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Data Report on the Littleton Quarry Blast Experiment

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This experiment was designed to characterize multiple delay quarry explosions as sources of seismic energy, and was divided into two distinct parts, those being observations in the near and far field. Ground motion resulting from three quarry shots at the Lone Star San-Vel quarry in Littleton, Mass., and from one excavation shot at a construction site in Westford, Mass., was measured. Collaborators from five institutions fielded 27 digital seismographs in five separate arrays for the four shots. The array configurations used for this experiment were: (1) a near field array of accelerometers set up on the quarry property at ranges up to a few hundred meters; (2) a linear array of seismographs at a spacing of approximately 2.5 km extending from the quarry to a distance of 32 km in the direction of Boston College's seismic network station QUA; (3) an azimuthal array of four stations along an arc of a radius of approximately 25 km centered on the quarry; (4) a reproduction of the A and B rings of the NORESS array located 21 km from the quarry; (5) a linear array of four seismographs extending from the quarry to the site of the (cont.)

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Massachusetts Institute of Technology, Cambridge, MA: Faith Guler, George Keough.

Lone Star San-Vel, Littleton, MA: Dennis Lydon.

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Overview

The Littleton Quarry Blast Experiment (LQBE) was designed and implemented to begin the characterization of multiple row quarry explosions as sources of seismic energy. This experiment was divided into two distinct parts. The first dealt with the waveforms as they are observed at regional distances (tens to hundreds of kilometers). The second part was designed to quantify the waveforms in the near-source region (tens to hundreds of meters). The philosophy behind this division was that the near-source data would have minor propagation path contributions and the source could be characterized as broadband. Participants included the Air Force Geophysics Laboratory (AFGL), the Air Force Weapons Laboratory (AFWL), Southern Methodist University (SMU), Massachusetts Institute of Technology (MIT), and Boston College (BC). The experiment took place during the three weeks from 13 to 31 July 1987.

1. MEASUREMENT EQUIPMENT

Ground motion resulting from three quarry shots at the Lone Star San-Vel gravel quarry in Littleton, Massachusetts, and from one excavation shot at a construction site in Westford, Massachusetts, were recorded. Among the collaborators, there were a total of 27 digital recorders, 10 from AFGL, 12 from AFWL, 3 from MIT, and 2 from BC. The number of

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stations that could be installed for any one shot was limited by the number of recorders. Five array configurations were used for this experiment:

--a near field array of accelerometers was deployed by the AFWL/SMU group on the San-Vel premises at ranges on the order of a few hundred meters from the shot.

--a linear array of seismographs was deployed by the AFGL and MIT/BC groups at a spacing of approximately 2.5 km extending approximately 32 km from the San-Vel quarry in the direction of BC's New England Seismic Network (NESN) station QUA.

--an azimuthal array of four seismometers was deployed by the MIT/ BC group on a ring of approximately 25 km radius centered on the quarry.

--a reproduction of the A and B rings of the NORESS array was deployed by the AFGL group at a range of approximately 21 km from the quarry.

--a linear array of four seismographs was deployed by the MIT/BC group along a line extending from the quarry to the NORESS array site.

In addition, refraction data were gathered at each of the stations in the near field array and the NORESS array using portable refraction equipment.

For the shot at the substation excavation site in Westford, Massachusetts, less complete information was provided by Weston Geophysical,, Inc., which was responsible for monitoring the shot.

The Westford Excavation blast EB1

Shot Data:

280 holes, average depth of 30 feet
4 series
30 delays
2 blasting agents: Hydromite and Austinite
280 Brown cap boosters (1/2 lb equivalent of dynamite each)
total of 27,490 lb of explosive, 916 lb/delay
location: latitude = 42 degrees 34.1938 minutes
longitude = 71 degrees 31.6088 minutes
origin time: 19h 25m 00s (approximately, roughly constrained by the second hand of a wristwatch)

Because of the varied nature of the experiment and the number of collaborators, this report will be presented in three sections, each of the contibuting organizations (AFGL/SMU, AFGL, MIT/BC) being responsible for its respective part of the experiment.

2. THE SHOTS

Three San-Vel shots were detonated on 15 July (196d, QB1), 21 July (202d, QB2), and 27 July (209d, QB3). The Westford excavation blast was detonated on 20 July (201d, EB1); however, only the AFGL NORESS array recorded this shot. Essential shot information can be found in the table.

For the shots in the San-Vel quarry in Littleton, Massachusetts, complete information on shot size, geometries, and timing was made available by San-Vel personnel and is included as part of the AFWL/SMU report in Section 1.

Contents

1. Near-Source Data

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This section contains the near-source data from the Littleton Quarry Blast Experiment (LQBE) along with other pertinent information. The regional data were intended to be used to investigate propagation problems in New England and quantify differences between quarry blasts, single explosions, and earthquakes as generators of waveforms. This last goal has direct applications to problems of discrimination and yield determination at regional distances for test-ban treaty monitoring. Unique separation of source and propagation effects at these distances is greatly enhanced with the near-source observations.

1. EXPERIMENTAL DESIGN

The site chosen for the experiment was the San-Vel Quarry in Littleton, Mass., operated by Lonestar. The location is given on the topographic map of Figure 1-1. The quarry outline with coordinates tied to the topographic map is in Figure 1-2. It is located northeast of State Road 110, west of Interstate 495. The north boundary is Spectacle Pond Road; to the northeast is Hartwell Avenue. Numerous homes and business establishments surround the site.

The primary purpose of the near-source array was to characterize the equivalent seismic source. In particular, we wished to quantify the spatial and temporal character of the explosions used to break and excavate the rock. The instrument array utilized in the recording of three shots is given in Figure 1-2. Each triangle is representative of one to three force-balanced accelerometers. The accelerometers were placed as close as 30 m and as far as 350 m from the explosions. Good azimuthal coverage was included so that the spatial character of the source could be constrained. Although not included in this report, full wave refraction data were taken at each receiver to constrain local site effects. A weathered layer between 2-6 m was found at all sites. Local P velocities in the weathered material ranged between 300-1800 m/sec, while below this material was competent rock with velocities between 5000-6000 m/sec. The quarry is located in granite diorite, although other metamorphic rocks are found nearby.

2. EXPLOSION CHARACTERISTICS

One of the unique aspects of the experiment was the fine cooperation given by the quarry superintendent, Dennis Lydon, and the blaster, Todd Harrington. Information about shot size, location, and timing was made available. Shots consisted of several rows of cylindrical charges. A typical single cylindrical charge is depicted in Figure 1-3. The explosive used in all shots was Iregel 1207 with an Engle 400 cap and two 1-lb cast boosters. The drill holes were 60 ft with approximately 4-8.5 ft of stemming to minimize venting and airblast. Each hole used a nonel cap. Explosive weight varied between 328 and 348 lb per hole.

The locations of the three shots within the quarry are included in Figures 1-1 and 1-2. The hole array for shot QB1 is given in Figure 1-4. This array consisted of 69 holes with a burden spacing of 7 ft and a between-hole spacing of 9 ft. The predicted times for the individual holes are given in the figure. Delays of 25 msec between charges in a row and 42 msec between rows were used. A histogram that records the time between consecutive explosions is given in Figure 1-5. The vast majority of delays fall between 8 and 9 msec when the entire explosive array is considered. The total charge in this shot was 23,620 lb.

when the entire explosive array is considered. The total charge in this shot was 23,620 lb. Shot time estimated from the closest station was 18 h 59 min 55.35.01 sec on 9 July 1987. The total duration of the explosive array was 659 msec.

The hole array for shot QB2 (21 July 1987) consisted of 47 holes and is given in Figure 1-6. This explosion was the smallest of the three with a total charge weight of 15,670 lb. The explosive front is bi-directional, unlike the uni-directional propagation recorded for shot 1. Delay times of 17, 25, and 42 msec were used. The shot duration was 296 msec, less than half that of the first shot. Figure 1-7 is a histogram recording the delay times per hole. The majority of times again fall between 8 and 9 msec. Shot time is 15 h 58 min 14.97 sec.

The hole configuration for shot QB3 consisted of 72 holes and is given in Figure 1-8. This shot is the largest, with a total explosive weight of 24,350 lb. The array was detonated at 18 h 13 min 56.22.01 msec on 29 July 1987. Delay times of 25 and 42 msec were used for a total source duration of 684 msec. The histogram of delay times between holes (Figure 1-9) shows again an average time separation of 8 and 90 msec. Like the first shot, the explosive array propagation is uni-directional.

3. INSTRUMENTATION

All instruments were force-balance accelerometers with natural corners at 70 Hz. Above the corner, the instruments behave as a two-pole Butterworth filter. The outputs of the accelerometers were recorded by a Terra-Technology digital event recorder. Three-component data were acquired at 200 samples per sec, using a five-pole anti-aliasing filter at 70 Hz. Twelve-bit data words were recorded.

To check the adeequacy of the anti-alias filters and the bandwidth of the data, single vertical channel data were acquired at 600 samples per sec at station 11 for shot QB1; stations 5, 7, and 11 for shot QB2; and stations 3, 5, and 7 for shot QB3.

4. DATA

Acceleration waveforms along with spectral estimates for each instrument fielded are reproduced in this report. Raw data are available from AFGL/LWH. Two seconds of data are displayed with the vertical scale being g's. The horizontal linear frequency scale runs between 0 and 100 Hz for the 200 sample per sec data (Figures 1-10 through 1-39) and betwen 0 and 300 Hz for the 600 samples per sec data (Figures 1-40 through 1-42). The logarithmic vertical scale has the units of g-sec. The records are identified by: shot--qua1 (15 July), qua2 (21 July), qua3 (29 July); station number in Figure 1-2--St1, St2, . . .; and component--ch1 vertical, ch3 magnetic north, ch2 perpendicular to magnetic north (east).

Figures 1-10 through 1-20 contain the data from shot 1. The data from shot 2 are given in Figures 1-21 through 1-30. The shot 3 data are reproduced in Figures 1-31 through 1-39. Finally, the 600 samples per sec data from all three shots are reproduced in Figures 1-40 through 1-42. Note that all acceleration waveforms have instrument corrections applied.

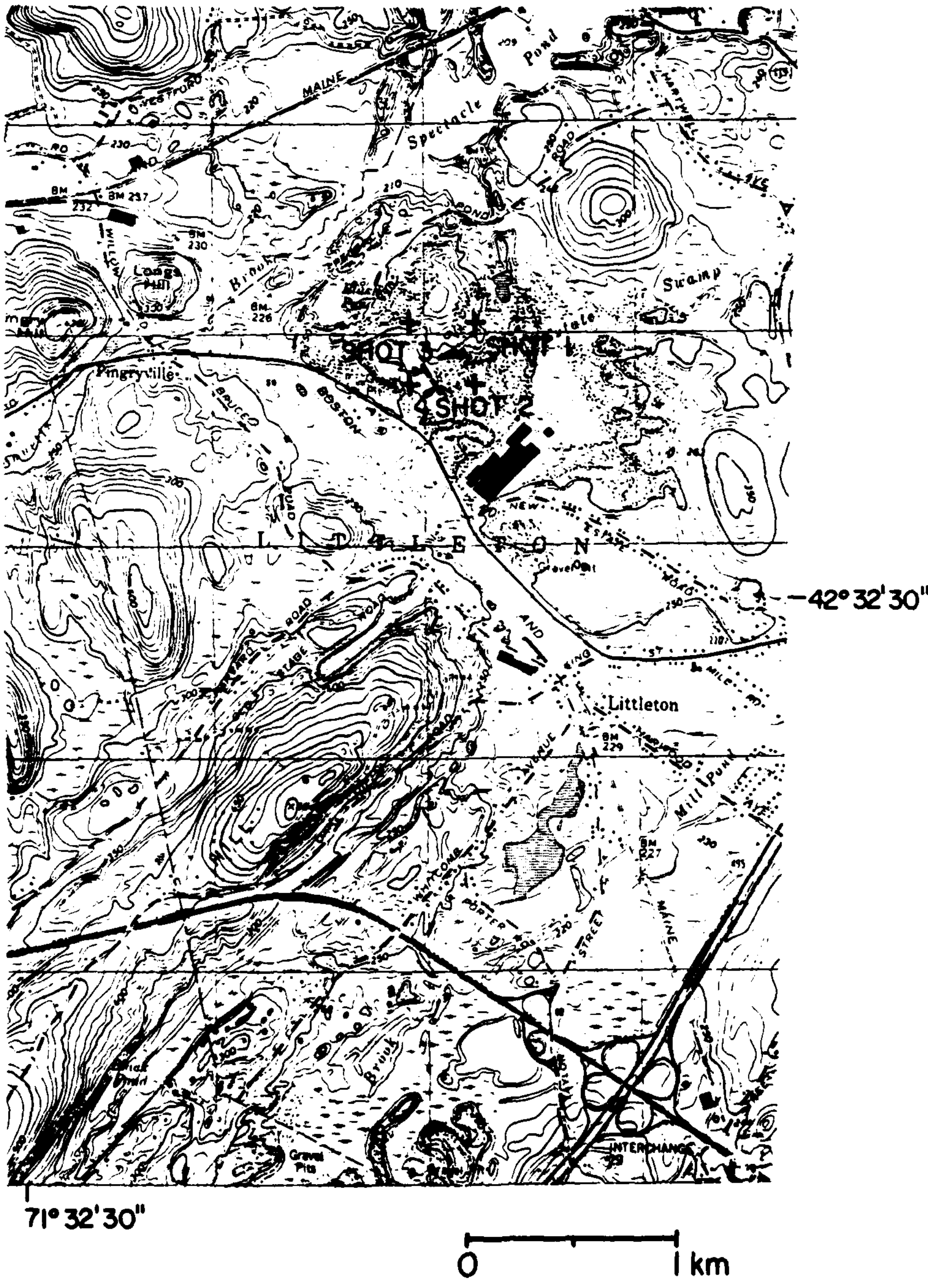


Figure 1-1. Map Showing Lone Star SAN-VEL Quarry. Map taken from U.S. Geologic Survey Ayer topographic quadrangle

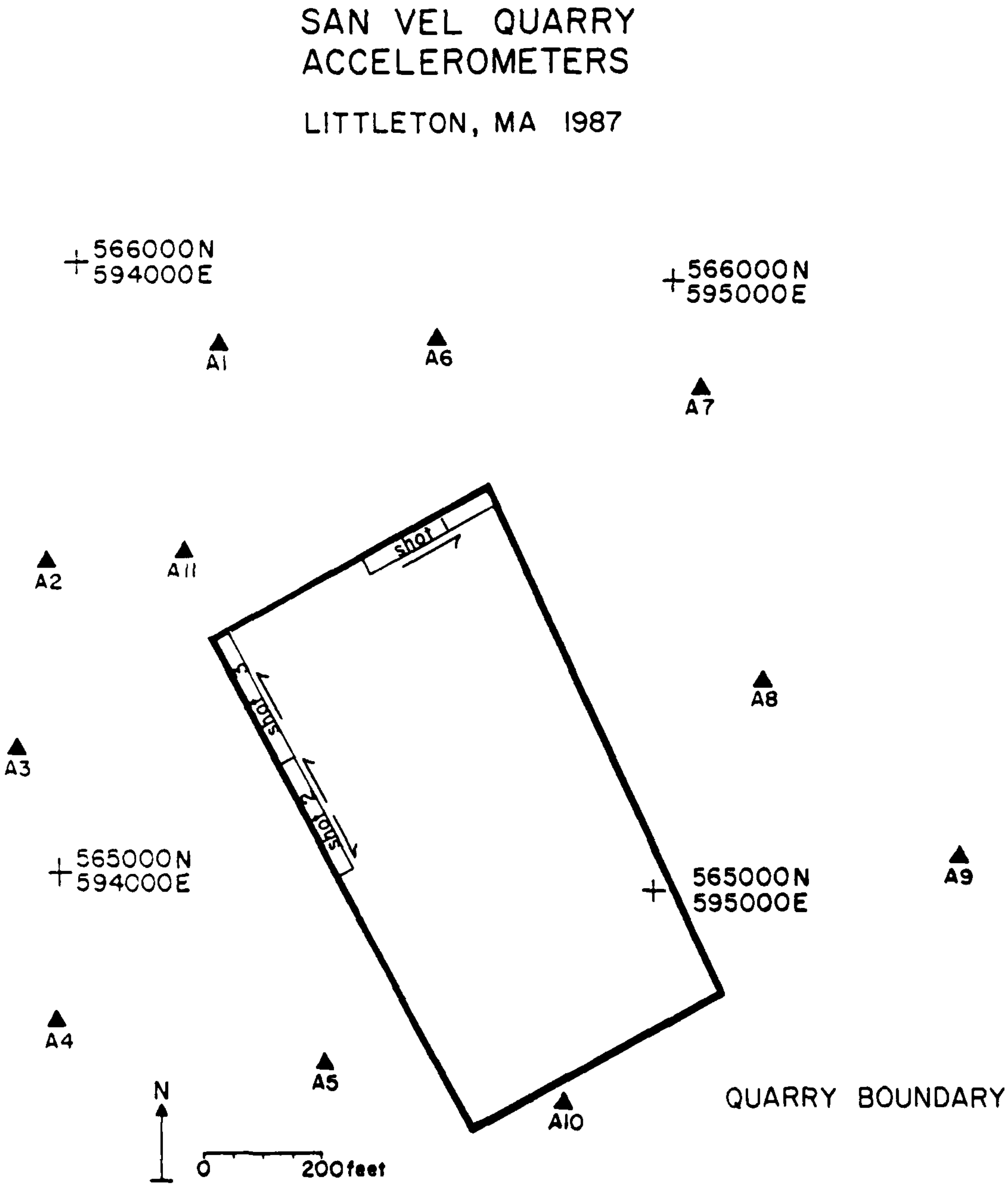


Figure 1-2. Map Showing Gravel Pit, Shot Locations, and Accelerograph Locations. Map also shows coordinates of longitude and latitude that tie down to Figure 1-1

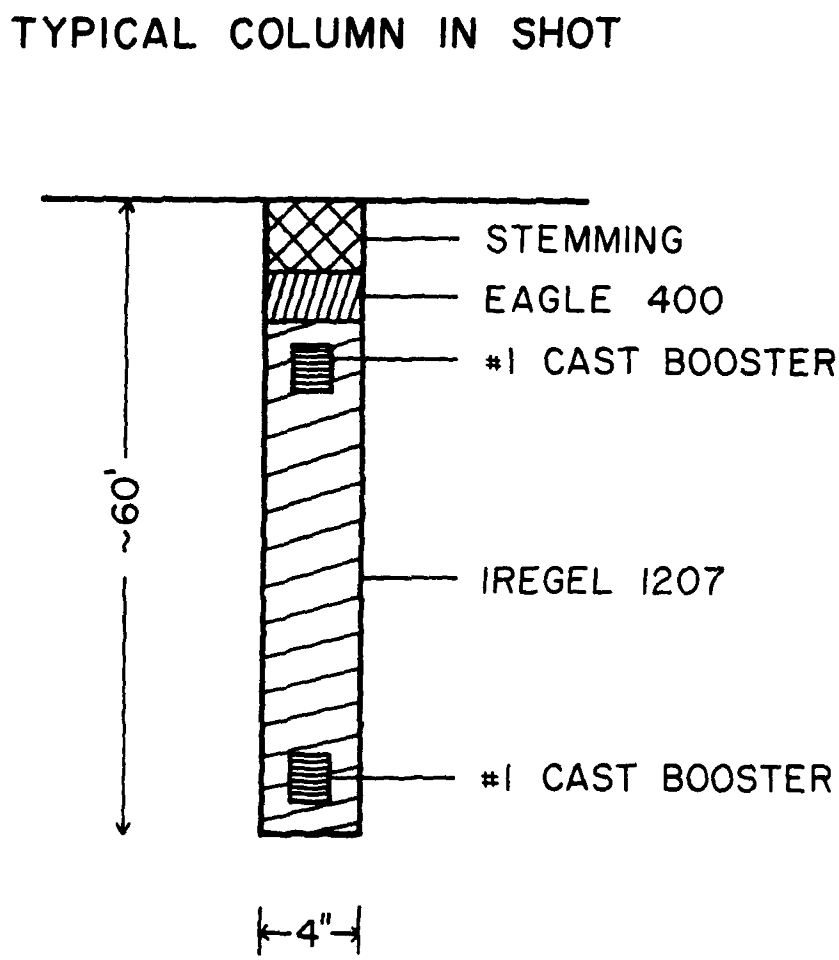


Figure 1-3. Typical Charge Configuration for One Shot Hole

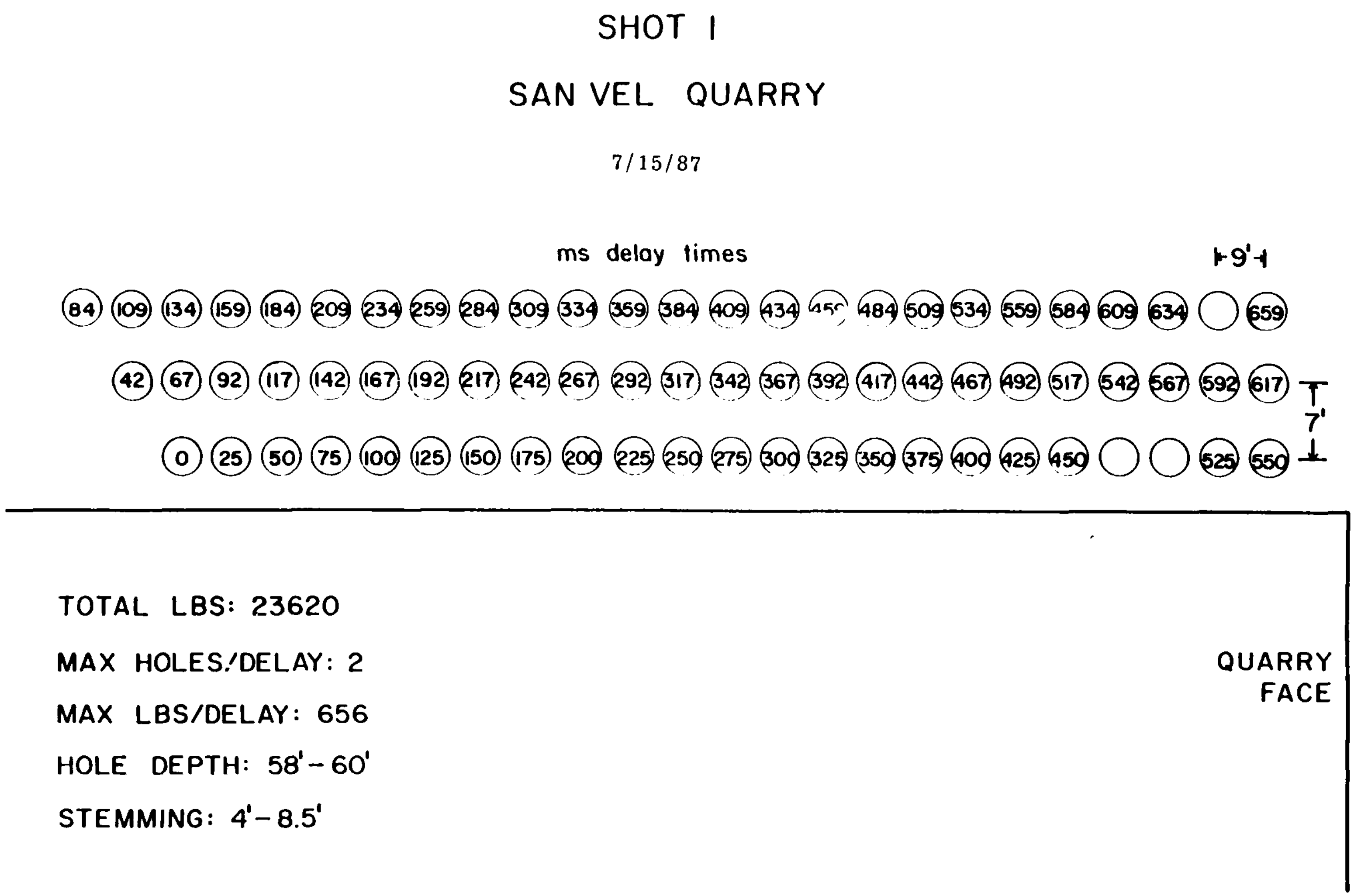


Figure 1-4. Shot Hole Configuration for Shot QB1

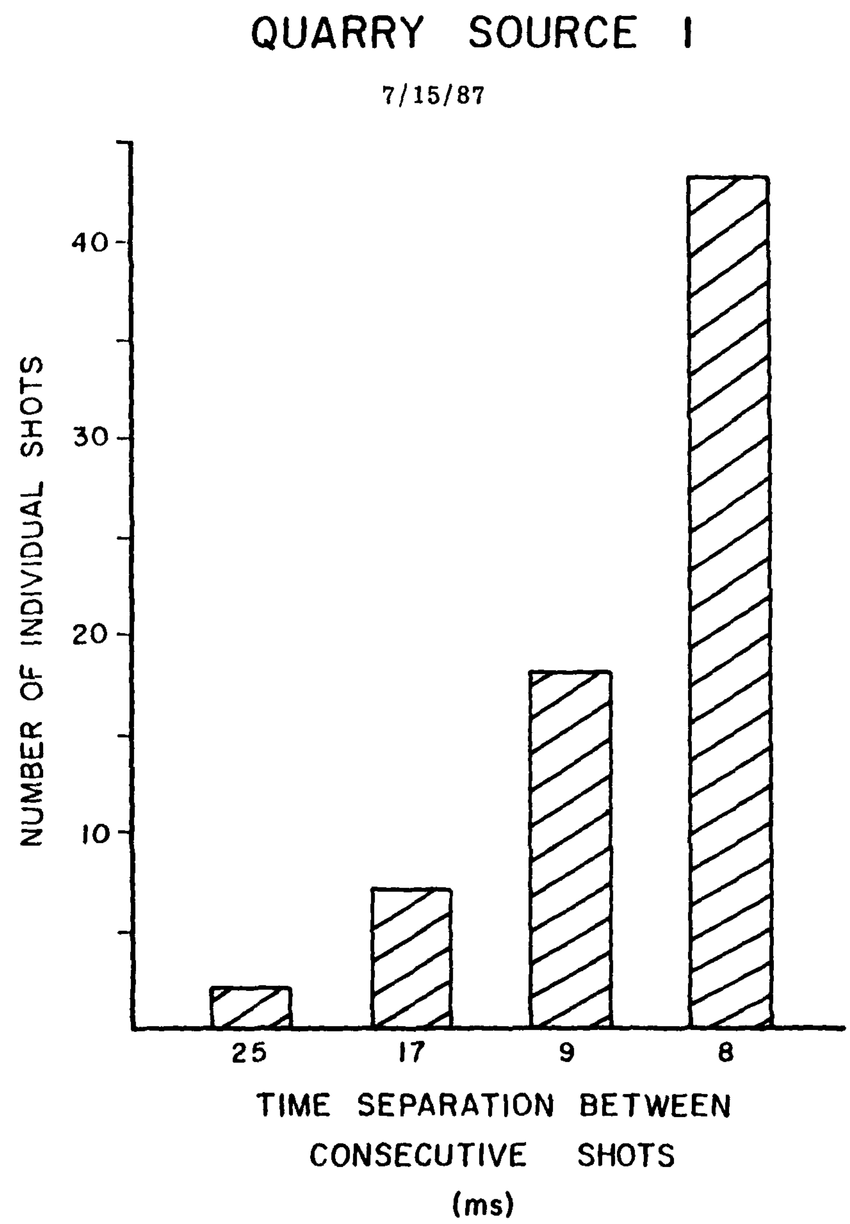


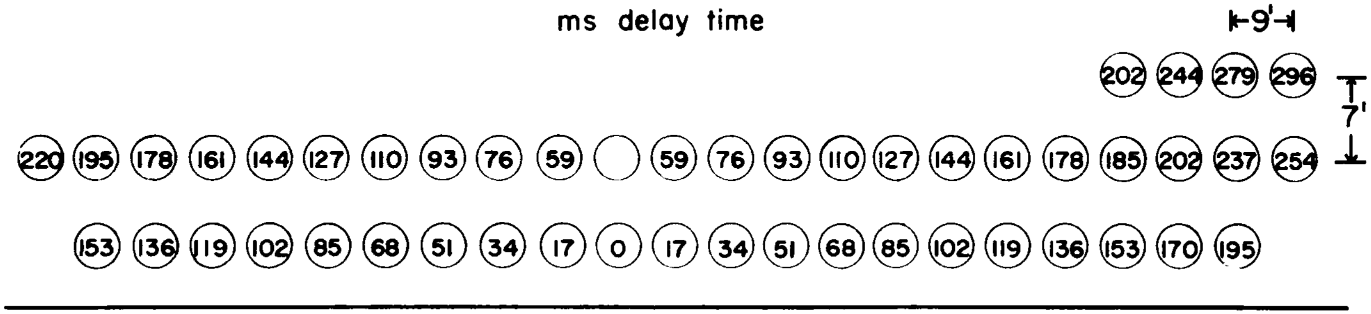
Figure 1-5. Histogram Showing Number of Individual Shots vs Time Separation for Shot QB1

SHOT 2

SAN VEL QUARRY

7/21/87

ms delay time



TOTAL LBS: 15670

MAX HOLES/DELAY: 2

MAX LBS/DELAY: 664.68

HOLE DEPTH: 58'–60'

STEMMING: 4'–8.5'

Figure 1-6. Shot Hole Configuration for QB2

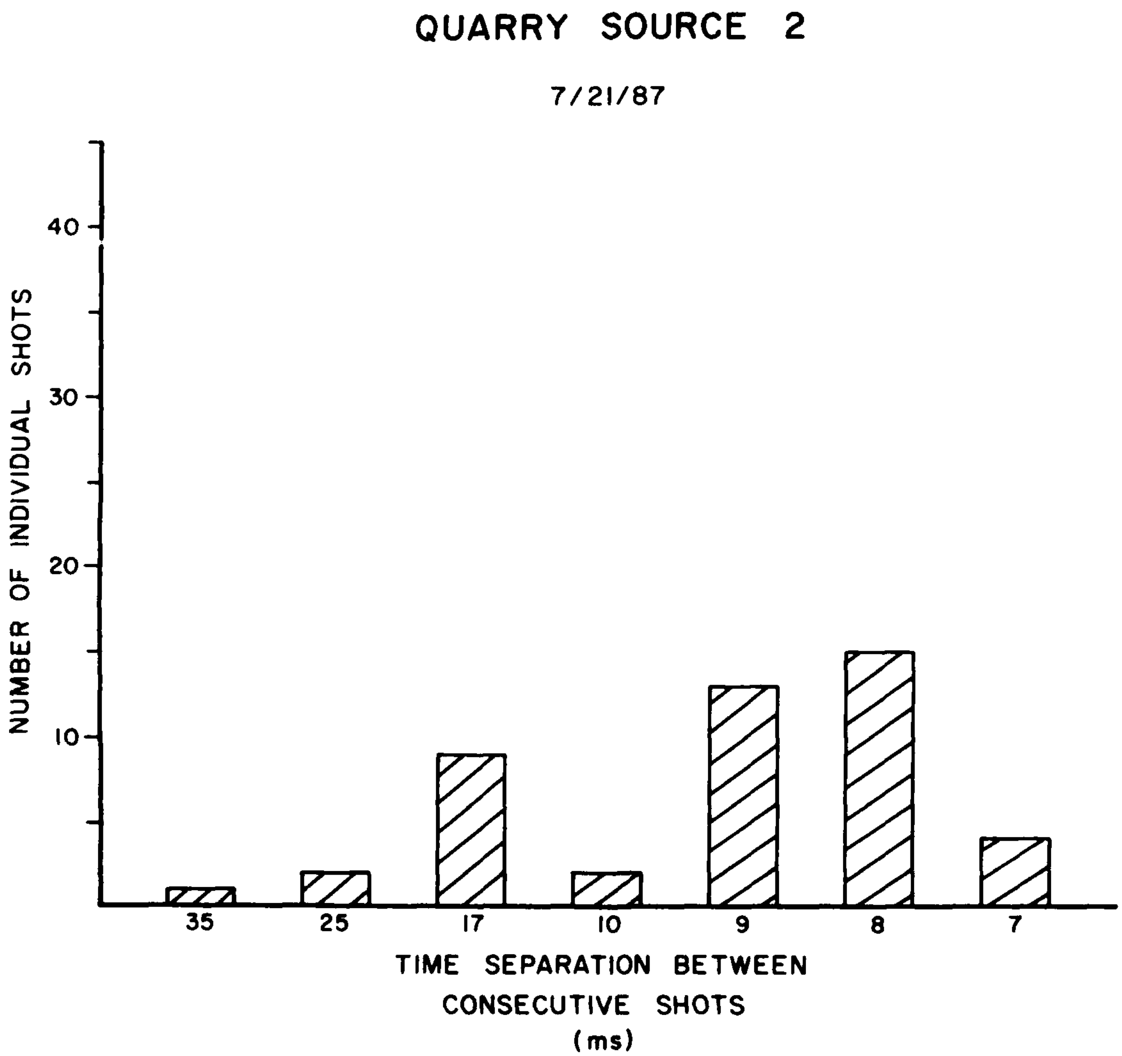


Figure 1-7. Histogram Showing Number of Individual Shots vs Time Separation for Shot QB2

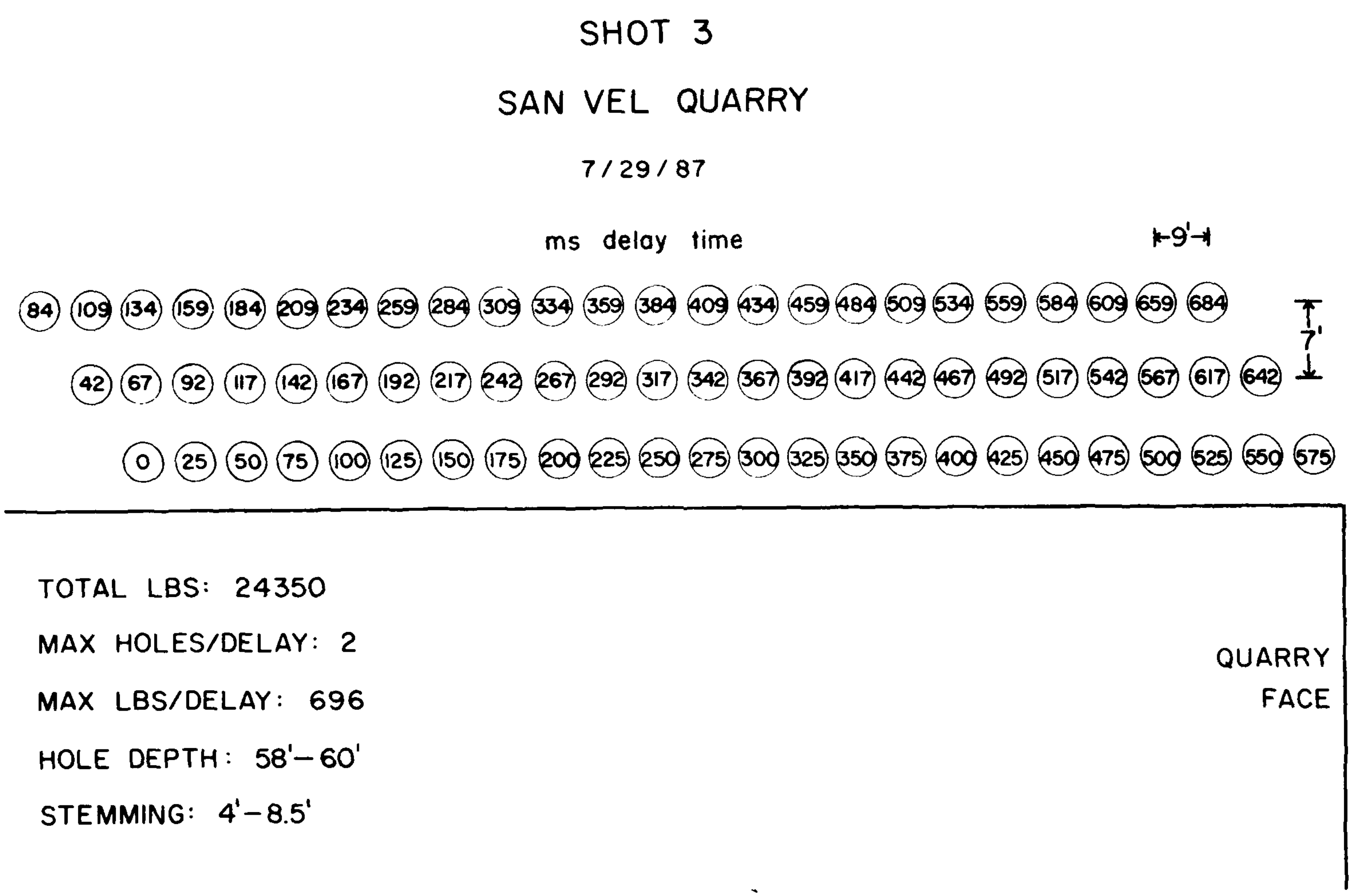


Figure 1-8. Shot Hole Configuration for Shot QB3

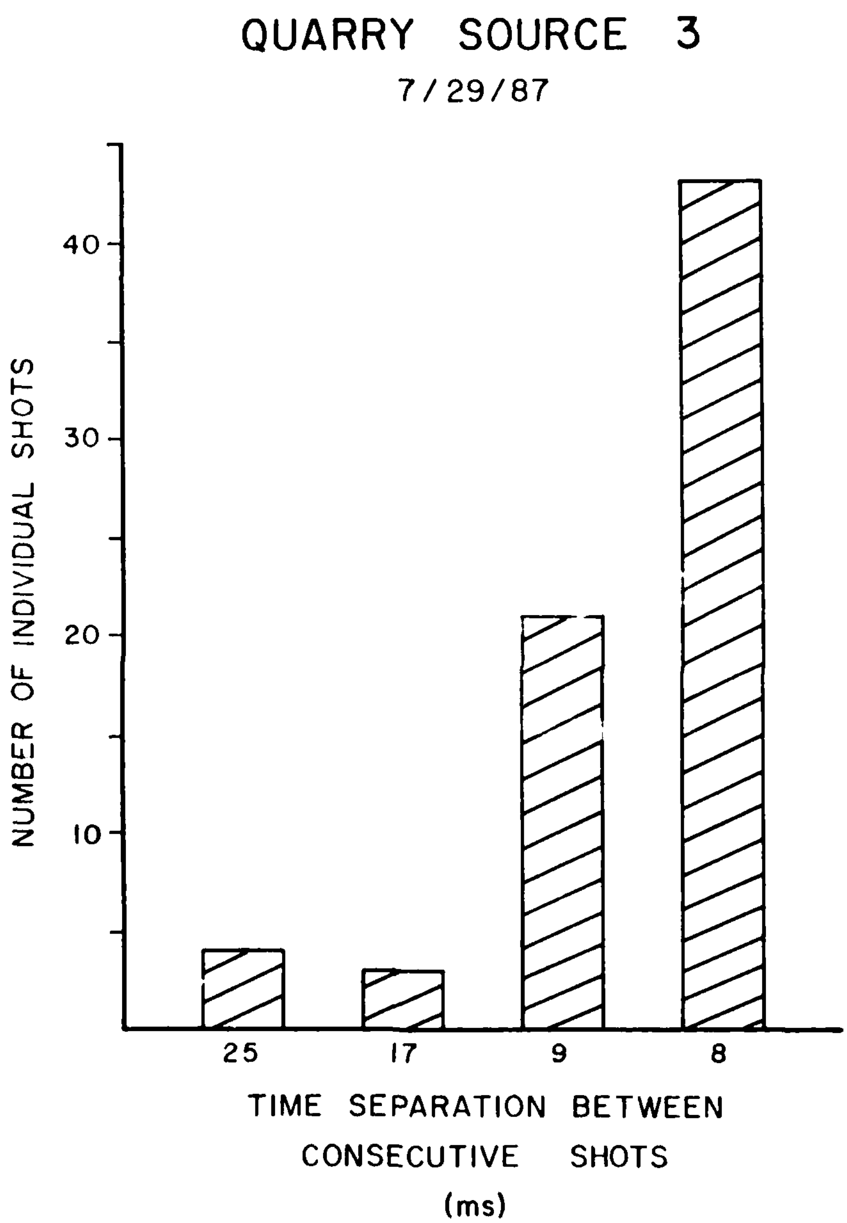


Figure 1-9. Histogram Showing Number of Individual Shots vs Time Separation for Shot QB3

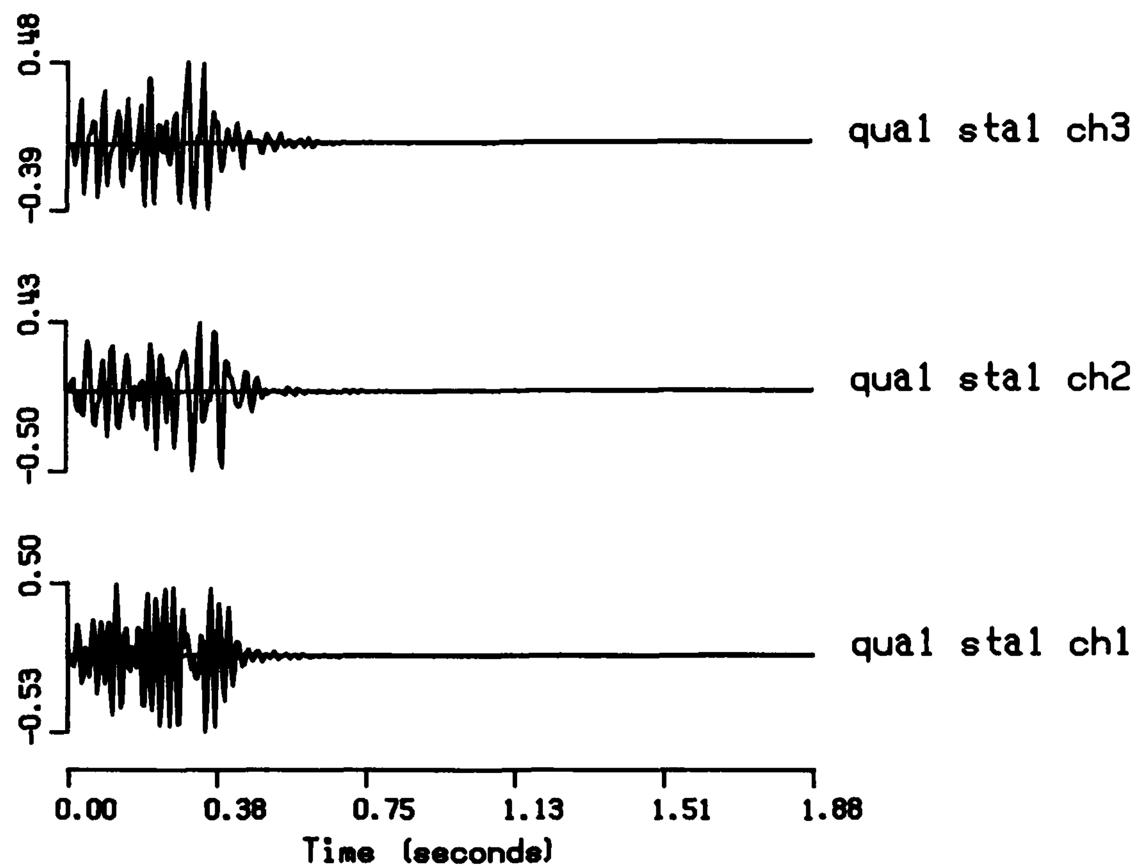


Figure 1-10. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A1 at 200 Samples/Sec. Maximum amplitudes, in g's, are shown at left. Time following shot origin time is shown along bottom of plot

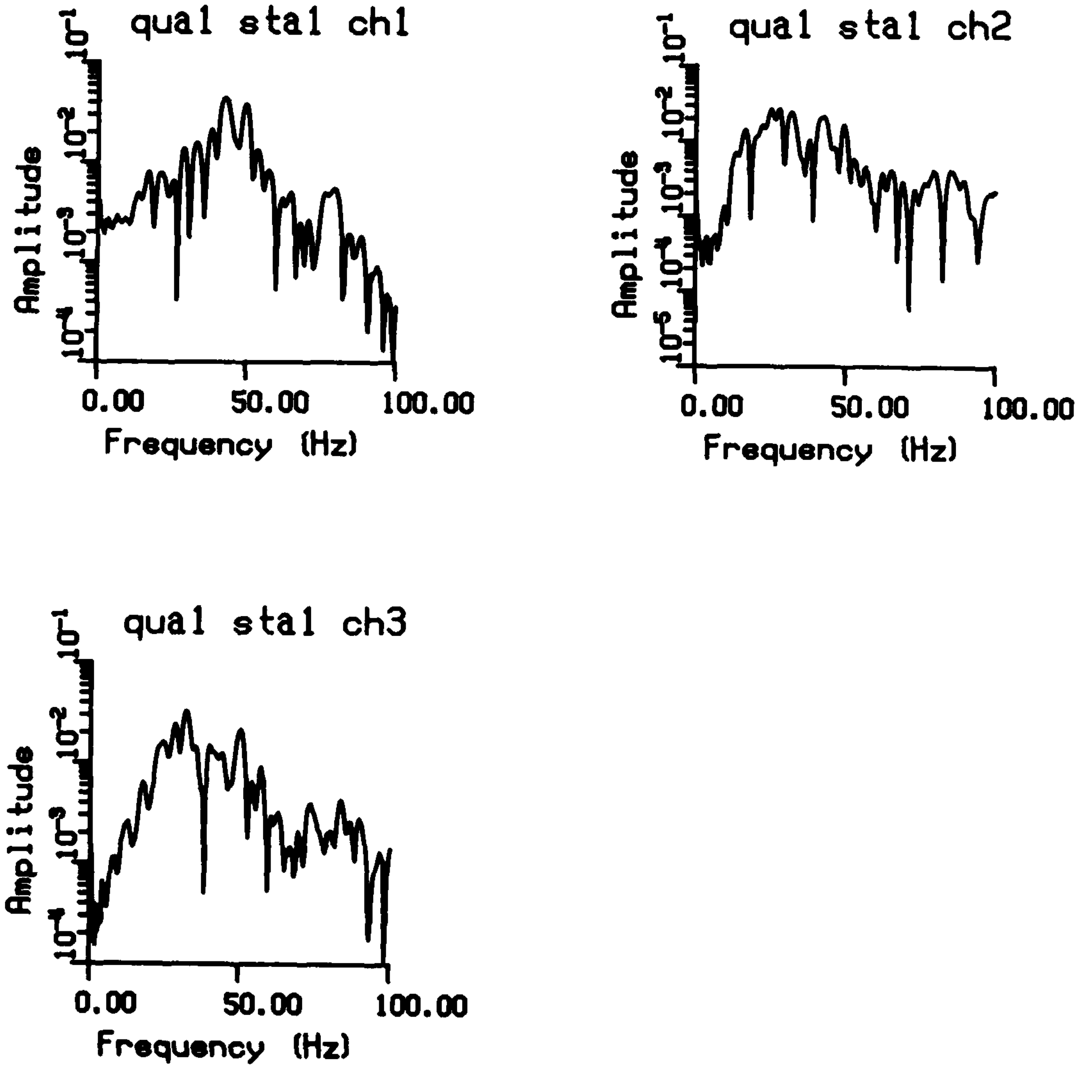


Figure 1-10. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A1. Linear horizontal scale shows frequency from 0 to 100 Hz. Logarithmic vertical scale shows amplitude from 1.0E-5 to 1.0E-1 g-sec

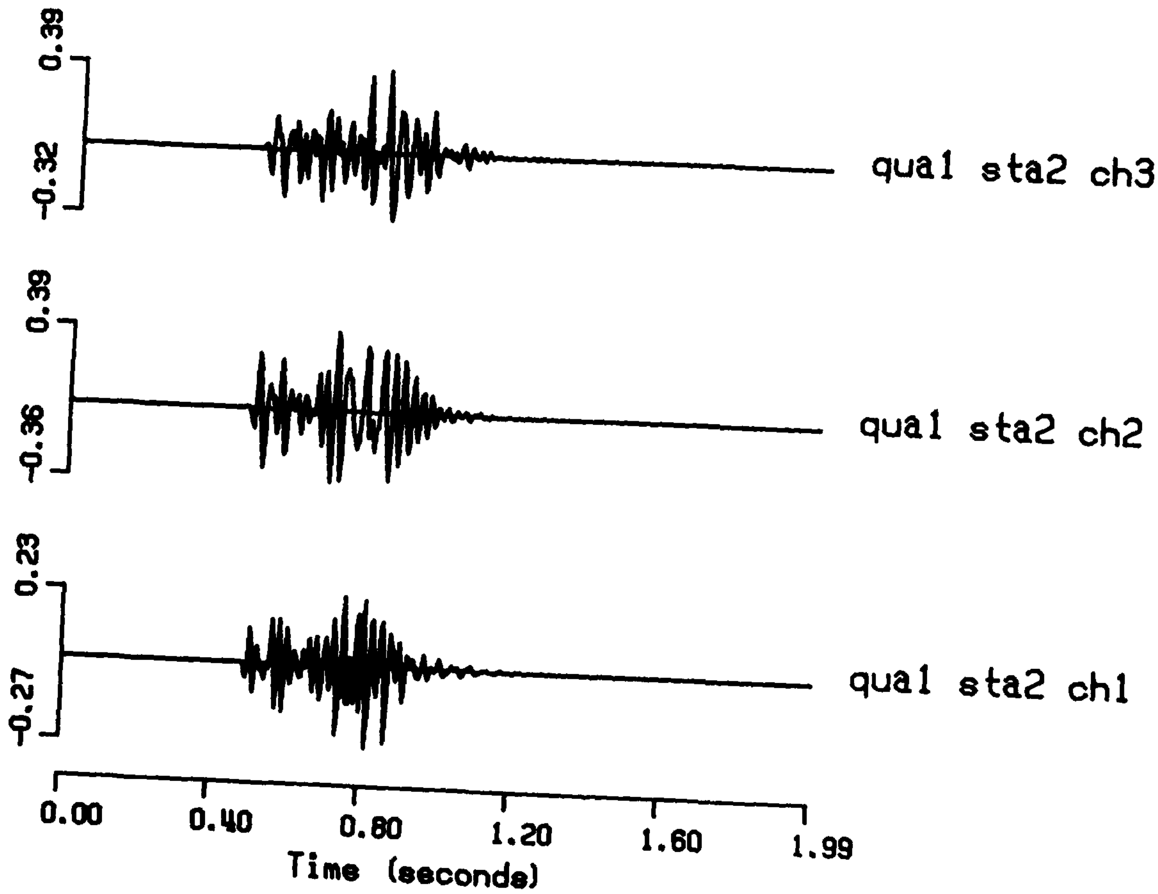


Figure 1-11. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A2. See Figure 1-10a.

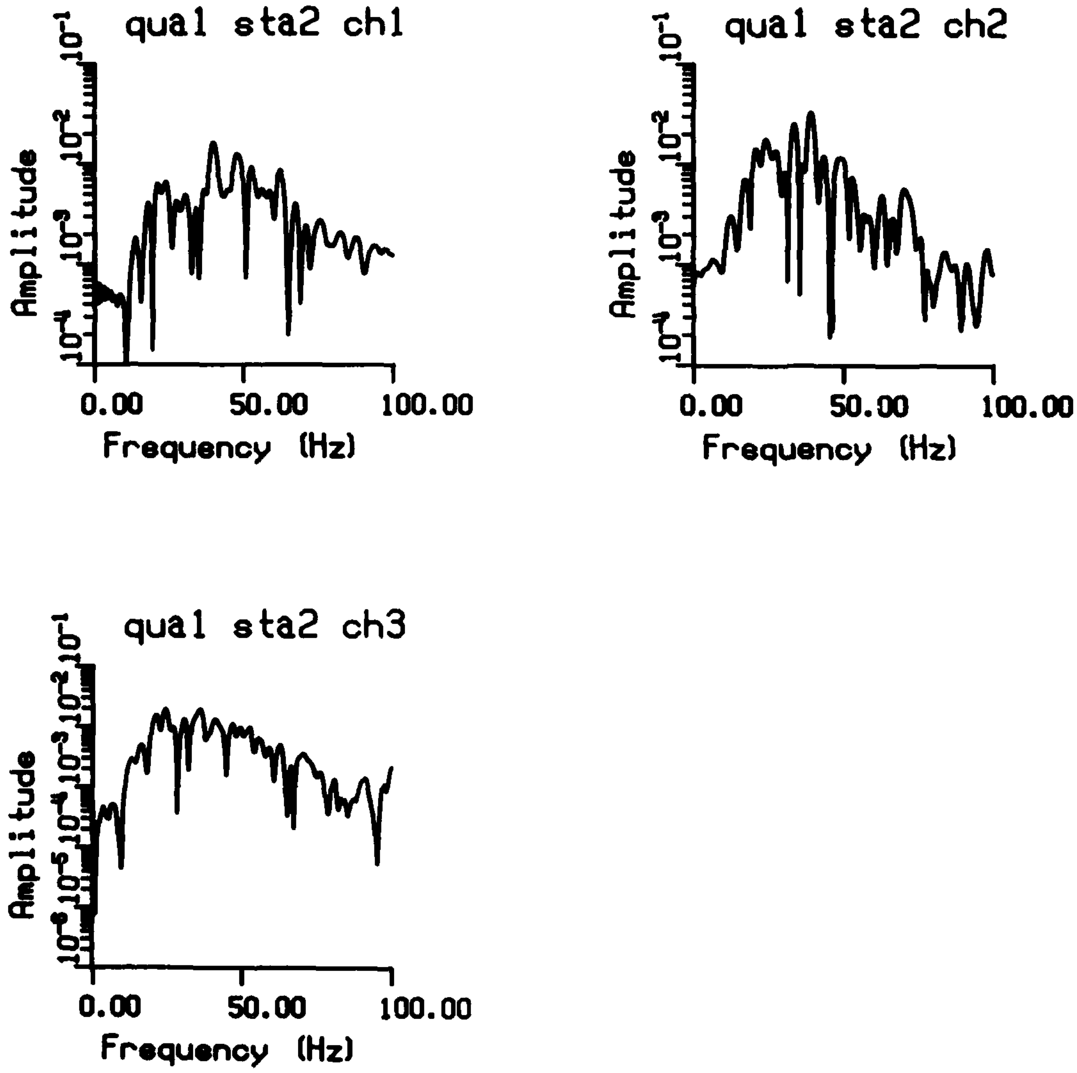


Figure 1-11. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A2. See Figure 1-10b

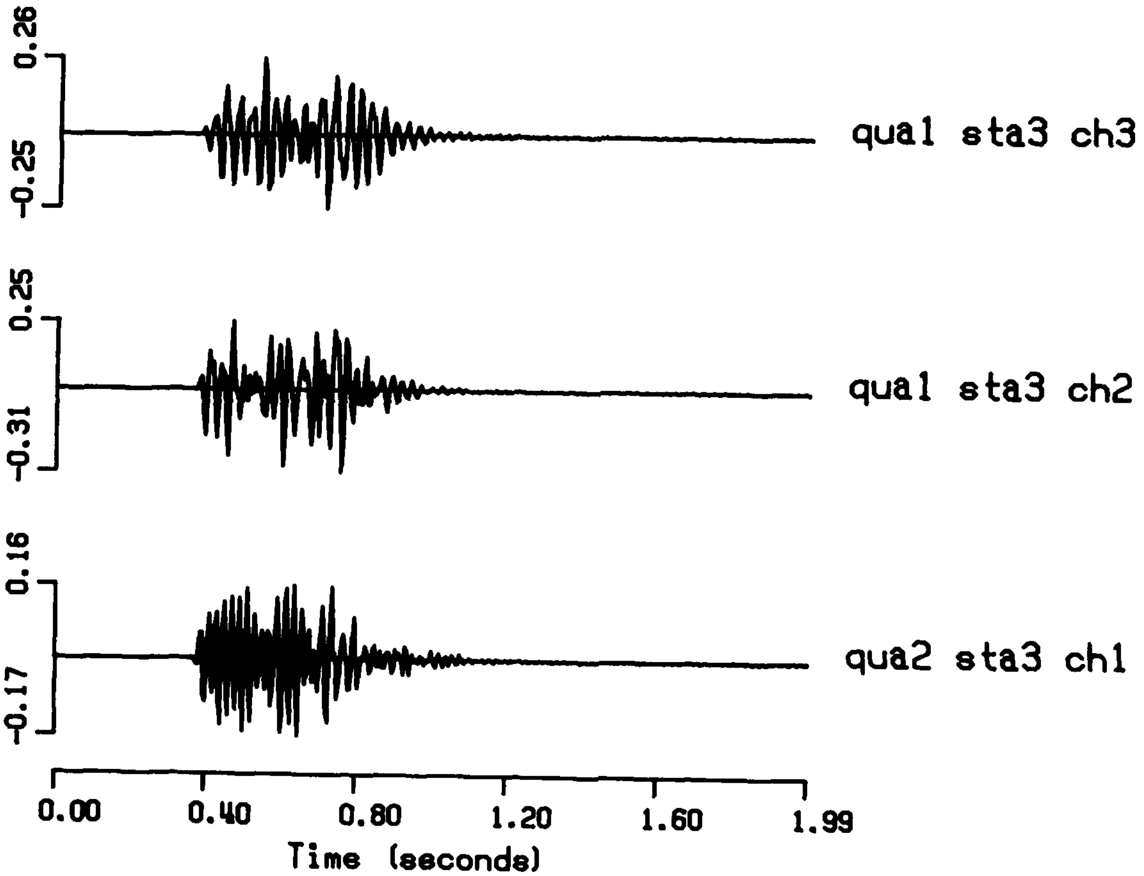


Figure 1-12. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A3. See Figure 1-10a.

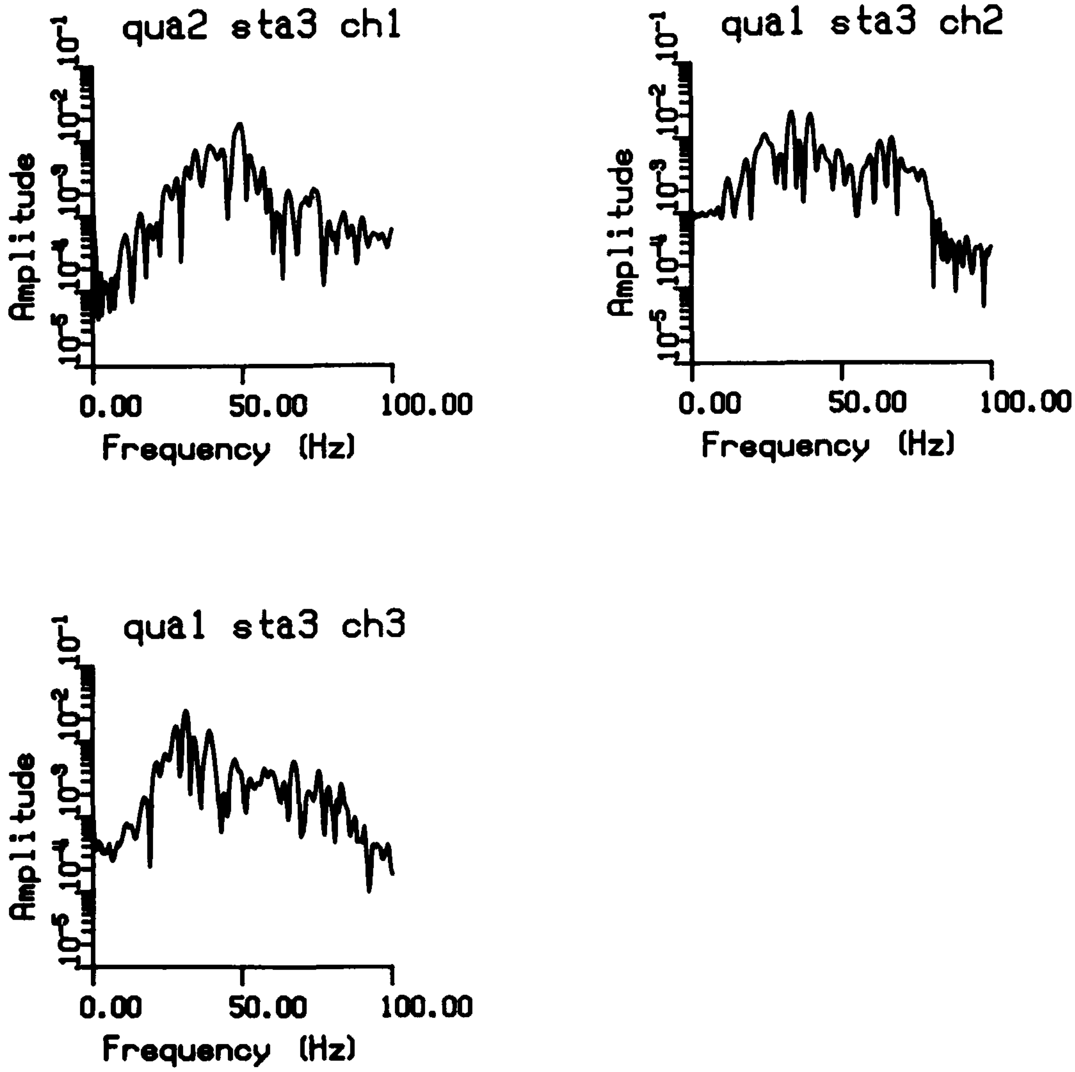


Figure 1-12. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A3. See Figure 1-10b

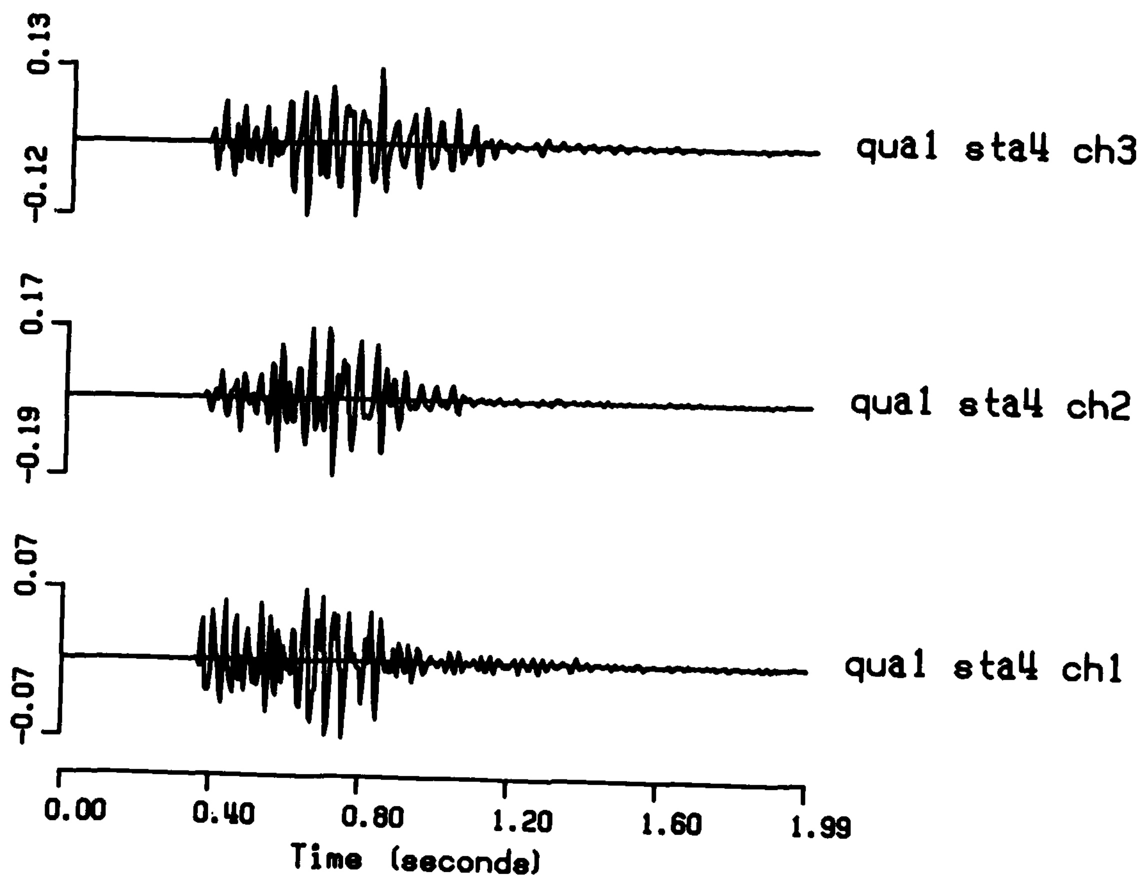


Figure 1-13. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A4. See Figure 1-10a

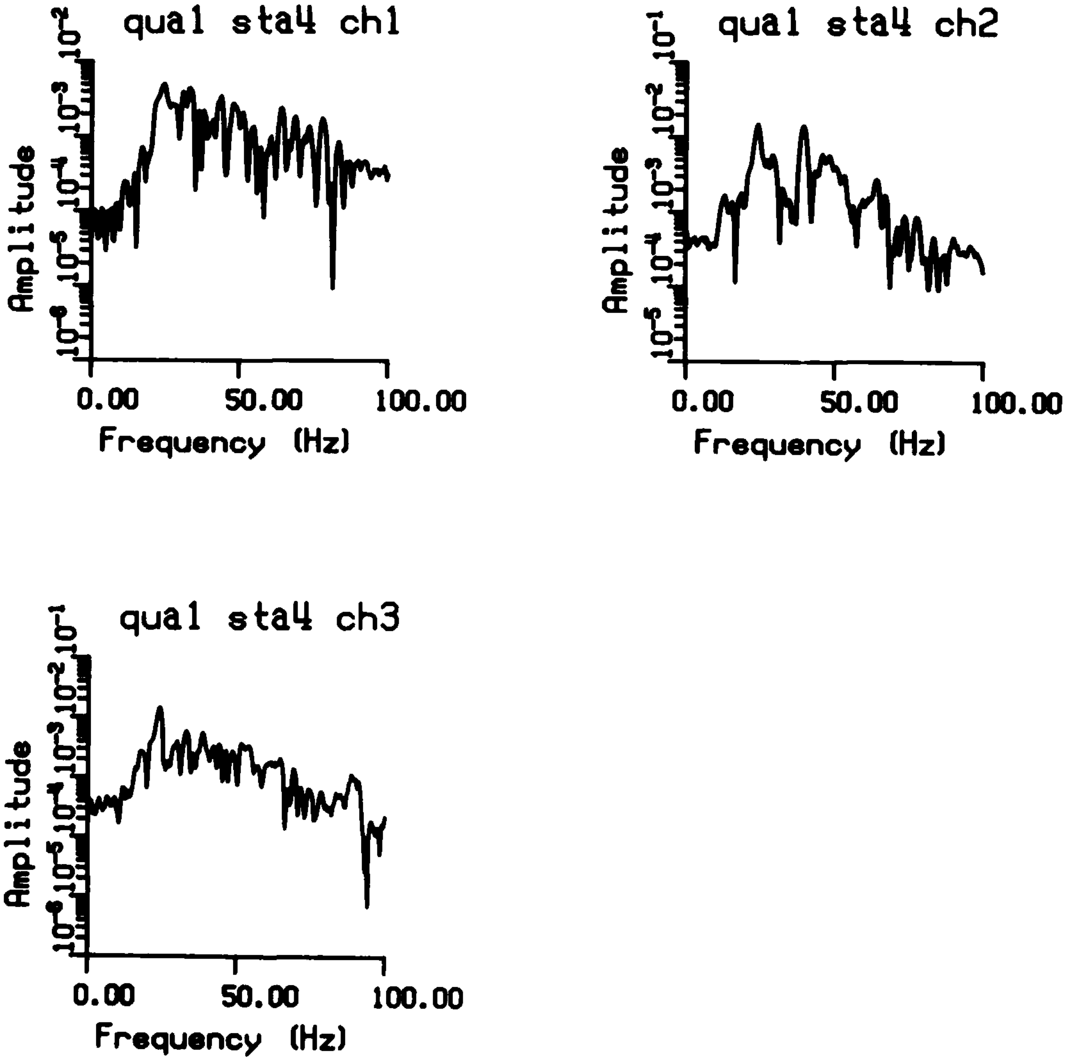


Figure 1-13. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A4. See Figure 1-10b

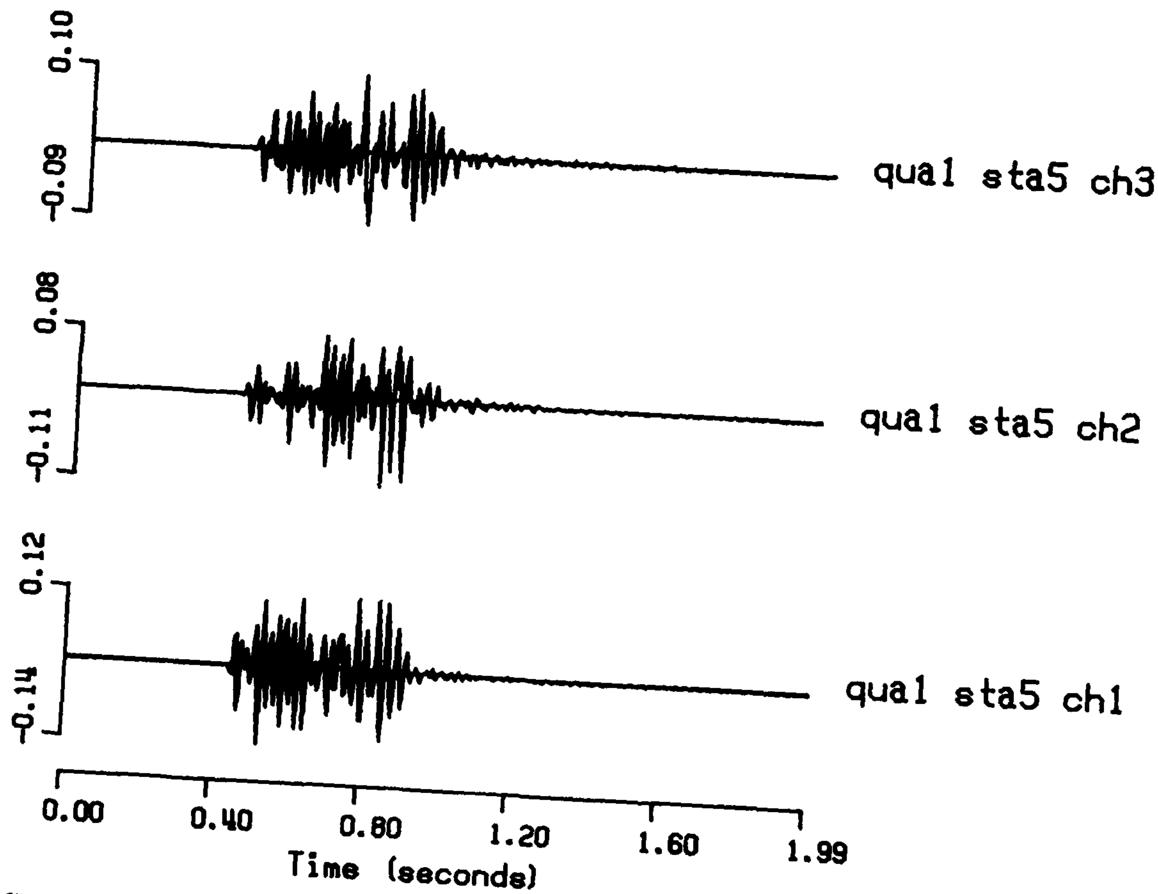


Figure 1-14. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A5. See Figure 1-10a

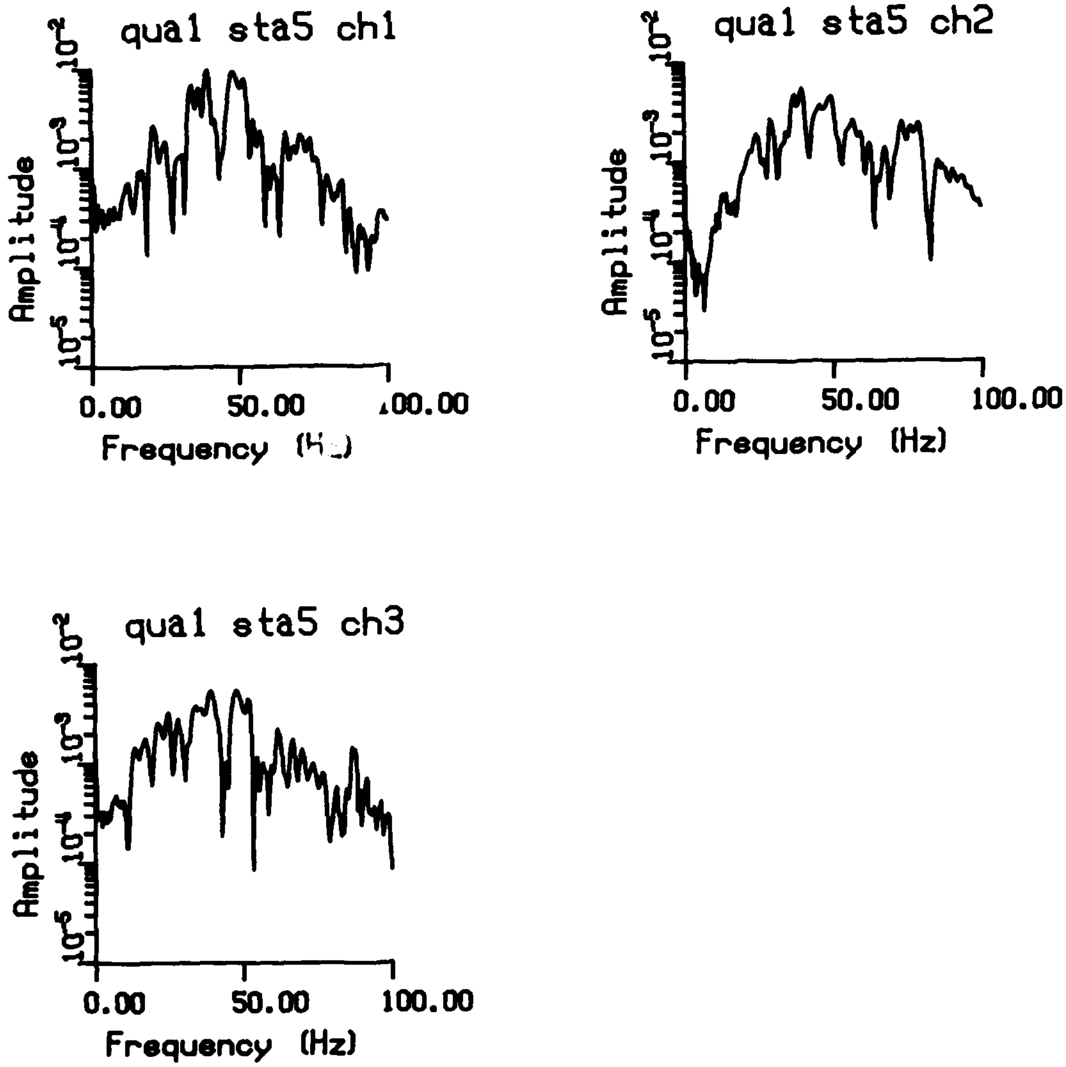


Figure 1-14. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A4. See Figure 1-10b

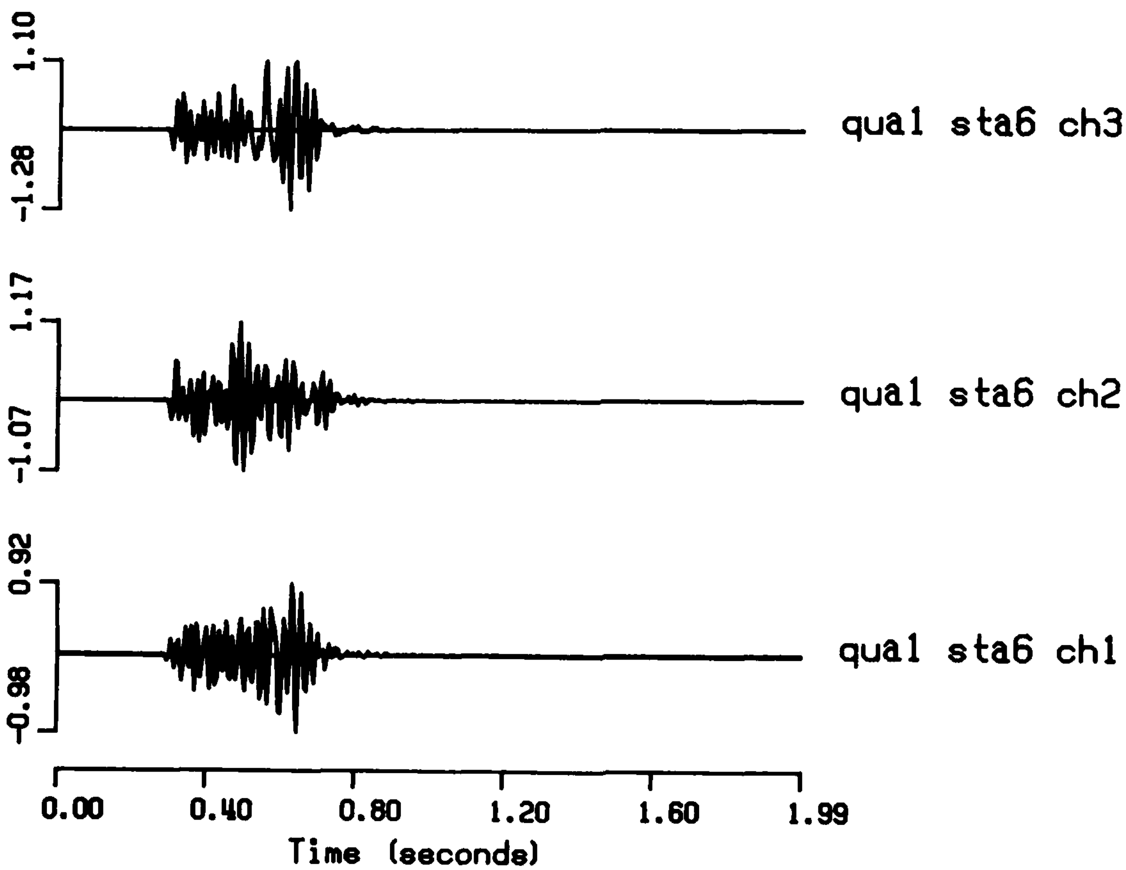


Figure 1-15. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A6. See Figure 1-10a

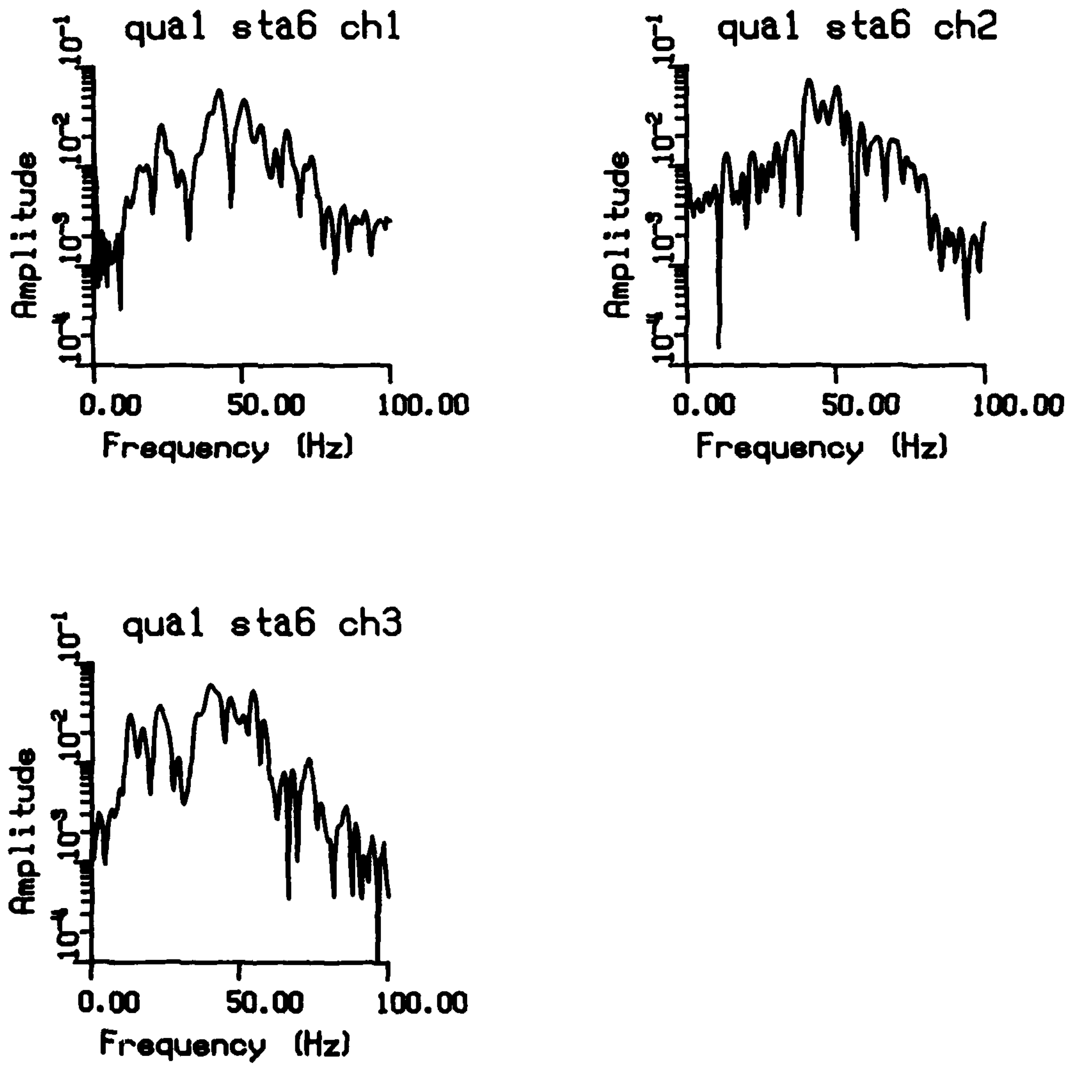


Figure 1-15. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A6. See Figure 1-10b

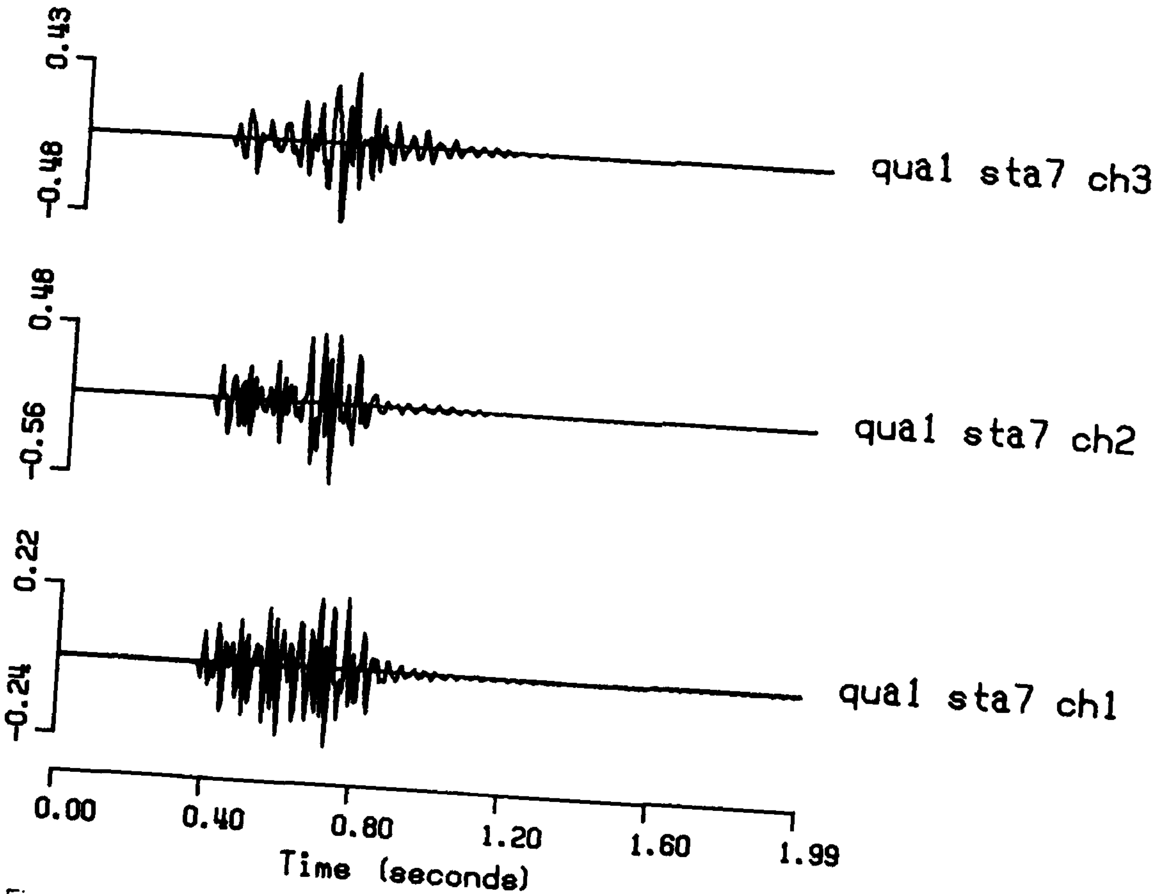


Figure 1-16. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A7. See Figure 1-10a

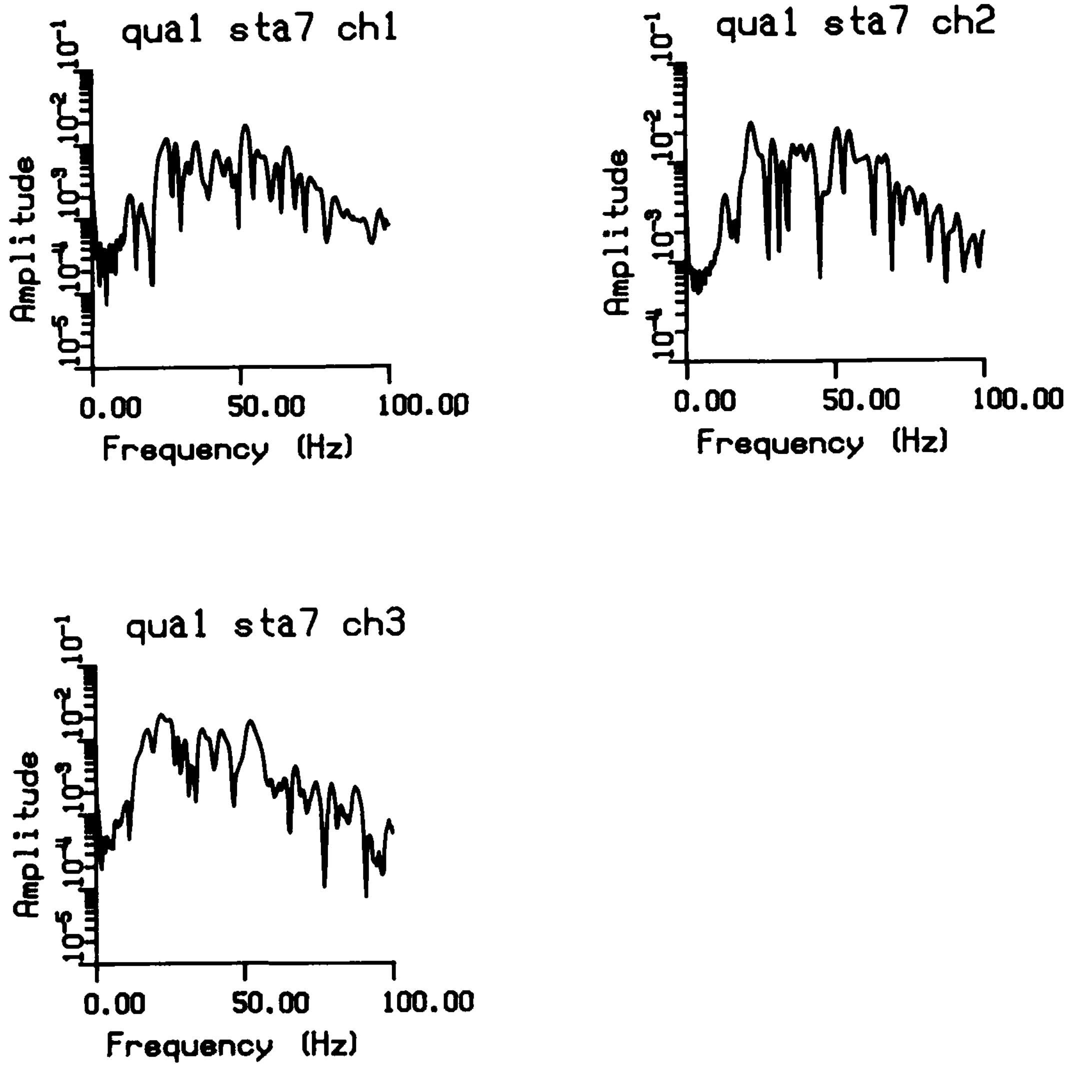


Figure 1-16. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A7. See Figure 1-10b

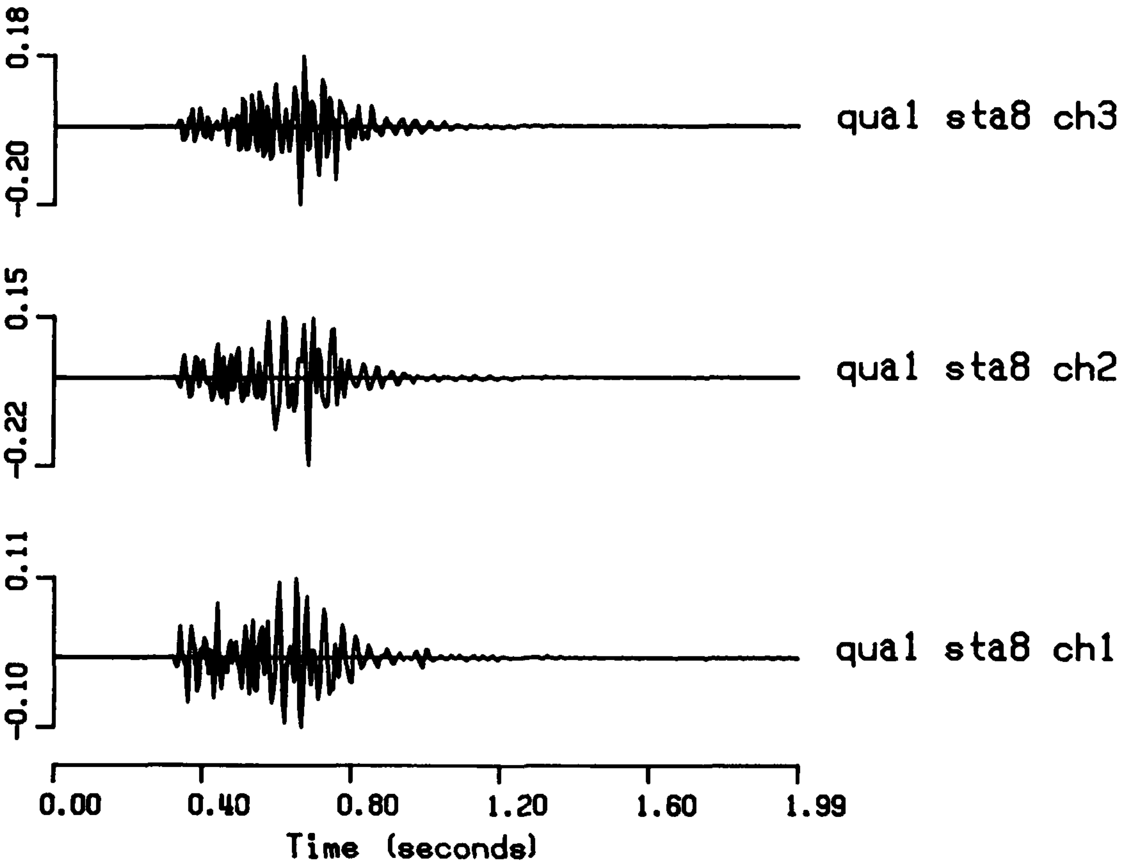


Figure 1-17. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A8. See Figure 1-10a

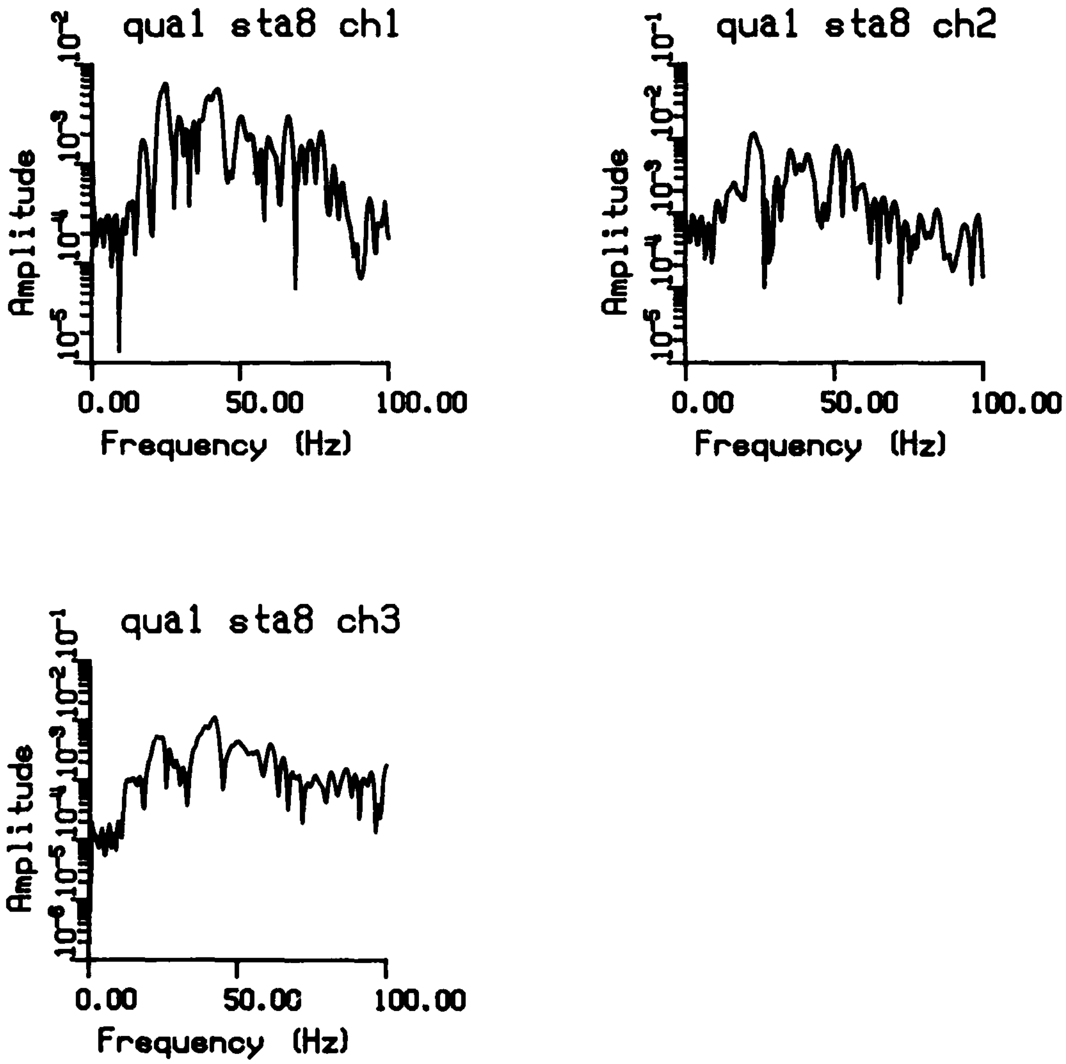


Figure 1-17. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A8. See Figure 1-10b

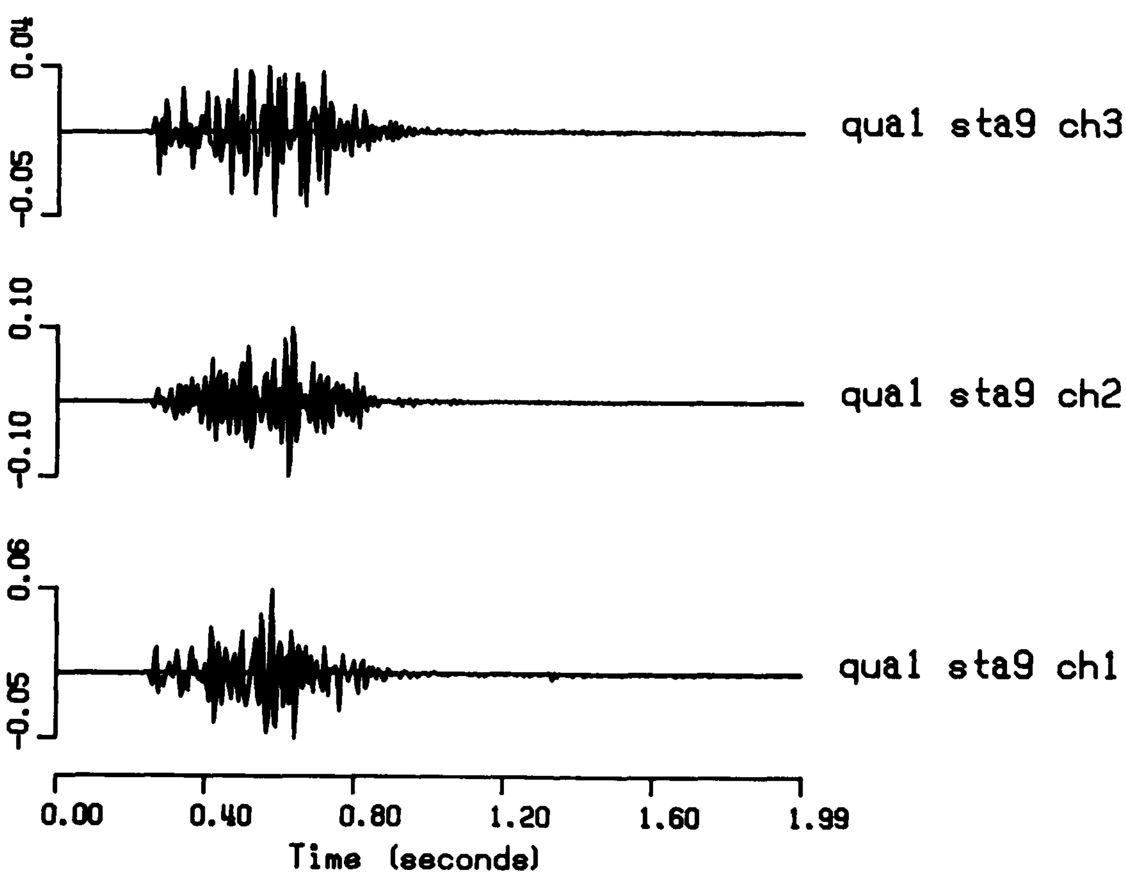


Figure 1-18. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A9. See Figure 1-10a

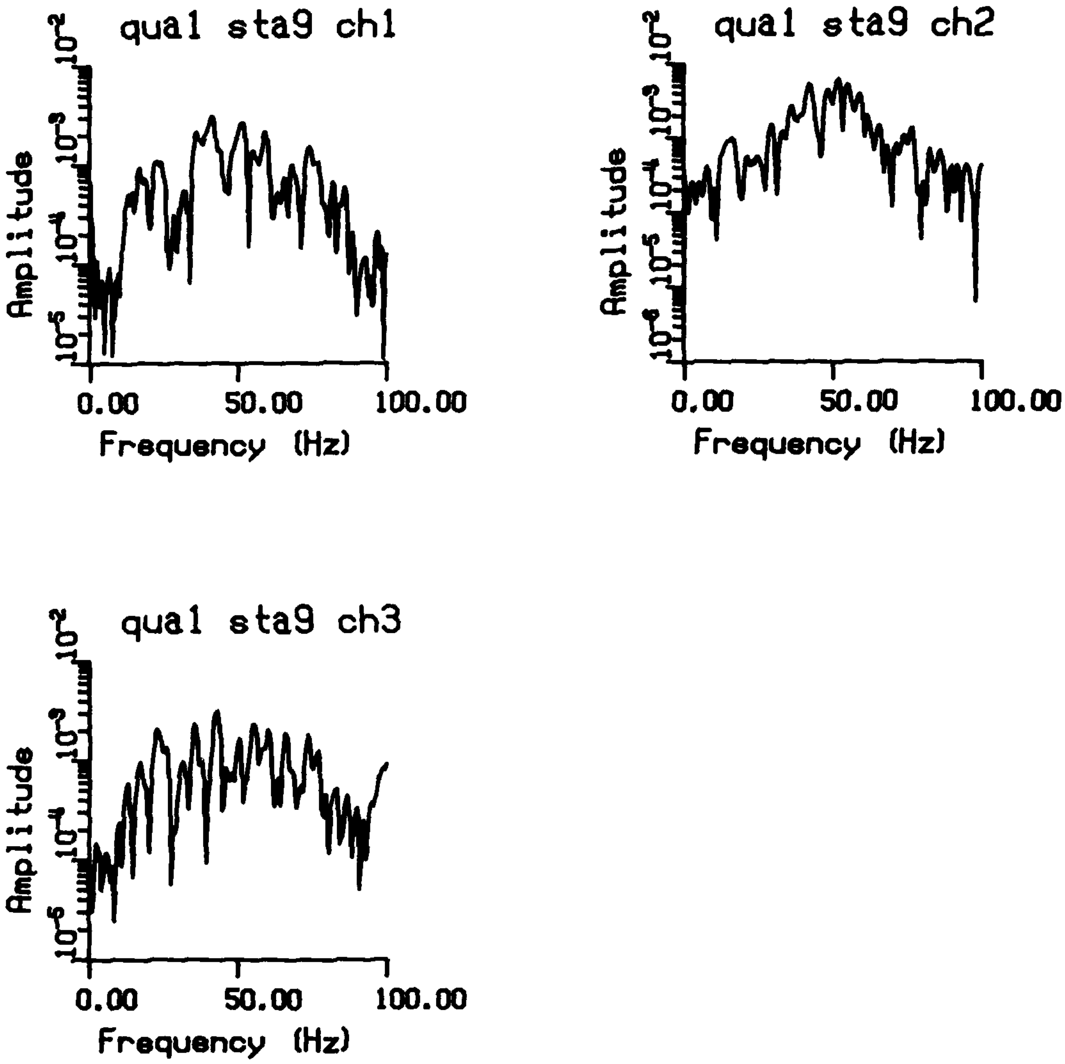


Figure 1-18. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A9. See Figure 1-10b

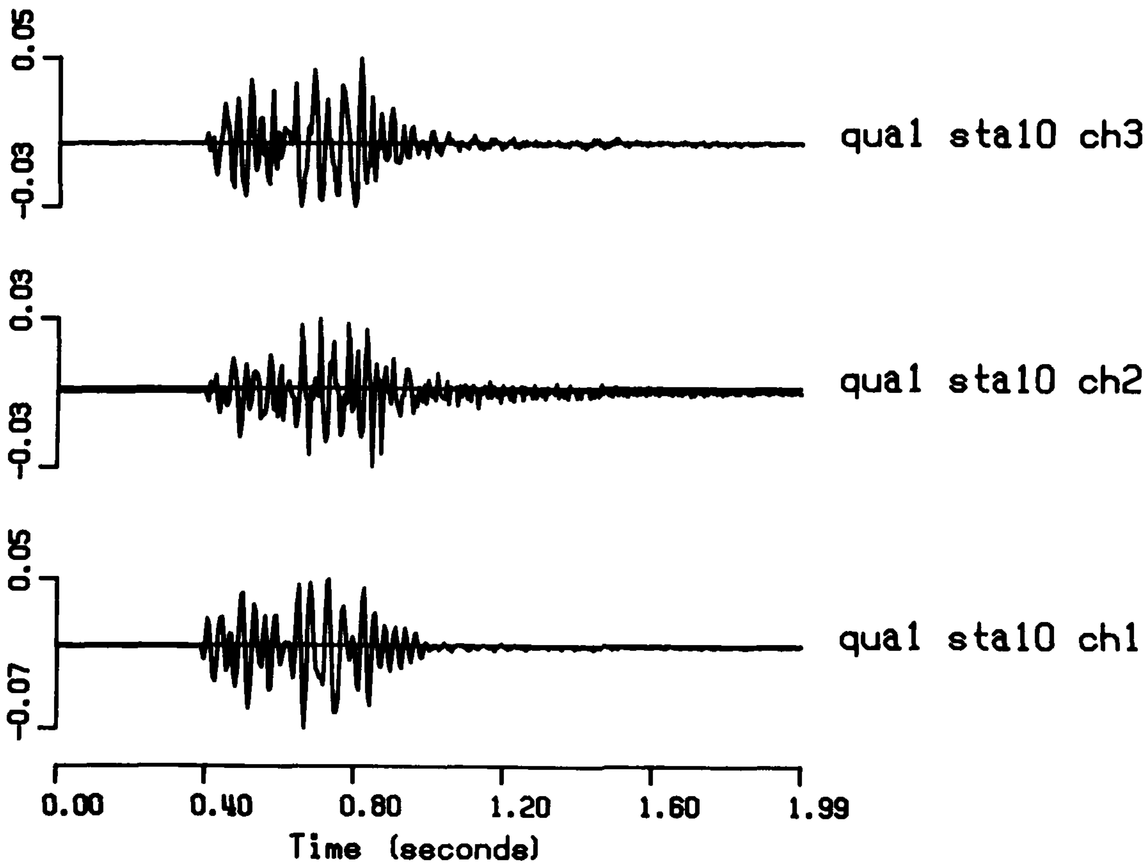


Figure 1-19. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A10. See Figure 1-10a

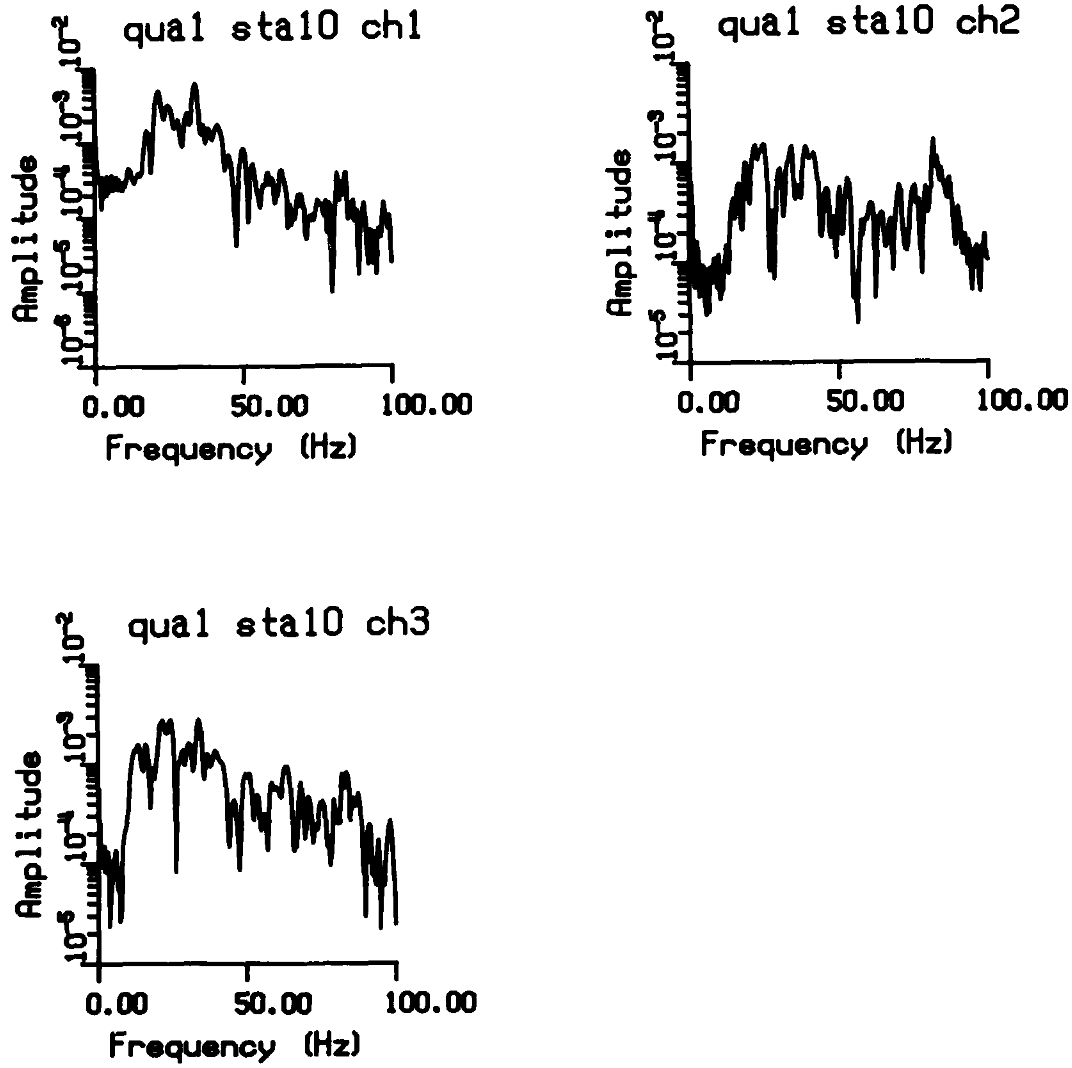


Figure 1-19. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A10. See Figure 1-10b

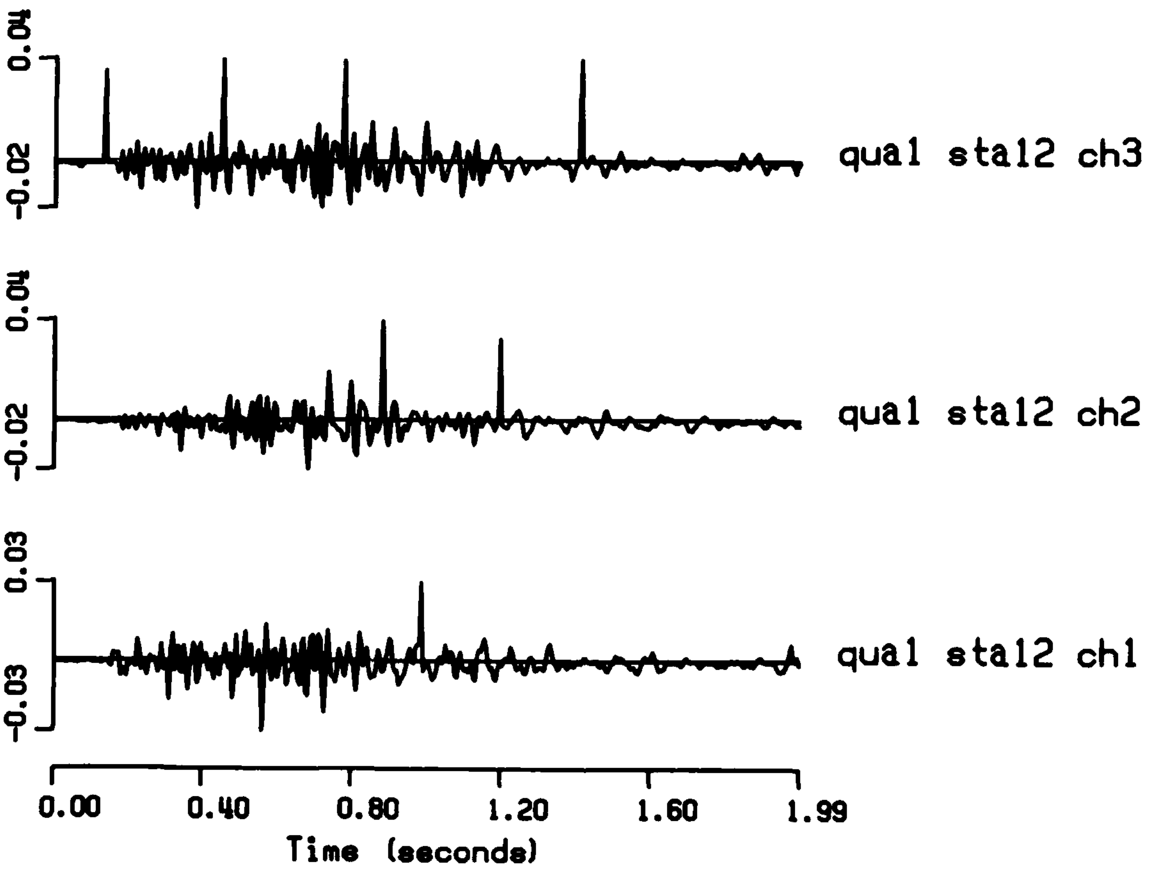


Figure 1-20. (a) Three-Component Accelerogram of Shot QB1 Recorded at Station A12. See Figure 1-10a

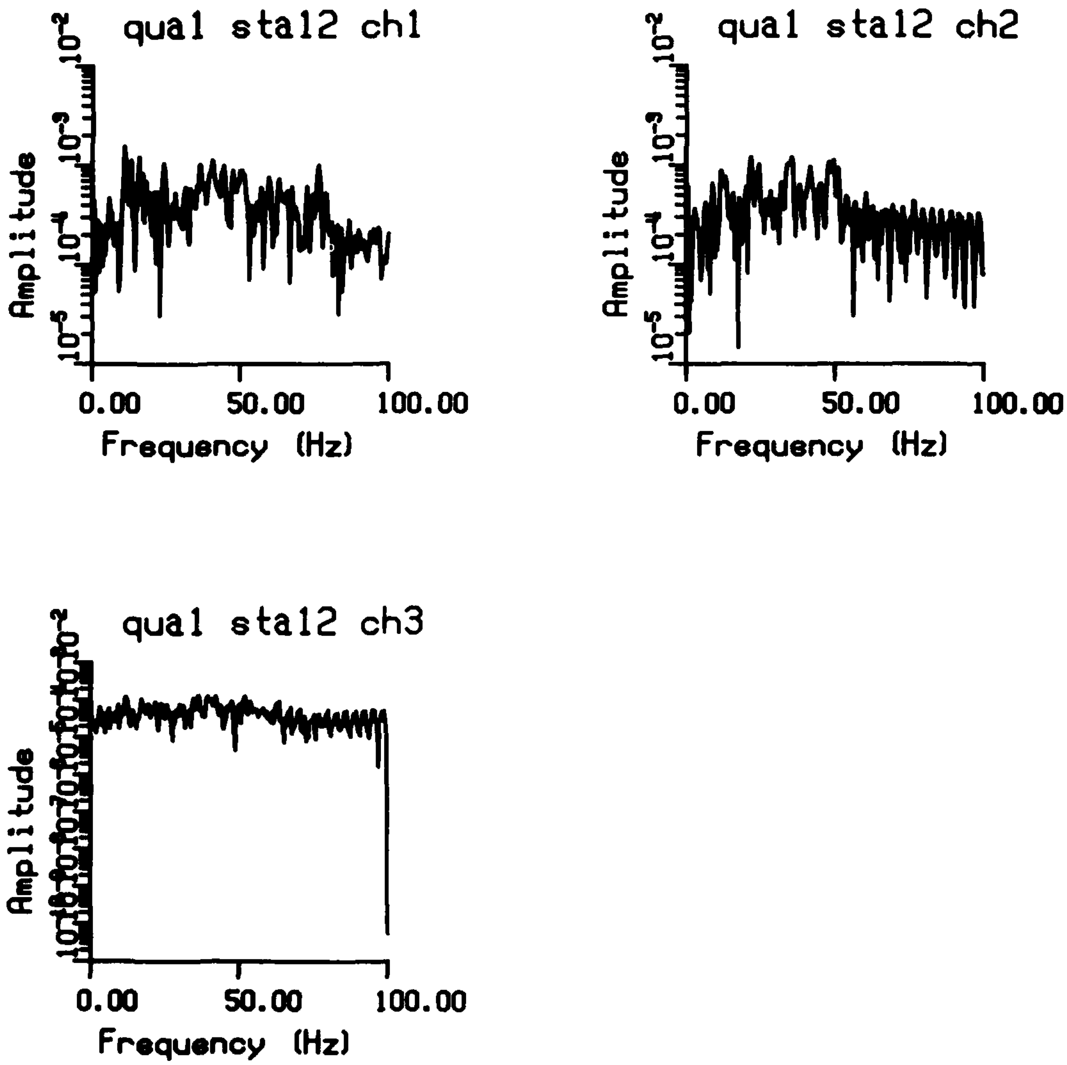


Figure 1-20. (b) Amplitude Spectra for Three Components of Shot QB1 Recorded at Station A12. See Figure 1-10b

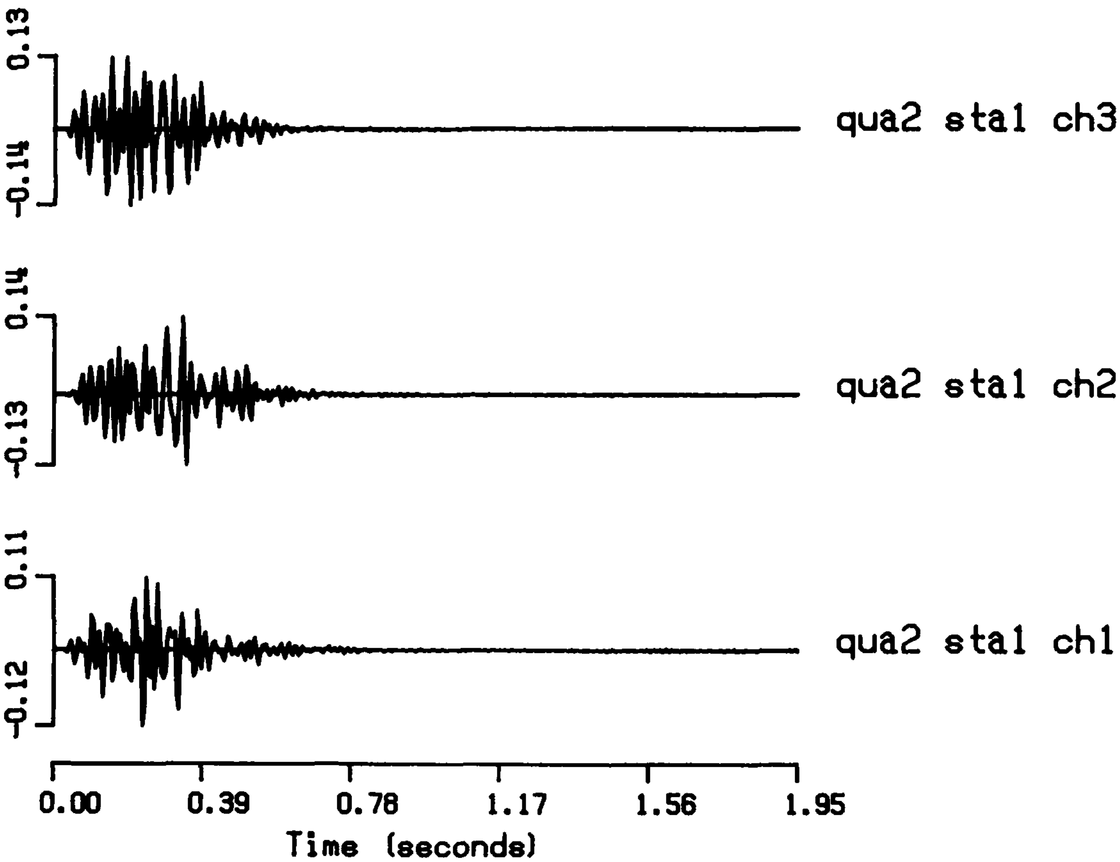


Figure 1-21. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A1. See Figure 1-10a

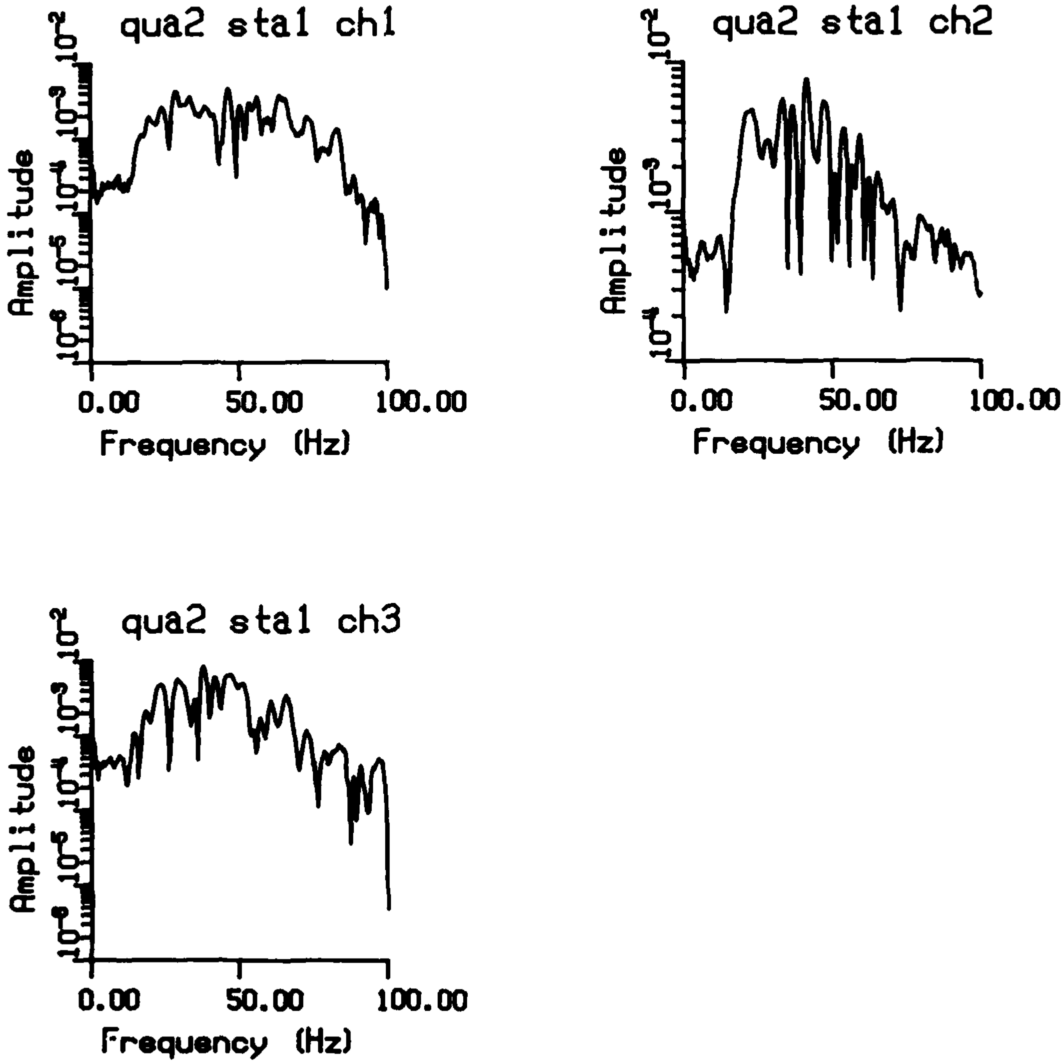


Figure 1-21. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A1. See Figure 1-10b

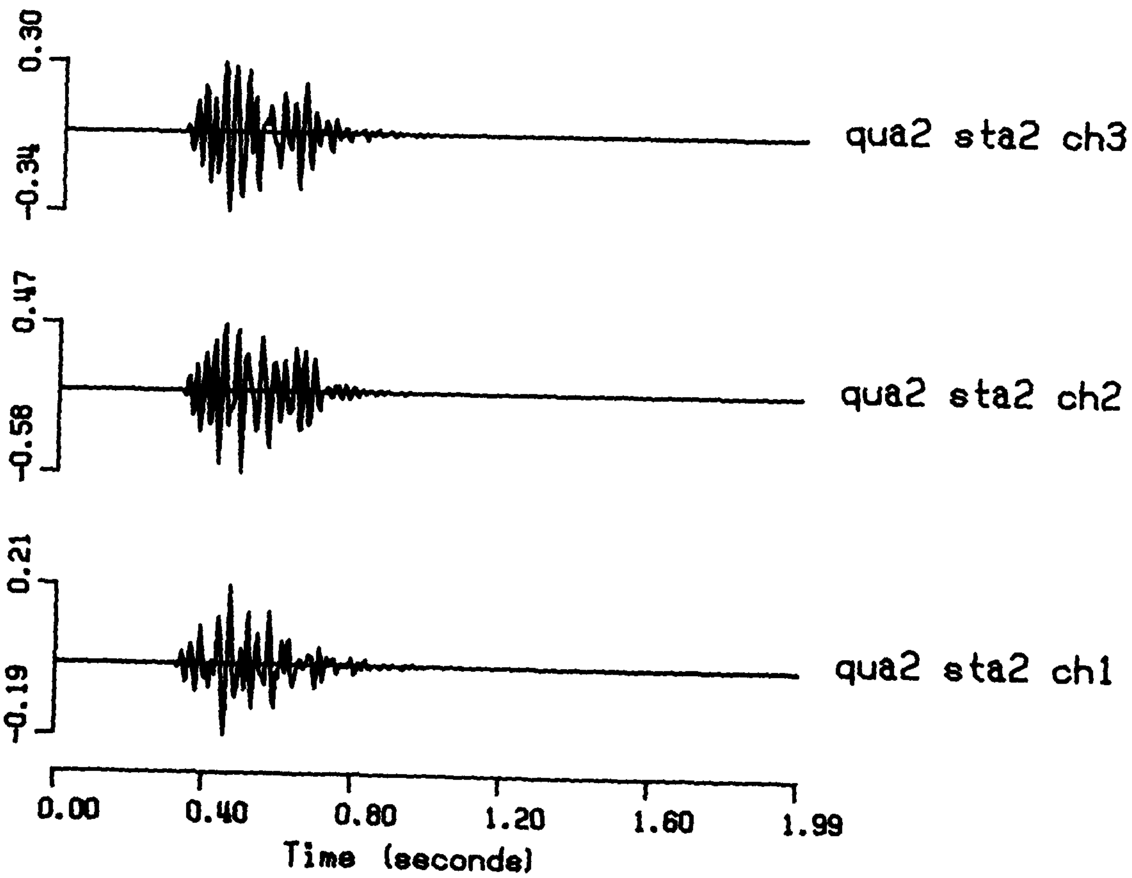


Figure 1-22. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A2. See Figure 1-10a.

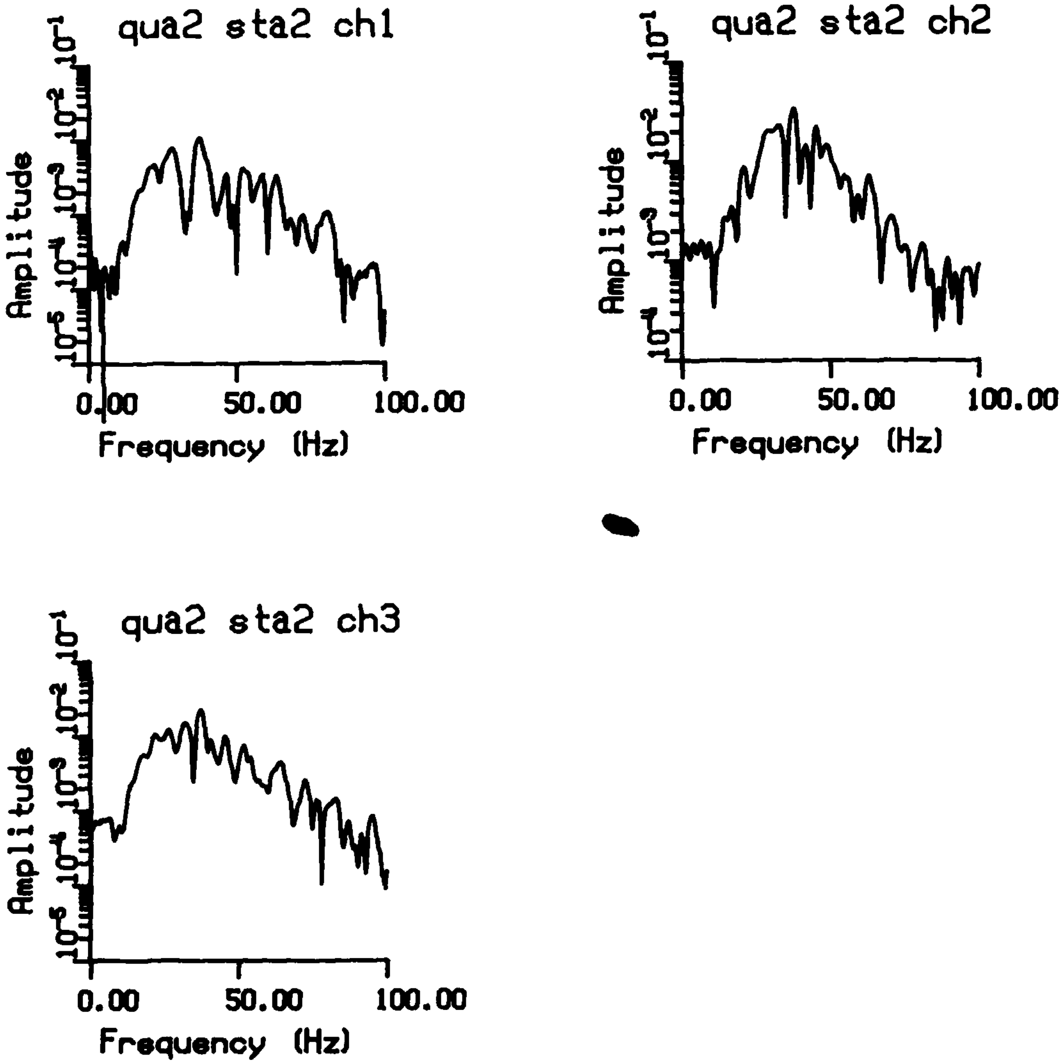


Figure 1-22. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A2. See Figure 1-10b

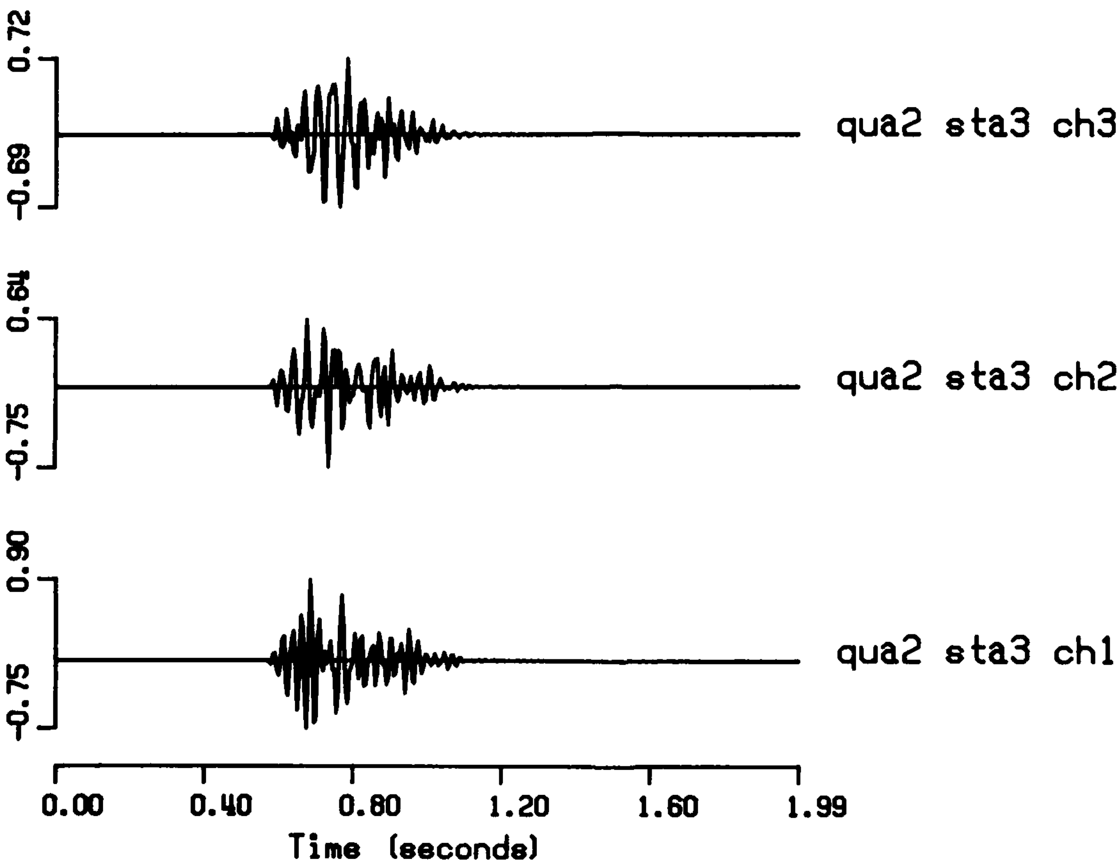


Figure 1-23. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A3. See Figure 1-10a

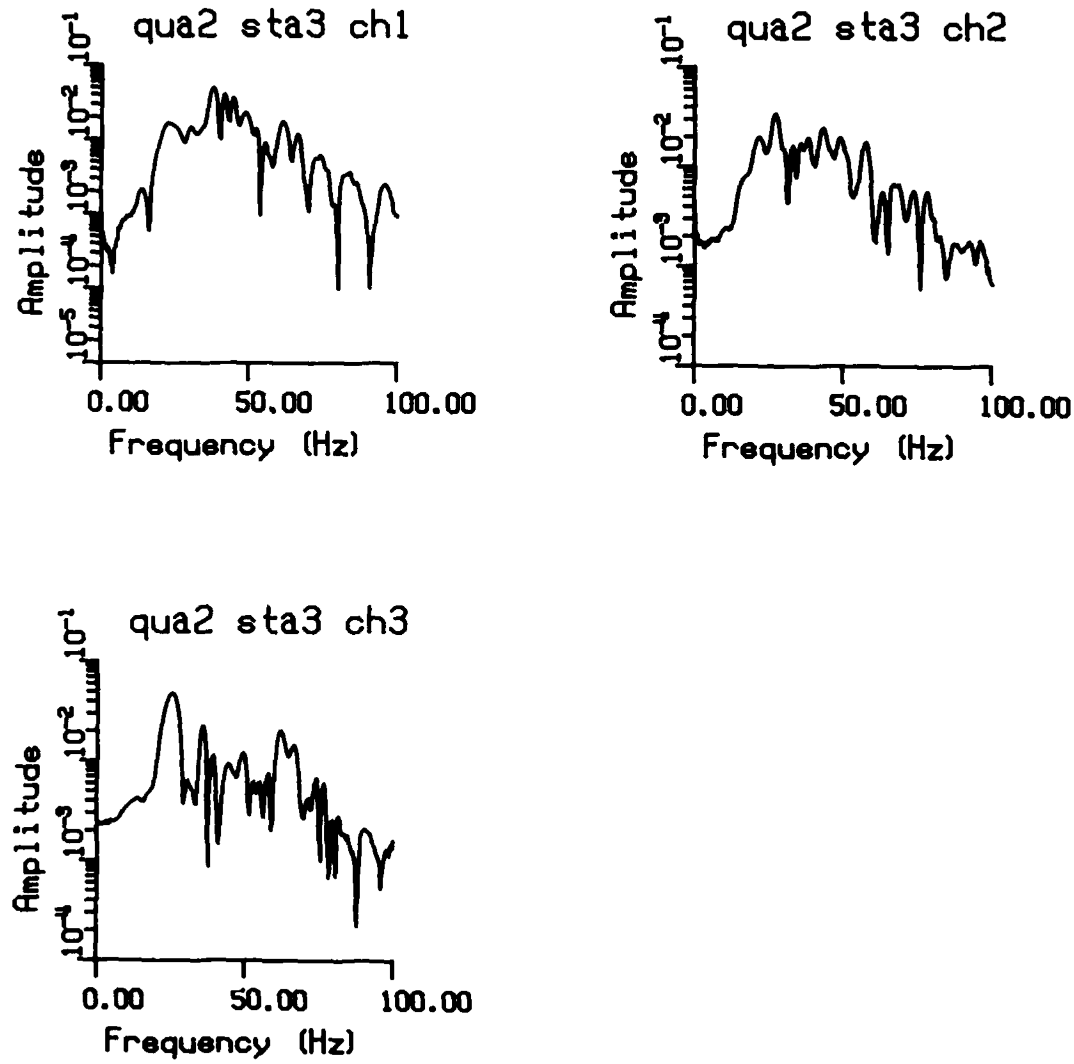


Figure 1-23. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A3. See Figure 1-10b

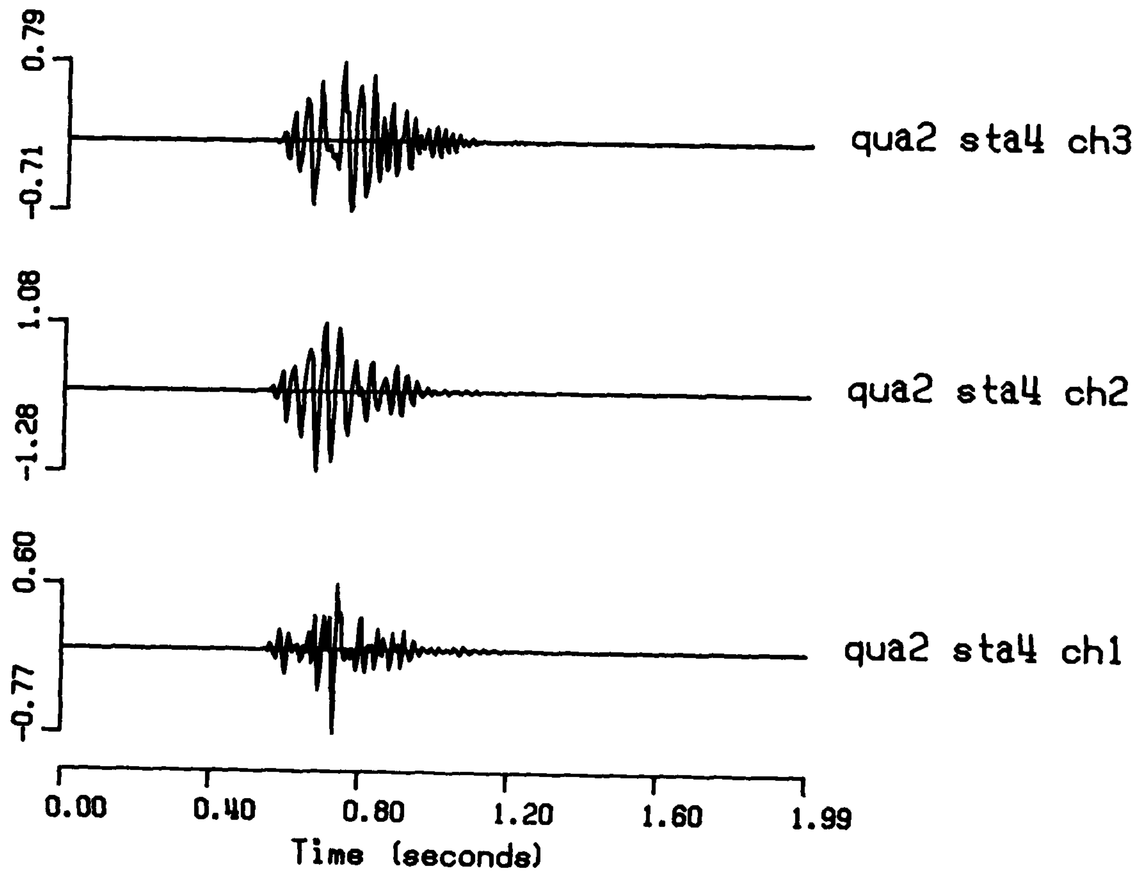


Figure 1-24 (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A4. See Figure 1-10a

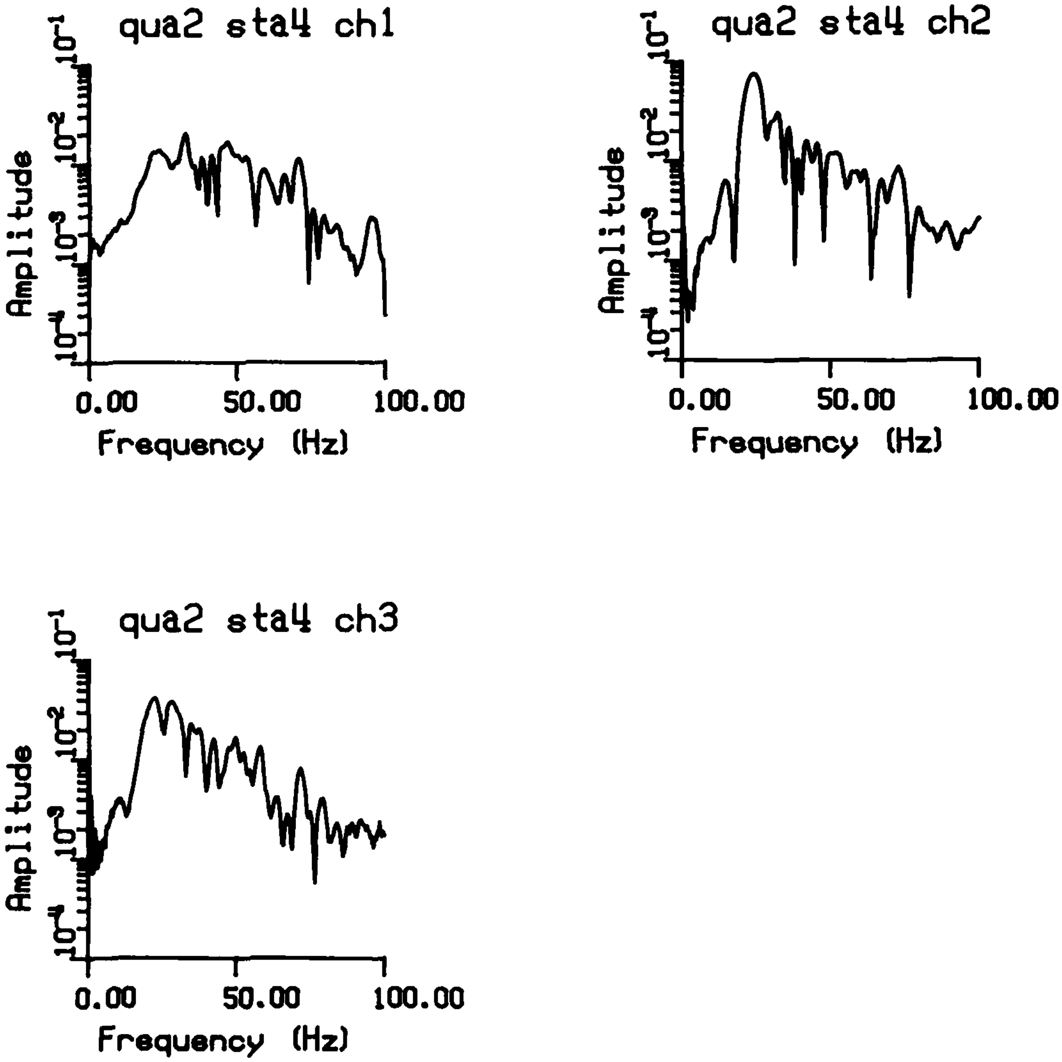


Figure 1-24. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A4. See Figure 1-10b

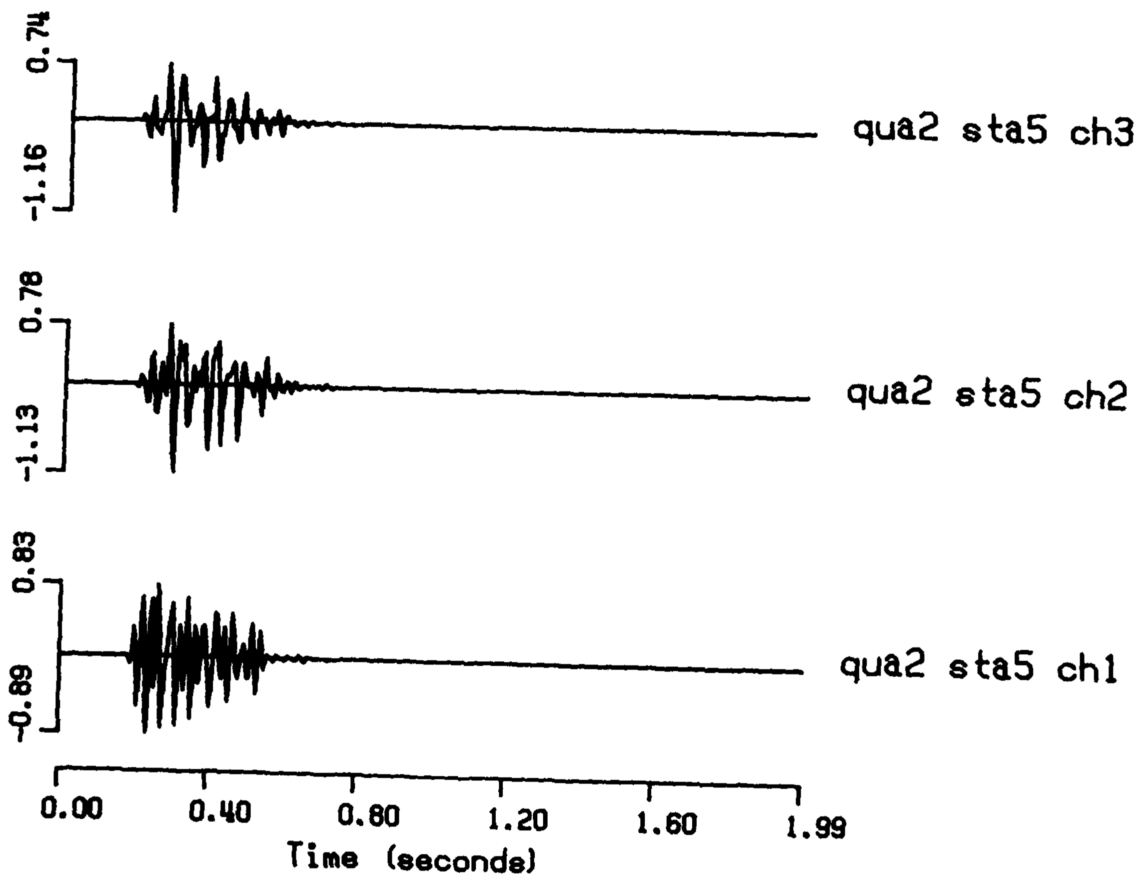


Figure 1-25. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A5. See Figure 1-10a

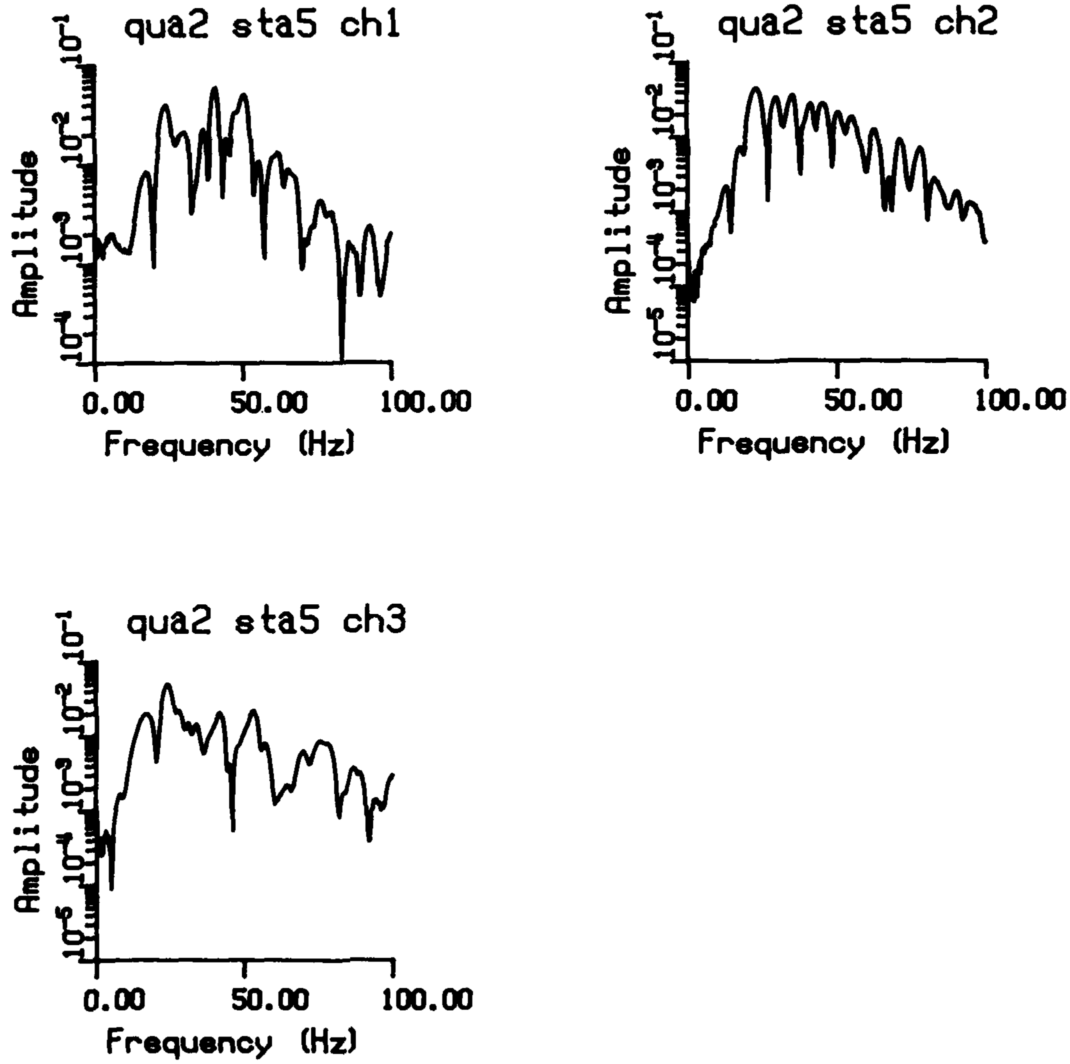


Figure 1-25. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A5. See Figure 1-10b

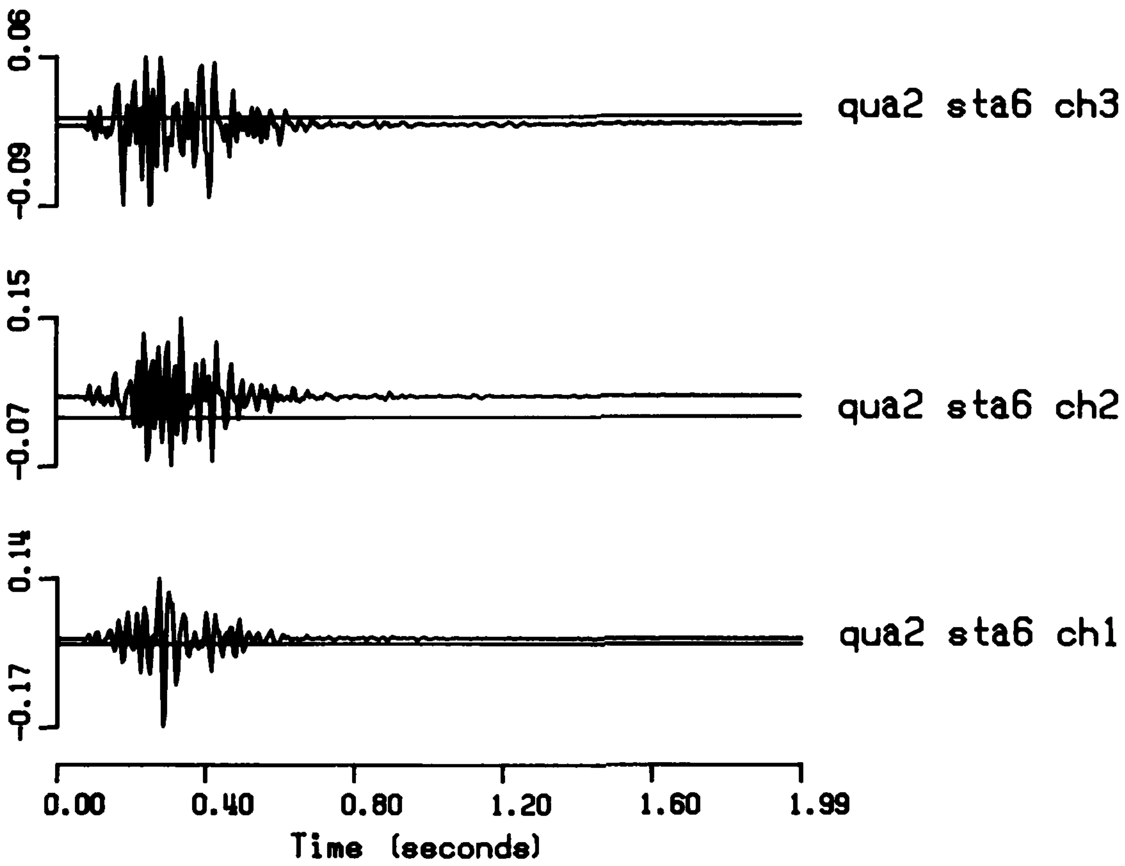


Figure 1-26. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A6. See Figure 1-10a

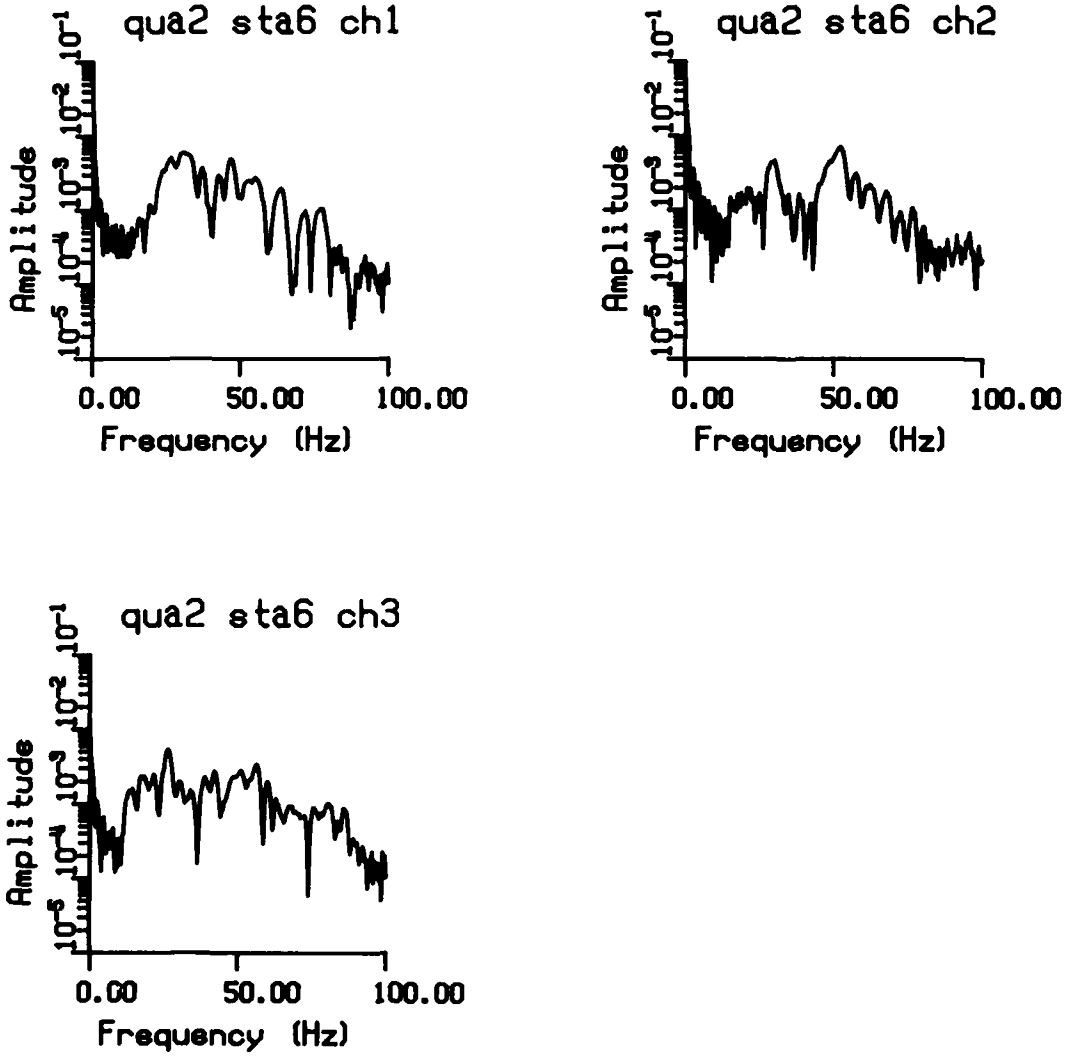


Figure 1-26. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A6. See Figure 1-10b

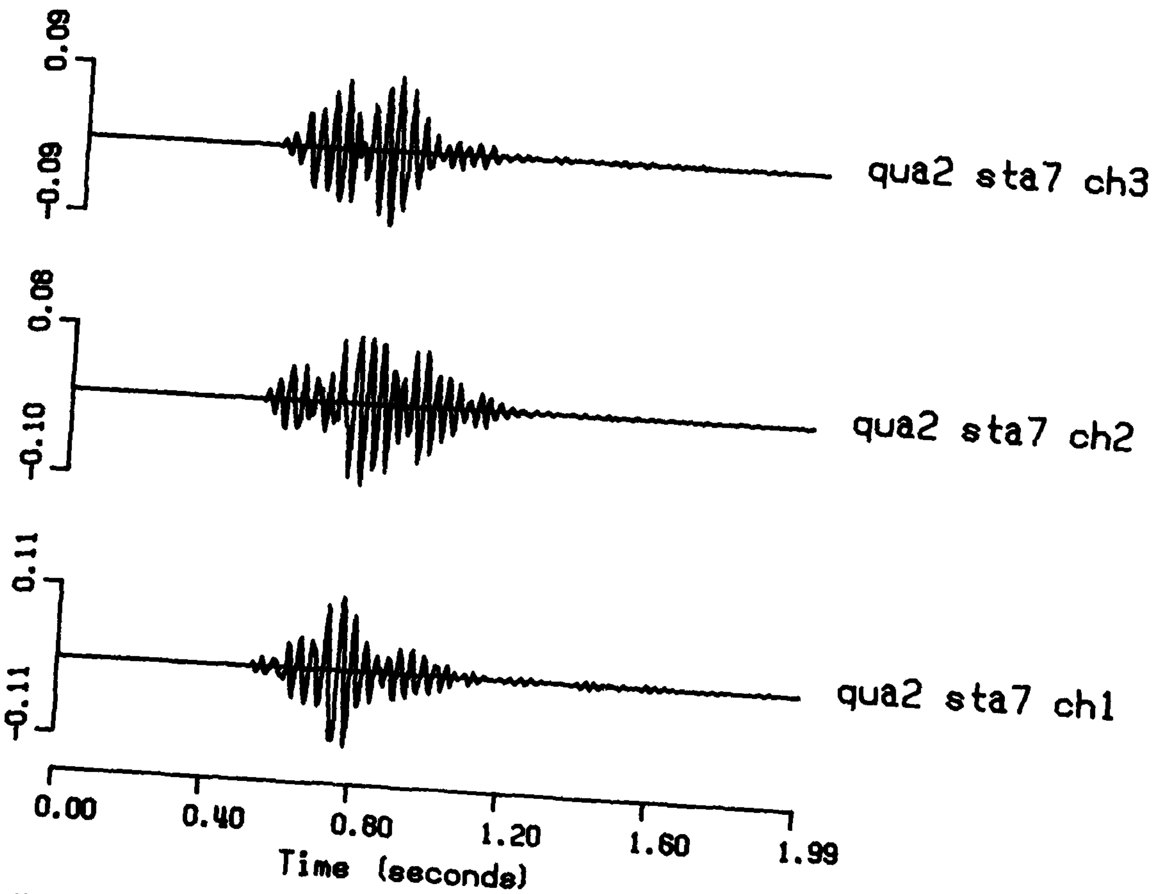


Figure 1-27. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A7. See Figure 1-10a

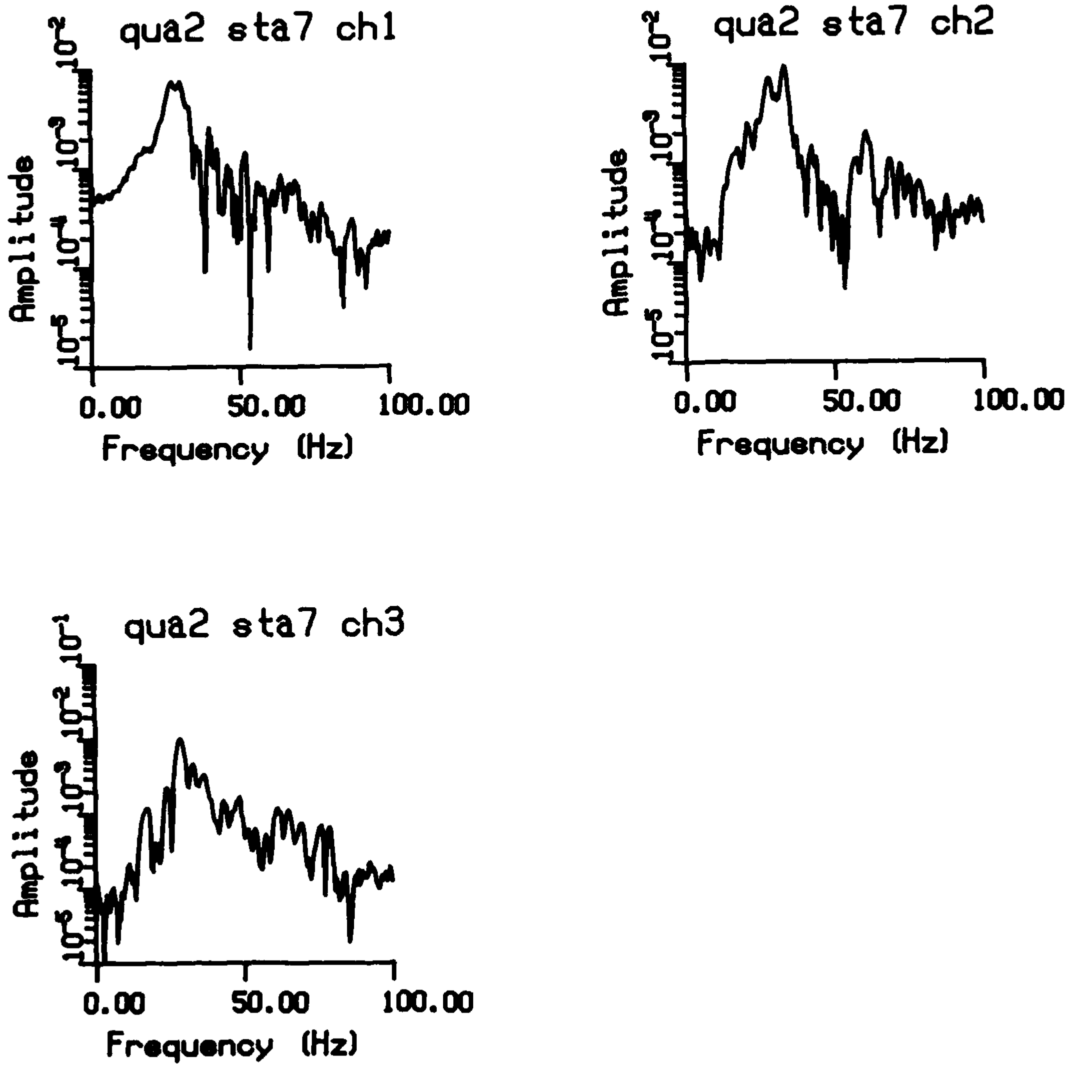


Figure 1-27. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A7. See Figure 1-10b

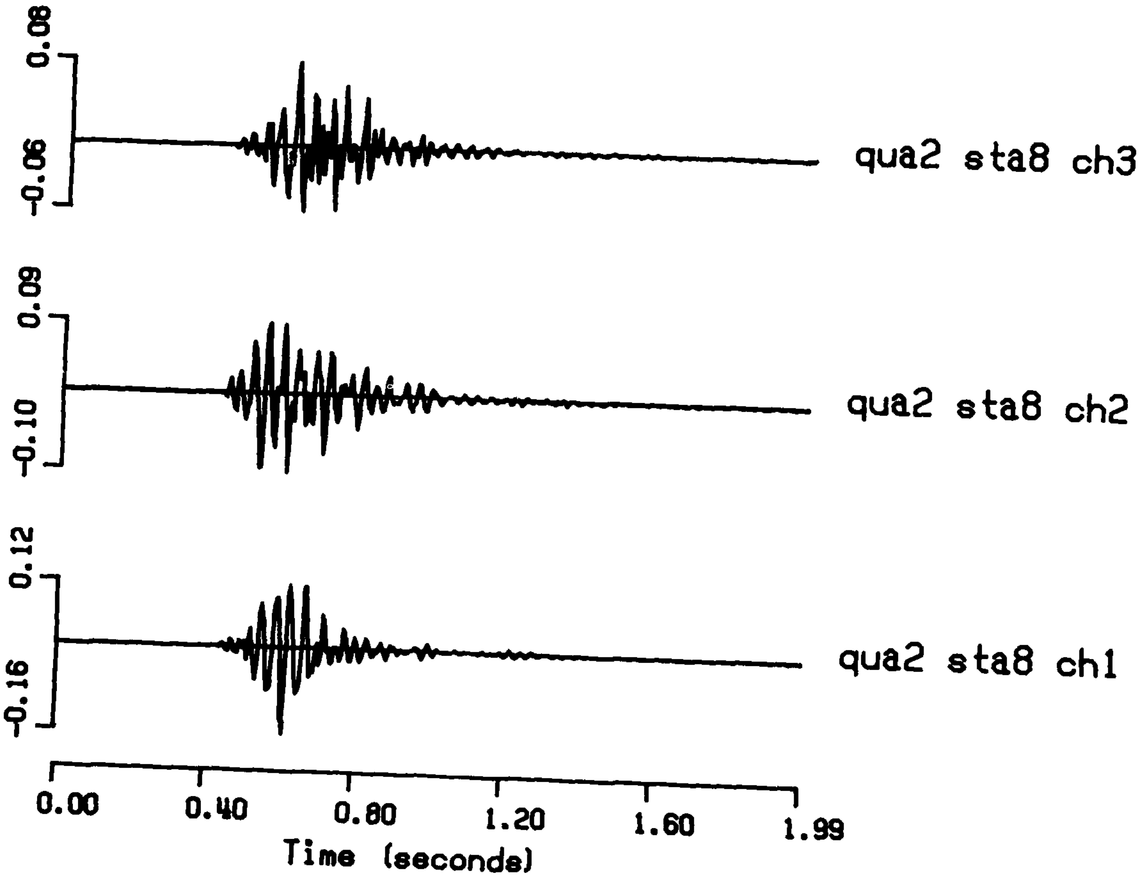


Figure 1-28. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A8. See Figure 1-10a

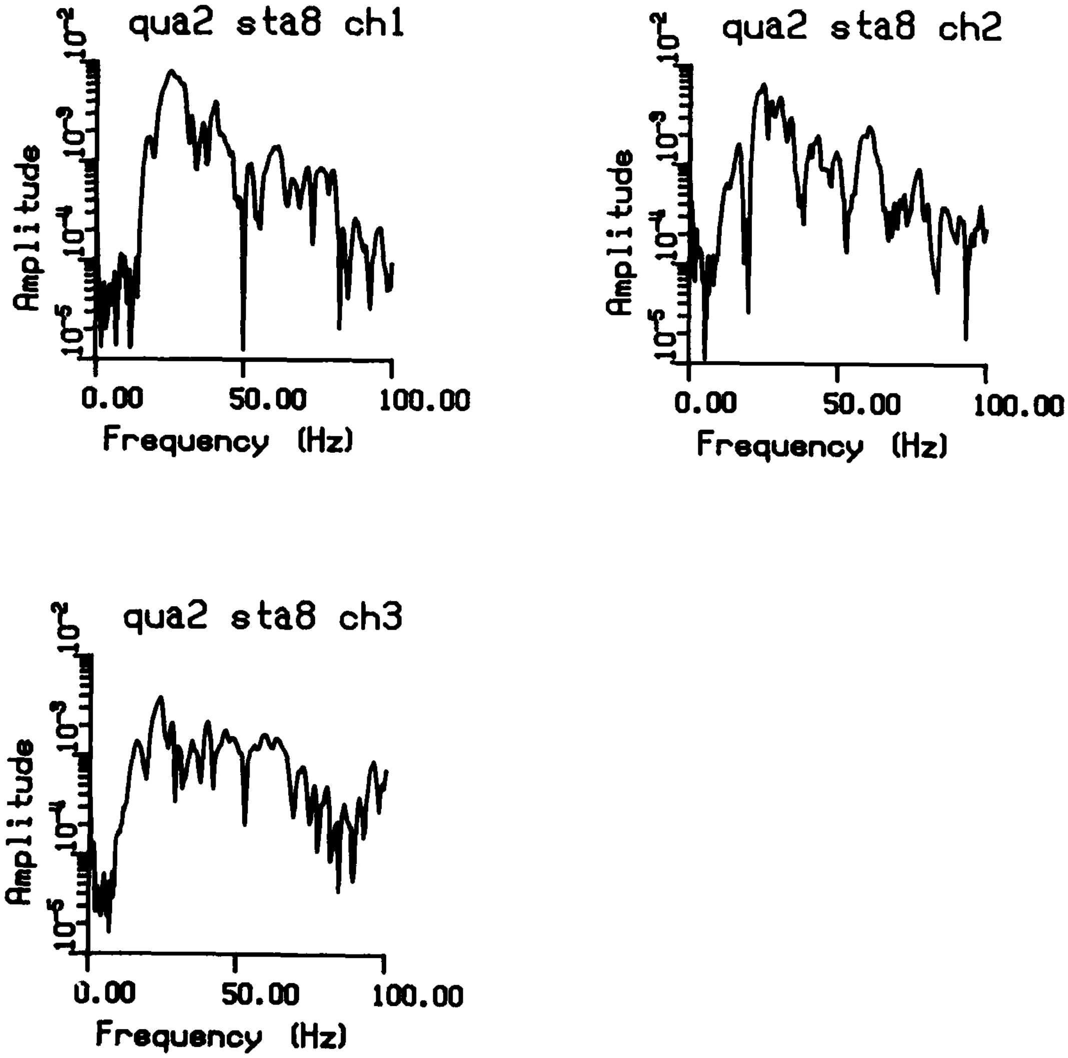


Figure 1-28. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A8. See Figure 1-10b

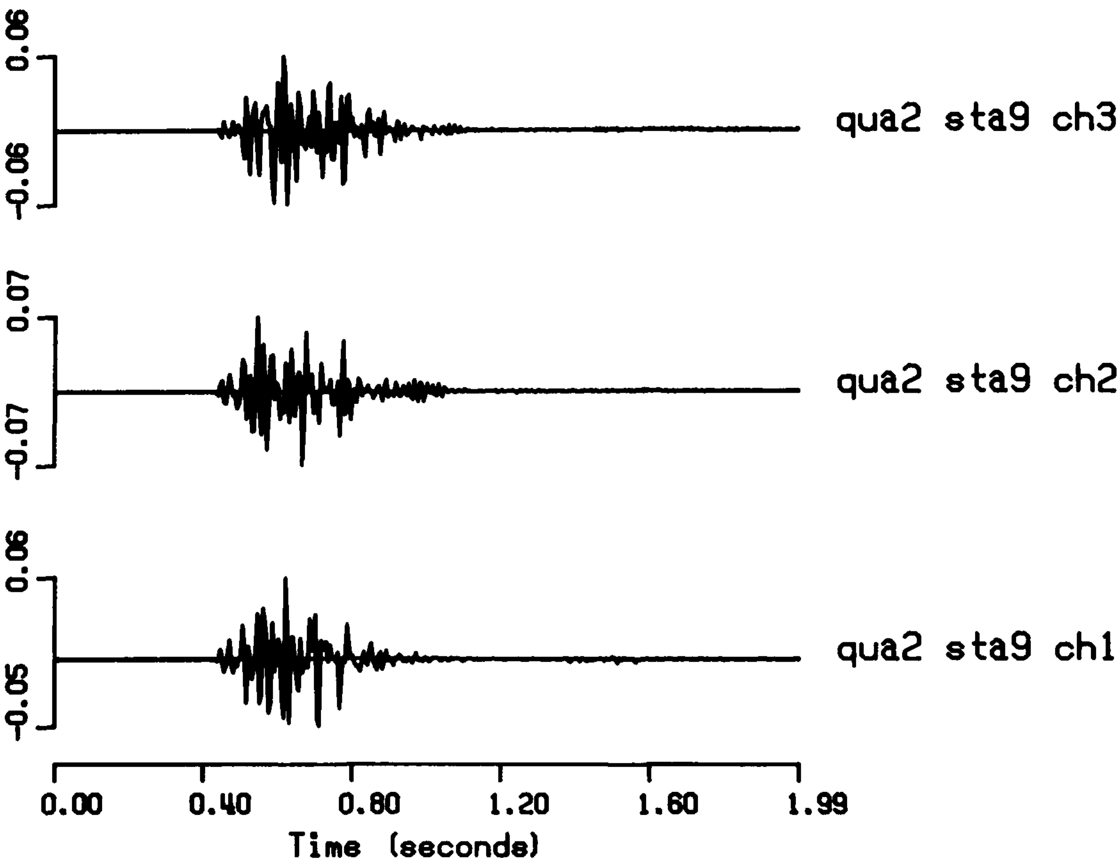


Figure 1-29. (a) Three-Component accelerogram of Shot QB2 Recorded at Station A9. See Figure 1-10a

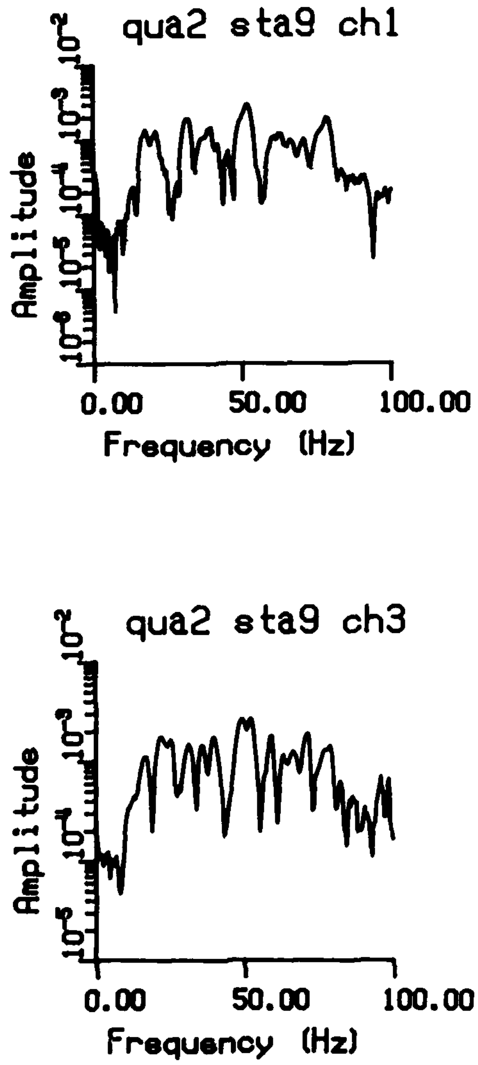


Figure 1-29. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A9. See Figure 1-10b

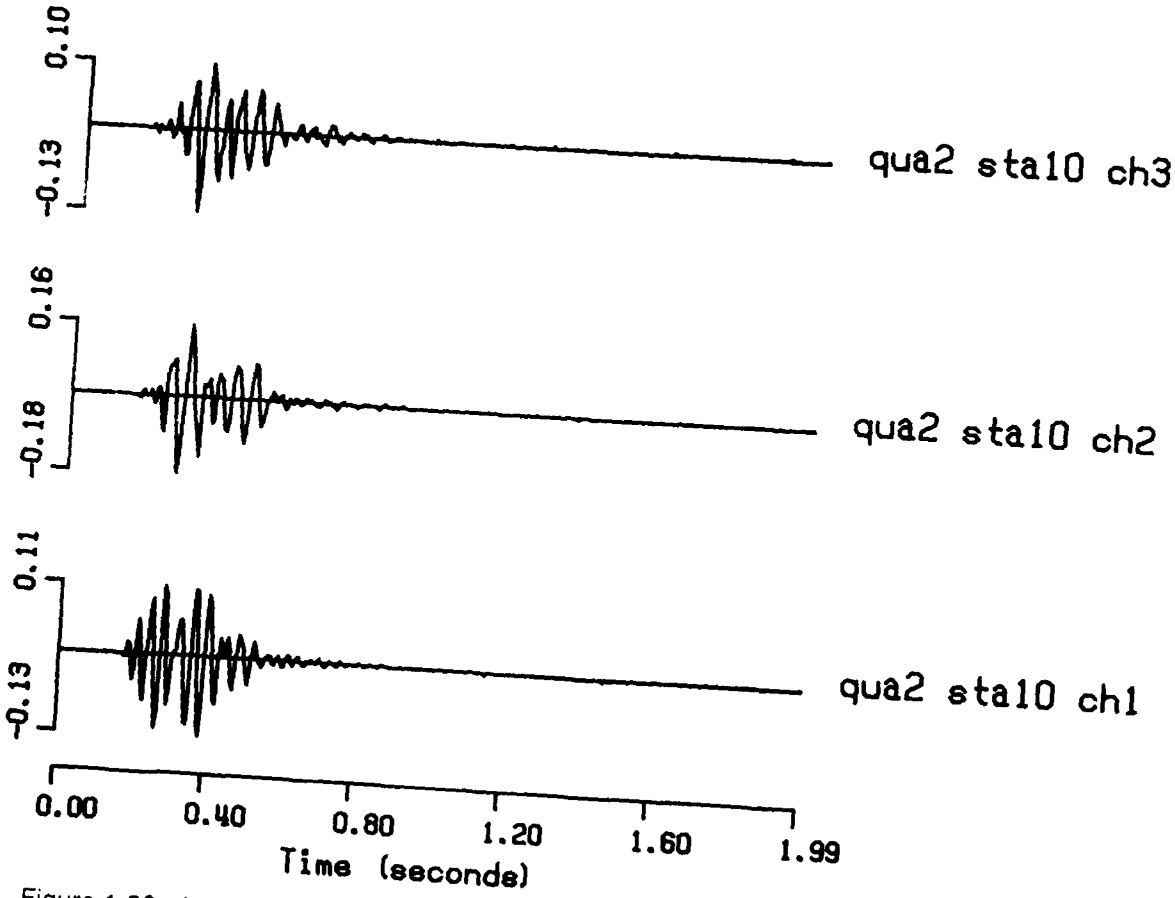


Figure 1-30. (a) Three-Component Accelerogram of Shot QB2 Recorded at Station A10. See Figure 1-10a

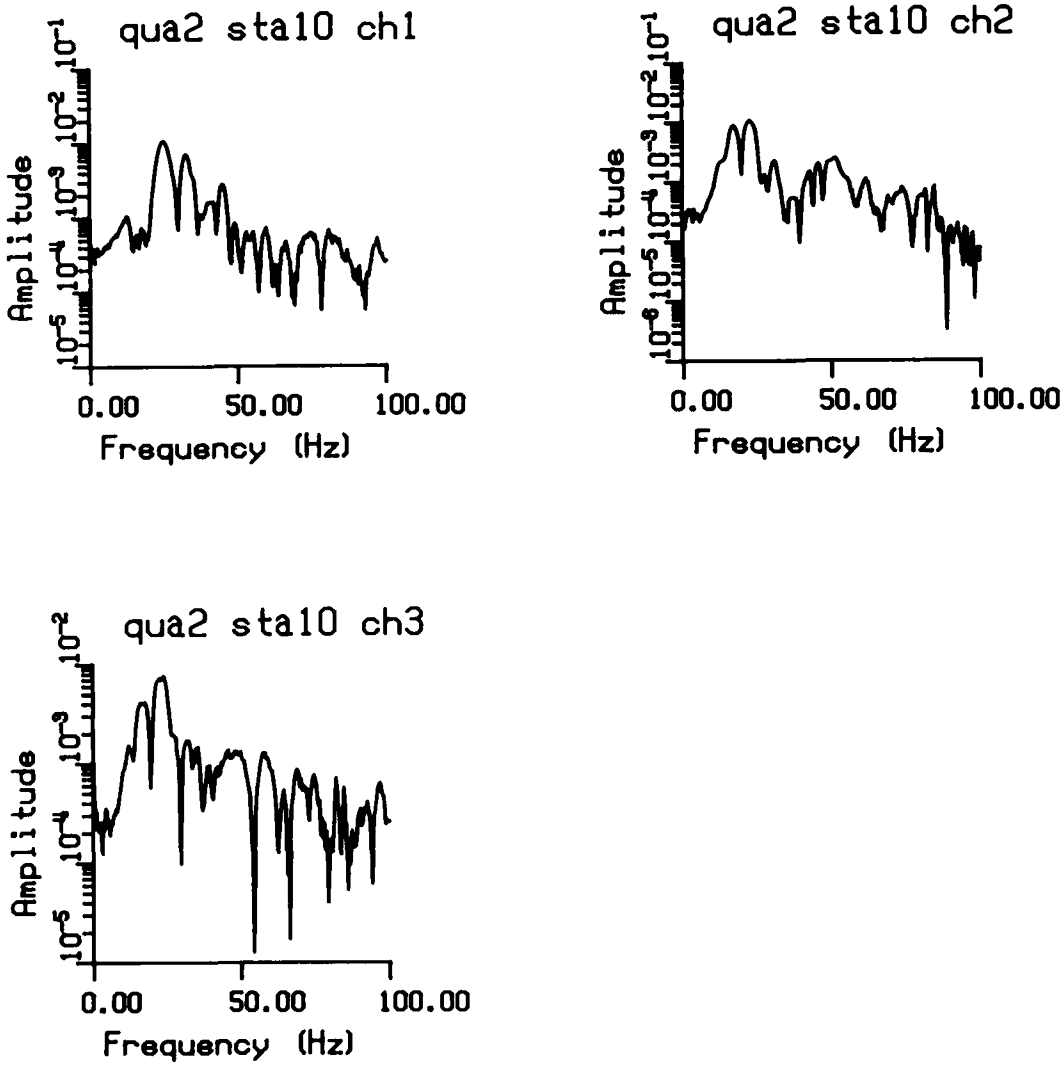


Figure 1-30. (b) Amplitude Spectra for Three Components of Shot QB2 Recorded at Station A10. See Figure 1-10b.

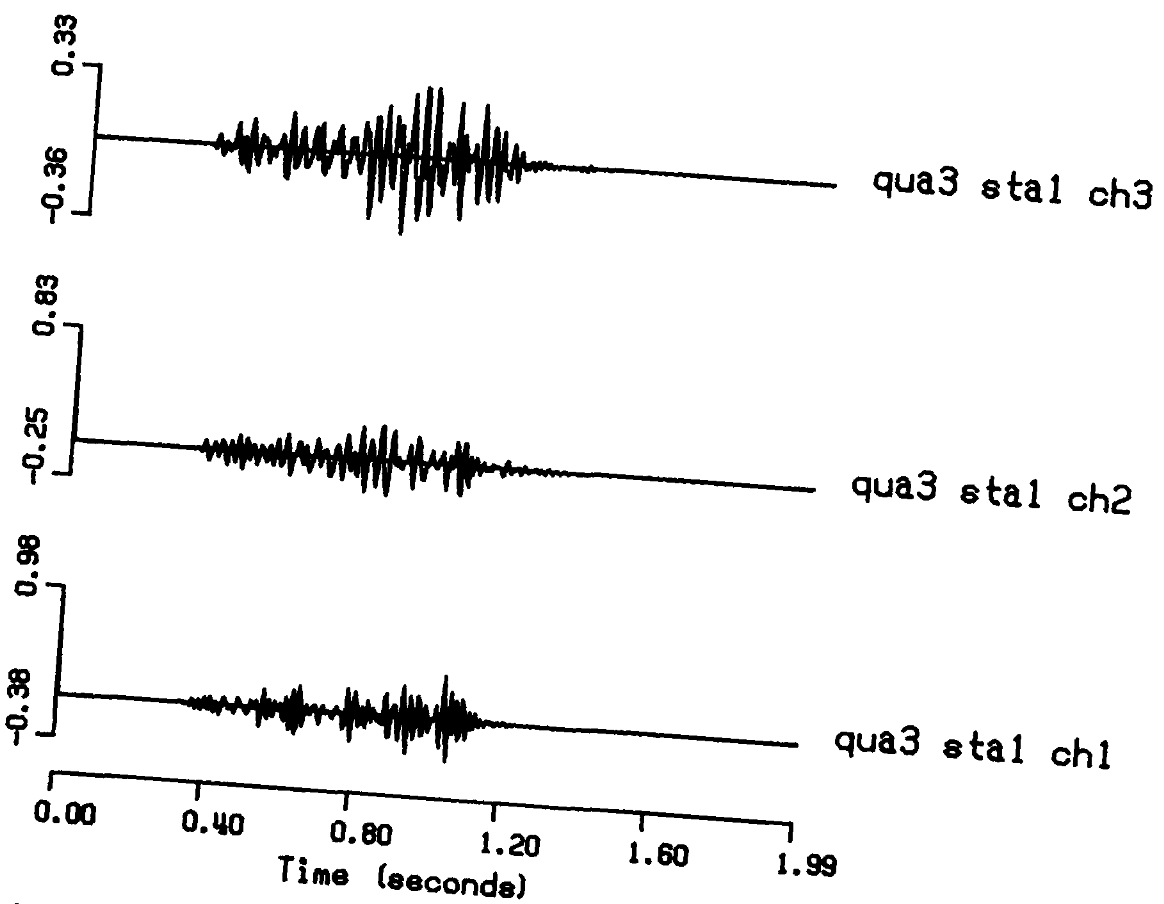


Figure 1-31. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A1. See Figure 1-10a

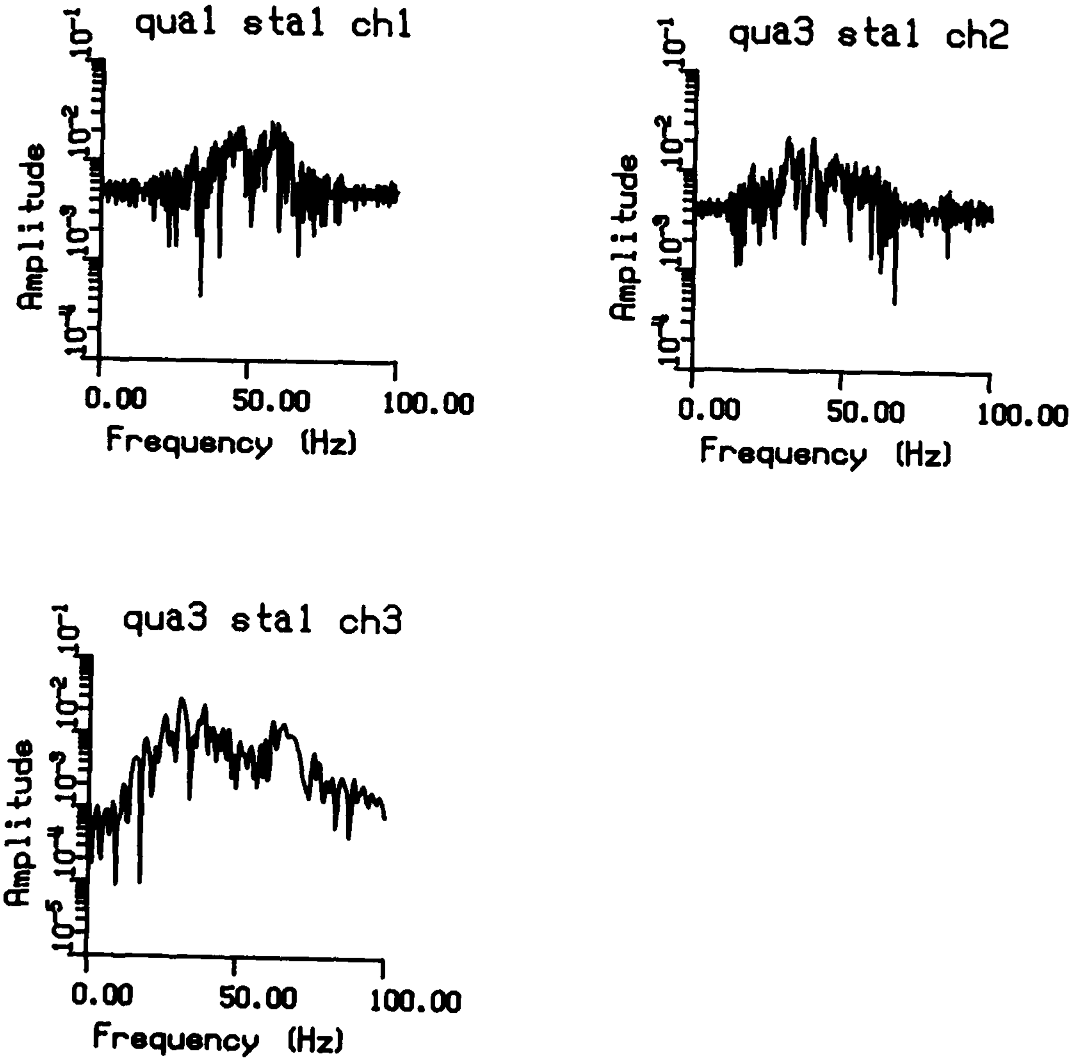


Figure 1-31. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A1. See Figure 1-10b

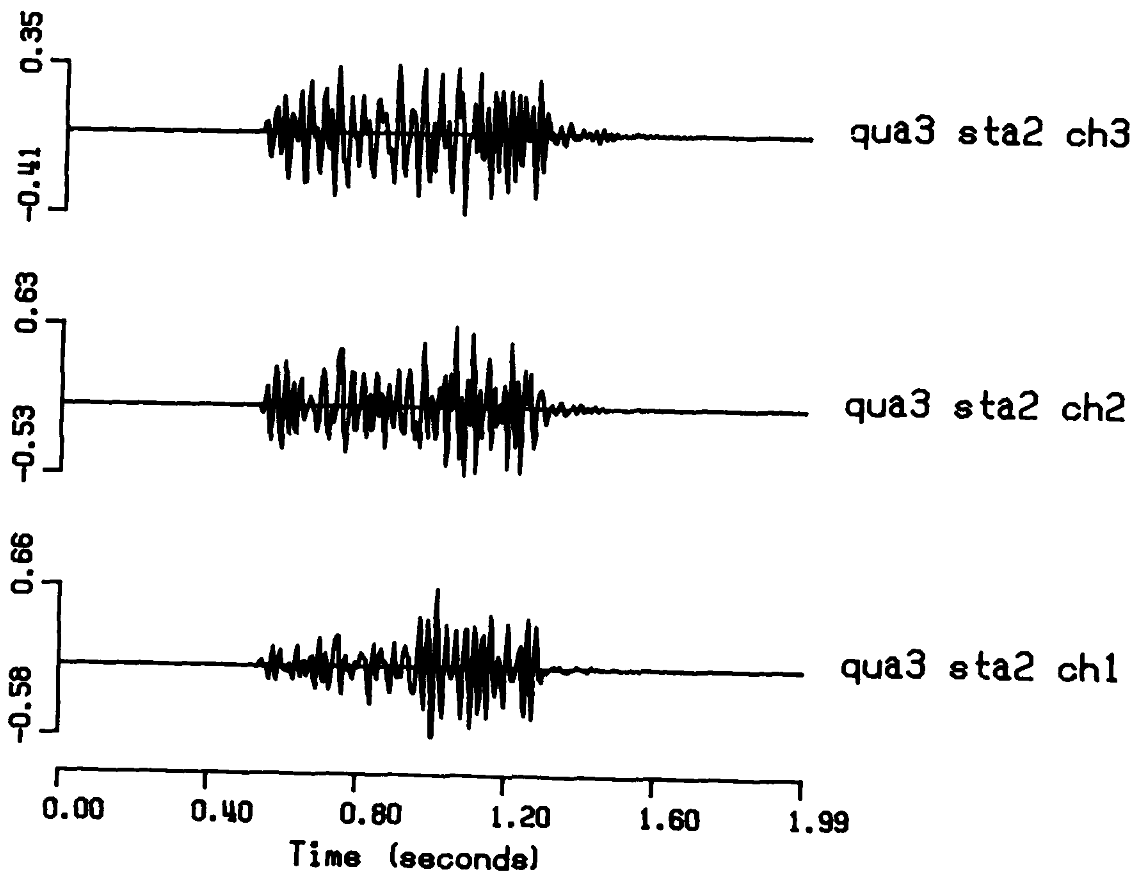


Figure 1-32. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A2. See Figure 1-10a

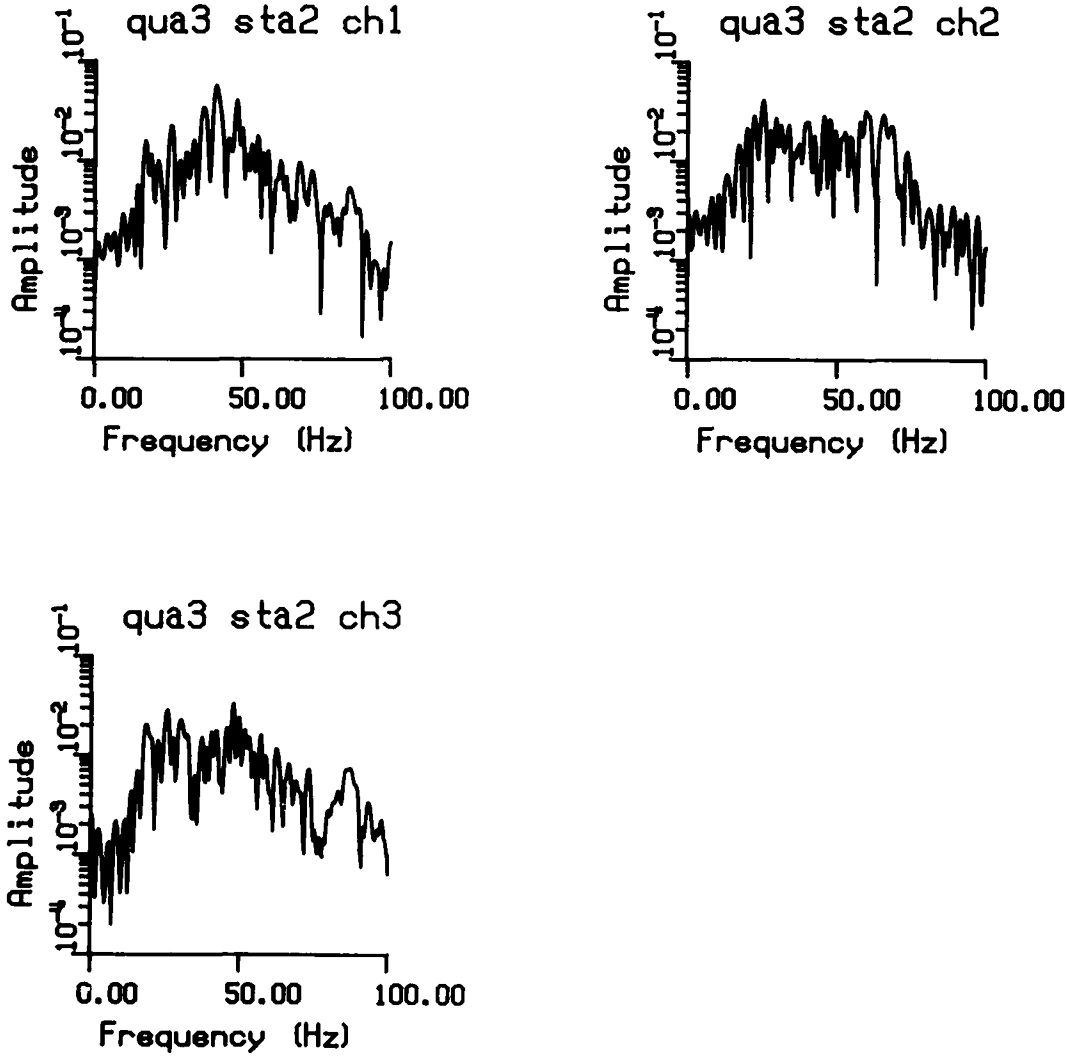


Figure 1-32. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A2. See Figure 1-10b

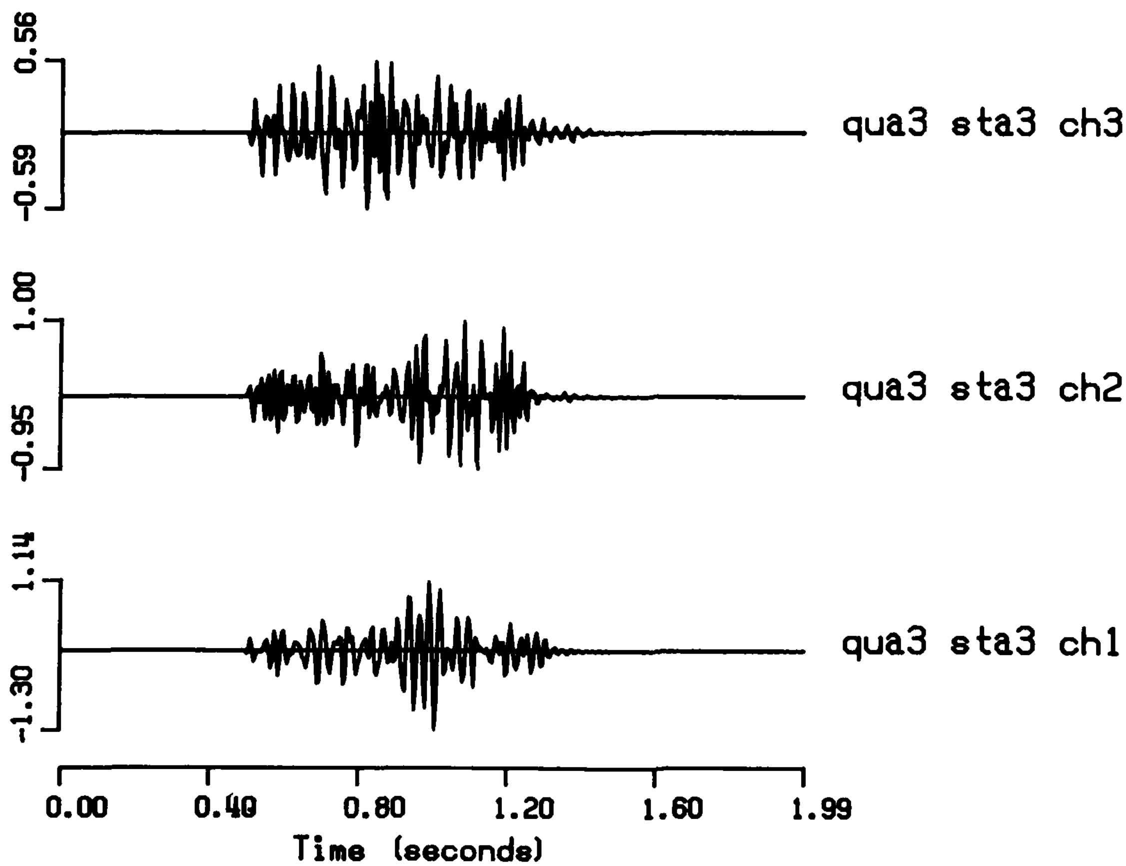


Figure 1-33. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A3. See Figure 1-10a

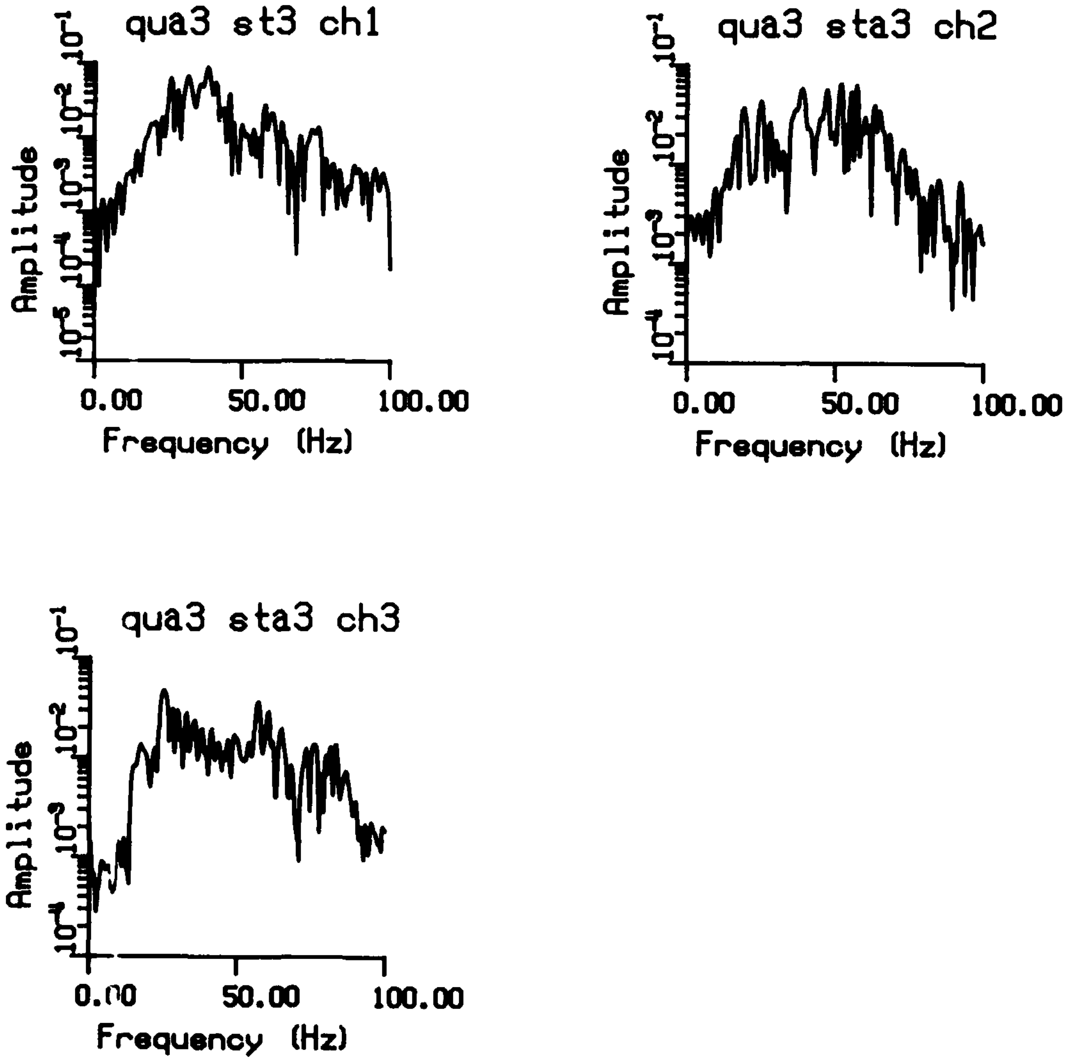


Figure 1-33. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A3. See Figure 1-10b

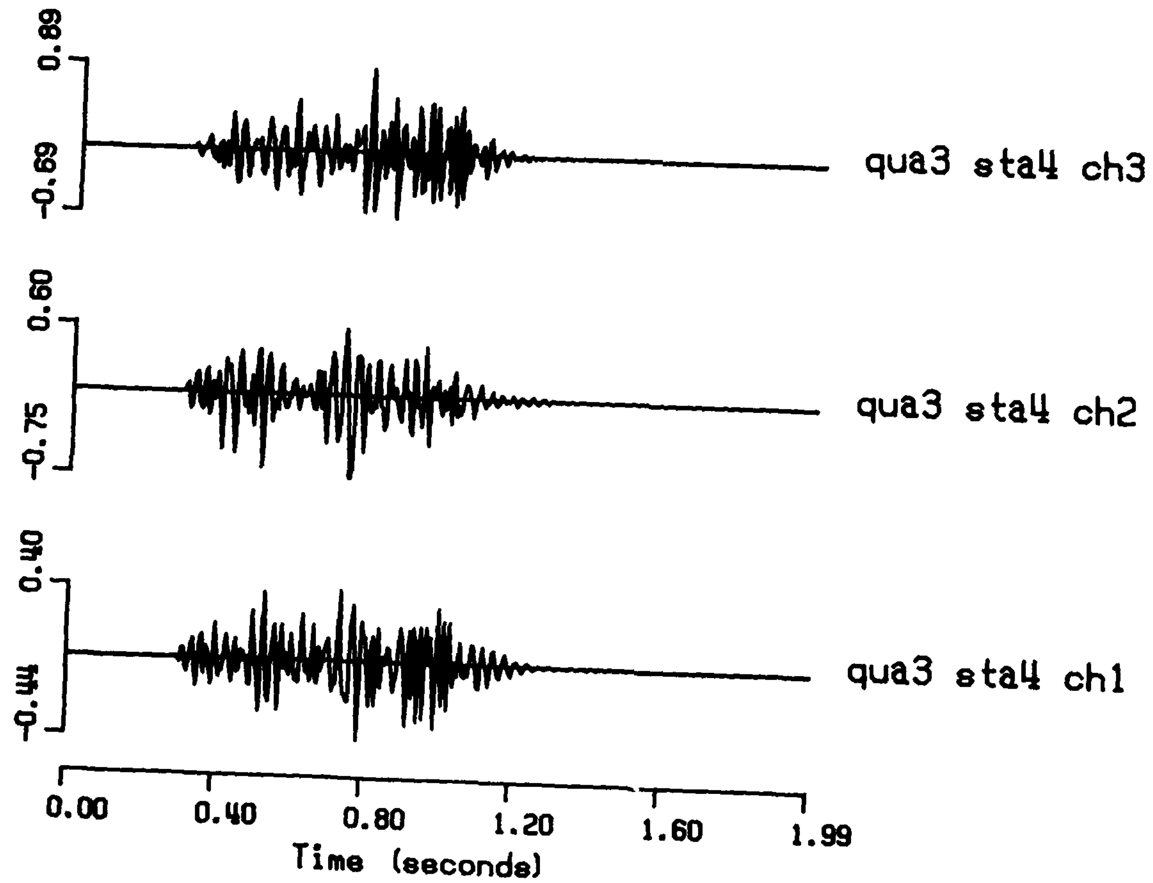


Figure 1-34. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A4. See Figure 1-10a

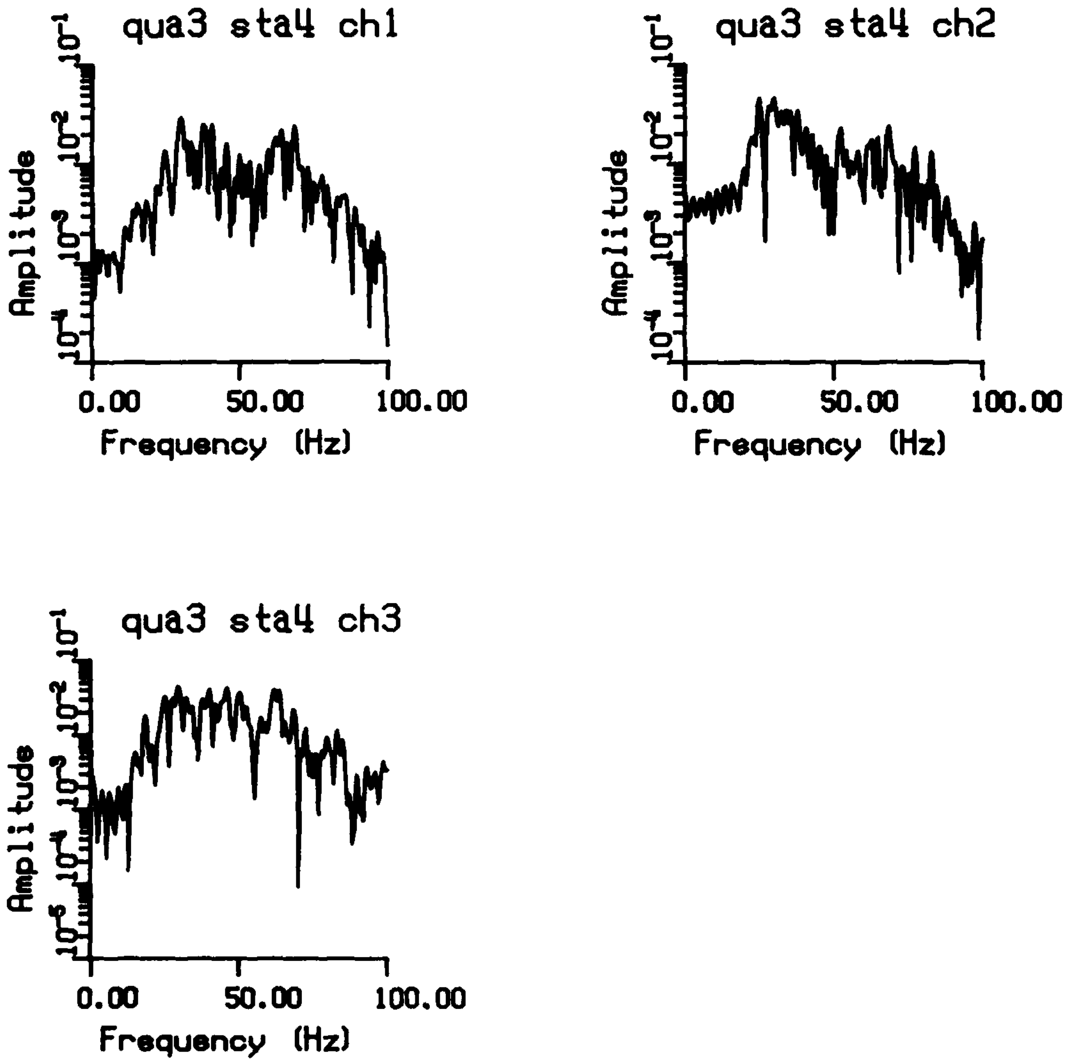


Figure 1-34. (b) Amplitude Spectra for Three Components of Shot QB3 Reccrded at Station A4. See Figure 1-10b

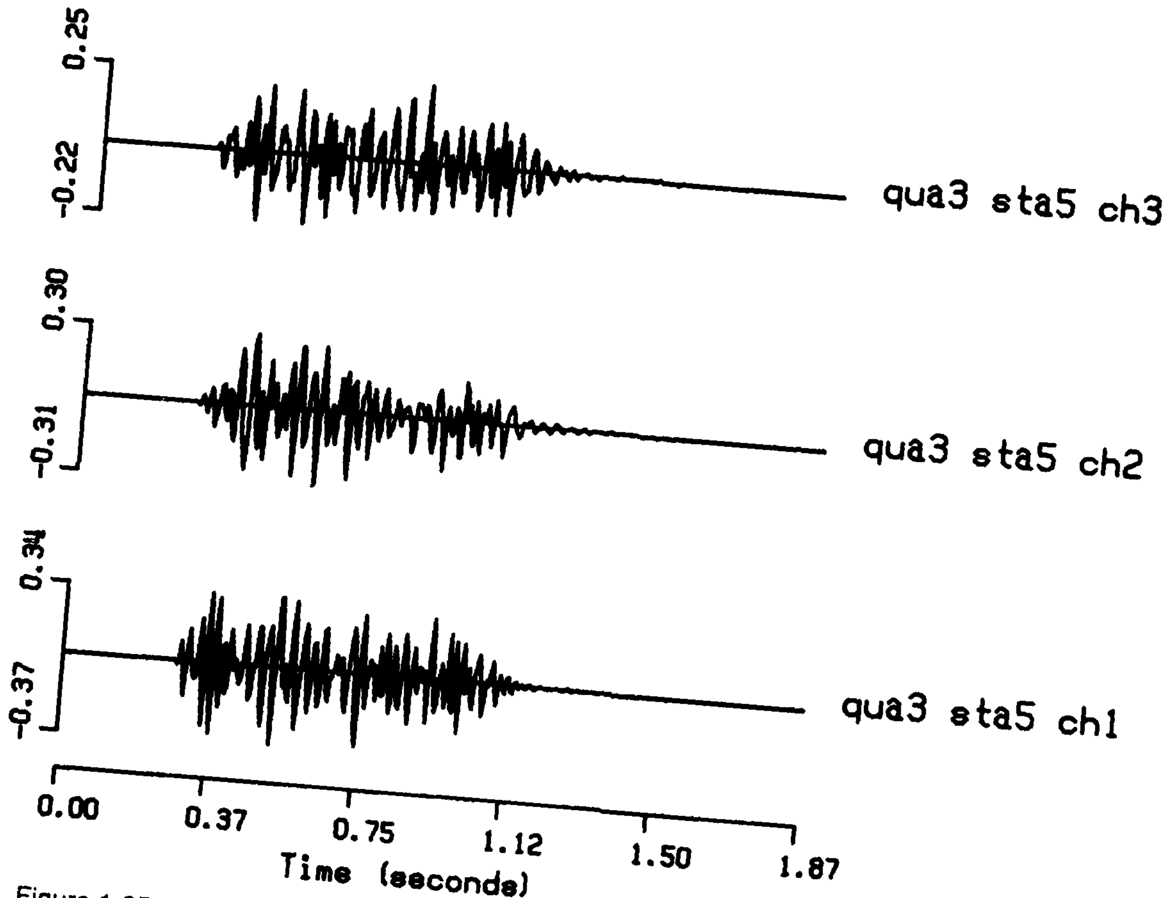


Figure 1-35. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A5. See Figure 1-10a

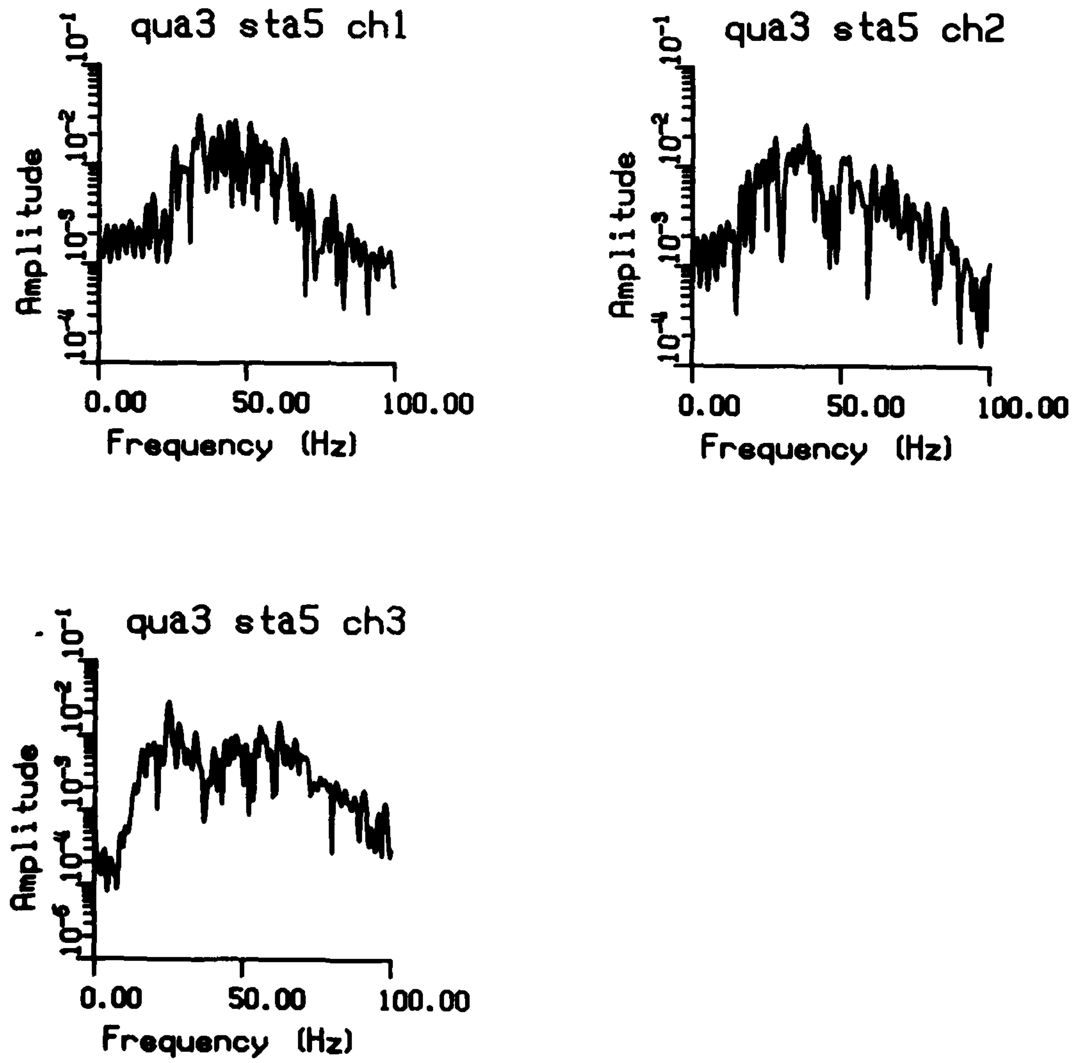


Figure 1-35. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A5. See Figure 1-10b

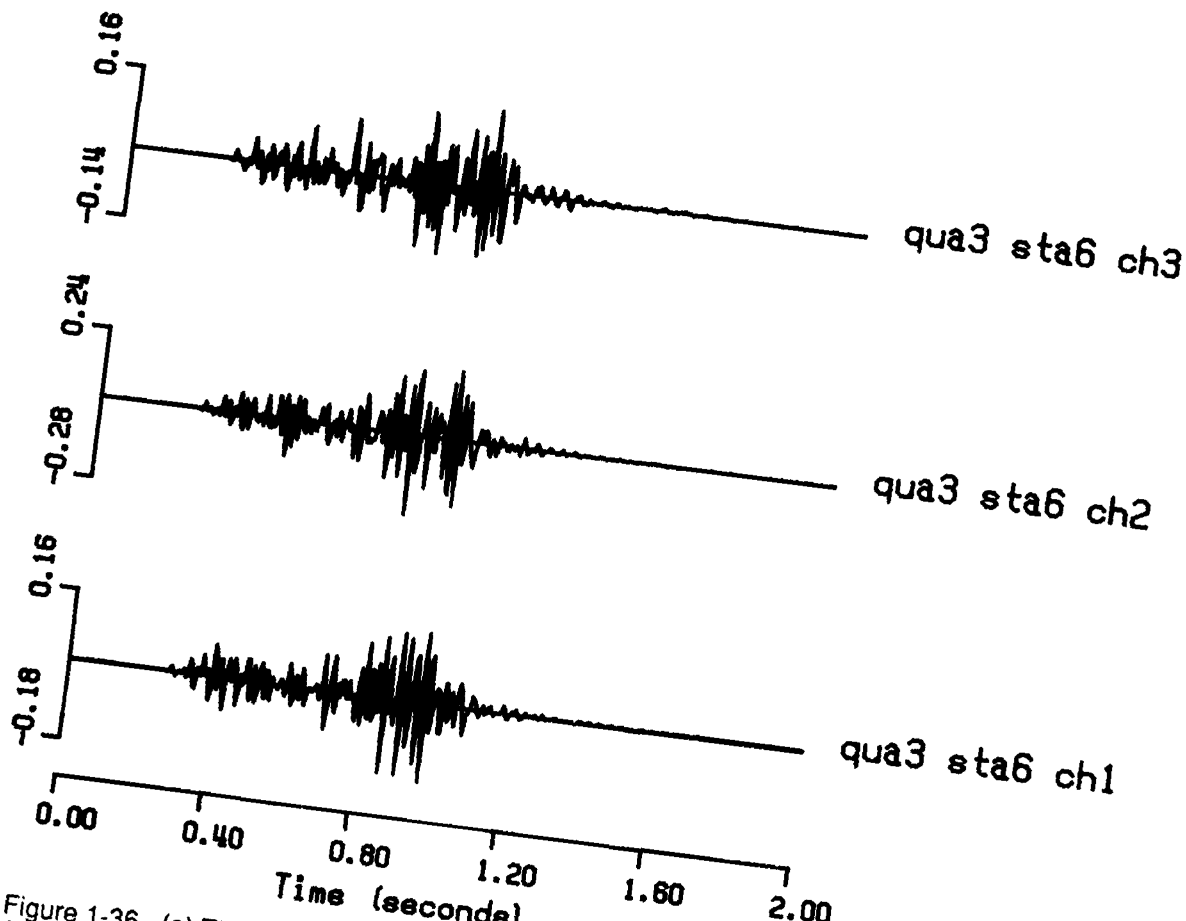


Figure 1-36. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A6.
See Figure 1-10a

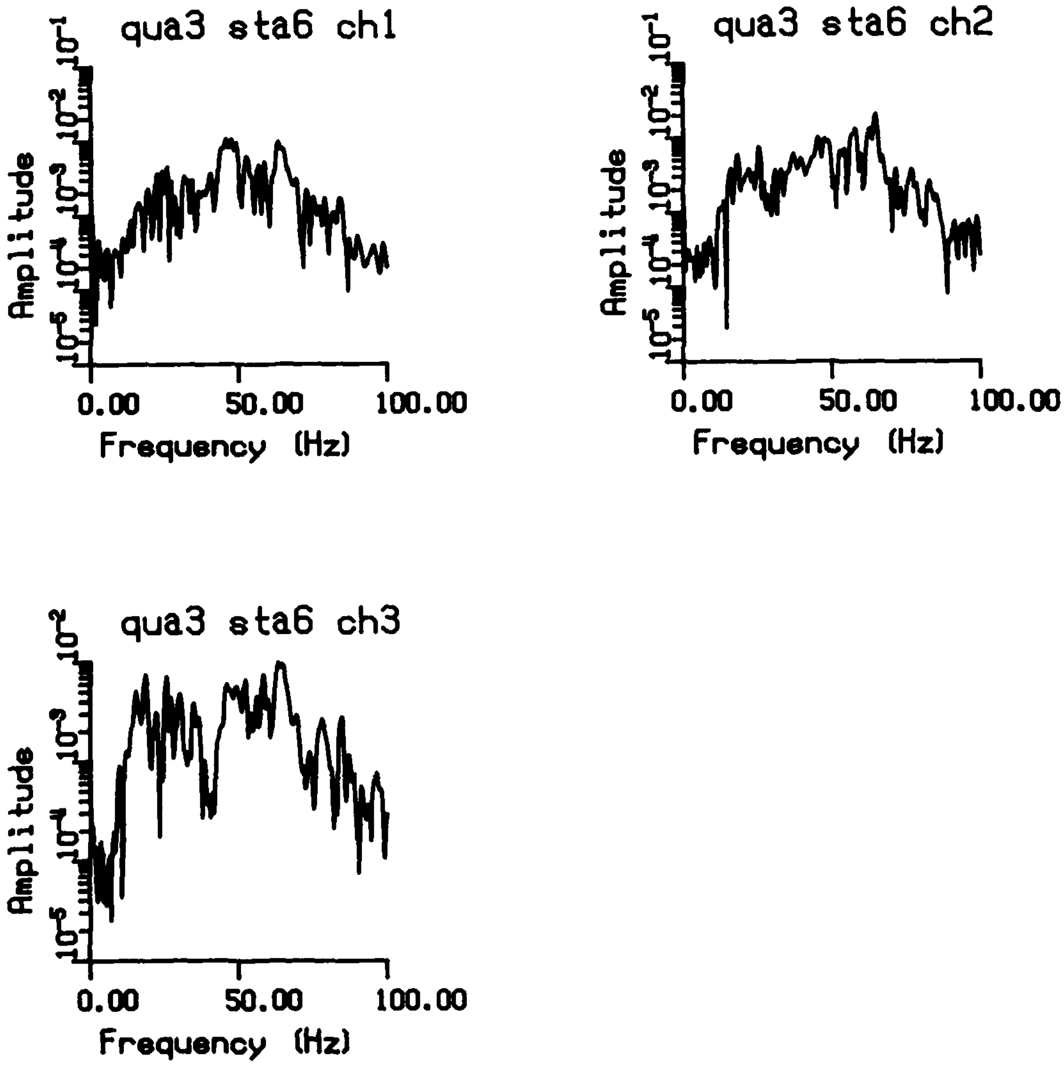


Figure 1-36. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A6. See Figure 1-10b

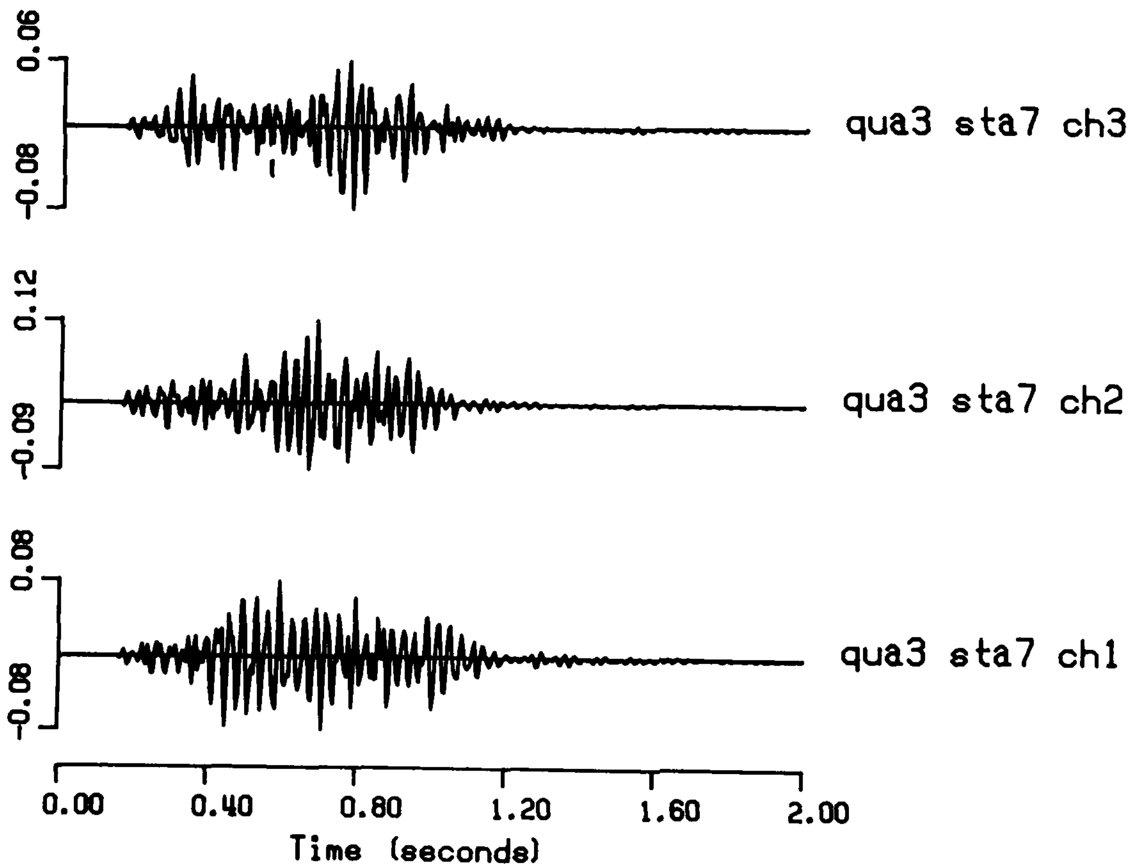


Figure 1-37. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A7. See Figure 1-10a

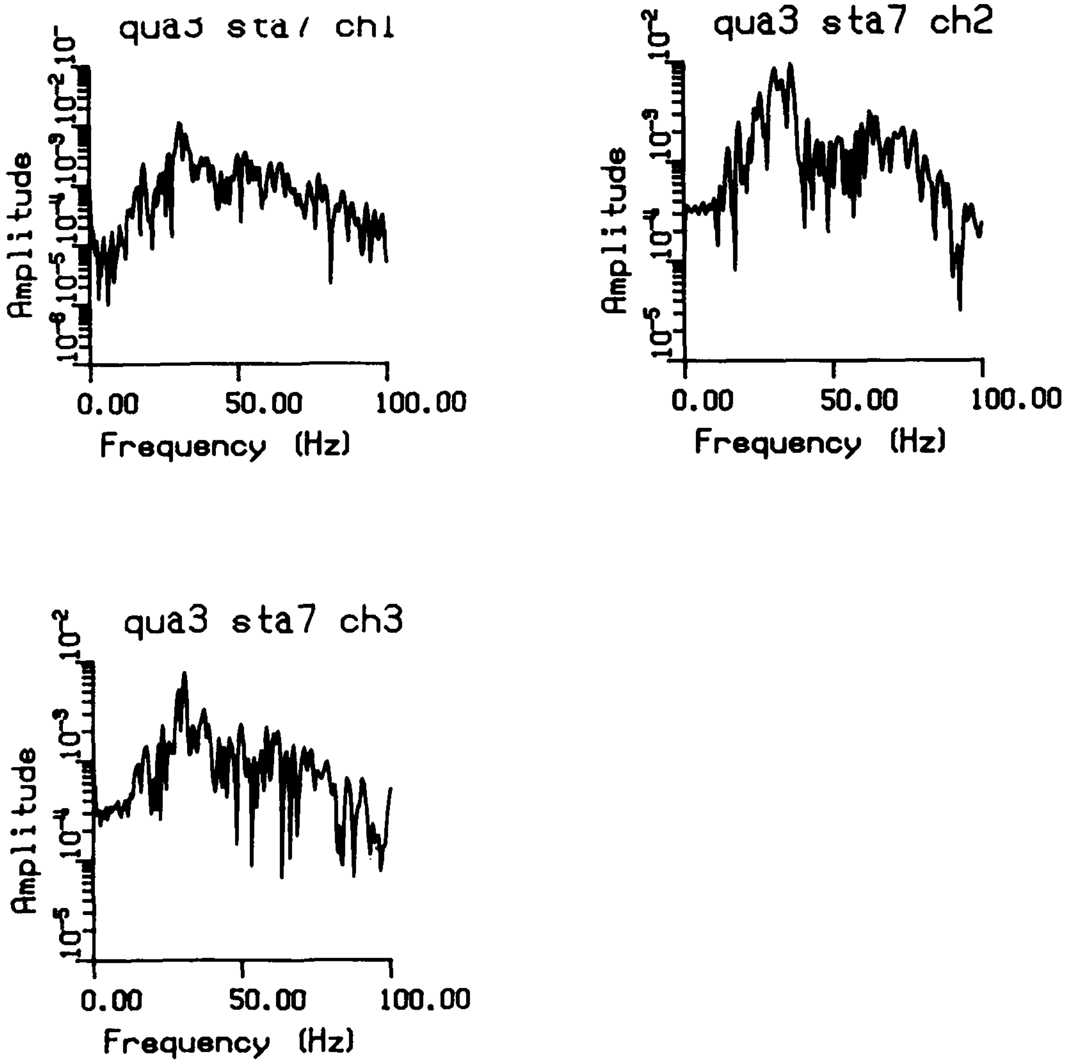


Figure 1-37. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A7. See Figure 1-10b

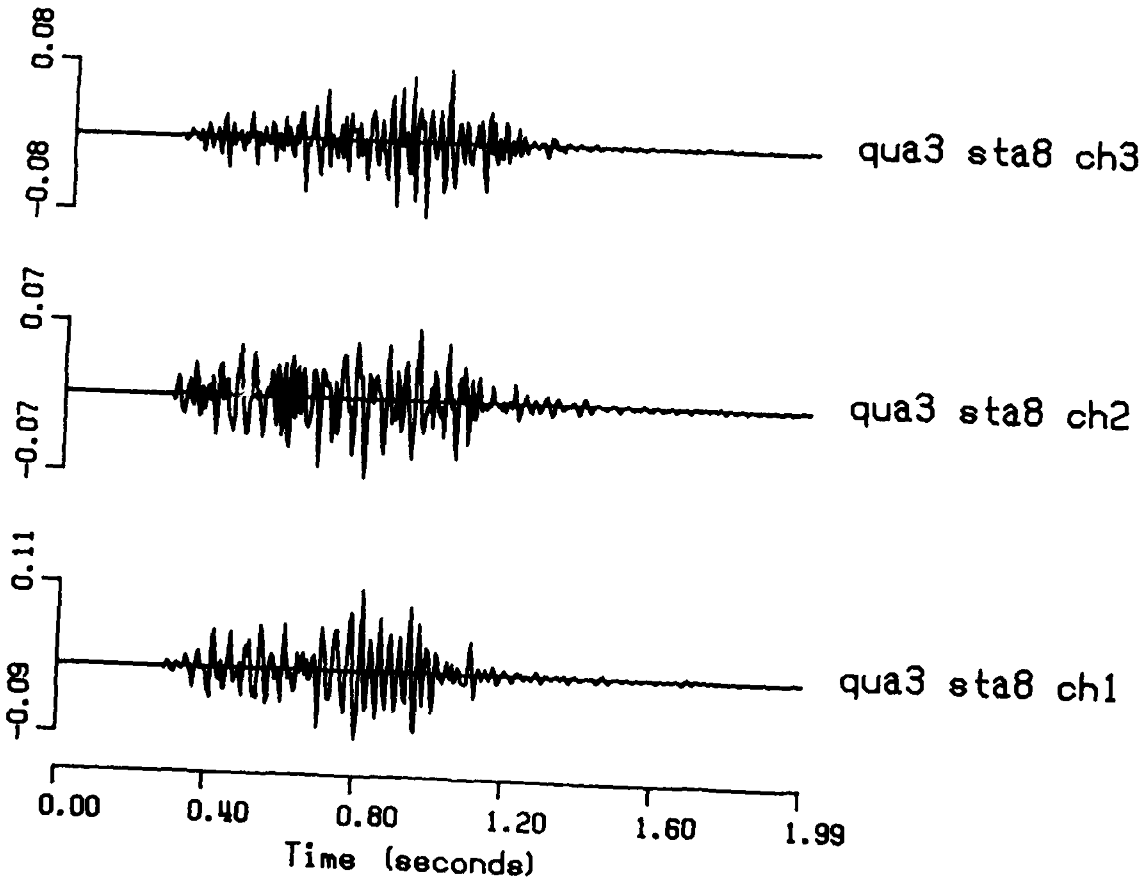


Figure 1-38. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A8. See Figure 1-10a

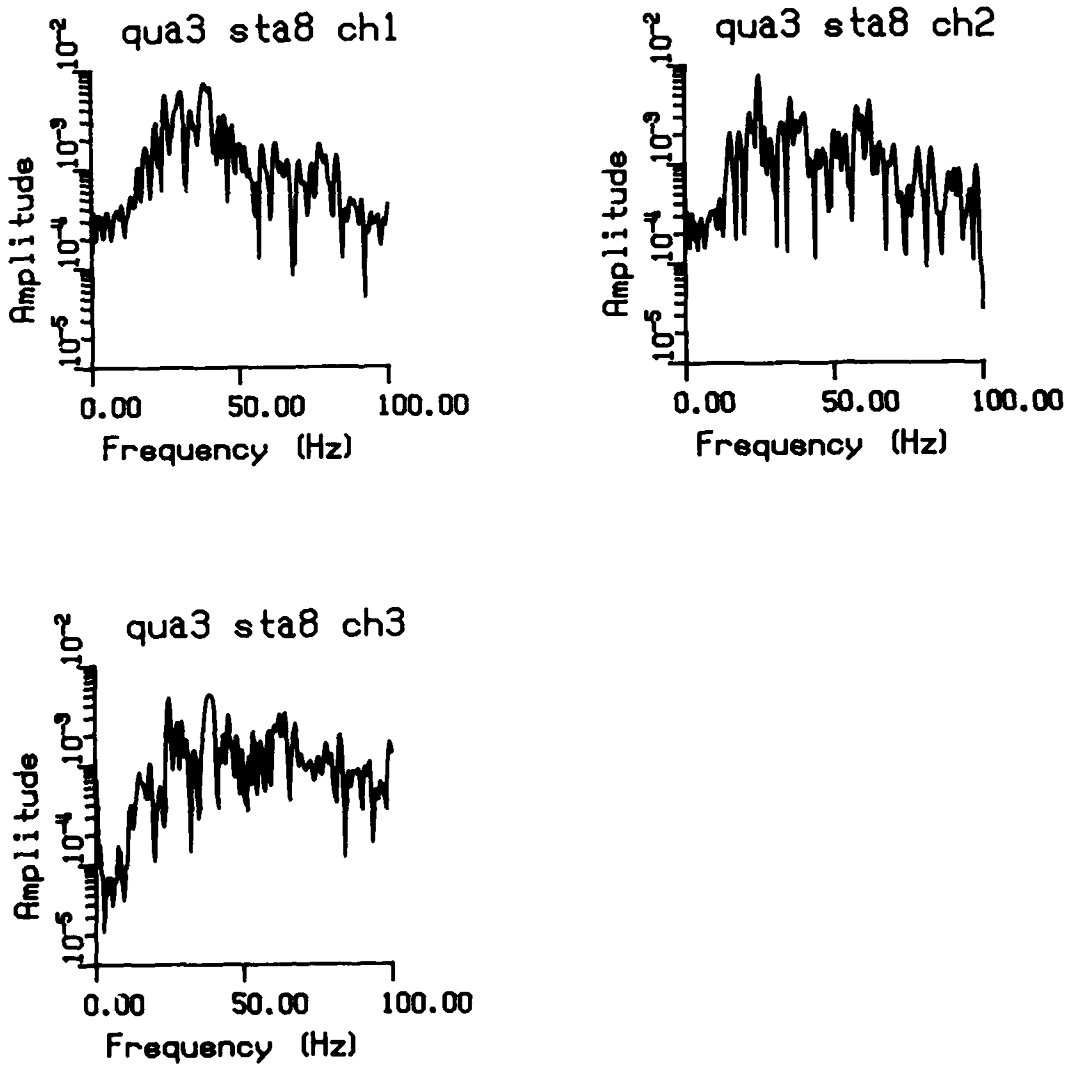


Figure 1-38. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A8. See Figure 1-10b

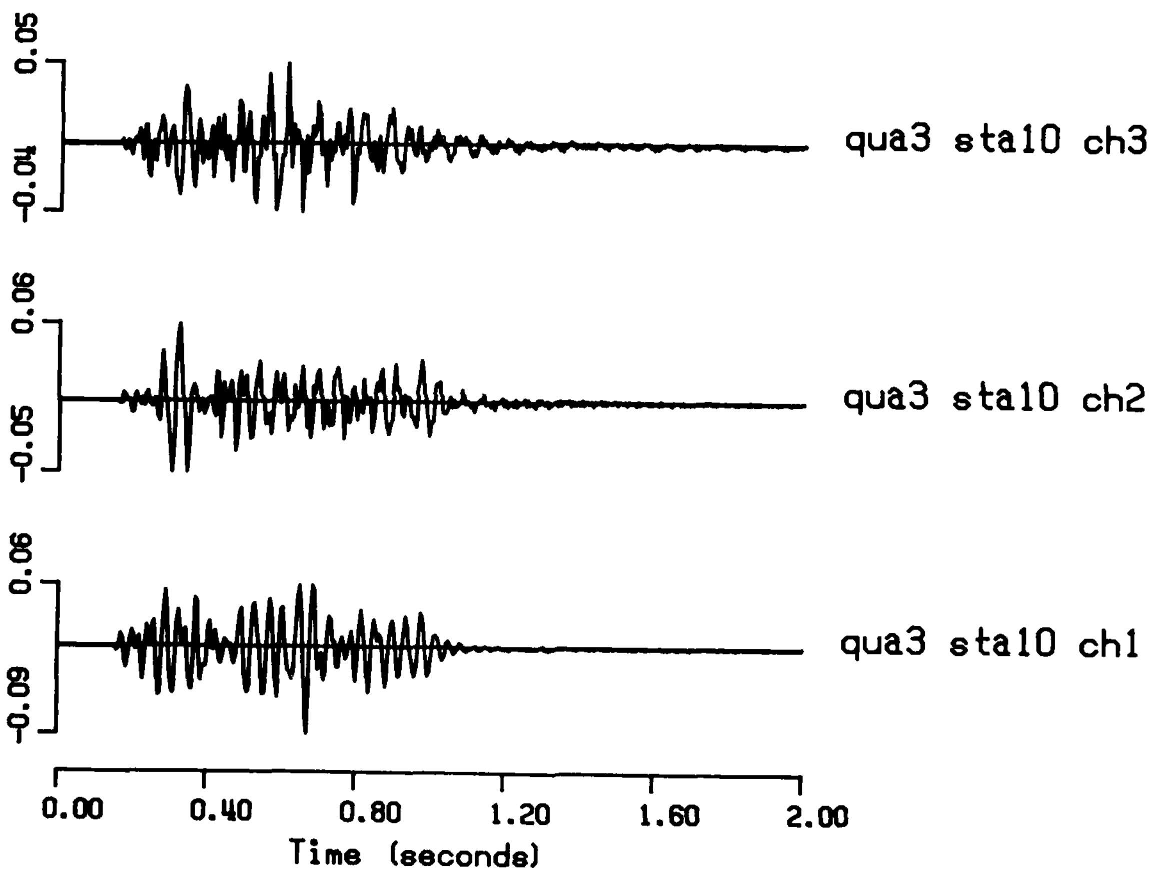


Figure 1-39. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A10. See Figure 1-10a

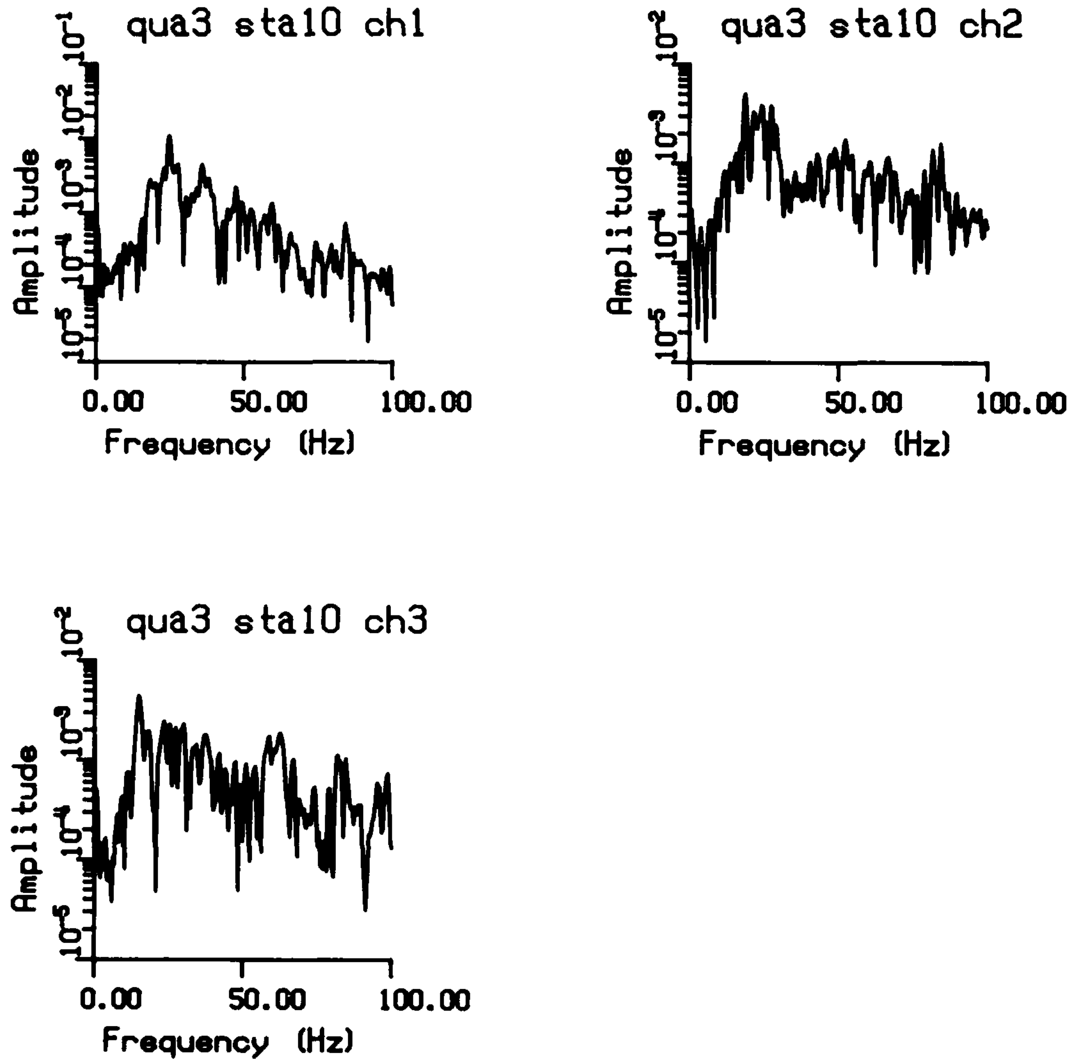


Figure 1-39. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A10. See Figure 1-10b

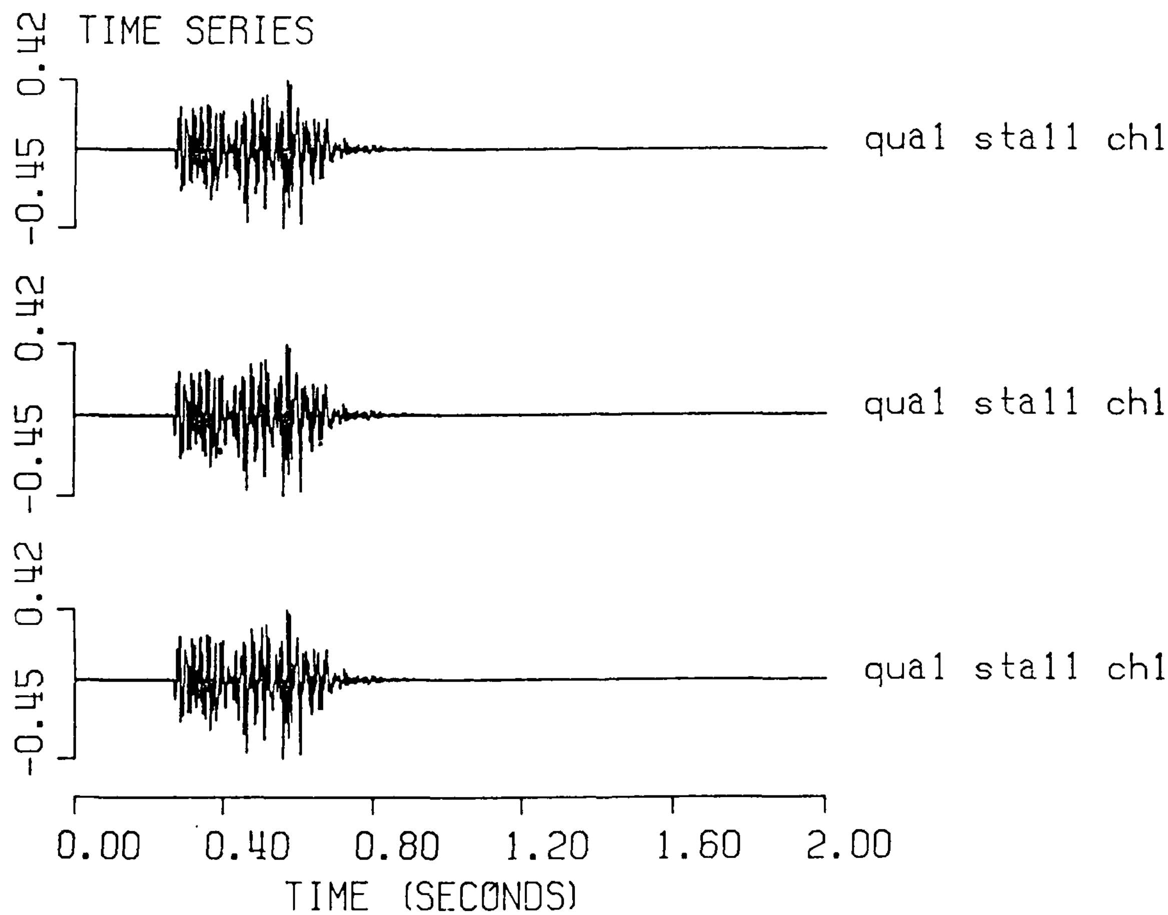


Figure 1-40. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A11 at 600 Samples/Sec. See Figure 1-10a

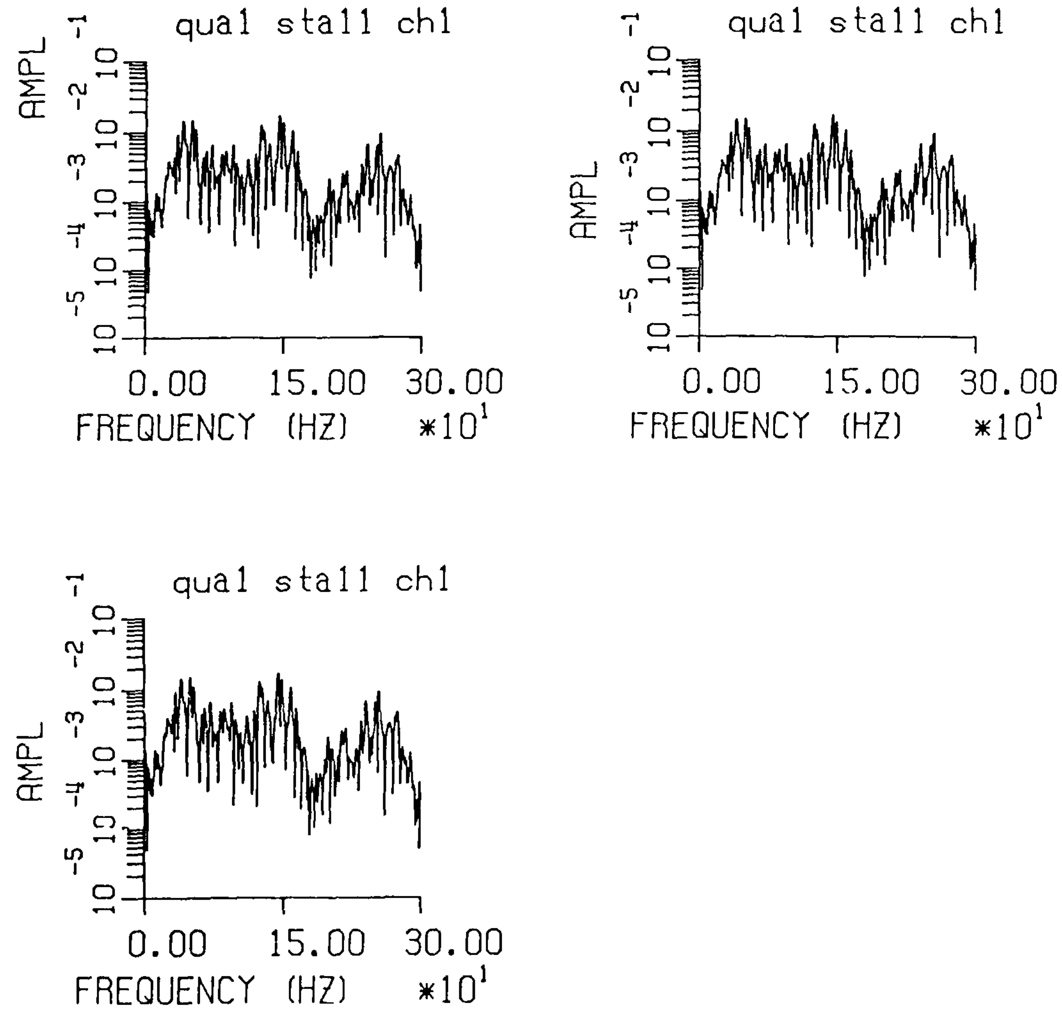


Figure 1-40. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A11. Horizontal scale shows frequency from 0 to 300 Hz. See Figure 1-10b

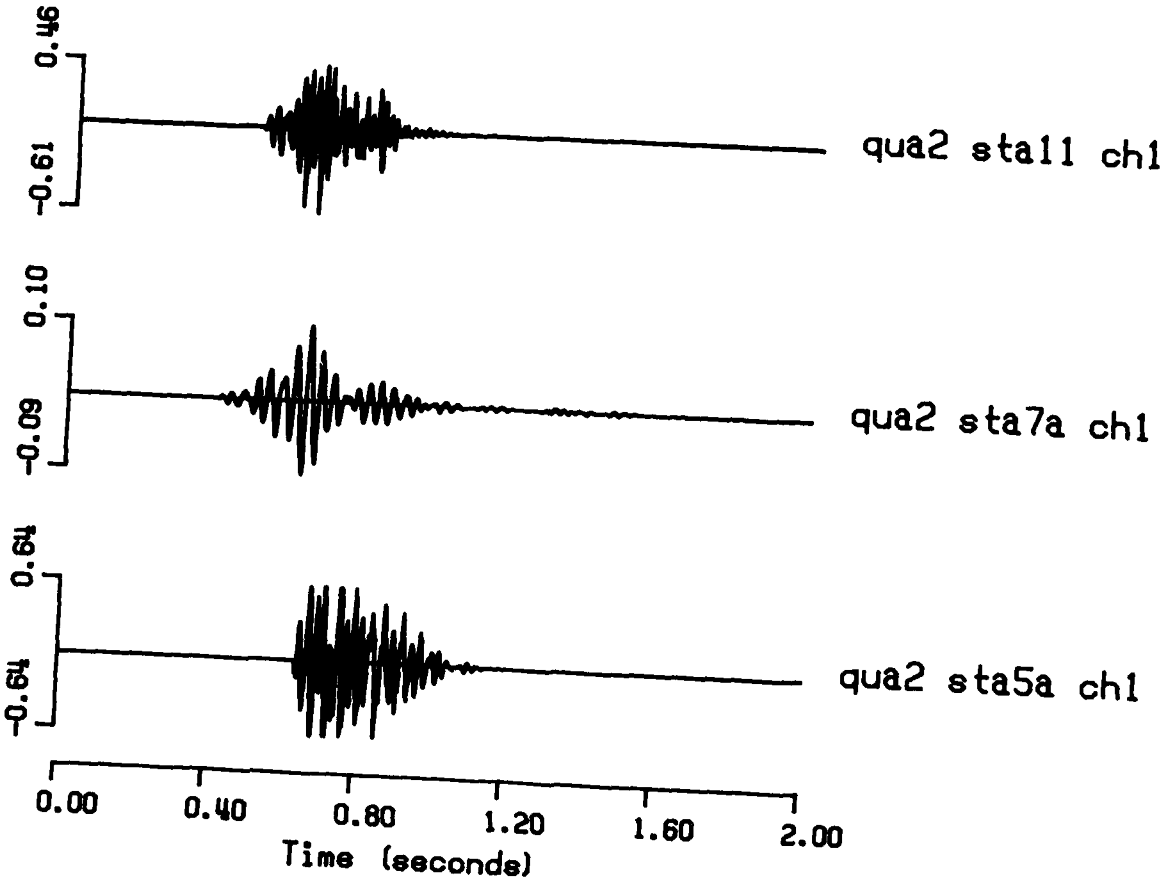


Figure 1-41. (a) Three-Component Accelerogram of Shot QB3 Recorded at Station A11 at 600 Samples/Sec. See Figure 1-10a

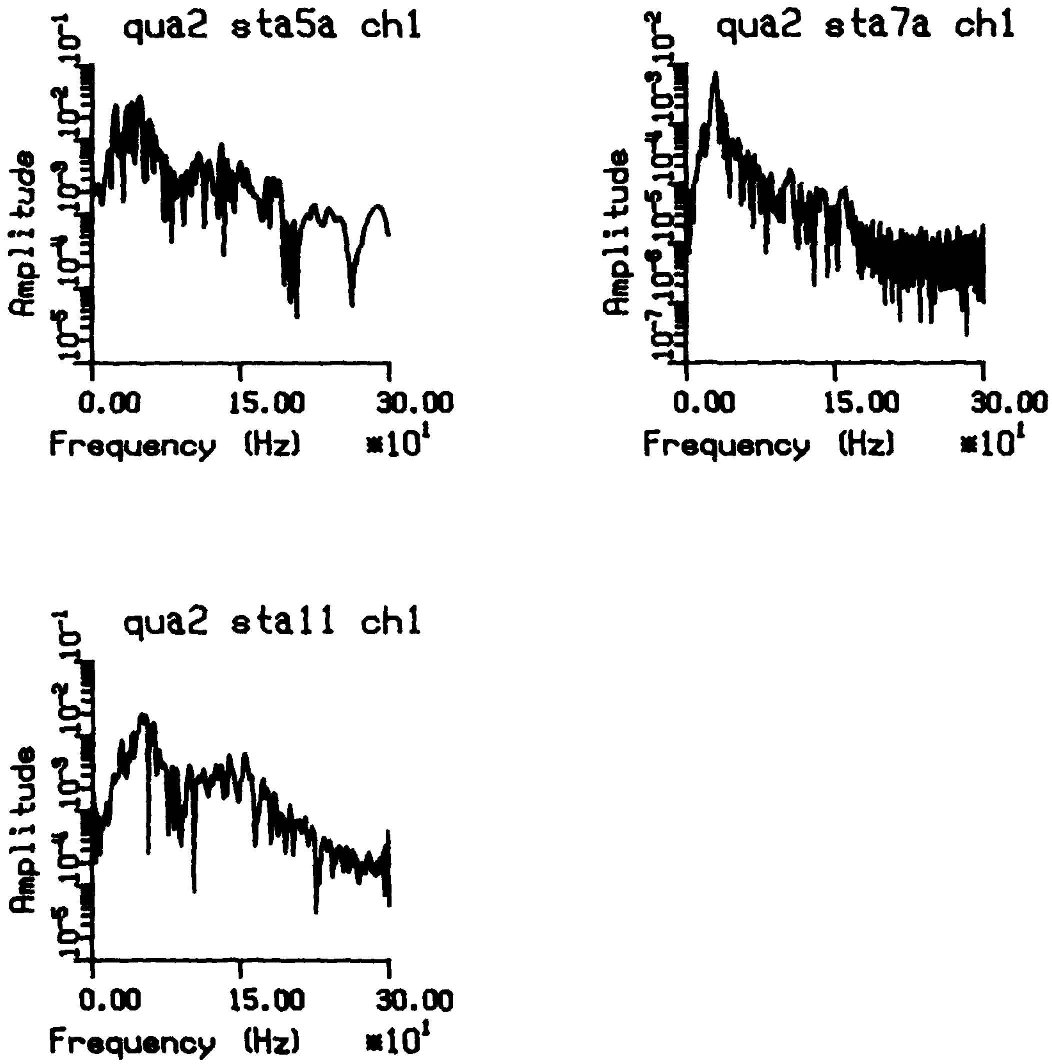


Figure 1-41. (b) Amplitude Spectra for Three Components of Shot QB3 Recorded at Station A11. Horizontal scale shows frequency from 0 to 300 Hz. See Figure 1-10b

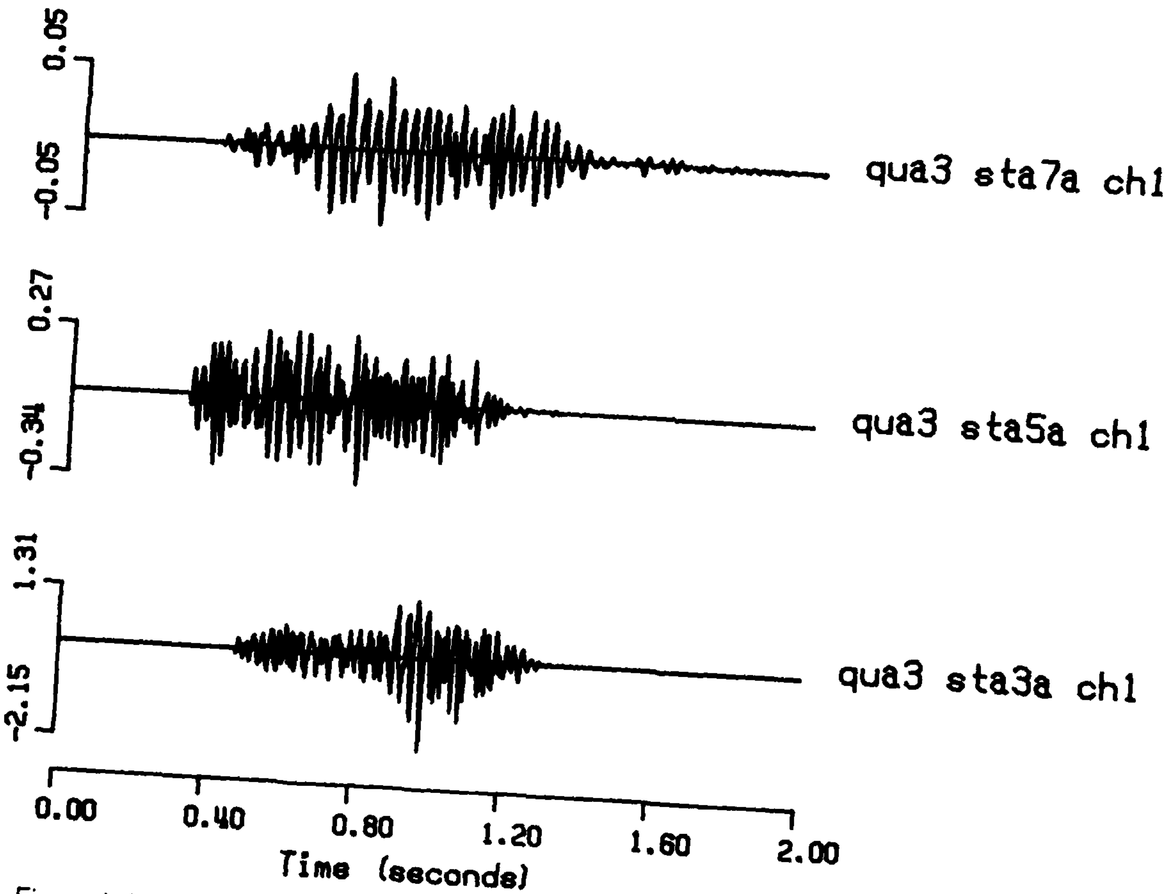


Figure 1-42. (a) Three Vertical-Component Accelerograms of Shot QB3 Recorded at Stations A7a, A5a, and A3a, Respectively, at 600 Samples/Sec. See Figure 1-10

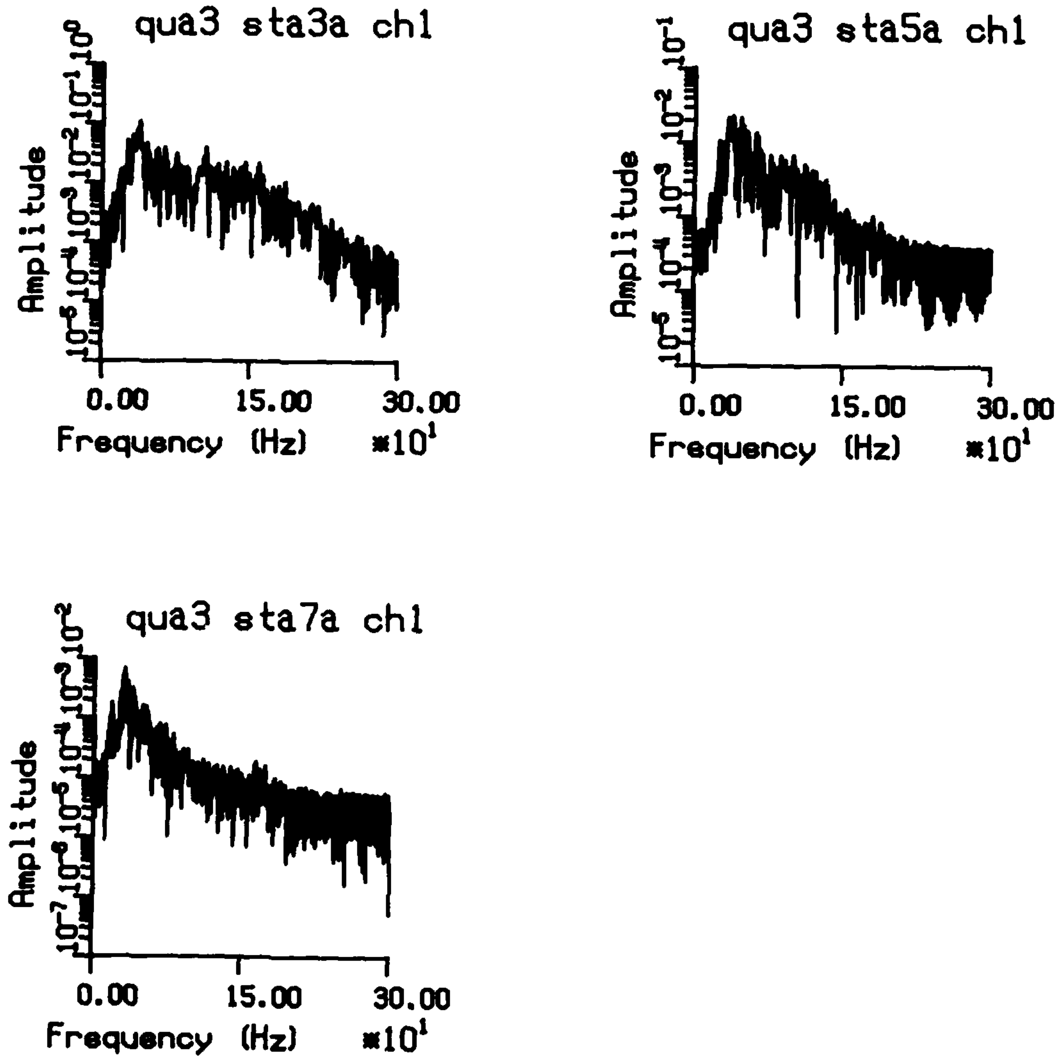


Figure 1-42. (b) Amplitude Spectra for the Three Components Mentioned in Figure 1-42a From Recordings of Shot QB3. Horizontal scale shows frequency from 0 to 300 Hz. See Figure 1-10b

Contents

2. Regional Analysis

by

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Alan Kafka
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In this section, we describe part of the Littleton Quarry Blast Experiment (LQBE) that was conducted by representatives from two institutions: the Earth Resources Laboratory, Massachusetts Institute of Technology (MIT), and Weston Observatory, Boston College (BC). Both of these institutions operate regional seismic networks in New England, and similar field equipment is available at the two institutions. Thus, it was convenient for personnel from these institutions to work in close collaboration. Additional information on this aspect of the LQBE can be obtained from Katherine Kadinsky-Cade (MIT) and Bob Lory (BC).

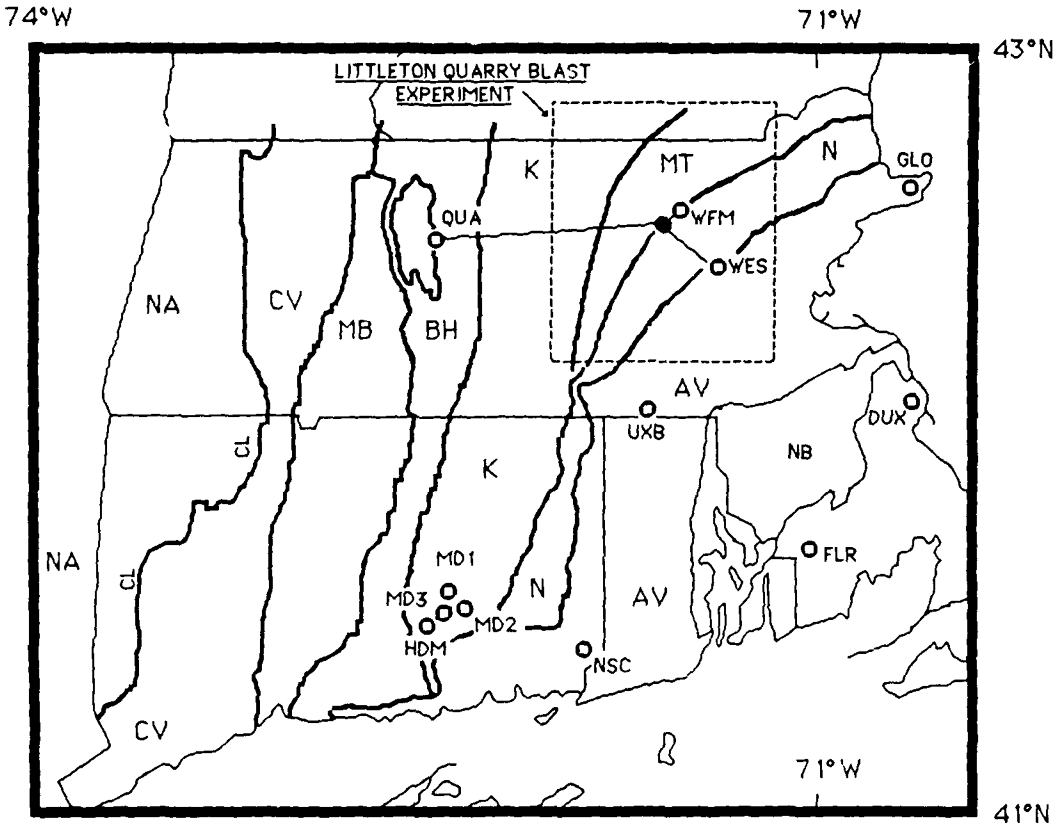
The strategy of the MIT/BC effort was to complement the simultaneous experiments being conducted by the AFWL/SMU and AFGL groups (near-source recording, NORESS-type array, and linear profile between 0 and 25 km from the source), while also providing an independent data set that could be analyzed as a unit by the MIT/BC group. MIT/BC participated in all three of the quarry blast experiments (QBI--15 July, QB2--21 July, QB3--29 July). For QB1 (15 July), MIT/BC instruments were positioned at the westernmost end of the AFGL Profile array, which extended west from the quarry in the direction of Quabbin Reservoir, where BC station QUA is located. The five MIT/BC stations (P111-P115) were located at a range of 26-32 km from the quarry. During this first blast, two of the five instruments failed and only stations P112, P113, and P115 successfully recorded the shot. Due to serious malfunctioning of one recorder and one seismometer, the number of instruments was reduced to four 3-component stations for the remaining experiments after pooling our working equipment. We had 100 percent data recovery for QB2 and QB3. For QB2 (21 July), we deployed our four instruments along a line between the quarry and the AFGL's NORESS-type array located 21 km SW of the quarry (stations LC1-LC4). The MIT/BC instruments were intended to be equally spaced along this linear segment, but population and terrain conditions in the area required a variable spacing. For QB3 (29 July), we set up an azimuthal array: the four MIT/BC instruments were deployed approximately equidistant from the quarry, but at varying azimuths (stations AZ1-AZ4). The distance from the quarry was chosen to be as close as possible to the distance from the Air Force array to the quarry. This configuration was designed to examine the source radiation pattern and the azimuthal variation in wave propagation through the laterally heterogeneous New England crust.

Figures 2-1 and 2-2 show the configuration of the MIT/BC portable instruments and the locations of permanent stations of the MIT and BC regional networks as well as the general features of the geology of the region. Latitude, longitude, and elevation of the field sites are listed in Table 2-1 for all three quarry blasts.

1. EQUIPMENT AND FIELD PROCEDURES

The seismometers used by the MIT/BC group were 2 Hz, 3-component Sprengnether S6000s. Digital recorders were Sprengnether DR200s. Recorder clocks were synchronized about 1 to 2 hr before each quarry blast with one of three available Kinemetrics satellite-synchronized clocks: one each at MIT and BC, and one portable satelite clock belonging to the Air Force Geophysics Laboratory. Recorder clocks were compared with the satellite clocks after each experiment. Recorder clock drift measurements are shown in Table 2-2.

Sites were selected by investigating each general site area on the day before each quarry blast. At each potential site, a noise study was conducted using a Sprengnether MEQ-800 smoke drum recorder and a buried 1 Hz (HS-10) vertical seismometer. Sites



NA = North American Craton
CL = Cameron's Line
CV = Connecticut Valley Synclinorium
MB = Mesozoic Basin
BH = Bronson Hill Anticlinorium
K = Kearsarge Synclinorium
N = Nashoba Terrane
AV = Avalonian Terrane
NB = Narragansett Basin
MT = Merrimack Trough

O STATIONS
● BLASTS

Figure 2-1. Regional Tectonic Map Showing the San-Vel Quarry Site and Some of the MIT/BC Permanent Regional Seismic Network Stations

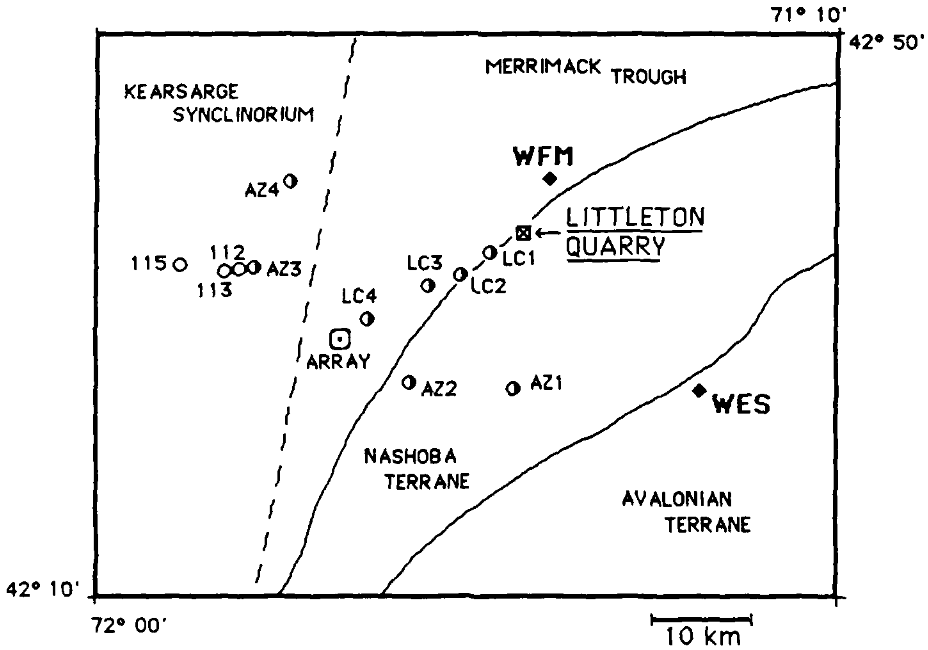


Figure 2-2. Detailed Map of the MIT/BC Station Locations in the Field Area

Table 2-1. Field Site Locations

SITE	LATITUDE	LONGITUDE	ELEVATION	USGS MAP
Blast # 1				
112	42.5145 °N	71.8396 °W	915 feet	Fitchburg
113	42.5121	71.8546	850	Fitchburg
115	42.5187	71.9054	1225	Gardner
Blast # 2				
LC1	42.5312	71.5571	315	Ayer
LC2	42.5071	71.5910	360	Ayer
LC3	42.4962	71.6267	230	Clinton
LC4	42.4603	71.6935	370	Clinton
Blast #3				
AZ1	42.3864	71.5311	210	Hudson
AZ2	42.3937	71.6467	435	Clinton
AZ3	42.5156	71.8221	845	Fitchburg
AZ4	42.6079	71.7821	625	Fitchburg
Selected Permanent Sites				
WES	42.3847	71.3221	197	Concord
QUA	42.4566	72.3738	659	Quabbin Reservoir
WFM	42.6106	71.4906	285	Westford

Notes:

(1) The site numbers for Blast #1 are chosen to match the AFGL site numbers along the same linear profile. LC terminology for Blast #2 means Littleton-Clinton, i.e., sites located between the Littleton quarry and the Clinton NORESS-type array. AZ in Blast#3 means azimuthal.

(2) Permanent network sites other than WES, QUA and WFM are not shown here, but can be easily obtained from MIT and BC.

(3) The USGS maps are the 7.5 minute topographic quadrangle series (for Massachusetts).

Table 2-2. Recorder Clock Drifts

Blast, site	Recorder#	time set /clock	time checked/clock	offset
1, 112	173	(196)14:13:00 /AFGL	(196)21:58 /AFGL	0.011s (F)
1, 113	210	(196)14:37:50 /AFGL	(197)00:01:30 /MIT	0.002s (F)
1, 115	178	(196)14:36:10 /AFGL	(197)00:09:20 /MIT	0.001s (S)
2, LC1	178	(202)14:06:30 /BC	(202)19:23 /BC	0.001s (S)
2, LC2	210	(202)13:59:30 /BC	(202)19:21 /BC	0.001s (F)
2, LC3	201	(202)13:37:00 /BC	(202)20:26:15 /BC	0.005s (S)
2, LC4	173	(202)13:42:30 /BC	(202)20:28:30 /BC	0.009s (F)
3, AZ1	201	(210)13:47:30 /BC	(211)14:15 /BC	0.017s (S)
3, AZ2	173	(210)13:52:10 /BC	(211)14:24 /BC	0.030s (F)
3, AZ3	178	(210)13:50:00 /MIT	(210)23:12:00 /MIT	0.001s (S)
3, AZ4	210	(210)13:50:30 /MIT	(210)23:12:30 /MIT	0.002s (F)

Notes:

(1) (F), (S) in offset column mean fast, slow with respect to satellite clock used.

(2) The AFGL clock is a Kinemetrics portable satellite clock (model 468-FPC). The MIT and BC clocks are non-portable Kinemetrics satellite clocks (model 468-DC).

(3) The offset between satellite clock and recorder clock were measured using a strip chart recorder in the cases of the AFGL and BC satellite clocks. In the case of the MIT satellite clock, offsets were measured using a home-built comparator with a digital display, with resolution 1 msec.

(4) Before these offsets are used to correct the data, it will be necessary to compare the three satellite clocks. These may or may not have been corrected for position.

were rejected if they were too noisy with the MEQ-800 set at the 72-78 dB level. Background noise could generally be correlated with traffic or wind, but was sometimes inferred to result from buried pipes or other non-apparent sources. Once a favorable site was found, the 3-component seismometer was buried and camouflaged so that it would not be disturbed overnight. It was oriented so that the "Longitudinal" arrow pointed towards magnetic north and leveled properly. We took care to ensure that our compass readings were not disturbed by the proximity of seismometer magnets during the determination of magnetic north (a nontrivial consideration). The free connectors (cable terminations) were wrapped in plastic bags for protection from humidity. The final selected sites were generally in close proximity to bedrock, in secluded wooded areas away from large tree roots (to avoid noise generated by wind-blown trees).

Recorder internal batteries were recharged for 2-3 days before each blast. On the day of the blast, we synchronized the recorder clocks, and then set the recorders on trigger. Although the DR200 recorders are capable of recording continuously for over an hour at 100 samples/sec, we decided that the quarry blast time was too unpredictable for the continuous recording mode. Rather than risk running out of tape before the occurrence of a late quarry blast, we chose to set up the recorders to respond to a very sensitive trigger.

This procedure was successful for catching the blasts, although there were often 30-40 false triggers per recorder within a 2-3 hour period. We always set up an MEQ-800 drum recorder at one or two of the sites to visually monitor the quarry blasts. By dispatching someone to phone the quarry and by observing the MEQ records, we could usually tell whether the quarry blast had occurred or had been delayed a couple of hours.

Data were recorded at 100 samples per sec (sps), except at the site closest to the quarry on 21 July (4 km distance from the quarry; sample rate 200 sps). All trigger, filter/amplification settings, and instrument identification for the MIT/BC records are listed in Table 2-3. Plots of 3-component data recorded by MIT/BC portable instruments for all three quarry blasts are included in Figures 2-3 through 2-13.

Table 2-3. Recorder Settings and Recorder/Seismometer ID Numbers

Blast, site #	recorder I.D.	seis. I.D.	trigger*	sample rate(sps)	filters**	gain / range***	pre-event memory	post-event duration
1,112	173	9332	contin.	100	out / 25	x1000 /A	13.3s	50s
1,113	210	8257	ratio	100	out / 25	x1000 /A	13.3s	50s
1,115	178	8778	ratio	100	out / 25	x1000 /A	13.3s	50s
2,LC1	178	8778	ratio	200	out / 50	x100 /A	6.67s	50s
2,LC2	210	8257	ratio	100	out / 25	x1000 /A	13.3s	50s
2,LC3	201	9336	ratio	100	out / 12.5	x1000 /A	13.3s	50s
2,LC4	173	9332	ratio	100	out / 25	x1000 /A	13.3s	50s
3,AZ1	201	9336	ratio	100	out / 25	x1000 /A	13.3s	50s
3,AZ2	173	9332	ratio	100	out / 25	x1000 /A	13.3s	50s
3,AZ3	178	8257	ratio	100	out / 25	x1000 /A	13.3s	50s
3,AZ4	210	8778	ratio	100	out / 25	x1000 /A	13.3s	50s

Notes:

Seismometers were all triaxial. All 3 components were recorded.

* Trigger settings. Continuous means that the recorder was turned on manually, and recorded continuously until the tape was used up. Ratio means that the following settings were used in all cases:

Long term average (LTA) = 25.6 seconds
Short term average (STA)= 0.2 seconds
Ratio (STA/LTA) =6 dB
Logic = OR (i.e., Channel 1 OR 2 OR 3 could trigger the recorder)

**Filters: High pass filter= OUT for all channels
Low pass anti-alias filter corner frequency (e.g., 25 Hz) applied to all channels

***Gains: The first number (e.g., x1000) is the amplifier gain. The subsequent "/A" means that the gain of the analog to digital converter board (ADC) is set for AUTO. This is an instantaneous floating point mode where the gain is varied for each data sample, so as to provide a higher dynamic recording range. Gain steps are 0, 12, 24 and 36 dB.

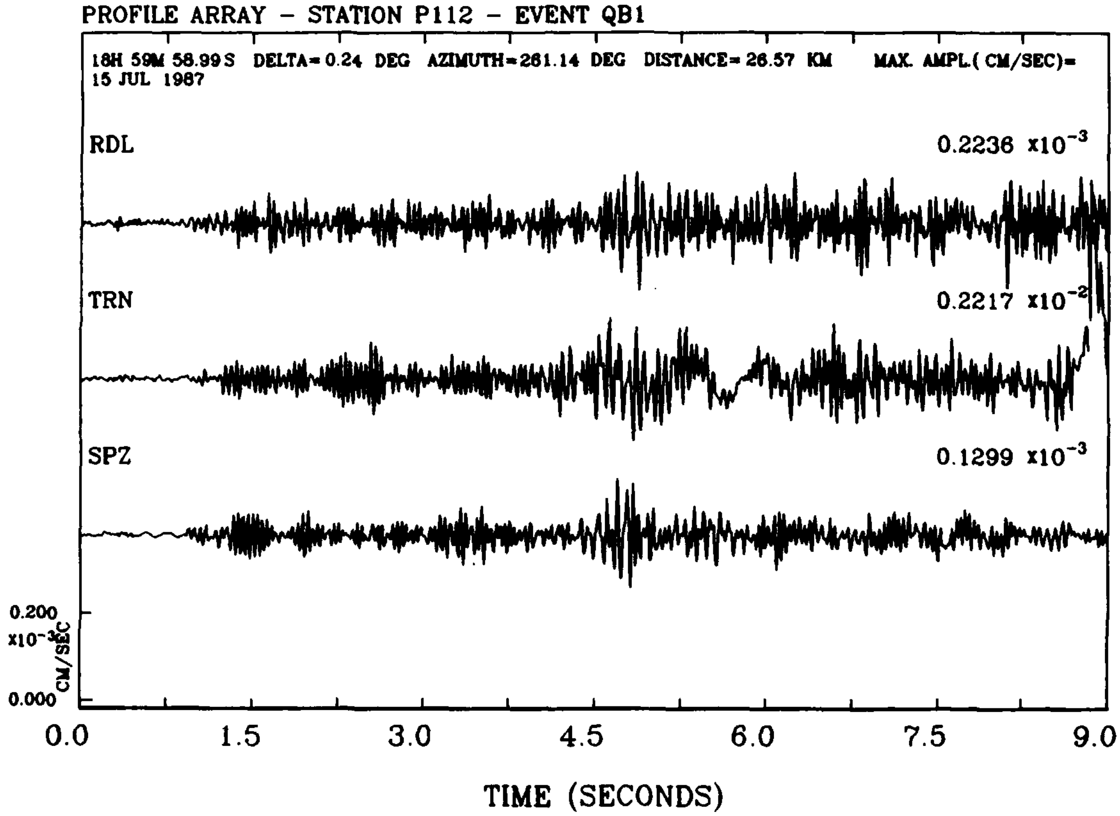


Figure 2-3. Event QB1, Station P112

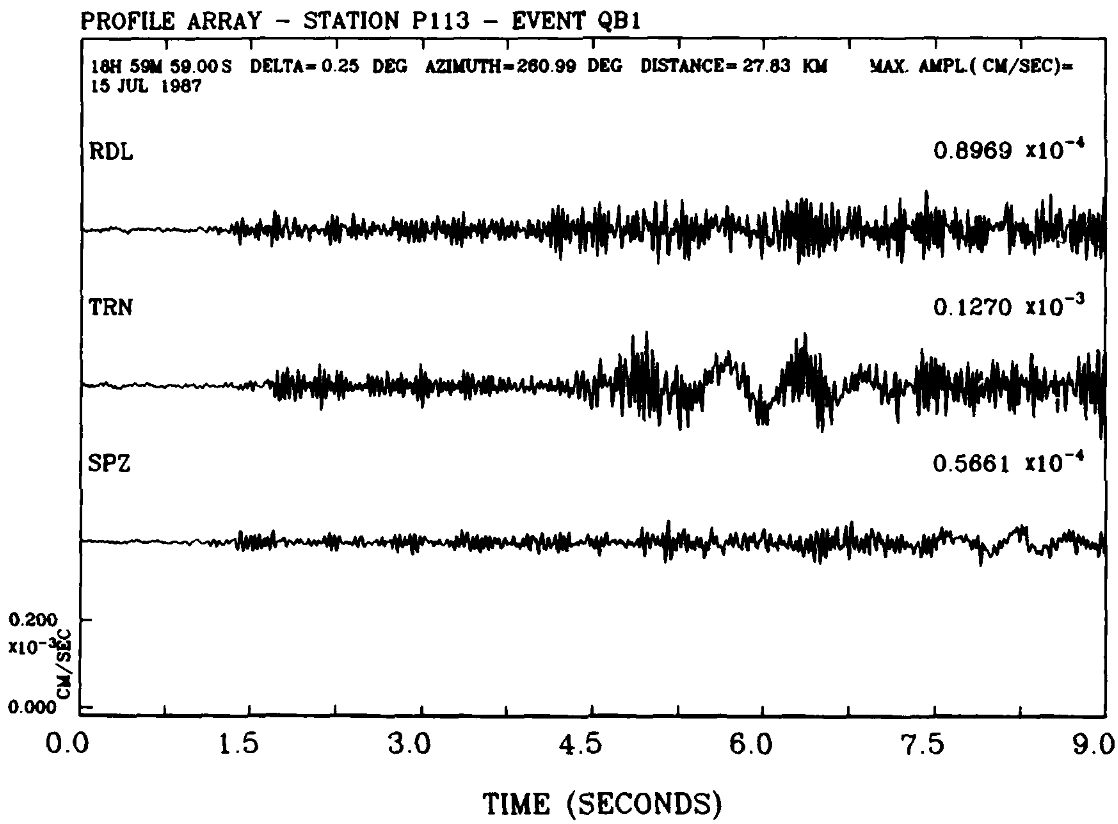


Figure 2-4. Event QB1, Station P113

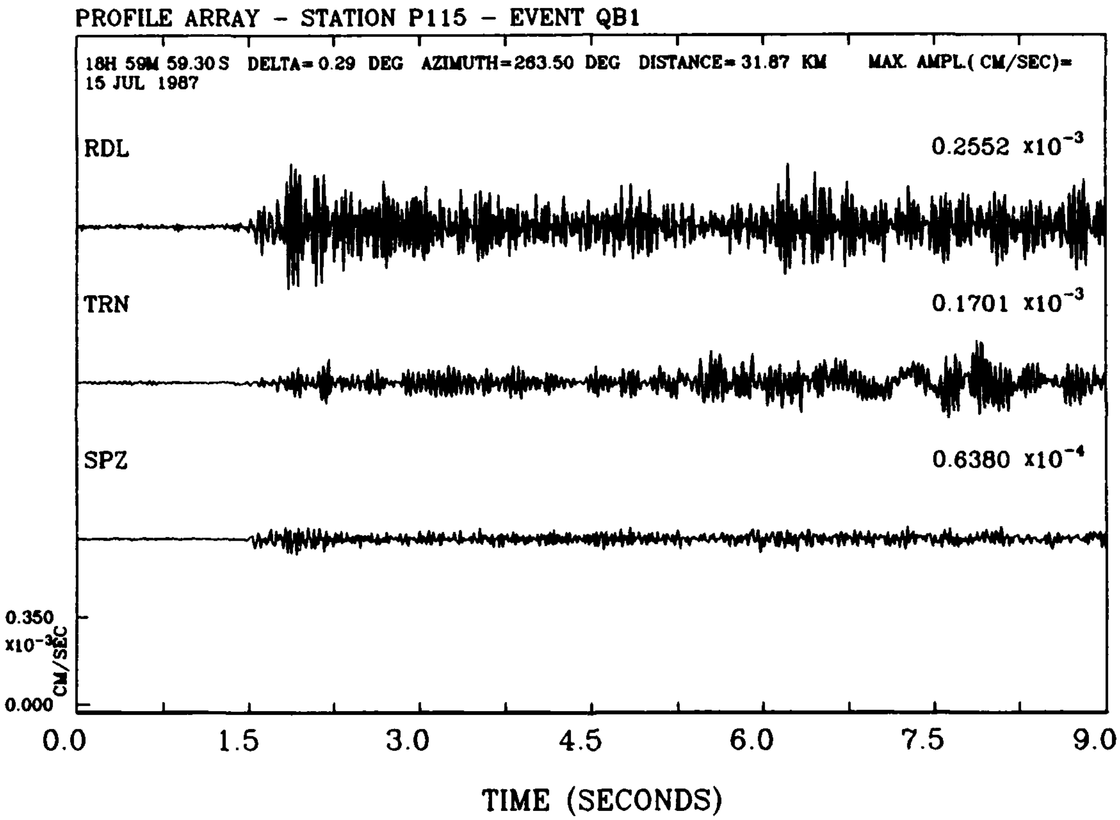


Figure 2-5. Event QB1, Station P115

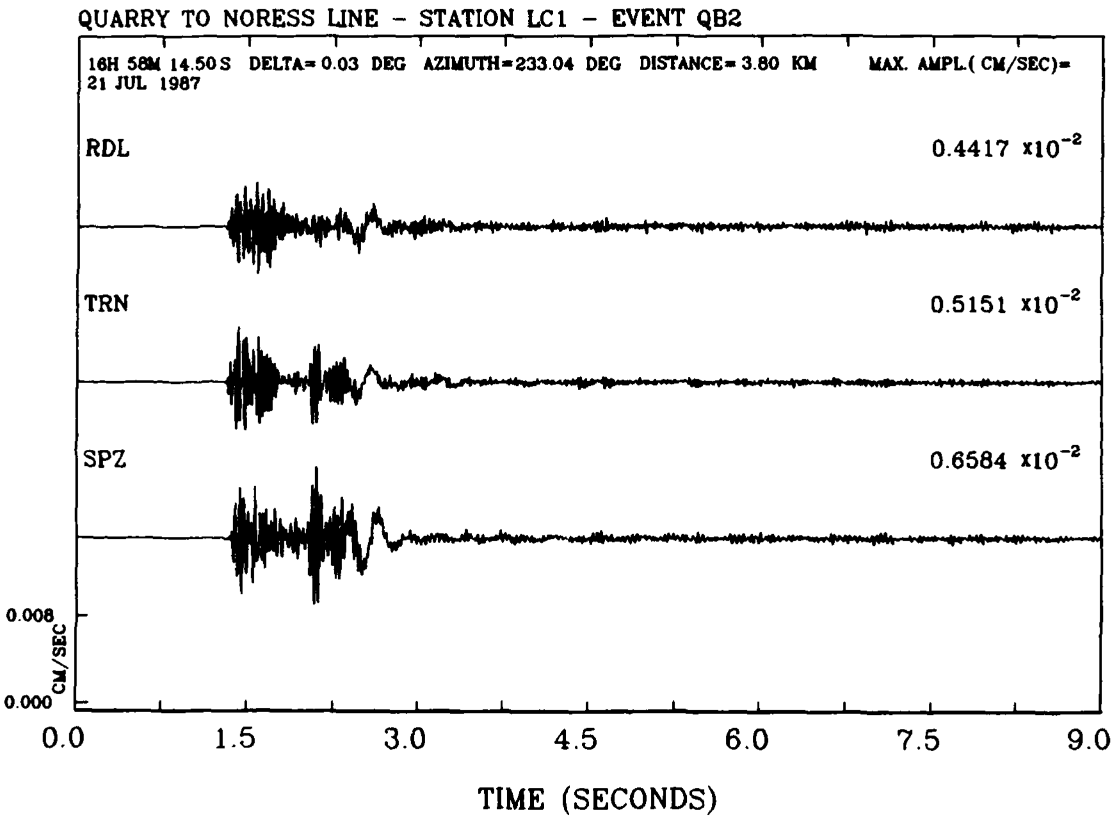


Figure 2-6. Event QB2, Station LC1

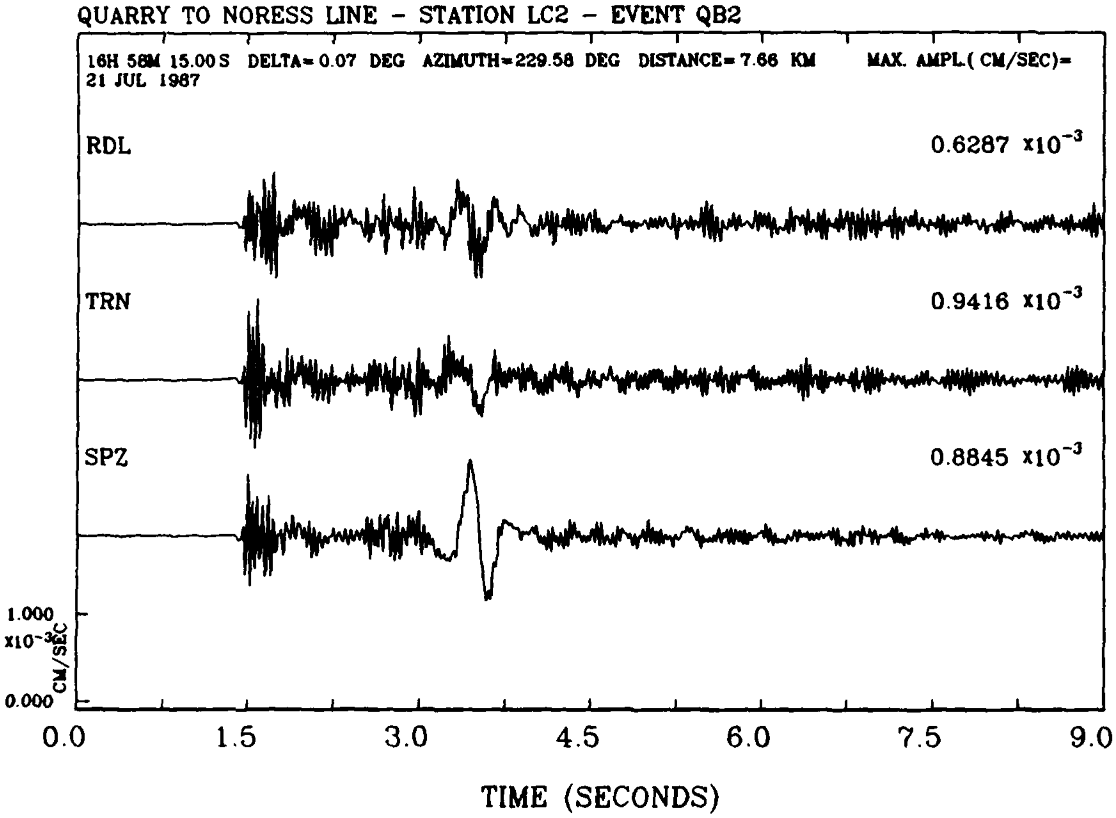


Figure 2-7. Event QB2, Station LC2

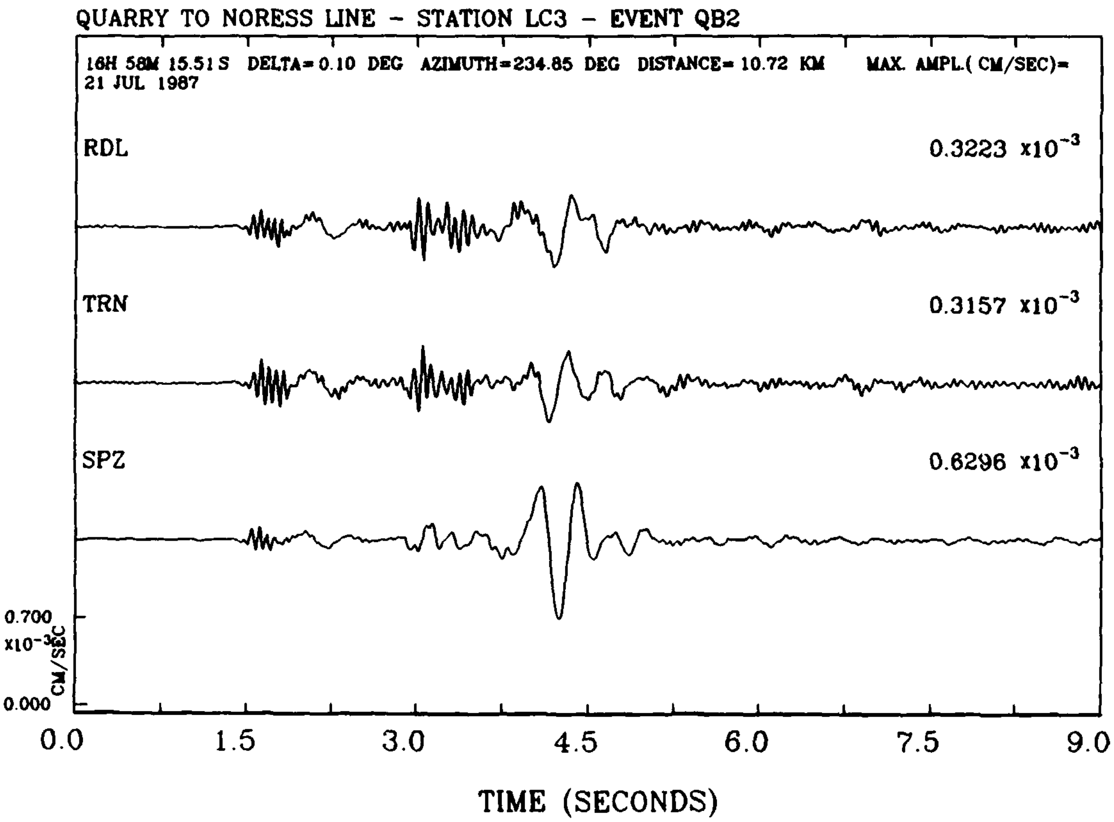


Figure 2-8. Event QB2, Station LC3

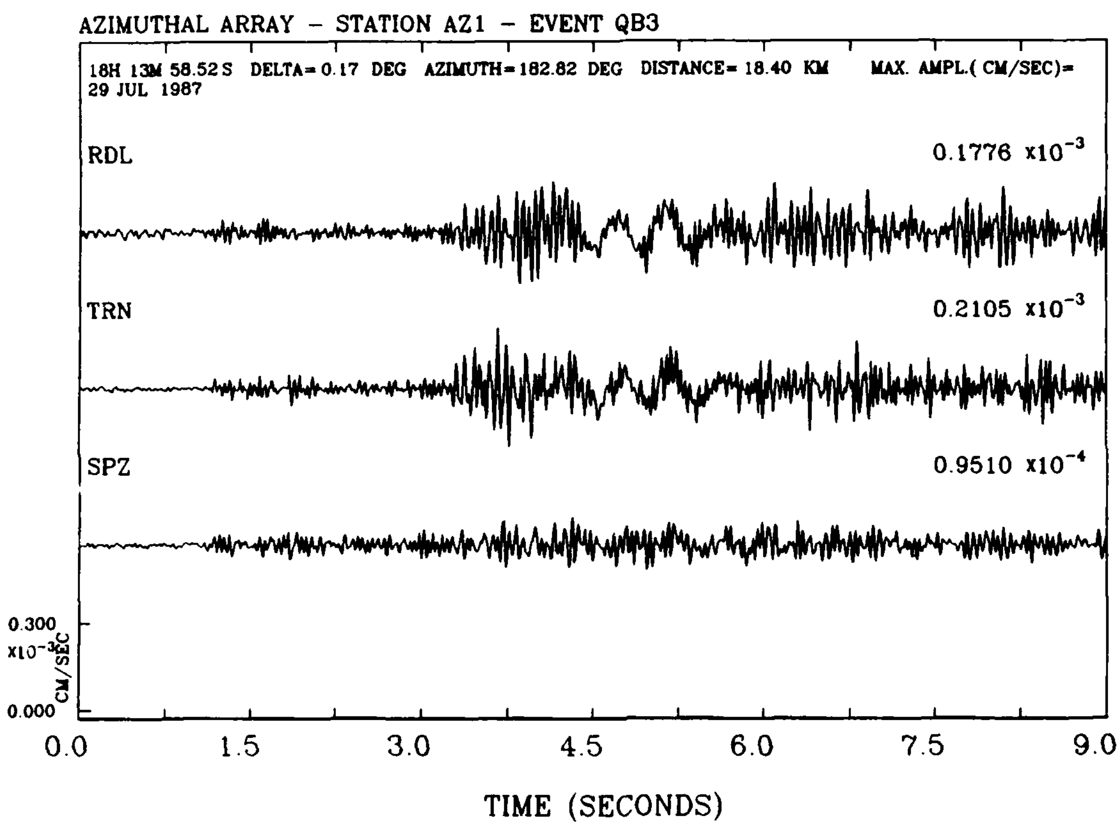


Figure 2-9. Event QB2, Station LC4

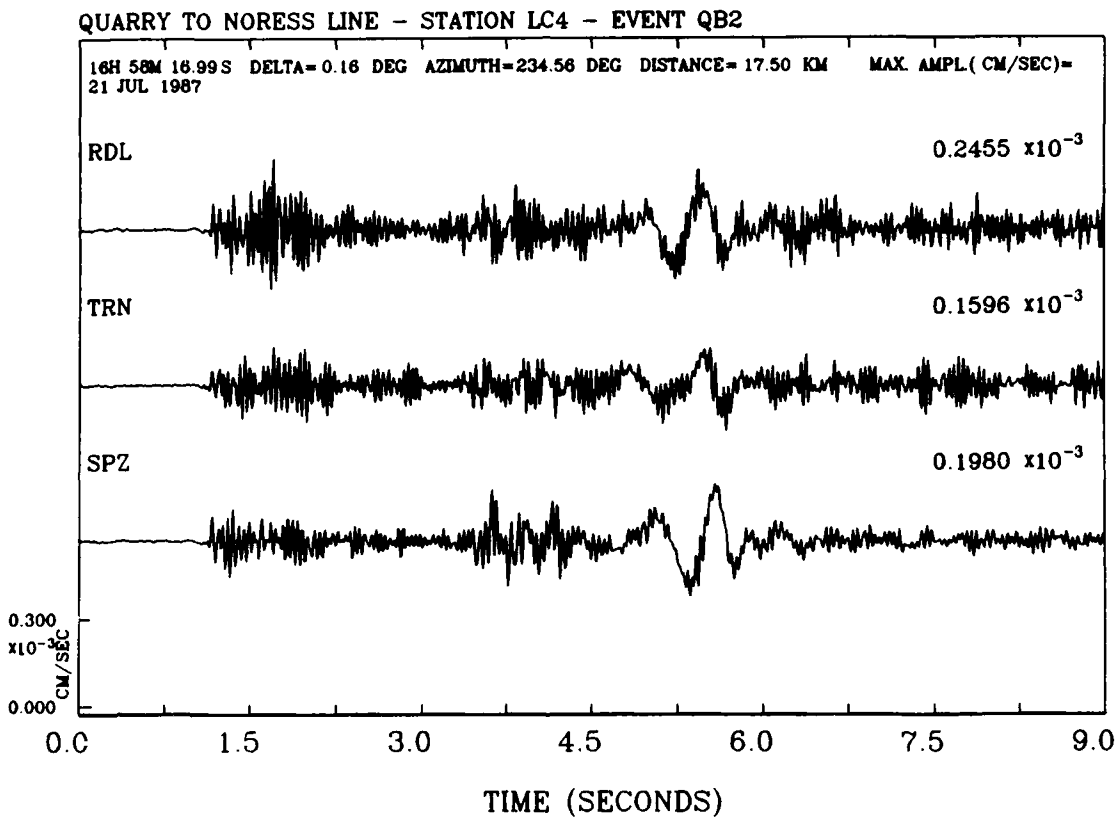


Figure 2-10. Event QB3, Station AZ1

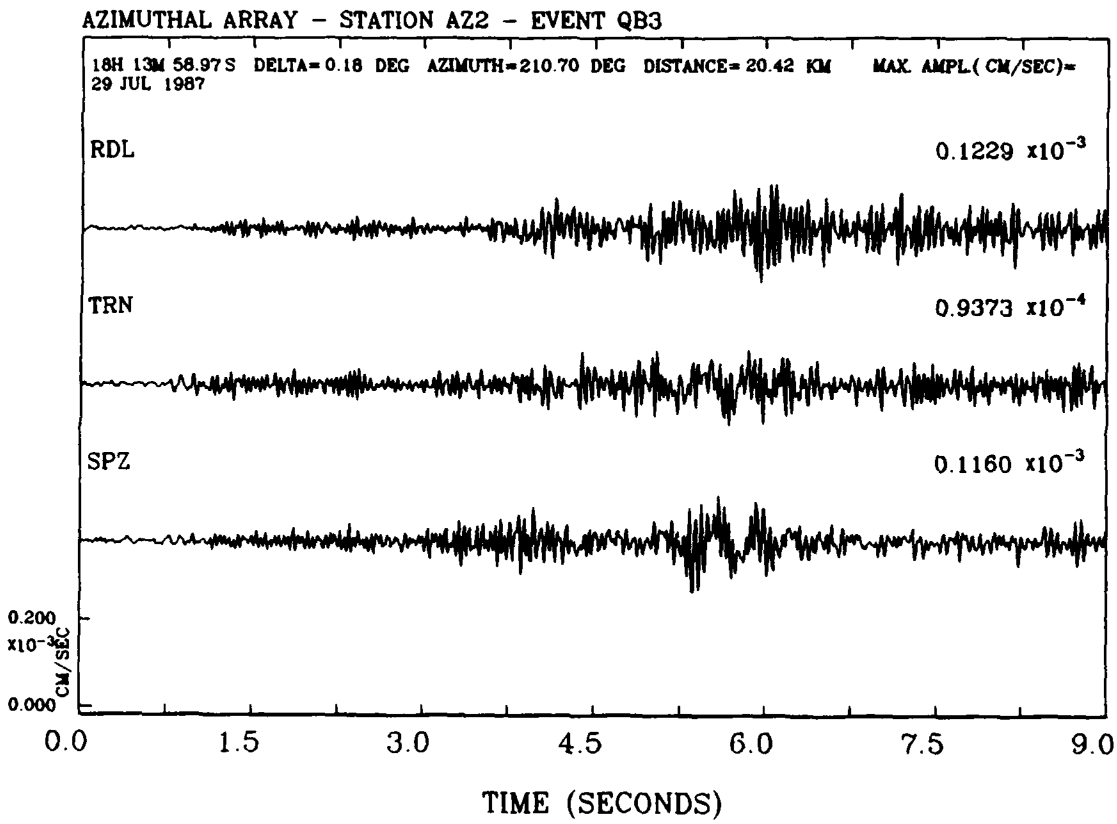


Figure 2-11. Event QB3, Station AZ2

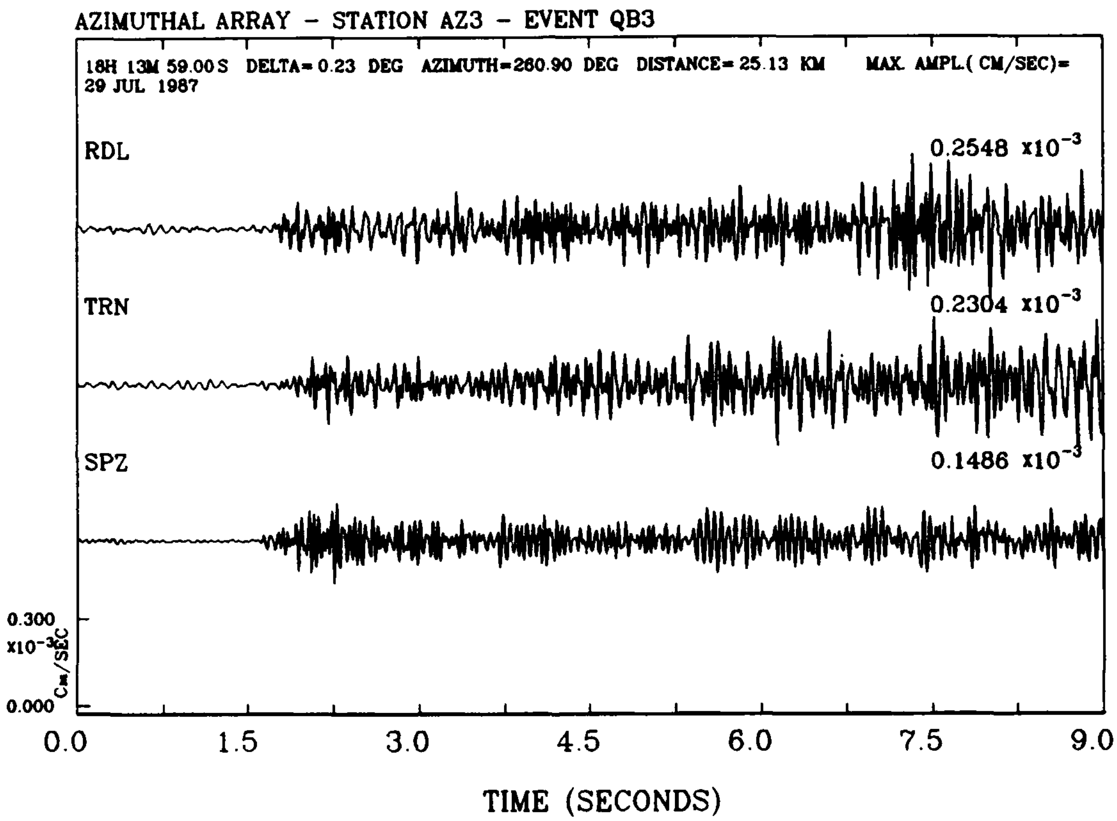


Figure 2-12. Event QB3, Station AZ3

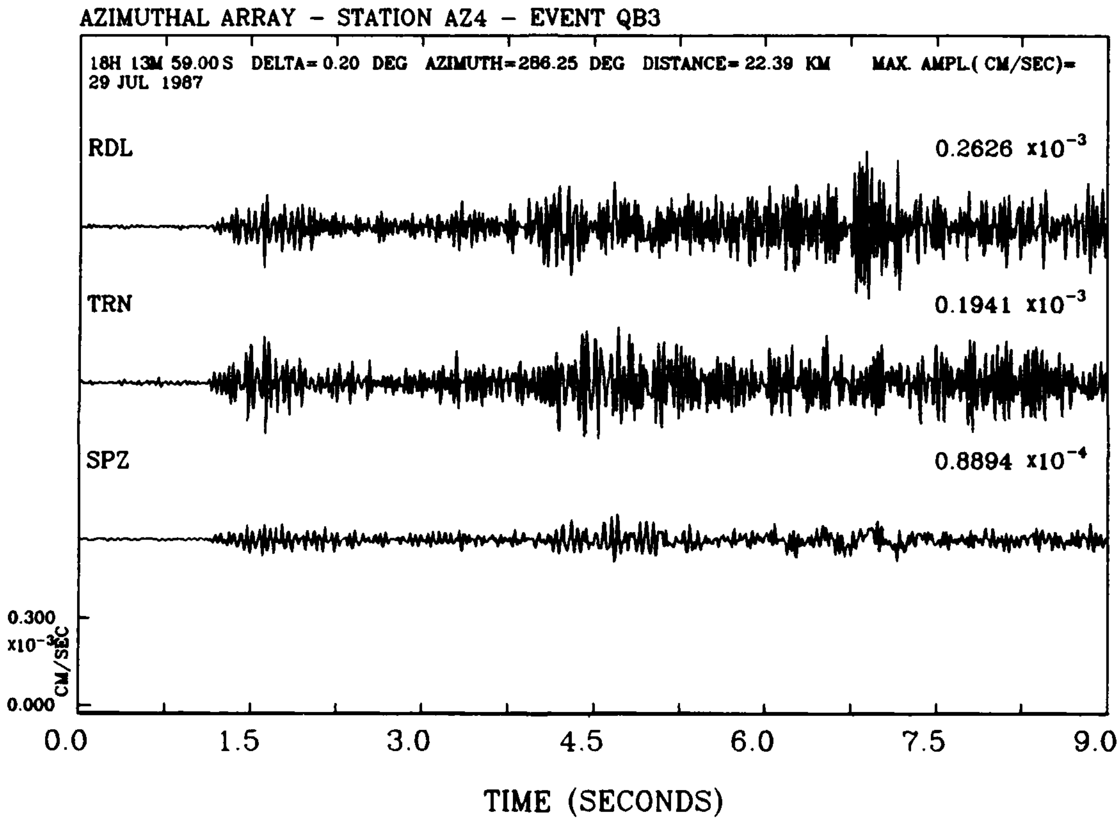


Figure 2-13. Event QB3, Station AZ4

2. ADDITIONAL DATA RECORDED BY WWSSN AND REGIONAL NETWORKS

In addition to the portable instruments described above, the three quarry blasts were also recorded by several permanent regional seismograph stations operated by MIT and BC. These data sets are described briefly here. More detailed information can be obtained by contacting MIT and BC directly. All three blasts were recorded by the short-period vertical component of the WSSN station at Weston Observatory (WES), located 25 km from the quarry (Figure 2-14). All three blasts were recorded on MIT/BC analog short-period records from regional network stations throughout New England (New England Seismic Network--NESN). The MIT network seismometers are 1 Hz Mark Products L-4C vertical component sensors, and the BC network seismometers are 1 Hz HS10 vertical component sensors. Data are telemetered to MIT and BC by phone line and recorded continuously on develocorder or helicorder records. An example of develocorder records from two BC stations (WES, QUA) is shown in Figure 2-15. The data are also recorded digitally when a trigger condition is met. The first blast triggered the BC digital network (Figure 2-16), and the second and third blasts triggered the MIT digital network (Figures 2-17 and 2-18). Sampling rates were 50 sps at BC and 100 sps at MIT. A low-pass filter with 10 Hz cutoff was applied to the MIT data after phone line transmission to reduce noise levels. During the second and third blasts, digital 3-component records were obtained at MIT's WFM station, located about 9 km from the quarry (Figures 2-19 and 2-20). During the second blast, the horizontal components were taken from the French GEOSCOPE global network equipment (GEOSCOPE's WFM station). The broadband instrument response for the horizontal records shown in Figure 2-19 is such that voltage is proportional to ground velocity between about 1 and 20 sec. This signal was sampled by MIT at 100 sps, after applying a low-pass filter with 1 Hz cutoff. During the third blast, the horizontal sensors were 1 Hz Mark Products L-4-3D's. The corresponding signals were sampled and filtered using the same procedure as for the vertical signals mentioned above (100 sps, 10 Hz low-pass filter).

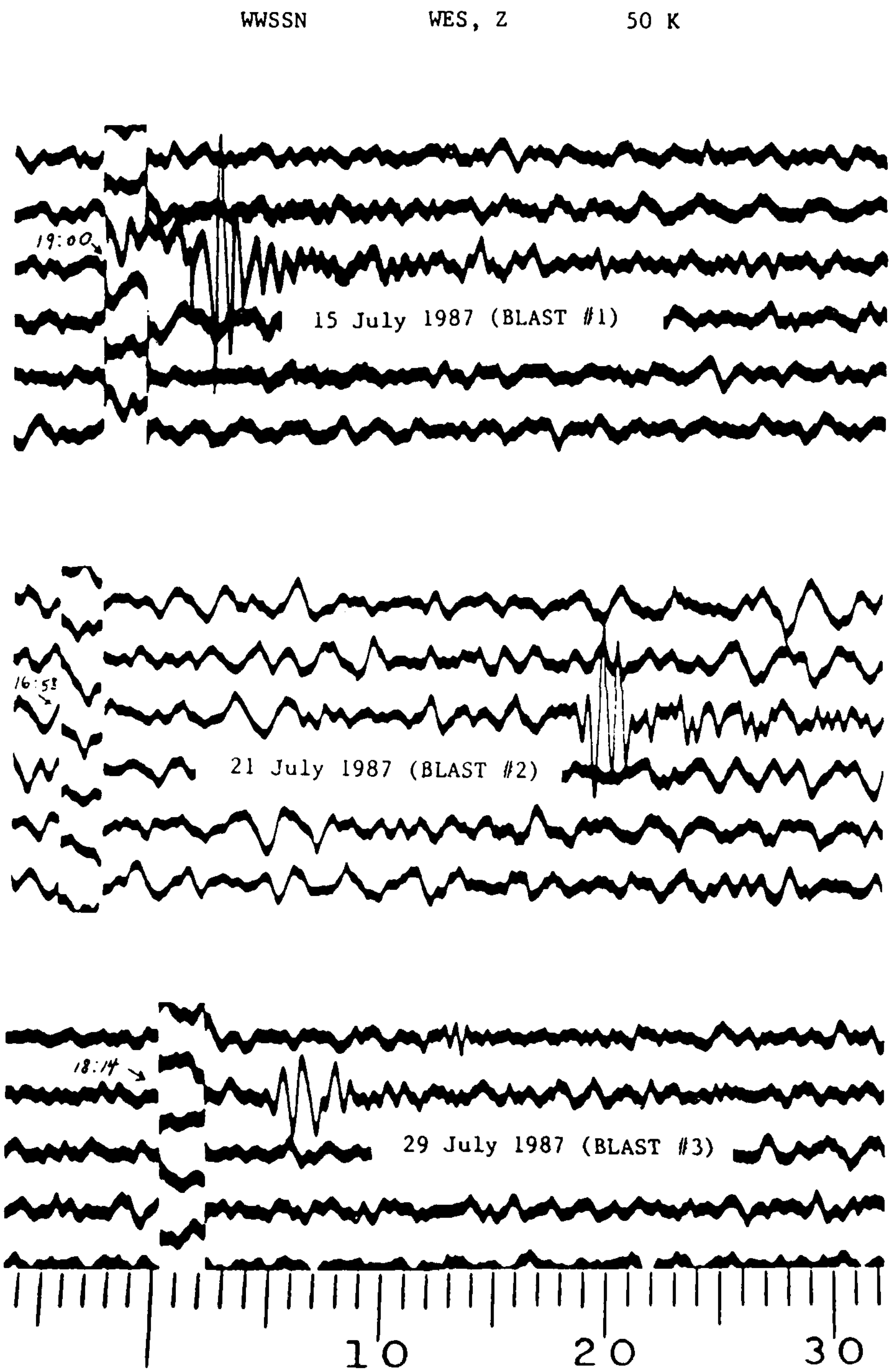


Figure 2-14. WWSSN Short Period Vertical of All Three Quarry Blasts (QB1, QB2, QB3)

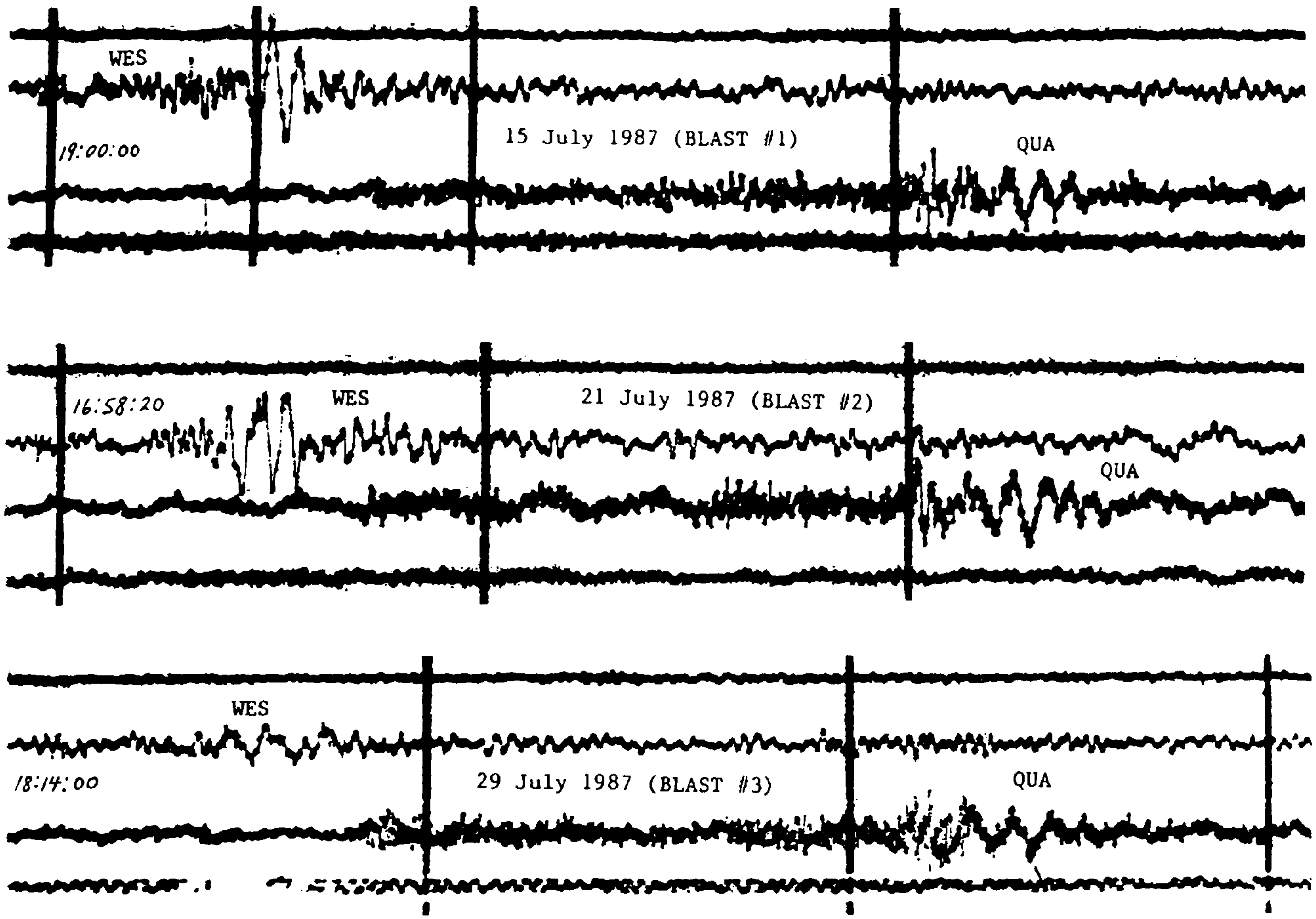
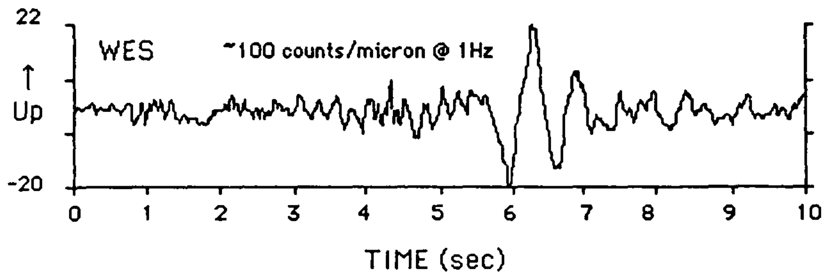


Figure 2-15. Develocorder Records (Stations WES, QUA) of All Three Quarry Blasts

Littleton, MA Quarry Blast
July 15, 1987 18:59:55.3



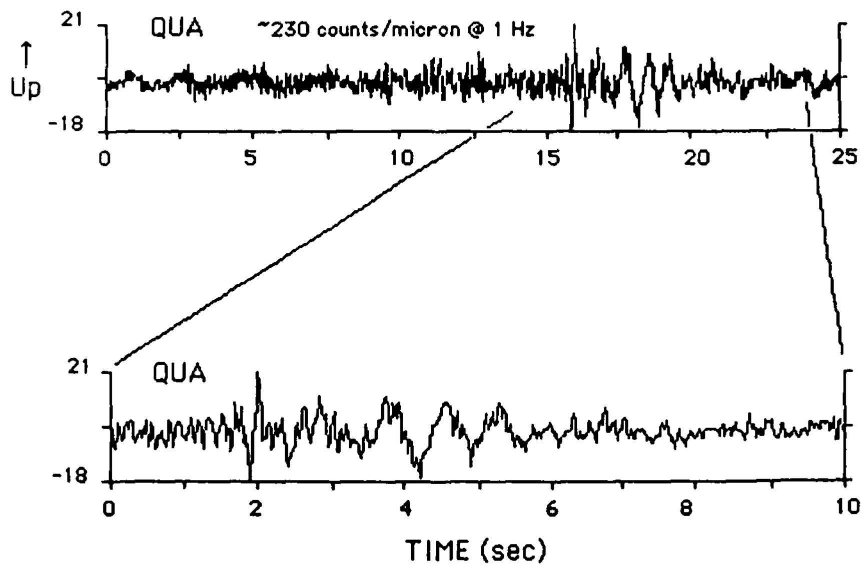
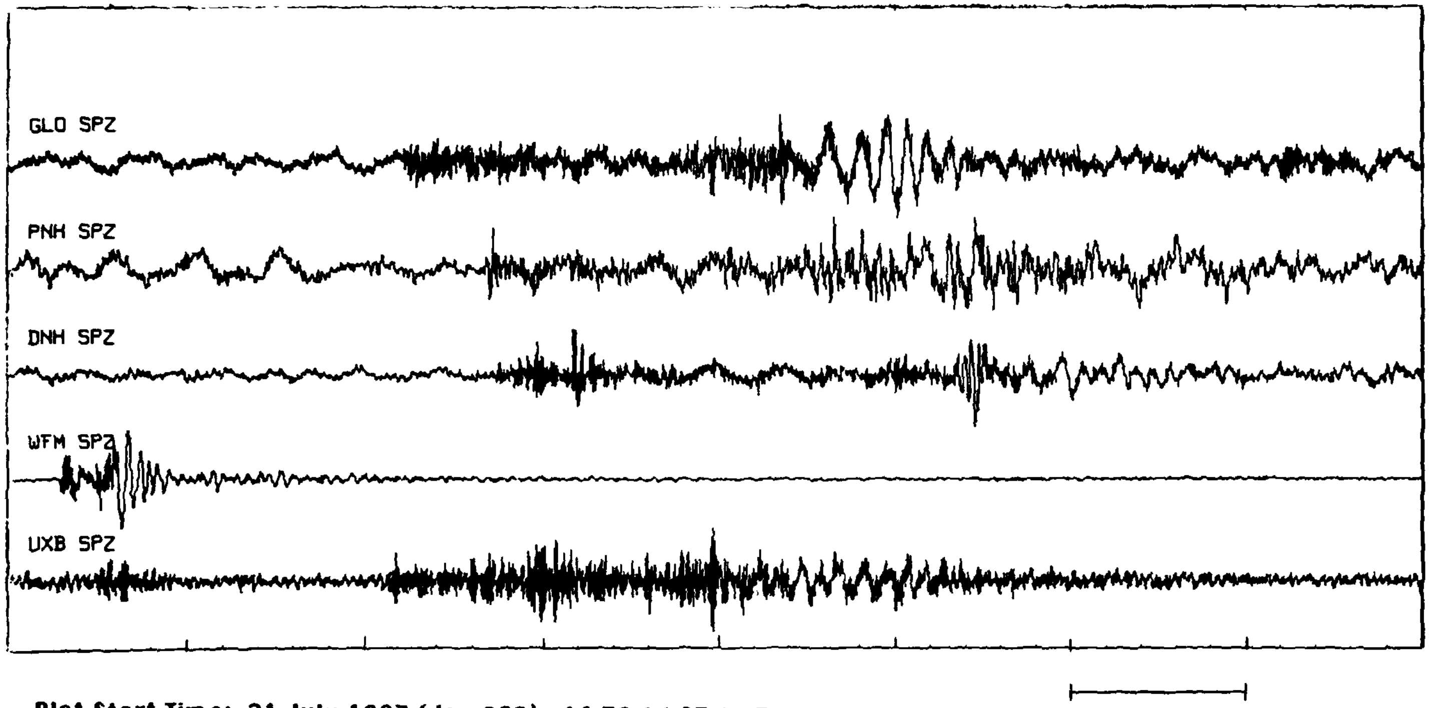


Figure 2-16. BC's Digital Records: QB1 at WES, QUA

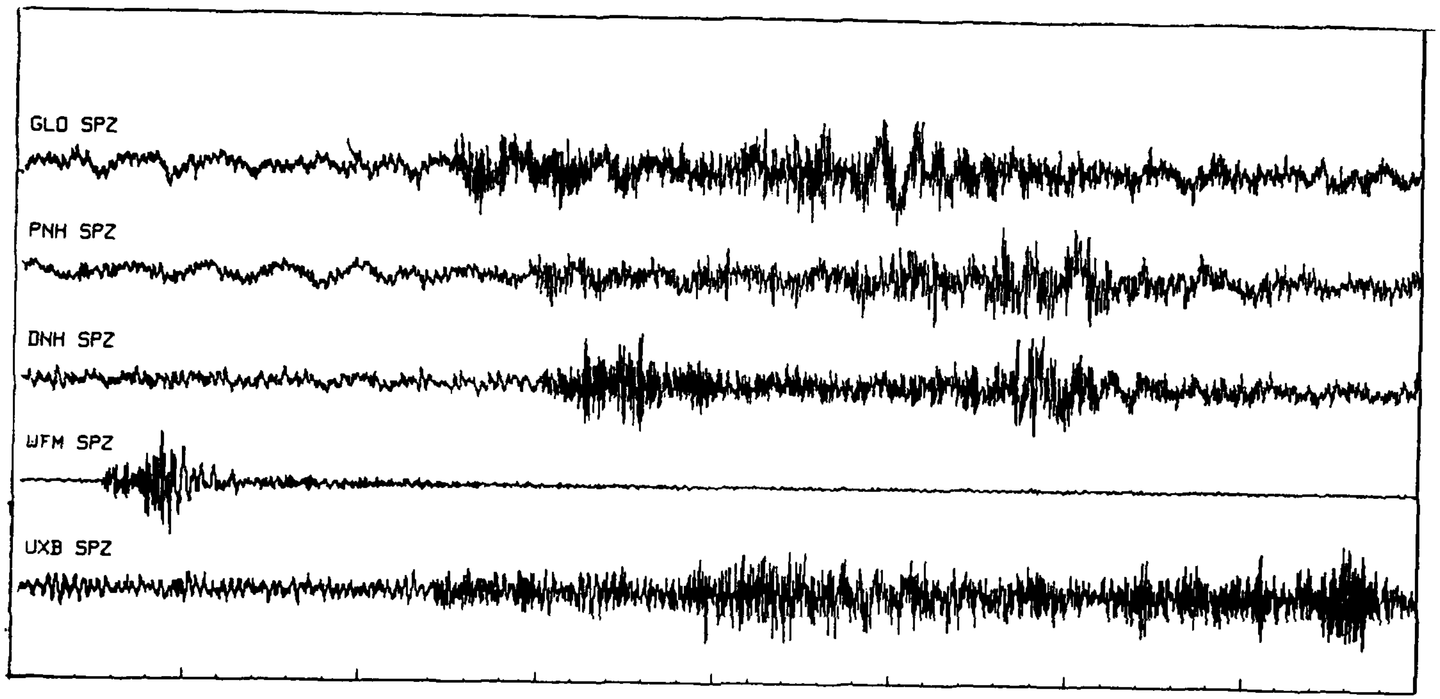


Plot Start Time: 21 July 1987 (day 202), 16:58:14.97 GMT

Station	Distance (km)	Azimuth (°)	Max 0-peak ampl (Volts)
GLO	65.4	81	0.42
PNH	78.7	320	0.18
DNH	81.1	39	0.55
WFM	6.7	18	6.35
UXB	56.2	194	0.55

Sampling Rate: 100 sps

Figure 2-17. MIT's Digital Records: QB2 at Stations Within 100 km of Shot Point



Plot Start Time: 29 July 1987 (day 210), 18:13:54.93 GMT

Sampling Rate 100 sps

Station	Distance (km)	Azimuth (°)	Max 0-peak ampl (Volts)
GLO	65.4	81	0.25
PNH	78.7	320	0.18
DNH	81.1	39	0.30
WFM	6.7	18	4.95
UXB	56.2	194	0.28

Figure 2-18. MIT's Digital Records: QB2 at Stations Within 100 km of Shot Point

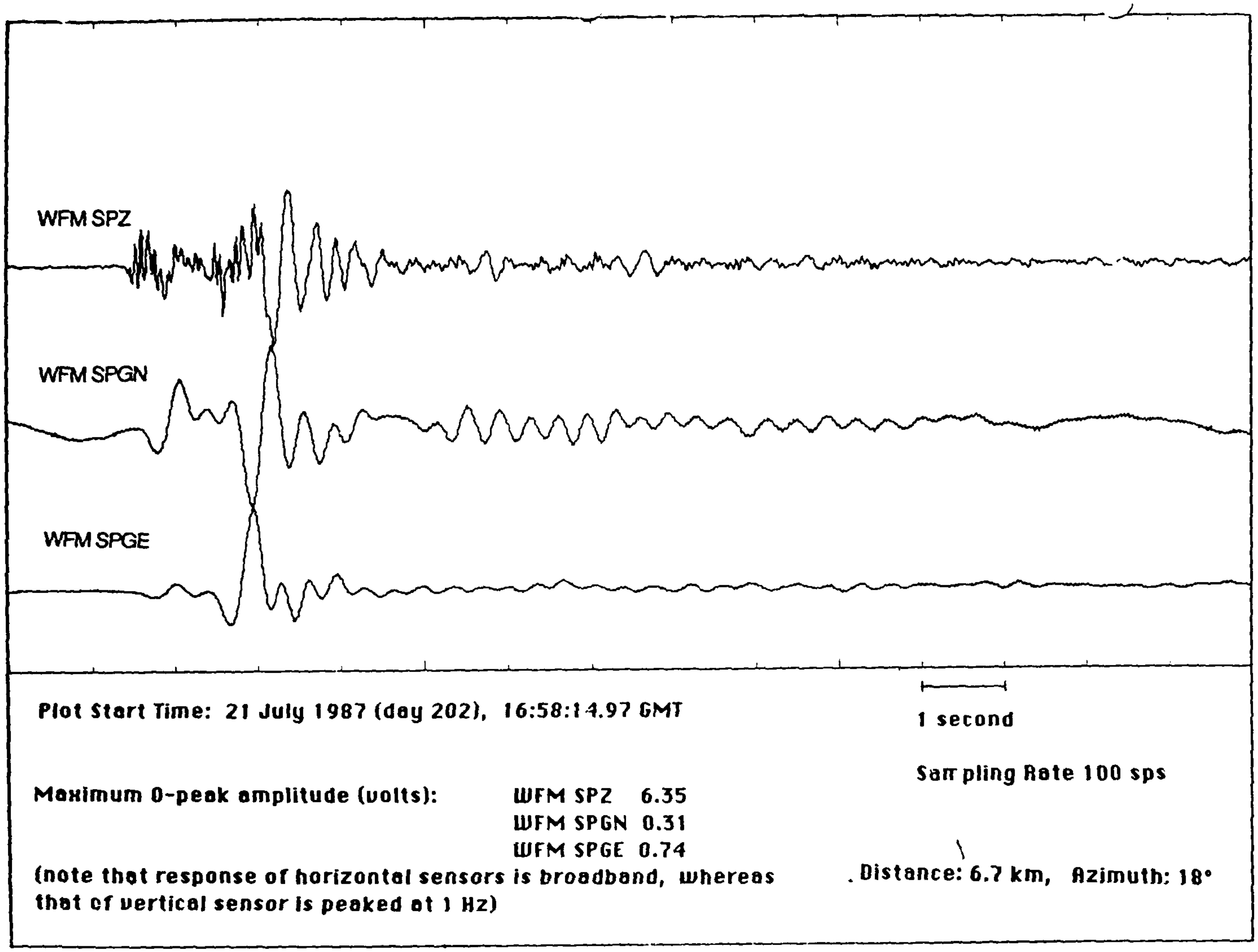


Figure 2-19. Three-Component Digital Records for QB3 at WFM. Note that the frequency response of horizontal instruments is different from that of the vertical component

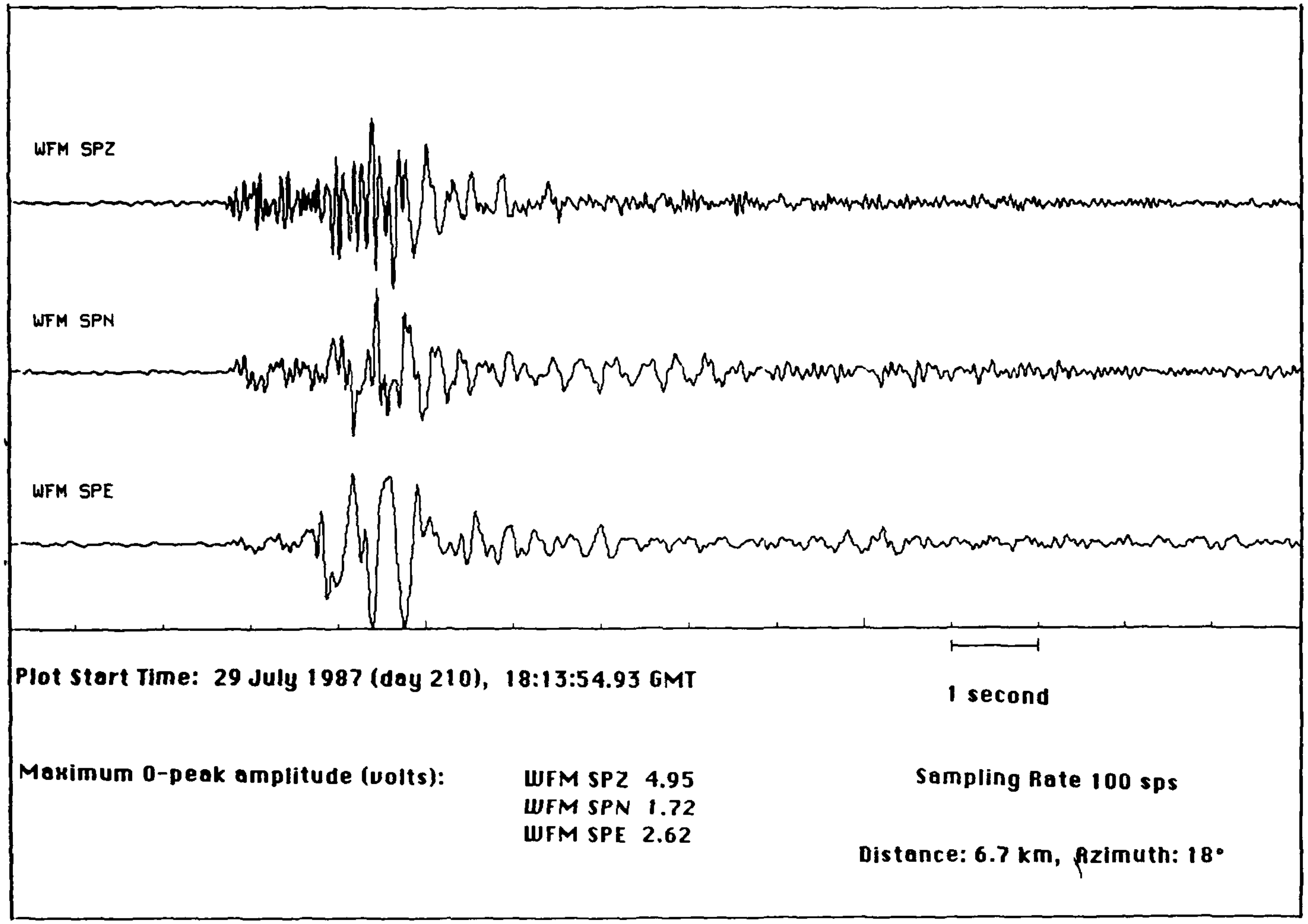


Figure 2-20. Three-Component Digital Records for QB3 at WFM. Similar frequency response for all three instruments

3. COMBINING THE DIFFERENT DATA SETS

One difficulty in interpreting the data recorded in this experiment is that several different types of instruments were used. As part of this study, the MIT/BC group is working on combining the data recorded by the various instruments. Response curves are being determined for each of the seismometer-recorder configurations. In Figure 2-21, we show approximate relative response curves for the S6000-DR200 recording systems, the MIT/BC regional networks, and the short-period records of the WWSSN station at Weston Observatory. Absolute gains are more difficult to determine. Our most recent estimates of absolute gain for several of the instruments are given in Table 2-4. The absolute gain of the SR6000-DR200 recording system (when set at x1000) is on the order of several hundred counts/micron at 2 Hz, and we are currently working on determining the gain of that system more accurately.

We are testing our calculations of relative and absolute response curves by simultaneously recording events with adjoining instruments at the same site. Thus, we have recorded events in the following settings: (1) A Littleton quarry blast was recorded earlier this year with the S6000-DR200 system set up at MIT's WFM station on the same pier as the permanent network short-period vertical seismometer; (2) A similar experiment has been conducted on a recording pier at Weston Observatory; (3) Some of the refraction experiment shots made at the AFGL NORESS array-type site during the July experiment were recorded by one of MIT's Sprengnether recorders and by one of AFGL's Terratech recorders hooked up to adjacent S6000 seismometers, buried within 10 meters of the refraction shot locations. Results of these and other tests will be used to correlate records made by different types of instruments.

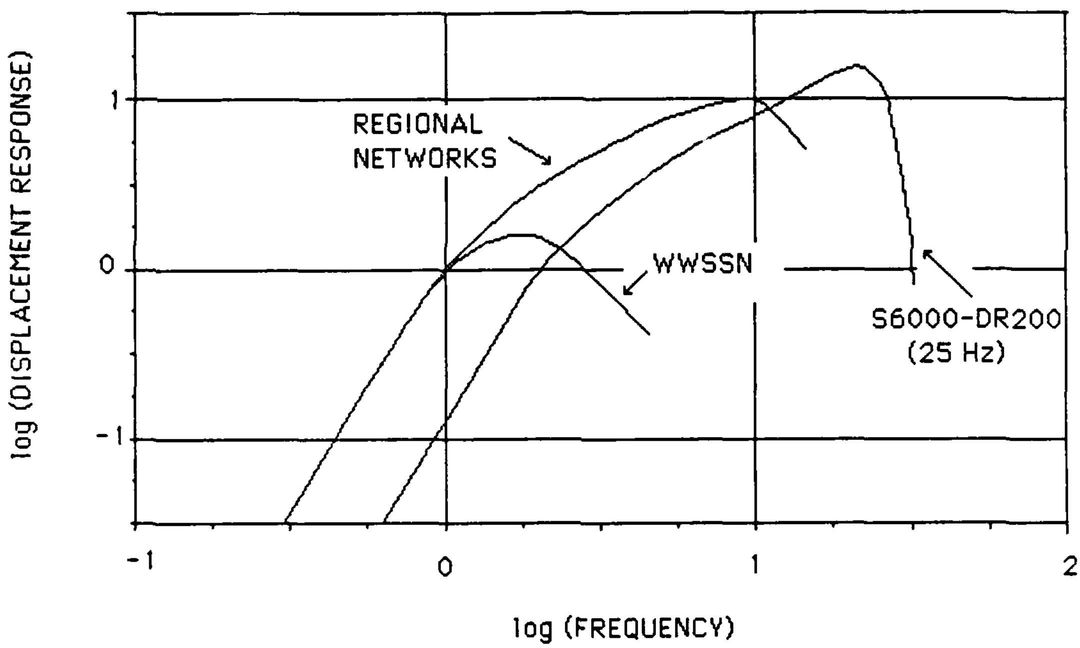


Figure 2-21. Response Curves for S6000-DR200 System, Regional Networks, and WWSSN

Table 2-4. Approximate Absolute Gains of Selected Stations

Station	Gain (@ 1 Hz)
WES (regional network)	100 counts / micron
WES (WWSSN)	50,000 microns / micron
QUA (regional network)	230 counts / micron

Contents

3. NORESS and Profile Arrays

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The AFGL group was responsible for operation of the NORESS array and the first 10 stations (P101-P110) along the profile array. That part of the experiment and its respective data are discussed here.

1. PROFILE ARRAY

The azimuth of the profile line was constrained by the following criteria:

-that, for background noise considerations, the line had to traverse as few towns and major roads as possible;

--that it would be desirable to tie down the line at the far end with one of the NESN stations maintained by BC's Weston Observatory.

Accordingly, an azimuth of 268.5 degrees, departing from the San-Vel quarry, was chosen as the direction of the profile line. This would allow the far end of the line to be located at the NESN QUA station in Cooleysville, Massachusetts (inset, Figure 3-1). The profile array traversed four geoglogic units, from east to west:

--Tadmuch Brook Schist, an andalusite phyllite and sillimanite schist of Silurian (?) age;

--Clinton Facies, a porphyritic biotite granite with a non-porphyritic border phase, of lower Silurian age;

--Oakdale Formation, a metamorphosed, thin-bedded, pelitic, and calcareous siltstone and muscovite schist, of Silurian age;

--Worcester Formation, carbonaceous slates and phyllites, of lower Devonian and Silurian age.[2]

Station locations were selected as follows: A line was drawn on the appropriate United States Geologic Survey (USGS) planimetric map (scale = 1:100,000) along the chosen azimuth. That line was then marked off at 2.5 km intervals. Stations P (profile) 101 through P110 were then located at the nearest easily identifiable feature (for example, intersection of two roads, of power lines and road). Location, distance, azimuth, and elevation information for the profile stations is given in Table 3-1.

The profile array was in place to record the San-Vel Quarry blast of 15 July 1987 (QBI). The morning of the shot, AFGL recorder No. 282 was found to be out of order, so its corresponding station (P109) was scratched from the array. Based on findings prior to the actual experiment, it was decided that not enough was known about the noise levels at the various station sites, nor about appropriate instrument settings for operation in automatic trigger mode. Accordingly, it was planned that each station would be operated manually, using automatic triggers only as a last resort. The automatic trigger is enabled when the ratio (alpha, in dB) of short term energy to long term energy reaches a certain level. Those settings were, for all stations:

S.T.A. = 1.0 s, L.T.A. = 20.0 s, alpha = 10 dB

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2. Zen, E-an, Ed. (1983) Bedrock Map of Massachusetts. Massachusetts State Geologic Survey.

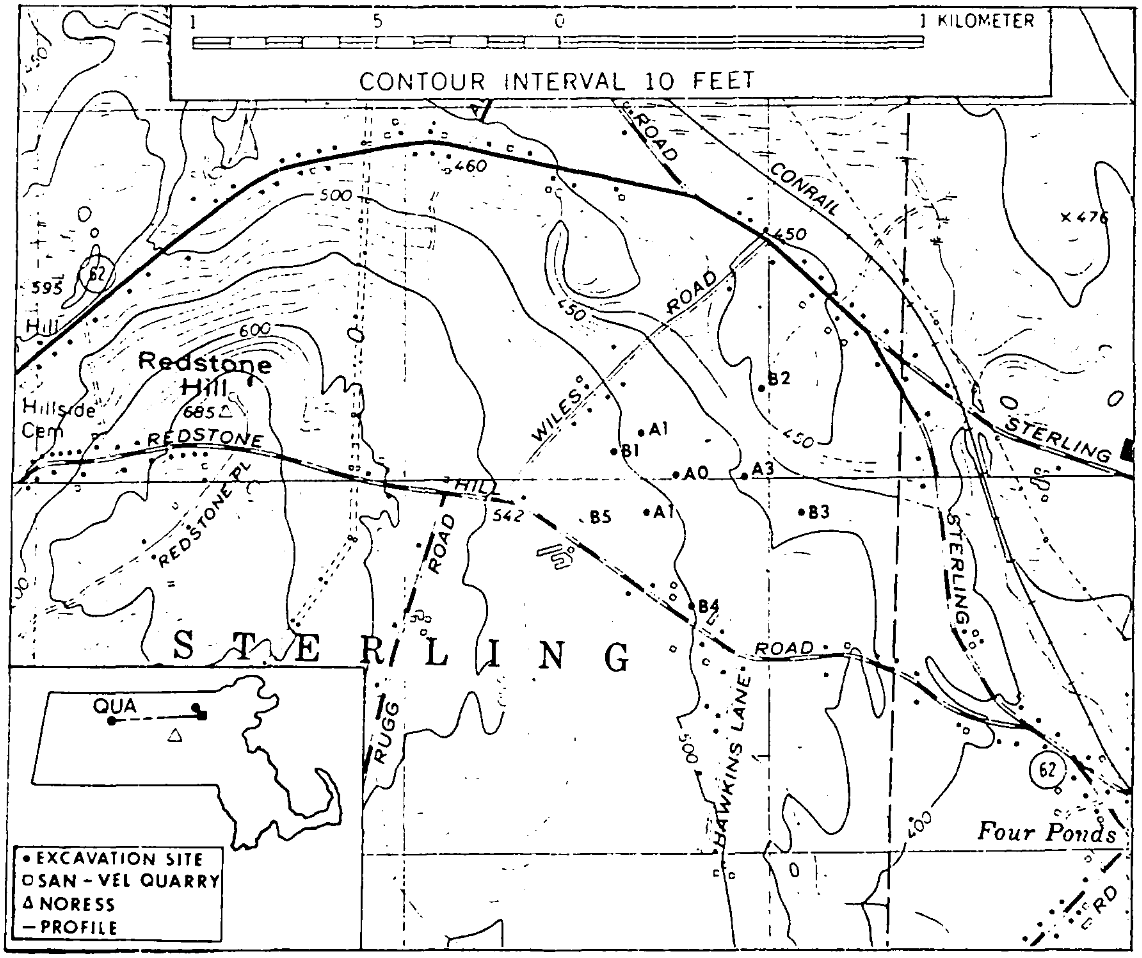

Figure 3-1. Map Showing NORESS Stations and Inset Showing NORESS Array Locations, Profile Array Location, and Shot Locations. Note: Clear drafting of this figure required that NORESS station names be shortened from NSA0-NSB5 to A0-B5. Map taken from U.S. Geologic Survey Clinton topographic quadrangle

Table 3-1. Profile Station Locations

DATE	ORIGIN TIME	LATITUDE	LONGITUDE	DEPTH	ELEVATION
JUL 15, 1987	196D 18H 59M 55.345S	42.553N	71.515W	0.0	76.0

LOCATION: SAN VEL QUARRY

STATION	LATITUDE (DEG)	LONGITUDE (DEG)	ELEVATION (METERS)	DELTA (DEG)	DISTANCE (KM)	AZIMUTH (DEG)	BACK AZIMUTH (DEG)
P101 280 AFGL	42.546N	71.552W	89.91	0.028	3.12	255.38	75.37
P102 320 AFGL	42.540N	71.564W	91.44	0.038	4.27	250.06	70.03
P103 281 AFGL	42.540N	71.587W	85.34	0.055	6.07	256.16	76.11
P104 312 AFGL	42.533N	71.604W	94.48	0.069	7.63	253.01	72.96
P105 322 AFGL	42.537N	71.648W	85.34	0.099	11.05	260.73	80.64
P107 278 AFGL	42.528N	71.688W	117.34	0.130	14.47	258.95	78.83
P110 334 AFGL	42.518N	71.798W	233.16	0.212	23.56	260.57	80.38

The shot was scheduled for 17h 00m 00s UTC. Each person operating each station was provided with three tapes, each tape having 12 minutes of total recording time, with two tapes to be run on manual at the approximate shot time and a third to be run on automatic trigger mode in the event that the shot was late. The shot was actually detonated at approximately 19h 35m 00s, well after the expected shot window; therefore, any stations that successfully recorded the shot did so in automatic trigger mode. Excessive noise from a nearby construction site caused a very low signal-to-noise ratio at station P106; that recorder failed to trigger and did not record the shot. Station P108, for reasons unknown, also failed to trigger and did not record the shot. Station P105 did trigger. However, the pre-event memory seems to have malfunctioned; hence, the first arrival of the signal was not recorded. A record section and seismograms of the shot recorded by the profile array are given in Figures 3-2.through 3-10. Before the array was disassembled, calibration pulses were recorded at each station. Seismometer and recorder information are given in Tables 3-2 and 3-3, respectively. Typical instrument responses and calibration pulses are given in Figures 3-11 and 3-12.

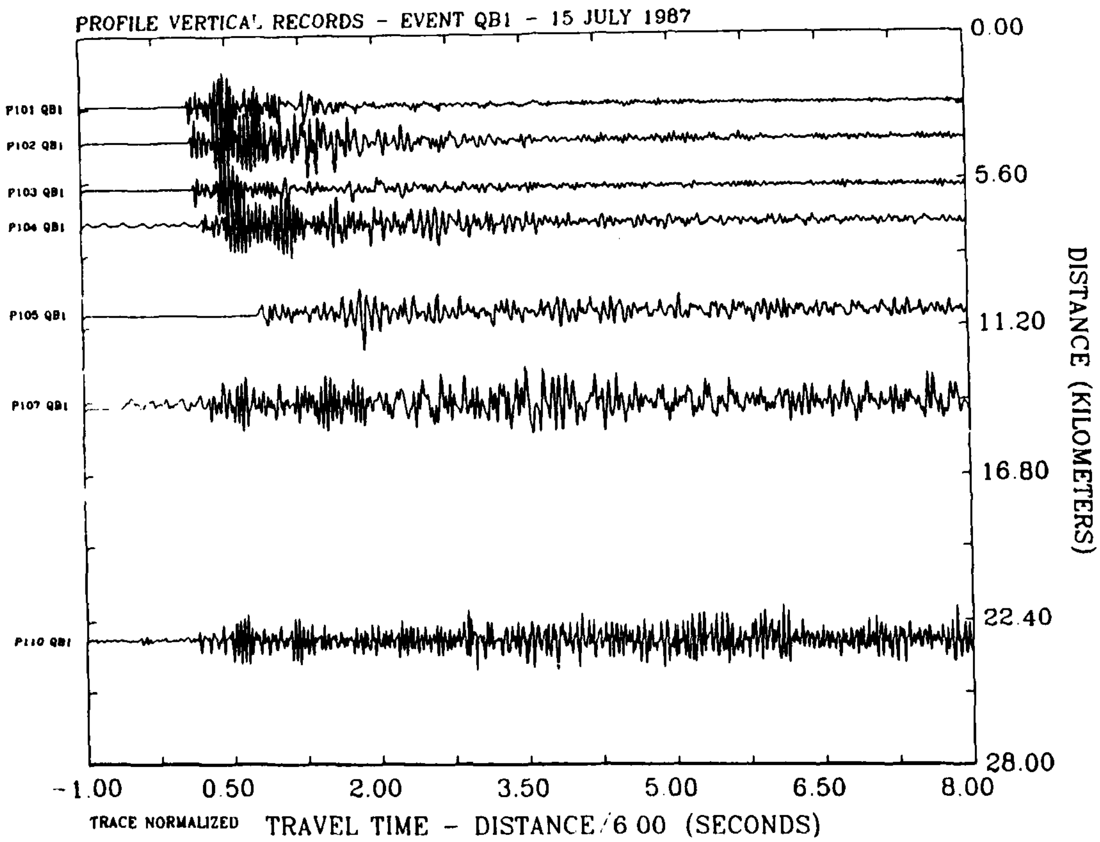

Figure 3-2. Record Section of Vertical Seismograms for Shot QB1. Records are trace-normalized to unit amplitude

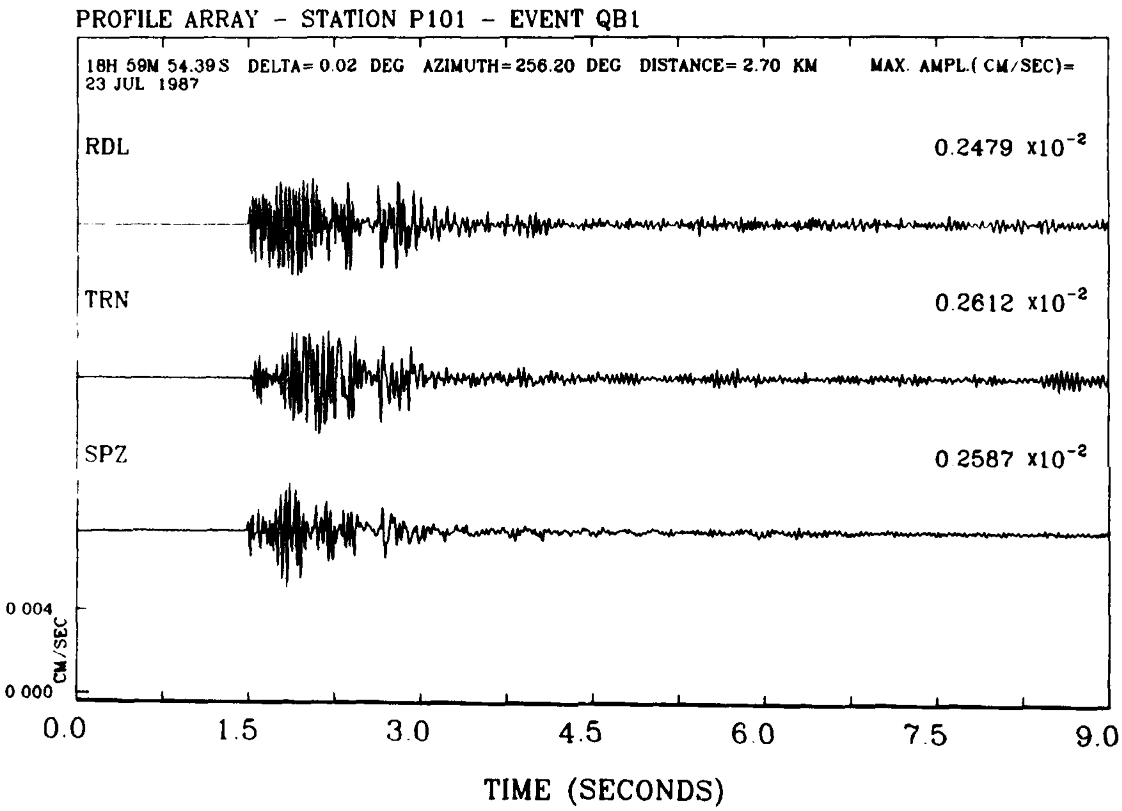

Figure 3-3. Three-Component Seismogram of Shot QB1 Recorded at Station P101. Amplitude scale, in cm/sec, is shown at bottom left. Maximum amplitude for each record is shown at right of plot. Starting time in UTC is given in upper left corner

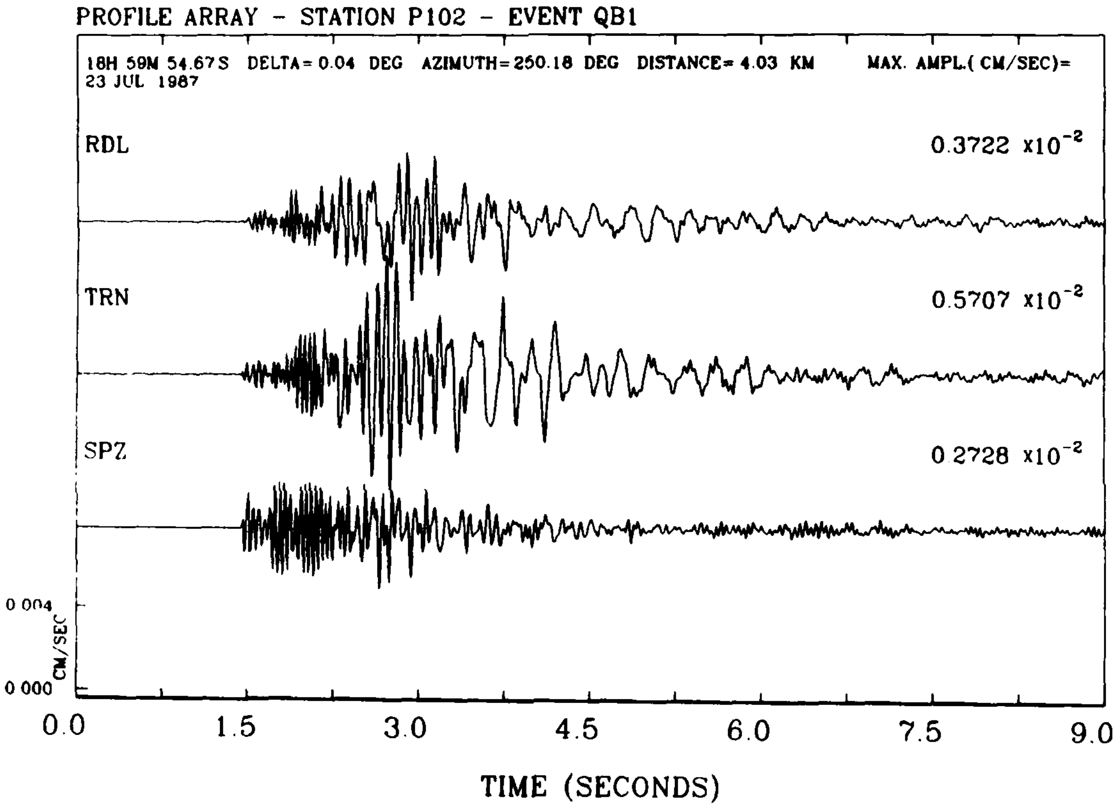

Figure 3-4. Three-Component Seismogram of Shot QB1 Recorded at Station P102. See Figure 3-3

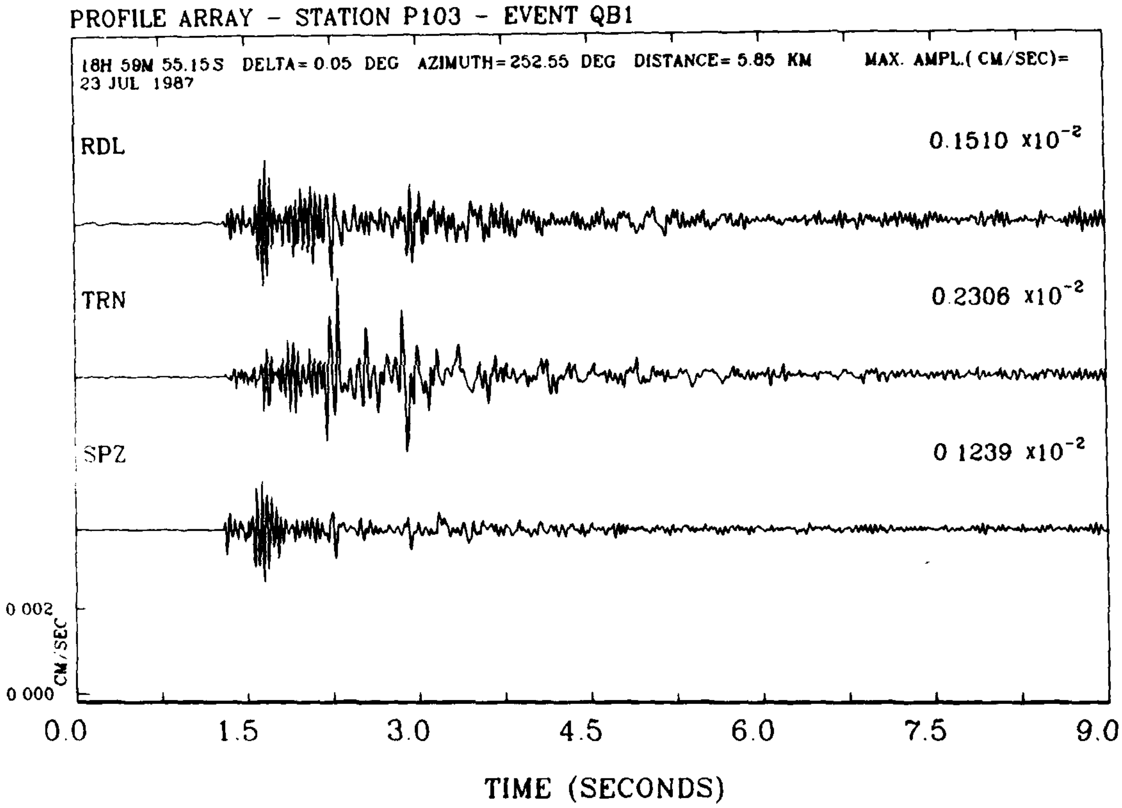

Figure 3-5. Three-Component Seismogram of Shot QB1 Recorded at Station P103. See Figure 3-3

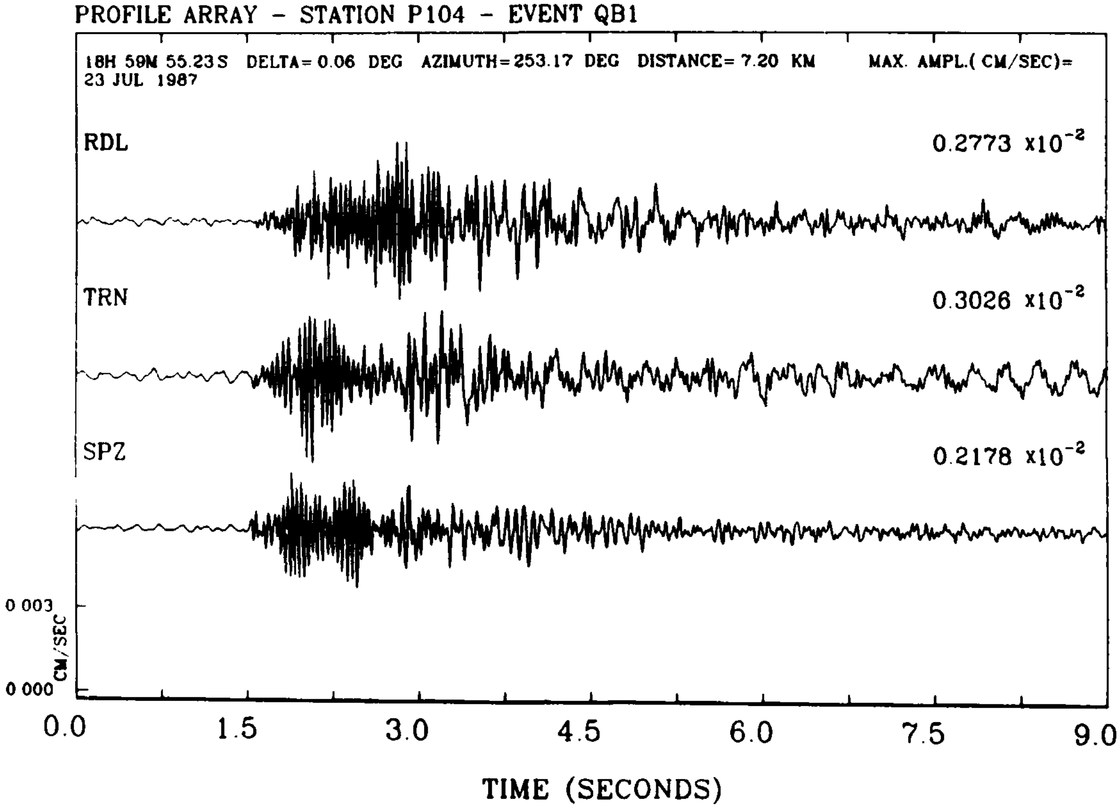

Figure 3-6. Three-Component Seismogram of Shot QB1 Recorded at Station P104. See Figure 3-3

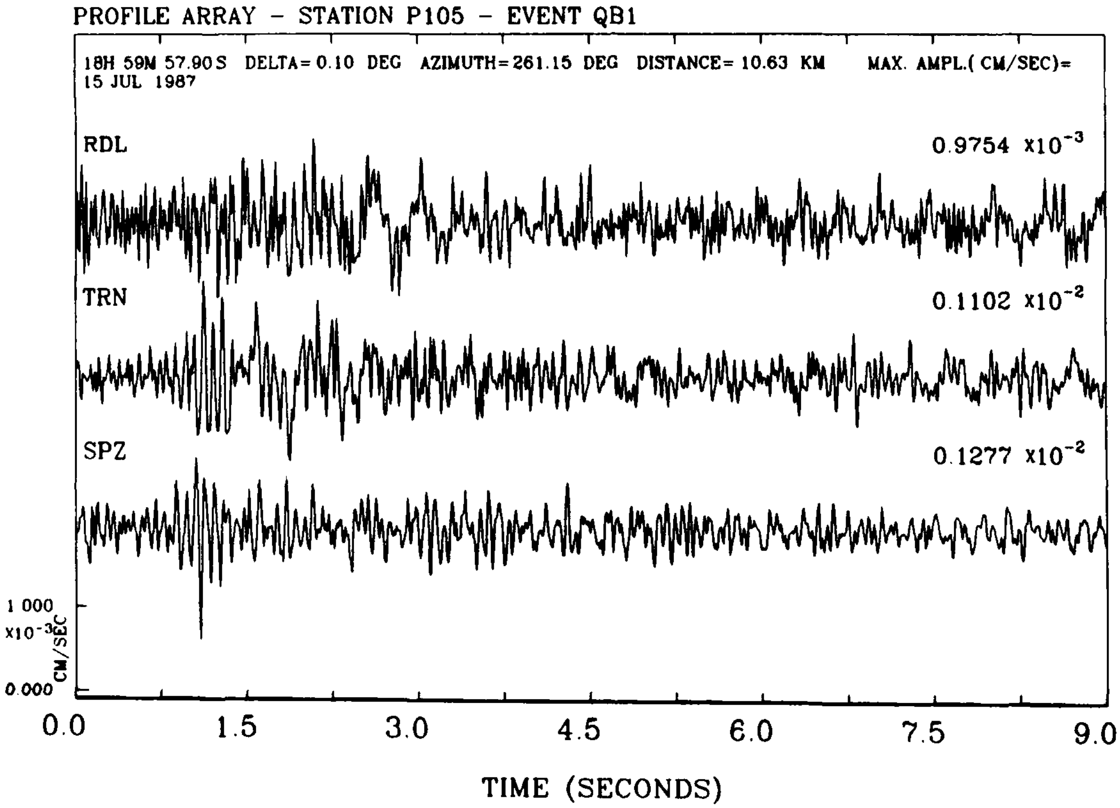

Figure 3-7. Three-Component Seismogram of Shot QB1 Recorded at Station P105. See Figure 3-3

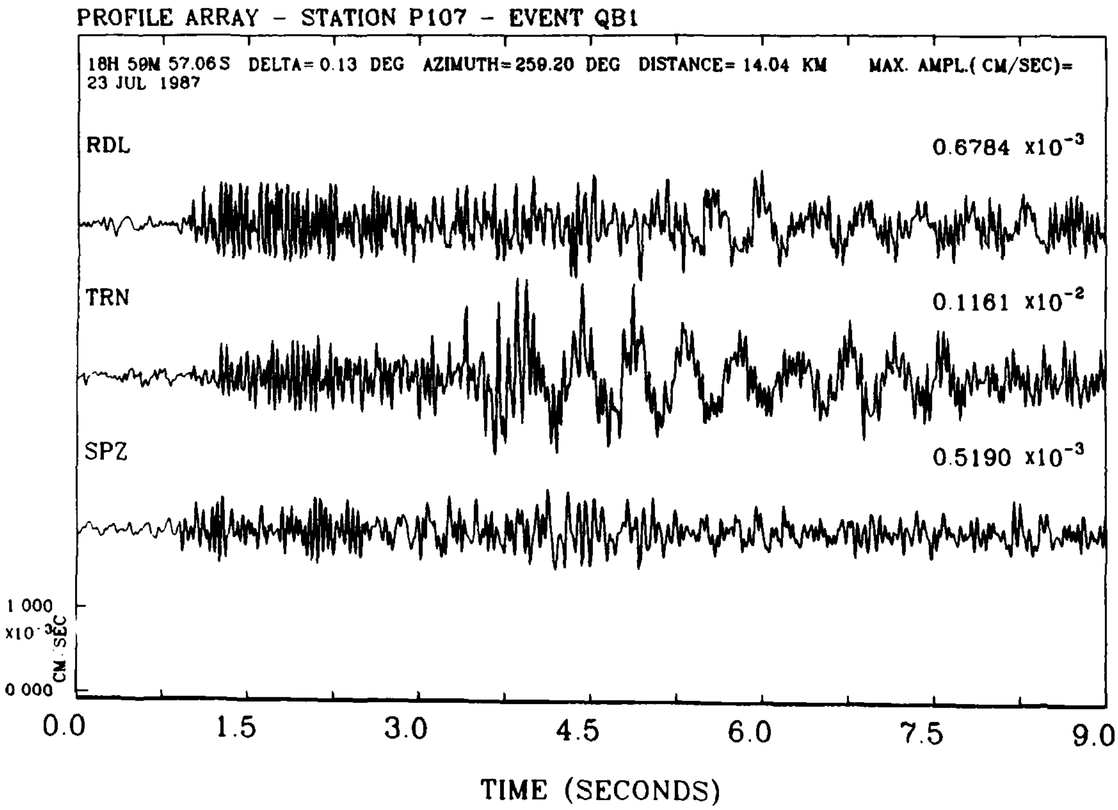

Figure 3-8. Three-Component Seismogram of Shot QB1 Recorded at Station P107. See Figure 3-3

PROFILE ARRAY - STATION P110 - EVENT QB1

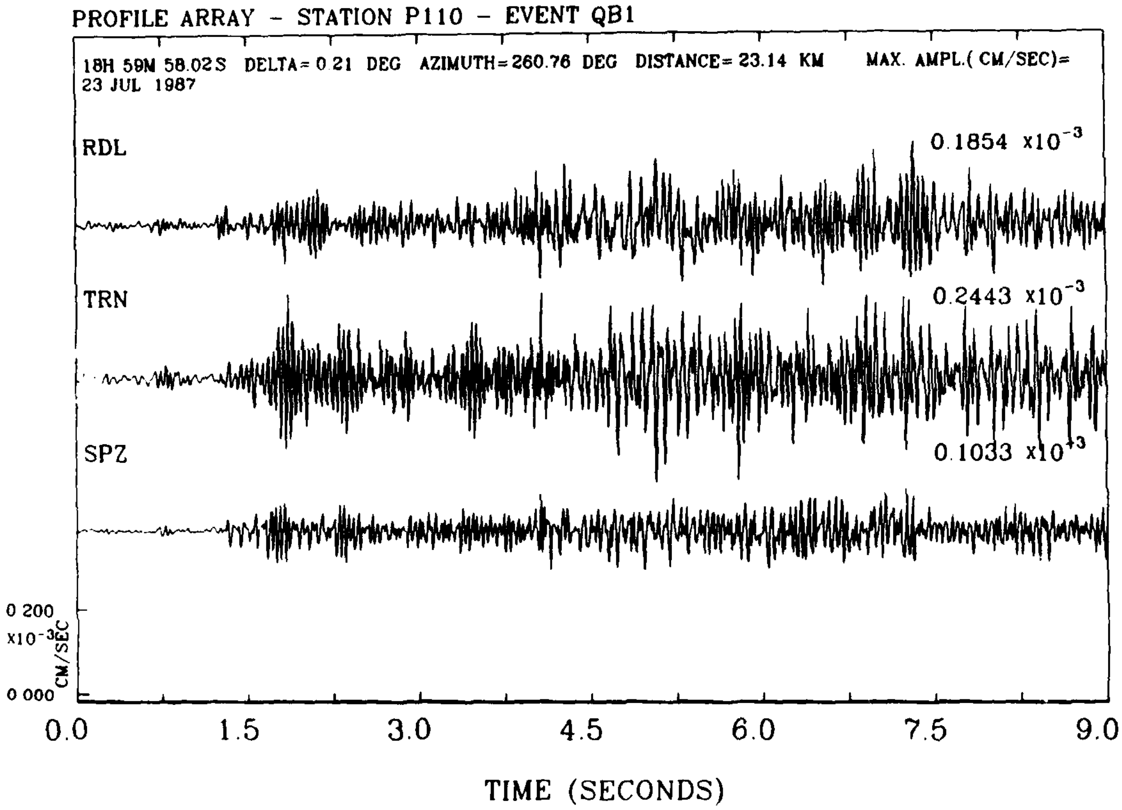

Figure 3-9. Three-Component Seismogram of Shot QB1 Recorded at Station P110. See Figure 3-3

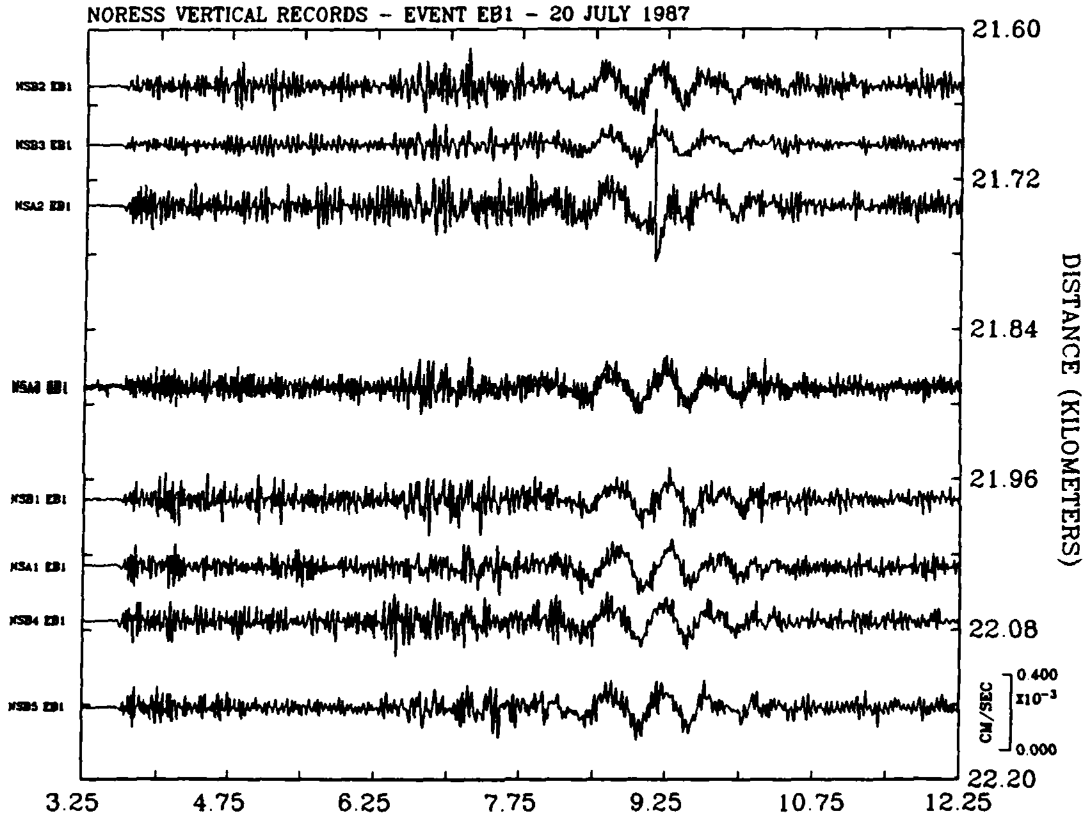

Figure 3-10. Record Section of Vertical Seismograms for Shot EB1

Table 3-2. Seismometer Constants

SEISMOGRAM			TIME CORRECTION (SECONDS)	SEISMOMETER ORIENTATION (DEGREES)	SEISMOMETER SENSITIVITY (VOLTS/M/SEC)	PENDULUM PERIOD (SECONDS)	DAMPING RATIO	SERIAL NUMBER
P101	QB1	SPN	0.0140	-15.00	205.9180	2.041	0.447	9319
P101	QB1	SPE	0.0140	75.00	236.4150	2.540	0.367	9319
P101	QB1	SPZ	0.0140	VERT	199.1890	1.972	0.456	9319
P102	QB1	SPN	0.0200	-15.00	252.1490	2.012	0.490	9261
P102	QB1	SPE	0.0200	75.00	253.2480	2.093	0.439	9261
P102	QB1	SPZ	0.0200	VERT	231.7810	2.595	0.361	9261
P103	QB1	SPN	0.0080	-15.00	238.7790	2.046	0.432	9325
P103	QB1	SPE	0.0080	75.00	223.2340	2.053	0.442	9325
P103	QB1	SPZ	0.0080	VERT	215.1590	2.419	0.360	9325
P104	QB1	SPN	0.0140	-15.00	210.9800	1.984	0.472	9324
P104	QB1	SPE	0.0140	75.00	190.4290	2.072	0.408	9324
P104	QB1	SPZ	0.0140	VERT	220.1210	2.349	0.397	9324
P105	QB1	SPN	-0.0040	-15.00	194.4550	1.755	0.466	9322
P105	QB1	SPE	-0.0040	75.00	187.7690	1.888	0.399	9322
P105	QB1	SPZ	-0.0040	VERT	158.3920	2.262	0.325	9322
P107	QB1	SPN	-0.0360	-15.00	1123.0859	1.020	0.310	104539
P107	QB1	SPE	-0.0360	75.00	1146.0547	1.042	0.325	104704
P107	QB1	SPZ	-0.0360	VERT	1223.8188	1.053	0.329	104551
P110	QB1	SPN	0.0500	-15.00	1146.0547	1.042	0.325	104705
P110	QB1	SPE	0.0500	75.00	1146.0547	1.042	0.325	104700
P110	QB1	SPZ	0.0500	VERT	1084.9606	1.020	0.280	104688

Table 3-3. DCS-302 Recorder Constants

SEISMOGRAM			CUT-OFF FREQUENCY (HERTZ)	RECORDER GAINS (MILLIVOLTS/COUNT)				SERIAL NUMBER
				GAIN 1	GAIN 2	GAIN 3	GAIN 4	
P101	QB1	SPN	30.00	0.24561	0.04947	0.00978	0.00235	280
P101	QB1	SPE	30.00	0.24531	0.04949	0.00980	0.00238	280
P101	QB1	SPZ	30.00	0.24538	0.04964	0.00977	0.00235	280
P102	QB1	SPN	30.00	0.24381	0.04926	0.00980	0.00244	320
P102	QB1	SPE	30.00	0.24344	0.04917	0.00990	0.00246	320
P102	QB1	SPZ	30.00	0.24381	0.04918	0.00983	0.00241	320
P103	QB1	SPN	30.00	0.24448	0.04897	0.00970	0.00244	281
P103	QB1	SPE	30.00	0.24433	0.04902	0.00976	0.00259	281
P103	QB1	SPZ	30.00	0.24426	0.04929	0.00976	0.00261	281
P104	QB1	SPN	30.00	0.24396	0.04964	0.00974	0.00240	312
P104	QB1	SPE	30.00	0.24396	0.04884	0.00987	0.00245	312
P104	QB1	SPZ	30.00	0.24374	0.04893	0.00982	0.00239	312
P105	QB1	SPN	30.00	0.25326	0.04907	0.00970	0.00245	322
P105	QB1	SPE	30.00	0.25511	0.04952	0.00980	0.00246	322
P105	QB1	SPZ	30.00	0.25564	0.04973	0.00981	0.00242	322
P107	QB1	SPN	30.00	0.24414	0.04883	0.00977	0.00244	278
P107	QB1	SPE	30.00	0.24414	0.04883	0.00977	0.00244	278
P107	QB1	SPZ	30.00	0.24414	0.04883	0.00977	0.00244	278
P110	QB1	SPN	30.00	0.25326	0.04907	0.00970	0.00245	334
P110	QB1	SPE	30.00	0.25511	0.04952	0.00980	0.00246	334
P110	QB1	SPZ	30.00	0.25564	0.04973	0.00981	0.00242	334

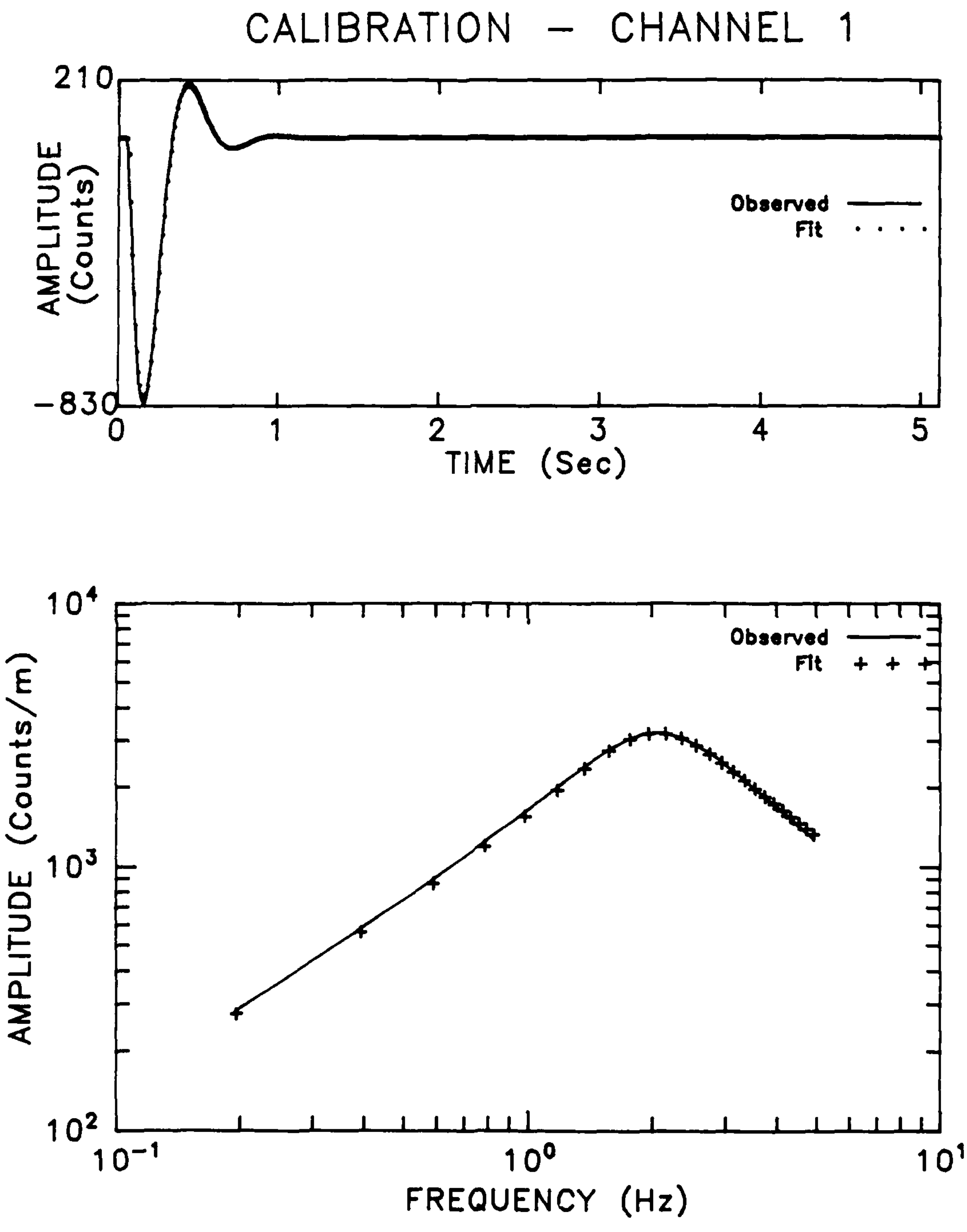

Figure 3-11. Typical Calibration Pulse Showing Both Observed and Calculated Frequency and Time-Domain Representations

------------- SEISMOMETER CALIBRATION ----------

SEISMOMETER DATA

Seismometer S/N:9319
Seismometer Mass: 0.5000 Kg
Motor Constant: 0.5000 Newtons/Amp
Alias Filter Corner: 30.0 Hz
Intrinsic Sensitivity (Gs): 199.18 Volts/(M/Sec)
Natural Frequency (Fo): 2.546 Hz
Damping Ratio (Bo): 0.3673

SOURCE FILE DATA

File Name: MA012C1.DEC
Sample Time: 196 Ds 20 : 59: 49.900

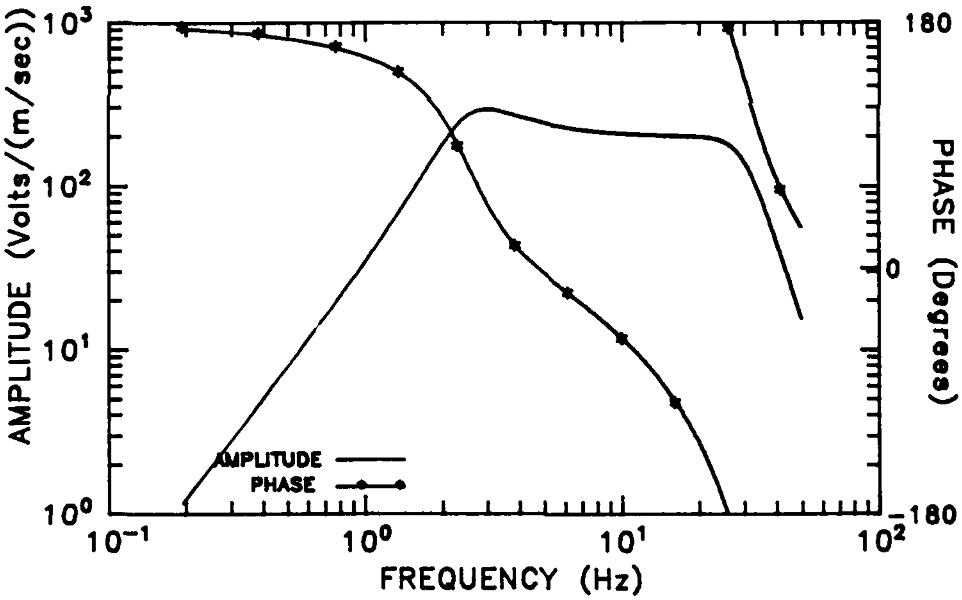

Figure 3-12. Amplitude and Phase Spectra of Typical Instrument Response

2. NORESS

The location of the NORESS array was constrained by the following criteria:

--The site had to be between 25 and 35 km from the shot site.

--The site would preferably be located near the line of the profile array so that information about the structure obtained from the profile array could be applied to the NORESS data.

--The site should be relatively clear and level so that the individual stations could be located accuratey by theodolite wihout much difficulty.

Accordingly, the NORESS array was sited on the farm of Mr. John Davis of Sterling, Massachusetts (see inset, Figure 3-1). The array was located on the geologic unit known as the Worcester Formation, which consists of carbonaceous slates and phyllites with minor metagreywacke and is of lower Devonian and Silurian age.[1]

The array consisted of two concentric rings, the A ring with three equally spaced stations (stations NSA1 to NSA3), the B ring with five equally spaced stations (stations NSB1 to NSB5), and a center station (station NSA0) (see Figure 3-1). The recorders were all wired together to allow for a common time base provided by a portable satellite clock. The investigators, therefore, did not need to check the clock drift of each recorder as the satellite time was encoded directly onto the tape. Common wiring also allowed the central recorder to trigger each of the other recorders once its trigger condition had been met. Because the master triggering recorder was at the center station, where the background noise was very low, this arrangement would prevent any of the recorders from being triggered by a car or other spurious source. Trigger settings for the master recorder were determined as a result of a preliminary investigation. Those settings were:

S.T.A. = 1.0 s, L.T.A. = 20.0 s, alpha = 10 dB

Because the NORESS array was located on an operational dairy farm, some deviation from the ideal NORESS array geometry was necessary. Location, distance, azimuth, and elevation information for the NORESS stations are given in Table 3-4 for shot EB1 and in Table 3-5 for shot QB2.

Table 3-4. NORESS Station Locations

DATE	ORIGIN TIME	LATITUDE	LONGITUDE	DEPTH	ELEVATION
JUL 20, 1987	201D 19H 25M 0.000S	42.570N	71.527W	0.0	82.0

LOCATION: SUBSTATION

STATION	LATITUDE (DEG)	LONGITUDE (DEG)	ELEVATION (METERS)	DELTA (DEG)	DISTANCE (KM)	AZIMUTH (DEG)	BACK AZIMUTH (DEG)
NSA0 277 AFGL	42.440N	71.727W	142.00	0.197	21.89	228.75	48.61
NSA1 320 AFGL	42.439N	71.728W	156.00	0.198	22.03	228.65	48.51
NSA2 322 AFGL	42.440N	71.724W	143.00	0.196	21.74	228.36	48.23
NSA3 312 AFGL	42.441N	71.728W	152.00	0.197	21.88	229.05	48.91
NSB1 278 AFGL	42.440N	71.729W	153.00	0.198	21.98	229.10	48.97
NSB2 279 AFGL	42.442N	71.726W	136.00	0.195	21.64	229.12	48.98
NSB3 334 AFGL	42.439N	71.723W	133.00	0.195	21.69	227.93	47.80
NSB4 280 AFGL	42.437N	71.726W	154.00	0.199	22.07	228.01	47.88
NSB5 281 AFGL	42.439N	71.730W	156.00	0.199	22.14	228.90	48.77

Table 3-5. NORESS Station Locations

DATE	ORIGIN TIME	LATITUDE	LONGITUDE	DEPTH	ELEVATION
JUL 21, 1987	202D 16H 58M 14.970S	42.553N	71.515W	0.0	76.0

LOCATION: SAN-VEL

STATION	LATITUDE (DEG)	LONGITUDE (DEG)	ELEVATION (METERS)	DELTA (DEG)	DISTANCE (KM)	AZIMUTH (DEG)	BACK AZIMUTH (DEG)
NSA0 277 AFGL	42.440N	71.727W	142.00	0.193	21.47	234.19	54.05
NSA1 320 AFGL	42.439N	71.728W	158.00	0.194	21.60	234.05	53.91
NSA2 322 AFGL	42.440N	71.724W	143.00	0.192	21.31	233.84	53.70
NSA3 312 AFGL	42.441N	71.728W	152.00	0.193	21.47	234.49	54.35
NSB1 278 AFGL	42.440N	71.729W	153.00	0.194	21.57	234.53	54.38
NSB2 279 AFGL	42.442N	71.726W	136.00	0.191	21.24	234.63	54.48
NSB3 334 AFGL	42.439N	71.723W	133.00	0.191	21.24	233.41	53.27
NSB4 280 AFGL	42.437N	71.726W	154.00	0.195	21.62	233.40	53.25
NSB5 281 AFGL	42.439N	71.730W	156.00	0.195	21.72	234.28	54.14

All stations were instrumented with Terra Technology DCS-302 recorders and Sprengnether Instruments S-6000 seismometers, provided by the AFGL and AFWL. The seismometers were buried in rocky soil at a depth of 1 foot with the horizontal components oriented to magnetic north and east. The four stations in the center and on the A ring were initially instrumented with AFWL seismometers and recorders, and the five stations on the B ring were initially instruments with AFGL seismometers and recorders. Vandalism to the AFGL seismometer S-6000 No. 9261 at station NSB1 necessitated that station NSB1 be moved and that the AFWL seismometer S-6000 No. 8767 be used at the new station NSB1 for shots on Julian Day 201 and subsequent days.

Only the shots EB1 and QB2 were recorded by the array. The array was in place for the shot QB3, but, for unknown reasons, the array did not trigger. The shot QB3 had the largest charge of all the shots, yet observation of the records at BC's Weston Observatory revealed that surface waves were excited to a lesser extent than during previous shots, suggesting a smaller shot. Record sections and seismograms of the two shots recorded by the NORESS array are given in Figures 3-13 through 3-31.

Following the shots, the array was surveyed using portable refraction gear to determine soil thickness, bedrock configuration, and local anisotropy effects. The equipment used was an EGG Geometrics 24-channel signal enhancement seismograph, Model ES-2415F, in connection with a string of 24 geophones with a resonant frequency of 14 Hz. The source used for the refraction survey was a Betsy 8-gauge seis-gun. For any given reverse profile, two shots were recorded at each end of each line, one shot to obtain arrival times, and another, at higher resolution, to obtain full waveform. Each station at the NORESS array was surveyed with a reverse profile along a 24 meter line with 1 meter receiver spacing. The results of the refraction survey are as follows: In all but one of the profiles, three layers were apparent. Layer one, taken to be the soil layer, had velocities ranging from 239 m/s - 444 m/s, averaging 340 m/s, and thickness ranging from 0.8 m - 1.9 m, averaging 1.42 m. Layer two had velocities ranging from 845 m/s - 1279 m/s, averaging 1137 m/s, and thickness ranging from 6.0 m - 8.1 m, averaging 6.6 m. Layer three had velocities ranging from 2185 m/s - 5419 m/s, averaging 3704 m/s.

Prior to disassembly of the array, calibration pulses were recorded at each station. Seismometer and recorder information are given in Tables 3-6 and 3-7, respectively. Typical instrument responses and calibration pulses are given in Figures 3-30 and 3-31.

Reference

1. Zen, E-an, Ed. (1983) Bedrock Map of Massachusetts, Massachusetts State Geologic Survey.

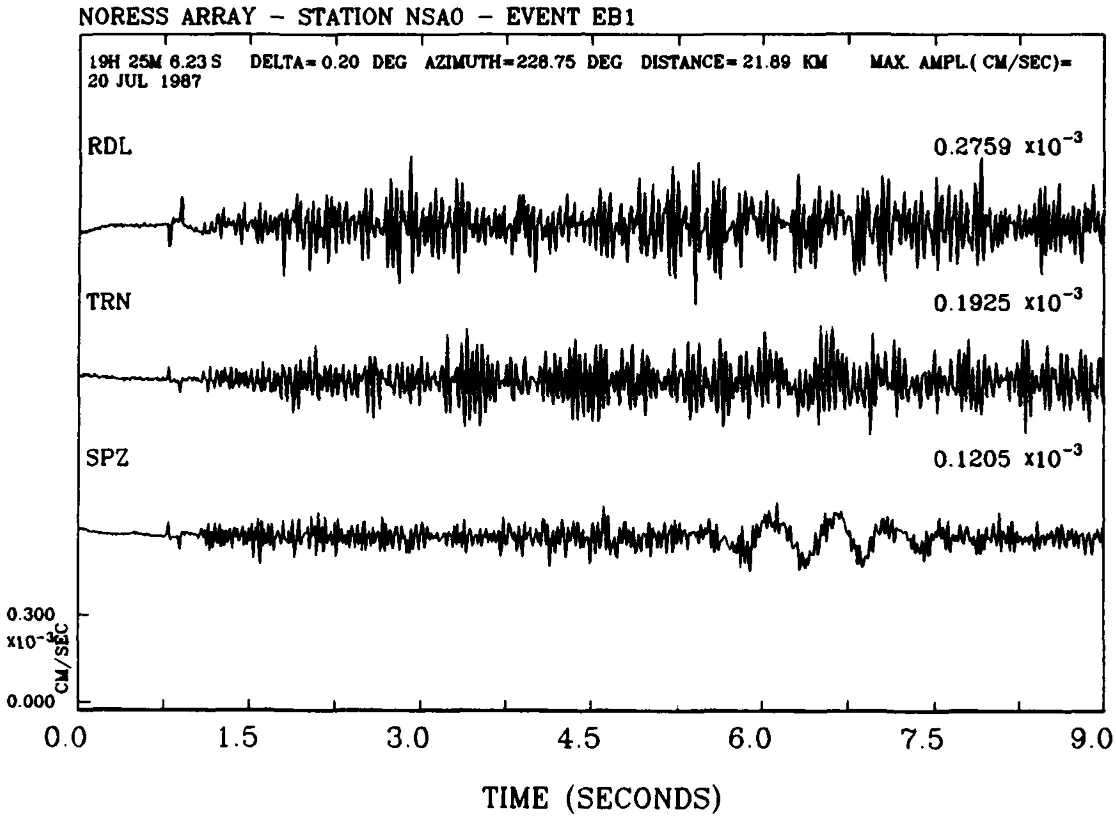

Figure 3-13. Three-Component Seismogram of Shot EB1 Recorded at Station NSAO. See Figure 3-3

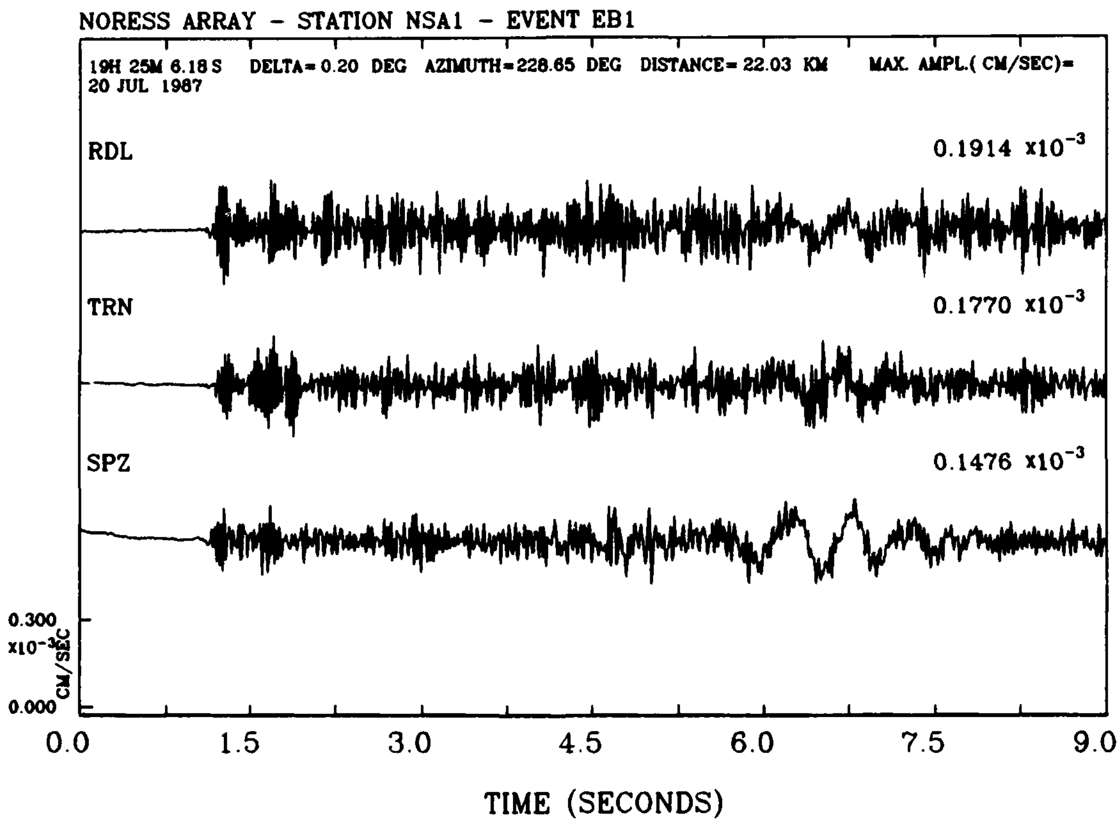

Figure 3-14. Three-Component Seismogram of Shot EB1 Recorded at Station NSA1. See Figure 3-4

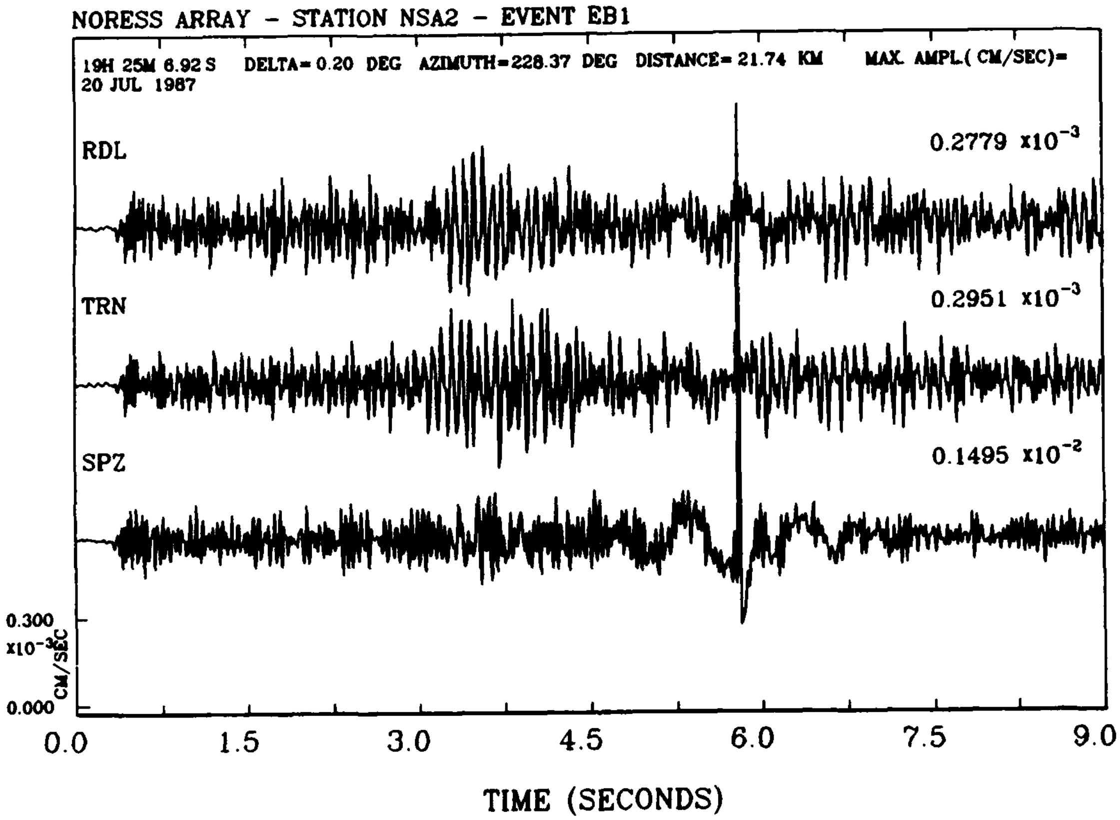

Figure 3-15. Three-Component Seismogram of Shot EB1 Recorded at Station NSA2. See Figure 3-3

NORESS ARRAY - STATION NSA3 - EVENT EB1

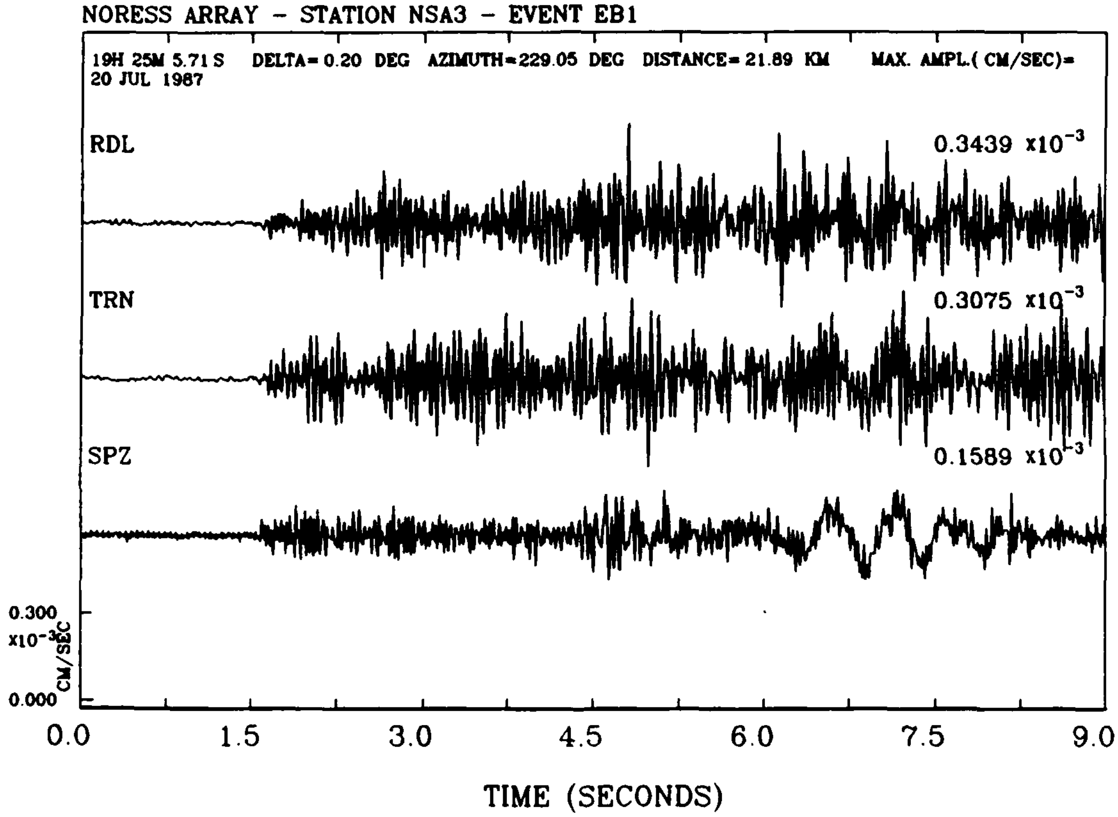

Figure 3-16. Three-Component Seismogram of Shot EB1 Recorded at Station NSA3. See Figure 3-3

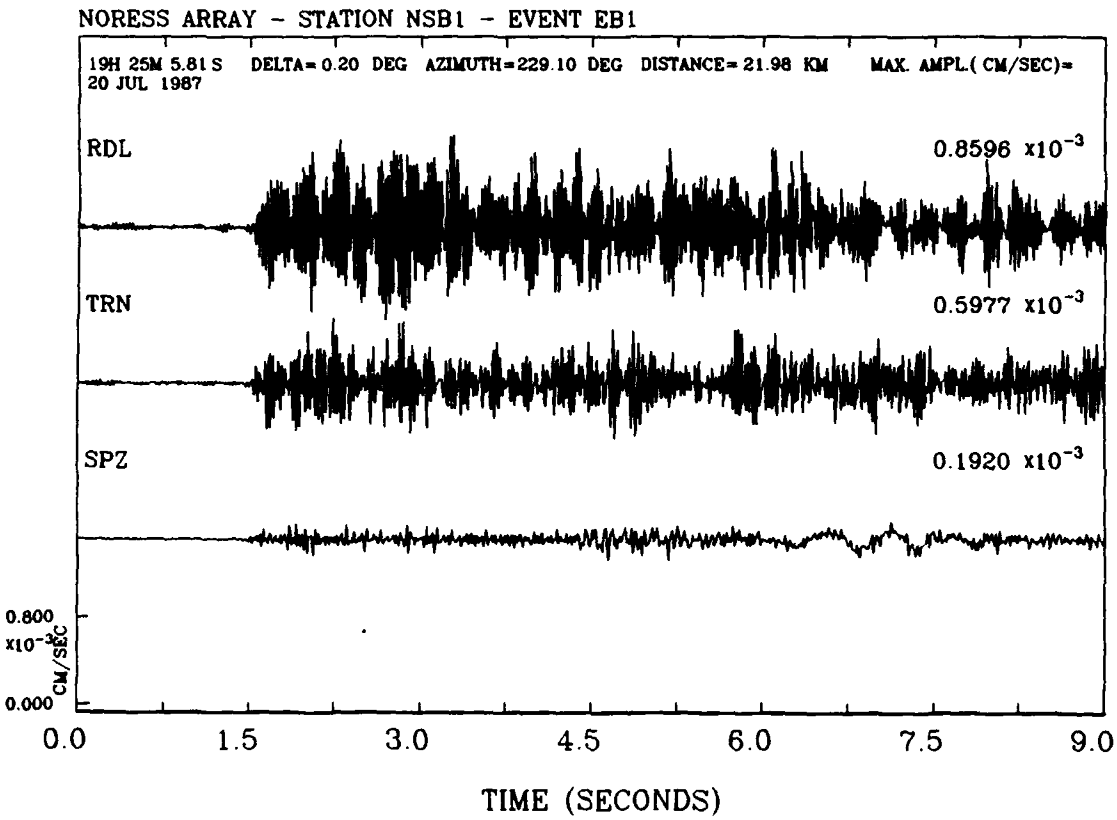

Figure 3-17. Three-Component Seismogram of Shot EB1 Recorded at Station NSB1. See Figure 3-3

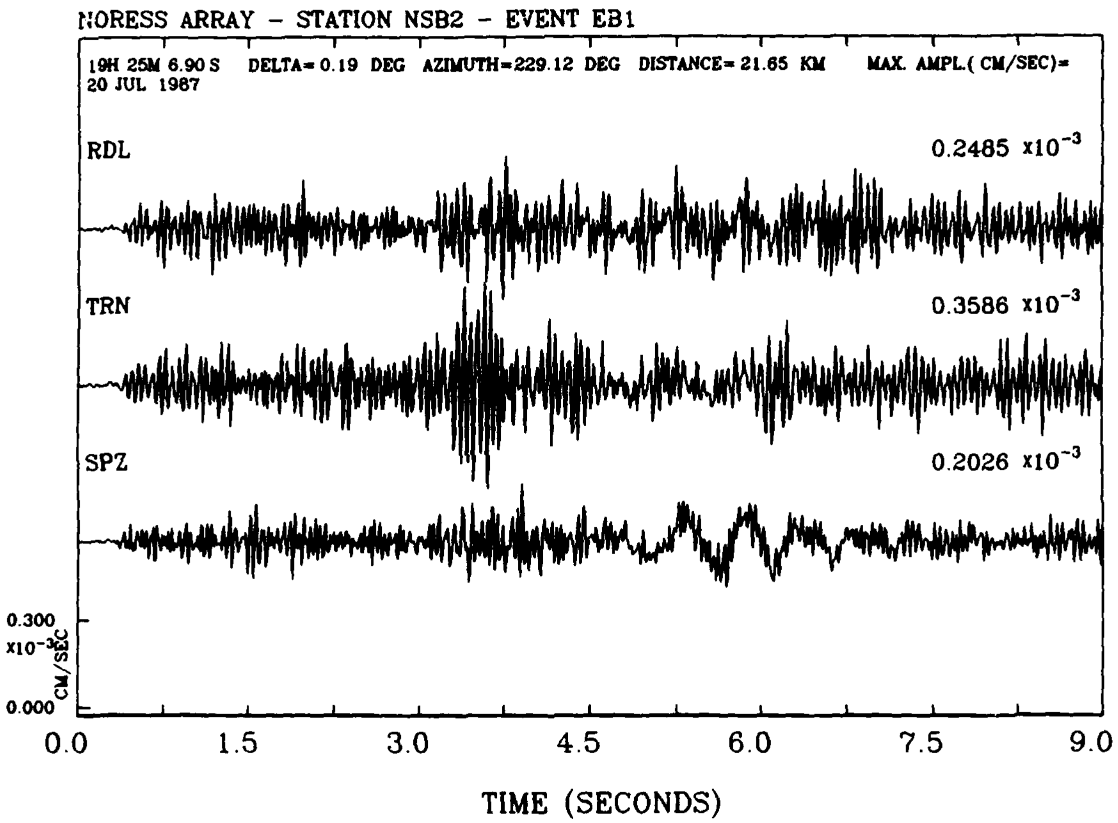

Figure 3-18. Three-Component Seismogram of Shot EB1 Recorded at Station NSB2. See Figure 3-3

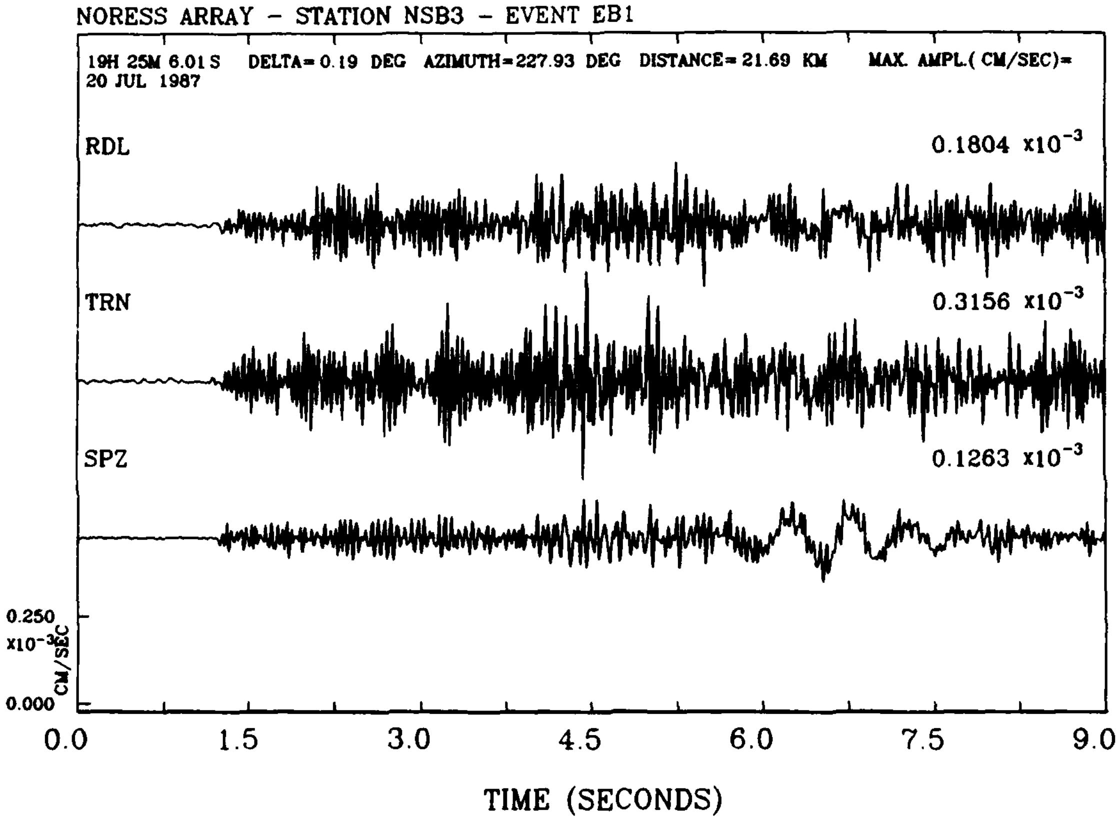

Figure 3-19. Three-Component Seismogram of Shot EB1 Recorded at Station NSB3. See Figure 3-3

NORESS ARRAY - STATION NSB4 - EVENT EB1

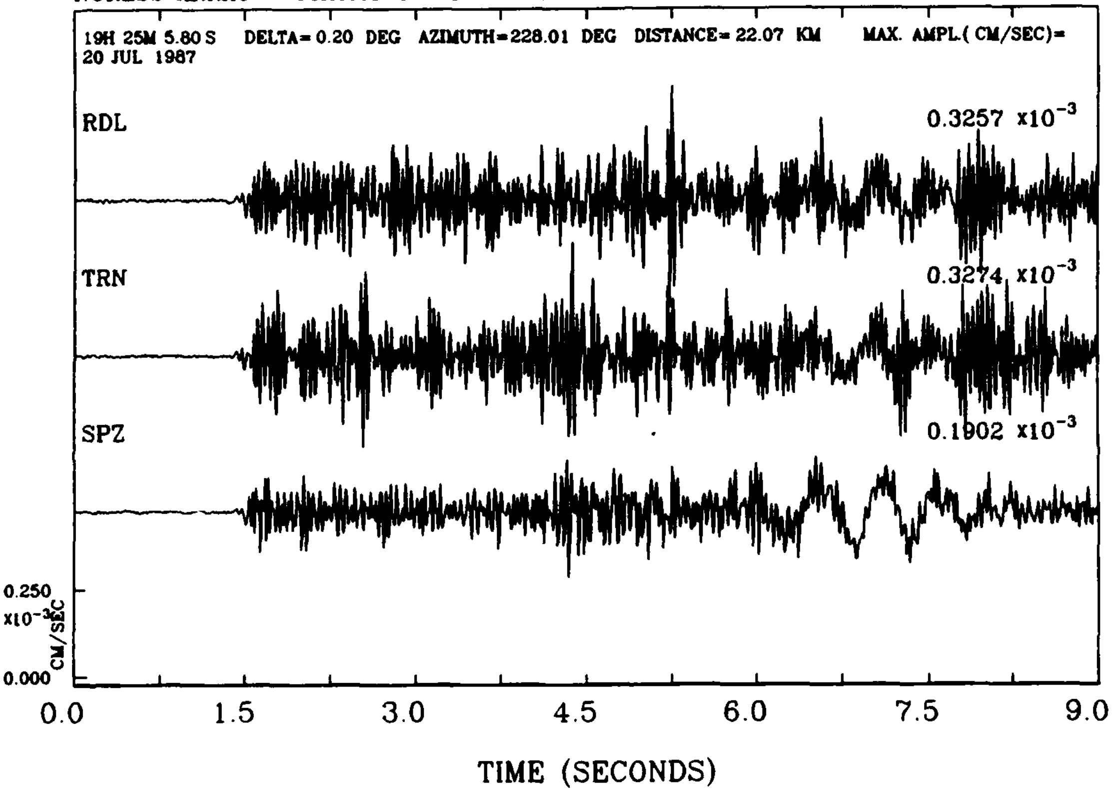

Figure 3-20. Three-Component Seismogram of Shot EB1 Recorded at Station NSB4. See Figure 3-3

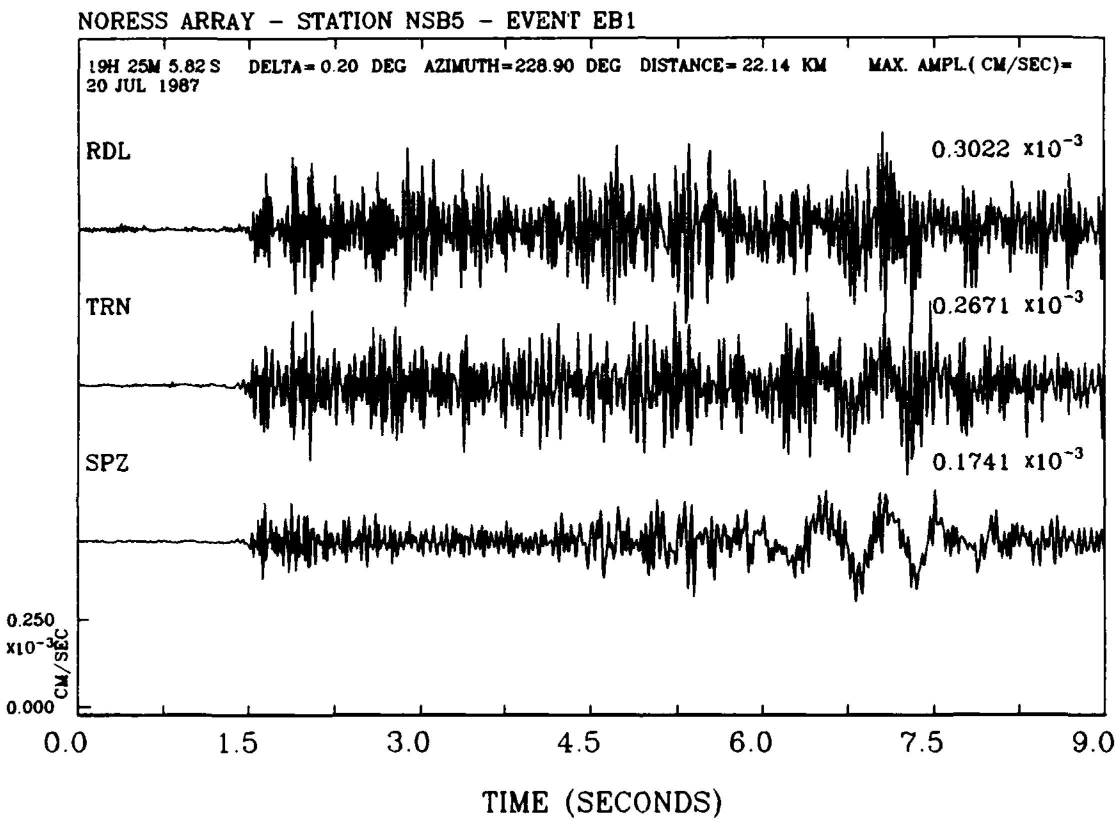

Figure 3-21. Three-Component Seismogram of Shot EB1 Recorded at Station NSB5. See Figure 3-3

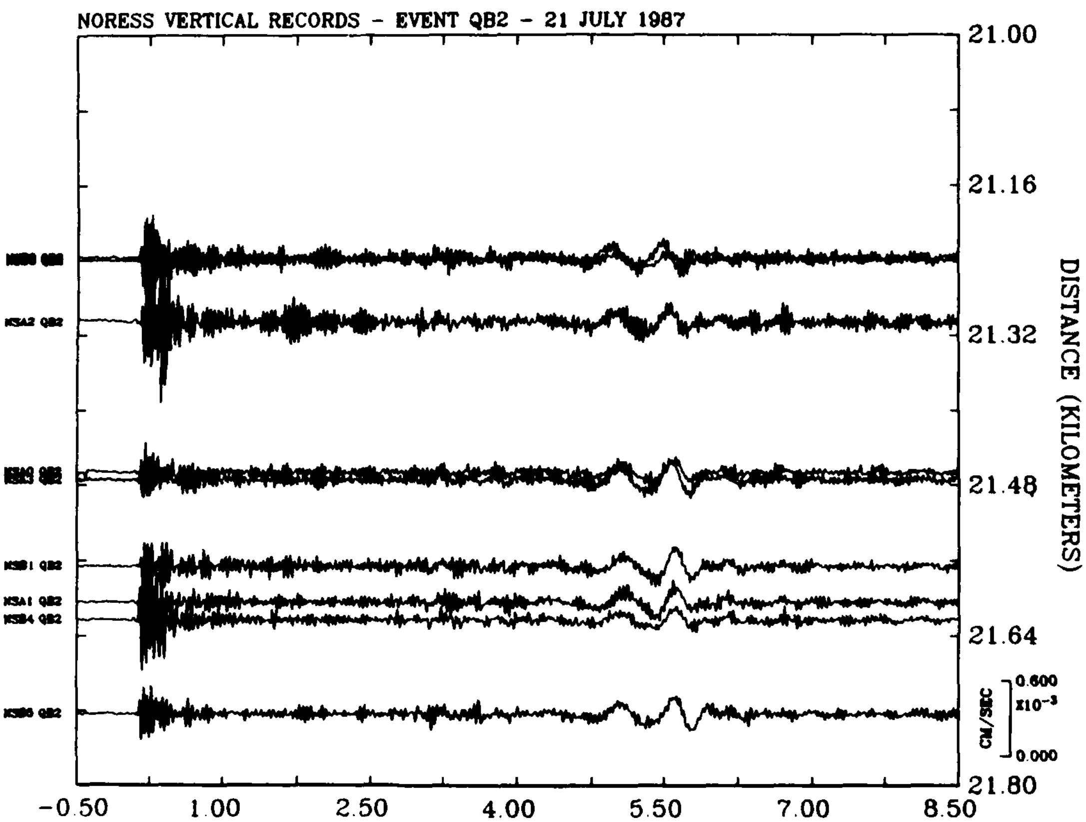

Figure 3-22. Record Section of Vertical Seismograms for Shot QB2

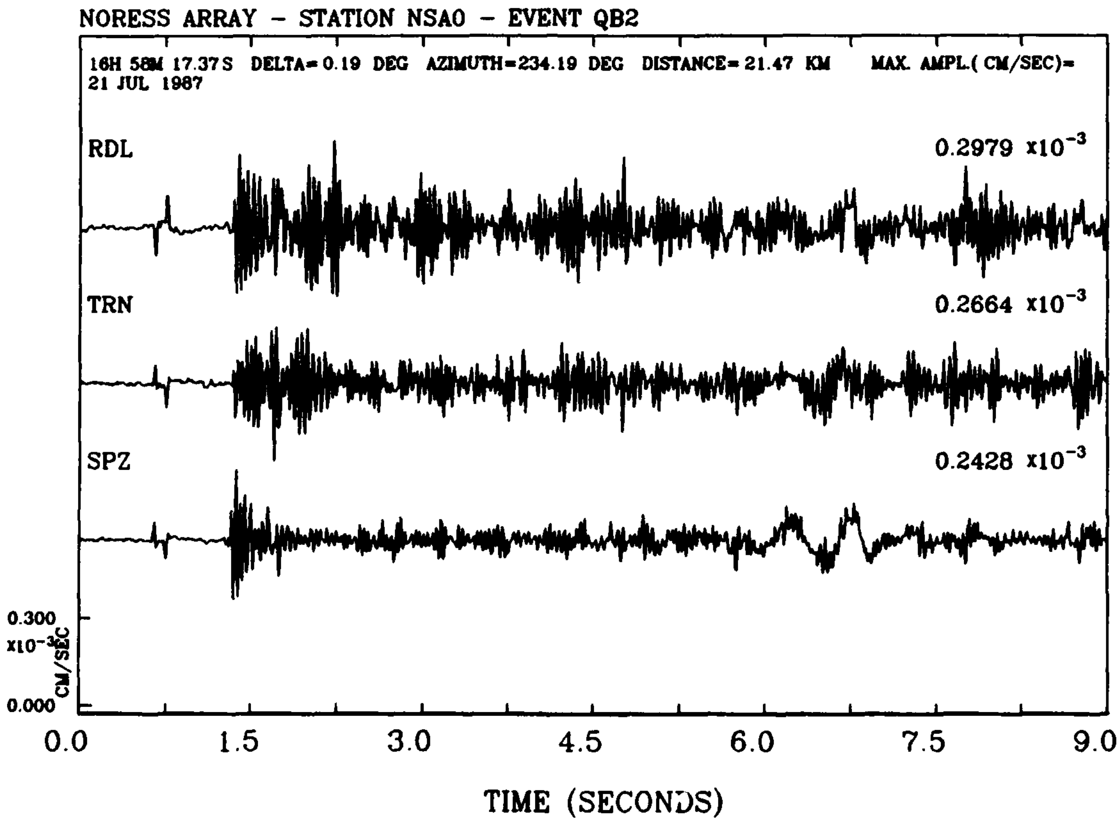

Figure 3-23. Three-Component Seismogram of Shot QB2 Recorded at Station NSA0. See Figure 3-3

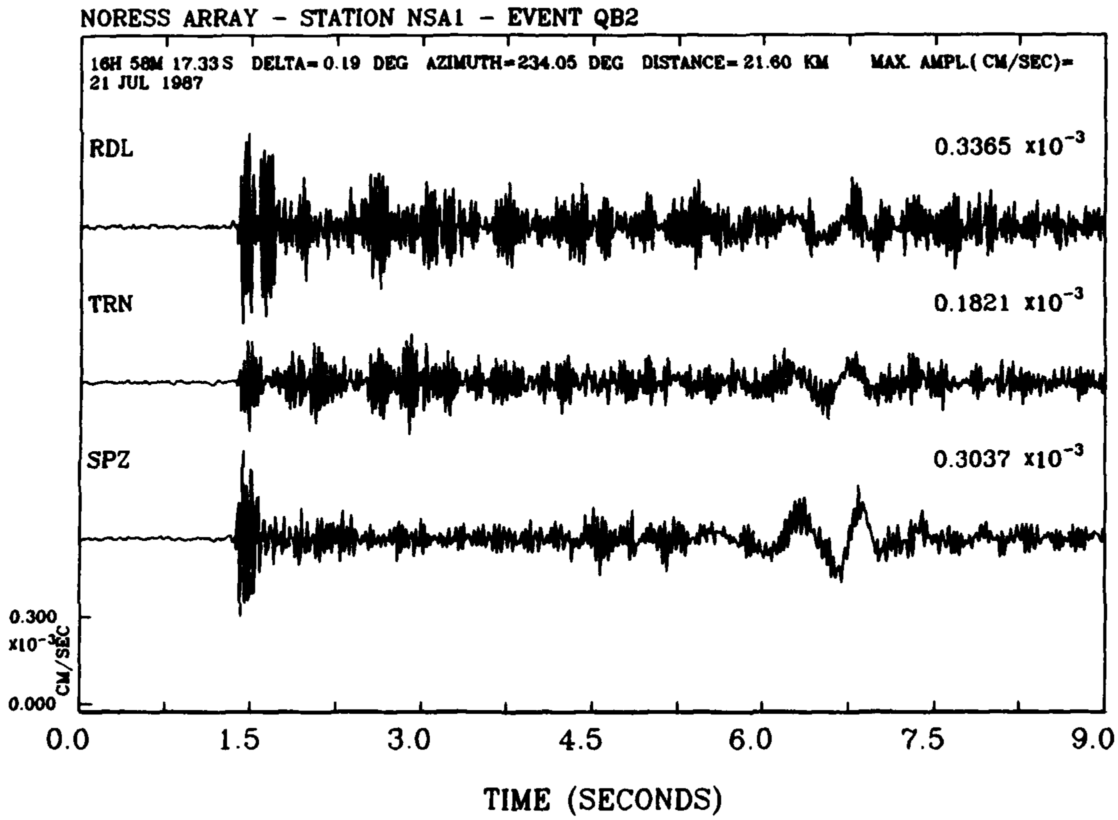

Figure 3-24. Three-Component Seismogram of Shot QB2 Recorded at Station NSA1. See Figure 3-3

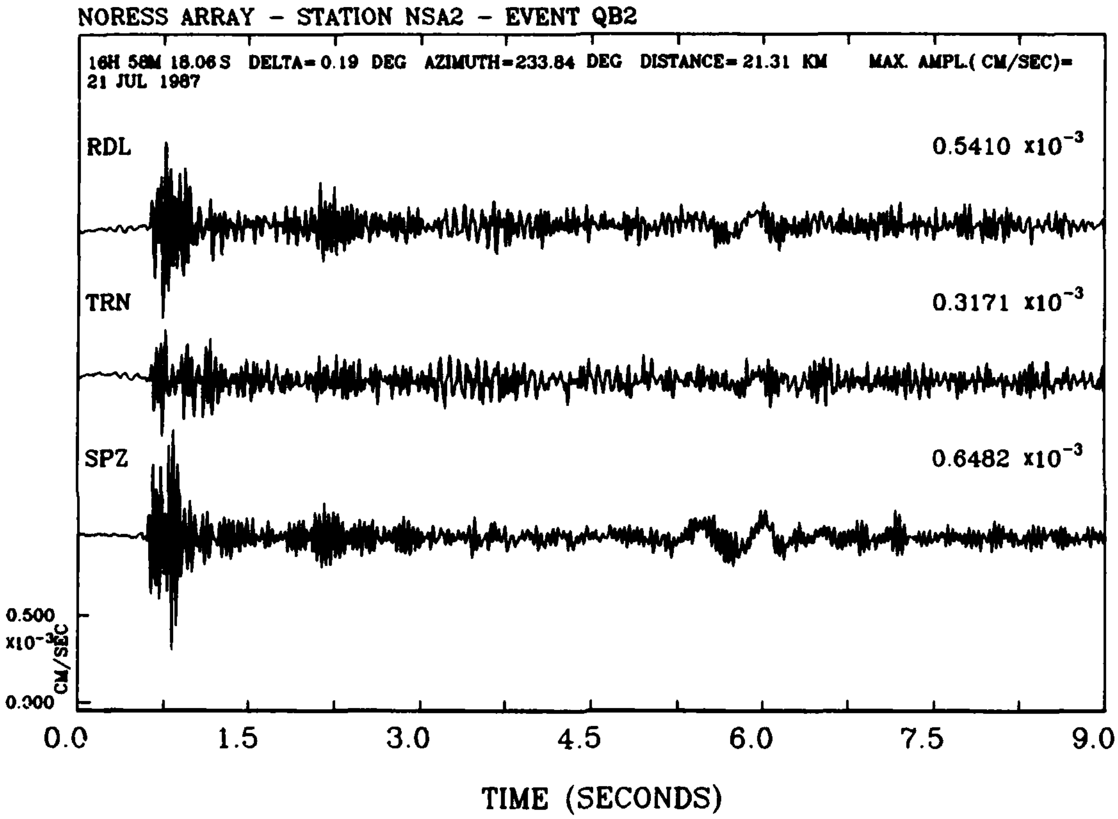

Figure 3-25. Three-Component Seismogram of Shot QB2 Recorded at Station NSA2. See Figure 3-3

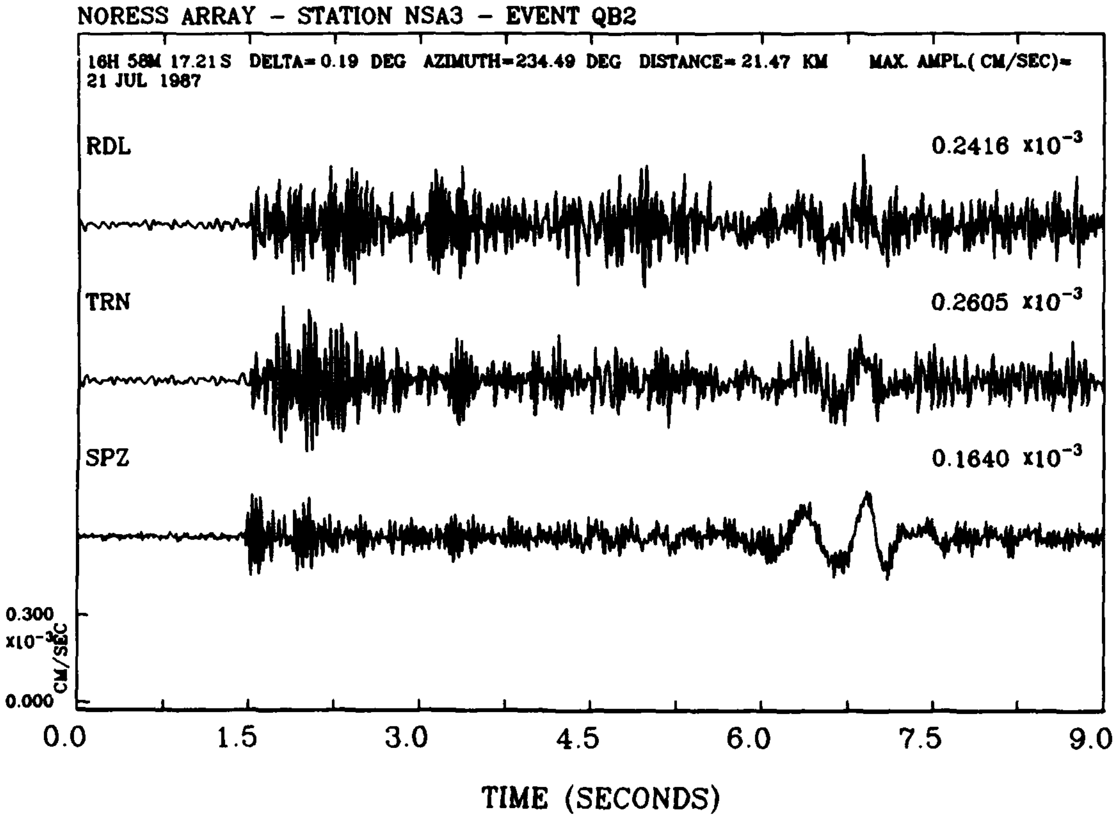

Figure 3-26. Three-Component Seismogram of Shot QB2 Recorded at Station NSA3. See Figure 3-3

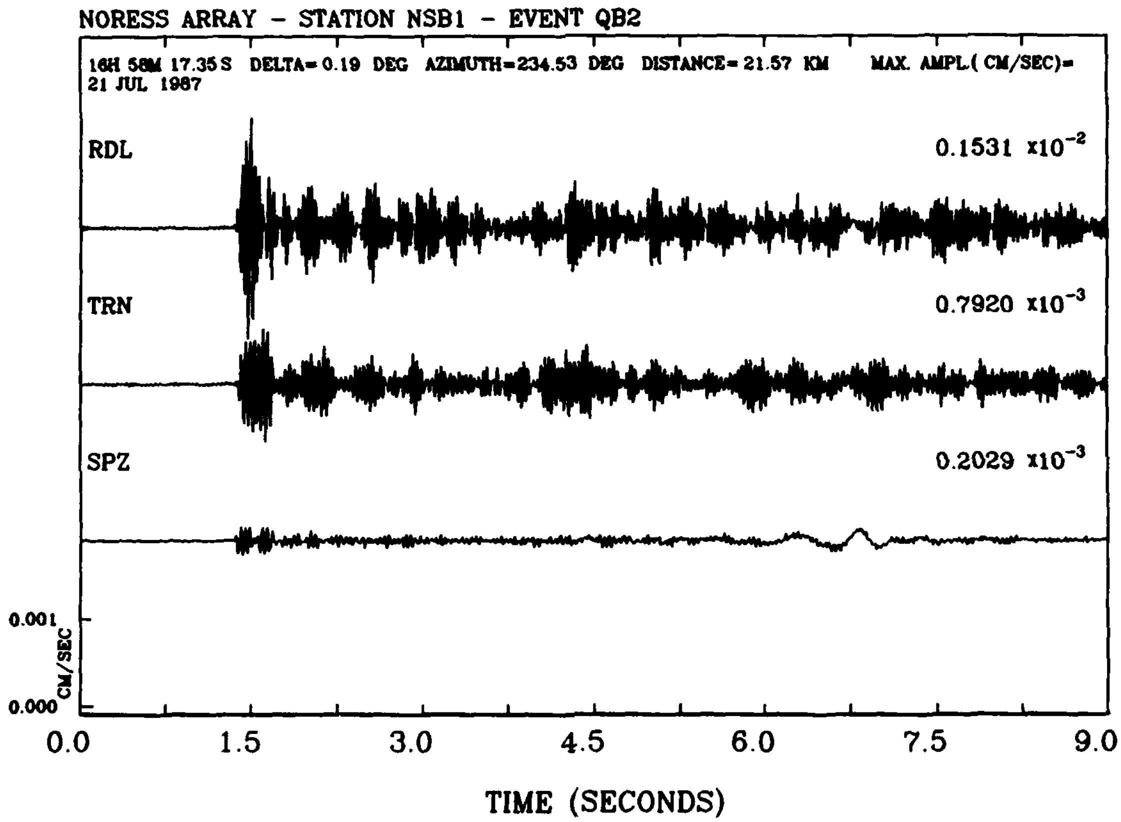

Figure 3-27. Three-Component Seismogram of Shot QB2 Recorded at Station NSB1. See Figure 3-3

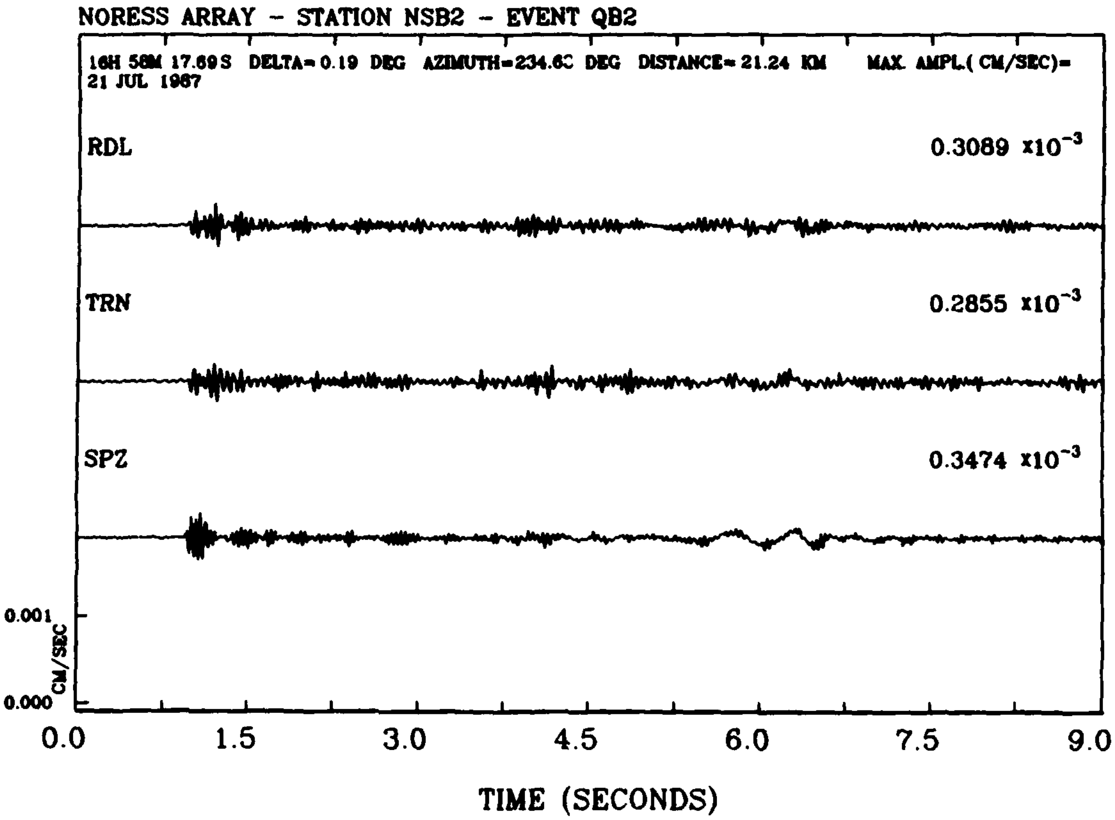

Figure 3-28. Three-Component Seismogram of Shot QB2 Recorded at Station NSB2. See Figure 3-3

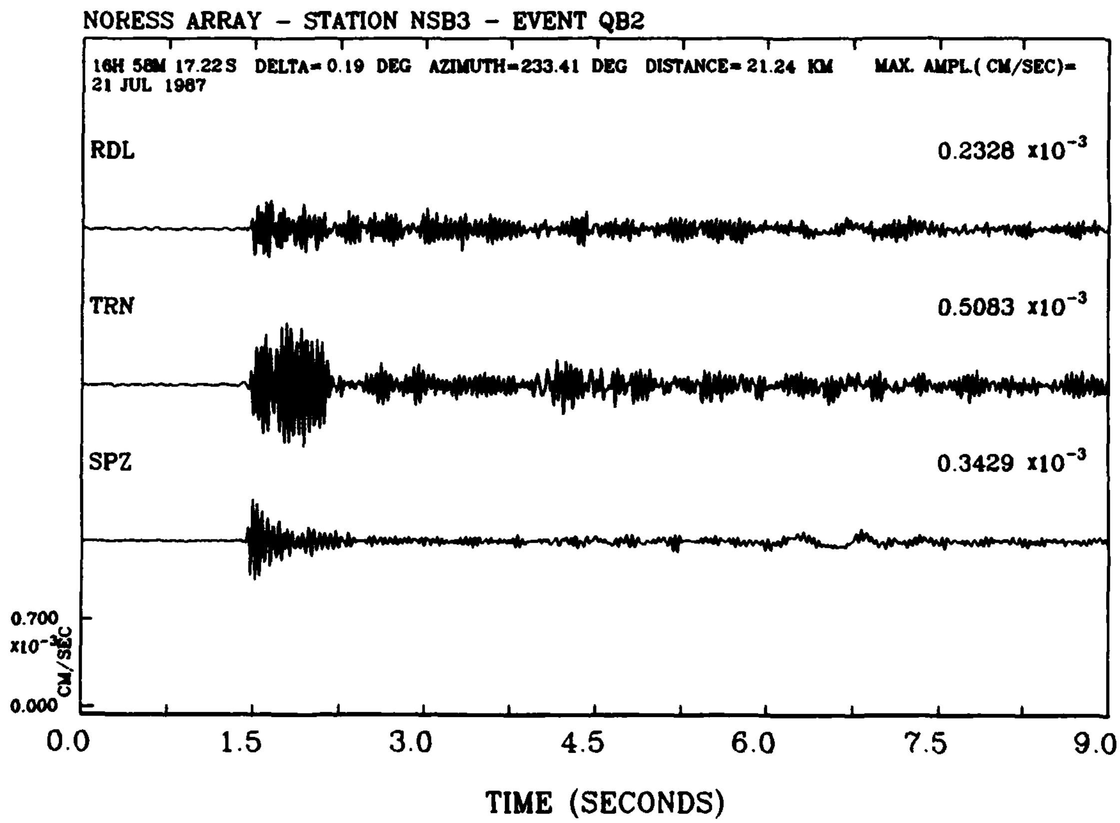

Figure 3-29. Three-Component Seismogram of Shot QB2 Recorded at Station NSB3. See Figure 3-3

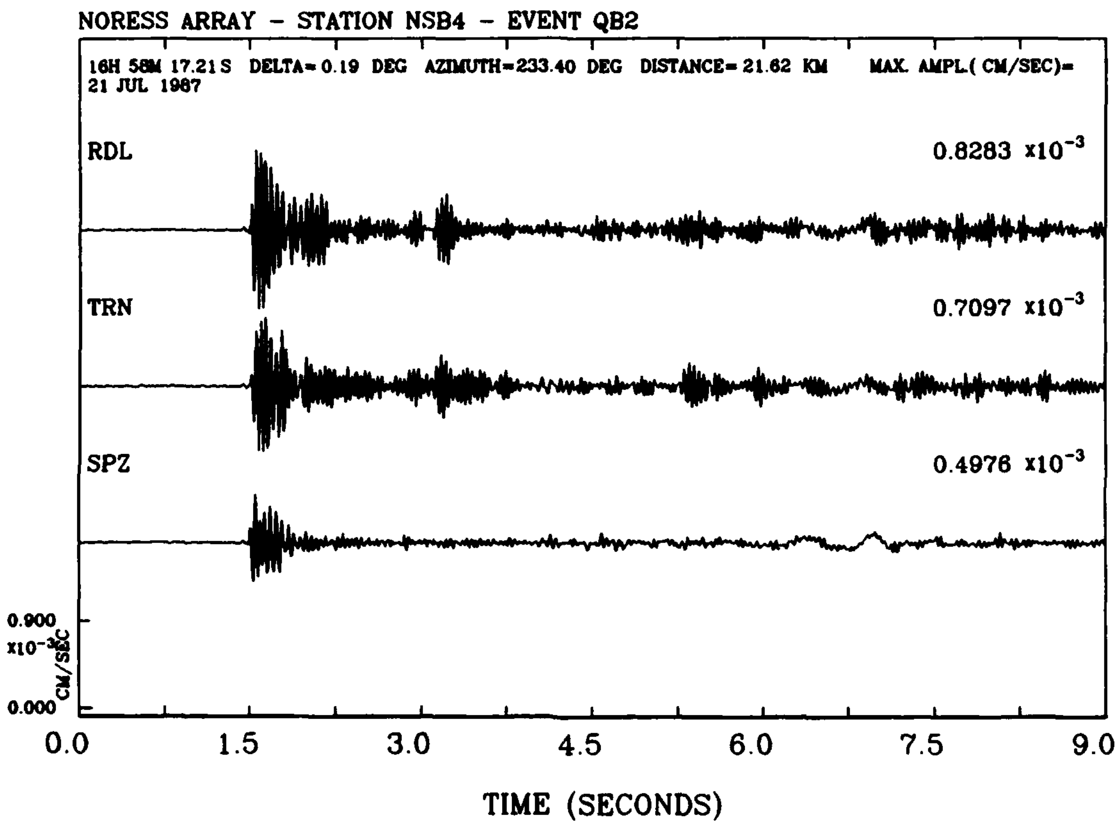

Figure 3-30. Three-Component Seismogram of Shot QB2 Recorded at Station NSB4. See Figure 3-3

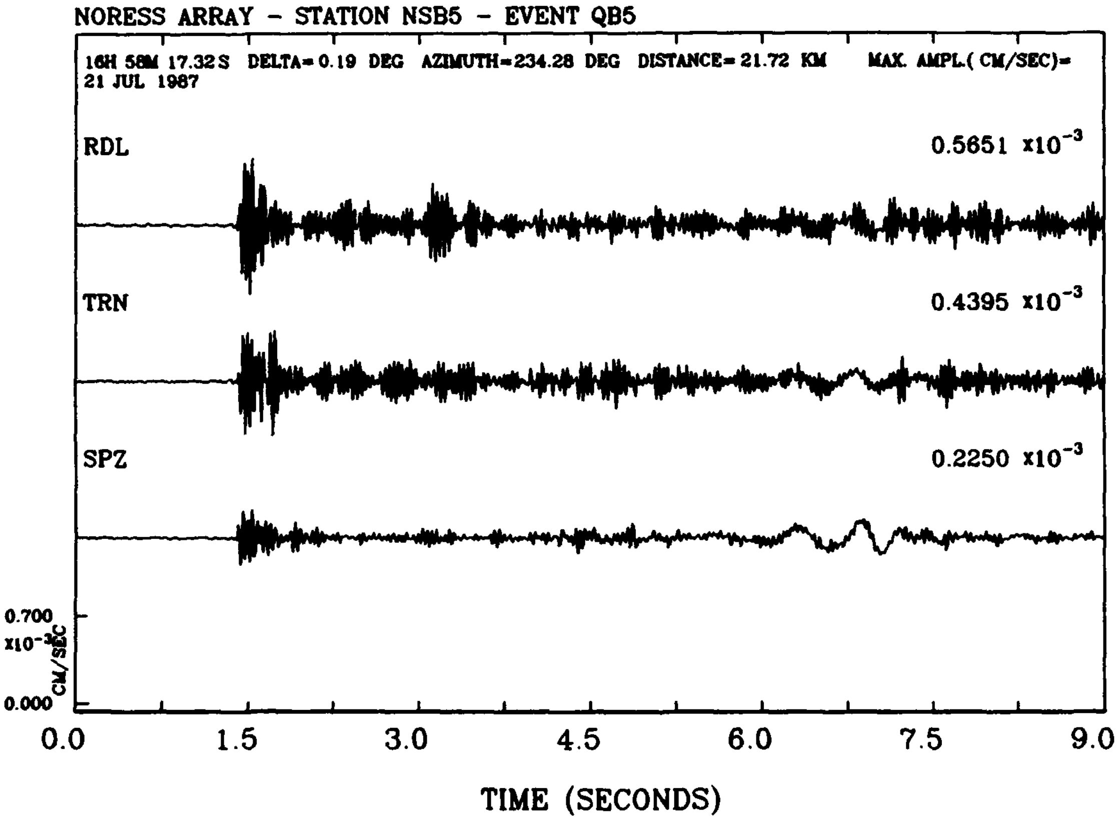

Figure 3-31. Three-Component Seismogram of Shot QB2 Recorded at Station NSB5.
See Figure 3-3

Table 3-6. Seismometer Constants

SEISMOGRAM			CUT-OFF FREQUENCY (HERTZ)	RECORDER GAINS (MILLIVOLTS/COUNT) GAIN 1	GAIN 2	GAIN 3	GAIN 4	SERIAL NUMBER
NSA0	EB1	SPZ	30.00	0.23894	0.05039	0.00974	0.00238	277
NSA0	EB1	SPN	30.00	0.23851	0.04903	0.00964	0.00246	277
NSA0	EB1	SPE	30.00	0.23872	0.04906	0.00971	0.00246	277
NSA1	EB1	SPZ	30.00	0.24381	0.04926	0.00980	0.00244	320
NSA1	EB1	SPN	30.00	0.24344	0.04917	0.00990	0.00246	320
NSA1	EB1	SPE	30.00	0.24381	0.04918	0.00983	0.00241	320
NSA2	EB1	SPZ	30.00	0.25326	0.04907	0.00970	0.00245	322
NSA2	EB1	SPN	30.00	0.25511	0.04952	0.00980	0.00246	322
NSA2	EB1	SPE	30.00	0.25564	0.04973	0.00981	0.00242	322
NSA3	EB1	SPZ	30.00	0.24396	0.04964	0.00974	0.00240	312
NSA3	EB1	SPN	30.00	0.24396	0.04884	0.00987	0.00245	312
NSA3	EB1	SPE	30.00	0.24374	0.04893	0.00982	0.00239	312
NSB1	EB1	SPZ	30.00	0.24414	0.04883	0.00977	0.00244	278
NSB1	EB1	SPN	30.00	0.24414	0.04883	0.00977	0.00244	278
NSB1	EB1	SPE	30.00	0.24414	0.04883	0.00977	0.00244	278
NSB2	EB1	SPN	30.00	0.24414	0.04883	0.00977	0.00244	279
NSB2	EB1	SPE	30.00	0.24414	0.04883	0.00977	0.00244	279
NSB2	EB1	SPZ	30.00	0.24414	0.04883	0.00977	0.00244	279
NSB3	EB1	SPN	30.00	0.25326	0.04907	0.00970	0.00245	334
NSB3	EB1	SPE	30.00	0.25511	0.04952	0.00980	0.00246	334
NSB3	EB1	SPZ	30.00	0.25564	0.04973	0.00981	0.00242	334
NSB4	EB1	SPN	30.00	0.24561	0.04947	0.00978	0.00235	280
NSB4	EB1	SPE	30.00	0.24531	0.04949	0.00980	0.00238	280
NSB4	EB1	SPZ	30.00	0.24538	0.04964	0.00977	0.00235	280
NSB5	EB1	SPN	30.00	0.24448	0.04897	0.00970	0.00244	281
NSB5	EB1	SPE	30.00	0.24433	0.04902	0.00976	0.00259	281
NSB5	EB1	SPZ	30.00	0.24426	0.04929	0.00976	0.00261	281

Table 3-7. DCS-302 Recorder Constants

SEISMOGRAM			TIME CORRECTION (SECONDS)	SEISMOMETER ORIENTATION (DEGREES)	SEISMOMETER SENSITIVITY (VOLTS/M/SEC)	PENDULUM PERIOD (SECONDS)	DAMPING RATIO	SERIAL NUMBER
NSA0	EB1	SPZ	-0.5000	VERT	271.5400	0.501	0.468	8297
NSA0	EB1	SPN	-0.5000	-15.00	286.9820	0.426	0.433	8297
NSA0	EB1	SPE	-0.5000	75.00	262.6740	0.521	0.496	8297
NSA1	EB1	SPZ	0.0930	VERT	227.0300	0.500	0.572	6843
NSA1	EB1	SPN	0.0930	-15.00	232.4030	0.458	0.526	6843
NSA1	ZB1	SPE	0.0930	75.00	221.5700	0.492	0.533	6843
NSA2	EB1	SPZ	0.0000	VERT	219.7450	0.505	0.475	7679
NSA2	EB1	SPN	0.0000	-15.00	222.3760	0.418	0.409	7679
NSA2	EB1	SPE	0.0000	75.00	220.2720	0.500	0.447	7679
NSA3	EB1	SPZ	0.0730	VERT	203.3510	0.523	0.479	8768
NSA3	EB1	SPN	0.0730	-15.00	199.5380	0.419	0.389	8768
NSA3	EB1	SPE	0.0730	75.00	232.7650	0.539	0.519	8768
NSB1	EB1	SPZ	-0.2540	VERT	200.0000	0.500	0.400	8767
NSB1	EB1	SPN	-0.2540	-15.00	200.0000	0.500	0.400	8767
NSB1	EB1	SPE	-0.2540	75.00	200.0000	0.500	0.400	8767
NSB2	EB1	SPN	-0.0200	-15.00	235.9070	0.502	0.444	9319
NSB2	EB1	SPE	-0.0200	75.00	209.2730	0.397	0.365	9319
NSB2	EB1	SPZ	-0.0200	VERT	204.9050	0.496	0.435	9319
NSB3	EB1	SPN	1.1610	-15.00	287.2340	0.483	0.389	9324
NSB3	EB1	SPE	1.1610	75.00	339.1400	0.420	0.392	9324
NSB3	EB1	SPZ	1.1610	VERT	319.1060	0.510	0.458	9324
NSB4	EB1	SPN	0.0630	-15.00	166.0340	0.385	0.328	9325
NSB4	EB1	SPE	0.0630	75.00	207.0090	0.490	0.456	9325
NSB4	EB1	SPZ	0.0630	VERT	191.5650	0.440	0.362	9325
NSB5	EB1	SPN	0.0830	-15.00	191.5650	0.440	0.362	9322
NSB5	EB1	SPE	0.0830	75.00	166.0340	0.385	0.328	9322
NSB5	EB1	SPZ	0.0830	VERT	207.0090	0.490	0.456	9322

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