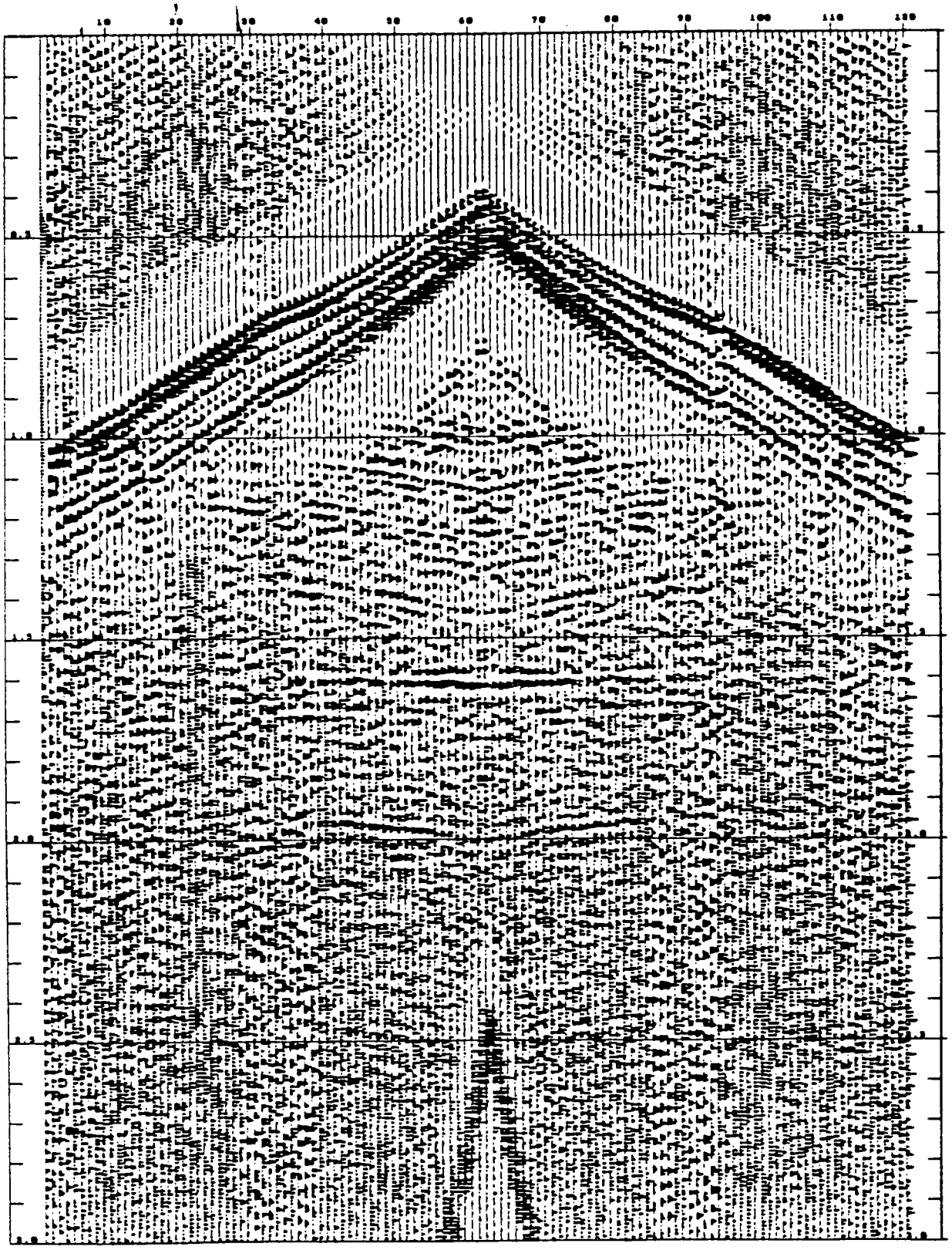
FFID: 0020
TIME: 19:46:43
DATE: Sun Aug 18



2590' GAP
VIB TO PHONES

FILE: D:\DATA\TEST2\0021.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

FFID: 0021
TIME: 19:49:05
DATE: Sun Aug 18



APPENDIX F
Filter Panels of Test Sweeps #2

FILTER PANELS
There are two sets of filter panels. The first panel (far left) displays the input window. The next nine panels show the band pass filtered outputs of 10-20, 20-40, 30-60, 40-80, 50-100, 60-120, 70-140, 80-140, and finally 90-140.

Basically the panels increment by 10 hz and they have a half octave bandwidth.

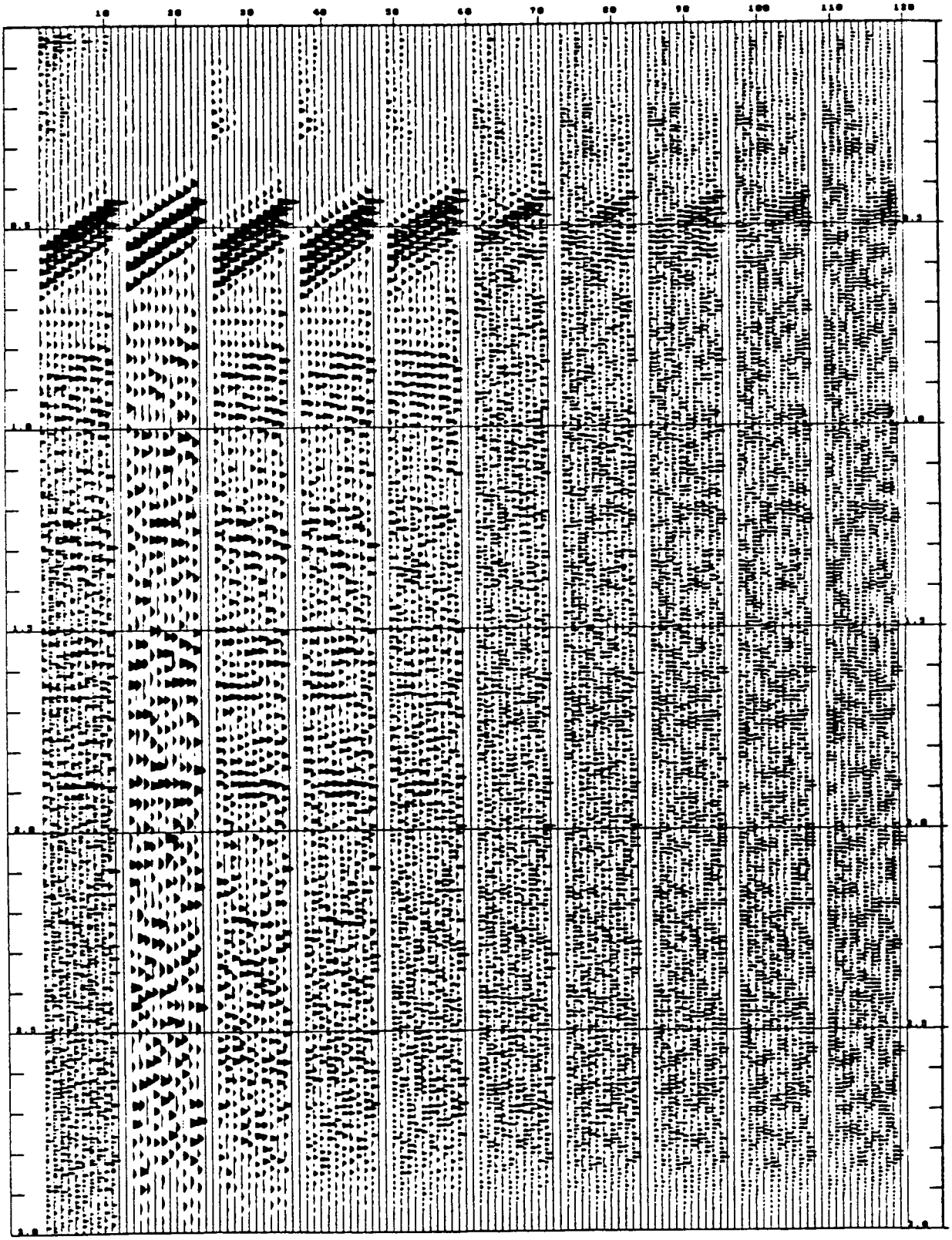
These panels were AGC'd. In some cases AGC of a filter panel will give erroneous results. There is the possibility to gain up the frequencies that were supposed to be filtered. It is fairly obvious when this occurs however. Note the 90-140 panel (farthest to the right) in sweep 011 (10-80 hz. band width).

BASE SWEEP #2

+3 db/OCT, 12 SEC., 3 x 12 SWEEPS, 110' VIB ARRAY, 55' GAP

FILE: D:\DATA\TEST2\0015.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

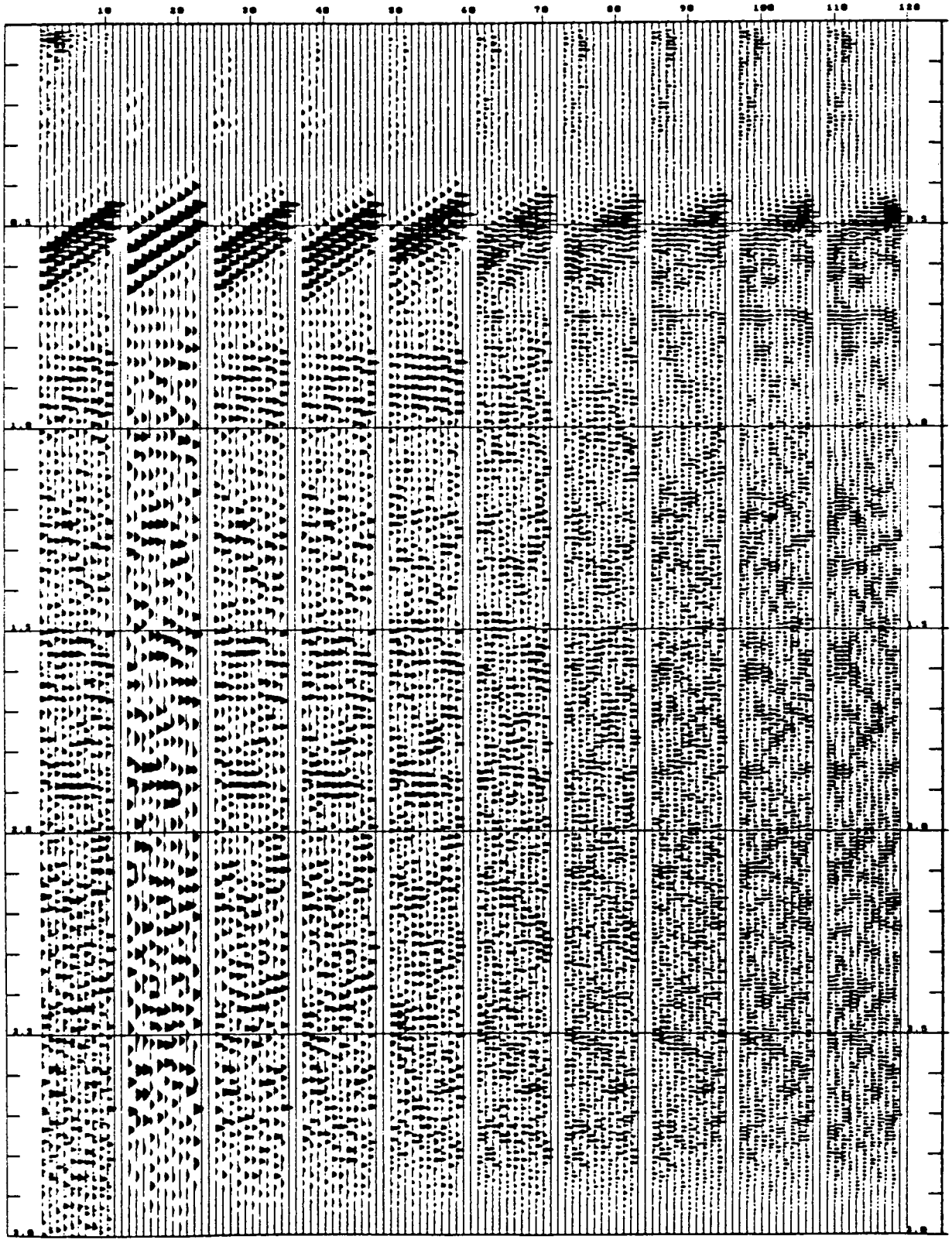
FFID: 0015
TIME: 19:04:24
DATE: Sun Aug 18



165' GAP
VIB TO PHONE

FILE: D:\DATA\TEST2\0016.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

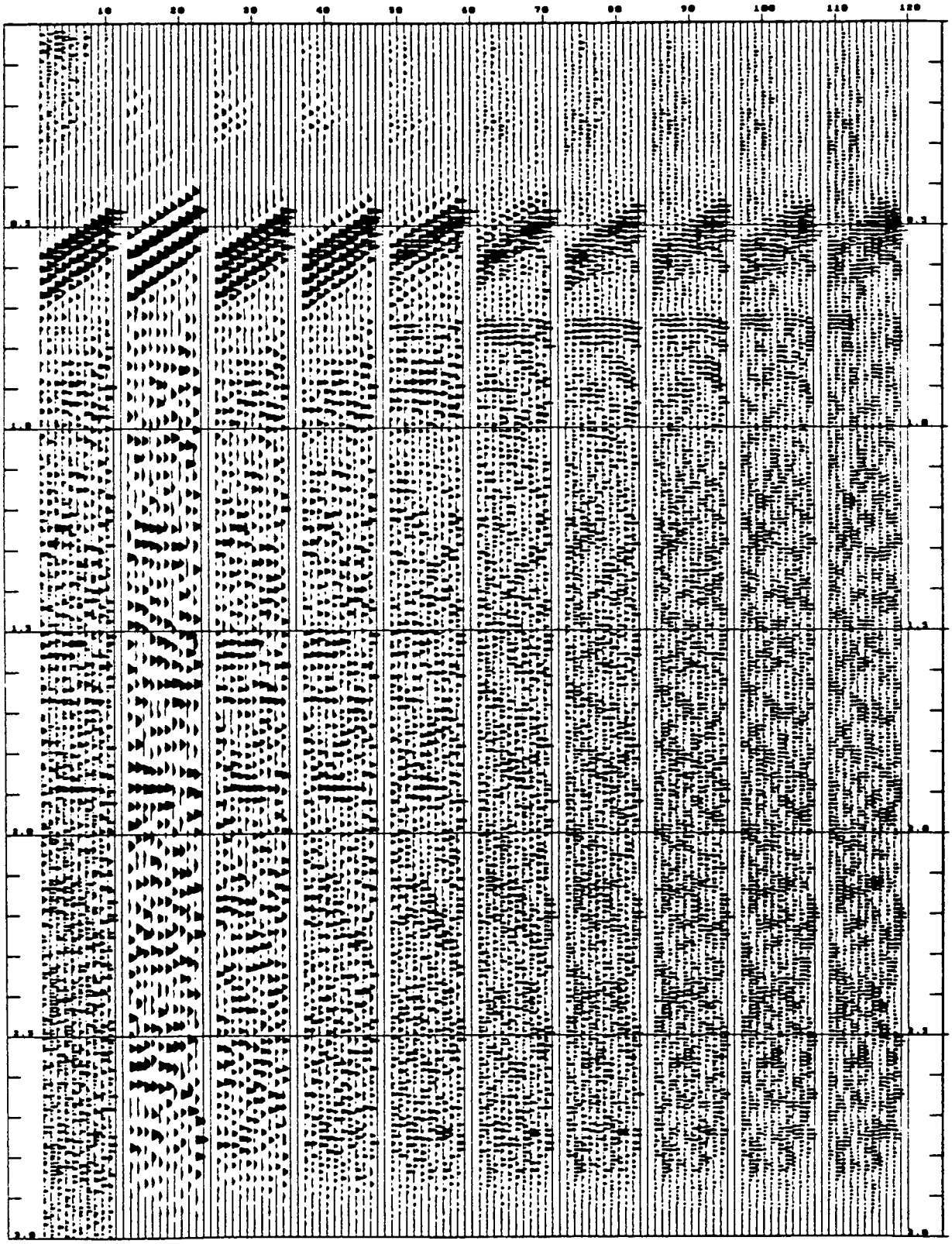
FFID: 0016
TIME: 19:08:06
DATE: Sun Aug 18



175' GAP
VIB TO PHONE

FILE: D:\DATA\TEST2\0017.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

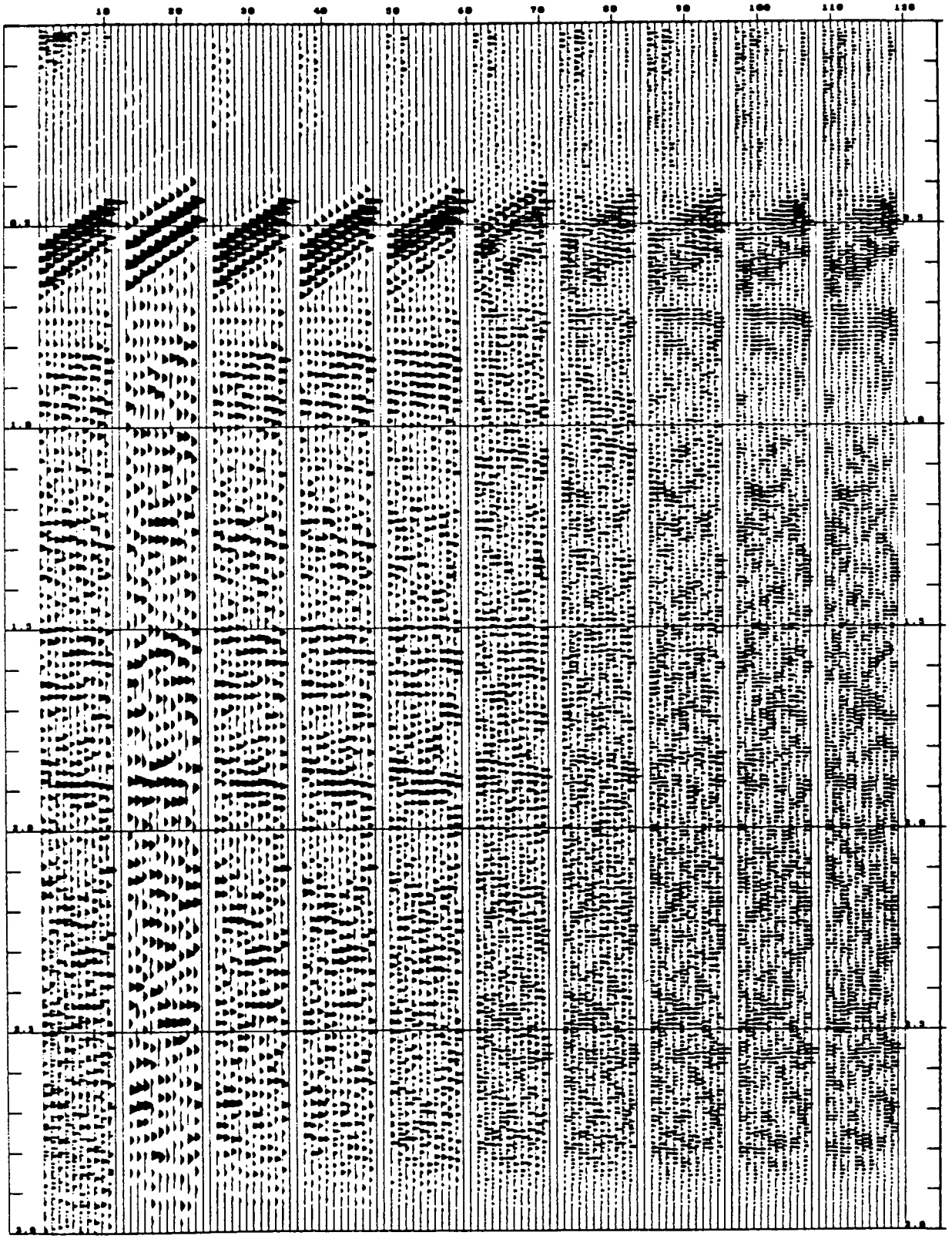
FFID: 0017
TIME: 19:11:46
DATE: Sun Aug 18



3 x 14 SWEEPS
SUMMED 8

FILE: D:\DATA\TEST2\0018.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

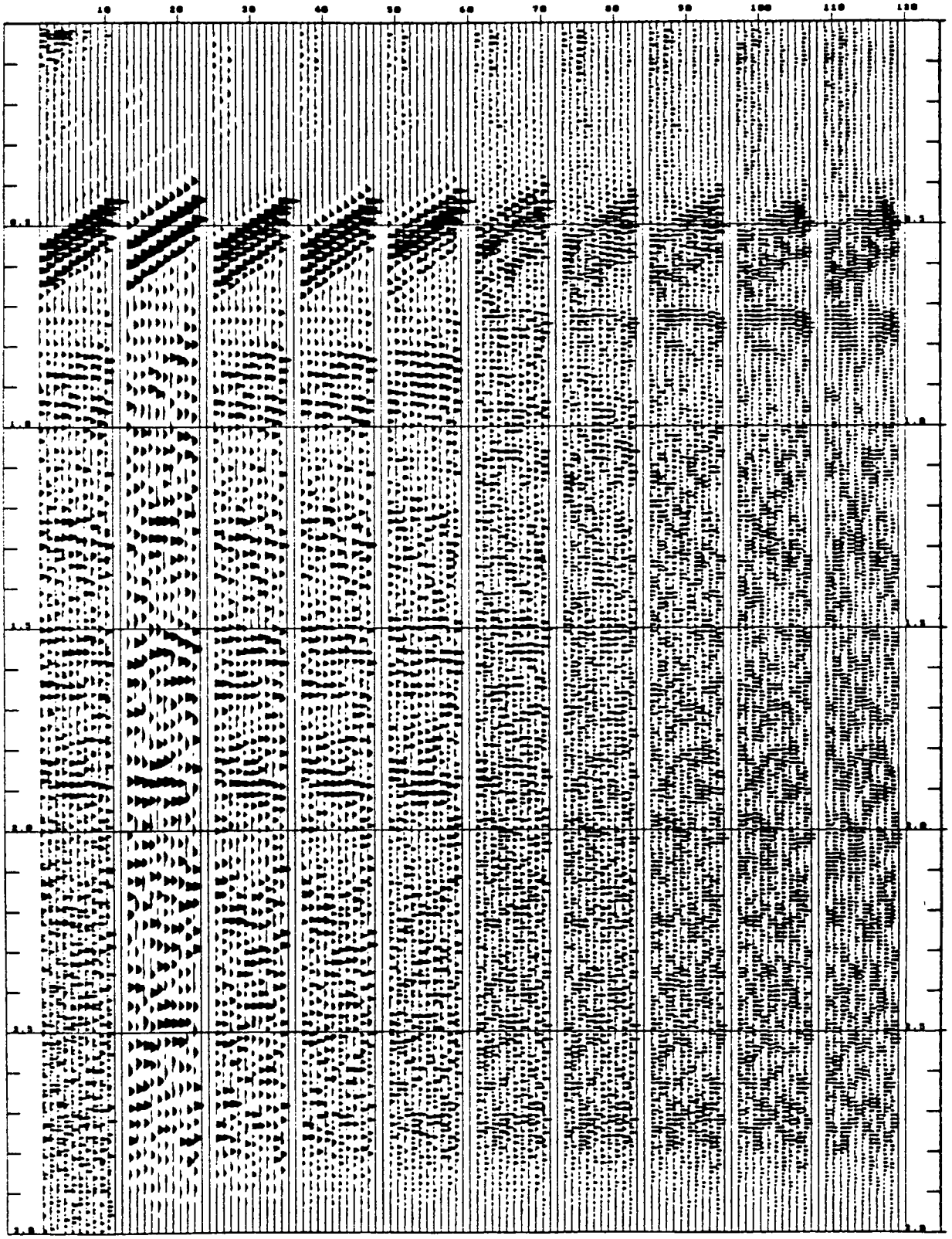
FFID: 0018
TIME: 19:15:26
DATE: Sun Aug 18



3 X 10 SWEEPS
SUMMED

FILE: D:\DATA\TEST2\0019.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

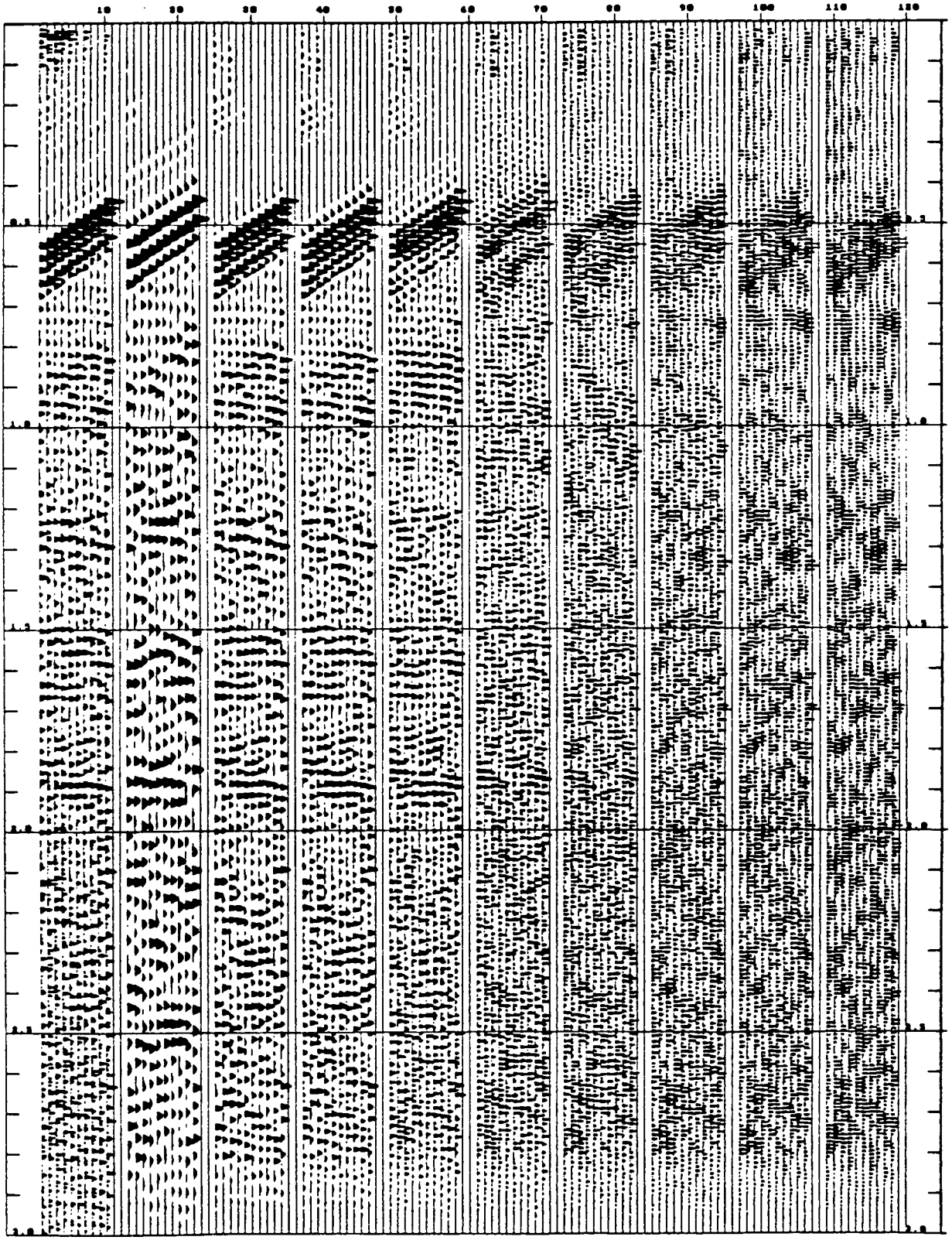
FFID: 0019
TIME: 19:19:07
DATE: Sun Aug 18



14 SECOND SWEEP LENGTH

FILE: D:\DATA\TEST2\0020.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

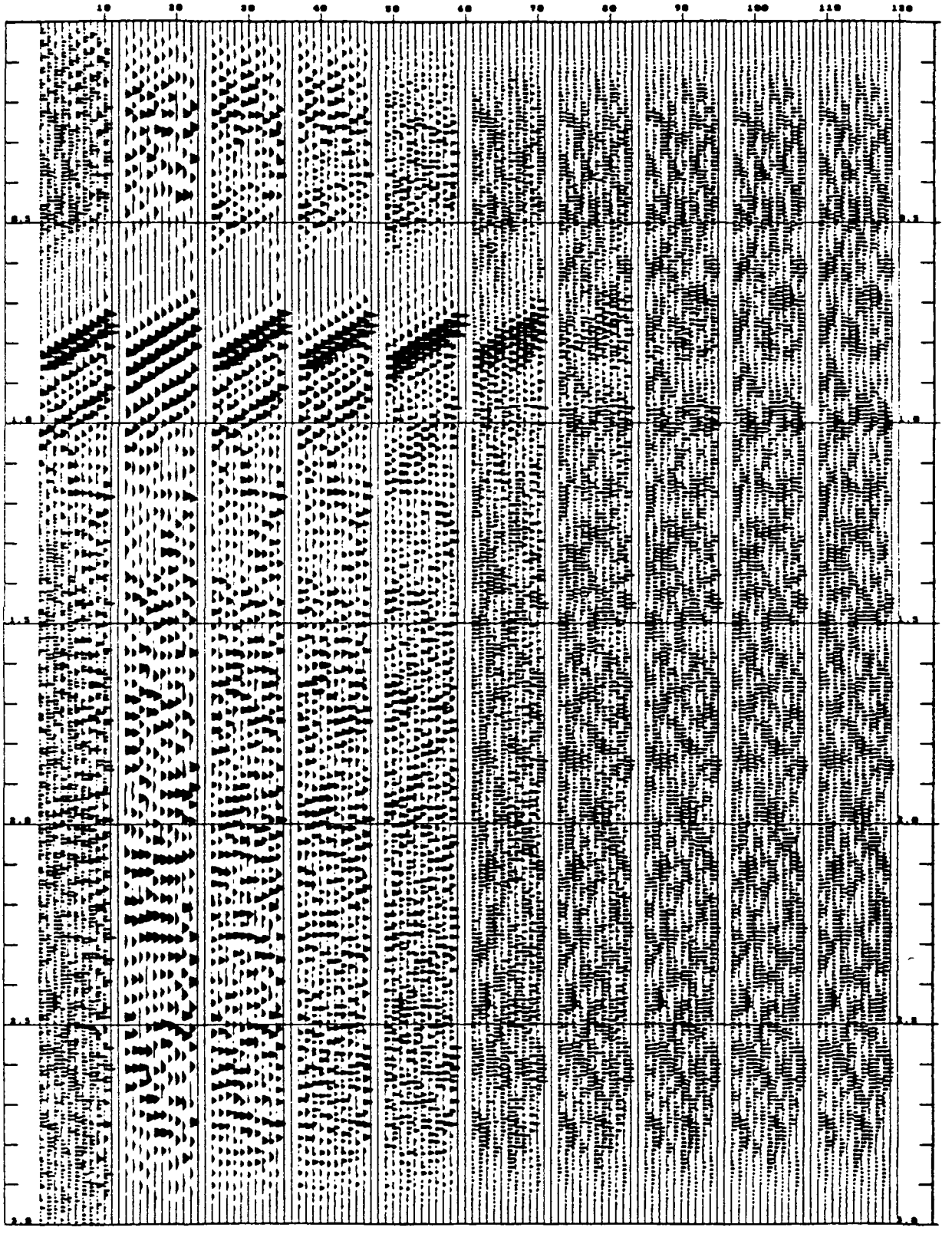
FFID: 0020
TIME: 19:22:48
DATE: Sun Aug 18



2590' GAP
VIB TO PHONE

FILE: D:\DATA\TEST2\0021.gnR
AMPLITUDE: 0005.0
SCALE: 3=TRUE_AMP
PLOT MODE: VA

FFID: 0021
TIME: 19:26:28
DATE: Sun Aug 18



APPENDIX G

Amplitude Analysis of Test Sweeps #2

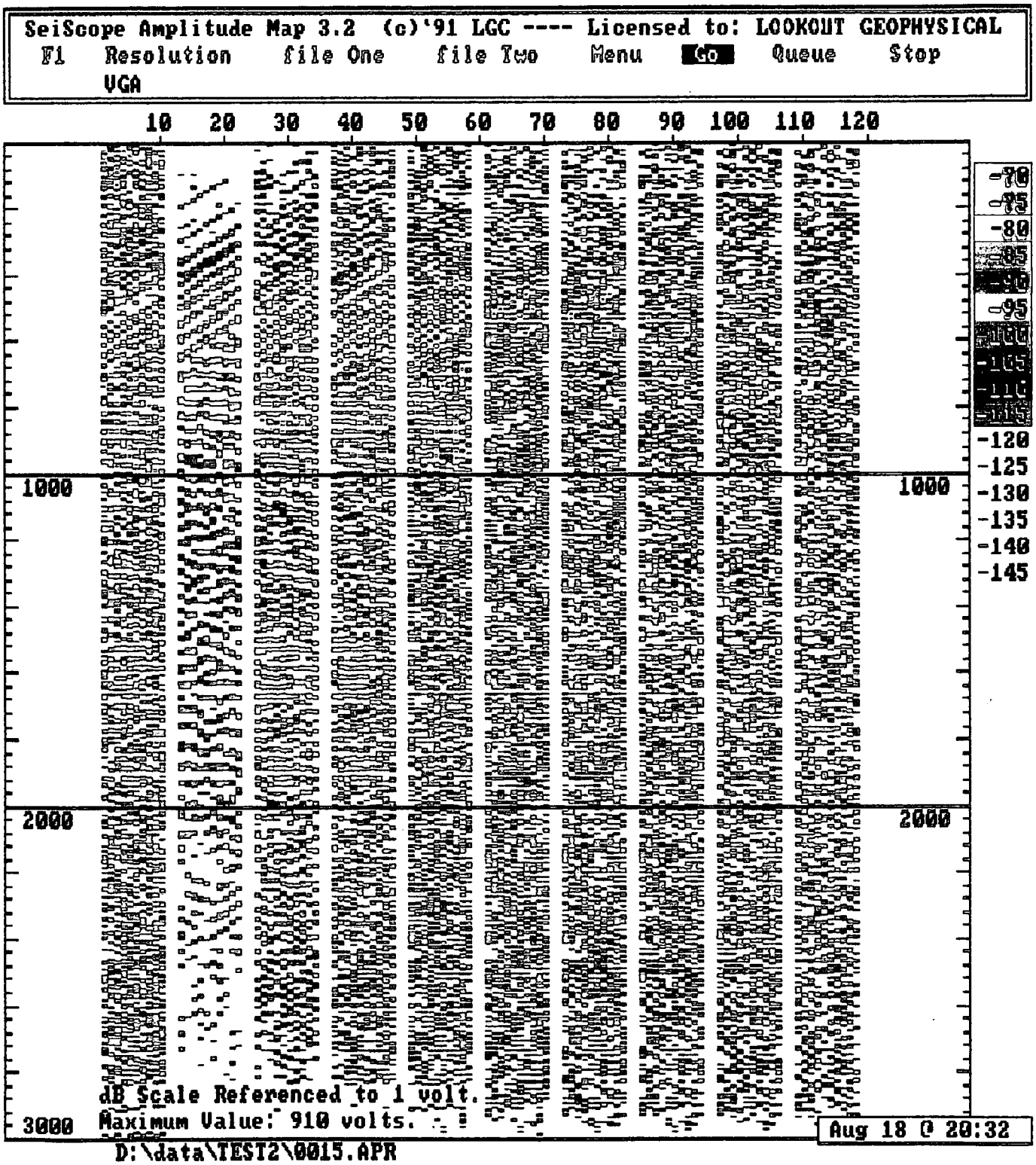
Amplitude analysis provides feel for the relative strength and amplitude coherency of events in the tests records.

When we create these amplitude maps of the filter panels we have a perfect tool for analyzing which sweeps return the most of a given frequency range from the zone of interest.

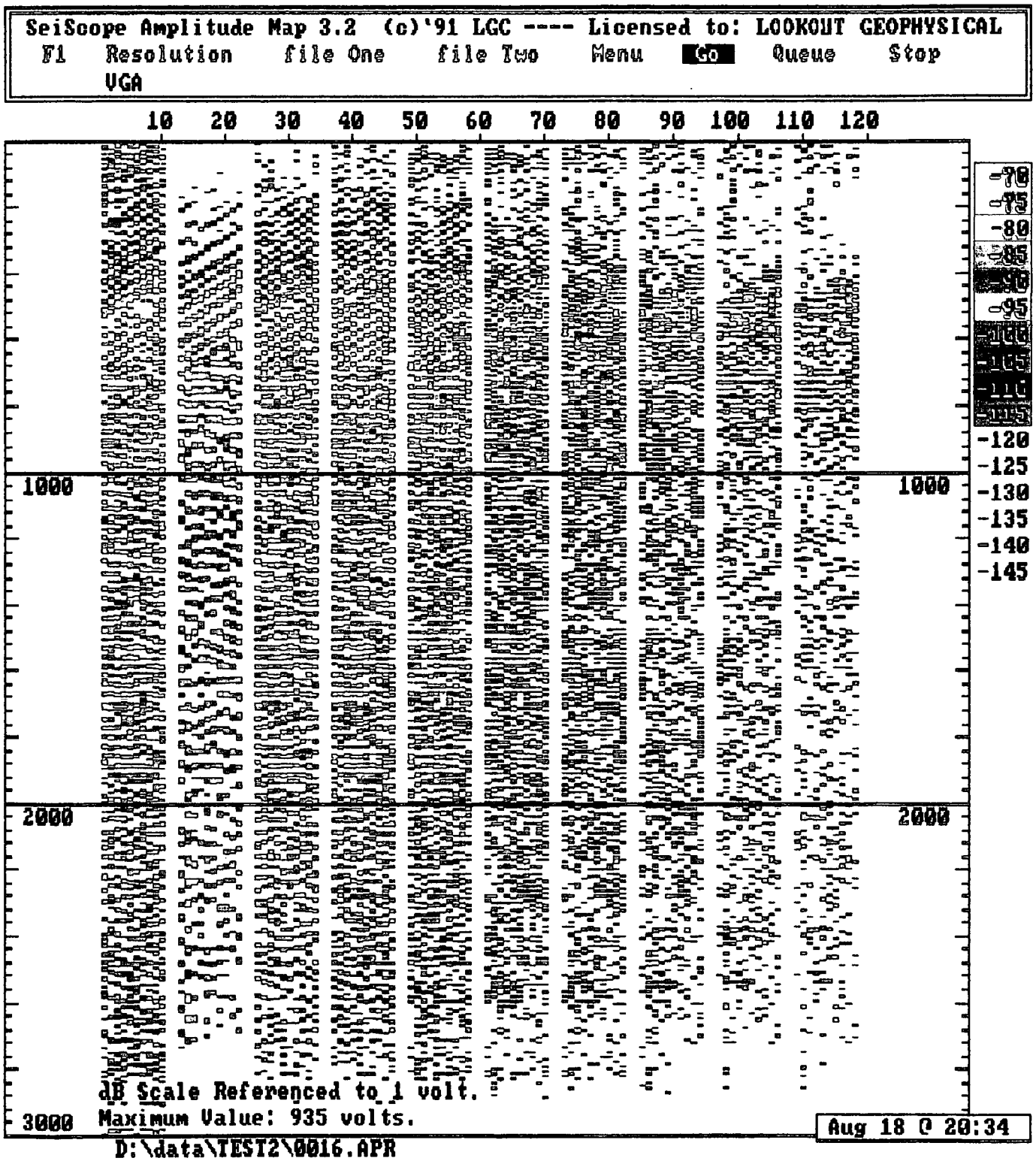
Notes:
These "Amp-maps" were computed with an identical maximum value sample of 1 volt. The colored db scale is referenced to a 1 volt level.

Theses records have had no gain or other enhancement besides band-pass filtering.

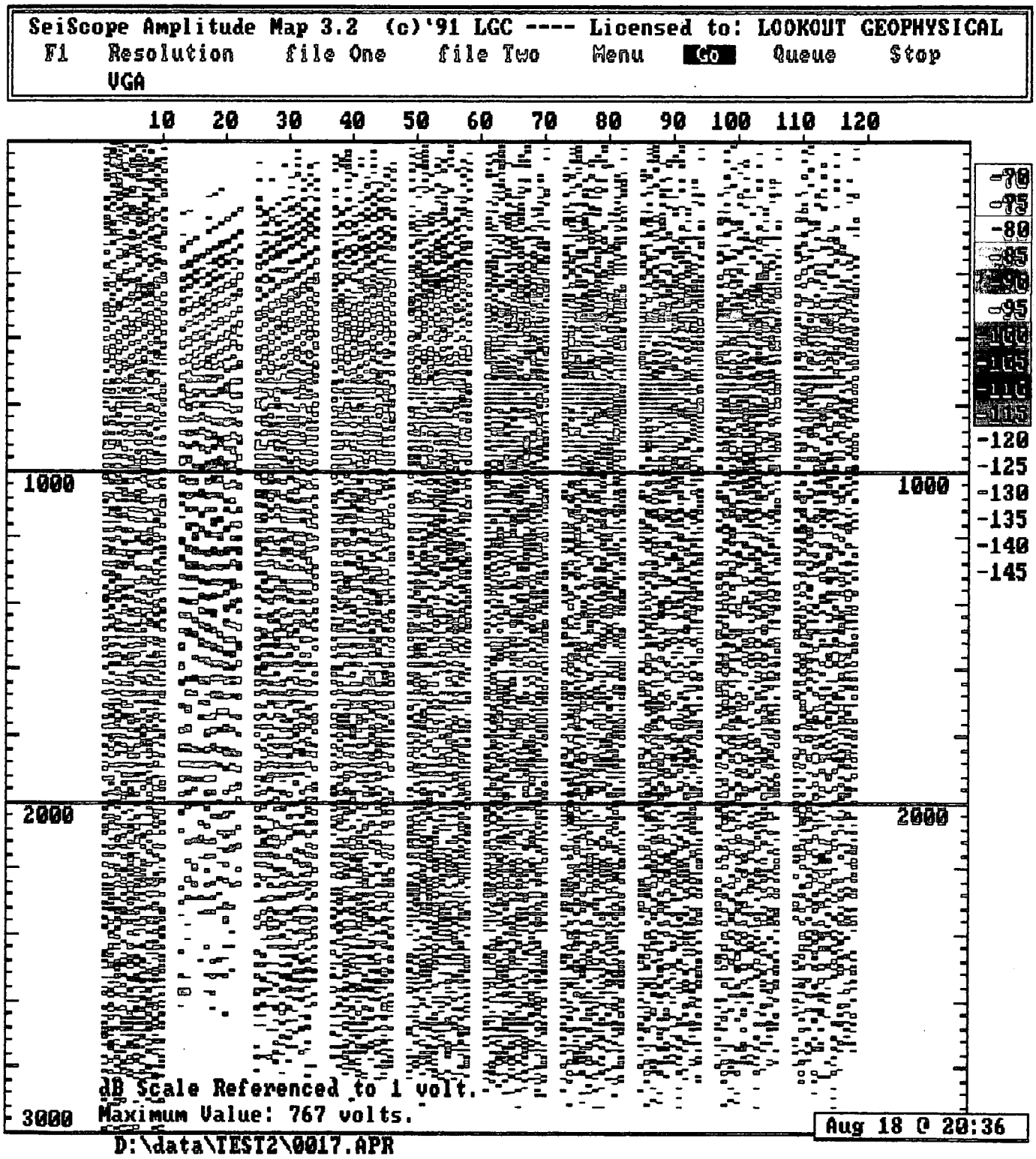
AMPITUDE MAP: BASE SWEEP #2



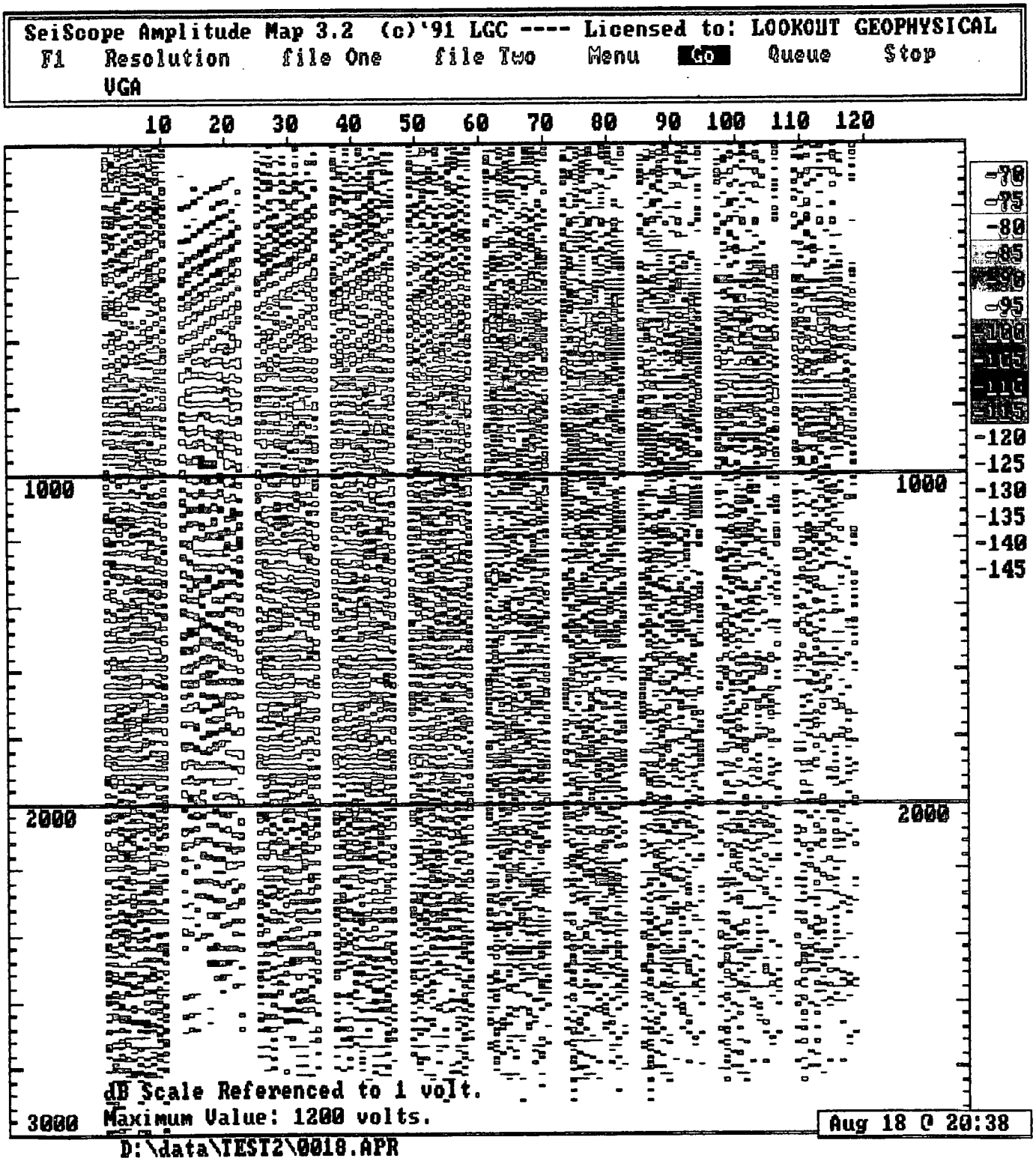
AMPITUDE MAP; 165' GAP, VIBS TO PHONES



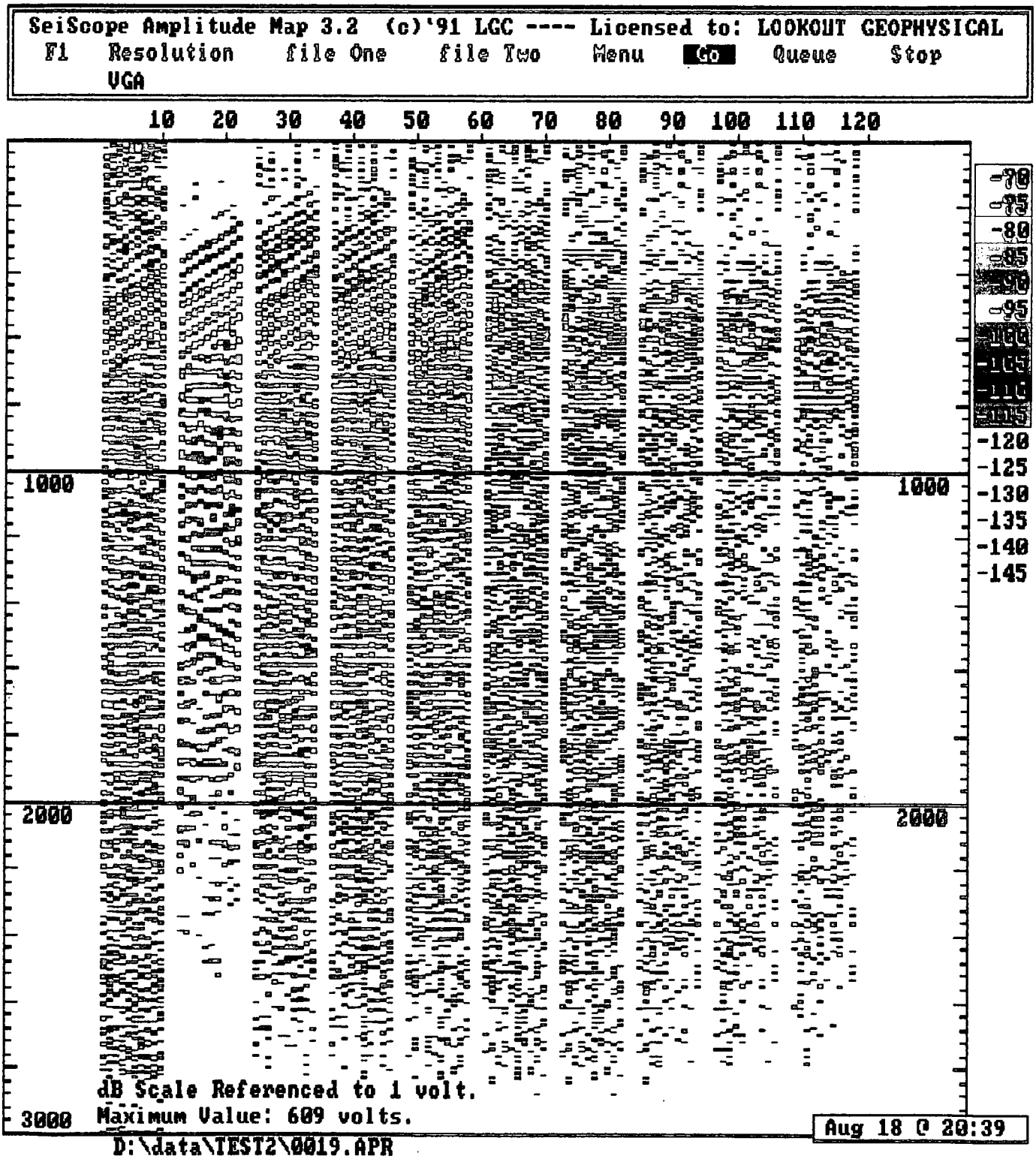
AMPITUDE MAP; 275' GAP VIB TO PHONES



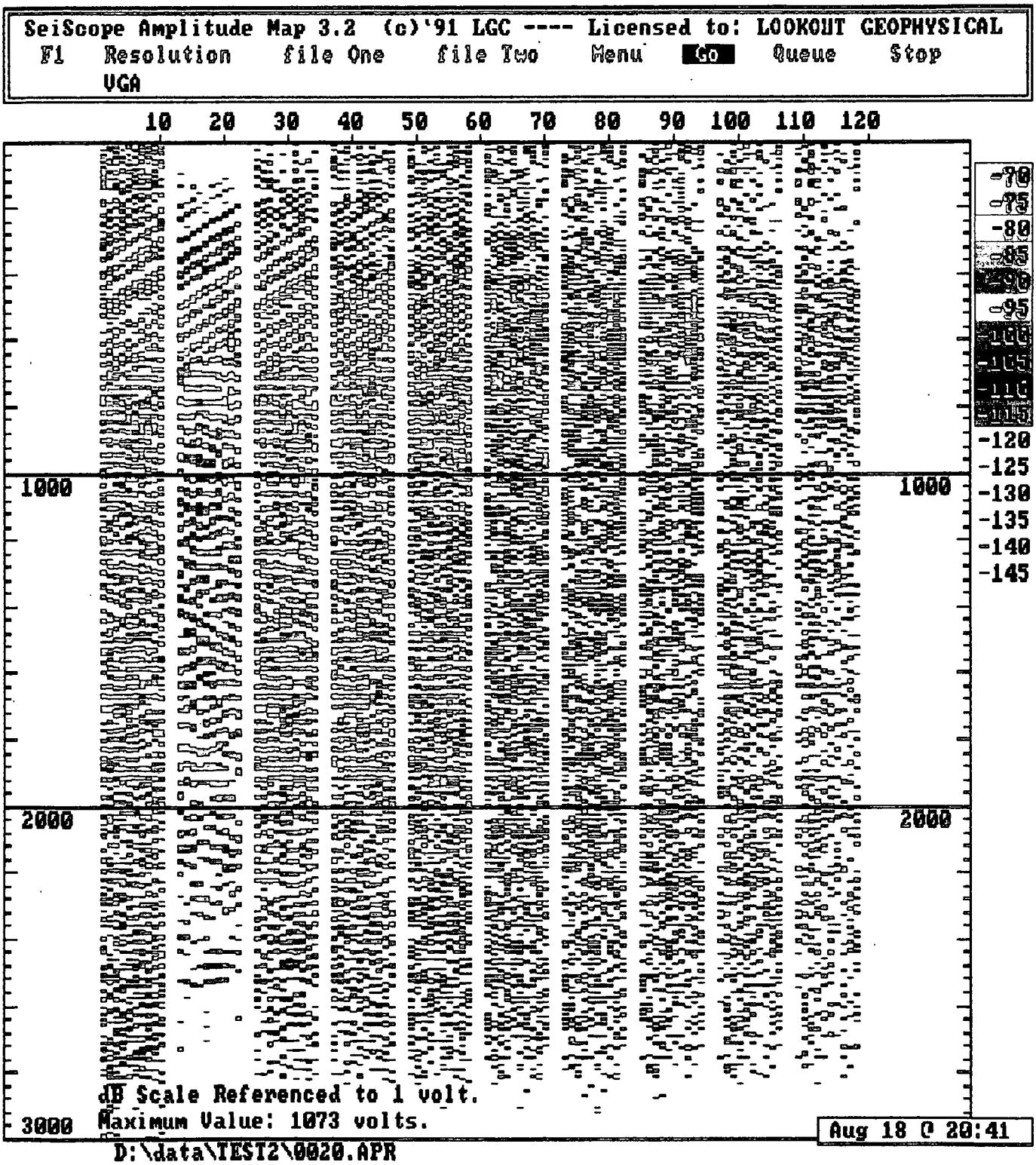
AMPITUDE MAP; 3 x 14 SWEEPS SUMMED



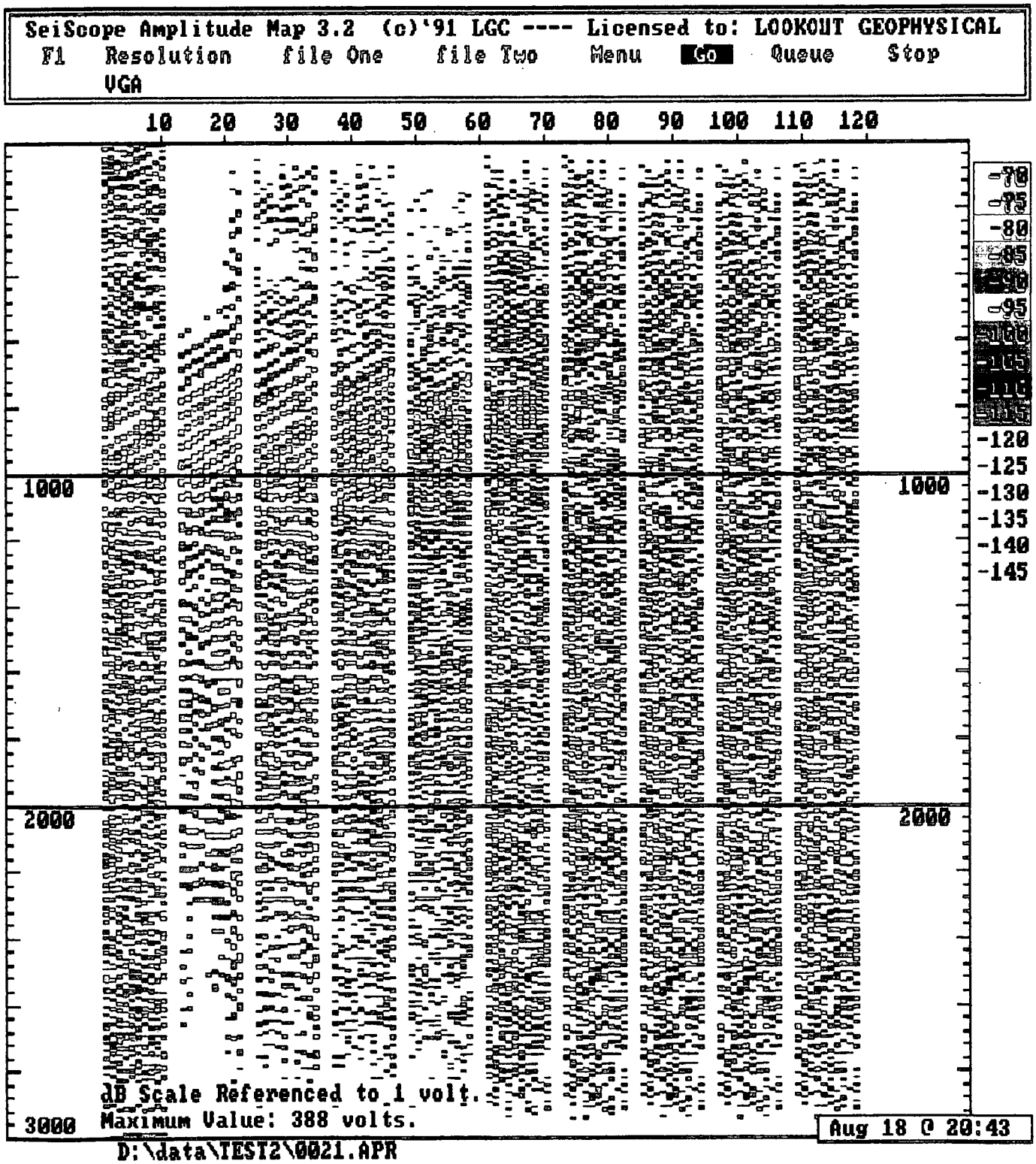
AMPITUDE MAP; 3 x 10 SWEEPS SUMMED



AMPITUDE MAP; 14 SECOND SWEEP LENGTH



AMPITUDE MAP; 2590' GAP, VIBS TO PHONES



APPENDIX H

Instrument Tests Graphic plots

There six plots in the section:

1) The first is a perspective waterfall of the pulse test for the recorder. It shows a consistent spectrum for all channels.

2) This shows the waterfall of the harmonic distortion test. This shows the harmonic distortion and noise is clean for all channels.

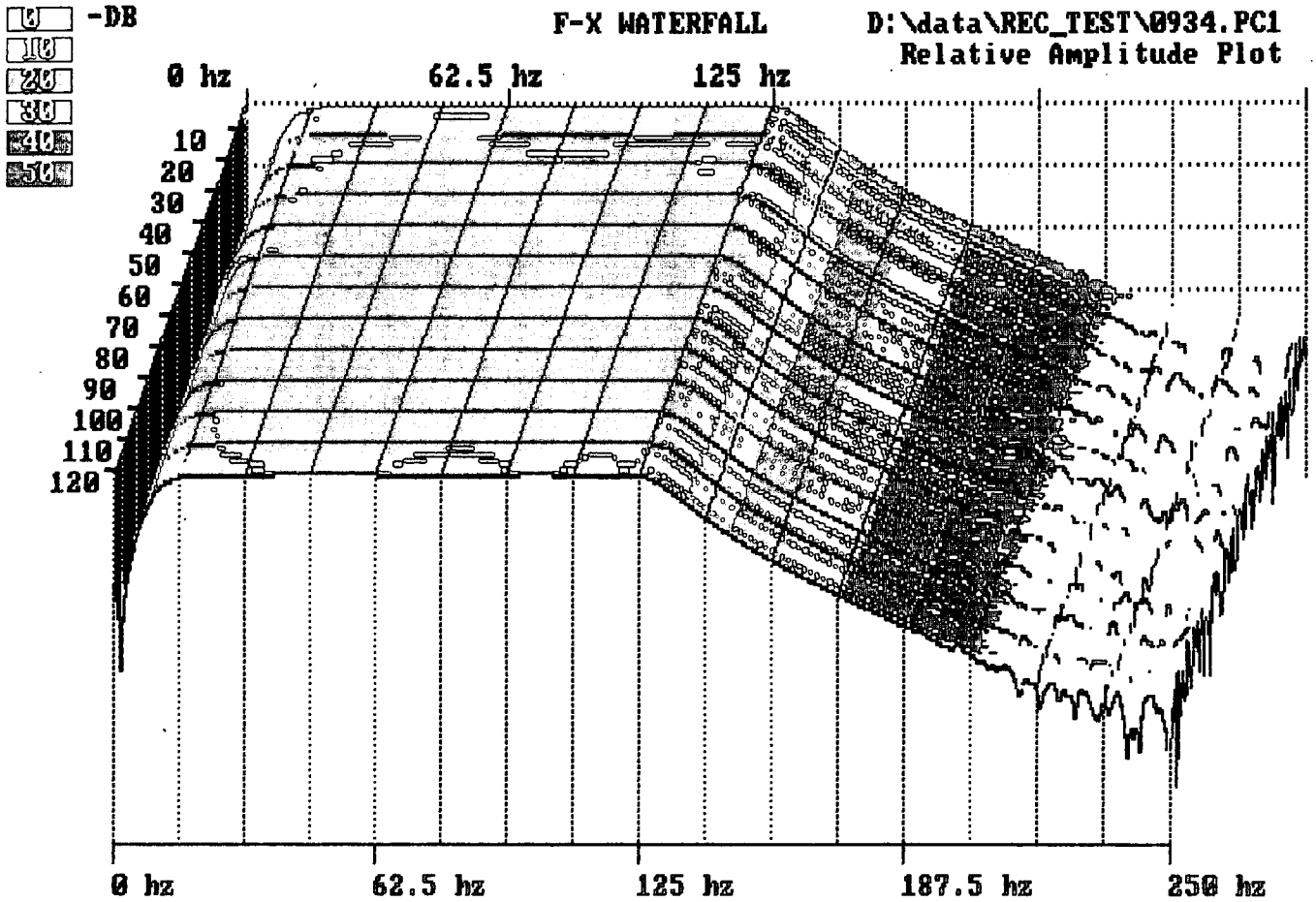
3) This shows the above waterfall with an end view. This vantage, while not as colorful shows the variations better.

4) This shows the waterfall of the Exponential oscillator for the master. This shows the harmonic distortion and noise is clean for all channels.

5) This shows the above waterfall with an end view. You can see a slight amount on one channel. This is not a problem because it such a small level and it occurs above 125 hz.

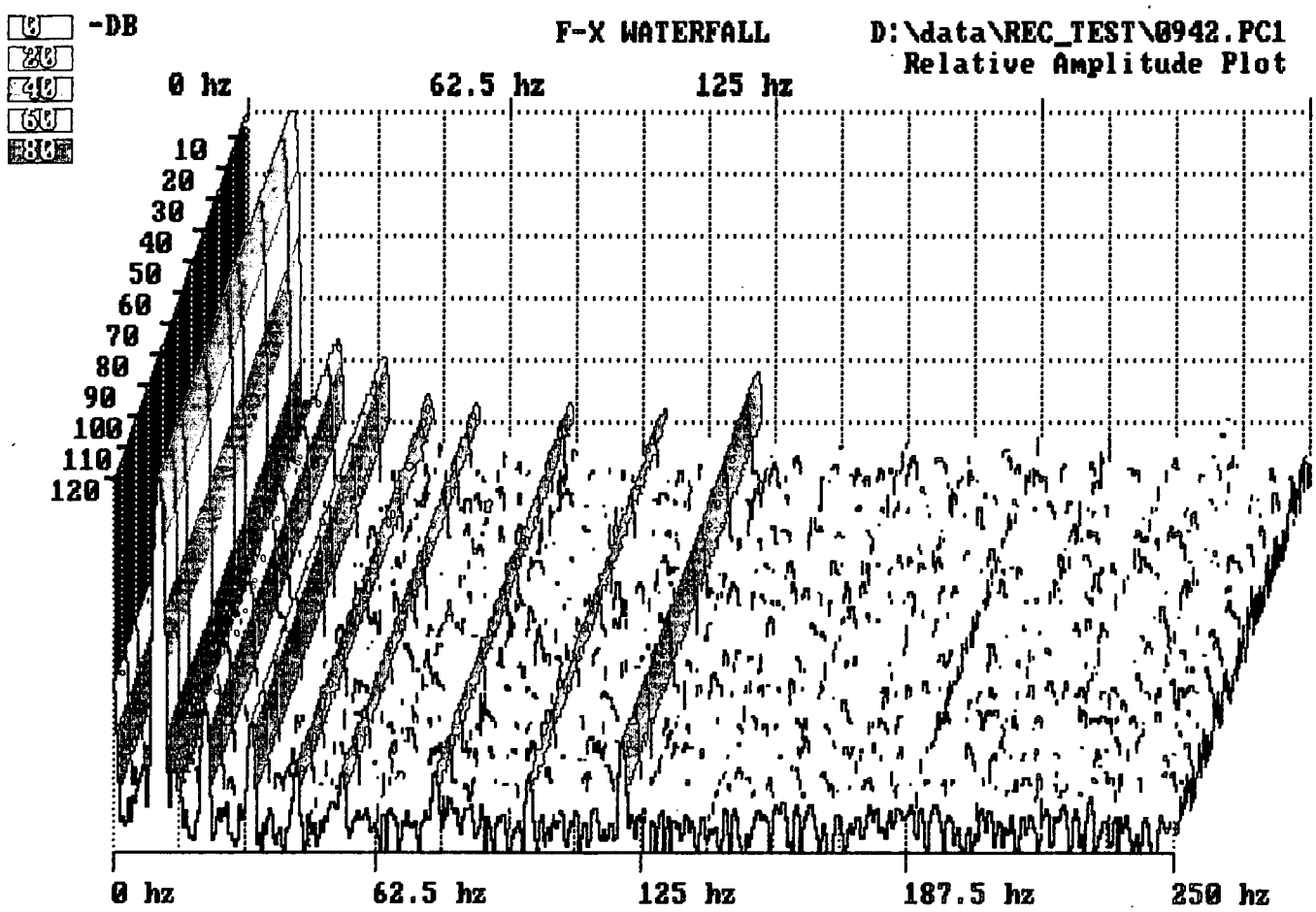
6) This is an Amplitude Analysis of the Exponential Oscillator. This is normal looking. This is useful for diagnosing problems with the IFP amplifiers.

Pulse waterfall, 12 Hz. Low-cuts



Aug 17 @ 11:48

Prespective View, Harmonic Distortion Waterfall.

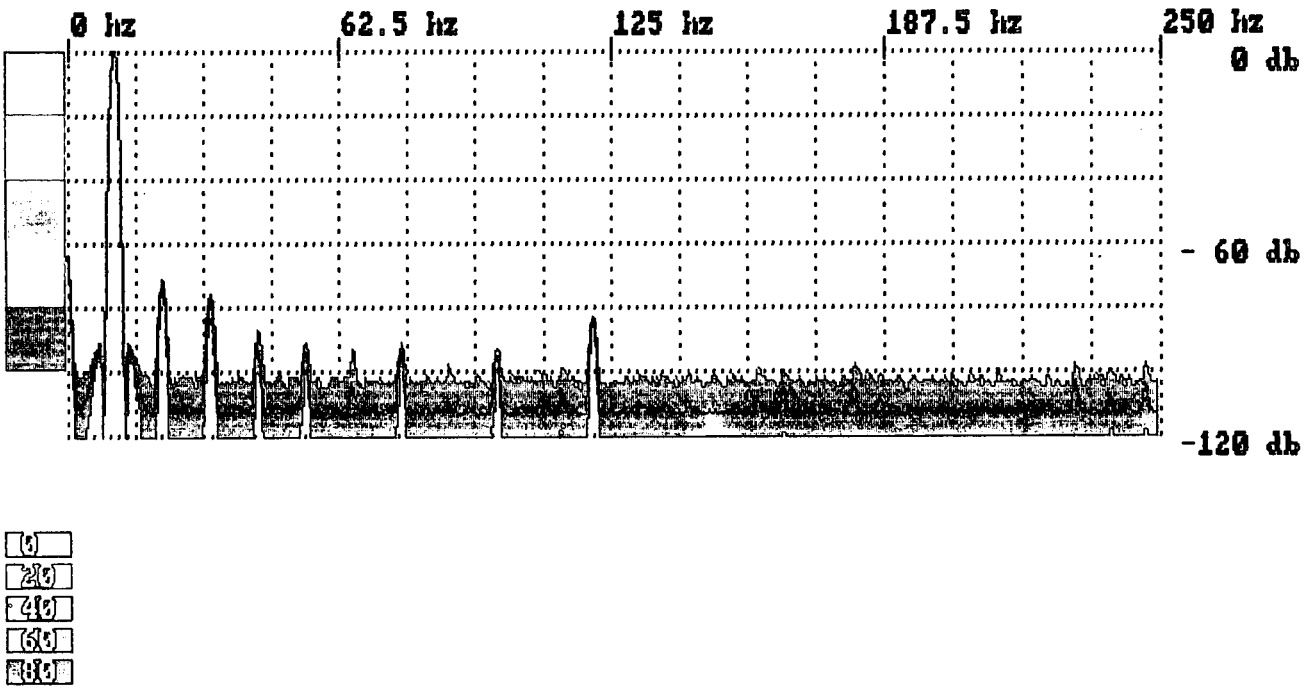


Aug 17 @ 11:58

End View, Harmonic Distortion Waterfall.

Trace

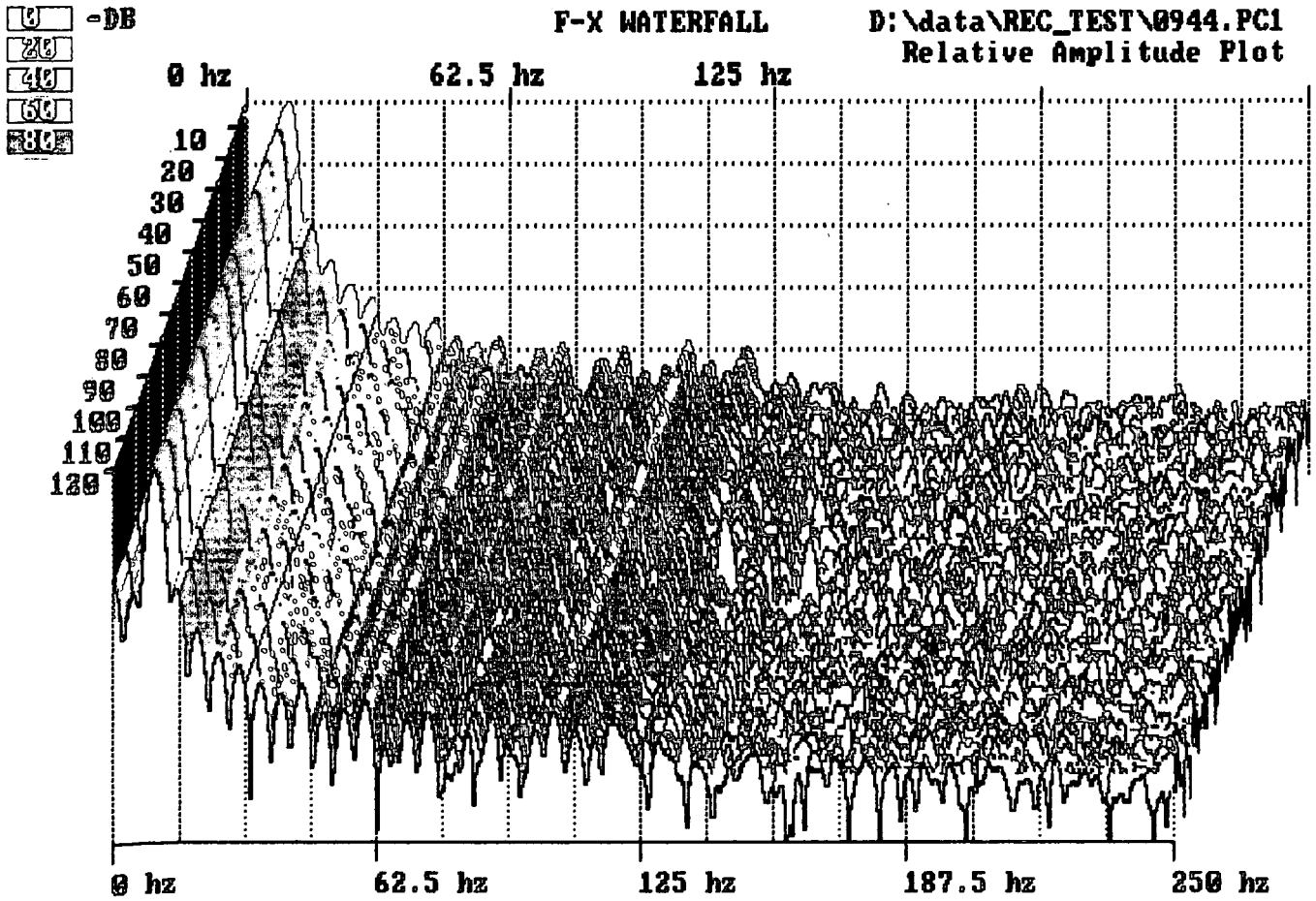
D:\data\REC_TEST\0942.PC1
Maximum Value: 62460 uvolts
Relative Amplitude
DSP active



DB down

Aug 17 @ 11:53

Prespective View, Exponetial Oscilator waterfall.

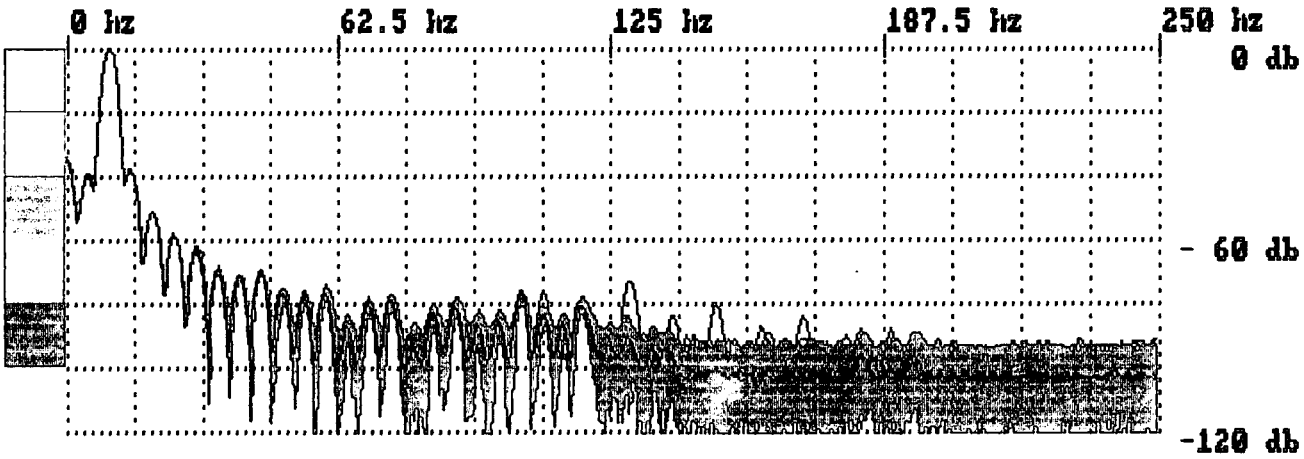


Aug 17 @ 12:13

End View, Exponetial Oscilator Waterfall

Trace

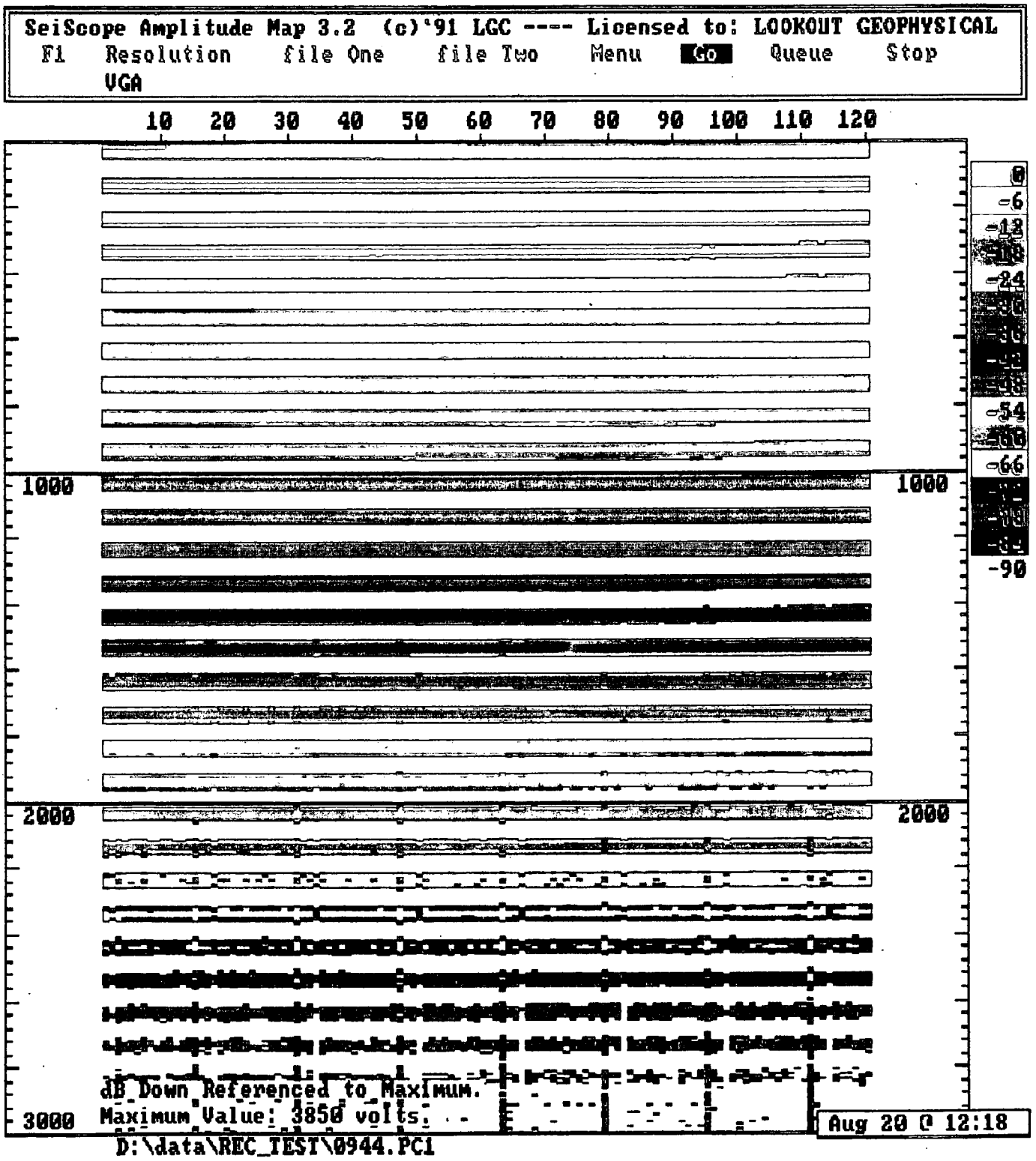
D:\data\REC_TEST\0944.PC1
Maximum Value: 2460 uvolts
Relative Amplitude
DSP active



DB down

Aug 17 @ 12:10

AMPLITUDE MAP; EXPONETIAL OSCILATOR SIGANAL



APPENDIX I

Vibrator Similarity Analysis

The first plot shows the Phase Error vs. Time curve of all four Vibrators. From top to bottom the Vibrators are:

# 906	labeled	as	7-3	(means 7th trace compared with trace 3 which is the reference)
# 915	"	"	8-3	
# 904	"	"	9-3	
# 4	"	"	10-3	

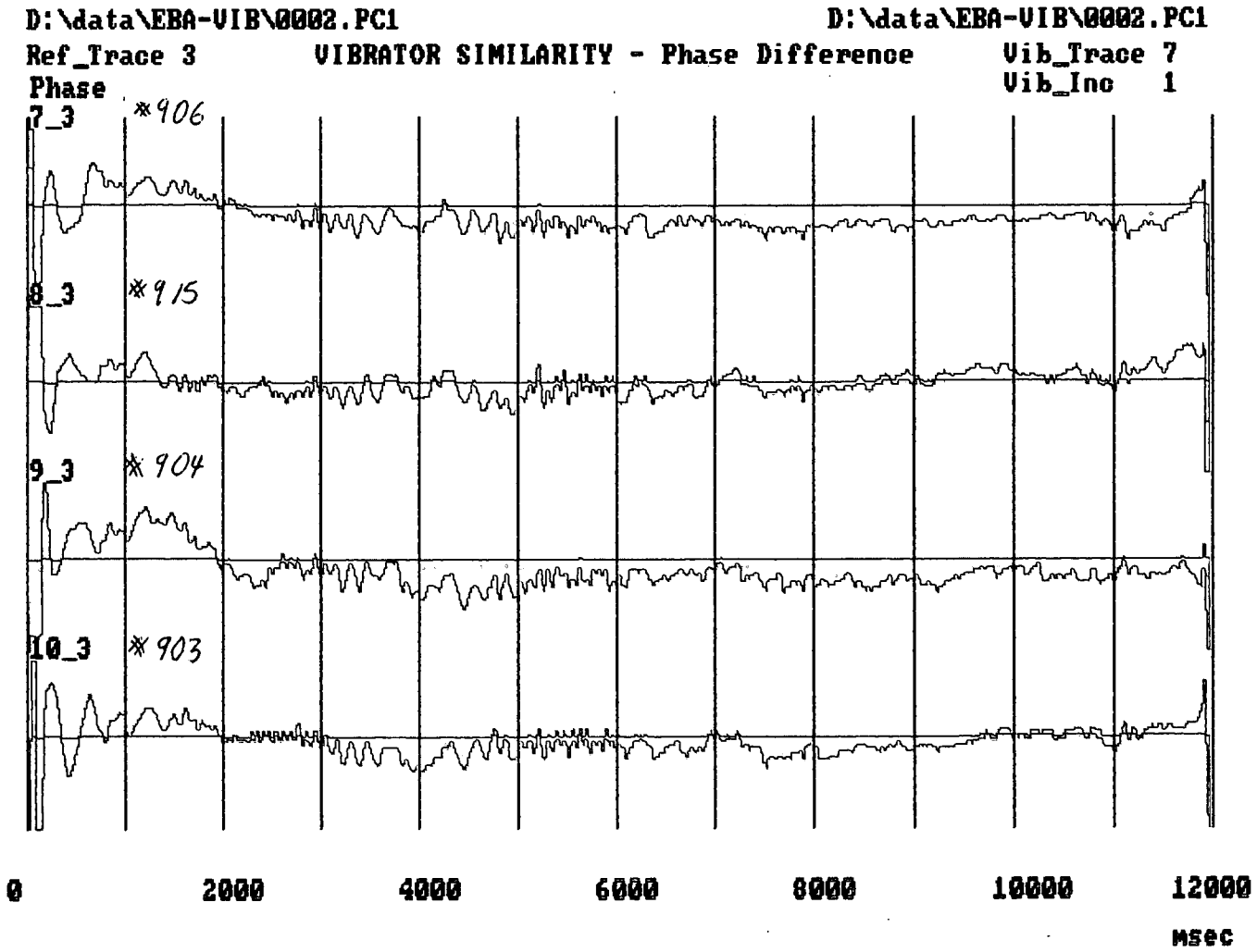
The curves are blue within +/- 15 degrees of phase error and red when the error is greater than that.

The next four plots display each vibrator's Frequency vs. Time vs. Amplitude (FTA) graph. The FTA is a signatures of overall vibrator performance.

The first and second harmonics lobes are fairly small on all the vibs. Large harmonics indicate inaccuracy in the baseplate waveform. They are often a function of ground coupling.

The amplitudes of the fundamental varies a little on vib #915. Also #904 has some noise but, it is less than 60 db down. Frankly, I am somewhat surprised that all the Vibrators don't exhibit more noise because the rocky ground makes it very easy to de-couple.

Vib Sims; PHASE ERROR VS. TIME



Phase Window = -30 to 30 degrees
Tolerance = -15 to 15 degrees

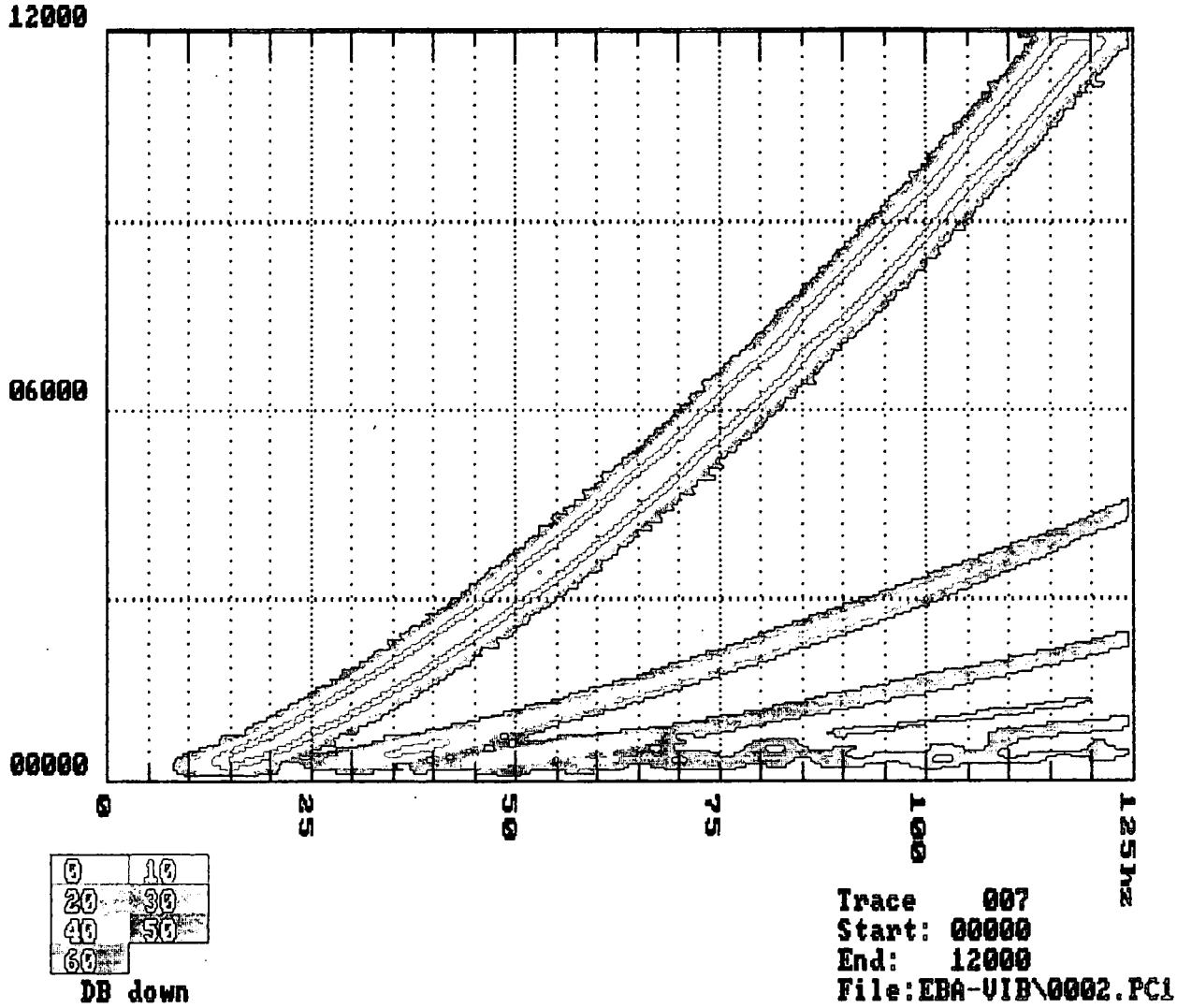
ZeroCross
Rotation= -110 deg

Smoothed 20 msec

Aug 19 @ 07:31

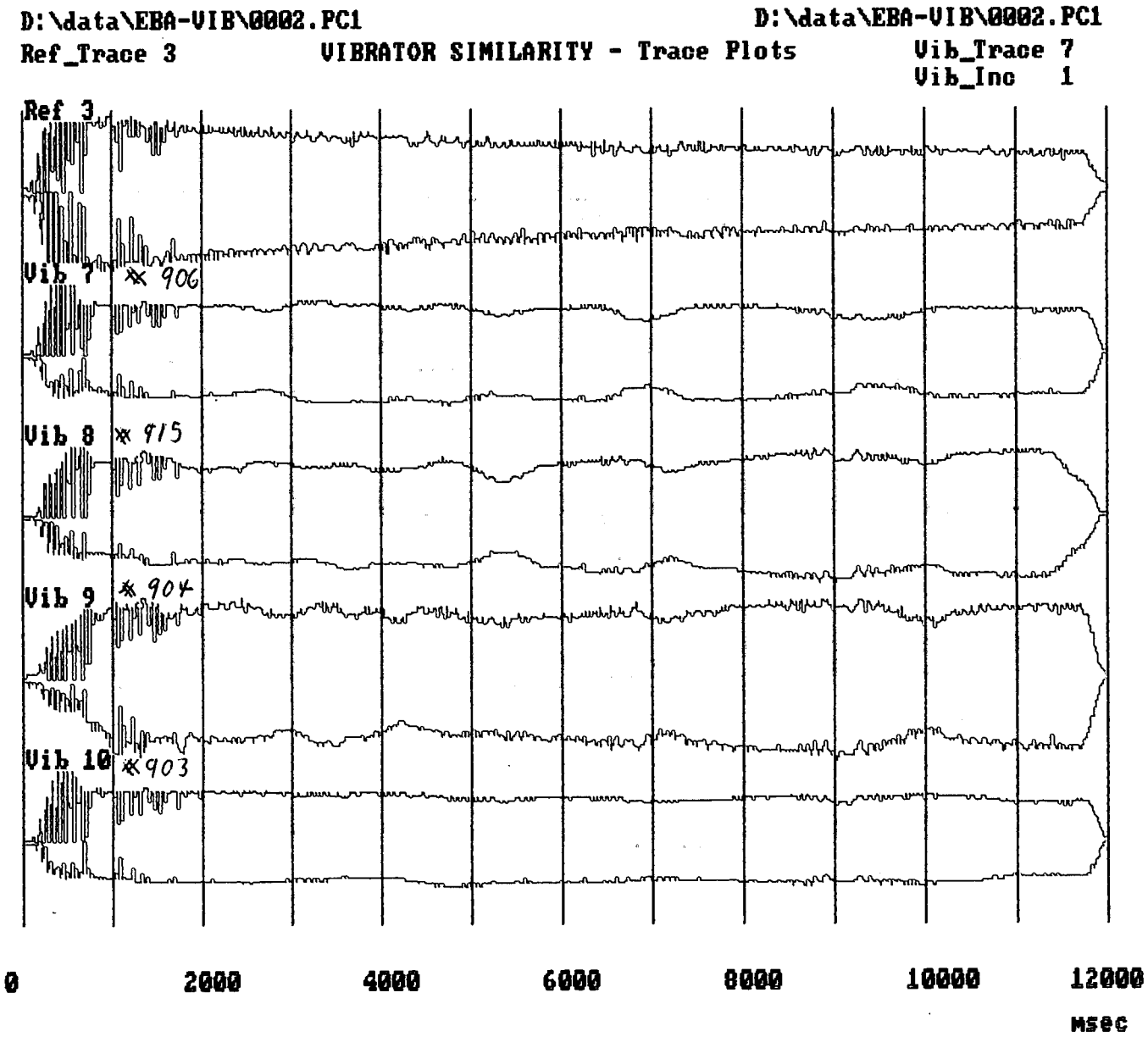
F10 Plotque

FREQUENCY VS TIME VS AMPLITUDE; VIB # 906



Aug 19 @ 10:02

Vib Sims; AMPLITUDE VS TIME.

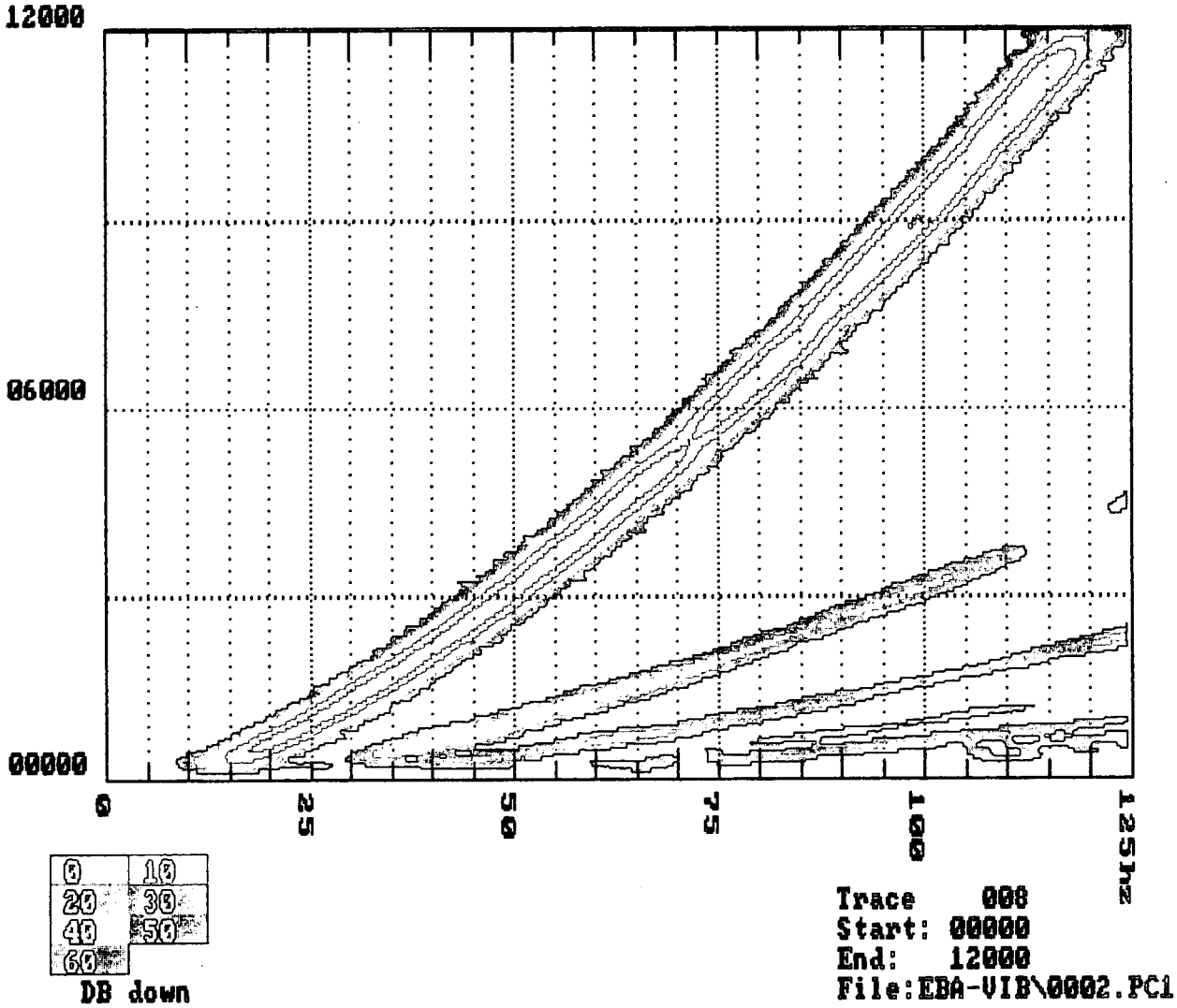


F10 Plotque

ENTER to Continue

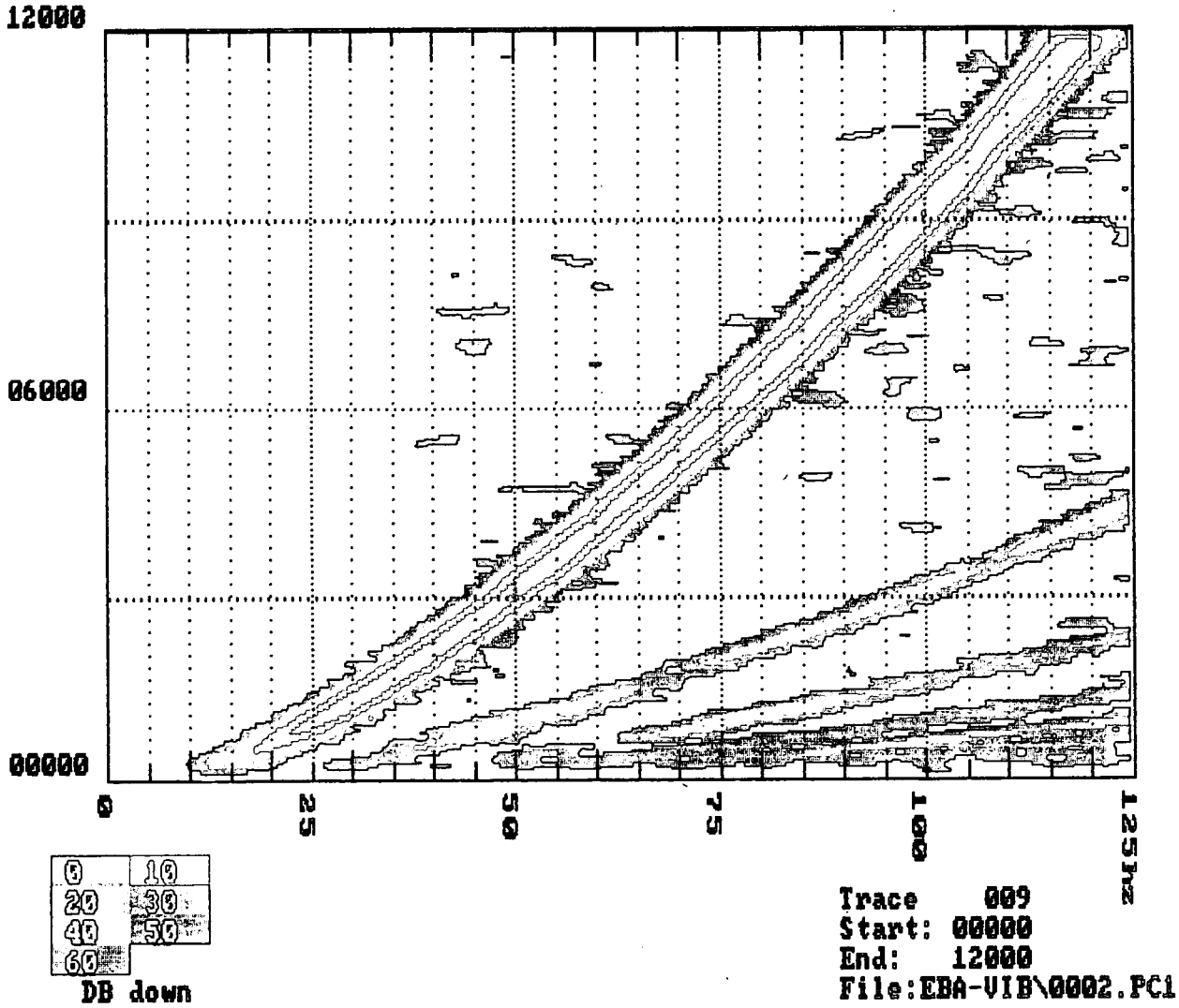
Aug 19 @ 07:32

FREQUNCY VS TIME VS AMPLITUDE; VIB # 915



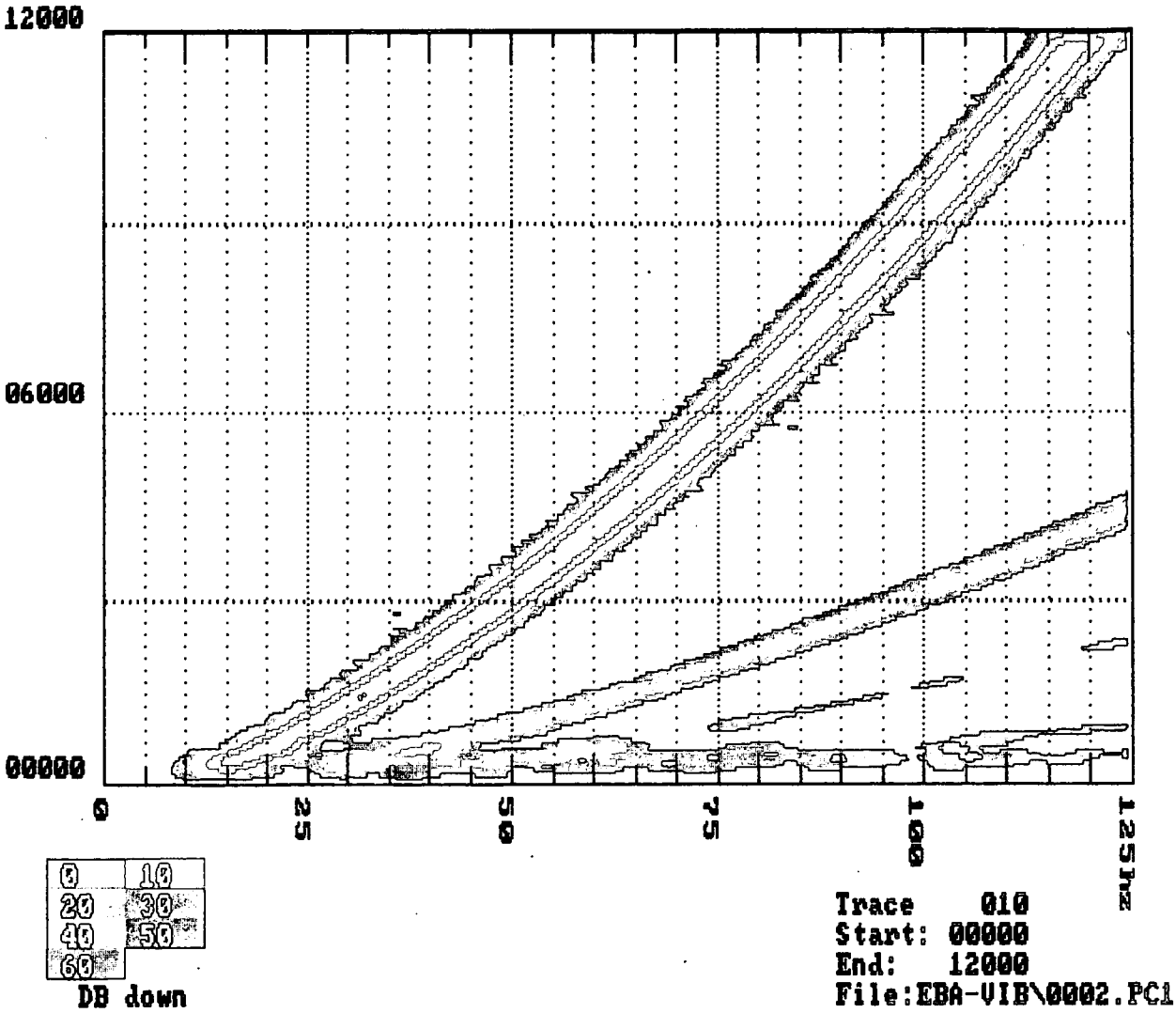
Aug 19 @ 10:34

FREQUENCY VS TIME VS AMPLITUDE; VIB # 904



Aug 19 @ 10:37

FREQUENCY VS TIME VS AMPLITUDE; VIB #903



Aug 19 @ 10:39

PROCESSING INFORMATION PRESENTED ON A SEISMIC REFLECTION PROFILE

Labeling on a seismic reflection profile (section) indicates the type of seismic reflection data and provides information about the field acquisition parameters and the data processing steps. As shown for Line RFD-1 the label is located on the right side of the seismic section. Above the actual reflection data, the surface topography is presented.

SIDE LABEL

At the top of the side label on the far right of the section indicates the name of the client ordering the data processing services, i.e. Ebasco Services Inc. for EG&G Rocky Flats. Below the client name is the seismic line identifier, i.e. Line RFD-1. The version or type of display is shown below the line identifier. Below the display version is a directional arrow pointing the direction of line acquisition.

The line's source points (or stations), abbreviated as "SPS" are displayed as 1001-1515. The state and county location of the line are also given, The seismic datum and correctional velocity are displayed below the line location.

FIELD PARAMETERS

Line 1 of the side label indicates the recorder of the seismic data, i.e., Century Geophysical Corporation and the recording date, August 1991.

Line 2 indicates the instrument model, i.e., MDS-10 and the seismic source interval (the distance interval between successive seismic records).

Line 3 shows the recording tape format, SEG-B. The SEG-B format is the standard magnetic tape format 'B' as specified by the Society of Exploration Geophysicists (SEG). Line 3 also shows the station interval to be 110 ft. This is the ground distance between receiver (geophone) stations.

Line 4 shows the sample interval, 2 milliseconds. This is the time between successive data readings on each individual data channel. Line 4 also shows the geophone model and resonant frequency.

Line 5 shows the record length. This is the total time (4 seconds) that the seismograph recorded. Line 5 also shows the geophone array, 12 geophones were placed over a 155 ft interval diagonal to the line.

Line 6 indicates the seismic source type. In this case the seismic sources were dynamite and vibroseis.

Line 7 indicates the type of gain or amplifier setting for each channel. IFP means instantaneous floating point gain. The amplifier setting for each channel is adjusted dynamically by the seismograph based on the input signal amplitude.

Line 8 indicates the explosive array (source pattern). Seismic reflection surveys may utilize more than one source of the same type simultaneously. The source pattern can be in-line or in a geometric pattern, such as a rectangle. In this case the source was located on the line at a depth of 50 feet. The amount of explosive was 10 pounds.

Line 9 shows the other source array. The entry indicates 4 vibrators were placed over a 90 ft interval. Line 9 also shows that the notch filter was "in" i.e., the 60 Hertz (Hz) notch filter was used to attenuate noise caused by electrical transmissions lines.

Line 10 indicates that the vibrators generated 10 sweeps per source point. Line 10 also indicates that the field filter was set to pass the frequencies between 12 and 125 Hz.

Line 11 shows the frequencies generated during each vibroseis sweep. In this case 10 to 120 Hz.

Line 12 indicates the common depth point (CDP), also known as common midpoint (CMP), redundancy coverage. These data were 3000% or 30 fold. Each stacked trace on the display is a composite of 30 raw traces having the same subsurface reflecting point, but different source and receiver points.

Line 13 shows the length of the vibrator sweep. In this case the vibroseis sweep was generated for 12 seconds.

Lines 14 and 15 at the bottom of the field parameters box show the geophone cable geometry. They show the source point location between the 80th and 81st trace locations and the corresponding distances from the source to each end of the active geophones.

DISPLAY PARAMETERS

The display parameters box describes the manner of displaying the seismic section. The number of seismic traces displayed per inch is 24. The vertical scale is 6 inches per second (i.e. one second of data requires 6 inches to display).

PROCESSING SEQUENCE

The next box displays the final processing sequence. The functions of each process are discussed later below.

STACKING FOLD DISPLAY

At the bottom of the seismic section is a graphical display of the CDP stacking fold (see Appendix I). The fold varies between 1 and 30.

VELOCITY ANALYSIS

Above the data are several boxes displaying the results of the stacking velocity analyses. Each analysis is displayed with the station location below. In the analysis box on the left are the two-way times and on the right the corresponding root mean squared seismic velocity used to stack seismic reflection events, the interval velocity between the reflection events, and the approximate depth to these reflection events.

SURFACE PROFILE

Above the velocity analyses boxes is the surface elevation profile. The elevation is displayed on both ends of the profile. The upper line indicates the surface elevation, and the lower line indicates the elevation of the unweathered zone.

SEISMIC DATA DISPLAY

Immediately above the seismic reflection data display are station numbers. On the left and right side of the data display is the two-way time scale (in seconds). Below each station is displayed one stacked seismic data trace, starting at time 0.0 second and ending at time 1.0 second. Positive reflection events are displayed as dark-shaded positive peaks, with deflections to the right. Negative reflection events are displayed unshaded with deflections to the left.

PROCESSING PARAMETERS

The following is a brief description of the processing algorithms applied to the seismic data. Some algorithms may be applied more than once with different parameters. Subsequent applications are used to enhance different aspects of the data.

1. DEMULTIPLEXING

In the field, seismic data were recorded by the EG&G ES-2420 seismic acquisition unit in multiplexed format. Multiplexing is a process whereby multiple channels of data can be transmitted through a single channel without loss of information. Multiplexed data samples are stored on tape in channel sequential order, whereas demultiplexed data samples are stored in time sequential order. The seismic data traces are demultiplexed in the initial data processing stage.

2. SPHERICAL DIVERGENCE COMPENSATION

A seismic wave travels in a spherical shape. As the wave front expands, the energy density decreases inversely as the square of the distance traveled. A data processing program compensates for the decrease in the seismic energy with time.

3. MINIMUM PHASE COMPENSATION ON VIBROSEIS RECORDS

A seismic pulse has characteristic frequency and phase components. Two pulses can have the same frequency components but different phase components resulting in different pulse shapes. The dynamite and vibroseis seismic sources have different phase components. To equalize the records a filter is designed and applied to the vibroseis data resulting in records comparable to the dynamite data.

4. CROOKED LINE GEOMETRY APPLICATION

Seismic reflection data collected in areas where the seismic source or receivers must follow existing trails and roads sometimes results in a crooked line. Some of the resulting CDP data stack into bins that are off the line. Some of these data are removed because they are not representative of the data along the line.

5. REFRACTION STATICS DERIVATION

Each seismic reflection record contains both reflection and refraction data. The refraction data are analyzed and time corrections are made to the source and receiver stations to compensate for zones of weathering in the near surface.

6. DISTANCE/TIME DEPENDENT SCALING

Geophones close to the seismic source receive more energy than those furthest from the source. Also seismic reflections from shallow reflectors are greater in amplitude than those from deep reflectors. All seismic events are equalized by compensating for distance and depth.

7. DECONVOLUTION - SURFACE CONSISTENT

Convolution is a mathematical process of passing one function through another to form a third function. The appearance of a final seismic section is a result of the convolution of a seismic source signal with the earth's reflectivity characteristics. An infinite bandwidth seismic signal convolved with the earth's reflectivity series would produce a very detailed cross-section of the earth's subsurface.

A seismic source signal in the shape of a spike in the time domain has an infinite frequency bandwidth. Unfortunately, seismic sources do not resemble perfect spikes. Since the final seismic section is the result of filtering the reflectivity of the earth with the seismic source signal, an inverse filter can be designed (a deconvolution process) to recover the true reflectivity.

A convolution with a "spike" (or broad-band frequency wavelet) will reproduce the original function. The goal of deconvolution is to observe the spectrum of the seismic source pulse and design an inverse operator which reduces the pulse to a "spike". In completing this task, the processing geophysicist can

apply the inverse operator to the reflected signals, thereby removing the effect of the source signal in them.

8. DISTANCE/TIME DEPENDANT SCALING

As explained in 6 above.

9. STRUCTURE STATICS

The quality of the final seismic section is dependent upon the proper utilization of static corrections. Static corrections are applied to seismic data to eliminate the effects of elevation, the weathering zone thickness and velocity variation. The greater the variation in the surface elevation or near surface velocities, the more important static corrections become.

10. CONSTANT VELOCITY STACK ANALYSIS

All data processing performed up to this stage has been based on sequential data for every shotpoint. The data are now rearranged by CDP, gathering into CDP format, whereby all the traces common to one depth point are collected together.

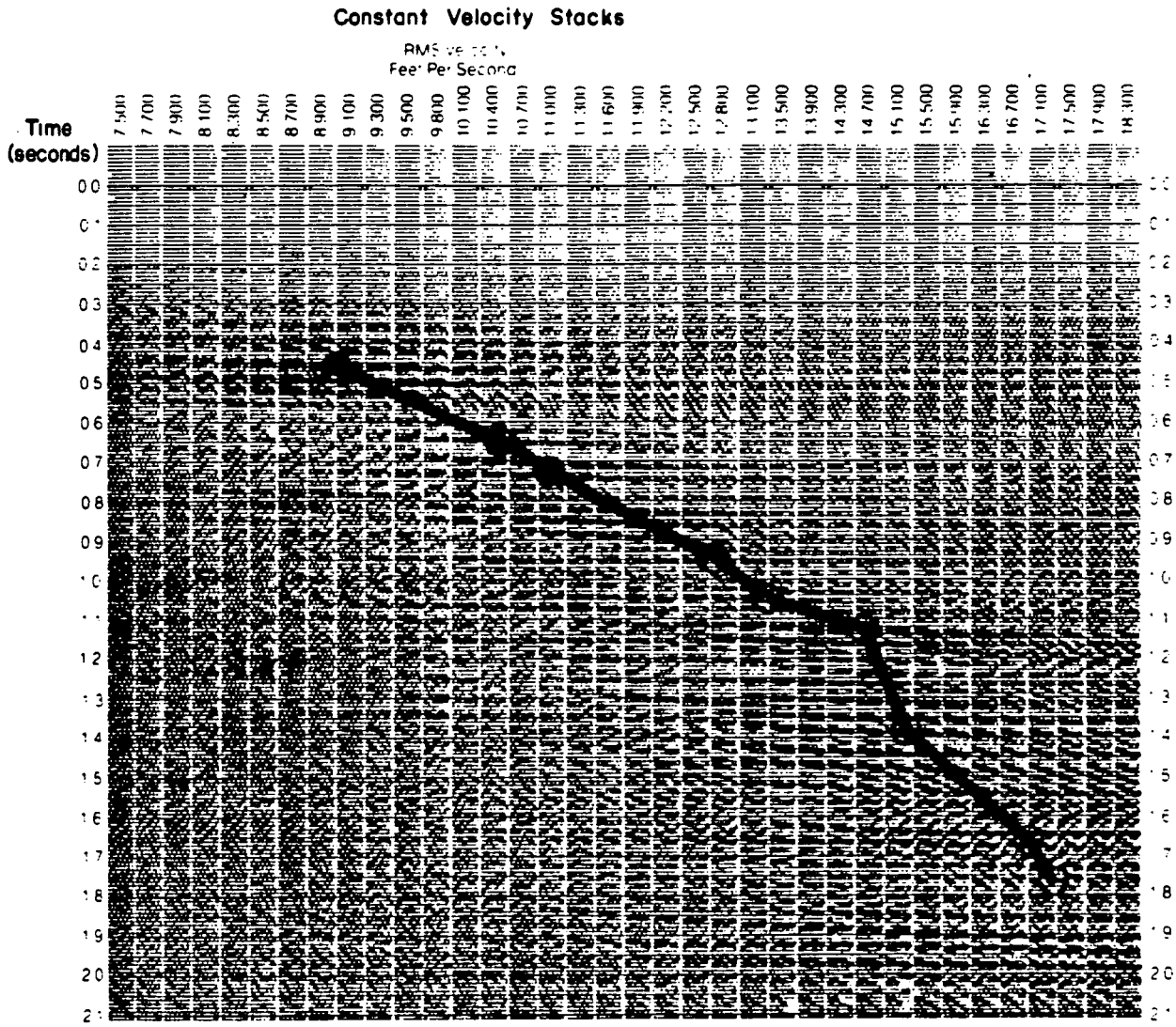
The difference in arrival times at two geophone locations for the same reflection is termed normal moveout. This time difference can be utilized to estimate seismic velocities of different reflecting horizons. After these velocities are assigned to the CDP gathered data, the resulting seismic section is examined for anomalous character that may indicate further velocity analysis is needed.

Commonly constant velocity stacks are made to analyze the seismic velocities. An example is shown in Figure III-1.

11. STATICS - AUTOMATIC SURFACE CONSISTENT

Another statics routine as described in 9. However, this routine makes minor alignments to improve data quality.

12. TIME DOMAIN - SPECTRAL WHITENING



Interpeted Velocity Analysis Function for Stacking CDP Data

E G & G Rocky Flats, Inc. Dec 1992

FIGURE III-1

COMMON DEPTH POINT VELOCITY ANALYSIS

Source: Dobrin, 1976

This is a specialized deconvolution process. A spectral whitening (or balancing) increases the amplitude of the higher frequencies of the seismic data. Whitening also causes an increase in the amplitude of noise.

13. VELOCITY SEMBLANCE AND CONSTANT VELOCITY STACK ANALYSIS

As described in 10 above.

14. NORMAL MOVEOUT

The resulting velocities from 13 above are applied to the CDP format data.

15. STATICS - AUTOMATIC SURFACE CONSISTENT

As described in 11 above.

16. FIRST BREAK SUPPRESSION MUTE

The refraction data are removed from the seismic record.

17. BULK SHIFT

The data were shifted in time by an arbitrary amount for display purposes.

18. STRUCTURE STATICS

As described in 9 above.

19. RESIDUAL TRIM STATICS

As described in 15 above.

20. INVERSE NORMAL MOVEOUT

The normal moveout applied in step 14 is removed.

21. DMO VELOCITY SEMBLANCE

In areas of high geologic dip, the normal moveout velocities are anomalously high. Dip Moveout (DMO) analysis is applied to obtain realistic stacking velocities.

22. DIP - MOVEOUT

The velocities determined in step 21 above are applied to the data.

23. STACKING

Stacking the seismic reflection data is one of the most important steps in the data processing sequence. Seismic reflection data are recorded multi-fold to improve the S/N ratio. For random noise (i.e. airplanes, raindrops, cars, etc.) the improvement in the S/N ratio is equal to the square root of **n**, where **n** is the CDP fold. Random noise effects on the data are reduced and multiple reflections (multiples) are attenuated by the stacking process. Properly stacked seismic data will result in a significant reduction of noise within the final seismic section.

24. FILTER

A digital filter is applied to the data to remove unwanted noise and improve the quality of the display.

25. TRACE EQUALIZATION

The overall display is enhanced by boosting the amplitude of weaker traces and the data at later times.

FINAL SECTION

The final seismic profile was displayed using a combination of variable area and wiggle trace. The wiggle trace display enhances the wavelet shape, giving added insight to stratigraphic interpretation. The variable area display emphasizes the wavelet amplitude, enhancing the lithologic identification.

MIGRATION

Steeply dipping structures in the subsurface will be displaced from their true position on the seismic profile due to raypath imaging inconsistencies. Migration processing can effectively remove the raypath inconsistencies and return a reflector to its true position on the final seismic section. Migration processing becomes an increasingly important tool when there are steeply dipping structures present.

The effect of the migration processing was noticeable when comparing the migrated and unmigrated seismic sections, as migration improves the S/N ratio by approximately 6 db.

REFERENCES

SEG (Society of Exploration Geophysicists) Technical Standards Committee. 1980. Digital Tape Standards.

Appendix IV

CSM Gravity & Magnetic Data

Gravity Technique

The gravity method involves measuring the earth's gravitational acceleration at various points on the earth's surface. The earth's gravitational field is a composite of contributions from all depths; it varies from one point to another due to lateral differences in the density of materials below the surface. Many types of rocks have characteristic ranges of densities which may differ from those of other types that are laterally adjacent. Thus, an anomaly in the earth's gravitational attraction can often be related to a buried geological feature.

The theory behind the gravitational method is based on Newton's law expressing the force of mutual attraction between two particles in terms of their masses and separation. This law states that two very small particles of mass m_1, and m_2, respectively, each with dimensions very small compared with the separation r of their centers of mass, will be attracted to one another with a force:

$$F = \gamma \frac{m_1 m_2}{r^2}$$

where γ, known as the universal gravitational constant, depends on the system of units employed.

In the centimeter-gram-second (cgs) system, the value of γ is 6.670×10^{-8}. This is the force in dynes that will be exerted between two masses of 1 gram (g) each with centers 1 centimeter (cm) apart.

The acceleration of a mass m_2 due to the attraction of a mass m_1, a distance r away can be obtained simply by dividing the attracting force F by the mass m_2 (since force is mass times acceleration), where upon

$$a = \frac{F}{m_2} = \gamma \frac{m_1}{r^2}$$

The acceleration is the conventional quantity used to measure the gravitational field acting at any point. In the cgs system, the dimension of acceleration is centimeters per second squared (cm/s^2). Among geophysicists this unit is referred to as the *gal* (in honor of Galileo). The gravitational acceleration at the earth's surface is about 980 cm/s^2 or 980 gals. For convenience in working with gravity data obtained for geological and geodetic studies, the *milligal* (mgal), one thousandth of a gal, has come to be the common unit for expressing gravitational accelerations.

Gravity measurements must be corrected for variations due to natural causes before being used for geological studies. Because the earth is not a perfect sphere, the earth's gravity is 5,300 mgals less at the equator than at the poles.

Diurnal variations caused by the gravitational attraction of the sun and moon are recorded by taking measurements every hour or two at a base station. These diurnal variations are then removed from the field data.

Because gravity acceleration decreases with height above sea level, a correction is made for altitude and is known as the free-air correction. In addition, the attraction of the material between the station and sea level is removed by the Bouguer correction. The remaining value is known as the Bouguer anomaly.

The interpretation of Bouguer gravity data involves the use of geometric models approximating geological structures. Two commonly-used shapes are the semi-infinite slab and the horizontal cylinder of infinite strike length. The slab represents a block disrupted by faulting. The cylinder is used to represent anticlines or other buried features. The equation for the gravity effect of a semi-infinite slab is

$$g = 4.07 \; x \; 10^{-3} \; \sigma\tau \; (\pi/2 + \tan^{-1} x/h)$$

where

g = gravitational acceleration in mgal

σ = density contrast in gm/cm^3

τ = thickness of slab in ft

x = distance from edge of slab, x < 0 is away from slab, x > 0 is over slab in ft

h = depth to the slab's mid-thickness in ft

The equation for the gravity effect of a horizontal cylinder with infinite strike length is

$$g = \frac{12.77 \; x \; 10^{-3} \; R^2\sigma}{z \; (1 + x^2/z^2)}$$

where

g = gravitational acceleration in mgal

σ = density contrast in gm/cm^3

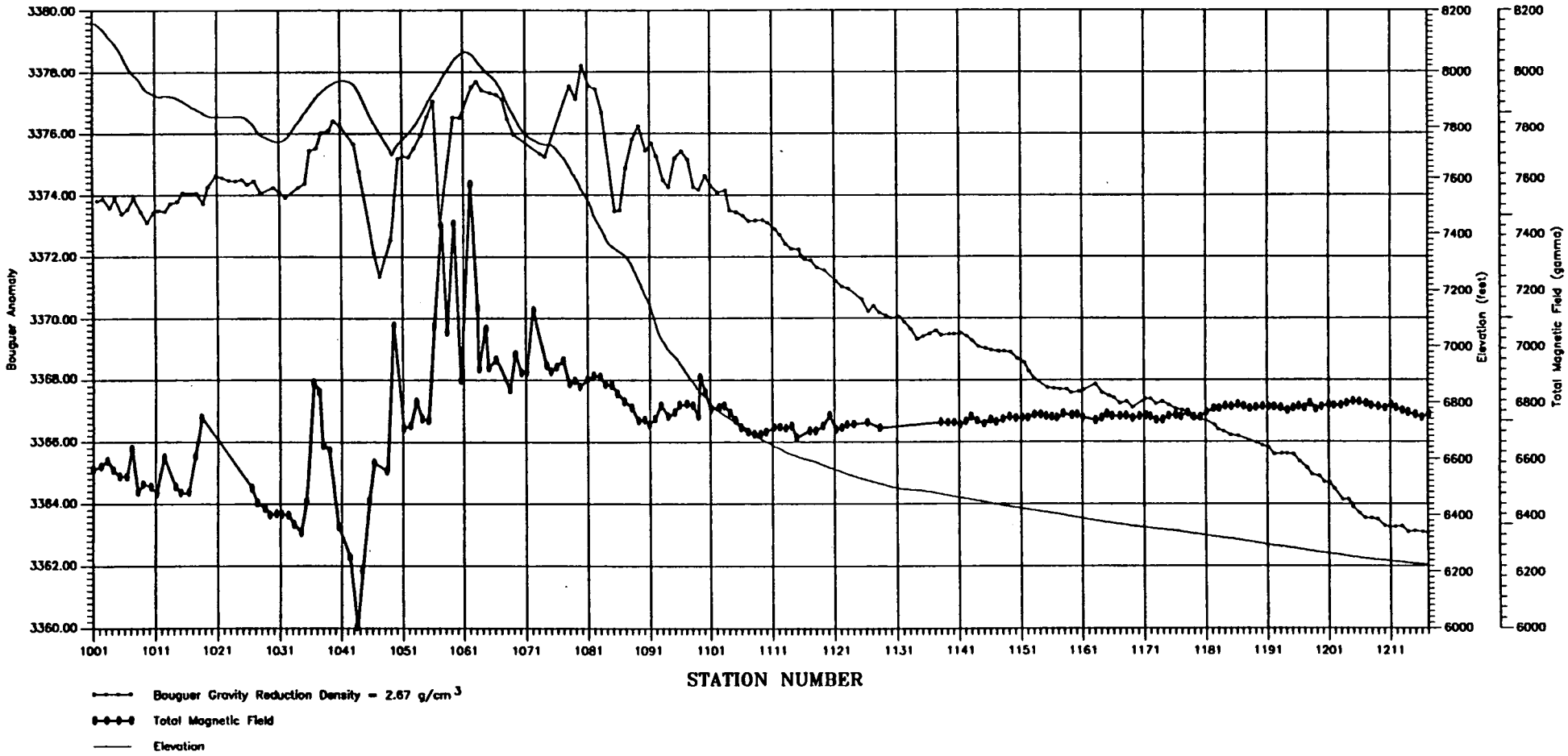
R = radius of cylinder in ft

z = depth to center of cylinder in ft

x = distance on surface from location of the center of the cylinder in ft

ROCKY FLATS GRAVITY SURVEY

Complete Bouguer Anomaly



E G & G Rocky Flats, Inc. Dec 1992

Figure IV-1

Gravity, Magnetic, and Surface Elevation Profile

FIELD GRAVITY AND MAGNETI DATA

STN	TIM	GRAV RE	TIM	MAG RED
Aug	27	1991		
1171	12.35	3074.865	12.4	54455
1172	12.55	3075.013	12.59	54450
1173	13.05	3075.018	13.8	54443
1174	13.13	3075.377	13.15	54447
1175	13.2	3075.561	13.36	54451
1171	13.31	3074.89	13.28	54461
1176	13.44	3075.69	13.46	54460
1177	13.51	3075.849	13.54	54457
1178		3075.9	14.2	54466
1179	14.07	3075.949	14.9	54454
1180	14.17	3076.147	14.2	54460
1181	14.26	3076.28	14.29	54466
1175	14.37	3075.516	14.43	54472
1182	14.48	3076.42	14.51	54485
1183	14.55	3076.505	14.57	54483
1184	15	3076.622	15.3	54494
1185	15.18	3076.677	15.21	54485
1186	15.25	3076.85	15.28	54493
1187	15.33	3076.95	15.35	54495
AUG	28	1991		
1171	12.35	3074.865	12.5	54455
1172	12.55	3075.013	12.59	54450
1173	13.05	3075.018	13.08	54443
1174	13.13	3075.377	13.15	54447
1175	13.2	3075.561	13.36	54451
1171	13.31	3074.89	13.28	54461
1176	13.44	3075.69	13.46	54460
1177	13.51	3075.849	13.54	54457
1178	14	3075.9	14.02	54466
1179	14.07	3075.949	14.09	54454
1180	14.17	3076.147	14.2	54460
1181	14.26	3076.28	14.29	54466
1175	14.37	3075.516	14.43	54472
1182	14.48	3076.42	14.51	54485
1183	14.55	3076.505	14.57	54483
1184	15	3076.622	15.03	54494

1185	15.18	3076.677	15.21	54489
1186	15.25	3076.85	15.28	54493
1187	15.33	3076.95	15.35	54495
1181	15.47	3076.27	15.53	54494

AUG	29	1991		
1217	14.14	3080.747	14.16	54476
1216	14.2	3080.659	14.22	54484
1215	14.29	3080.515	14.31	54499
1214	14.37	3080.324	14.4	54502
1213	14.46	3080.25	14.5	54510
1212	14.55	3080.043	14.58	54513
1211	15.04	3079.908	15.08	54519
1217	15.15	3080.787	15.2	54515
1210	15.3	3079.821	15.36	54520
1209	15.39	3079.849	15.4	54524
1208	15.48	3079.675	15.51	54526
1207	16	3079.533	16.02	54532
1206	16.08	3079.419	16.1	54536
1211	16.18	3079.94	16.21	54545
1205	16.34	3079.12	16.36	54537
1204	16.43	3078.972	16.46	54537
1203	16.5	3078.772	16.54	54535
1202	16.58	3078.688	17.01	54537
1201	17.09	3078.6	17.12	54543
1206	17.18	3078.43	17.15	54551

AUG	30	1991		
1202	9.55	3078.609	9.68	54481
1201	10.02	3078.561	10.05	54492
1200	10.1	3078.373	10.13	54480
1199	10.18	3078.29	10.19	54466
1198	10.26	3078.144	10.34	54498
1197	10.38	3078.032	10.42	54474
1196	10.46	3077.94	10.5	54474
1202	10.57	3078.042	11	54489
1195	11.14	3077.846	11.16	54472
1194	11.21	3077.679	11.29	54462
1193	11.31	3077.514	11.35	54467
1192	11.41	3077.401	11.45	54460
1196	11.53	3078.034	11.5	54475
1191	13.04	3077.334	13.05	54467

1190	13.11	3077.224	13.08	54476
1189	13.2	3077.107	13.21	54470
1188	13.25	3077.035	13.23	54465
1187	13.34	3076.897	13.39	54476
AUG	31	1991		
1186	13.44	3076.775	13.47	54477
1192	13.58	3077.322	13.53	54488
1170	14.2	3074.656	14.29	54466
1169	14.32	3074.492	14.32	54463
1168	14.41	3074.465	14.4	54475
1167	14.47	3074.304	14.45	54475
1166	14.54	3074.254	14.57	54471
1165	15.01	3074.158	15	54481
1164	15.1	3074.063	15.15	54472
1170	15.25	3074.744	15.35	54481
Sept	1	1991		
1165	14.57	3074.173	15.02	54472
1164	15.02	3074.062	15.05	54471
1163	15.25	3073.92	15.19	54467
1161	15.41	3073.351	15.35	54472
1160	15.48	3073.001	15.43	54481
1159	16.15	3072.699	16.18	54478
1158	16.24	3072.559	16.23	54485
1157	16.33	3072.349	16.36	54475
1156	16.39	3072.14	16.39	54478
1155	16.5	3071.963	16.44	54479
1154	16.56	3071.813	16.53	54476
1160	17.09	3072.844	17.06	54486
1153	17.22	3071.66	17.25	54484
1152	17.39	3071.36	17.41	54477
1151	17.55	3071.202	17.45	54476
1150	18.03	3070.942	17.58	54475
1149	18.17	3070.858	18.08	54472
1154	18.27	3070.766	18.22	54481
Sept	2	1991		
1150	9.12	3070.847	9.14	54448
1149	9.21	3070.746	9.16	54453
1148	9.29	3070.509	9.26	54446
1147	9.35	3070.345	9.39	54423
1146	9.42	3070.104	9.41	54437
1145	9.52	3069.941	9.54	54421
1144	10.02	3069.632	9.58	54428
1150	10.12	3070.775	10.09	54433

1150	13.26	3070.726	14.56	54453
1143	13.38	3069.508	15	54447
1142	13.5	3069.297	15.02	54437
1140	13.58	3069.058	15.13	54429
1139	14.04	3068.813		
1138	14.15	3068.588		
1144	14.31	3069.729		
Sept	6	1991		
1141	12.37	3069.451	18.52	54429
1140	12.51	3069.234	18.5	54446
1139	13	3069.088	18.48	54449
1138	13.08	3069.005	18.46	54448
1137	13.15	3068.567		
1136	13.25	3068.214		
1135	13.37	3067.805		
1134	13.46	3067.596		
1133	13.56	3067.603		
1132	14.04	3067.556		
1137	14.16	3068.582		
1131	14.34	3067.444		
1130	14.46	3067.377		
1129	14.58	3067.159		
1128	15.12	3066.951	18.3	54422
1132	15.31	3067.572		
1127	15.48	3067.025		
1126	16	3066.295	18.24	54444
1125	16.15	3066.015		
1124	16.25	3065.78	18.18	54431
1128	16.44	3066.545		
1123	17.04	3065.46	18.17	54430
1122	17.13	3065.081	18.16	54412
1121	17.23	3065.752	18.14	54411
1120	17.41	3064.25		
1124	17.51	3065.788		
SEP	17	1991		
1121	10.22	3064.575	10.26	54380
1120	10.31	3064.1	10.31	54454
1119	10.39	3063.529	10.39	54406
1118	10.46	3063.082	10.49	54387
1117	10.55	3062.667	11.04	54395
1116	11.05	3062.077		
1115	11.14	3061.698	11.14	54359
1121	11.25	3064.612	11.21	54398

1114	11.4	3061.16	11.36	54395
1113	11.48	3060.55	11.52	54389
1112	12	3060.312	11.55	54392
1111	12.09	3059.888	12.09	54397
1110	12.17	3059.495	12.13	54373
1115	12.32	3061.691		
1109	1.13	3058.86	1.15	54373
1108	1.3	3058.175	1.31	54367
1107	1.39	3057.175	1.42	54377
1106	1.51	3056.353	1.45	54390
1105	2	3055.779	1.55	54425
1104	2.1	3055.03	2.07	54470
1110	2.22	3059.6	2.18	54389
1103	2.4	3055.033	2.42	54480
1102	2.47	3054.31	2.44	54478
1101	2.55	3053.505	2.51	54473
1100	3.05	3052.575	3.08	54533
1099	3.15	3050.93	3.1	54438
1104	3.28	3055.79	3.21	54435
1098	3.45	3049.538		
1097	4	3048.395		
1096	4.11	3046.362		
1099	4.23	3050.855		
1095	4.41	3044.062		
1094	4.47	3042.218		
1093	4.59	3040.705		
1092	5.09	3038.763		
1096	5.2	3046.445		
SEP	21	1991		
1100			9.55	54506
1099			9.59	54521
1098			10	54415
1097			10.02	54418
1096			10.03	54419
1095			10.05	54393
1094			10.07	54370
1093	10	3040.639	10.09	54421
1092	10.07	3038.465	10.12	54374
1091	10.17	3035.774	10.15	54333
1090	10.28	3031.882	10.2	54364
1089	10.37	3029.007	10.22	54362
1088	10.49	3025.365	10.26	54406
1093	11.1	3040.57		
1087	11.48	3022.405	10.3	54429
1086	12	3020 210	10.33	54459

1085	12.1	3019.662	10.35	54495
1084	12.2	3019.548	10.45	54495
1083	12.32	3018.769	10.39	54515
1088	12.47	3025.395		
1100			11.03	54422
1082	13.32	3016.41	11.57	54527
1081	13.45	3013.453	12	54513
1080	13.54	3010.65	12.03	54487
1079	14.05	3006.69	12.06	54509
1078	14.18	3004.135	12.09	54501
1083	14.45	3018.8		
1077	15.25	3001.436	12.14	54592
1076	15.37	2999.35	12.16	54569
1075	15.5	2997.636	12.2	54545
1074	16	2996.873	12.21	54562
1083			12.37	54527
1073	16.13	2997.25		
1072	16.3	2997.92	13.34	54788
1078	16.5	3004.29		
1071			13.39	54546
1070			13.41	54540
1069			13.44	54607
1068			13.47	54477
1067			13.49	54569
1066			13.52	54590
1065			14.19	54564
1064			13.59	54712
1063			14.01	54798
1074			14.41	54511

TABLE 1 BOUGUER GRAVITY

STATION	ELEVATION	GRAVITY
1002	8155	3373.853
1003	8135	3373.914
1004	8107	3373.603
1005	8079	3373.973
1006	8038	3373.416
1007	8006	3373.569
1008	7976	3373.949
1009	7947	3373.501
1010	7919	3373.101
1011	7901	3373.445
1012	7896	3373.547
1013	7900	3373.485
1014	7899	3373.775
1015	7895	3373.845
1016	7881	3374.119
1018	7854	3374.036
1019	7837	3373.737
1020	7821	3374.304
1021	7822	3374.659
1022	7822	3374.573
1023	7825	3374.503
1024	7828	3374.473
1025	7824	3374.513
1026	7811	3374.32
1027	7796	3374.466
1028	7759	3374.035
1029	7752	3374.842
1030	7738	3374.234
1031	7729	3374.097
1032	7745	3373.926
1033	7764	3374.076
1034	7794	3374.272
1035	7822	3374.433
1036	7859	3375.446
1037	7893	3375.551
1038	7918	3376.056
1039	7934	3376.149
1040	7945	3376.436
1041	7951	3376.228
1042	7953	3373.613
1043	7934	3375.639
1044	7908	3374.776
1046	7823	3372.149
1047	7772	3371.333
1048	7726	3373.762
1049	7677	3372.594
1050	7728	3375.142
1051	7743	3375.244
1052	7775	3375.223

1053	7798	3375.519
1054	7830	3375.9
1055	7866	3376.58
1056	7908	3377.061
1057	7952	3373.158
1058	7989	3374.452
1059	8026	3376.52
1060	8049	3376.513
1061	8060	3376.972
1062	8045	3377.528
1063	8022	3377.702
1064	7996	3377.404
1065	7970	3377.299
1066	7940	3377.246
1067	7899	3377.05
1068	7856	3376.428
1069	7820	3375.944
1070	7785	3376.542
1071	7746	3375.615
1072	7737	3376.806
1073	7719	3375.313
1074	7722	3375.208
1075	7724	3376.607
1076	7703	3377.812
1077	7675	3377.139
1078	7639	3377.553
1079	7593	3377.083
1080	7552	3378.249
1081	7500	3377.56
1082	7453	3377.457
1083	7404	3376.66
1084	7368	3374.996
1085	7346	3373.458
1086	7339	3373.575
1087	7323	3374.896
1088	7288	3375.73
1089	7237	3376.236
1090	7178	3375.41
1091	7120	3375.724
1092	7064	3375.218
1093	7018	3374.523
1094	6986	3374.177
1095	6970	3375.197
1096	6936	3375.434
1097	6896	3375.101
1098	6862	3374.231
1099	6835	3374.145
1100	6809	3374.621
1101	6786	3374.234
1102	6768	3374.074
1103	6756	3374.138
1104	6743	3373.498
1105	6730	3373.449

1106	6717	3373.296
1107	6700	3373.102
1108	6683	3373.196
1109	6670	3373.186
1110	6657	3373.105
1111	6646	3372.861
1112	6636	3372.701
1113	6628	3372.442
1114	6615	3372.229
1115	6606	3372.213
1116	6597	3371.906
1117	6588	3371.864
1118	6578	3371.662
1119	6570	3371.58
1120	6560	3370.995
1121	6551	3371.979
1122	6546	3371.024
1123	6539	3370.931
1124	6533	3370.792
1125	6528	3370.64
1126	6520	3370.245
1127	6512	3370.435
1128	6512	3370.237
1129	6507	3370.127
1130	6501	3369.998
1131	6501	3370.051
1132	6496	3369.837
1133	6493	3369.637
1134	6489	3369.368
1135	6487	3369.469
1136	6483	3369.564
1137	6479	3369.617
1138	6475	3369.468
1139	6470	3369.509
1140	6466	3369.499
1141	6462	3369.508
1142	6460	3369.412
1143	6455	3369.251
1144	6451	3369.126
1145	6446	3369.048
1146	6443	3368.962
1147	6439	3368.953
1148	6436	3368.941
1149	6432	3368.85
1150	6429	3368.661
1151	6425	3368.516
1152	6422	3368.253
1153	6418	3368.047
1154	6414	3367.797
1155	6412	3367.773
1156	6409	3367.698
1157	6405	3367.689
1158	6402	3367.687

1159	6399	3367.55
1160	6396	3367.601
1161	6392	3367.664
1163	6386	3367.866
1164	6380	3367.624
1165	6377	3367.505
1166	6374	3367.399
1167	6371	3367.212
1168	6369	3367.28
1169	6366	3367.08
1170	6364	3367.138
1171	6360	3367.422
1172	6357	3367.366
1173	6354	3367.177
1174	6351	3367.291
1175	6346	3367.168
1176	6342	3367.034
1177	6339	3367.032
1178	6337	3366.955
1179	6334	3366.755
1180	6331	3366.743
1181	6327	3366.672
1182	6324	3366.534
1183	6321	3366.398
1184	6318	3366.333
1185	6315	3366.196
1186	6312	3366.194
1187	6309	3365.797
1188	6307	3366.342
1189	6304	3365.955
1190	6301	3365.891
1191	6298	3365.763
1192	6295	3365.564
1193	6293	3365.632
1194	6290	3365.631
1195	6286	3365.568
1196	6282	3365.33
1197	6279	3365.14
1198	6276	3364.95
1199	6274	3364.883
1200	6270	3364.653
1201	6268	3364.649
1202	6265	3364.397
1203	6262	3364.134
1204	6261	3364.127
1205	6258	3363.875
1206	6254	3363.689
1207	6250	3363.554
1208	6247	3363.49
1209	6244	3363.425
1210	6241	3363.226
1211	6239	3363.159
1212	6237	3363.217

1213	6234	3363.214
1214	6231	3363.025
1215	6227	3363.046
1216	6225	3363.041
1217	6222	3362.967

TABLE 2 MAGNETI INTENSITY/GAMMA

1001	53517
1002	53534
1003	53555
1004	53512
1005	53489
1006	53491
1007	53596
1008	53439
1009	53460
1010	53448
1011	53426
1012	53569
1014	53452
1015	53432
1016	53439
1017	53575
1018	53723
1019	54295
1026	53450
1027	53392
1028	53370
1029	53347
1030	53351
1031	53344
1032	53342
1033	53308
1034	53280
1035	53400
1036	53853
1037	53827
1037	53827
1038	53615
1039	53592
1040	53303
1042	53184
1043	52921
1044	53129
1045	53399
1046	53544
1048	53511
1049	54074

1051	53682
1052	53693
1053	53789
1054	53713
1055	53707
1056	54075
1057	54455
1058	54058
1059	54476
1060	53876
1062	54624
1063	54151
1063	53916
1064	54065
1064	54065
1065	53917
1066	53943
1067	53922
1068	53830
1069	53960
1070	53893
1071	53899
1072	54141
1074	53922
1075	53898
1076	53922
1077	53945
1078	53854
1079	53862
1080	53840
1081	53866
1082	53880
1083	53874
1084	53848
1085	53848
1086	53812
1087	53782
1088	53759
1089	53715
1090	53717
1091	53686
1092	53727
1093	53774
1094	53723
1095	53746

1096	53772
1097	53771
1098	53768
1099	53722
1099	53874
1100	53817
1100	53817
1101	53757
1102	53762
1103	53764
1104	53737
1105	53709
1106	53674
1107	53661
1108	53651
1109	53657
1110	53665
1111	53681
1112	53676
1113	53673
1114	53679
1115	53643
1117	53679
1118	53671
1119	53690
1120	53738
1121	53673
1121	53673
1122	53674
1123	53692
1124	53693
1126	53706
1128	53684
1138	53710
1139	53711
1140	53708
1140	53708
1141	53691
1142	53716
1143	53726
1144	53707
1145	53700
1146	53716
1147	53702
1148	53725

1149	53721
1149	53732
1150	53724
1150	53724
1151	53725
1152	53726
1153	53733
1154	53728
1155	53728
1156	53727
1157	53724
1158	53734
1159	53727
1160	53733
1161	53721
1163	53716
1164	53725
1164	53720
1165	53734
1165	53734
1166	53724
1167	53728
1168	53728
1169	53716
1170	53727
1171	53727
1172	53719
1173	53712
1174	53716
1175	53730
1176	53729
1177	53726
1178	53735
1179	53723
1180	53729
1181	53749
1182	53754
1183	53752
1184	53763
1185	53758
1186	53762
1186	53765
1187	53764
1187	53764
1188	53753

1189	53758
1190	53760
1191	53755
1192	53762
1193	53755
1194	53750
1195	53760
1196	53762
1197	53762
1198	53786
1199	53754
1200	53768
1201	53780
1201	53780
1202	53773
1202	53774
1203	53772
1204	53774
1205	53774
1206	53780
1207	53769
1208	53763
1209	53761
1210	53757
1211	53769
1212	53750
1213	53747
1214	53739
1215	53736
1216	53721
1217	53733

FIELD GRAVITY AND MAGNETI DATA

STN	TIM	GRAV RE	TIM	MAG RED
Aug	27	1991		
1171	12.35	3074.865	12.4	54455
1172	12.55	3075.013	12.59	54450
1173	13.05	3075.018	13.8	54443
1174	13.13	3075.377	13.15	54447
1175	13.2	3075.561	13.36	54451
1171	13.31	3074.89	13.28	54461
1176	13.44	3075.69	13.46	54460
1177	13.51	3075.849	13.54	54457
1178		3075.9	14.2	54466
1179	14.07	3075.949	14.9	54454
1180	14.17	3076.147	14.2	54460
1181	14.26	3076.28	14.29	54466
1175	14.37	3075.516	14.43	54472
1182	14.48	3076.42	14.51	54485
1183	14.55	3076.505	14.57	54483
1184	15	3076.622	15.3	54494
1185	15.18	3076.677	15.21	54485
1186	15.25	3076.85	15.28	54493
1187	15.33	3076.95	15.35	54495
AUG	28	1991		
1171	12.35	3074.865	12.5	54455
1172	12.55	3075.013	12.59	54450
1173	13.05	3075.018	13.08	54443
1174	13.13	3075.377	13.15	54447
1175	13.2	3075.561	13.36	54451
1171	13.31	3074.89	13.28	54461
1176	13.44	3075.69	13.46	54460
1177	13.51	3075.849	13.54	54457
1178	14	3075.9	14.02	54466
1179	14.07	3075.949	14.09	54454
1180	14.17	3076.147	14.2	54460
1181	14.26	3076.28	14.29	54466
1175	14.37	3075.516	14.43	54472
1182	14.48	3076.42	14.51	54485
1183	14.55	3076.505	14.57	54483
1184	15	3076.622	15.03	54494

Appendix V

Glossary of Geophysical and Geological Terms

GLOSSARY

A selection of relevant geophysical terms extracted from
Encyclopedic Dictionary of Exploration Geophysics (Sheriff, 1984),
Applied Geophysics (Telford et al., 1976),
Geophysical Prospecting (Dobrin, 1976; Dobrin and Savit, 1988).

ACCELEROMETER - A geophone whose output is proportional to the acceleration of earth particles. For example, a moving coil geophone, with velocity response proportional to frequency (as may be the case below the natural frequency) operates as an accelerometer.

ACOUSTIC - IMPEDANCE Seismic velocity multiplied by density. Reflection coefficient at normal incidence depends on changes in acoustic impedance.

ACOUSTIC LOGGING - A borehole logging survey which will display any of several aspects of seismic-wave propagation, i.e., a sonic, amplitude, character or 3D-log.

AIR WAVE - Energy from the shot which travels in the air at the velocity of sound (V): V = 1051 + 1.1F feet/second (fps), where F = Fahrenheit temperature, or V = 331.5 + 0.607C meters/second (m/s), where C = Celsius temperature.

ALIAS - Data in sampled form have an ambiguity where there are fewer than two samples per cycle. This creates a situation where an input signal at one frequency appears to have another frequency at the output of the system. Half of the frequency of sampling is called the folding or Nyquist frequency, f_N, and a frequency larger than this, $f_N + Y$, appears to have the smaller frequency f_N-Y. To avoid this ambiguity, frequencies above f_N must be removed by an anti-alias filter before the sampling. Otherwise the system will react as if the spectral characteristics were folded back at f_N. Thus, for a system sampled over 4 milliseconds (msec), or 250 times per second, the Nyquist frequency is 125 cycles per second (cps); if, for example, 50 cps is within the pass band, then 200 cps will also be passed if an anti-alias filter is not used, appearing upon output to have a 50 cps frequency. The pass bands obtained by folding about the Nyquist frequency are also called "alias bands," "side lobes," and "secondary lobes." Aliasing is an inherent property of all sampling systems and applies to digital seismic recording

and also to the sampling which is done by the separate elements of geophone and shotpoint arrays.

ANALOG - (1) A continuous physical variable (such as voltage or rotation) which bears a direct relationship (usually linear) to another variable (such as earth motion) so that one is proportional to the other. (2) Continuous, as opposed to discrete or digital.

ANOMALY - A deviation from uniformity in physical properties, often of exploration interest. For example, a travel time anomaly, Bouguer anomaly, free-air anomaly.

APPARENT VELOCITY - (1) The phase velocity which a wavefront appears to have along a line of geophones. (2) The inverse of the slope of a time-distance curve.

ATTENUATION - A reduction in amplitude or energy caused by the physical characteristics of the transmitting media or system. Usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from a source. Also used for instrumental reduction effects such as might be produced by passage through a filter.

AUTOMATIC GAIN CONTROL (AGC) - A system in which the output amplitude is used for automatic control of the gain of a seismic amplifier, usually individual for each channel, although multi-channel devices are sometimes used.

BACK THRUSTING - Thrust faulting in an orogenic belt, with the direction of displacemnt toward its interior, or contrary to the general direction of tectonic transport.

BEDROCK - Any solid rock, such as may be exposed at the surface of the earth or overlain by unconsolidated material.

BODY WAVES - P-waves and S-waves, which travel through the body of a medium, as opposed to surface waves..

CABLE - The assembly of electrical conductors used to connect the geophone groups to the recording instrument.

CAPACITANCE - The ratio of charge (Q in coulombs) on a capacitor to the potential across it (V in volts) is the capacitance (C in farads):

$$C = Q/V$$

CHANNEL - (1) A single series of interconnected devices through which geophysical data can flow from sources to recorder. Most seismic systems are 24 channel, allowing the simultaneous recording of energy from 24 groups of geophones. (2) A localized elongated geological feature resulting from present or past drainage or water action; often presents a weathering problems. (3) An allocated portion of the radio-frequency spectrum.

CHANNEL WAVE - An elastic wave propagated in a layer of lower velocity than those on either side of it. Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays which tend to escape are bent back toward the channel by the increasing velocity away from it in either direction.

CHARACTER - (1) The recognizable aspect of a seismic event, usually in the waveform, which distinguishes it from other events. Usually a frequency or phasing effect, often not defined precisely and hence dependent upon subjective judgment. (2) A single letter, numeral, or special symbol in a processing system.

COMMON DEPTH POINT (CDP) - The situation where the same portion of subsurface produces reflections at different offset distances on several profiles.

COMPRESSIONAL WAVE - An elastic body wave in which particle motion is in the direction of propagation. (Same as P-waves, longitudinal wave, dilation wave).

CONVERTED WAVE - A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.

CRITICAL ANGLE - Angle of incidence, q_c, for which the refracted ray grazes the surface of contact between two media (of velocities V_1 and V_2):

$$\sin q_c = V_1/V_2$$

CRITICAL DISTANCE - (1) The offset at which the reflection time equals the refraction time; that is, the offset for which the reflection occurs at the critical angle (see

Sheriff, 1984 p. 45). (2) Sometimes incorrectly used for crossover distance, the offset at which a refracted event becomes the first break.

CROSSFEED - Interference resulting from the unintentional pickup of information or noise on one channel from another channel. Also crosstalk.

CROSS-HOLE METHOD - Technique for measuring in situ compressional (p) and/or shear (s) wave velocities by recording transit times from a source within one borehole to receivers at the same elevation in one or more other boreholes. Sources may be explosive or directional to enhance either p- or s-wave generation.

CROSS SECTION - A plot of seismic events.

DATUM - (1) The arbitrary reference level to which measurements are corrected. (2) The surface from which seismic reflection times or depths are counted, corrections having been made for local topographic and/or weathering variations. (3) The reference level for elevation measurements, often sea level.

DELAY TIME - (1) In refraction work, the additional time required for a wave to follow a trajectory to and along a buried marker over that which would have been required to follow the same marker considered hypothetically to be at the ground surface or at a reference level. Normally, delay time exists separately under a source and under a detector; and is dependent upon the depth of the marker at wave incidence and emergence points. Shot delay time plus geophone delay time equals intercept time (See Dobrin, 1988 p. 472). (2) Delay produced by a filter.

DIELECTRIC CONSTANT - A measure of the capacity of a material to store charge when an electric field is applied. It is the dimensionless ratio of the capacitivity (or permittivity, the ratio of the electrical displacement to the electric field strength) of the material to that of free space.

DIFFRACTION - (1) Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity. It frequently blends with a reflection and obscures the fault location or becomes confused with dip. (2) Interference produced by scattering at edges. (3) The phenomenon

by which energy is transmitted laterally along a wave crest. When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow.

DIGITAL - Representation of quantities in discrete units. A digital system is one in which the information is contained and manipulated as a series of discrete numbers as opposed to an analog system, in which the information is represented by a continuous flow of the quantity constituting the signal.

DOWN-HOLE METHOD - Technique for measurement of in situ compressional and shear wave velocities utilizing a seismic source at ground surface and a clamped triaxial geophone at depth in a borehole. Shear wave energy is often enhanced by use of directional sources such as striking the ends of a weighted plank.

END LINE - Shotpoints that are shot near the end of the spread.

FIRST BREAK - The first recorded signal attributable to seismic wave travel from a known source. First breaks on reflection records are used for information about the weathering. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used. Also first arrival.

FOLD - The multiplicity of common-midpoint data. Where the midpoint is the same for 12 offset distances, e.g., the stack is referred to as "12-fold".

FREQUENCY DOMAIN - A representation in which frequency is the independent variable; the Fourier transform variable when transforming from time.

GAIN - An increase (or change) in signal amplitude (or power) from one point in a circuit or system to another, often from system input to output.

GALVANOMETER - A part of a seismic camera consisting of a coil suspended in a constant magnetic field. The coil rotates through an angle proportional to the electrical current flowing through the coil. A small mirror on the coil reflects a light beam, which exhibits a visual record of the galvanometer rotation.

GEOPHONE - The instrument used to convert seismic energy into electrical voltage. Same as seismometer.

GEOPHONE STATION - Point of location of a geophone on a spread, expressed in engineering notation as 1+75 taken from 0+00 at the beginning of the line.

GROUND ROLL- Surface-wave energy which travels along or near the surface of the ground. It is usually characterized by relatively low velocity, low frequency, and high amplitude. Ground roll tends to mask desired reflection signals

GROUP VELOCITY - The velocity with which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train. The velocity of the envelope is the group velocity. Same as dispersion.

HYDROPHONE - (Pressure detector) A detector which is sensitive to variations in pressure, as opposed to a geophone which is sensitive to particle motion. Used when the detector can be placed below a few feet of water, as in marine or marsh or as a well seismometer. The frequency response of the hydrophone depends on its depth beneath the surface.

IMPEDANCE - The apparent resistance to the flow of alternating current, analogous to resistance in a dc circuit. Impedance is (in general) complex, of magnitude **Z** with a phase angle **g**. These can be expressed in terms of resistance **R** (in ohms), inductive reactance $X_L=2\pi L$ and capacitive reactance $X_c = {}^1/_2\pi fC$:

$$Z = [R^2 + (X_L - X_C)^2]^{1/2},$$
$$g = \tan^{-1}[(X_L - X_C)/R].$$

Z is in ohms when frequency **f** is in hertz, **L** is inductance in henrys, and **C** is capacitance in farads.

IN-LINE OFFSET - A spread which is shot from a shotpoint which is separated (offset) from the nearest active point on the spread by an appreciable distance (more than a few hundred feet) along the line of spread.

INPHASE - Electrical signal with the same phase angle as that of the exciting signal or comparison signal.

IMBRICATE FAULTING - A series of nearly parallel and overlapping minor thrust faults, high angle reverse faults, or slides, and characterized by rock slices, sheets, plates, blocks, or wedges that are approximately equidistant and have the same displacement and that are all steeply inclined in the same direction (toward the source of stress).

LEAD - An electrical conductor for connecting electrical devices. Geophones are connected to cables at the takeouts via leads on the geophones.

LINE - A series of profiles shot in line.

LOVE WAVE - A surface seismic channel wave associated with a surface layer which has rigidity, characterized by horizontal motion perpendicular to the direction of propagation with no vertical motion.

LOW-VELOCITY LAYER - A near-surface belt of very low-velocity material often abbreviated LVL; also called weathering.

MAGNETIC PERMEABILITY - The ratio of the magnetic induction **B** to the inducing field strength **H**: denoted by the symbol m:

$$\mathbf{m = B/moH}$$

mo is the permeability of free space = $4\pi 10^{-7}$ weber/ampere meter or (henrys/meter) in SI system, and 1 gauss/oersted in the cgs system, so that the permeability **m** is dimensionless. The quantity **mmo** is sometimes considered the permeability (especially in the cgs system).

MIGRATION- Originally, rearrangement of interpreted seismic data so that reflections and diffractions are plotted at the locations of the reflectors and diffracting points rather than with respect to observation points. Now, generally a computer operation on raw data to accomplish this purpose.

MIS-TIE - (1) The time difference obtained on carrying a reflection, phantom, or some other measured quantity around a loop; or the difference of the values at identical points on intersecting lines or loops. (2) In refraction shooting, the time difference from reversed profiles which gives erroneous depth and dip calculations.

MULTIPLE - Seismic energy which has been reflected more than once. Same as long-path multiple, short path multiple, peg-leg multiple, and ghost.

MULTIPLEX - A process which permits transmitting several channels of information over a single channel without crossfeed. Usually different input channels are sampled in sequence at regular intervals and the samples are fed into a single output channel; digital seismic tapes are multiplexed in this way. Multiplexing can also be done by using different carrier frequencies for different information channels and in other ways.

NOISE - (1) Any undesired signal; a disturbance which does not represent any part of a message from a specified source. (2) Sometimes restricted to energy which is random. (3) Seismic energy which is not resolvable as reflections. In this sense noise includes microseisms, shot-generated noise, tape-modulation noise, harmonic distortions, etc. Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent). To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements. (4) Sometimes restricted to seismic energy not derived from the shot explosion. (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near surface material.

NOISE ANALYSIS- A profile or set of profiles designed to gather data for an analysis of coherent noise trains. Also called a **walkaway test**.

NOISE SURVEY - A mapping of ambient, continuous seismic noise levels within a given frequency band. As some geothermal reservoirs are a source of short-period seismic energy, this technique is a useful tool for detecting such reservoirs. Also called ground noise survey.

OBSERVER - The geophysicist in charge of recording and overall field operations on a seismic crew.

OFFSET- The distance from the source point to a geophone, or more commonly to the center of a geophone group. Often resolved into components: **porpendicular offset**, the distance at right angles to the spread line, and, **in line offset**, the distance from the projection of the shotpoint onto the line of the spread.

ON-LINE - Shotpoints that are shot at any point on a spread other than at the ends of the spread.

OSCILLOGRAPH - An instrument that renders visible a curve representing the time variations of electric phenomena.

OSCILLOSCOPE - A type of oscillograph that visually displays an electrical wave on the screen of a cathode ray tube type.

PERMITTIVITY - Capacitivity (q.v.) of a three-dimensional material, such as a dielectric. Relative permittivity is the dimensionless ratio of the permittivity of a material to that of free space; it is also callec the dielectric constant.

PHASE VELOCITY - The velocity with which any given phase (such as a trough or a wave of single frequency) travels; may differ from group velocity because of dispersion.

PLANT - The manner in which a geophone is placed on or in the earth; the coupling to the ground.

PROFILE - The series of measurements made from several shotpoints into a recording spread from which a seismic data cross section or profile can be constructed.

PROFILING - A geophysical survey in which the measuring system is moved about an area (often along a line) with the objective of determining how measurements vary with location. Specifically, a resistivity, IP, or electromagnetic field method wherein a fixed electrode or antenna array is moved progressively along a traverse to create a horizontal profile of the apparent resistivity.

RADAR - A system in which short electromagnetic waves are transmitted and the energy scattered back by reflecting objects is detected. Acronym for "radio detection and ranging." Ships use radar to help "see" other ships, buoys, shorelines, etc. Beacons sometimes provide distinctive targets. Radar is used in aircraft navigation (see Doppler-radar), in positioning, and in remote sensing.

RADIO FREQUENCY - A frequency above 3kHz. Radio frequencies are subdivided into bands.

RAYLEIGH

WAVE - A seismic wave propagated along the free surface of a semi-infinite medium. The particle motion near the surface is elliptical and retrograde, in the vertical plane containing the direction of propagation.

RAYPATH - A line everywhere perpendicular to wavefronts (in isotropic media). The path which a seismic wave takes.

REFLECTION- The energy or wave from a seismic source impedance contrast (**reflector**) or series of contrasts within the Earth.

REFLECTION SURVEY - A survey of geologic structure using measurements made of arrival time of events attributed to seismic waves which have been reflected from interfaces where the acoustic impedance changes.

REFLECTOR- A contrast in acoustic impedance which gives rise to a seismic **reflection**.

RESOLUTION - The ability to separate two features which are very close together.

RICKER WAVELET - A particular seismic waveform which results from the transmission of a seismic impulse through an ideal viscoelastic material with attenuation proportional to the square of the frequency. See Ricker, 1953, The Form and Laws of Propagation of Seismic Wavelets: Geophysics, V. 18, p. 10-40.

ROLL-ALONG SWITCH- A switch which permits connecting different geophone groups to the recording instruments, used in common-midpoint recording.

SEISMIC AMPLIFIER - An electronic device used to increase the electrical amplitude of a seismic signal. (See geophone)

SEISMIC CAMERA - A recording oscillograph used to produce a visible pattern of electrical signals to make a seismic record.

SEISMIC SOURCE- A device for generating seismic waves. Or, the point at which seismic waves are generated.

SEISMIC VELOCITY - The rate of propagation of a seismic wave through a medium.

SEISMOGRAM - A seismic record.

SEISMOGRAPH- An instrument that detects, magnifies and records vibrations of the earth.

SHEAR WAVE - A body wave in which the particle motion is perpendicular to the direction of propagation. (Same as s-wave, equivoluminal, transverse wave).

SHOOTER - The qualified, licensed individual (powderman) in charge of all shotpoint operations and explosives handling on a seismic crew.

SHOT DEPTH - The distance down the hole from the surface to the explosive charge, often measured with loading poles. With small charges the shot depth is measured to the center or bottom of the charge, but with large charges the distances to both the top and bottom of the column of explosives are usually given.

SHOT INSTANT - (Time Break (TB), Zero Time) - The time at which a shot is detonated.

SHOTPOINT - Point of location of the energy source used in generating a particular seismogram. Expressed either sequentially for a line (i.e. SP 3) or in engineering notation (i.e. SP 3+00).

SIGNAL ENHANCEMENT - A hardware development utilized in seismographs and resistivity systems to improve signal-to-noise ratio by real-time adding (stacking) successive waveforms from the same source point and thereby discriminating against random noise.

SIGNAL-TO-NOISE RATIO SOUNDING- The energy (or sometimes amplitude) divided by all remaining energy (noise) at the time; abbreviated S/N.

SOUNDING - Measuring a property as a function of depth; a depth probe or expander. Especially a series of electrical resistivity readings made with successively greater electrode spacing while maintaining one point in the array fixed, thus giving resistivity-versus-depth information (assuming horizontal layering); electric drilling, probing, VES (vertical electric sounding).

SPLIT SPREAD- A method of reflection shooting in which the source point is at (or perpendicularly offset from) the center of the geophone spread.

SPREAD - The layout of geophone groups from which data from a single shot are recorded simultaneously.

SOLE FAULT - A low-angle thrust fault forming the base of a thrust sheet; also, the basal main fault of an imbrication.

STATIC CORRECTIONS- Often shortened to **statics**: Corrections applied to seismic data to compensate for the effects of variations in elevation, weathering, thickness, weathering velocity, or reference to a datum. The objective is to determine the reflection arrival times which would have been observed if all measurements had been made on a flat plane with no weathering or low velocity material present.

STONELEY WAVE - A type of seismic wave propagated along an interface.

SURFACE WAVE - Energy which travels along or near the surface (ground roll).

SYNTHETIC SEISMOGRAM - An Artificial seismic record manufactured from velocity log data used to compare with and actual seismogram to aid in identify events or in predicting how stratigraphic variations might affect seismic record. Often constructed from sonic log data alone although density data may also be incorporated.

TAKEOUT - A connection point to a multiconductor cable where geophones can be connected.

THRUST FAULT - A fault with a dip of 45 degrees or less over much of its extent, on which the hanging wall appears to have moved upward relative to the footwall. Horizontal compression rather than vertical displacement is its characteristic feature.

TIME BREAK (TB)- The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated.

TIME DOMAIN - 1. Expression of a variable as a function of time, as opposed to its expression as a function of frequency (frequency domain). Processing can be done using time as the variable, i.e., "in the time domain". For

example, convolving involves taking values at successive time intervals, multiplying by appropriate constants, and recombining; this is equivalent to filtering through frequency-selective circuitry. It is also equivalent to Fourier transforming, multiplying the amplitude spectra, and adding the phase spectra ("in the frequency domain"), and then inverse-Fourier transforming.

2. Time-domain induced polarization is called the pulse method (q.v.)

TOMOGRAPHY - The reconstruction of an object from a set of its projections. Tomographic techniques are utilized in medical physics as well as in cross-borehole electromagnetic and seismic transmission surveys.

TRACE - A record of one seismic channel. This channel may contain one or more geophones. A trace is made by a galvanometer.

UPHOLE METHOD- Also called the Meissner technique, a method of reconstructing wave front diagrams by shooting at several depths and recording on a full surface spread of geophones. Derived wavefront diagrams yield a true picture of wavepaths and, therefore, layering in the subsurface.

VELOCITY- A vector quantity which indicates time rate of change of displacement. Usually refers to the propogation rate of a seismic wave without implying any direction. Velocity is a property of the medium. It is measured (or inferred) from sonic logs, normal moveout, in well shooting (vertical seismic profiles [VSP's]), and from refraction time-distance curves.

VELOCITY PULL-UP - An apparent uplift produced by a local, shallower high-velocity region.

WAVE TRAIN - (1) The sum of a series of propagating wave fronts emanating from a single source. (2) The complex wave form observed in a seismogram obtained from an explosive source.

REFERENCE

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Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1976. Applied Geophysics, Cambridge University Press.

NOTICE

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EG&G Rocky flats Line RFD-1

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Line RFD-1 Dec 1991

Fiche location: 8A-5W M36

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Titled: Plate 3 EG&G Rocky Flats line RFD-1 Dec. 1991

Fiche location: A-SWM36

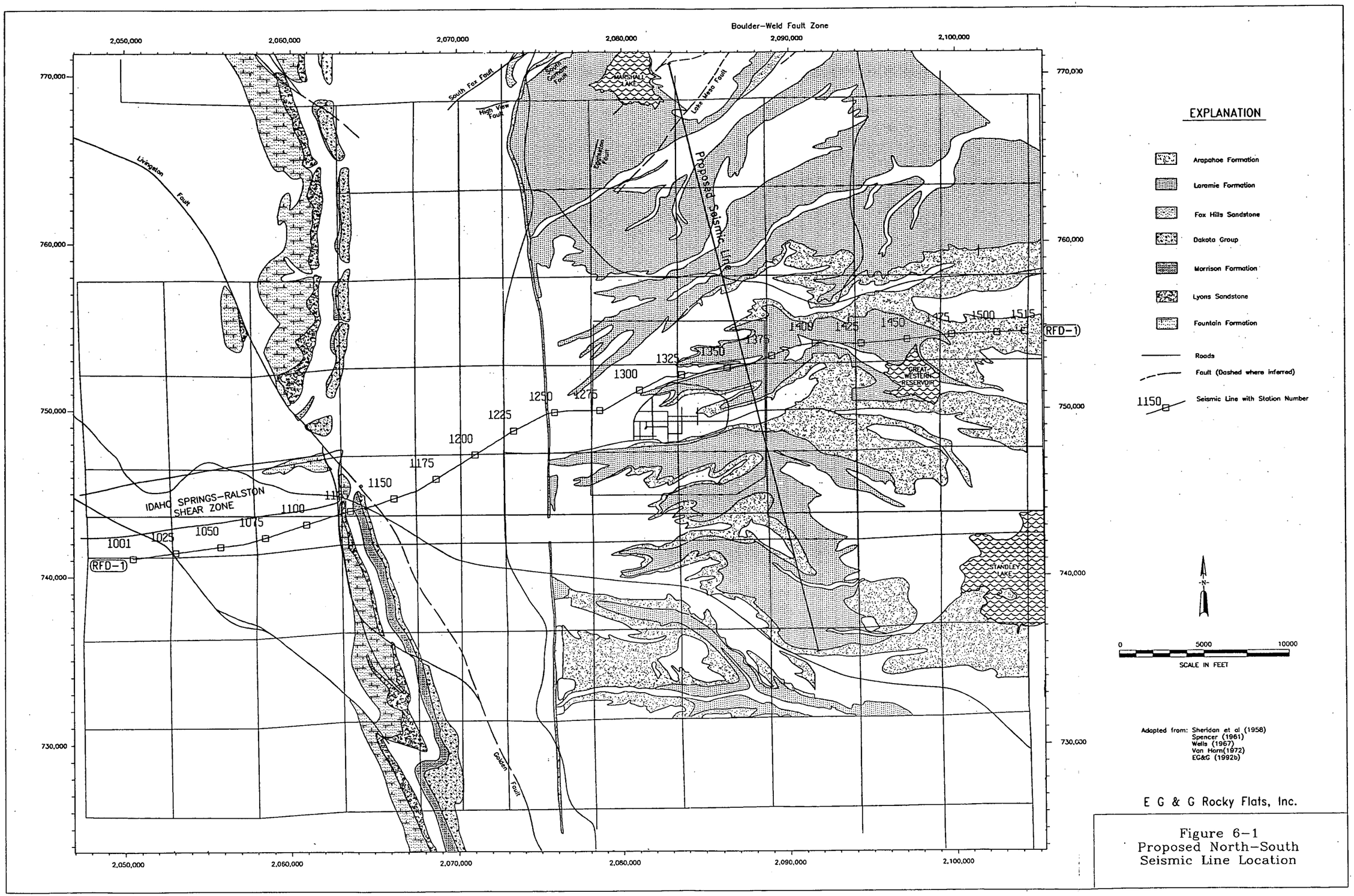
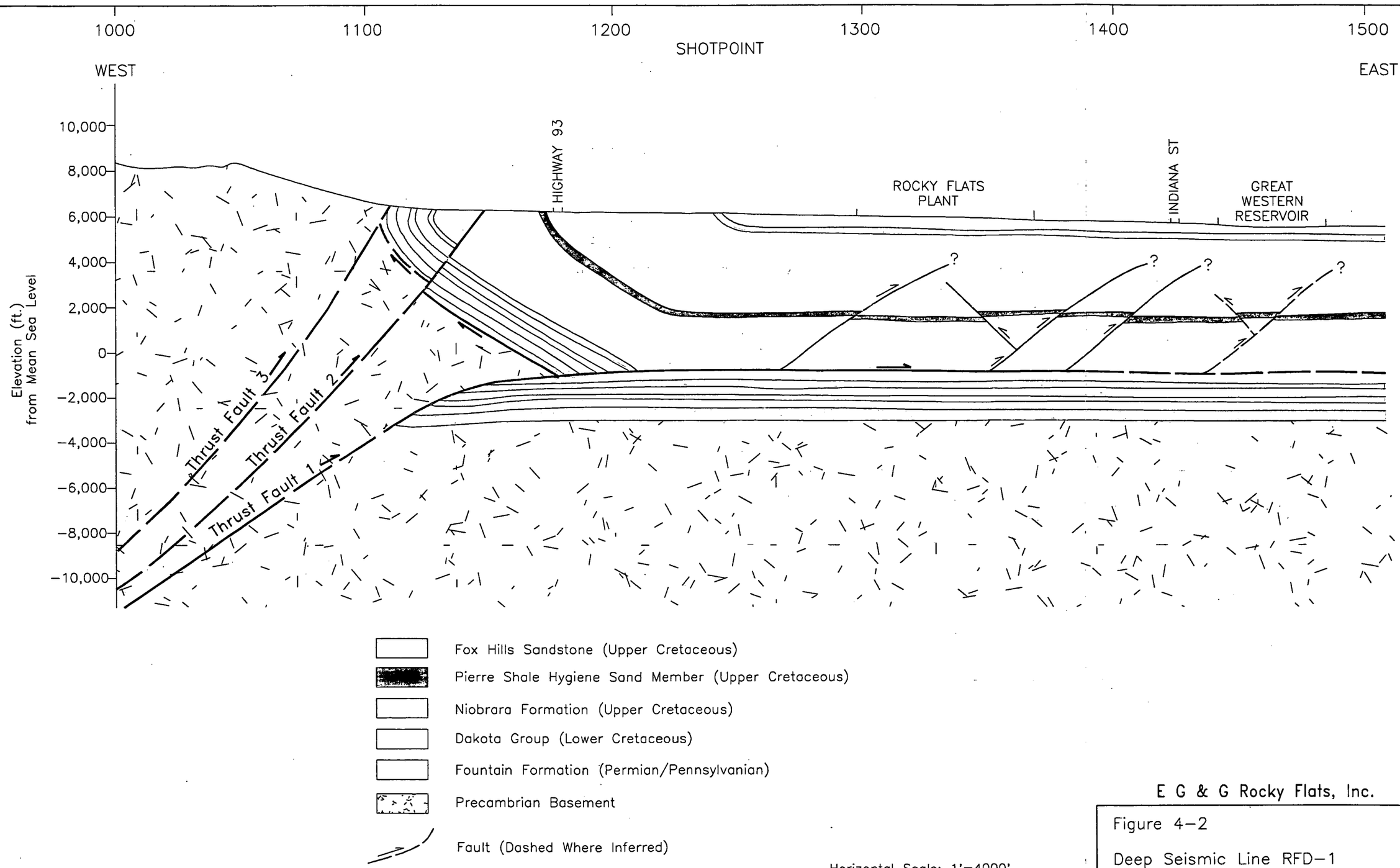


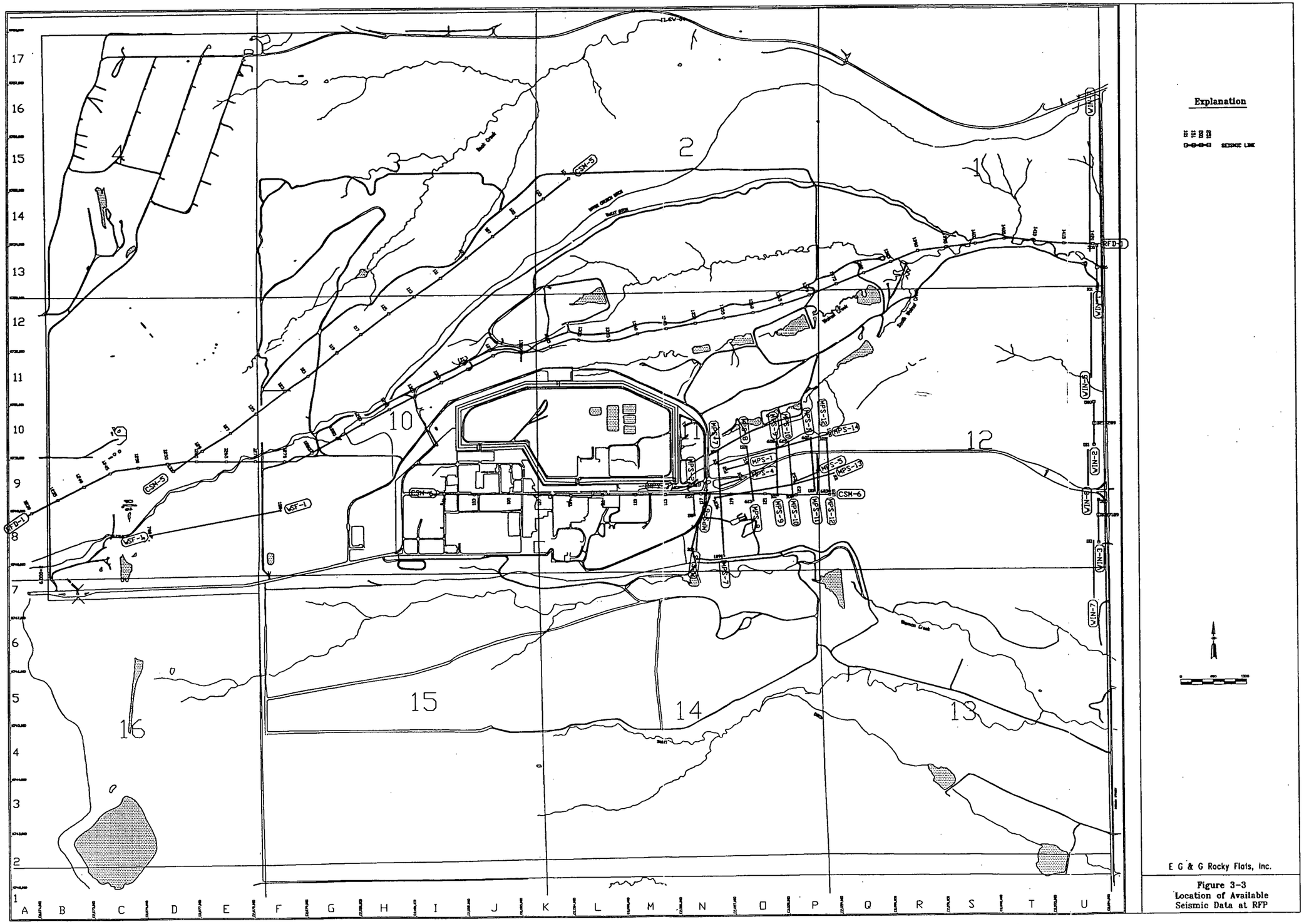
Figure 6–1
Proposed North–South
Seismic Line Location



E G & G Rocky Flats, Inc.

Figure 4−2

Deep Seismic Line RFD−1
Interpreted Geologic Cross Section


Explanation
SEISMIC LINE
CSM-5
CSM-6
VSF-1
RFD-1
VIN-1
VIN-2
VIN-3
VIN-4
VIN-5
VIN-6
VIN-7
MPS-1
MPS-2
MPS-3
MPS-4
MPS-5
MPS-6
MPS-7
MPS-8
MPS-9
MPS-10
MPS-11
MPS-12
MPS-13
MPS-14
MPS-15
MPS-16
MPS-17
MPS-18
MPS-19
MPS-20
MPS-21
MPS-22
MPS-23
MPS-24
MPS-25
MPS-26
MPS-27
MPS-28
MPS-29
MPS-30
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MPS-38
MPS-39
MPS-40

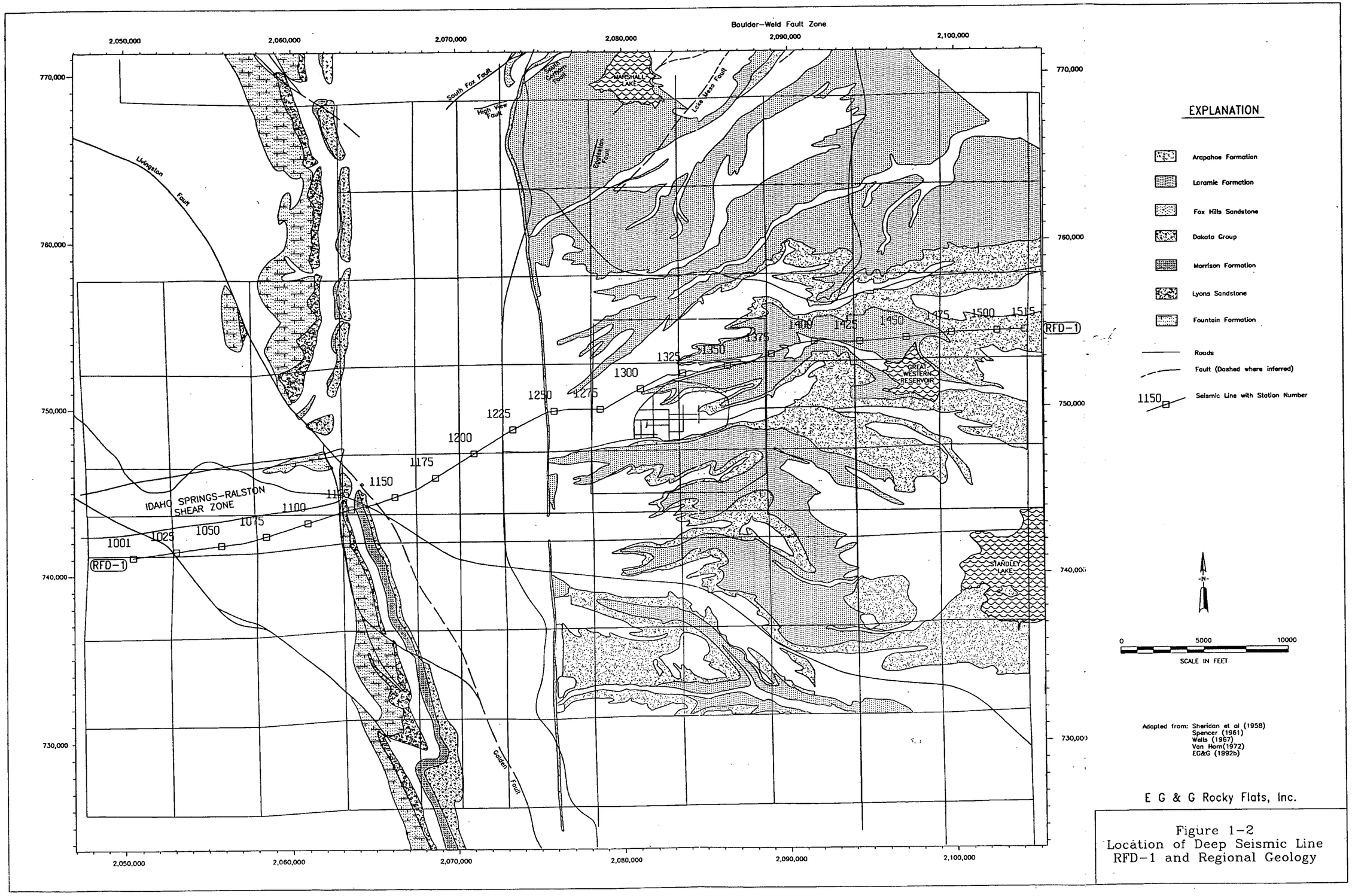
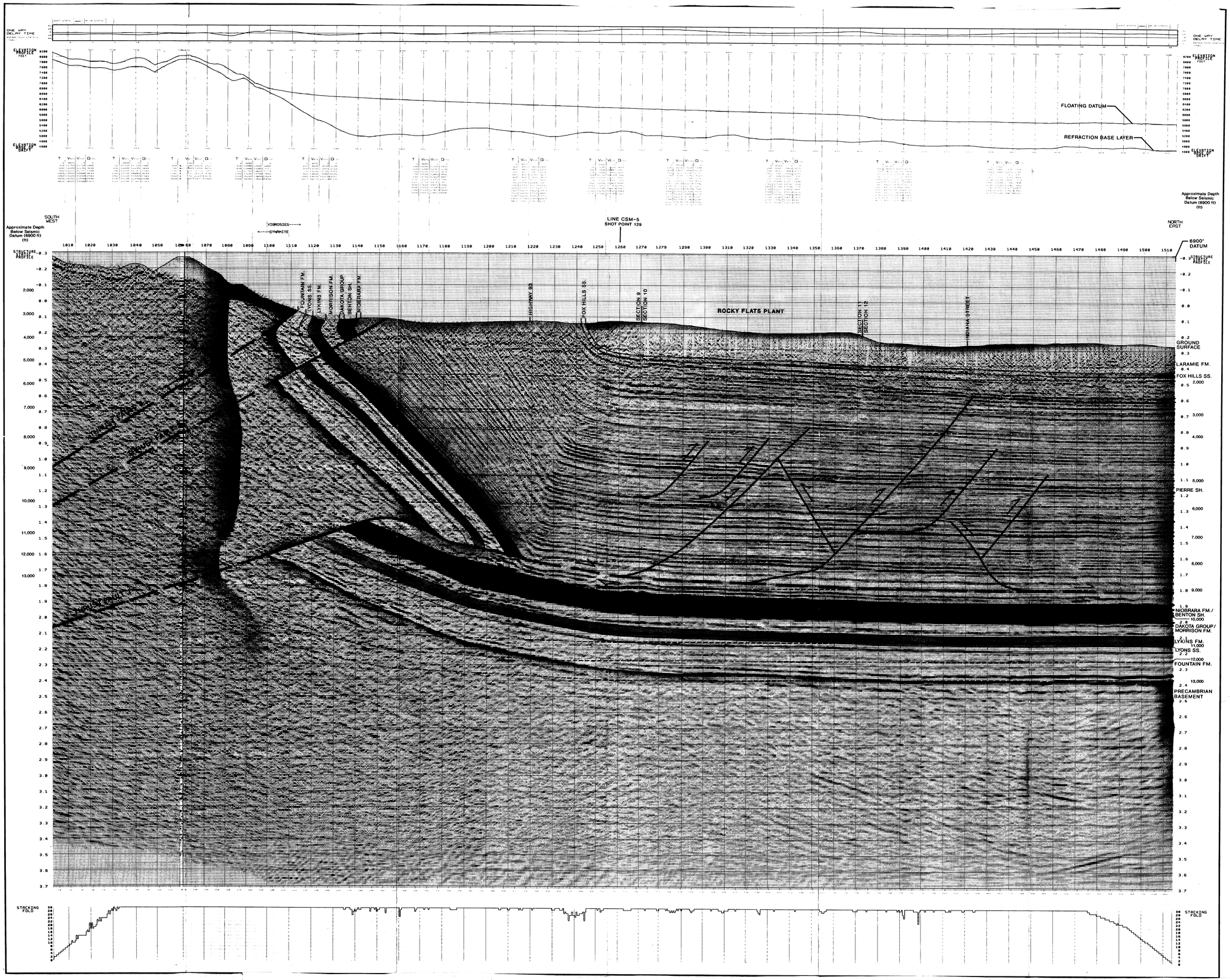


Figure 1–2
Location of Deep Seismic Line
RFD–1 and Regional Geology



EBASCO

EG&G ROCKY FLATS LINE RFD-1

MIGRATED DMO STACK NORMAL POLARITY

SW → NE

SPS: 1001 - 1515

STATE: COLORADO CNTY: JEFFERSON

DATUM: 6900 FT V_c: 8500 FT/SEC

FIELD PARAMETERS

SHOT BY:	CENTURY GEOPHYSICAL CORP.	DATE SHOT:	August, 1991
RECORDING SYSTEM:	MDS-10	SOURCE INTERVAL:	220 Ft.
FORMAT:	SEG-B	GROUP INTERVAL:	110 Ft.
SAMPLE INTERVAL:	2 ms.	GEOPHONE MODEL:	LRS-1000 20 Hz.
RECORD LENGTH:	4 sec.	GEOPHONE ARRAY :	12 Phones/155 ft Diagonal to line
SOURCE TYPE:	DYNA. & VIBRO.		
DYNAMITE ARRAY:	10 lbs/50 ft Hole	GAIN MODE:	IFP
VIBROSEIS ARRAY:	4 VIBES/90 ft	NOTCH FILTER:	IN
NO. OF SWEEPS:	10	FIELD FILTER:	12 - 125 Hz.
SWEEP FREQ.:	10 - 120 Hz.	COVERAGE:	3000%
SWEEP LENGTH:	12 sec.		

TRACE SPREAD: 1 - 80 5 81 - 120

DISTANCE 9820' - 330' 0 220' - 4520'

DISPLAY PARAMETERS

TRACES/INCH 24 INCHES/SECOND 6

Depth & Interval Velocities Calculated Using the DIX Equation

PROCESSING PARAMETERS

1. DEMULTIPLEX
2. SPHERICAL DIVERGENCE COMPENSATION
3. MINIMUM PHASE COMP. ON VIBROSEIS RECORDS
4. CROOKED LINE GEOMETRY APPLICATION
   Trace Edits
5. REFRACTION STATICS DERIVATION
   Generalized Linear Inversion
   Vo = 3300 Ft/Sec
6. DISTANCE/TIME DEPENDANT SCALING
7. DECONVOLUTION - SURFACE CONSISTENT
   150 ms. Operator
   Minimum Phase
   .1% Prewhitening
8. DISTANCE/TIME DEPENDANT SCALING
9. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
   Datum FLOATING DATUM
   Replacement Velocity 8500 Ft/Sec
10. CONSTANT VELOCITY STACK ANALYSIS
11. STATICS - AUTOMATIC SURFACE CONSISTENT
12. TIME DOMAIN - SPECTRAL WHITENING
    Pass Band 3/10 - 80/90 Hz.
    Prewhitening .1%
13. VELOCITY SEMBLANCE & CONSTANT VELOCITY STACK ANALYSIS
14. NORMAL MOVEOUT
15. STATICS - AUTOMATIC SURFACE CONSISTENT
16. FIRST BREAK SUPPRESSION MUTE
17. RESIDUAL TRIM STATICS - CDP CONSISTENT
18. INVERSE NORMAL MOVEOUT
19. DMO VELOCITY SEMBLANCE & DMO CONSTANT VELOCITY STACK ANALYSIS
20. DIP-MOVEOUT
21. BULK SHIFT +300 ms.
22. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
    Datum FLAT DATUM 6900 Ft
    Replacement Velocity 8500 Ft/Sec
23. STACK 3000%
    Stack Output to SEG-Y Format Tape
24. FILTER - DIGITAL BAND-PASS
    7/10 - 80/90 Hz.
25. TRACE EQUALIZATION
    4 Window Mean Scaling
26. FINITE-DIFFERENCE MIGRATION
    90% of RMS Stacking Velocities Used
    Stack Output to SEG-Y Format Tape

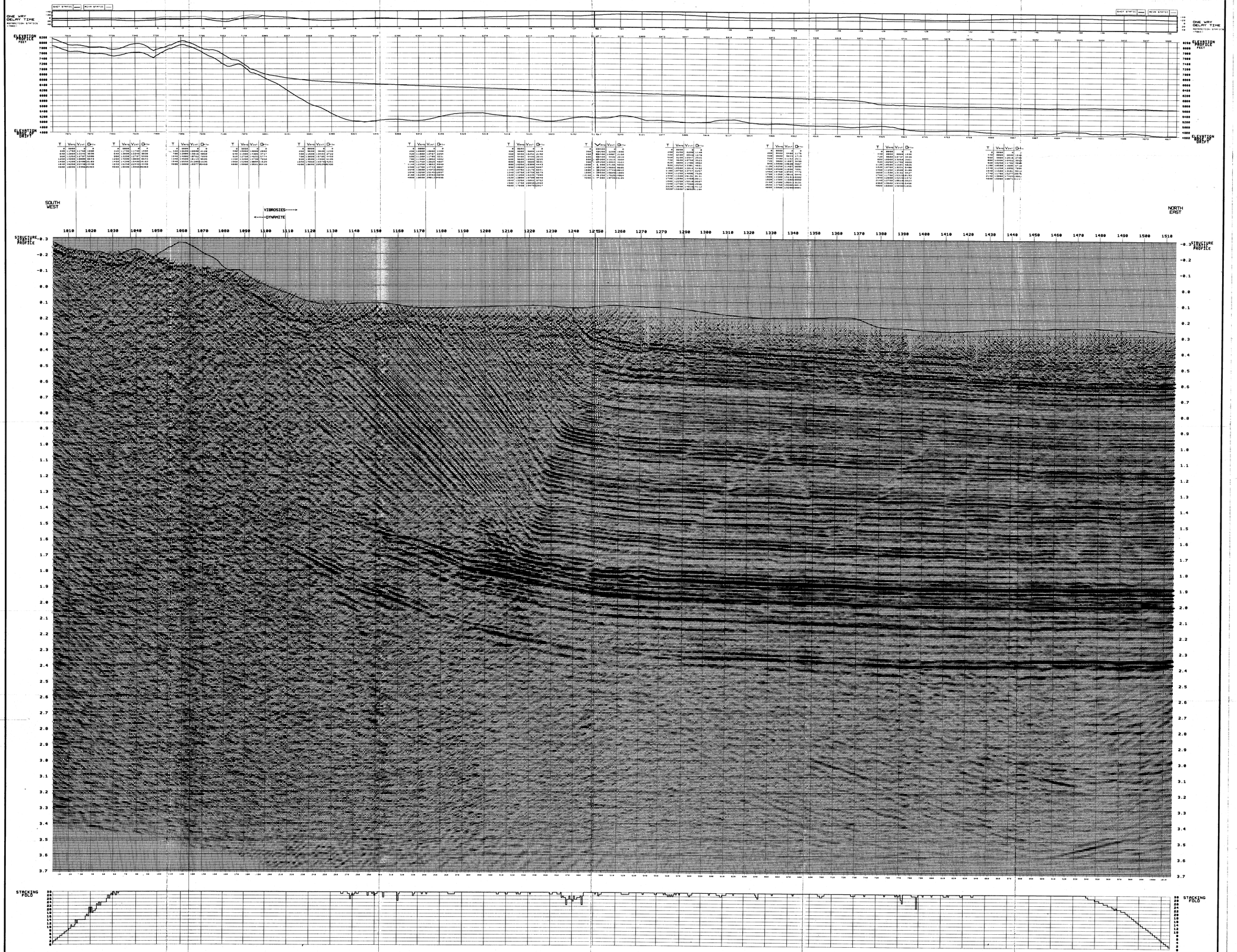
VECTOR

SEISMIC DATA PROCESSING INC.

Denver, Colorado

Date Processed: December, 1991

SW-A-000592



EBASCO

EG&G ROCKY FLATS
LINE RFD-1

MIGRATED DMO STACK
NORMAL POLARITY

SW → NE

SPS: 1001 - 1515

STATE: COLORADO CNTY: JEFFERSON

DATUM: 6900 FT V_R: 8500 FT/SEC

FIELD PARAMETERS

SHOT BY:	CENTURY GEOPHYSICAL CORP.	DATE SHOT:	August, 1991
RECORDING SYSTEM:	ARS-18	SOURCE INTERVAL:	220 ft.
FORMAT:	SEG-B	GROUP INTERVAL:	110 ft.
SAMPLE INTERVAL:	2 ms.	GEOPHONE MODEL:	LRS-1000 28 Hz.
RECORD LENGTH:	4 sec.	GEOPHONE ARRAY:	12 Phones/155 ft Diagonal to line
SOURCE TYPE:	DYNA. & VIBRO.		
DYNAMITE ARRAY:	10 lbs/50 ft Hole	ARM MODE:	IFP
VIBROSEIS ARRAY:	4 VIBES/90 ft	NOTCH FILTER:	IN
NO. OF SWEEPS:	10	FIELD FILTER:	12 - 125 Hz.
SWEEP FREQ.:	10 - 120 Hz.		
SWEEP LENGTH:	12 sec.	COVERAGE:	3000%

TRACE SPREAD: 1 - 00 S 01 - 120

DISTANCE 9020' - 330' @ 220' - 4520'

DISPLAY PARAMETERS

TRACES/INCH 24 INCHES/SEC DMO 6

Depth & Interval Velocities Calculated Using the DIX Equation

PROCESSING PARAMETERS

1. DEMULTIPLEX
2. SPHERICAL DIVERGENCE COMPENSATION
3. MINIMUM PHASE COMP. ON VIBROSEIS RECORDS
4. CROOKED LINE GEOMETRY APPLICATION
   Trace Edits
5. REFRACTION STATICS DERIVATION
   Generalized Linear Inversion
   Vo = 3300 Ft/Sec
6. DISTANCE/TIME DEPENDANT SCALING
7. DECONVOLUTION - SURFACE CONSISTENT
   160 ms. Operator
   Minimum Phase
   .1% Prewhitening
8. DISTANCE/TIME DEPENDANT SCALING
9. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
   Datum FLOATING DATUM
   Replacement Velocity 8500 Ft/Sec
10. CONSTANT VELOCITY STACK ANALYSIS
11. STATICS - AUTOMATIC SURFACE CONSISTENT
12. TIME DOMAIN - SPECTRAL WHITENING
    Pass Band 3/10 - 80/90 Hz.
    Prewhitening .1%
13. VELOCITY SEMBLANCE & CONSTANT VELOCITY STACK ANALYSIS
14. NORMAL MOVEOUT
15. STATICS - AUTOMATIC SURFACE CONSISTENT
16. FIRST BREAK SUPPRESSION MUTE
17. RESIDUAL TRIM STATICS - CDP CONSISTENT
18. INVERSE NORMAL MOVEOUT
19. DMO VELOCITY SEMBLANCE & DMO CONSTANT VELOCITY STACK ANALYSIS
20. DIP-MOVEOUT
21. BULK SHIFT +300 ms.
22. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
    Datum FLAT DATUM 6900 ft
    Replacement Velocity 8500 Ft/Sec
23. STACK 3000%
    Stack Output to SEG-Y Format Tape
24. FILTER - DIGITAL BAND-PASS
    7/10 - 80/90 Hz.
25. TRACE EQUALIZATION
    4 Window Mean Scaling
26. FINITE-DIFFERENCE MIGRATION
    80% of RMS Stacking Velocities Used
    Stack Output to SEG-Y Format Tape

VECTOR

SEISMIC DATA PROCESSING INC.
Denver, Colorado

Date Processed: December, 1991

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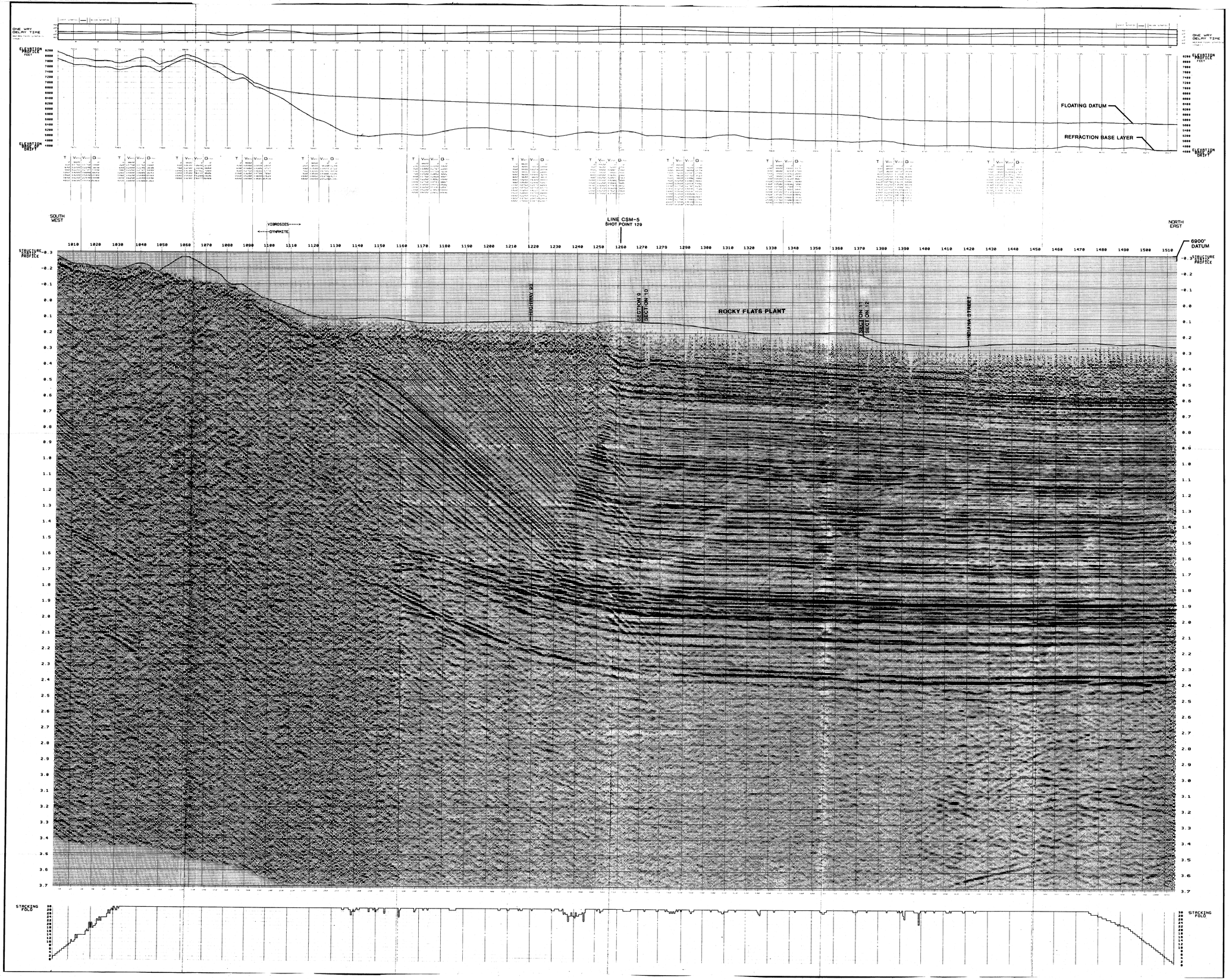

EBASCO

EG&G ROCKY FLATS
LINE RFD-1

DIP-MOVEOUT STACK
NORMAL POLARITY

SW → NE

SPS: 1001 - 1515
STATE: COLORADO CNTY: JEFFERSON
DATUM: 6900 FT V_R: 8500 FT/SEC

FIELD PARAMETERS

SHOT BY:	CENTURY GEOPHYSICAL CORP.	DATE SHOT:	August, 1991
RECORDING SYSTEM:	MDS-10	SOURCE INTERVAL:	220 ft.
FORMAT:	SEG-B	GROUP INTERVAL:	110 ft.
SAMPLE INTERVAL:	2 ms.	GEOPHONE MODEL:	LRS-1000 28 Hz.
RECORD LENGTH:	4 sec.	GEOPHONE ARRAY:	12 Phones/155 ft Diagonal to line
SOURCE TYPE:	DYNA. & VIBRO.		
DYNAMITE ARRAY:	10 lbs/50 ft Hole	GAIN MODE:	IFP
VIBROSEIS ARRAY:	4 VIBES/50 ft	NOTCH FILTER:	IN
NO. OF SWEEPS:	10	FIELD FILTER:	12 - 125 Hz.
SWEEP FREQ.:	10 - 120 Hz.		
SWEEP LENGTH:	12 sec.	COVERAGE:	3000%
TRACE SPREAD:	1 - 00	5 01 - 120	
DISTANCE	9020' - 330'	0 220' - 4520'	

DISPLAY PARAMETERS

TRACES/INCH 24 INCHES/SECOND 6
Depth & Interval Velocities Calculated Using the DIX Equation

PROCESSING PARAMETERS

1. DEMULTIPLEX
2. SPHERICAL DIVERGENCE COMPENSATION
3. MINIMUM PHASE COMP. ON VIBROSEIS RECORDS
4. CROOKED LINE GEOMETRY APPLICATION
   Trace Edits
5. REFRACTION STATICS DERIVATION
   Generalized Linear Inversion
   V_0 = 3300 Ft/Sec
6. DISTANCE/TIME DEPENDANT SCALING
7. DECONVOLUTION - SURFACE CONSISTENT
   160 ms. Operator
   Minimum Phase
   .12 Prewhitening
8. DISTANCE/TIME DEPENDANT SCALING
9. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
   Datum FLOATING DATUM
   Replacement Velocity 8500 Ft/Sec
10. CONSTANT VELOCITY STACK ANALYSIS
11. STATICS - AUTOMATIC SURFACE CONSISTENT
12. TIME DOMAIN - SPECTRAL WHITENING
    Pass Band 3/10 - 80/90 Hz.
    Prewhitening .12
13. VELOCITY SEMBLANCE & CONSTANT VELOCITY STACK ANALYSIS
14. NORMAL MOVEOUT
15. STATICS - AUTOMATIC SURFACE CONSISTENT
16. FIRST BREAK SUPPRESSION MUTE
17. RESIDUAL TRIM STATICS - CDP CONSISTENT
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20. DIP-MOVEOUT
21. BULK SHIFT +300 ms.
22. STRUCTURE STATICS - ELEVATION CORRECTIONS + WEATHERING STATICS CORRECTIONS
    Datum FLAT DATUM 6900 Ft
    Replacement Velocity 8500 Ft/Sec
23. STACK 3000%
    Stack Output to SEG-Y Format Tape
24. FILTER - DIGITAL BAND-PASS
    7/10 - 80/90 Hz.
25. TRACE EQUALIZATION
    4 Window Mean Scaling

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