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## Recent Work

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## **Field Monitoring of Seismic Stimulation Sites**

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**Abstract.** This reports summarizes field observations at oil field sites conducting seismic stimulation operations. Five monitoring experiments at two field sites were conducted using surface sensors and borehole sensors in multiple monitoring wells at various depths. Analysis focused on borehole sensors which can record seismic energy within the reservoir formations. No conclusive evidence of source generated seismic waves was obtained. Background noise levels were measured and these can be used to define a radius of influence for a reservoir stimulation tool in the monitored reservoirs once the source energy level is measured.

## 1. Introduction

Lawrence Berkeley National Laboratory (LBNL) and Los Alamos National Laboratory have been involved with investigating the possibility of using seismic energy to enhance the flow of fluids in the subsurface. Until now there have been few if any controlled measurements at the reservoir scale to determine the level and nature of the seismic energy causing stimulation. As part of the DOE Fossil Energy Natural Gas and Oil Partnership LBNL and LANL have a joint effort involving laboratory and field measurements. The goal of the field effort is to monitor jointly with industry partners field scale stimulation efforts. The objective is to document and measure the threshold and nature of seismic energy causing stimulation.

Described here are the results of monitoring two separate field scale stimulation efforts using two different type of sources in two different oil reservoirs. The monitoring was conducted during 1998 and 1999 by placing seismic sensors in boreholes at the two sites using two different stimulation sources. The sites are the San Ardo field in central California operated by AERA Energy using a tool manufactured by Etrema Inc.; and the Wellington field in Northern Colorado operated by Wellington Operating Co. using a tool manufactured and operated by Wave Energy Resources Inc. Various sensors (see below) and recording systems were used because of varying field conditions and equipment availability. Because both accelerometers and velocity geophones were used, a common unit of ground motion had to be chosen. We have used velocity (m/s) as a comparison unit, requiring acceleration values to be converted. Where recording system calibrations of digital recordings were not available, visual inspection of in-field oscilloscope monitors have been used to determine ground motion.

## 2. Data Acquisition

A total of five monitoring experiments have been conducted to date by LBNL. We have used two different borehole sensors and two different recording systems for the monitoring. The details of data acquisition are listed here:

### 2.1. Experiment 1: Winter 1998-99 and March 15, 1999

**Location: Wellington**

*Stimulation source well: 35-4*

*Geology: sandstone reservoir*

*Stimulation source depth: 400-4600 ft.*

*Monitoring sensor well: 38-2*

*Sensor depth: 1000, 3000 and 3700 ft.*

*Source - Sensor distance: 1596 ft*

*Source Type: Direct Reservoir Seismic Stimulation Tool (DRSS)*

*Sensor Type: hydrophone ITI DH-6*

*Recording System: RefTek*

*Sensor response: -70 dB re: 1 V/g (or -180 dB re: 1 v/10<sup>-6</sup> Pa*

*Sensor gain: 20 dB*

*Background voltage: N/A*

*Background velocity: N/A*

This initial experiment left the sensor at depth (3700 feet) for multiple weeks while the stimulation source was running. The recording system used timed acquisition to record for 15 minutes each day. On March 15, 1999 the sensors were recorded with the source active and inactive. Simultaneous recording of the source with a surface

geophone was attempted. Figure 1-1 shows the spectral energy of a hydrophone sensor at 3700 ft. in well 38-2 for a series of 10 second recordings (labeled 33 to 57). The DRSS source was turned off during the recordings 40 to 52 shown in Figure 1-1, however no clear change in spectra is observed. The DRSS source is designed to produce maximum energy in the reservoir (about 4600 ft at Wellington), however various depths in the source well may produce measurable seismic energy because of the source design. The depth of maximum energy remains an important quantity to measure.

## **2.2. Experiment 2: April 15, 1999**

### **Location: San Ardo**

*Stimulation source well: 54-11*

*Stimulation source depth: N/A*

*Geology: shale reservoir*

*Monitoring sensor well: 55A-11*

*Sensor depth: 2200 - 1900 ft*

*Source - Sensor distance: 400 ft*

*Source Type: Etrema Power Wave*

*Sensor Type: 3-component geophone -Mark Products L-15B*

*Recording System: RefTek 72A-07 SN7007*

*Sensor response: 0.7 V/in/s*

*Sensor gain: 550*

*Background voltage: 1v +*

*Background velocity:  $6.5 \times 10^{-5}$  m/s*

Experiment 2 was not able to record while the source was operating because of

equipment problems with the source. However, background noise levels were monitored and recorded at multiple depths. A high temperature borehole geophone (max 450 F) was used because the San Ardo field site was undergoing steam flooding. The peak signals observed were noise bursts. Constant background noise was at a much lower level (20mv vs 1v). A typical recording with spectra is shown in Figure 2-1.

### 2.3. Experiment 3: June 9, 1999

#### Location: Wellington

*Stimulation source well: 35-4*

*Stimulation source depth: 400 ft - 4600 ft.*

*Monitoring sensor well: 26-2*

*Sensor depth: 3640 ft.*

*Source - Sensor distance: 4544 ft.*

*Source Type: DRSS*

*Sensor Type (borehole): 3-component accelerometer Wilcoxon 731-20A*

*Sensor Type (surface): Geo Space GSC-11D*

*Recording System: RefTek*

*Sensor response (borehole): 20 V/g*

*Sensor response (surface): 0.7 V/in/s*

*Sensor gain: 1*

*Background voltage (borehole): 20 mV (non-seismic frequency)*

*Background velocity: N/A (non-seismic noise)*

Experiment 3 was limited because the sensor well was blocked and the sensor could not be placed in the same formation as the source. Also, one horizontal component of the borehole sensor was not operational. Background noise levels were monitored

with an oscilloscope, operational problems prevented digital recording of the borehole data. The noise level of 20 mV seen on the oscilloscope was too high frequency to be seismic noise (about 200 kHz). The large distance between source and receiver wells limited the probability of recording source generated seismic energy.

In addition to borehole monitoring, a surface geophone at the source well was recorded by a second RefTek recording system. A "walkaway" survey was performed using the surface geophone. The geophone was moved at 50 ft intervals from 0 to 500 ft. away from the source well and at 100 ft intervals from 500 to 900 ft. Multiple "pops" of the source were recorded at each offset. Analysis of the walkaway showed that the dominant energy was a surface wave traveling away from the well (Figure 3-1) .

#### **2.4. Experiment 4: July 7, 1999**

##### **Location: Wellington**

*Stimulation source well: 35-4*

*Stimulation source depth: 400 ft - 4600 ft*

*Monitoring sensor well: 32-2*

*Sensor depth: 4450 ft.*

*Source - Sensor distance: 1200 ft.*

*Source Type: DRSS*

*Sensor Type (borehole): 3-component accelerometer Wilcoxon 731-20A*

*Sensor Type (surface): Geo Space GSC-11D*

*Recording System: DAS-1*

*Sensor response (borehole): 20 v/g*

*Sensor response (surface): 0.7 V/in/s*

*Sensor gain: 1*



*Peak voltage(surface, source well): 400 mV*

*Background voltage(borehole, monitor well):  $1.6 \times 10^{-3}$  V*

*Peak velocity(surface, source well): 0.15 m/s*

*Background velocity(borehole, monitor well):  $1.6 \times 10^{-5}$  m/s*

The DRSS source is a broadband impulsive source and its energy is easily measured on the surface near the source well. Experiment 4 used triggered recording of the monitor well sensor using a surface geophone at the source well for a zero time trigger. This allowed recordings from multiple "pops" of the source to be stacked together to improve signal-to-noise ratio. An example of the stacked recordings from multiple depths, comparing noise records with operating source records, in borehole 32-2 is shown in Figure 4-1. The source records (FFID 114 and 400) show possible arrivals near 700 and 825 ms at two the two depths (4450 and 4190 ft). However the maximum amplitude of these arrivals is equal to the peaks in the noise records at the same depths (FFID 229 and 308), therefore we believe these events can not be interpreted as source generated seismic energy. If the possible arrivals were signal, their maximum amplitudes of about 0.15 counts would correspond to amplitudes of  $2.9 \times 10^{-6}$  m/s. Despite stacking up to 100 source recordings, no discrete seismic arrivals could be identified. The signal-to-noise ratio remained around 1 or less (note that stacking reduces average noise level for random noise).

An example of the source monitor (surface geophone) recording with spectra is shown in Figure 4-2. The largest spectral peak is near 50 Hz. The digital recordings of the surface sensor showed a maximum of 200 counts which equals 400 mV and corresponds to 0.15 m/s velocity.

The digital recordings of the monitor well borehole sensor showed a maximum background noise level of  $1.6 \times 10^{-5}$  m/s at 440 ft. depth. (The recorded amplitude of 0.8 counts equals 1.6 mV sensor output and corresponds to  $7.9 \times 10^{-4}$  m/s/s acceleration

and  $1.6 \times 10^{-5}$  m/s velocity assuming 50 Hz energy.) Using the same analysis at 4180 ft. depth, the noise was  $2.35 \times 10^{-4}$  m/s, and at 4450 ft. depth the noise was  $2.0 \times 10^{-4}$  m/s (again using 50 Hz to convert acceleration to velocity). 50 Hz was used for conversion because the surface source monitor showed a peak at 50 Hz. The background noise is actually broadband and effective velocity values will change with frequency.

## 2.5. Experiment 5: July 28, 1999

### Location: San Ardo

*Stimulation source well: 54-11*

*Stimulation source depth: 2000 ft.*

*Monitoring sensor well: 55A-11*

*Sensor depth: 2000 ft.*

*Source - Sensor distance: 400 ft.*

*Source Type: Etrema Power Wave*

*Sensor Type: 3-component geophone, Mark Products L-15B*

*Recording System: DAS-1*

*Sensor response: 0.7 V/in/s*

*Sensor gain: 550*

*Peak voltage (bursts): 1v*

*Peak velocity (bursts):  $6.5 \times 10^{-5}$  m/s Peak voltage (background): 6 mv*

*Peak velocity (background):  $4.0 \times 10^{-7}$  m/s*

Experiment 5 used a loop current meter to record and monitor the source signal along with the sensor signal. The source ran a variable frequency sweep including periods of off time (no source output). Figures 5-1 through 5-3 show the spectra for three 10 second recordings. No evidence of signal is seen on the 3-component sensor. The Etrema

source would also stay at a constant frequency of about 205 Hz for about 2 minutes at a time. We took the combined spectra of 26 10 second recordings at constant source frequency, Figures 5-4a and 5-4b. In Figure 5-4b, there is a peak in the monitor sensor at 205 Hz, however this is within a band with high noise ( 180 to 240 Hz, see Figures 5-1b, 5-2b and 5-3b) and the signal at 205 Hz is still no larger than other noise peaks (such as 30 Hz, 140 Hz and 180 Hz). Therefore, we believe that there is no conclusive evidence that the source generated seismic energy is being seen at the monitor well.

### **3. Equipment Calibrations**

The sensor analysis used manufacturer's published response specifications. The 3-component geophone is a high temperature, hydraulic wall-locking borehole sensor manufactured by Seismograph Service Corp. with temperature compensation and downhole gain of 550 using 3 Mark Products L-15B geophones. The borehole accelerometer is a mechanical locking arm sensor manufactured by Conoco Inc and has 3 Wilcoxon 731-20A accelerometers. The borehole hydrophones are manufactured by Innovative Transducers Inc. The DAS-1 recording system was manufactured by OYO GeoSpace and was calibrated by inputting a sine wave of known voltage (100 to 1000 mV) into data channels. The data was internally recorded with 24 dB gain in SEG-2 format and then written to a 4mm DAT tape in SEG-D 8048 format. The tape was read using ProMAX seismic software running on a unix OS SUN computer. The resulting data file had 500 counts per volt of input, where a count is the numerical value of a sample in the digitized sine wave.

### **4. Summary**

The monitoring conducted to date has been unable to positively identify the signal of a stimulation source. The monitoring has been able to quantify background noise levels at two different sites, both of which appear approximately equal with about

$10^{-4}$  to  $10^{-5}$  m/s subsurface motion. The level of background noise is important since it will control the radius of influence for a stimulation source. No source can be expected to alter physical properties if the transmitted seismic energy is less than the ambient ground motion. The DRSS source could be easily seen by surface sensors and its impulsive signal was easily used to trigger a recording system, thereby improving monitoring precision. The stacked data from well 32-2 had possible arrivals, but they were not above the noise level. In summary, none of the monitoring wells used at Wellington could observe source generated energy. We believe the distances were too large to observe signal.

The Etrema source could be monitored using a current meter, allowing spectral analysis to search for its swept frequency signal. A possible spectral energy peak was seen, however none of the recordings gave definitive evidence of source generated signal in the monitoring well. Again, the monitoring well was probably too distant to observe source signal.

A monitoring well close to the stimulation source well (100 ft or less) should allow definitive recording of energy levels and estimation of radiation patterns. Unfortunately, well access in a producing oil field is often not optimal. When we successfully measure the subsurface ground motion from a stimulation source, standard attenuation models can be used to estimate the radius of influence from the background noise levels measured in this report. We expect that the background noise levels will vary from field to field (and even within a single oil field), and the radius of influence will vary concurrently.

## **5. Acknowledgements**

We would like to thank Reed Juett of Wave Energy Resources, Mike Frame of AERA for facilitating monitoring. Thanks to Don Lippert, Russel Sell, Jim Dougherty, Ken Williams and John Beck of LBNL for help with field work. This work was funded

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**Figure 1-1.** Spectral content of hydrophone recordings from Wellington field during operation of the DRSS source. Each horizontal color bar is the spectra for one 10 second recording. The recordings are labeled from 33 to 57. The source was off during times 40 to 52. No definitive change in the spectra can be seen during these times.

**Figure 2-1.** Example of background noise at AERA Energy San Ardo site showing seismogram (left), spectra (top right) and unwrapped phase (bottom right). The spectra is in dB, showing most of the energy (within 12 dB) is between 10 and 140 Hz. This data was recorded while the stimulation source was not operating.

**Figure 3-1.** Walkaway survey data from Wellington 35-4. Surface sensor offset from the well head is shown at top (50 to 900 ft.). The dominant arrivals are shown with a line labeled with the moveout velocity. Both arrivals have moveout velocity of surface waves. The zero time is arbitrary because this data did not use triggered recording.

**Figure 4-1.** Borehole recordings from well Wellington 32-2. Each of these five recordings has 4 channels, a three component borehole accelerometer (channels 1-3) and a surface geophone at the source well 35-4 (chan 4). FFIDs 114 and 400 are stacked records with the source running, recorded at 4450 and 4190 ft, respectively. FFIDs 229 and 308 are stacked records with the source not running, recorded at 4450 and 4190, respectively. FFID 500 is a stacked record with the source running, recorded at 500 ft; no stacked noise record was made at this depth. Both 4450 and 4190 source recordings show indications of arrivals at about 725 and 825 ms time, however the amplitude of these is not above the noise records. We believe these arrivals are interesting, but inconclusive and not identifiable as recordings of stimulation source energy propagating in the subsurface.

**Figure 4-2.** Example of surface geophone recording of the DRSS stimulation source at the source wellhead. Seismogram (left) and spectra (right) are for a typical recording. The spectra shows maximum energy (within 12 dB) between 10 and 70 Hz. This source has a clear impulsive signal at the wellhead which was used for triggering the recording system. The walkaway survey (Figure 3-1) demonstrated that this energy was mainly surface waves.

**Figure 5-1a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).

**Figure 5-1b.** Borehole geophone monitor in well 55A-11 for the same 10 s recording as Figure 5-1a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 300 - 400 Hz range which the source was generating. There is increased noise between 180 and 250 Hz.

**Figure 5-2a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).

**Figure 5-2b.** Borehole geophone monitor in well 55A-11 for the same 10 s recording as Figure 5-2a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 200 - 300 Hz range which the source was generating. There is increased noise between 180 and 250 Hz.

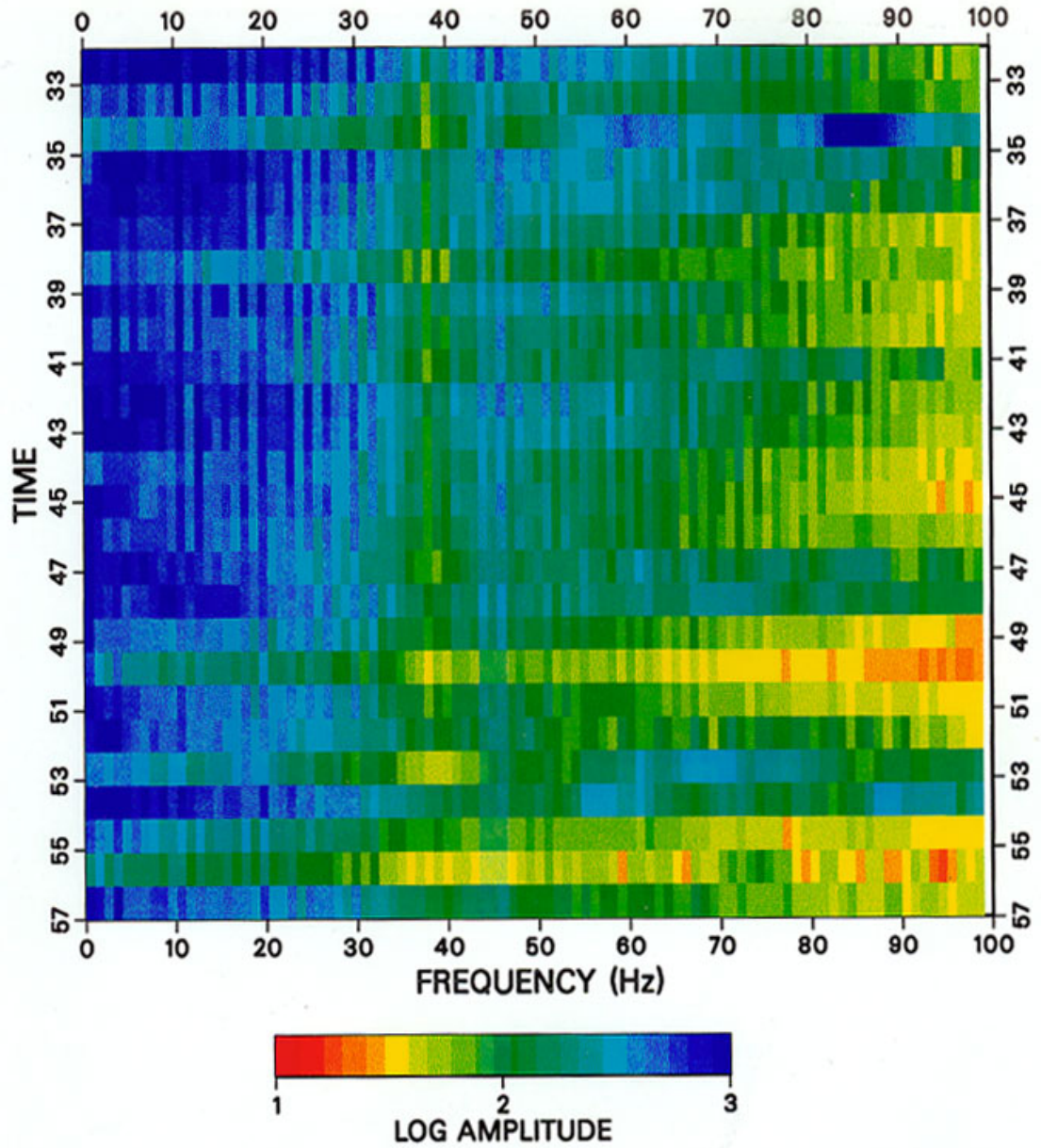
**Figure 5-3a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).

**Figure 5-3b.** Borehole geophone monitor in well 55A-11 for the same 10 s recording as Figure 5-3a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 80 - 190 Hz range which the source was generating. There is increased noise between 180 and 250 Hz.

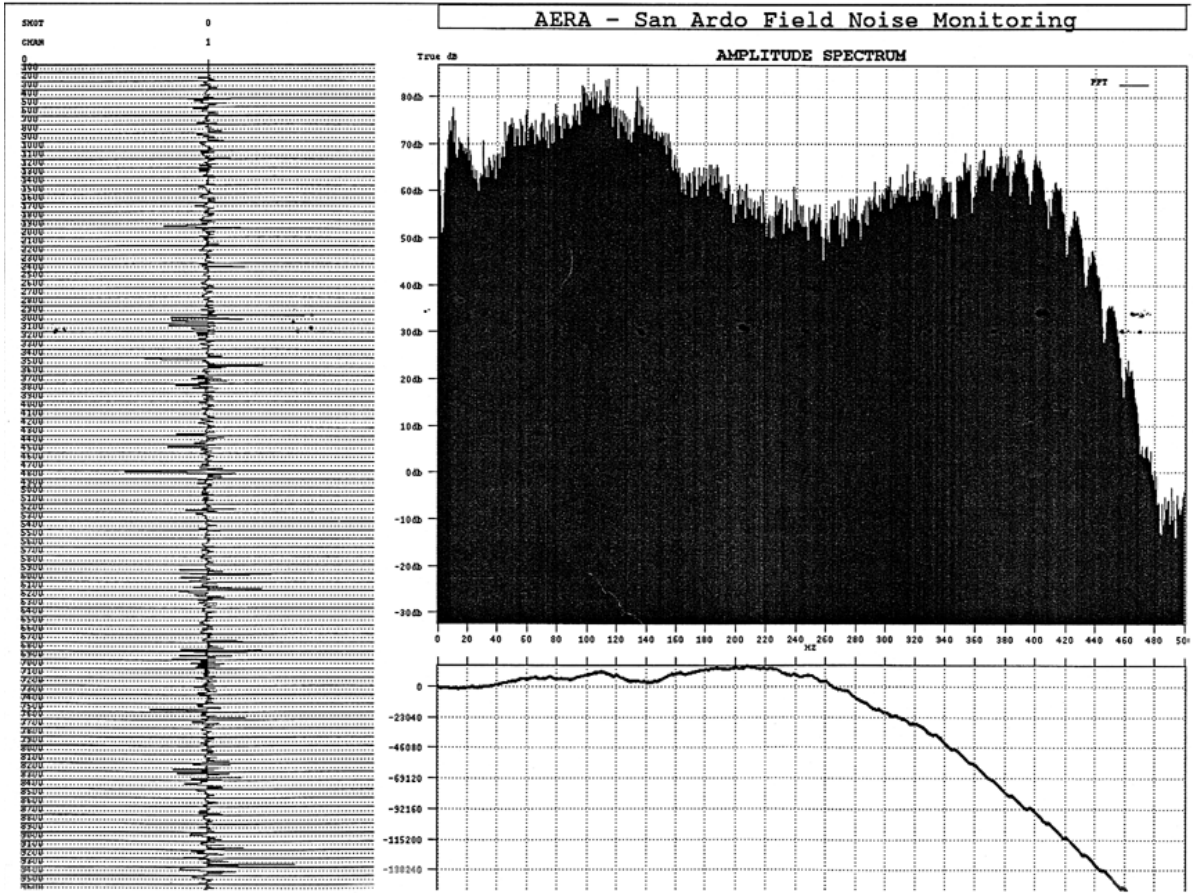
**Figure 5-4a.** Source monitor signal from the Etrema source showing time series (left) and spectral content (right) for a set of 26 10 second recordings made while the source was operating a constant frequency of about 205 Hz.

**Figure 5-4b.** Borehole geophone monitor in well 55A-11 for the same 26 10 s recordings as Figure 5-4a showing seismograms (left) and spectra (right). There is a peak in the spectra at about 205 Hz, however this spike is not above the other spectral peaks and it is within the relatively noisy 180 to 250 Hz band. We do not believe this can be considered evidence of energy generated by the stimulation source.

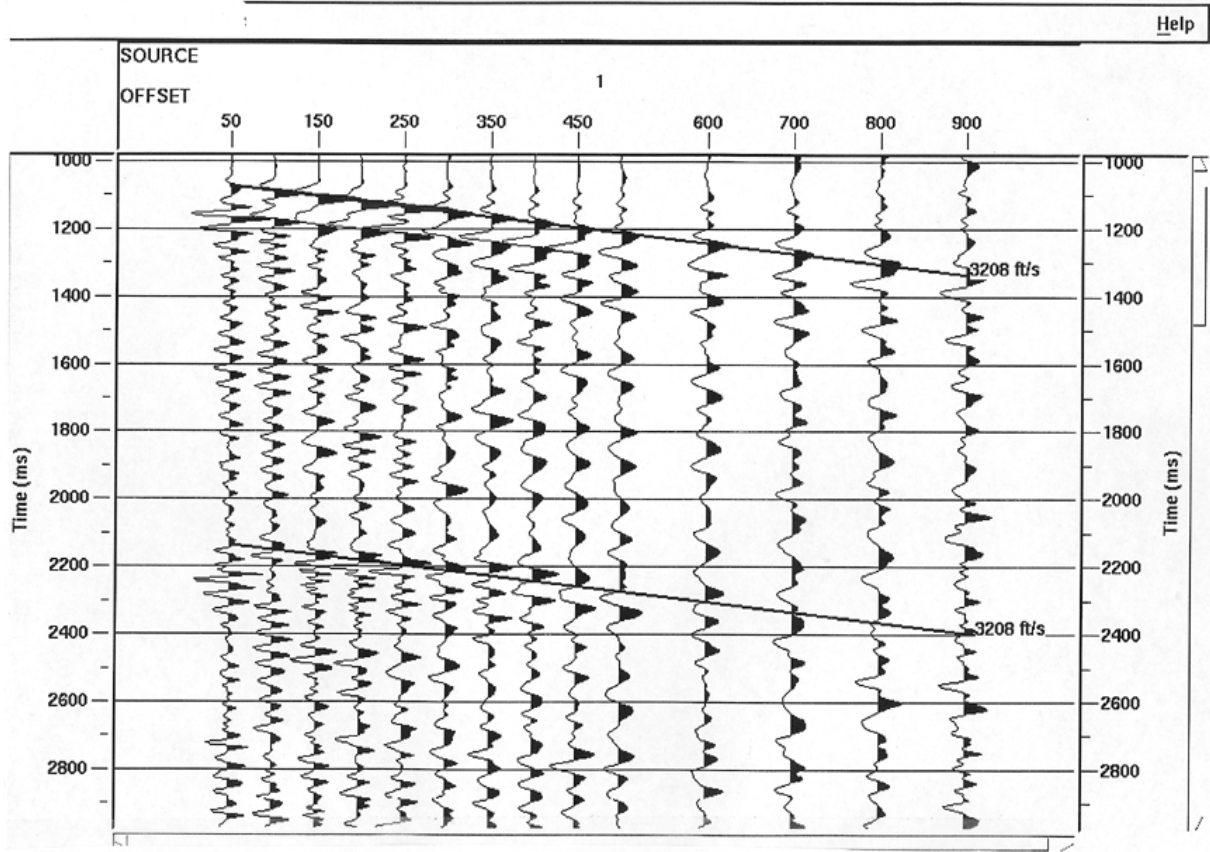




**Figure 1-1.** Spectral content of hydrophone recordings from Wellington field during operation of the DRSS source. Each horizontal color bar is the spectra for one 10 second recording. The recordings are labeled from 33 to 57. The source was off during times 40 to 52. No definitive change in the spectra can be seen during these times.

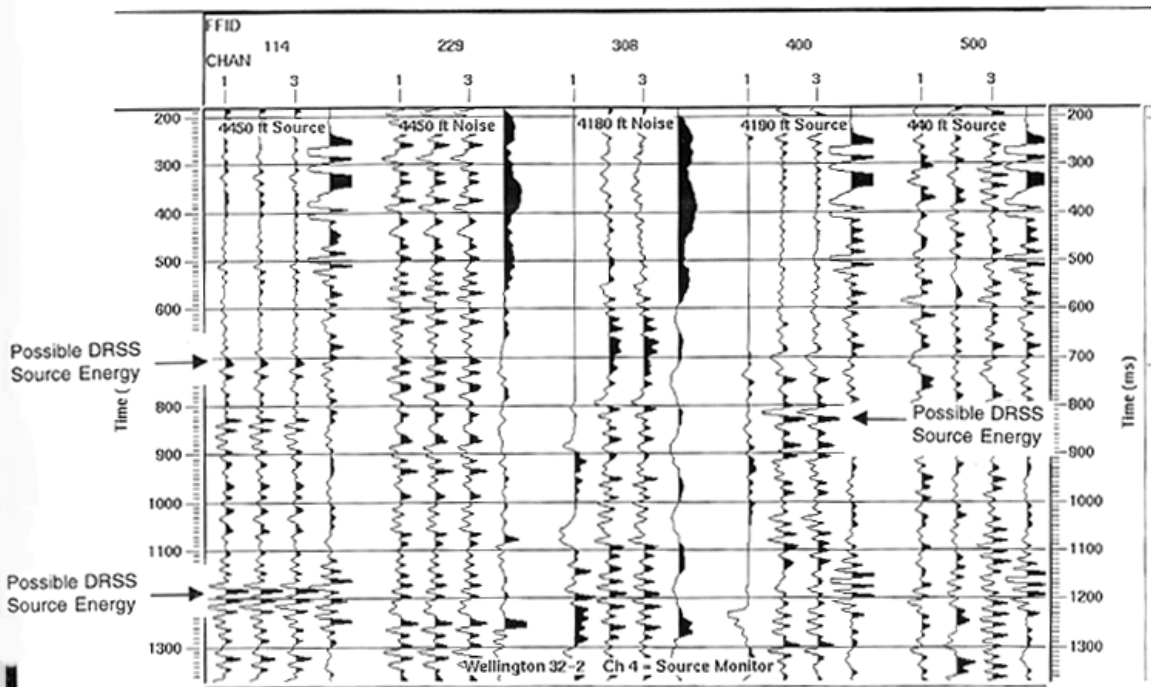


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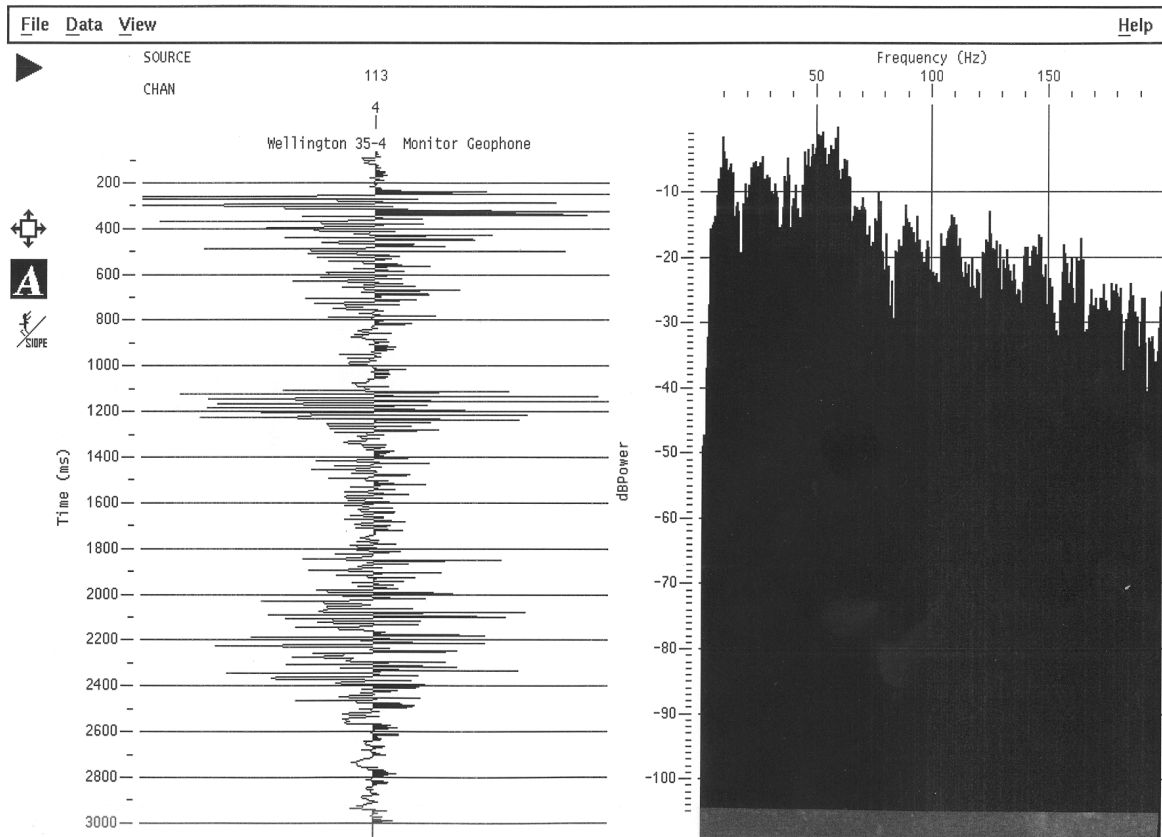


**Figure 3-1.** Walkaway survey data from Wellington 35-4. Surface sensor offset from the well head is shown at top (50 to 900 ft.). The dominant arrivals are shown with a line labeled with the moveout velocity. Both arrivals have moveout velocity of surface waves. The zero time is arbitrary because this data did not use triggered recording.

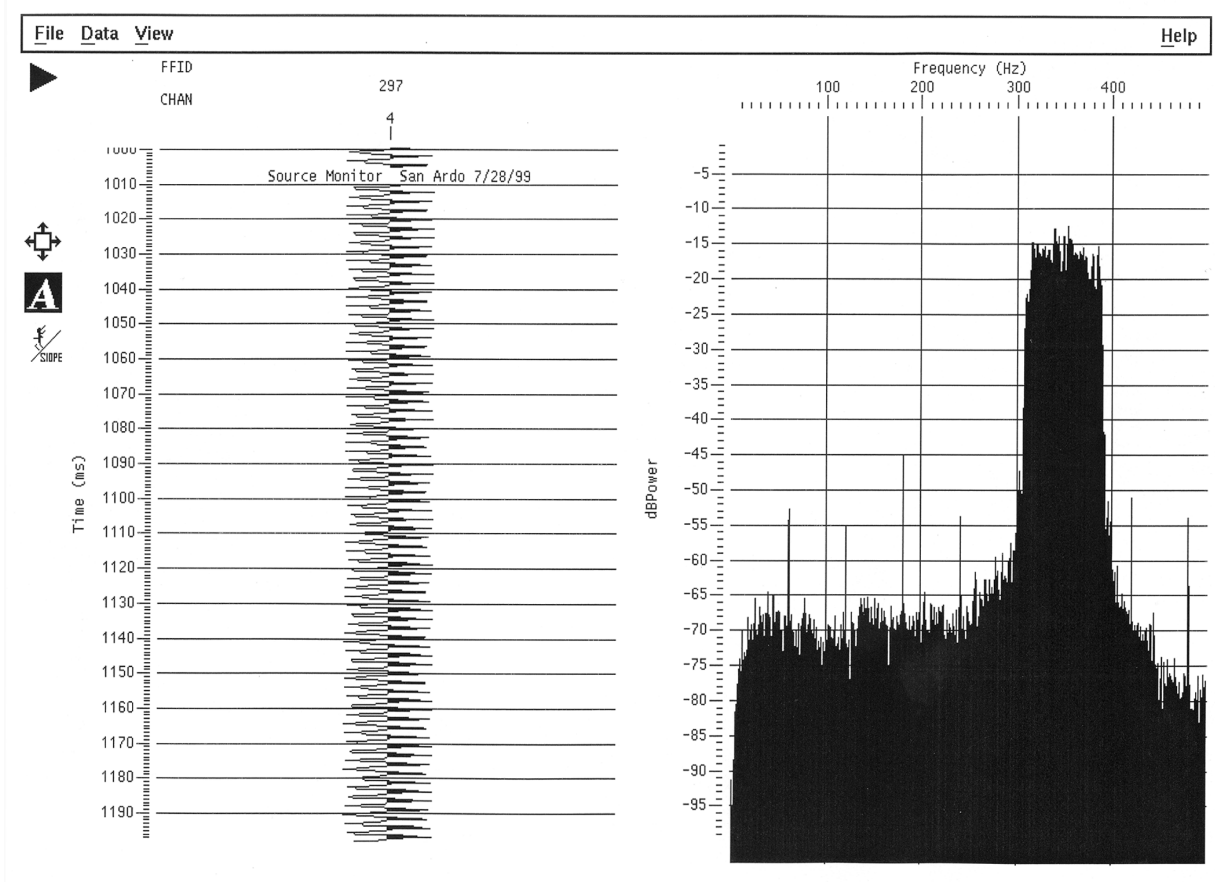
### Wellington #32-2 Stacked Recordings



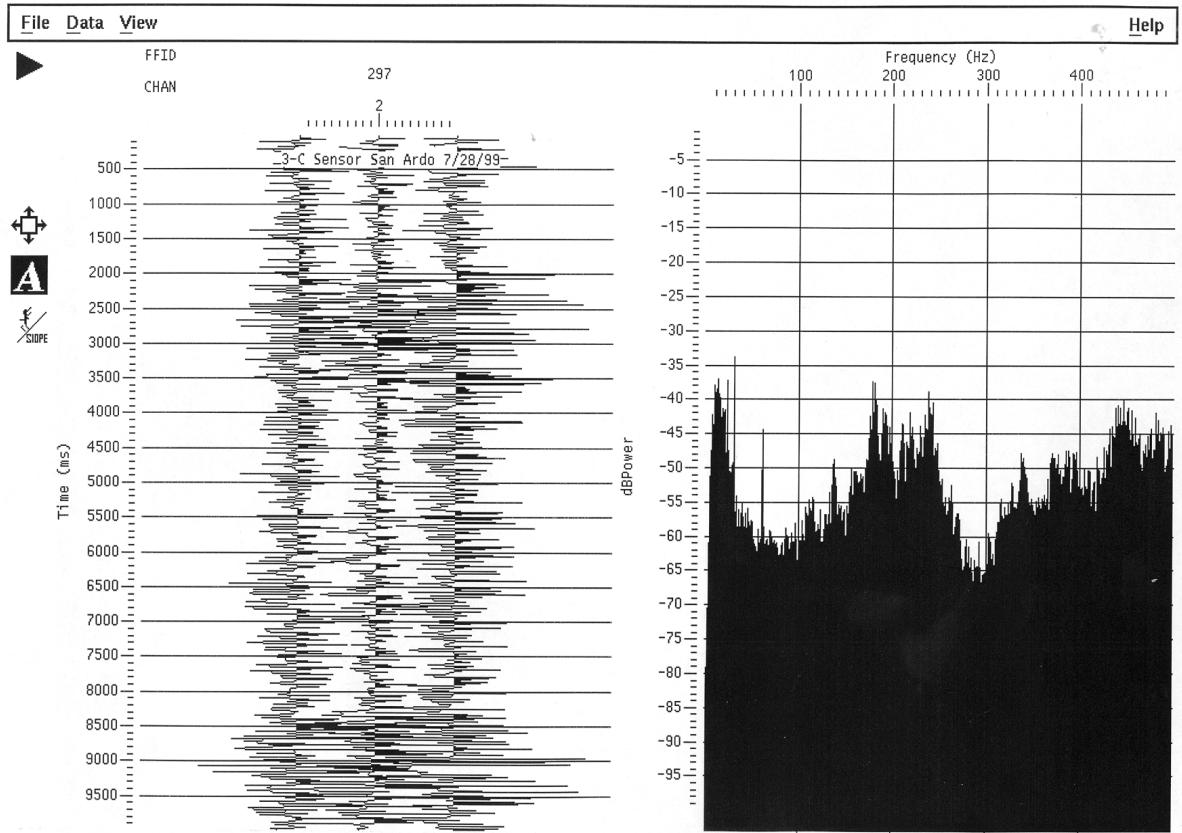
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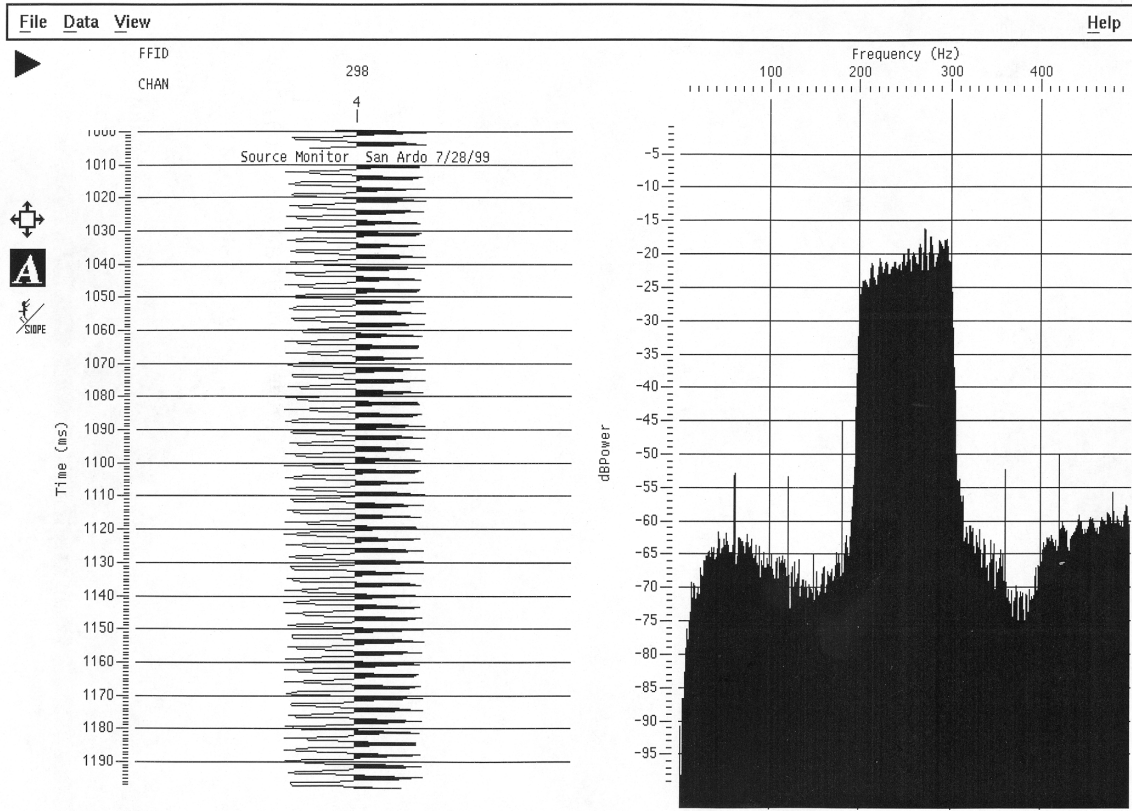
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**Figure 5-1a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).

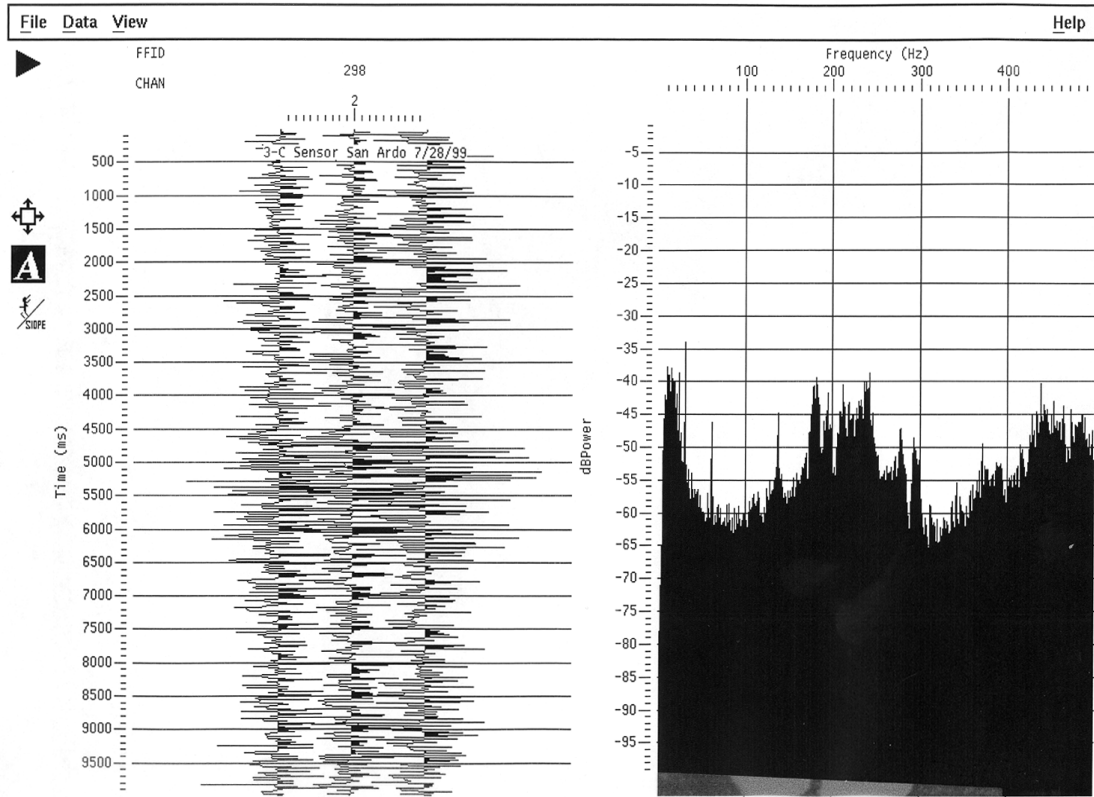


**Figure 5-1b.** Borehole geophone monitor in well 55A-11 for the same 10s recording as Figure 5-1a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 300 – 400 Hz range which the source was generating. There is increased noise between 180 and 250 Hz.

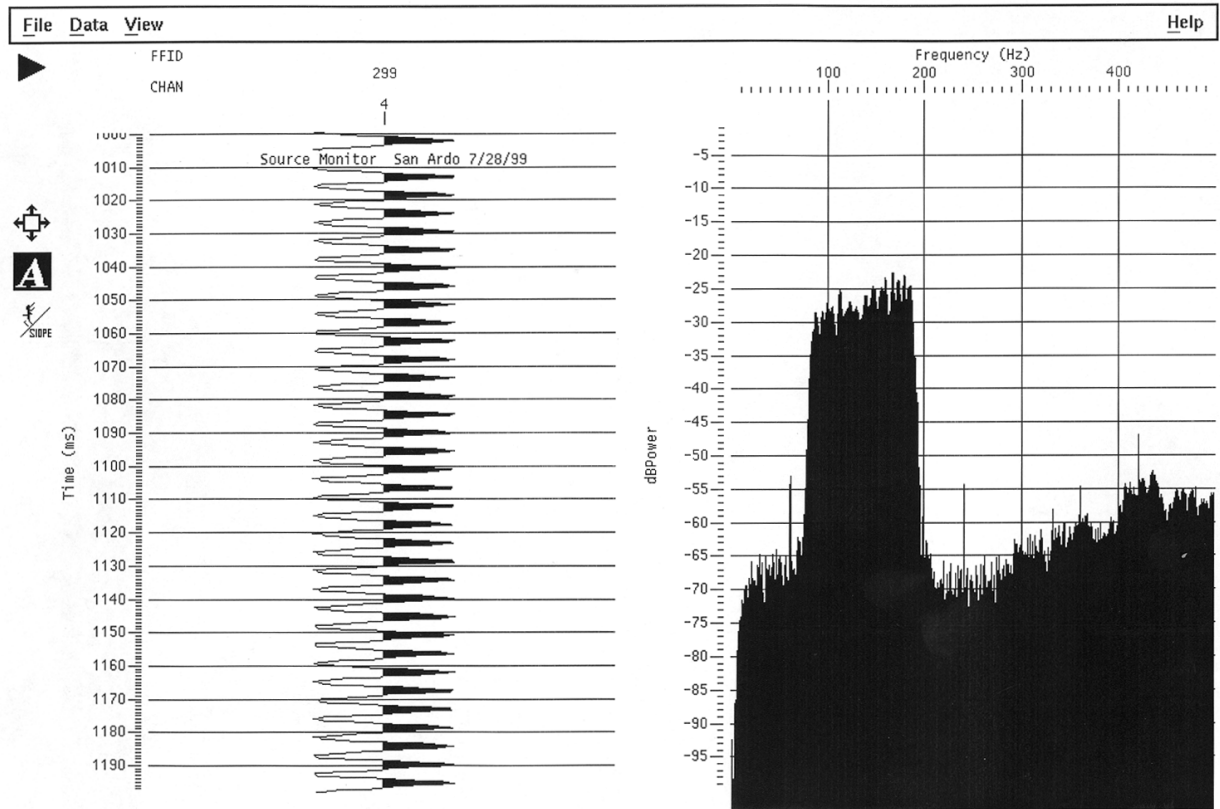


**Figure 5-2a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).

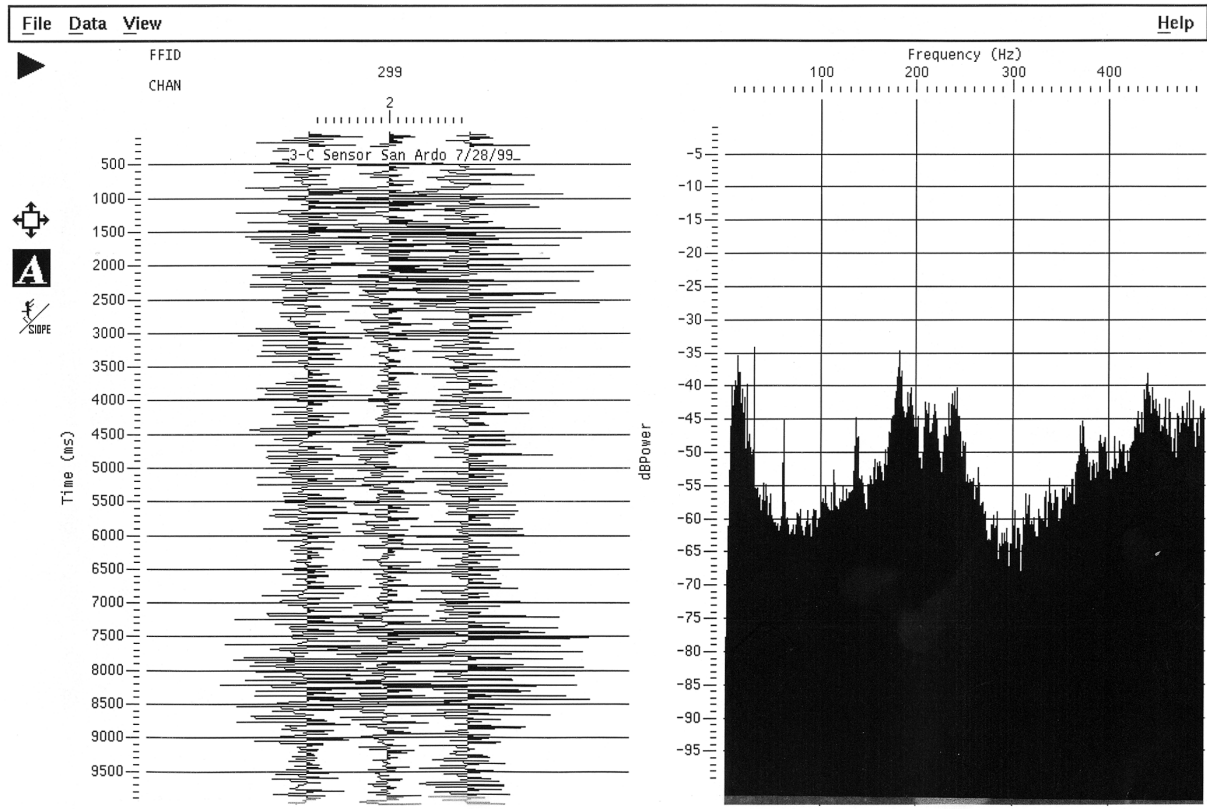




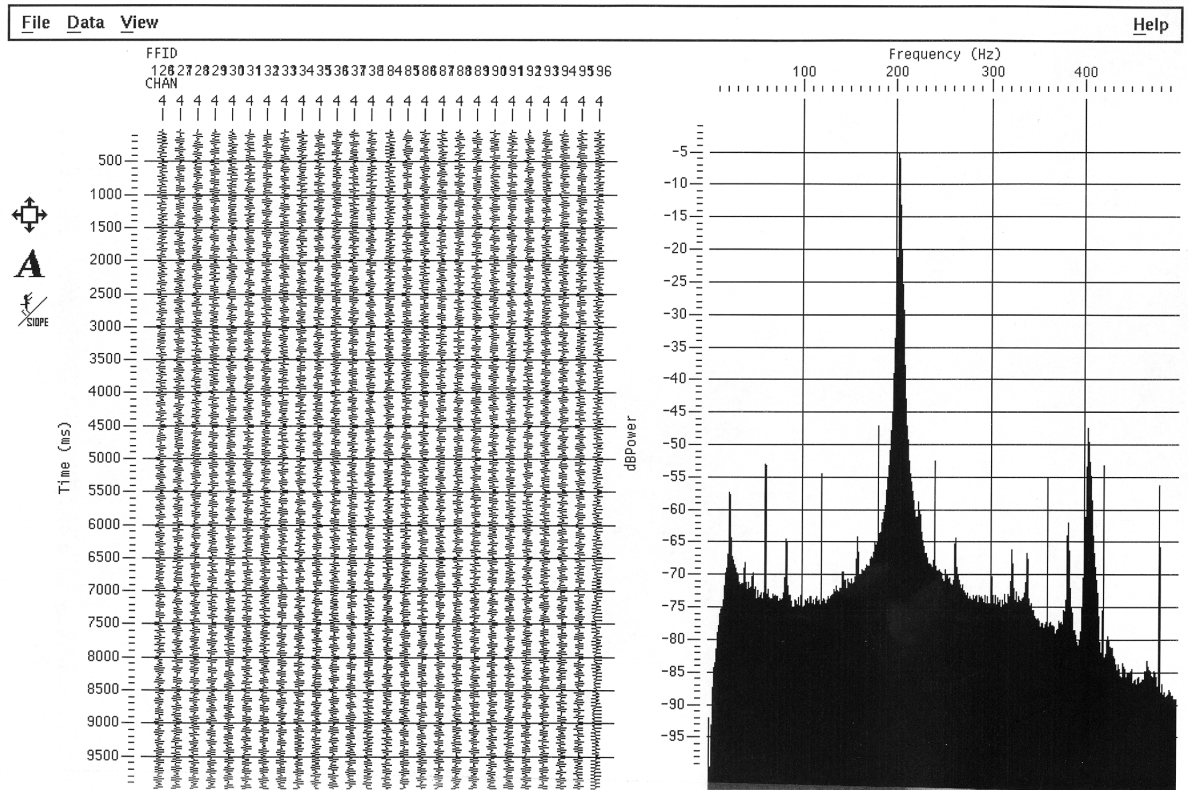
**Figure 5-2b.** Borehole geophone monitor in well 55A-11 for the same 10s recording as Figure 5-2a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 200 – 300 Hz range which the source was generating. There is increased noise between 180 and 250 Hz.



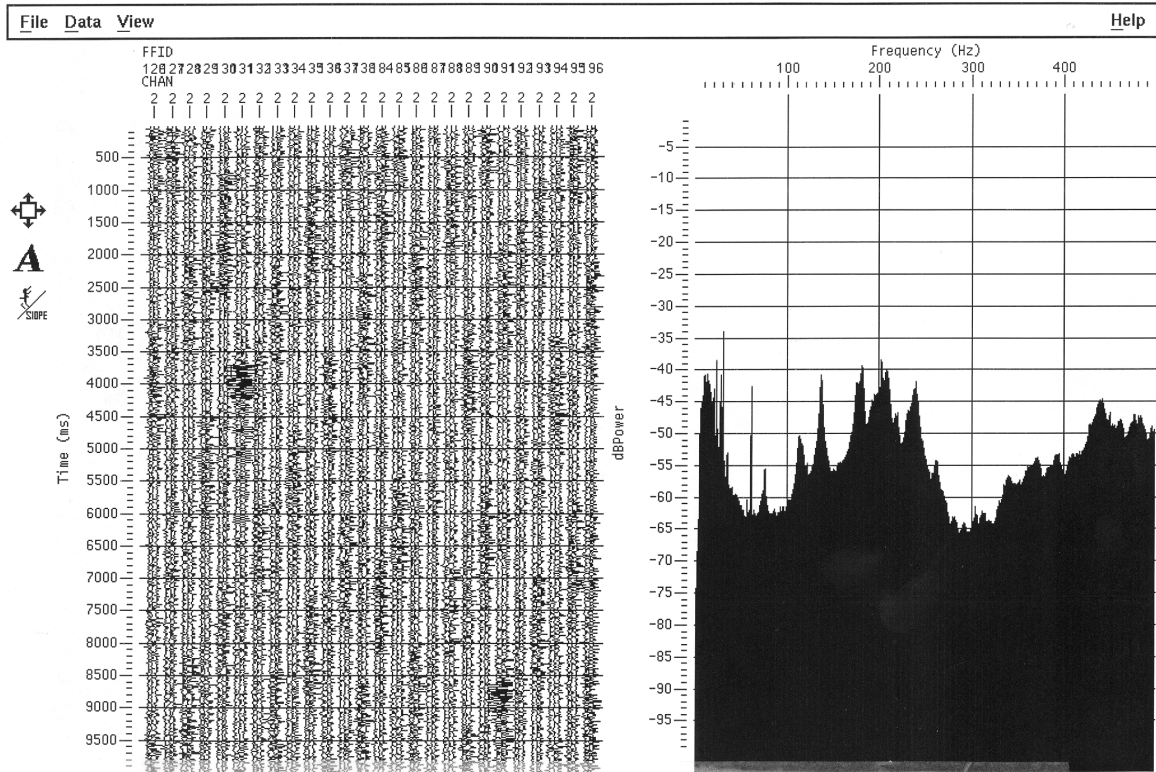
**Figure 5-3a.** Source monitor signal from the Etrema source showing partial time series (left) and spectral content (right).



**Figure 5-3b.** Borehole geophone monitor in well 55A-11 for the same 10s recording as Figure 5-3a showing seismogram (left) and spectra (right). The spectra does not show energy above background in the 80 – 190 Hz range which the source was generating. There is increased noise between 180 and 25 Hz.



**Figure 5-4a.** Source monitor signal from the Etrema source showing time series (left) and spectral content (right) for a set of 26 10 second recordings made while the source was operating a constant frequency of about 205 Hz.



**Figure 5-4b.** Borehole geophone monitor in well 55A-11 for the same 26 10s recordings as Figure 5-4a showing seismograms (left) and spectra (right). There is a peak in the spectra at about 205 Hz, however this spike is not above the other spectral peaks and it is within the relatively noisy 180 to 250 Hz band. We do not believe this can be considered evidence of energy generated by the stimulation source.