NASA CR- 132606

STUDY OF THE CHARACTERISTICS OF SEISMIC SIGNALS GENERATED BY NATURAL AND CULTURAL PHENOMENA

By

Tom T. Goforth and Robert K. Rasmussen

Prepared under Contract No. NAS1-11889

by

Teledyne Industries, Geotech Division

Garland, Texas

for

Langley Research Center
National Aeronautics and Space Administration

(NASA-CR-132606) STUDY OF THE CHARACTERISTICS OF SEISMIC SIGNALS GENERATED BY NATURAL AND CULTURAL PHENOMENA (Teledyne Industries, Inc.) 71 p HC $4.25 CSCL 08K

N75-20919

Unclas
G3/46 18545

ABSTRACT

Seismic data recorded at the Tonto Forest Seismological Observatory in Arizona and the Uinta Basin Seismological Observatory in Utah are used to compare the frequency of occurrence, severity, and spectral content of ground motions resulting from earthquakes and other natural and man-made sources with the motions generated by sonic booms.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS, Continued

TABLES

STUDY OF THE CHARACTERISTICS OF SEISMIC SIGNALS GENERATED BY NATURAL AND CULTURAL PHENOMENA

By Tom T. Goforth and Robert K. Rasmussen
Teledyne Industries, Geotech Division

1. INTRODUCTION

This is a report of the research study accomplished under NASA Langley Research Center, Contract NAS1-11889 entered into on 26 September 1972, to 31 December 1973.

The tasks assigned to this study were as follows:

1. To categorize seismic arrivals at two observatories by maximum ground velocity, and to determine the frequency of occurrence of each size category. Using the relationships between sonic boom overpressures and ground particle velocity, Reference 1, each ground velocity category is to be converted to an equivalent sonic boom overpressure category. The data will then be presented as to the frequency with which each of the two (2) observatory areas have been subjected to seismic disturbances with the size of the disturbances being represented in terms of sonic boom overpressure.

2. To tabulate quarry blasts and other disturbances not normally reported by the observatories and present this data in a manner similar to that in which the earthquake data are presented.

3. To publish a catalog containing typical seismic signatures and spectra of various seismic disturbances as observed at the two observatories.

1.1 SUMMARY OF THE STUDY

Seismic data recorded at the Tonto Forest Seismological Observatory (TFSO) in Arizona and the Uinta Basis Seismological Observatory (UBSO) in Utah have been used to compare the frequency of occurrence, severity, and spectral content of ground motions resulting from earthquakes and other natural and man-made seismic sources with the ground motions generated by sonic booms. A search of data recorded at the two observatories yielded a classification of over 180,000 earthquake phase arrivals on the basis of frequency of occurrence versus maximum ground velocity. During the period surveyed, there were seven occurrences at TFSO in which ground velocities due to earthquakes exceeded 50 microns/second, i.e., the equivalent of a 4.88 kilograms/meter^2 (1 pound/square foot) sonic boom. There were seven similiar instances at UBSO. There was one occurrence at each observatory in which a ground velocity equivalent to a 19.52 kg/m^2 (4 pound/square foot) sonic boom was exceeded The majority of the large ground velocities were produced by seismic surface waves from moderate to large earthquakes in the western United States and particularly along the Pacific Coast of the United States and northern Mexico. It was found that earthquakes in this belt of Richter magnitude (m_b) of approximately 5.5 or greater produce ground velocities at the observatories equivalent to or greater than a 4.88/kg/m^2 (1.0 pound/square foot) sonic boom. There are some instances in which Rayleigh waves from earthquakes of magnitude 6.0 and greater in South America produce ground velocities at the observatories which are as large as that produced by a 4.88 kg/m^2 (1.0 pound/square foot) sonic boom.

A visual analysis of raw film seismogram data over a 3-year period at TFSO and UBSO indicated that local and regional seismic events, including quarry blasts, are frequent in occurrence, but do not produce ground motions at the observatories comparable to either the large western United States earthquakes or to sonic booms.

Nuclear blasts detonated at the Nevada Test Site sometimes produce peak ground velocities in excess of 50 microns/second, the exact value depending upon the yield and the geologic medium surrounding the charge. Seismic data from the NTS blasts are used to derive magnitude-distance-sonic boom overpressure relations.

1.2 RELATED DATA

It is often desired that measurement of ground motion resulting from various types of seismic or acoustic disturbances be available for the purpose of assessing the damage potential of the motion to structures. Reference 1 reported on the nature and size of ground motions to be expected from sonic booms. Earth particle velocities produced by sonic booms were recorded at Edwards Air Force Base, California; the Tonto Forest Seismological Observatory near Payson, Arizona; and the Uinta Basin Seismological Observatory near Vernal, Utah. Analysis of the field data indicated that the seismic effects of sonic booms are largely confined, laterally, to the boom pressure envelope and vertically to the upper few meters of the earth's surface. The maximum particle velocity associated with a sonic boom was observed to be in response to the rapid pressure changes of the leading and trailing edges of the acoustic N-wave. Empirical relations developed from the recorded data indicated that the peak ground velocity was linearly related to the maximum positive overpressure of the N-wave. On hard, well-consolidated rock at Edwards AFB, each approximate 5 kg/m^2 (pound per square foot) of overpressure produced about 75 microns per second peak particle velocity. On more loosely consolidated rock, each approximate 5 kg/m^2 (pound per square foot) of overpressure produced about 100 microns per second. At TFSO and UBSO, each approximate 5 kg/m^2 (pound per square foot) produced 25-75 microns per second, the exact relation varying with the particular recording site at each observatory. For the purposes of the present study, a median value of 50 microns/second per pound/square foot was used. The purpose of the present data compilation is to augment the results of the sonic boom study and to provide the information necessary for a comparison of the ground motions due to sonic booms and other man-made disturbances with ground motions resulting from naturally occurring phenomena.

1.3 DATA SOURCE

The data used in this study were originally recorded at the Tonto Forest Seismological Observatory and at the Uinta Basin Seismological Observatory. Figure 1 shows the locations of the two observatories.

During the years 1963 through 1968, film seismograms were analyzed on a routine basis at these observatories. These analyses were compiled and listed along with epicenter information (e.g., earthquake origin time, geographic coordinates, depth, and Richter magnitude) in a Registration of Earthquakes report, published monthly. Data used in section 2 of this report were obtained from magnetic tape listings used to produce these reports.

Since local cultural seismic events were not routinely reported in the Registration of Earthquakes publications, it was necessary to perform visual analysis of film records from these observatories as part of this study. A representative sample of film records for a 3-year period were selected and analysed. These data were used to produce the results found in section 3 of this report.

General information concerning TFSO and UBSO, including facilities, instrumentation, and recording parameters, is given in appendix A.

1.4 LIST OF SYMBOLS

UBSO - Uinta Basin Seismological Observatory
TFSO - Tonto Forest Seismological Observaotory
RG - Redig, South Dakota
WN - Winner, South Dakota
CR - Crete, Nebraska
WMSO - Wichita Mountains Seismological Observatory
SW - Sweetgrass, Montana
AX2 - Alexander City, Alabama
JP - Jasper, Alberta, Canada
PG - Prince George, British Columbia, Canada
KC - Kansas City, Missouri
RK - Red Lake, Ontario, Canada
NP - Mould Bay, Northwest Territories, Canada
BE - Belleview, Florida
CGS - Coast and Geodetic Survey, Environmental Science Services Administration
PDE - Preliminary Determination of Epicenter
ABP - Automated Bulletin Process
P phase - Compressional body wave
S phase - Transverse body wave
Lg phase - Crustal guided wave

2. TABULATION OF EARTHQUAKE GROUND VELOCITIES AT TFSO AND UBSO LISTED IN THE REGISTRATION OF EARTHQUAKES 1966-1968

2.1 REGISTRATION OF EARTHQUAKES INFORMATION

Data used to compile the tables shown in this section were obtained from magnetic tape[1] used to produce the Registration of Earthquakes. This was a monthly publication produced by Teledyne Geotech using data recorded at observatories such as TFSO, UBSO, WMSO and other observatories during their period of operation. These bulletins contain the seismological data on earthquake phases recorded at the observatories and define the extent of ground motion at the observatories resulting from the world-wide distribution of earthquakes.

The preliminary analysis of film seismograms and coding of the analysis data were accomplished by the personnel at each observatory. The data were integrated with the Environmental Science Services Administration's Coast and Geodetic Survey (C&GS) epicentral data using an Automated Bulletin Process (ABP). The ABP identified as many as 23 phases for each earthquake and computed distance, azimuth, ground motion, and magnitude.

The following data are contained in the Registration of Earthquakes and on corresponding magnetic tapes:

a. All epicentral locations, times of origins, and depths of foci that were obtained from the C&GS Preliminary Determination of Epicenter (PDE) cards.

b. Data for all phases that were associated with the epicenters reported in the C&GS PDE cards.

c. Data for phase arrivals that could not be associated with epicenters reported in the C&GS PDE cards.

Appendix B shows a sample of the seismic data presented in the Registration of Earthquakes and gives an explanation of the format.

2.2 DATA TABULATION

Using a 3100 CDC computer, each shock was categorized according to observatory, maximum ground velocity, and frequency of occurrence of each velocity category. It should be emphasized that each tabulated shock does not represent a separate earthquake, but rather a distinct phase arrival. Depending upon the distance and magnitude of an earthquake, a given point on the earth will usually be subjected to the arrival of several phases from one earthquake. For example, an earthquake always generates a compressional body wave, or P phase, a transverse body wave, or S phase, and Rayleigh and Love surface waves. Each of these phases has a characteristic propagation velocity and therefore a different arrival time. In addition, the general increase of elastic velocities with depth and the existence of velocity discontinuities in the earth cause reflections and refractions of the body waves. Because of different travel paths, each of these has a different arrival time. Figure 2 shows schematically the travel paths of the different body phases.

Each phase also has a characteristic particle motion. P waves cause the earth to vibrate along the line of propagation. Since the P wave always arrives at some angle to the vertical, both a horizontal and a vertical component of motion are observed. The S wave causes the earth to vibrate in a plane perpendicular to the direction of propagation. Due to the angle of arrival, it also produces both horizontal and vertical components of motion, although the horizontal usually predominates. Rayleigh waves travel along the surface and have a retrograde elliptical motion. They produce both horizontal and vertical components of motion. Love waves are horizontally polarized in a plane perpendicular to the line of propagation and have only a horizontal component of motion. For purely continental propagation paths, there exists a crustal guided wave called Lg which travels over long continental paths with relatively little loss of energy; however, the Lg phase is cut off abruptly when the propagation path includes even a small segment of oceanic crustal structure.

The frequency spectrum of the seismic energy constituting a phase arrival depends upon the type of source, the type of phase, and the distance between the earthquake epicenter and the recording site. In general, the earth acts as a low-pass filter; the greater the length of the propagation path, the greater is the relative concentration of energy in the low frequency portion of the spectrum. For all phases and all distances, the frequency range of seismic spectral peaks extends over at least eight octaves. For example, a small near-by disturbance such as a quarry blast will have a P wave spectral peak on the order of 10 Hz, whereas the Rayleigh wave from a large earthquake thousands of kilometers away may have a spectral peak on the order of 0.02 Hz. Such a frequency range is too broad for one seismograph system to accommodate. Large seismic observatories such as UBSO and TFSO simultaneously operate several sets of seismographs with different frequency responses; reference appendix A. There are seismographs which separately measure the vertical motion component and the north-south and east-west horizontal components for each frequency response shown. All particle velocities discussed in this paper have been corrected for the appropriate frequency response.

As indicated by the frequency responses referenced in appendix A, the standard observatory instrumentation is tailored to respond to ground motions with frequencies less than about 5 Hz. The characteristic of the earth to act as a low-pass filter with respect to seismic energy propagated through it results in frequencies greater than about 5 Hz being effectively eliminated from all seismic waves which have been propagated more than a few kilometers. Thus, the standard observatory instrumentation covers the frequency range in which maximum ground velocities occur for disturbances other than those which are extremely local in origin. For a local disturbance such as the passage of a sonic boom, the standard observatory instrumentation does not respond to the frequency band (5-100 Hz) at which the peak velocities occur. However, the peak particle velocities resulting from sonic booms at TFSO and UBSO in the frequency band 1-100 Hz have been previously measured (reference 1). It is therefore possible to compare the maximum ground velocity resulting from sonic booms to the maximum ground velocities observed for earthquakes and other phenomena even though the maxima occur at greatly different frequencies. Obviously, a peak ground velocity which occurs at a high frequency will represent a greater acceleration and a smaller displacement than the same velocity occurring at a low frequency. Since many damage criteria are based on peak ground velocities, that quantity has been emphasized here.

Tables 1 and 2 give the average annual incidence at TFSO and UBSO, respectively, of earthquake phase arrivals in five ground velocity categories. The tables are based upon computer analysis of 27 months, 1966-1968, of data from the Registration of Earthquakes. Each velocity category is equated to a corresponding sonic boom overpressure on the basis that each 4.88 kg/m^2 (pound/square foot) of sonic boom overpressure produces 50 microns/second ground motion directly beneath the sonic boom. An annual average of over 36,000 distinct shocks were observed at TFSO, and over 43,000 at UBSO. The vast majority of these shocks produced ground velocities at the observatories which were insignificant as compared to the maximum ground velocity to be expected from a hypothetical 4.88 kg/m^2 (1.0 pound/square foot) sonic boom. There was, however, a yearly average at each observatory of three arrivals which caused ground velocities in excess of 50 microns/second, i.e., in excess of the ground velocity produced by 4.88 kg/m^2 (1.0 pound/square foot) sonic boom.

During the period surveyed, there were 7 occurrences at TFSO in which velocities due to earthquakes exceeded 50 microns/second and 7 occurrences at UBSO in which ground velocities due to earthquakes exceeded 50 microns/second, i.e., the equivalent of 4.88 kg/m^2 (1 pound/square foot) sonic boom.

Of the 14 occurrences at the two observatories in which the maximum ground velocity exceeded 50 microns/second, 10 were surface waves and 4 were body waves. The surface waves were primarily short-period (1.0-0.3 Hz) Lg waves from earthquakes in the western United States and northern Mexico. The body waves were from large earthquakes (m_b > 6.0) located in Central and South America. In addition to the 14 documented occurrences, there were numerous occasions on which seismic arrivals were entered in the Registration of Earthquake tapes as being unreadable by the analyst. Because of the uncertainty as to whether these entries were due to difficulties on the analyst's film viewer or to oversaturation of the seismograph systems due to the severity of the motion, we do not feel justified in equating a seismograph clipping level to a minimum ground velocity. ~~Thus,~~ the 14 occurrences probably do not constitute the total number of times a ground velocity of 50 microns/second was exceeded.

Table 1. Annual frequency of occurrence of earthquake phase arrivals at the Tonto Forest Seismological Observatory

Ground velocity (microns/sec)	Equivalent sonic boom overpressure kg/m^2 (lb/ft^2)	Total number of occurrences counted	Average annual occurence (rounded to nearest number)
< .050	.00488 <(.001)	55,091	24,485
.050 to .999	.00488 to .093 (.001 to .019)	25,706	11,425
1.0 to 9.9	.097 to 0.927 (.02 to 0.19)	2,372	1,054
10.0 to 49.9	0.076 to 4.83 (0.2 to 0.99)	74	33
> 49.9	4.83 >(0.99)	7	3
	Total	83,250	

Table 2. Annual frequency of occurrence of earthquake phase arrivals at the Uinta Basin Seismological Observatory

Ground velocity (microns/sec)	Equivalent sonic boom overpressure (lb/ft^2)	Total number of occurrences counted	Average annual occurrence (rounded to nearest number)
< .050	.00488 <(.001)	68,387	30.394
.00 to .999	.00488 to .093 (.001 to .019)	26,708	11,870
1.0 to 9.9	.097 to 0.927 (.02 to 0.19)	2,501	1,112
10.0 to 49.9	0.976 to 4.83 (0.2 to 0.99)	250	111
> 49.9	4.83 >(0.99)	7	3
	Total	97,853	

2.3 SEISMOGRAM PRESENTATION

The following seismograms and those found throughout this report are presented for the purpose of illustrating character and magnitude of the response of the earth to a variety of seismic sources, both natural and man-made. All seismograms were recorded at the Tonto Forest Seismological Observatory and the Uinta Basin Seismological Observatory, and are presented as displacement versus time, although values of maximum ground velocity are also indicated. Every seismogram recorded at TFSO or UBSO is shown as seen through one of the standard observatory frequency responses, reference appendix A.

A vertical and two horizontal seismograms are shown in figure 3. Displayed is a TFSO recording of a P wave and the phase pP from an epicenter in Hokkaido, Japan. The phase pP is a depth of focus indicator for the epicenter, in this case the depth of location was put at 176 km. The earthquake occurred on 2 February 1967, at a distance of approximately 80.3° (about 9,000 miles) from the recording site. The maximum ground velocity for the P phase was 0.572 micron /second and 0.508 micron/second for the pP phase.

Figure 4 shows a vertical and two horizontal instruments seismograms recorded at TFSO of a PKP phase (a P phase at such a distance that the travel path transversed the earth's core). The epicenter occurred in the Northern Celebes on 25 February 1967. The distance from TFSO was about 118° (approximately 13,200 miles). The maximum ground velocity of this phase was 0.291 micron/second.

3. TABULATION OF GROUND VELOCITIES AT TFSO AND UBSO GENERATED BY LOCAL DISTURBANCES

3.1 DATA ANALYSIS AND TABULATION

In addition to large, distant earthquakes, small, local earthquakes and quarry blasts are not uncommon in regions around UBSO and TFSO. A search and compilation of UBSO and TFSO seismic data was made for the purpose of evaluating the severity and frequency with which those areas are subjected to disturbances by earthquakes and quarry blasts, and to compare the results with earth motions expected from sonic booms.

Since seismic disturbances of the nature discussed were not routinely tabulated at the observatories for bulletin purposes, film seismograms were obtained and read for this report. Seismograms respresenting a 3-year period, 1964-1966, from each of the two observatories were analyzed specifically for seismic disturbances produced not only from small local earthquakes but also shocks from "man-made" or cultural sources. These were primarily construction and quarry blasts, bursts of noise from traffic, sonic booms, and other sources.

Records selected and read were taken from times confined to the "normal" work week, Monday through Friday, and only 9 hours of data each day were used in the tabulation of results (approximately 8 a.m. to 5 p.m. local time). This time frame best represents the period of maximum activity which is local and cultural in nature.

The results are shown in table 3 for TFSO and in table 4 for UBSO. UBSO averages about 2.5 times as many local and near-regional disturbances as TFSO. TFSO averages 6 such disturbances per working day (Monday-Friday), while UBSO averages 15.

The majority of local seismic disturbances at TFSO are caused by mine blasting with an occasional sonic boom. Mine blasts can be identified by comparing the arrival azimuths and distance determinations with known locations of mines and quarries. The azimuth can be determined from differences in the arrival time of the P waves at several sensors in the array, and the distance can be estimated from the time difference in the arrivals of the P and S waves at a single sensor. The region is thinly populated, and no heavy industry is located close by. Construction is light. The majority of disturbances observed at UBSO are those associated with construction, oil well drilling, and induced noise from the Green River at heavy runoff periods. The disturbances, although plentiful, were small in nature and did not produce ground velocities of greater than 10 microns/second at either observatory.

No seismic signatures were observed which could definitely be identified as due to thunder. The observatory instrumentation is not tuned to frequencies high enough to make such recordings likely.

Table 3. Annual frequency of occurrence of signatures associated with cultural causes at Tonto Forest Seismological Observatory

LOCAL SOURCES (within 180 kilometers of TFSO)

Ground velocity microns/sec	Equivalent overpressure lbs/ft^2	Annual occurrence[1]
< .050	.00448	
	<(.001)	-
.050 to .999	.00488 to .093	320
	(.001 to .019)	-
1.0 to 9.0	.097 to 0.927	-
	(.02 to 0.19)	
10.0 to 49.9	0.976 to 4.83	-
	(0.2 to 0.99)	
>49.9	4.83	-
	(>0.99)	

NEAR-REGIONAL SOURCES (within 180-670 kilometers of TFSO)
Primarily large mine blasts

Ground velocity microns/sec	Equivalent overpressure lbs/ft^2	Annual occurrence[1]
< .050	.00488	50
	<(.001)	
.050 to .999	.00488 to 0.093	45
	(.001 to 0.19)	
1.0 to 9.9	.097 to 0.927	-
	(.02 to 0.19)	
10.0 to 49.9	0.976 to 4.83	-
	(0.2 to 0.99)	
>49.9	4.83	-
	(>0.99)	

---

[1]Based on actual analysis over a 3-year period adjusted to reflect the normal cultural signal producing times, Mondays through Fridays, approximately 8 a.m. to 5 p.m., local time.

Table 3 (Continued)

MISCELLANEOUS SOURCES (includes sonic booms, and occurrences of noise bursts at acoustic velocity)

Ground velocity microns/sec	Equivalent overpressure lbs/ft^2	Annual occurrence[1]
< .050	< .001	5
.050 to .999	.001 to .019	1055
1.0 to 9.9	.02 to 0.19	80
10.0 to 49.9	0.2 to 0.99	-
>49.9	>0.99	
	TOTAL	
< .050	< .001	55
.050 to .999	.001 to .019	1420
1.0 to 9.9	.02 to 0.19	80
10.0 to 49.9	0.2 to 0.99	-
>49.9	>0.99	-

[1]Based on actual analysis over a 3-year period adjusted to reflect the normal cultural signal producing times, Mondays through Fridays, approximately 8 a.m. to 5 p.m., local time.

Table 4. Annual frequency of occurrence of signatures associated with cultural causes at Uinta Basin Seismological Observatory

LOCAL SOURCES (within 180 kilometers of UBSO)

Particle velocity microns/sec	Equivalent overpressure lbs/ft	Annual occurrence[1]
< .050	< .001	-
.050 to .999	.001 to .019	865
1.0 to 9.9	.02 to 0.19	60
10.0 to 49.9	0.2 to 0.99	-
>49.9	>9.99	-

NEAR-REGIONAL SOURCES (within 180-670 kilometers of UBSO)
Primarily large mine blasts

Particle velocity microns/sec	Equivalent overpressure lbs/ft	Annual occurrence[1]
> .050	> .001	20
.050 to .999	.001 to .019	1225
1.0 to 9.9	.02 to 0.19	-
10.0 to 49.9	0.2 to 0.99	-
>49.9	>0.99	

[1] Based on actual analysis over a 3-year period adjusted to reflect the normal cultural signal producing times, Mondays through Fridays, approximately 8 a.m. to 5 p.m., local time.

Table 4 (Continued)

MISCELLANEOUS SOURCES

Particle velocity microns/sec	Equivalent overpressure lbs/ft	Annual occurrence[1]
< .050	< .001	25
.050 to . .999	.001 to .019	1500
1.0 to 9.9	.02 to 0.19	110
10.0 to 99.9	0.2 to 0.49	-
>49.9	>0.99	

TOTAL

Particle velocity microns/sec	Equivalent overpressure lbs/ft	Annual occurrence[1]
< .050	< .001	45
.050 to .999	.001 to .019	3590
1.0 to 9 9.9	.02 to 0.19	170
10.0 to 49.9	0.2 to 0.99	
>49.9	>0.99	

3.2 SIGNATURE ILLUSTRATIONS

Several examples of seismograms follow which typically represent various seismic sources as noted in 3.1.

The seismogram shown in figure 5 is a three-component seismogram recorded at TFSO showing a small mine blast. The blast occurred on 2 March 1967, at a distance of approximately 145 kilometers from the observatory. The maximum ground velocity as measured from the seismogram was only 0.172 micron /second. This recording is typical of the numerous, small local disturbances which were counted and categorized by ground velocity in section 3.

Figure 6 is a three-component seismogram recorded at UBSO showing a quarry blast. The blast occurred on 2 March 1967, at a distance of approximately 290 kilometers from UBSO. The maximum ground velocity as measured from the seismogram is 0.267 micron/second. This recording is typical of the near-regional disturbances which were counted and categorized by ground velocity.

Figure 7 - vertical and two horizontal component seismograms recorded at TFSO during the passage of a sonic boom. The sonic boom was generated as part of a controlled test by NASA Langley Research Center on 16 February 1967. The aircraft generating the boom was a B-58 flying at an altitude of 48,000 feet and a speed of Mach 1.65. The flight path of the aircraft was northeast to southwest over the observatory. The seismograms were recorded by the standard short-period Johnson-Matheson seismographs whose frequency response is given in appendix A. The seismograms have been divided into three time blocks, each block containing the arrival of a distinct phase. The first block contains the first arrivals, which are compressional seismic waves generated at previous positions of the aircraft and which have traveled to the recording position at a speed greater than the speed of the aircraft. The second block contains seismic shear waves which also have arrived prior to the aircraft. Block 3 contains the maximum motion of the sonic boom which is contemporaneous with the arrival of the sonic boom pressure wave. This portion of the seismogram has been previously attributed (Reference 1) to resonant coupling of the sonic boom acoustic energy into seismic Rayleigh waves having a phase velocity equal to the speed of the aircraft. It has also been previously shown that the maximum ground motions associated with the sonic boom occur at this time, but at frequencies greater than 20 Hz which are out of the effective pass band of instrumentation. This high-frequency arrival is extensively discussed in Reference 1.

Figure 8 - the response of three vertical instruments to a signal traveling at apparent acoustic velocity. The direction of the signal was from southwest to northeast; source is unknown. The maximum ground velocities measured were 0.953 micron/second, 0.597 micron/second, and 0.370 micron/second, respectively. Recording was made at TFSO.

4. MAGNITUDE, DISTANCE, AND SONIC BOOM OVERPRESSURE RELATIONS

4.1 MAGNITUDE

In the discussion which follows, the term magnitude is used extensively. A brief note of explanation and definition follows.

A number of methods exist for assigning a value of size or energy to an earthquake. Magnitude scales are based on instrument observations and Intensity scales are based on damage and human reactions. All magnitudes referrred to in the following discussion are body wave magnitude (m_b)

This particular magnitude is defined by:

$$m_b = \mathrm{Log}_{10} \frac{A}{T} + B(\Delta)$$

Where A is the maximum vertical motion in millimicrons during the first few seconds of the P-wave arrival and T is the period in seconds associated with this maximum amplitude.

$B(\Delta)$ is a value, which in theory, takes into account the distance differences between recording sites from the epicenter to compensate for the effect of geometrical spreading and absorption of seismic waves. This would ideally result in all recording sites yielding the same magnitude for any earthquake.

4.2 GROUND VELOCITY - OVERPRESSURE RELATIONS USING EXPLOSION DATA

One of the main conclusions obtained from processing the Registration of Earthquakes data is that the maximum ground velocity at UBSO and TFSO is usually the result of the Lg phase from earthquakes in the western United States. The maximum velocity for this phase approximates 50 microns/second or greater for those earthquakes with m_b = 5.5 or greater. Unfortunately, the Registration of Earthquakes data cannot be used to more completely resolve the relationship between maximum velocity, earthquake magnitude, and distance because events which are larger than 5.5 and/or closer than the Pacific Coast usually overdrive the observatory instrumentation. However, seismic recordings of the nuclear explosions at the Nevada Test Site (NTS) can be used to draw some additional conclusions. During the years 1961 through 1970 there were 301 announced U. S. underground nuclear explosions. Most of these were detonated at the Nevada Test Site (NTS) but also include other sites such as the Tatum Salt Dome near Hattiesburg, Mississippi (SALMON), and Dulce, New Mexico (GASBUGGY). During most of the period 1961-1970 Geotech had mobile recording sites in positions across the United States and Canada. In addition, the seismograph systems at the permanent observatories, including TFSO and UBSO were set to low magnifications so that no clipping (saturation) would occur.

Some of the nuclear blasts were equivalent in energy release to a large earthquake. For example, on 20 December 1966, an atomic bomb, code named GREELEY, was detonated at a depth of 1232 meters in zeolitized tuff. The magnitude (m_b) of the explosion was measured to be 6.3. Seismic waves resulting from the explosion were recorded at 21 Geotech mobile and permanent observatories ranging in distance from NTS of from 200 kilometers to 4000 kilometers. The maximum ground velocities observed at these stations were due to the Lg phase. Figure 9 shows a plot of the maximum ground velocity observed at six of the closer stations as a function of the distance of the station from NTS. On the right ordinate of the plot is the sonic boom overpressure equivalent of the ground velocity shown on the left ordinate, assuming that the hypothetical sonic boom had occurred directly over each seismic station. It can be seen that this explosion produced ground velocities equivalent to a 4.88-9.76 kg/m^2 (1.0-2.0 pound/square foot) sonic boom at both UBSO and TFSO. At the two closest stations, the equivalent sonic boom overpressure was greater than 58.6 kg/m^2 (12 pounds/square foot).

Figure 10 shows a similar plot for the DUMONT nuclear blast at the Nevada Test Site on 19 May 1966. This explosion had a magnitude (m_b) of 5.5. The peak velocities at UBSO are seen to be significantly lower than for the GREELEY blast and to be below the 4.88 kg/m^2 (1.0 pound/square foot) mark in equivalent sonic boom overpressure. Note that the ground velocity versus distance relation can be approximated by the curve (a straight line on the log-log scale) which has a slope of -3. This relationship is generally true for all of the NTS explosions and also applies to earthquake Lg propagation through the western United States.

Earthquakes and explosions have been found to be about equally efficient in generating Lg waves. This is contrary to the efficiency of generation of longer period surface waves. For example, ground velocities from earthquake Rayleigh waves of a period of about 20 seconds are often 20 to 40 times greater than those from the same magnitude (m_b) explosion. This difference is one of the methods by which explosions, as recorded at inter-continental distances, can sometimes be discriminated from earthquakes.

Since earthquakes and explosions of equal magnitude can be considered to generate Lg waves of approximately equal size, it is permissible to consider Lg data plots for explosions, such as figures 9 and 10, to apply also to earthquakes. In addition, the propagation paths of the seismic waves from the NTS detonations involve the same western United States area which analysis of the Registration of Earthquakes data indicated was the source area for earthquakes which produce sonic boom-size ground velocities at TFSO and UBSO.

It is possible to relate magnitude to the distance-velocity relation indicated in figure 10 by utilizing data from the wide range of magnitudes of the NTS events. Figure 11 shows a plot of ground velocity versus distance for 11 NTS events of magnitudes ranging from 4.1 to 6.3. The velocity-distance curve for each event is indicated by a solid line, and the magnitude, name, and geologic medium of each event is written alongside. The distribution of magnitudes along a line of constant velocity, taken here for convenience as the 50 microns/second line, appears to be sufficiently regular to interpolate distance-velocity curves at 0.5 magnitude intervals. The interpolated curves for magnitudes of 5.0, 5.5, 6.0, and 6.5 are shown as the dotted lines in figure 11. They can be used to provide a useful estimate of the relationship between earthquake magnitude, distance from TFSO or UBSO of the earthquake, and the sonic boom overpressure equivalent of the maximum ground velocity observed at TFSO or UBSO.

A way to pictorially represent this relationship is shown in figure 12 which indicates the zones around TFSO and UBSO in which an earthquake of a given magnitude must occur in order to produce a maximum ground velocity equivalent to that which would be produced by the passage directly overhead, at TFSO or UBSO, of a sonic boom with overpressure of 4.88 kg/m^2 (1.0 pound/foot^2). Also shown in this figure are the zones of maximum seismic activity in the western United States. The inclusion of the earthquake zones within the circles indicates that both TFSO and UBSO are sufficiently close to major seismic zones to expect earthquake-produced ground velocities comparable to sonic booms.

It is possible to more specifically relate frequency of earthquake occurrence to the magnitude-distance-overpressure information. Taking epicenter and magnitude information for all earthquakes in the western United States for the years 1962-1968, table 5 shows the average yearly incidence of earthquakes of sufficient size and proximity to produce ground velocities at TFSO equivalent to sonic boom overpressures of at least 4.88, 9.76, 14.6 and 19.5 kg/m^2 (1.0, 2.0, 3.0 and 4.0 pounds/square foot), respectively. Table 6 gives similar information for UBSO. There is a yearly average of 2.9 earthquakes which produce ground velocities at TFSO equivalent to or greater than the maximum ground velocity associated with the directly overhead passage of a 4.88 kg/m^2 (1.0 pound/square foot) sonic boom. Similarly, there is a yearly average of 2.0 earthquakes equivalent to or greater than the maximum ground velocity due to a 9.76 kg/m^2 (2.0 pounds/square foot) sonic boom, 1.4 earthquakes for 14.6 kg/m^2 (3.0 pounds/square foot), and 1.0 earthquake for 19.5 kg/m^2 (4.0 pounds/square foot). The analogous yearly averages for UBSO are 2.3 earthquakes for 4.88 kg/m^2 (1.0 pound/square foot), 1.0 for 9.76 kg/m^2 (2.0 pounds/square foot), 0.6 for 14.6 kg/m^2 (3.0 pounds/square foot), and 0.4 for 19.5 kg/m^2 (4.0 pounds/square foot.

It is interesting to note that of the 20 earthquakes which were determined to cause ground velocities at TFSO in excess of the peak velocity expected from a 4.88 kg/m^2 (1.0 pound/square foot) sonic boom seven of them exceed the peak velocity associated with a 19.5 kg/m^2 (4 pounds/square foot) sonic boom. At UBSO, of the 16 earthquakes greater than 4.88 kg/m^2 (1.0 pound/square foot) only three exceeded at 19.5 kg/m^2 (4 pounds/square foot) sonic boom. This difference is due to the respective locations of the two

Table 5. Incidence of earthquakes of sufficient magnitude and proximity to produce maximum ground velocities at TFSO equivalent to a stated sonic boom overpressure

	4.88 kg/m^2 (1.0 lb/ft^2)	9.76 kg/m^2 (2.0 lb/ft^2)	14.6 kg/m^2 (3.0 lb/ft^2)	19.5 kg/m^2 (4.0 lb/ft^2)
Magnitude 4.5 and larger				
Δ (km)	0-195	0-155	0-135	000-120
Total events 1962-1968	0	0	0	0
Magnitude 5.0 and larger				
Δ (km)	196-400	156-315	136-275	212-250
Total events 1962-1968	2	0	0	0
Magnitude 5.5 and larger				
Δ (km)	401-650	316-510	276-440	251-400
Total events 1962-1968	16	10	6	1
Magnitude 6.0 and larger				
Δ (km)	1	3	4	6
Total events 1962-1968				
Magnitude 6.5 and larger				
Δ (km)	941-1270	741-1005	641-870	581-790
Total events 1962-1968	1	1	0	0
Total	20	14	10	7
Yearly average	2.9	2.0	1.4	1.0

Table 6. Incidence of earthquakes of sufficient magnitude and proximity to produce maximum ground velocities at UBSO equivalent to a stated sonic boom overpressure

	4.88 kg/m^2 (1.0 lb/ft^2)	9.76 kg/m^2 (2.0 lb/ft^2)	14.6 kg/m^2 (3.0 lb/ft^2)	19.5 kg/m^2 (4.0 lb/ft^2)
Magnitude 4.5 and larger				
Δ (km)	0-195	0-155	0-135	0-120
Total events 1962-1968	3	0	0	0
Magnitude 5.0 and larger				
Δ (km)	196-400	156-315	136-275	121-250
Total events 1962-1968	2	2	2	2
Magnitude 5.5 and larger				
Δ (km)	401-650	316-510	276-440	251-400
Total events 1962-1968	4	1	1	0
Magnitude 6.0 and larger				
Δ (km)	651-940	511-740	441-640	401-580
Total events 1962-1968	2	2	1	1
Magnitude 6.5 and larger				
Δ (km)	941-1270	741-1005	641-870	581-790
Total events 1962-1968	5	2	0	0
Total	16	7	4	3
Yearly Average	2.3	1.0	0.6	0.4

observatories relative to the active seismic zone. TFSO is near the southern California seismic zone in which the earthquakes tend to be larger than those occurring near UBSO.

Tables 5 and 6 specify the extent to which sonic boom-sized ground velocities are excited at TFSO and UBSO by earthquakes. In using these data, it should be recalled that they are predicated upon the Lg seismic phase only and to this extent should be a conservative estimate since other phases are occasionally observed to contribute large ground velocities. It was assumed that Lg waves from earthquakes and explosions of the same magnitude (m_b) will be approximately equal. This is an assumption based on observation; if anything, it also is conservative. Interpolation was used on the data in figure 9 to obtain velocity-distance values for integral multiples of 0.5 in magnitude values. This was not necessary for completeness, but rather for convenience in illustrating the magnitude-distance-overpressure relations on the maps. A value of 4.88 kg/m^2 (1.0 pound/square foot) of overpressure was used as the equivalent of 50 microns/second ground velocity. This value was based on research accomplished in Reference 1. The magnitude contours shown in figure 10 are circular, which is the result of averaging Lg data over different travel paths, and is not meant to suggest that no difference exists due to travel path.

4.3 EXPLOSION SEISMOGRAM

A three-component seismogram displays the recording at TFSO of the nuclear explosion AGILE in figures 13 and 14. The explosion was detonated at the Nevada Test Site, approximately 500 kilometers from TFSO, on 23 February, 1967. The maximum ground velocity in this particular case was produced by the phase Pg (40.8 microns/second), at TFSO. It is noted that slight variations in distance and azimuth between TFSO and the Nevada Test Site seemed to determine which phase, Pg or Lg was predominate in terms of ground velocity.

5. SUMMARY OF RESULTS AND CONCLUSIONS RESULTING FROM THE TABULATION OF EARTHQUAKE AND EXPLOSION DATA

Two independent approaches were used to compare the severity of ground motion at TFSO and UBSO resulting from earthquakes with ground motions known to result from sonic booms. First, a computer search of 27 months of data recorded at the two observatories yielded a classification of over 180,000 earthquake phase arrivals on the basis of frequency of occurrence versus maximum ground velocity. During the period survey, there were seven occurrences at TFSO in which ground velocities due to earthquakes exceeded 50 microns/second, i.e., the equivalent of a 4.88 kg/m^2 (pound/square foot) sonic boom. There were seven similar instances at UBSO. There was one occurrence at each observatory in which a ground velocity equivalent to a 19.5 kg/m^2 (4 pounds/square foot) sonic boom was exceeded. The majority of the large ground velocities were produced by seismic surface waves from moderate to large earthquakes in the western United States and particularly along the Pacific Coast of the United States and northern Mexico. It was found that earthquakes in this belt of Richter magnitude (m_b) of approximately 5.5 or greater produce ground velocities at the observatories equivalent to or greater than a 4.88 kg/m^2 (pound/square foot) sonic boom. There are some instances in which Rayleigh waves from earthquakes of magnitude 6.0 and greater in South America produce ground velocities at the observatories which are as large as that produced by a 4.88 kg/m^2 (1.0 pound/square foot) sonic boom. These data show by direct observation, that there are several occasions each year (average of 3.1/year) on which earthquakes subject both TFSO and UBSO to ground velocities which are at least as large as the maximum ground velocity associated with a small sonic boom 4.88 kg/m^2 (1.0 pound/square foot), and that there is an occasional occurrence (average of 0.44/year) in which a ground velocity at the observatories is as large as the maximum ground velocity associated with a strong sonic boom 19.5 kg/m^2 (4.0 pounds/square foot).

A visual analysis of raw film seismogram data over a 3-year period at TFSO and UBSO indicated that local and regional seismic events, including quarry blasts, are frequent in occurrence, but are not large in size.

A second approach utilized explosion data. Nuclear blasts detonated at the Nevada Test Site sometimes produce peak ground velocities in excess of 50 microns/second, the exact value depending upon the yield and the geologic medium surrounding the charge. Seismic data from the NTS blasts were used to derive magnitude-distance-sonic boom overpressure relations. Combining these relations with information concerning the location and magnitude of all earthquakes occurring in the western United States and Mexico during the years 1962-1968, it was determined that there is a yearly average of 2.9 earthquakes with foci in the western United States which produce ground velocities at TFSO equivalent to or greater than the maximum ground velocity associated with the directly overhead passage of 4.88 kg/m^2 (1.0 pound/square foot) sonic boom. Similarly, there is a yearly average of 2.0 earthquakes equivalent to or greater than the maximum ground velocity due to a 9.76 kg/m^2 (2.0 pounds/square foot) sonic boom, 1.4 earthquakes for 14.6 kg/m^2 (3.0 pounds/square foot), and 1.0 earthquake for 19.5 kg/m^2 (4.0 pounds/square foot). The analogous yearly averages for UBSO are 2.3 earthquakes for 4.88 kg/m^2 (1.0 pound/square foot), 1.0 earthquake for 9.76 kg/m^2 (2.0 pounds/square foot), 0.6 earthquake for 14.6 kg/m^2 (3.0 pounds/square foot), and 0.4 earthquake for 19.5 kg/m^2 (4.0 pounds/square foot).

The two independent approaches show reasonable agreement at the available points of comparison. For example, the analysis of 27 months of earthquake data gave an average of 3.1 times/year at each observatory that a ground velocity at least as large as the maximum velocity produced by a 4.88 kg/m^2 (1.0 pound/square foot) sonic boom was observed. Combining the explosion data with 7 years of earthquake epicentral data yielded analogous values of 2.9 times/year for TFSO and 2.3 times/year for UBSO.

It is concluded that both TFSO and UBSO, both located in active seismic zones, have been in the past and continue to be subjected to several earthquakes each year which produce maximum ground velocities at the observatories as large as those produced by the directly overhead passage of a sonic boom.

APPENDIX A

GENERAL INFORMATION CONCERNING THE TONTO FOREST SEISMOLOGICAL OBSERVATORY AND THE UINTA BASIN SEISMOLOGICAL OBSERVATORY

1. TONTO FOREST SEISMOLOGICAL OBSERVATORY

1.2 HISTORY AND SITE INFORMATION

The Tonto Forest Seismological Observatory (TFSO), located near Payson, Arizona, was constructed by the United States Corps of Engineers in 1963. TFSO was designed to record seismic events and to be used as a laboratory for testing, comparing, and evaluating advanced seismograph equipment and recording techniques. The instrumentation was assembled, installed, and operated until 30 April 1965, by United Electrodynamics (UED) under Contract AF 33(657)-7747.

On 1 May 1965, Geotech assumed the responsibility for operating TFSO. During the 20-month period from 1 May 1965, through 31 December 1966, the operation of TFSO under Project VT/5055 was closely allied with the work performed at the Blue Mountains, Uinta Basin, and Wichita Mountains Seismological Observatories, under Projects VT/1124, VT/4054, and VT/5054. When reasonable, operating procedural changes, observatory instrumentation improvements, and special research investigations were accomplished simultaneously at all observatories. In other instances, improvements, modifications, and/or procedures that had been developed and proven another observatory were incorporated into the TFSO operation. During 1967, under Contract AF 33657-67-C-0091, Project VT/7702, a 37-element, short-period array and a 7-element, long-period array were designed and installed.

The Tonto Forest Seismological Observatory is located in the center of the State of Arizona. It is approximately 14.5 kilometers (90 road miles) northeast of Phoenix and 13 kilometers (8 miles) south of the Mogollon Rim, south edge of the Colorado Plateau. Its location, with respect to other VELA-Uniform Observatories, is shown in figure 15. The terrain is hilly with an abundance of vegetation consisting of manzanita, shrub live oak, juniper sycamore, and ponderosa pine. The elevation ranges from approximately 1465 to 1740 meters. The surface geology in the array area consists of two types. The north half of the array is on thin (0-60 meters) Paleozoic sandstone and limestone and the south half on pre-Cambrian granite.

The temperature in the area ranges from a high of 40°C (105°F) to a low of -23°C (-10°F). Average annual precipitation is approximately 53 cm (21 inches).

PRECEDING PAGE BLANK NOT FILMED

SEISMOLOGICAL OBSERVATORY STATION INFORMATION

General information on each station is given in the table below. Coordinates and elevations refer to the locations of the three-component, short-period seismometers from which arrival times are determined - Z60, TFSO, and Z10, UBSO.

Observatory	TFSO	UBSO
Observatory identification on film seismograms	TFSO	UBSO
Locations	Payson, Arizona	Vernal, Utah
Geographic coordinates	34°16' 04" N-111°16' 13" W	40°19' 18" N-109°34' 07" W
Elevation (meters above mean sea level)	1492 (4894 feet)	1600 (5248 feet)
Geology of bedrock	Granite	Sandstone

1.3 STANDARD SEISMOGRAPH OPERATING PARAMETERS

The operating parameters and tolerances for the TFSO standard seismographs are shown in table 7. Frequency response tests are made monthly, and the parameters of seismograph systems not conforming to tolerances are reset to within tolerance limits as necessary. Figure 16 shows the response characteristics of the TFSO standard seismographs.

1.4 SEISMOMETER ARRAYS

The basic seismograph system in use at the TFSO prior to 1968 consisted of two arrays of short-period vertical seismometers. One was a 31-element array on an equilateral triangle base with a 610-meter spacing between seismometers. The other was a 21-element crossed linear array with spacing of 3464 feet or approximately 1 kilometer. Seismometer spacing varied slightly from the ideal locations to fit surface conditions. Figure 17 is a plan of the two arrays. The arrays are supplemented by short-period horizontal, intermediate band, broad-band, and long-period seismic systems. Each of these systems includes horizontal and vertical seismometers.

During 1967, construction was completed on a 37-element, short-period array and the older 31-element array was discontinued. Figure 18 shows the configuration of the short-period arrays in operation by the end of 1967.

1.5 GENERAL

Figures 19 through 23 are photographs of general interest taken at TFSO. Each photograph is labeled as to content.

Table 7. Orientation and configuration of UBSO short-period arrays

Seismograph				Operating parameters and tolerances				Filter settings		
System	Comp	Type	Model	Ts	λs	Tg	λg	Model	Bandpass at 3 dB cutoff (sec)	Cutoff rate at SP side (dB/oct)
SP[a]	Z	Johnson-Matheson	6480	1.25 ±2%	0.54 ±5%	---	---	2888-1	0.2 - 1.0	6
SP[b]	Z	Johnson-Matheson	6480	1.25 ±2%	0.54 ±5%	0.33 ±5%	0.65 ±5%	6824-1	0.1 - 100	12
SP[b]	H	Johnson-Matheson	7515	1.25 ±2%	0.54 ±5%	0.33 ±5%	0.65 ±5%	6824-1	0.1 - 100	12
SP	Z	Benioff	1051	1.0 ±2%	1.0 ±5%	0.2 ±5%	1.0 ±5%	6824-1	0.1 - 100	12
SP	H	Benioff	1101	1.0 ±2%	1.0 ±5%	0.2 ±5%	1.0 ±5%	6824-1	0.1 - 100	12
SP	Z	UA Benioff	1051	1.0 ±2%	1.0 ±5%	0.75 ±5%	1.0 ±5%	---	---	--
SP[c]	H	UA Benioff	1101	1.0 ±2%	1.0 ±5%	0.75 ±5%	1.0 ±5%	---	---	--
SP[c]	H	Wood-Anderson	TS 220	0.8	0.78	---	---	---	---	--
BB	Z	Press-Ewing	SV-282	12.5 ±5%	0.45 ±5%	0.64 ±5%	9.0 ±5%	6824-7	0.05- 100	12
LP	Z	Geotech	7505A	20.0 ±5%	0.77	---	---	30024	80 - 300	6
LP	H	Geotech	8700C	20.0 ±5%	0.77	---	---	30024	80 - 300	6

KEY

SP Short period
IB Intermediate band
LP Long period
UA Unamplified (i.e., earth powered)

Ts Seismometer free period (sec)
Tg Galvanometer free period (sec)
λs Seismometer damping constant
λg Galvanometer damping constant

[a] 37-element hexagonal array

[b] Linear array and 3 comp

[c] Discontinued after 18 Nov

2. THE UINTA BASIN SEISMOLOGICAL OBSERVATORY

2.1 HISTORY AND SITE INFORMATION

The Uinta Basin Seismological Observatory (UBSO) was constructed under Contract AF 33(657)-7185. Site selection and noise surveys were accomplished by Geotech. Texas Instruments, Incorporated (TI), was responsible for the construction of all physical facilities.

Contract AF 33(600)-43486, issued to TI, contained the authority for equipping and operating UBSO. Geotech was a TI subcontractor supplying the instrumentation and technical assistance during its installation. TI operated the observatory from November 1962 until 1 July 1963. Under Projects VT/1124 and VT/5054, Contract AF 33(657)-12373, Geotech operated UBSO from 1 July 1963, through 30 April 1966. Under Project VT/6705, the Uinta Basin Observatory was operated continuously from 1 May 1966, to 31 December 1968. In January 1969, the equipment and facilities were transferred to the University of Utah for use in research studies.

The Uinta Basin Seismological Observatory is located approximately 16 kilometers (10 miles) south of Vernal, Utah. Its location with respect to other VELA-Uniform observatories, is shown in figure 15. Located on the north flank of the Uinta Basin, the outcrop within the array area consists of the Duchesne River formation. This formation of friable, cross-bedded sandstone is overlain locally by thin Quaternary terrace deposits.

2.2 STANDARD SEISMOGRAPH OPERATING PARAMETERS

The operating parameters and allowable deviations from these parameters are shown in table 8. These parameters were checked and reset, as necessary, when the frequency response of a seismograph was found to be out of tolerance. The normal response characteristics are shown in figure 24.

2.3 SEISMOMETER ARRAYS

The basic seismograph system in use at the UBSO prior to 1966 consisted of an array of 10 short-period vertical seismometers. Figure 25 is a plan of this array, locations Z1 thorugh Z10. This plan also shows the orientation and configuration of the basic array in use beginning in 1966. This was a 10-element, short-period vertical array located and configured the same as the original array (see locations SH1 through SH10 in figure 25). The primary difference being that the seismometers in array 2 were placed in 250-foot shallow holes drilled and cased for this purpose.

Table 8. Operating parameters and tolerances of seismographs at UBSO

Seismograph				Operating parameters and tolerances					Filter settings	
		Seismometer								
System	Comp	Type	Model	T_s	λ_s	T_g	λ_g	σ^2	Bandpass at 3 dB cutoff (sec)	Cut off rate at SP side (dB/oct)
SP	Z and H	Johnson-Matheson	7515 6480	1.25 ±2%	0.51 ±5%	0.33 ±5%	0.65 ±5%	0.03	0.1-100	12
SP	SZ	Geotech	18300	1.25 ±2%	0.51 ±5%	0.33 ±5%	0.65 ±5%	0.053	0.1-100	12
SP	Z	UA Benioff	1051	1.0 ±5%	1.0	0.083 ±5%	≈1.4	1.0	-	-
IB	Z	Melton	10012	2.5 ±5%	0.65 ±5%	0.64 ±5%	1.2 ±5%	0.018	0.05-100	12
IB	H	Geotech	8700B	2.5 ±5%	0.65 ±5%	0.64 ±5%	1.2 ±5%	0.001	0.05-100	12
BB	Z	Geotech	7505	12.5 ±5%	0.485 ±5%	0.64 ±5%	9.0 ±5%	0.0007	0.05-100	12
BB	H	Geotech	8700A	12.5 ±5%	0.485	0.64 ±5%	9.0 ±5%	0.0007	0.05-100	12
LP	Z	Geotech	7505A	20.0 ±5%	0.74 ±5%	110 ±10%	0.85 ±10%	0.63	25-1000	12
LP	H	Geotech	8700A	20.0 ±5%	0.74 ±5%	110 ±10%	0.85 ±10%	0.63	25-1000	12

KEY

SP	Short period	T_s	Seismometer free period (sec)
IB	Intermediate band	T_g	Galvanometer free period (sec)
BB	Broad band	λ_s	Seismometer damping constant
LP	Long period	λ_g	Galvanometer damping constant
UA	Unamplified (i.e., earth powered)	σ^2	Coupling coefficient

A 7-element array of three-component, long-period seismometers were installed during 1967. The array was hexagonal in shape with an element spacing of approximately 23 km. Collection of data and management of the array was accomplished with a digital data acquisition, transmission, and control system. The short-period and long-period arrays were supplemented by intermediate and broad-band vertical and horizontal seismometers.

2.4 GENERAL

Figures 26 through 28 are photographs of general interest taken at UBSO. Each photograph is labeled as to content.

Figure 29 is a photograph of a mobile seismological van. This and other similar mobile units were used to collect and record the data as referenced in section 4.2 of this report.

APPENDIX B

REGISTRATION OF EARTHQUAKES, SAMPLE AND INTERPRETATION

INTERPRETATION OF COLUMN HEADINGS

DAY

The day of the month is printed each time the observatory designator changes within an event, each time the day on which arrivals were recorded changes, and each time a new event is recorded. All dates are reported in Greenwich Civil Time (G.C.T.).

STATION

In the column headed "STA" is printed the station code for the observatory at which the associated data were recorded. This observatory code is printed adjacent to each initial arrival and the first entry on each page. The codes used in this bulletin are the same as those printed on the film seismograms (section 2).

PHASE

Standard alphabetic characters are used to indicate the name of the phase reported. An "I" or an "E" will precede the phase name to indicate the character of phase arrival.

a. An "E" (emersio) designates a gradual beginning for which the direction of motion of the signal at onset is questionable.

b. An "I" (impetus) designates that the initial onset of signal was sudden and the direction of first motion is readily apparent.

c. An "E" or "I" alone designates an unidentified phase.

d. The () (parenthesis marks) indicate uncertainty.

e. The symbol ".P" indicates a pP phase.

f. The symbol "*P" indicates an sP phase.

SYSTEM

In the column headed "SYS," the seismograph (SP, UA, U, IB, BB, or LP) and the component (Z, N, or E) from which arrival time and amplitude data were measured are designated. If no component is designated, the phase data were obtained from the vertical seismogram. If no seismograph is designated, the phase data were obtained from the SP seismogram. When the component is designated as T or F, phase data were obtained from the short-period summation seismogram, or the filtered short-period summation seismogram, respectively.

TIME

The arrival time of the phase is given in hour, minutes, and seconds in G.C.T.

The arrival time is reported as the earliest time on Z, N, or E. The single Z which forms part of the three-component, short-period system is used for measuring arrival times on the SP seismograms when possible, rather than on the array summation seismograms.

AMPLITUDE

The column headed "AMP" contains the amplitude of the phase in terms of ground displacement. All amplitudes reported are corrected for seismograph response characteristics and are reported as one-half peak-to-peak values.

All amplitudes are measured from the largest pulse within the first five cycles whenever possible. If the amplitude of a signal cannot be measured with reliability, the digits 999.9 appear in the amplitude column.

For phases designated as impetus, a plus sign (+) or a minus sign (-) will precede the amplitude value designating compressional or dilational first motion, respectively.

The letter "U" following the amplitude value indicates that the amplitude is reported in microns. If no letter follows the amplitude value the amplitude is reported in millimicrons.

PERIOD

In the column headed "PER" is tabulated the period of each phase in seconds. Period and amplitude are measured from the same pulse. When the period of a phase cannot be measured reliably, the digits 99.9 are entered in the period column.

DELTA

In this column is tabulated the great circle distance in degrees between the observatory at which the event was recorded and the epicenter. Distances reported from events not associated with epicenters reported by the USC&GS are calculated from the S-P or Lg-P intervals.

When insufficient data were recorded for the accurate calculation of distance events are classified according to signal character, as follows:

L	(local) - - - - - - - - - - - - - - - - - - -	0-1.4°
N	(near-regional) - - - - - - - - - - - - - -	1.5-6.0°
R	(regional) - - - - - - - - - - - - - - - - -	6.1-16.0°
T	(teleseismic) - - - - - - - - - - - - - - -	16.1-180°

AZIMUTH

The column headed "AZI" contains the station to epicenter azimuth in degrees. When the calculation of azimuth is not possible, the direction to the epicenter is indicated by letters (i.e., NNW). Direction is obtained from either the step-out patterns across the array or the relative amplitudes of the phase as recorded on each component of the three-component seismographs.

MAGNITUDE

Magnitudes of earthquakes, as calculated from the observatory seismograms, are reported in the column headed "MAG" for all events for which sufficient hypocentral information is available, and for which adequate data are available from the seismograms. Magnitudes are listed following the phase from which the data used in calculation of the magnitude value were obtained.

a. Unified Magnitude, reported adjacent to P-phase data, is calculated from the maximum value of ground displacement/predominant period of the P phase.

b. Surface Wave Magnitude, reported adjacent to Rayleigh wave data, is calculated from the maximum amplitudes of surface waves with period in a 17-30 second range normalized to 20-second period (Geotech TR 63-54, 1 June 1963).

RESIDUAL

The column headed "RES" contains the arrival time residual of each identified phase in seconds to the nearest tenth of a second. The arrival time residual given is the observed arrival time minus the predicted arrival time (based on the 1958 Jeffreys-Bullen Travel Time Tables).

HYPOCENTER INFORMATION

Hypocentral data furnished by the USC&GS are listed in chronological order and are followed by associated phase arrivals. The hypocentral data are listed as follows:

First line (left to right)
- First group: Day of the month
- Second group: Origin time of the event (G.C.T.)
- Third group: Geographic coordinates of the epicenter
- Fourth group: Geographic description of the epicenter

Second line (left to right)
- First group: Depth of the hypocenter in kilometers
- Second group: Average magnitude as reported by the USC&GS.

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES
13	TFO	EP		15 43 02.4	4.7	1.4	T			
		E	LPN	16 09 49.	207.0	33.0				
13	UBO	EP		15 43 06.6	5.4	1.1	T			
		E		15.7	12.5	1.4				
13	WMO	EP		15 46 45.7	5.8	1.1	T			
13	CPO	EP		16 12 02.2	9.2	1.1	T			
13	UBO	EP		16 23 06.3	3.5	1.1	T			

13 17 05 10.3 43.6N 147.4E KURILE IS
H = 30 KM MAG = 4.7

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES
13	UBO	EP		17 16 30.2	4.3	0.7	71.5	312	4.63	0.3
		E		37.3	1.6	0.6				
		E(PCP)		44.4	5.7	0.9				-5.0
13	TFO	EP		17 16 48.6	2.0	1.0	74.5	312	4.08	0.9
		EPCP		17 05.3	1.7	0.9				2.9
13	CPO	EP		17 17 56.7	2.7	0.7	87.6	325	4.52	-0.1

13 17 14 55.0 16.0N 98.5W OFF CST OF GUERRERO,MEXICO
H = 9 KM MAG = 4.3

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES
13	WMO	EP		17 19 14.6	5.1	0.7	18.6	180	4.00	-0.4
		E		23.0	7.7	0.8				
		EPP		30.0	12.0	1.0				-1.5
		E		36.4	14.5	1.0				
		E		43.6	9.2	0.8				
		E		20 12.7	5.8	1.1				
		E	E	25 29.3	61.4	2.0				
		E	LPN	36.						
13	TFO	EP		17 19 47.8	4.4	0.9	21.5	145	3.88	1.3
		EP	IB	47.9						
		EPP		55.8	18.3	1.0				-14.9
		EPP	IB	55.8						
		E		20 38.2	15.6	1.5				

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES

11 09 27 29.6 52.0N 106.2E LAKE BAIKAL REG
H = 5 KM MAG = 5.4

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES
11	BMO	IP		09 39 22.2-	65.2	1.1	76.5	334	5.61	-0.1
		E(PP)		42 14.2	0.0	.				-1.5
		EPKKP1		58 06.5	0.0	.				-9.4
		ER	LP	10 05 10.	608.3	20.0				
11	UBO	IP		09 39 56.8-	57.9	1.3	82.9	339	5.53	0.0
		EP	LP	56.						
		E		40 03.3	32.3	1.3				
		EPP		43 02.5	6.7	1.3				-6.6
		EPP	LP	42 54.						
		E		45 11.1	4.0	1.1				
		E	LPE	50 37.	97.8	20.0				
		E	LPN	10 01 13.	99.5	23.0				
		E	LP	02 09.	130.8	18.0				
		E	LPE	05 00.	137.2	37.0				
		EL	LPE	07 22.	188.0	30.0				
		ER	LP	10 43.	645.2	20.0				
11	TFO	IP		09 40 23.2-	26.7	1.1	88.0	338	5.36	1.1
		EP	IB	23.4						
		E		30.4	11.0	1.0				
		E	IB	30.5						
		E		41 56.7	6.1	1.4				
		E		42 19.4	3.3	1.0				
		E		51.5	6.0	1.3				
		E		43 30.4	3.0	1.2				
		E		44 39.2	9.3	1.6				
		E		46 16.7	7.6	1.9				
		EL	LPN	10 11 22.	211.8	34.0				
		ER	LP	15 42.	432.8	24.0				
11	WMO	EP	U	09 40 36.0	37.5	1.2	91.0	345	5.55	0.1
		E	U	41.4	26.2	1.2				
		EL	LPE	10 12 46.	397.7	34.0				
		ER	LP	19 00.	217.0	24.0				
11	CPO	EP		09 40 40.6	9.9	1.1	92.2	353	5.06	-0.9
		ER	LP	10 17 02.	1.1U	20.0				

DAY	STA	PHASE	SYS	TIME	AMP	PER	DIST	AZI	MAG	RES
11	WMO	EP		10 02 08.5	3.5	0.9	T			
11	UBO	EP		10 20 23.4	1.9	0.7	T	SE		
11	UBO	EP		10 46 18.7	2.2	1.0	T			

REFERENCES

1. Goforth, T. T., and McDonald, J. A., 1968, Seismic effects of sonic booms: NASA Contractor Report CR-1137

2. Springer, D. L., and Kinnaman, R. L., 1971 Seismic source summary for U. S. underground nuclear explosions, 1961-1970: Bulletin of the Seismological Society of America, vol. 61, no. 4, pp 1073

3. Teledyne Inc., 1967, Long-range seismic measurements - GREELEY: Technical Report, LRSM staff

4. Teledyne Industries, Inc., 1966, Long-range seismic measurements - DUMONT: Technical Report, LRSM staff

5. Welch, P. D., 1967, The use of fast Fourier transforms for the estimation of power spectra: a method based on time averaging over short-modified periodograms: Trans. I.E.E.E., AV-12, 70-73

6. McDonald, J.A., 1972, Array studies of atmospheric disturbances, Southern Methodist University.

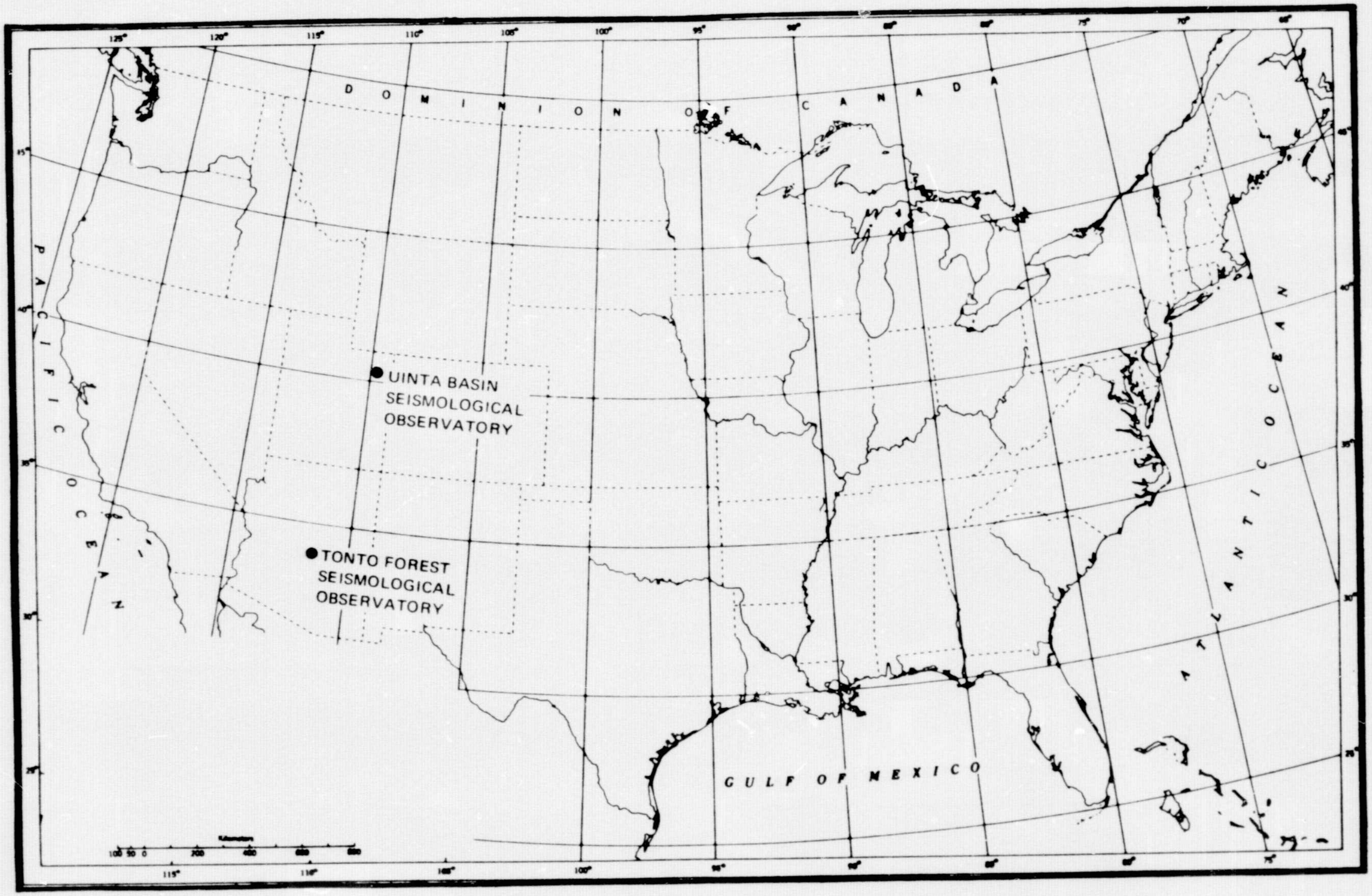

Figure 1. Location of Tonto Forest (TFSO) and Uinta Basin (UBSO) seismological observatories

G 7762

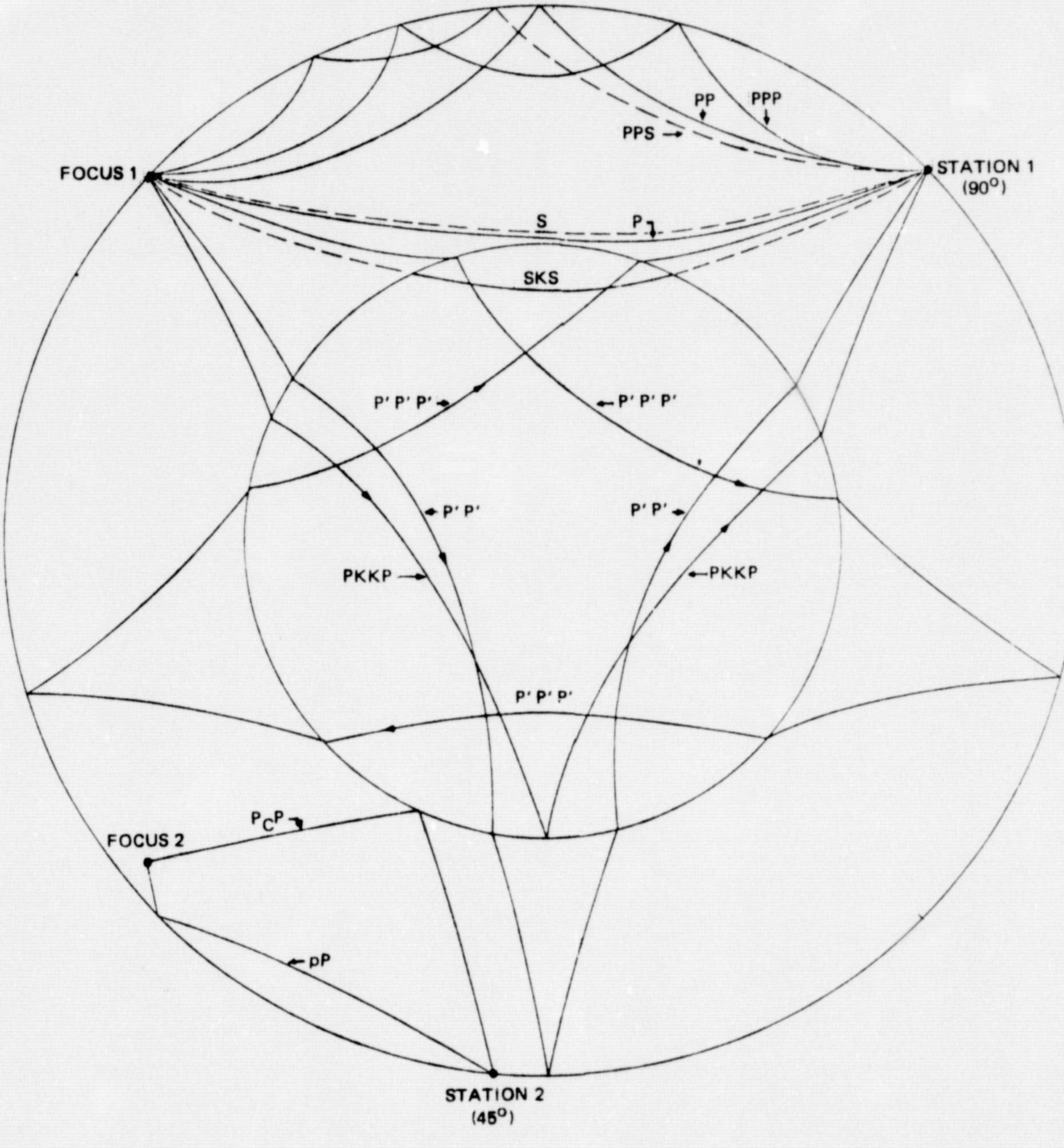

Figure 2. Travel paths within the earth of some seismic body phases

G 7763

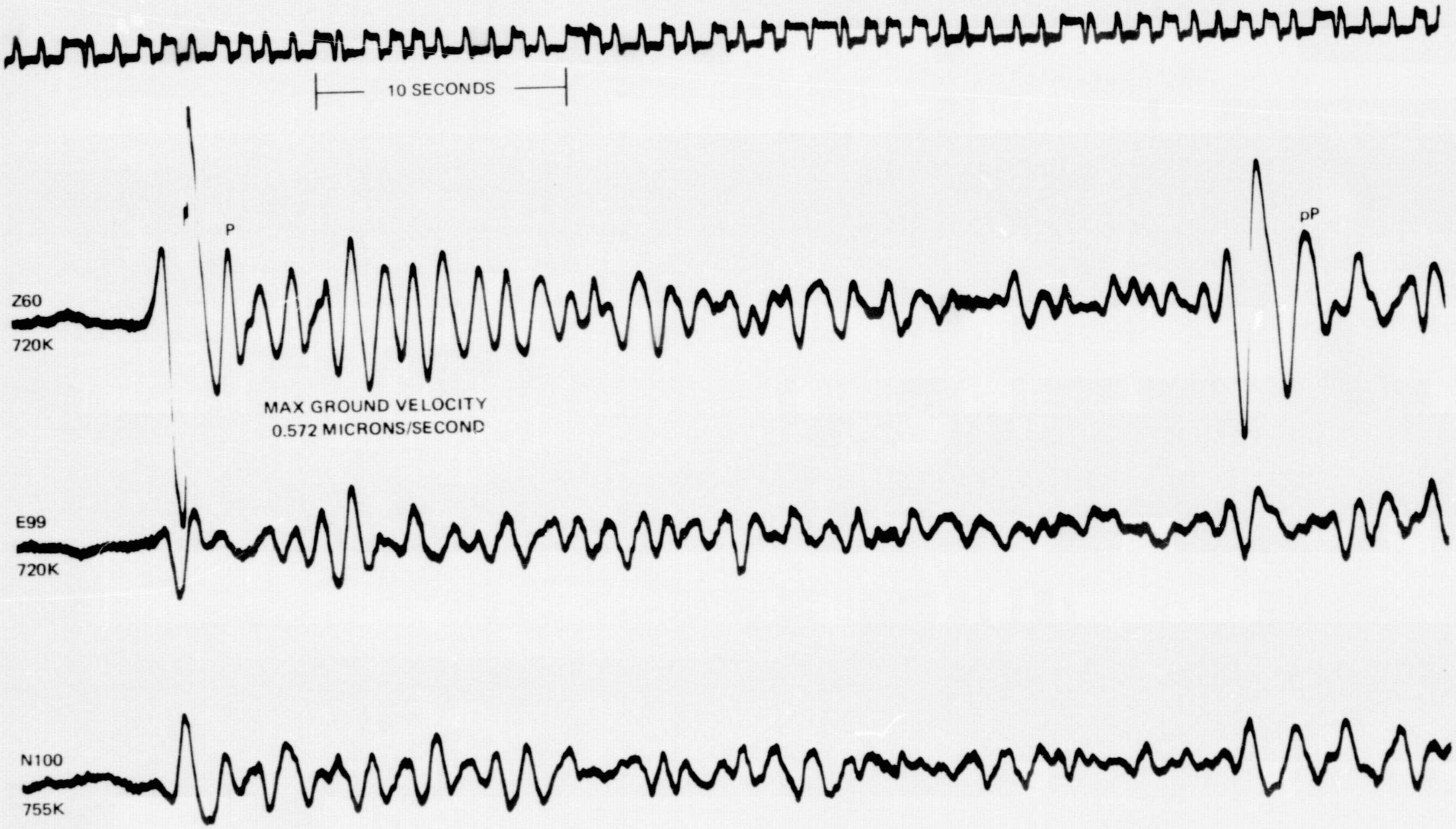

Figure 3. P phase and depth of focus indicator phase pP recorded at TFSO on 2 Feb 1967. Distance 80.3° (8930 km), magnitude 5.3, depth 176 km, location Hokkaido, Japan

G 7764

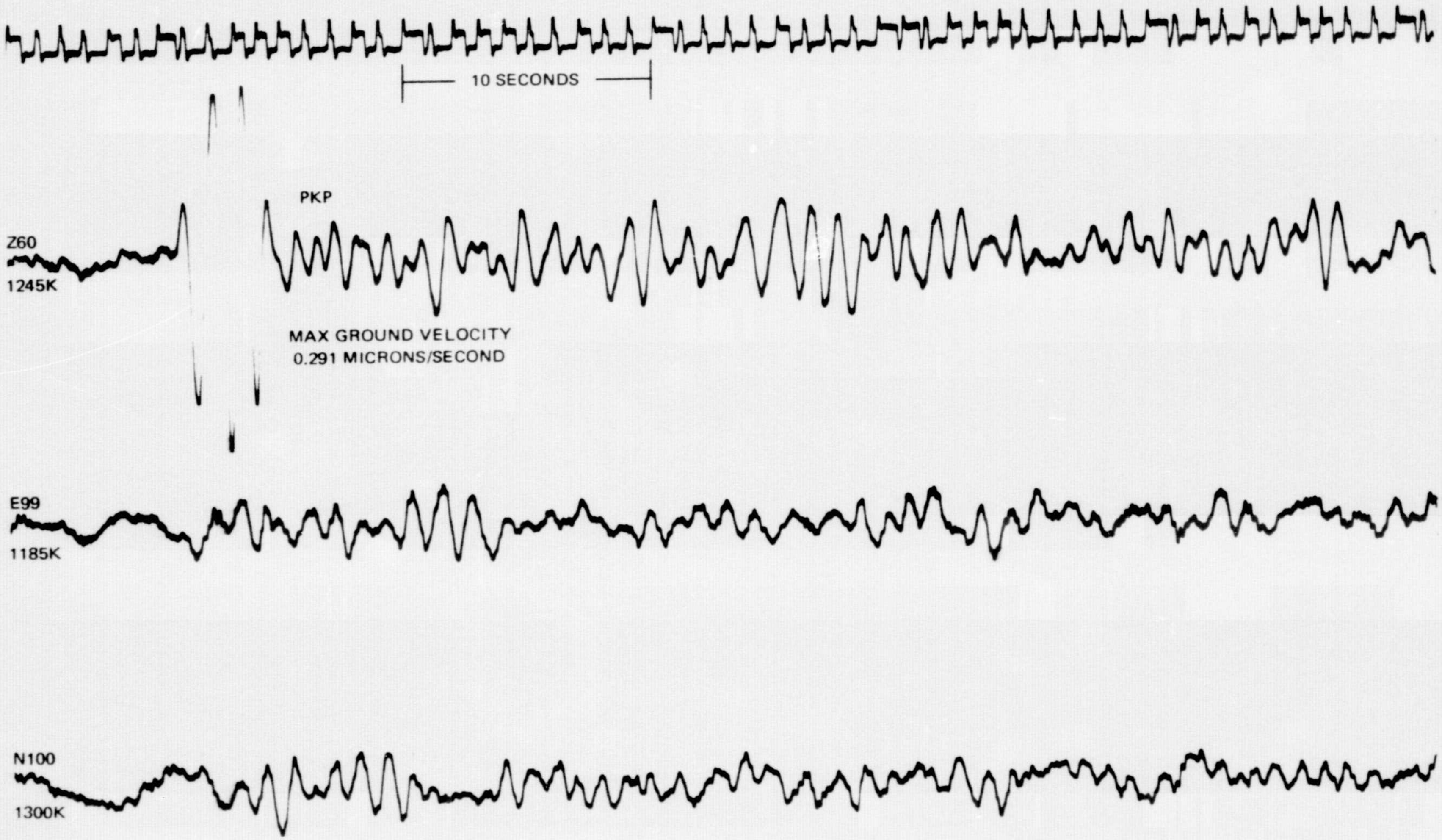

Figure 4. PKP phase recorded at TFSO on 25 Feb 1967. Location North Celebes, distance 118° (13,120 km), magnitude 5.8

G 7765

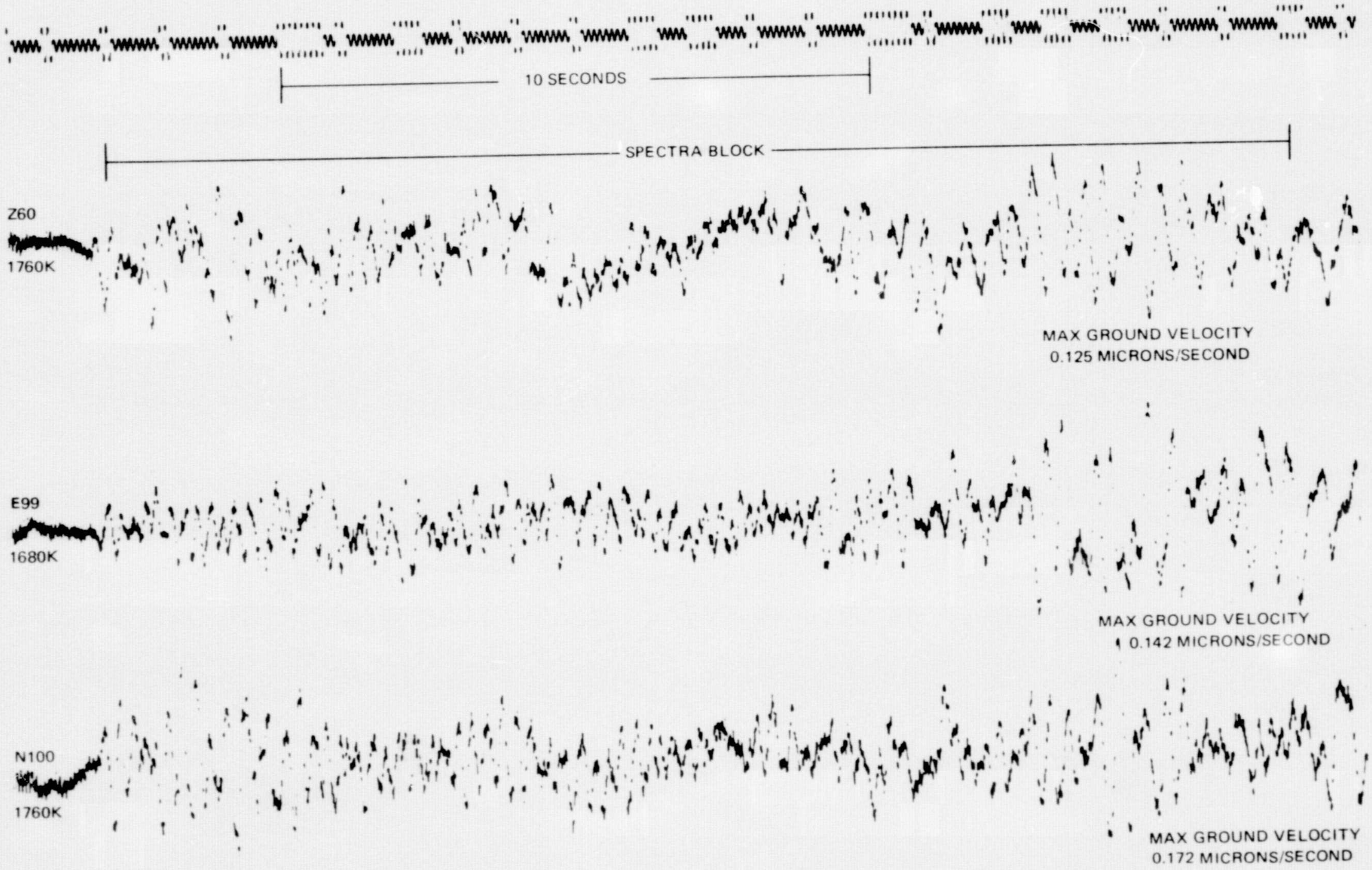

Figure 5. Small mine blast recorded at TFSO on 2 March 1967. Distance approximately 145 km

G 7766

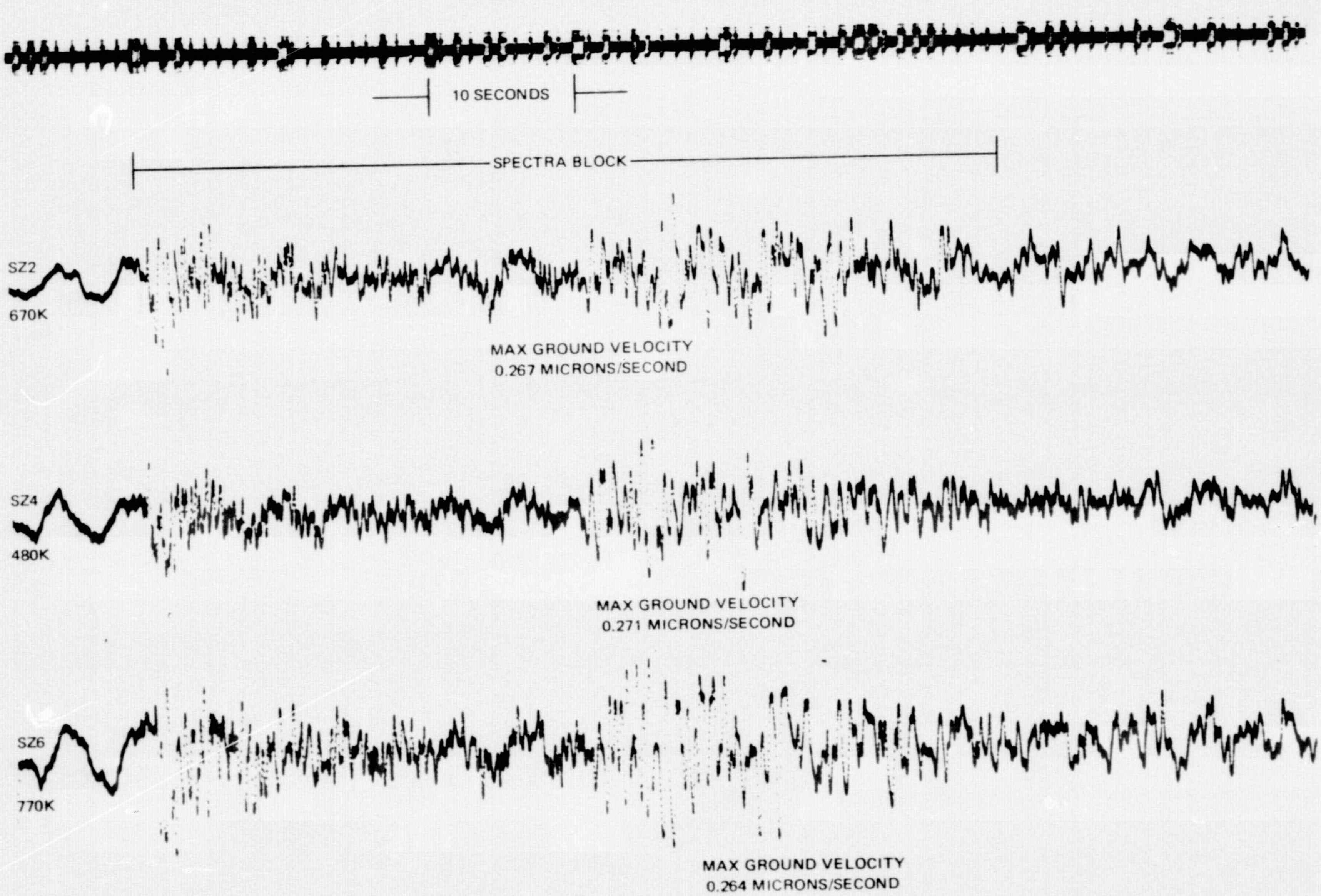

Figure 6. Near-regional event (QUARRY BLAST) recorded at UBSO on 2 March 1967. Distance approximately 290 km

G 7767

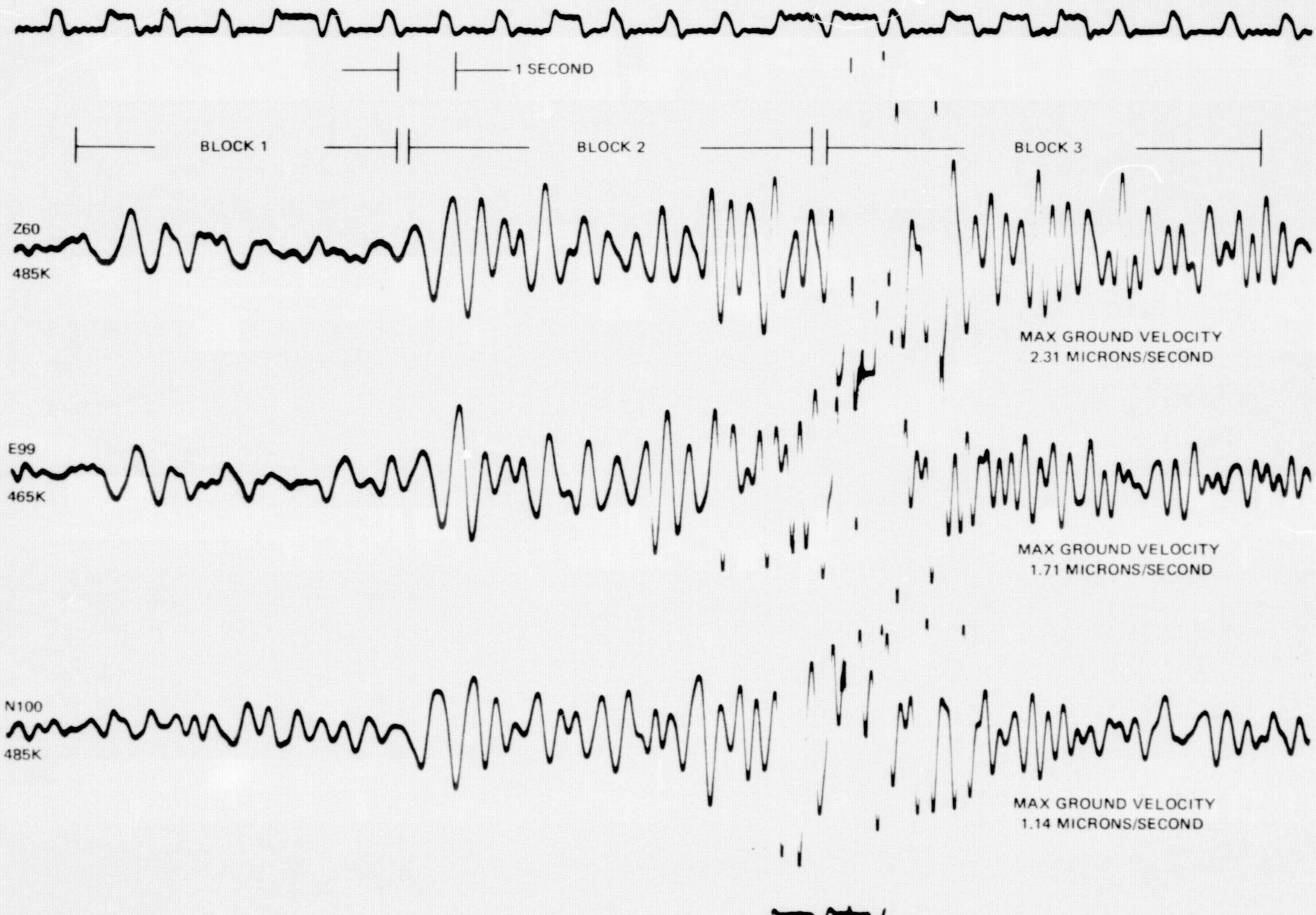

Figure 7. Sonic boom, controlled test Tonto 3 recorded at TFSO, 16 Feb 1967. B-58 at Mach 1.65, 48,000 ft.

G 7768

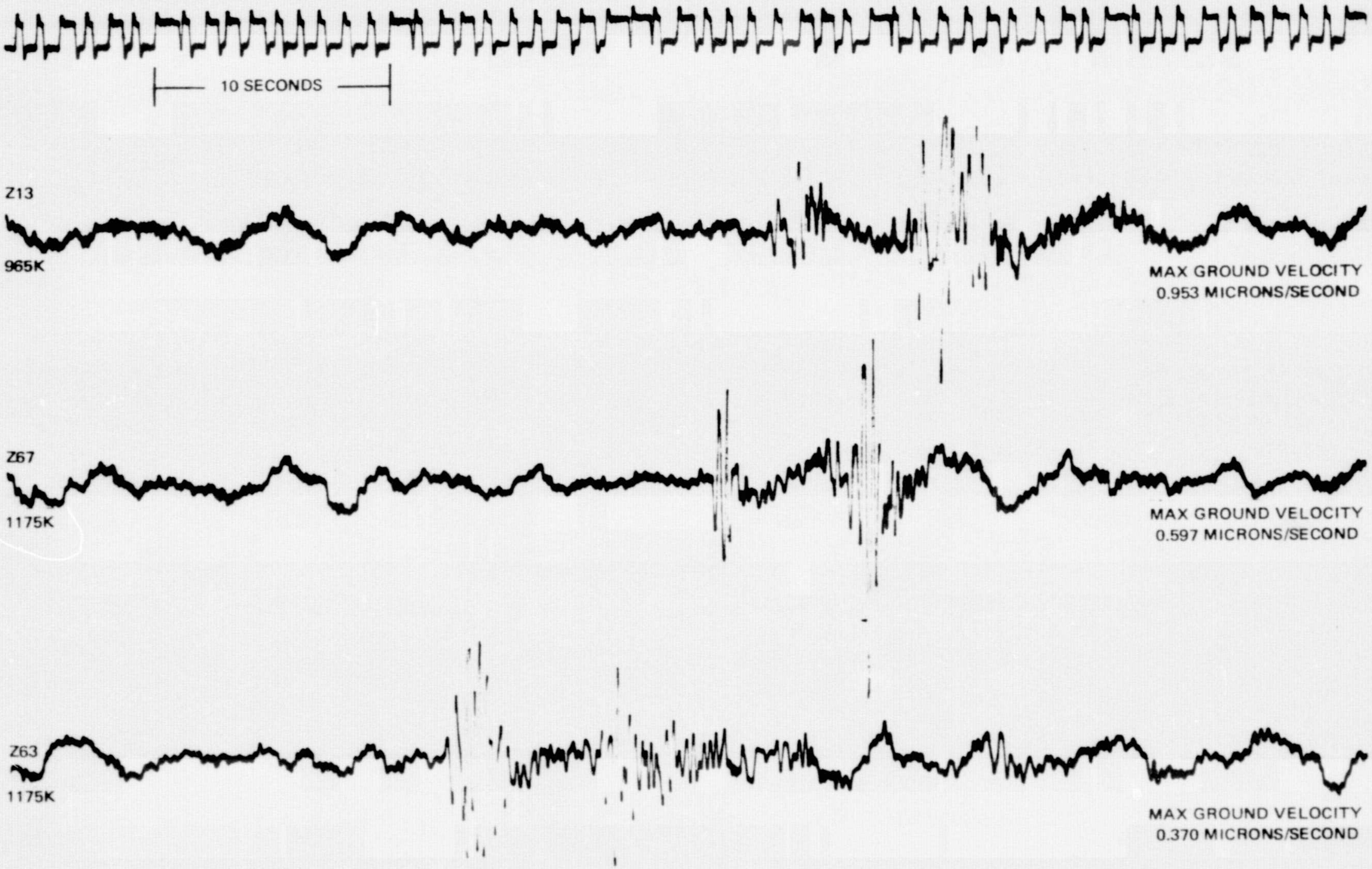

Figure 8. Acoustic signal - source unknown, recorded at TFSO on 4 November 1964

G 7769

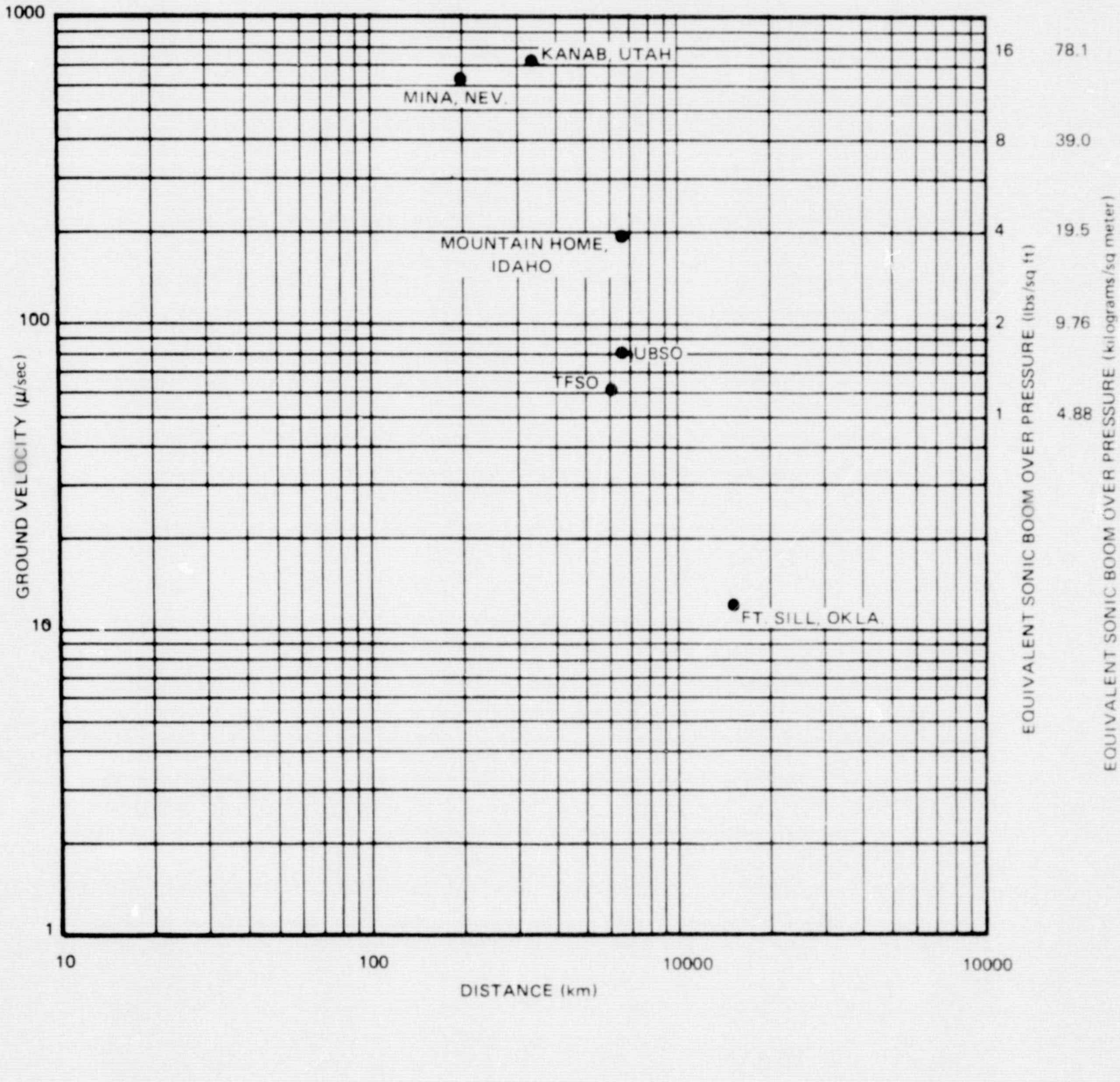

Figure 9. Peak ground velocities as a function of distance for the GREELEY nuclear blast at the Nevada Test Site, 20 Dec. 1966. The motion was recorded for the horizontal component of the Lg phase

G 7770

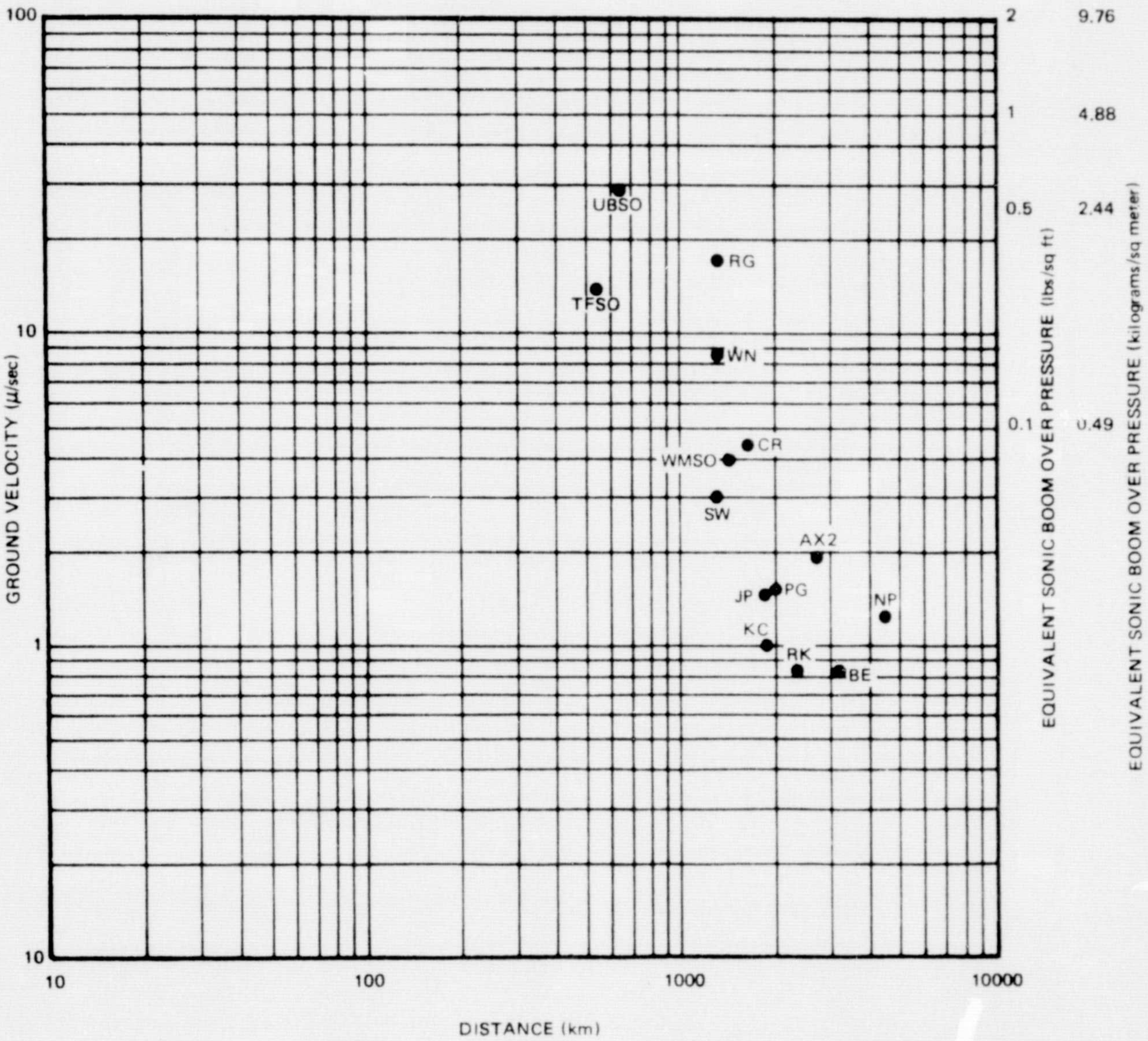

Figure 10. Peak ground velocities as a function of distance for the DUMONT nuclear blast at the Nevada Test Site, 19 May 1966. The motion was recorded for the horizontal component of the Lg phase

G 7771

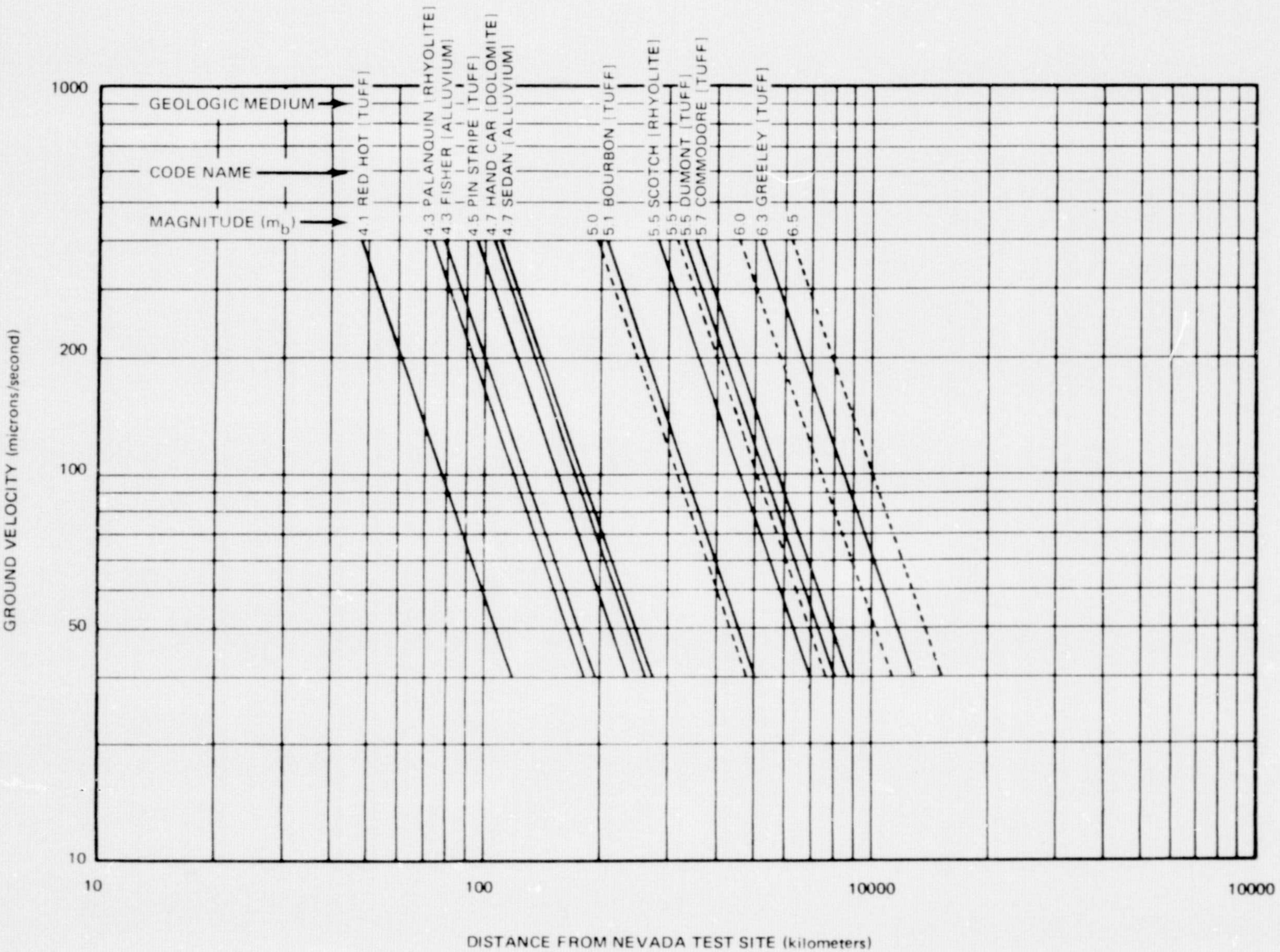

Figure 11. Ground velocity versus distance for 11 NTS events

G 7772

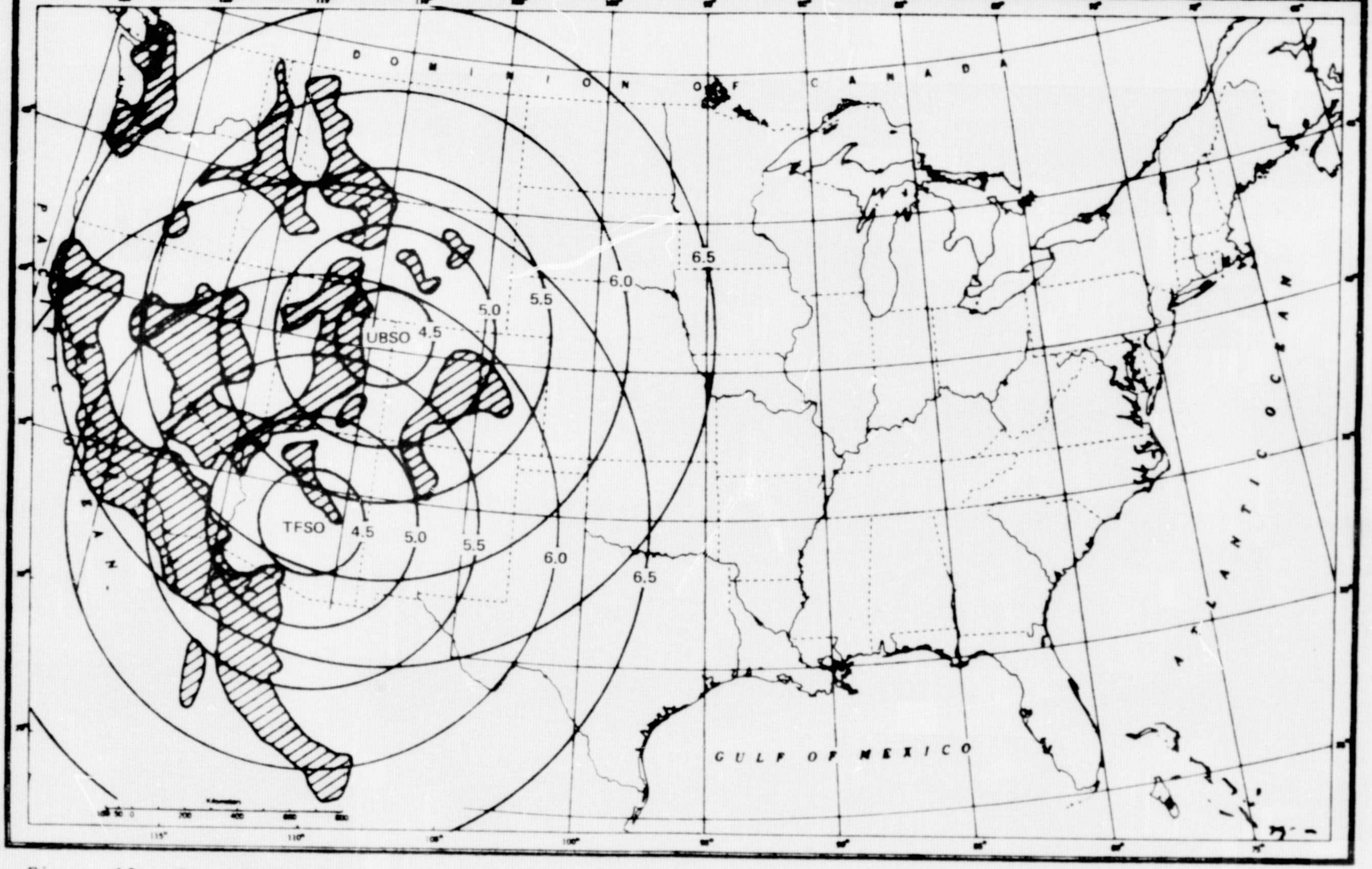

Figure 12. Specified magnitude ranges at two observatories. The circles show the approximate distances from each observatory within which an earthquake of the indicated magnitude (m_b) will produce a ground velocity equivalent to that produced by the overhead passage at TFSO and UBSO of a zonic boom with an overpressure of 4.89 kg/sq m (1.0 lb/sq ft). The crosshatched areas are zones of most likely seismic occurrence based on the years 1961-1969

G 7773

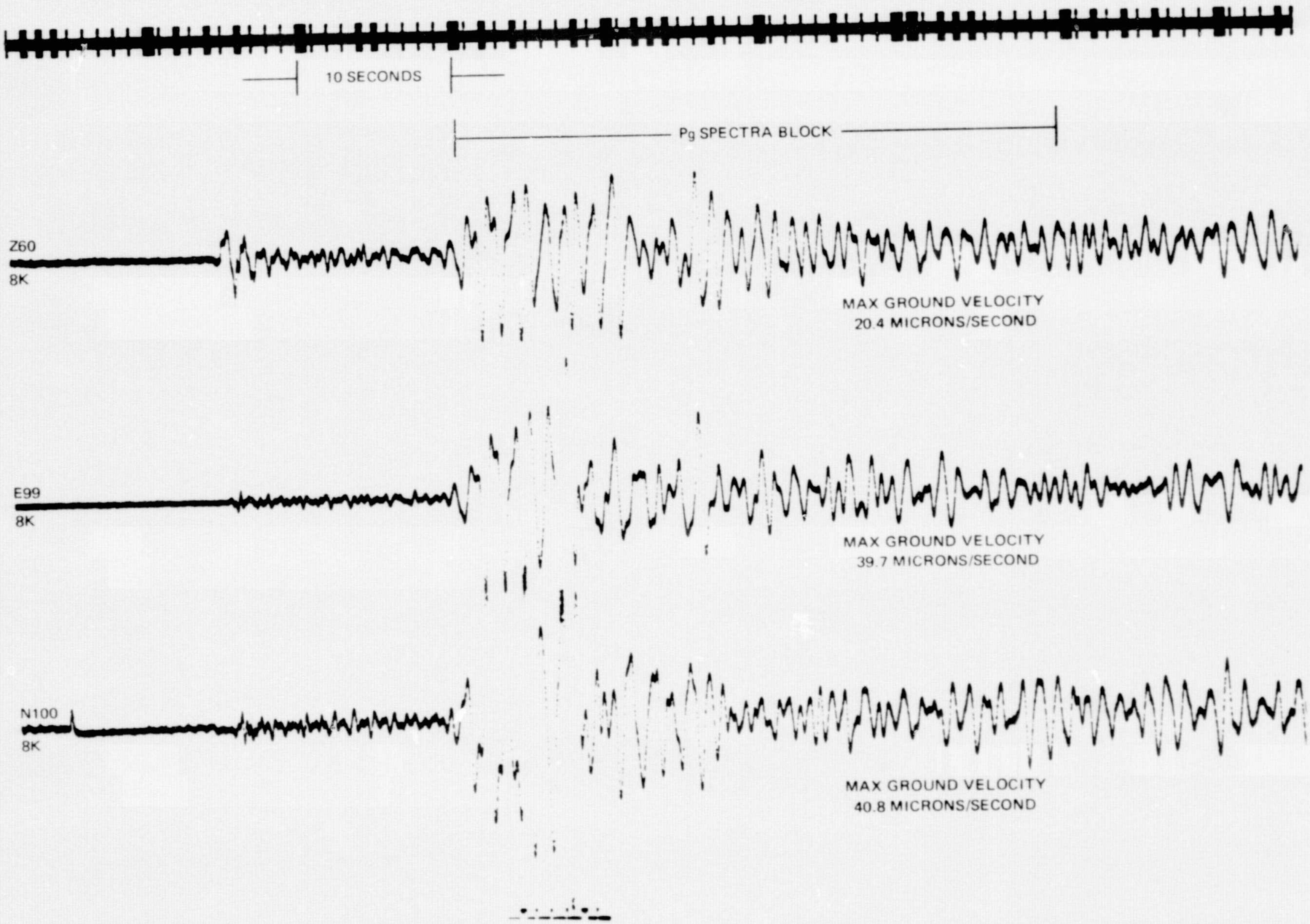

Figure 13. Nevada test site event - AGILE - recorded at TFSO 23 Feb 1967. Distance approximately 500 km

G 7774

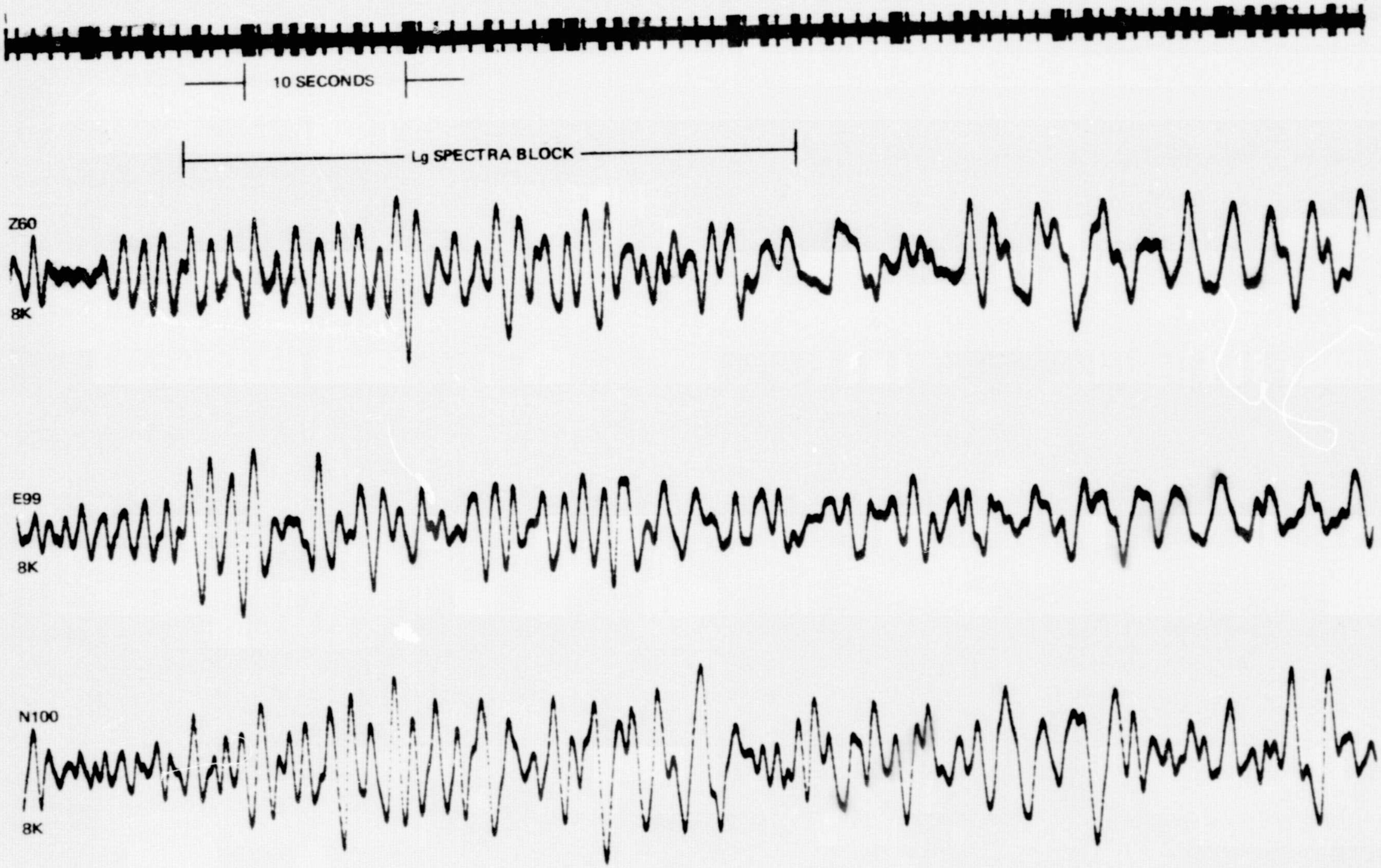

Figure 14. Nevada test site event - AGILE - recorded at TFSO 23 Feb 1967

G 7775

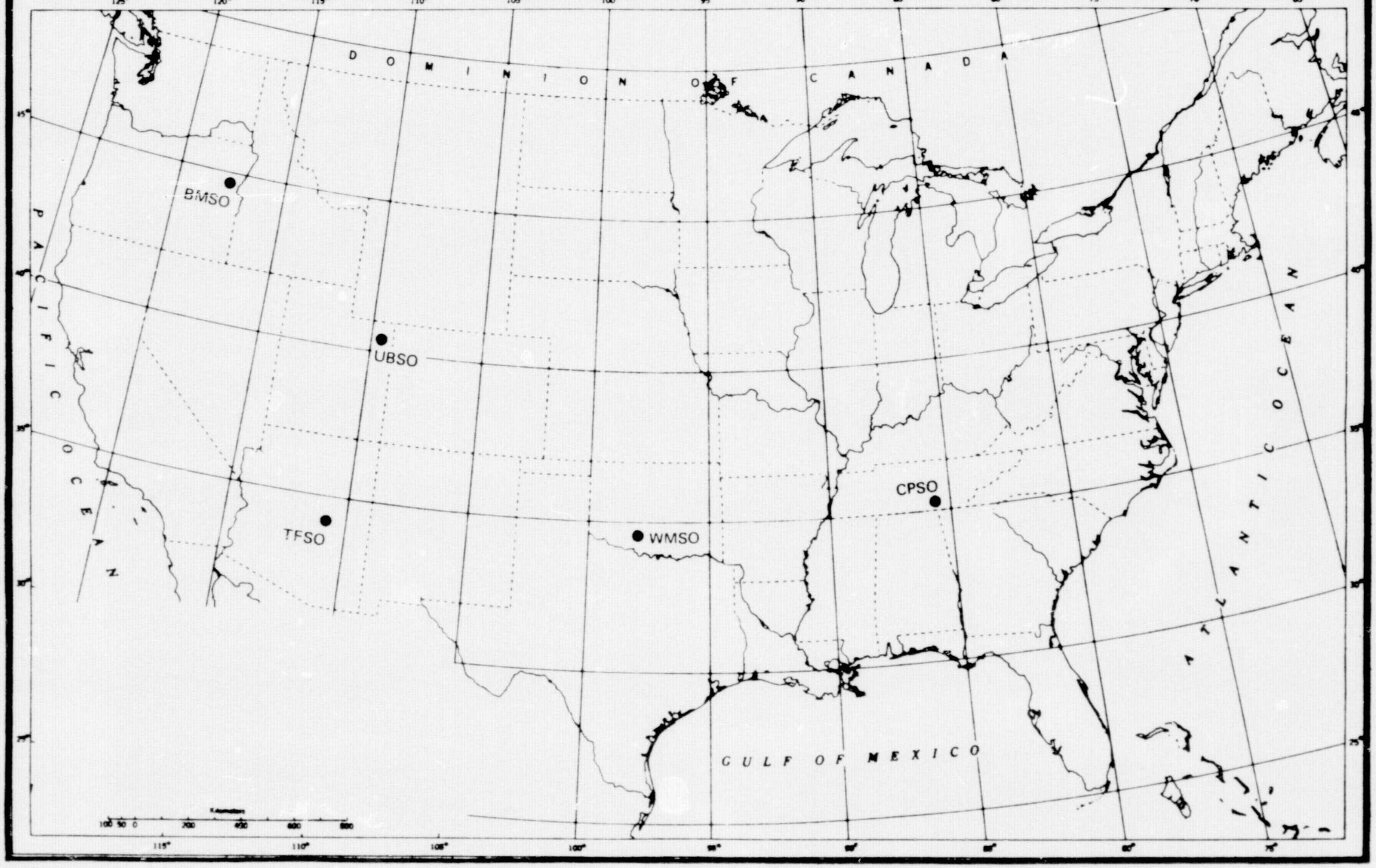

Figure 15. Locations of VELA-Uniform observatories

G 7776

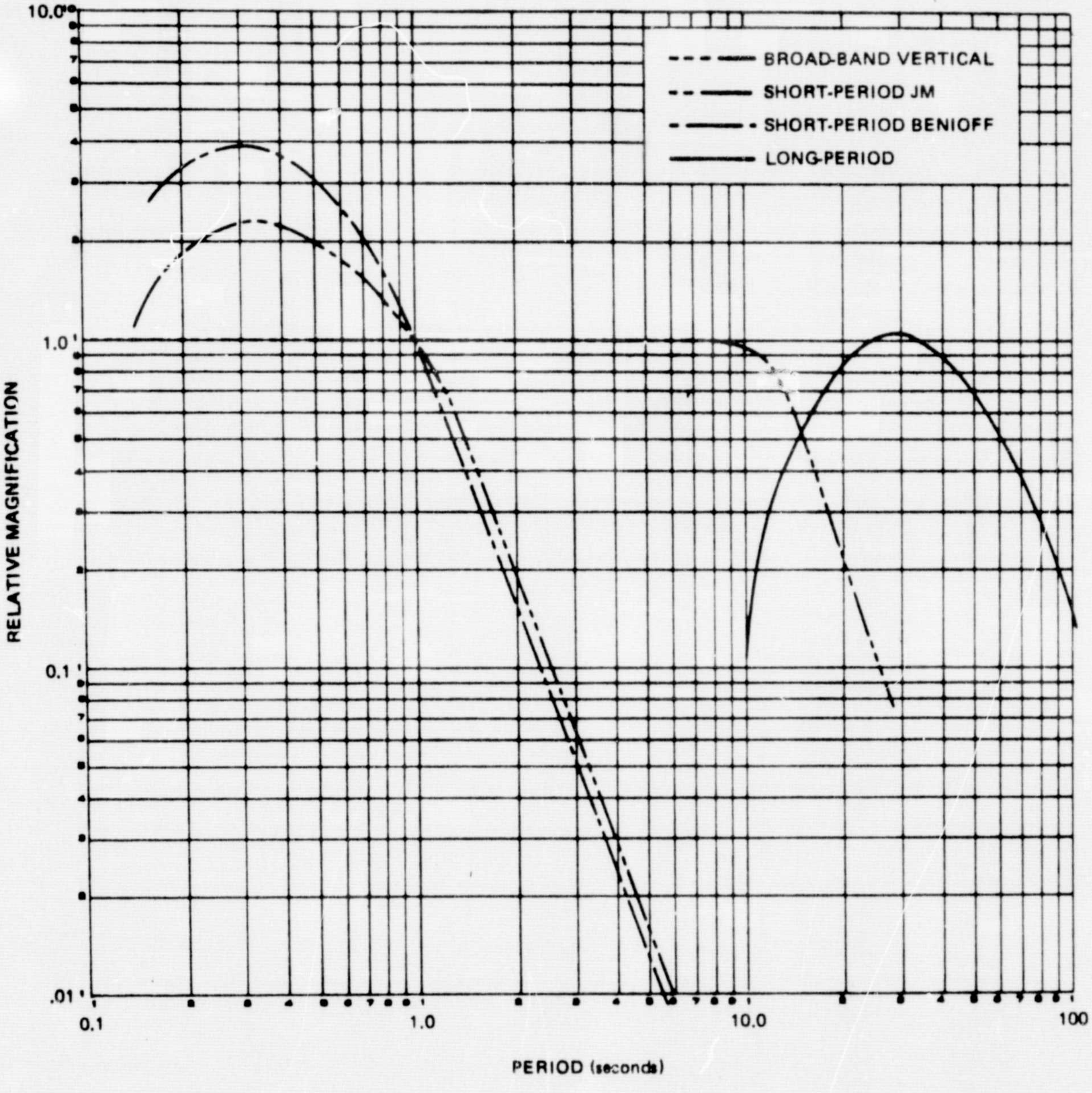

Figure 16. Response characteristics of TFSO standard seismographs normalized at a period of one second

G 7777

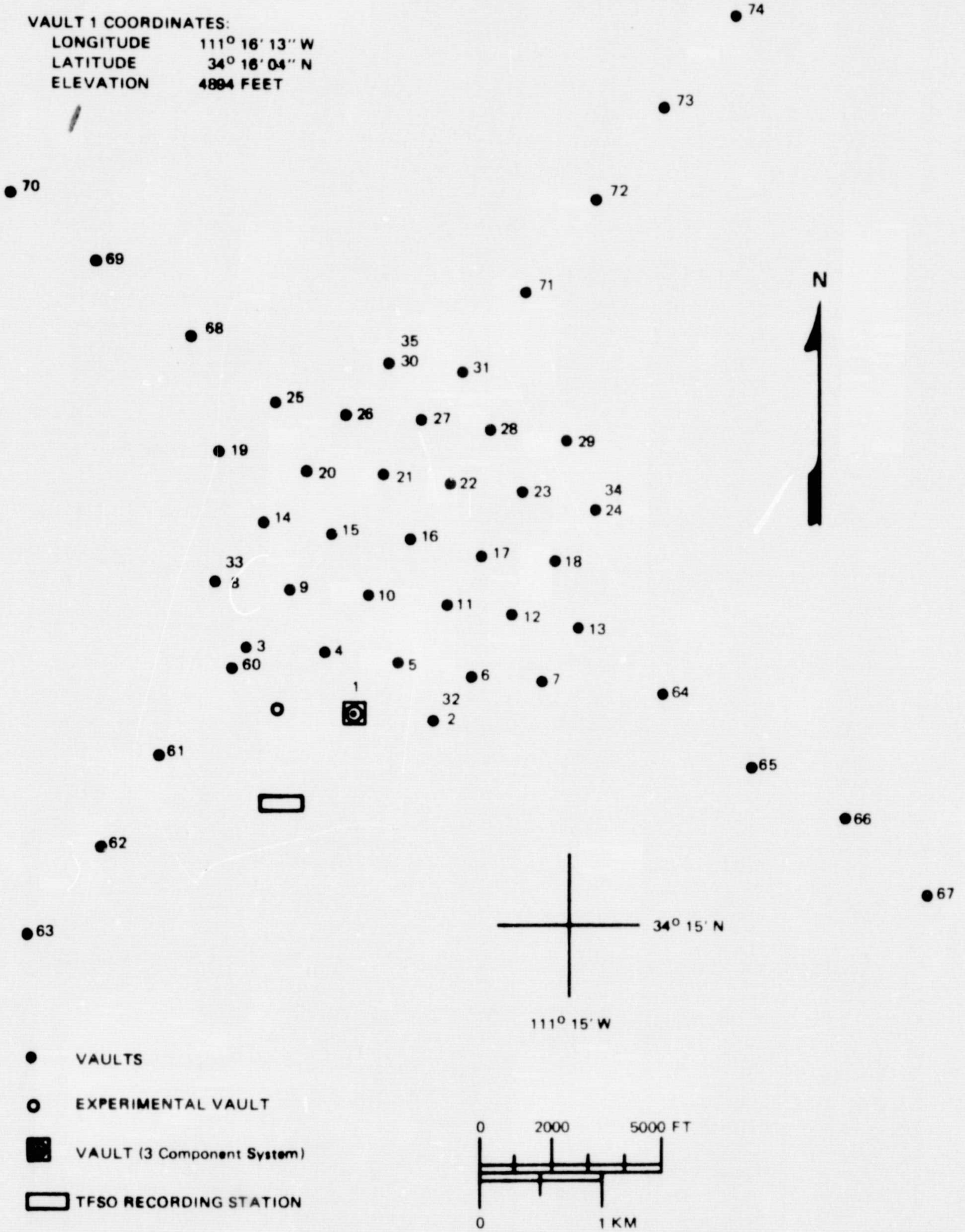

Figure 17. Tonto Forest Seismological Observatory vault locations (prior to 1968)

G 7778

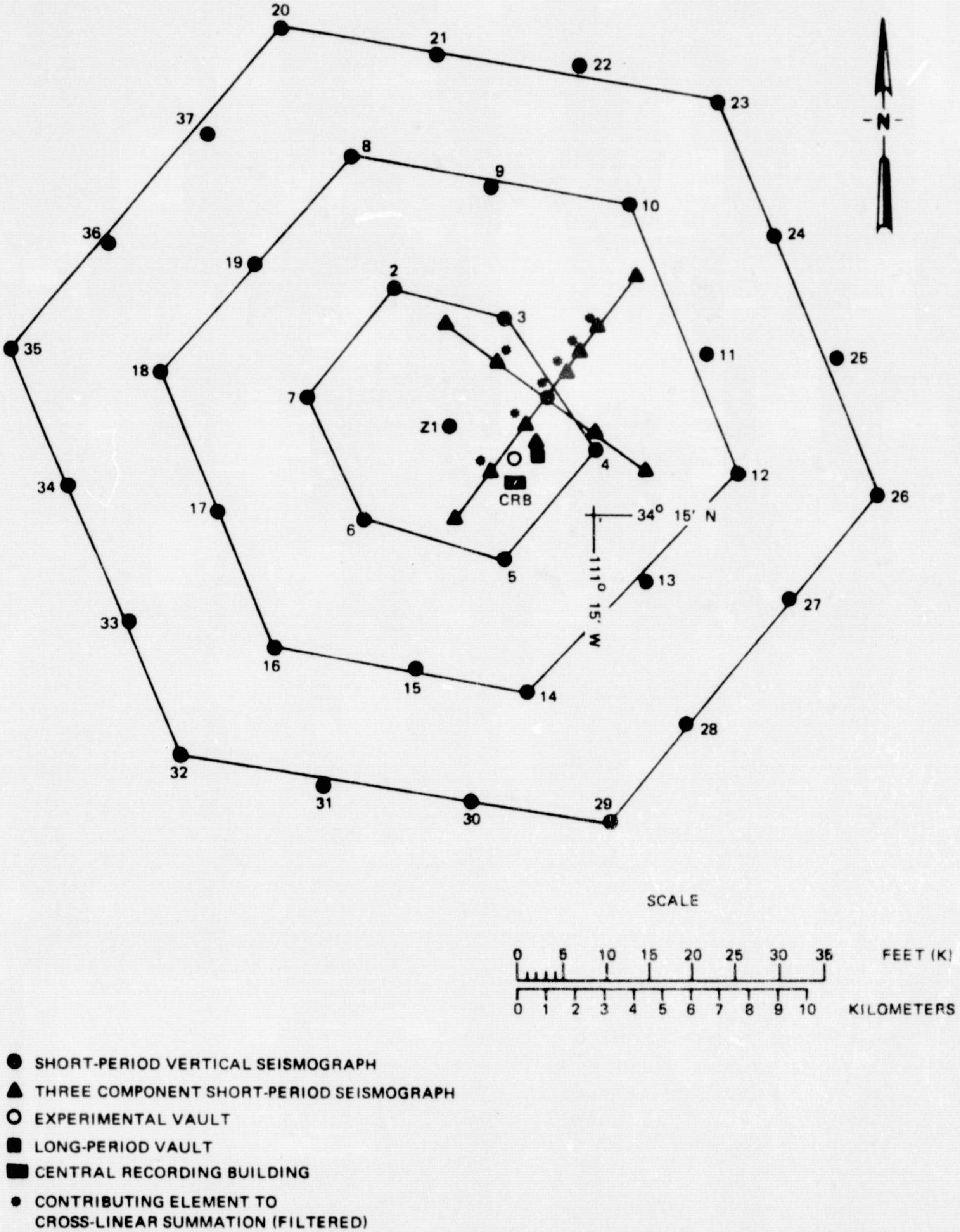

Figure 18. Tonto Forest Seismological Observatory 37-element and cross-linear arrays (completed during 1967)

G 7779

Figure 19. Central facility at TFSO

G 7780

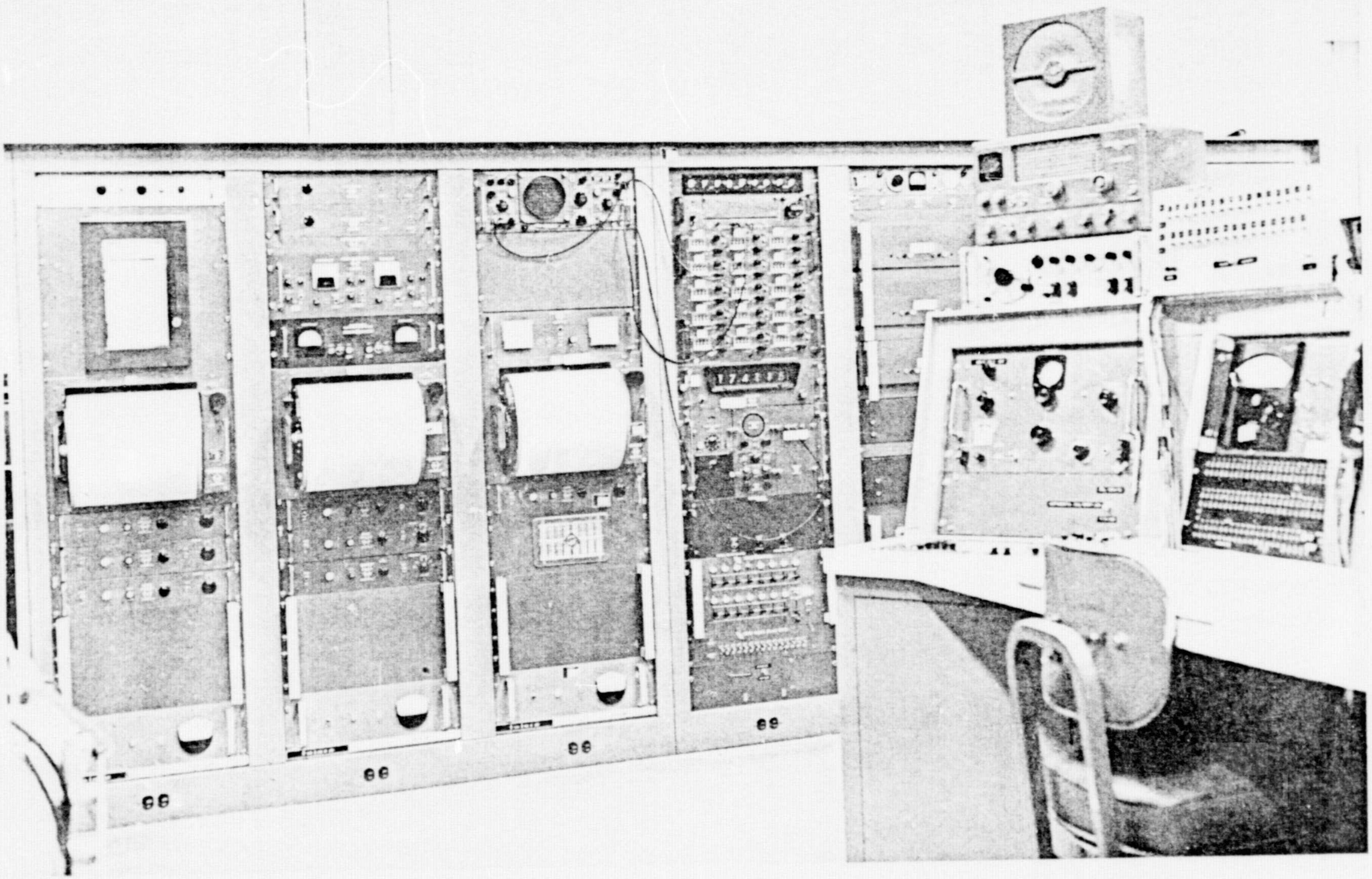

Figure 20. Equipment consoles in TFSO recording area

G 7781

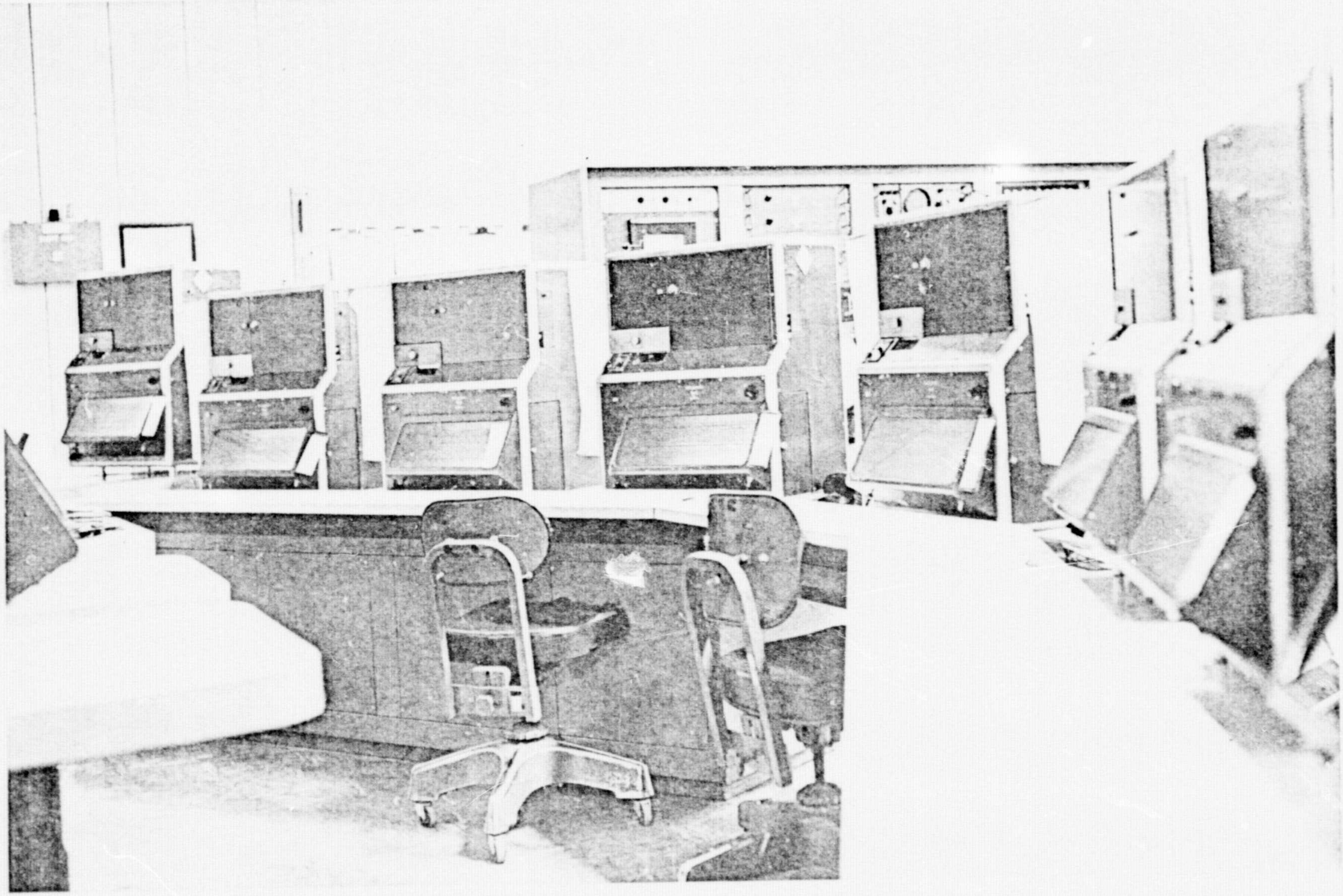

Figure 21. Film recorders at TFSO

G 7782

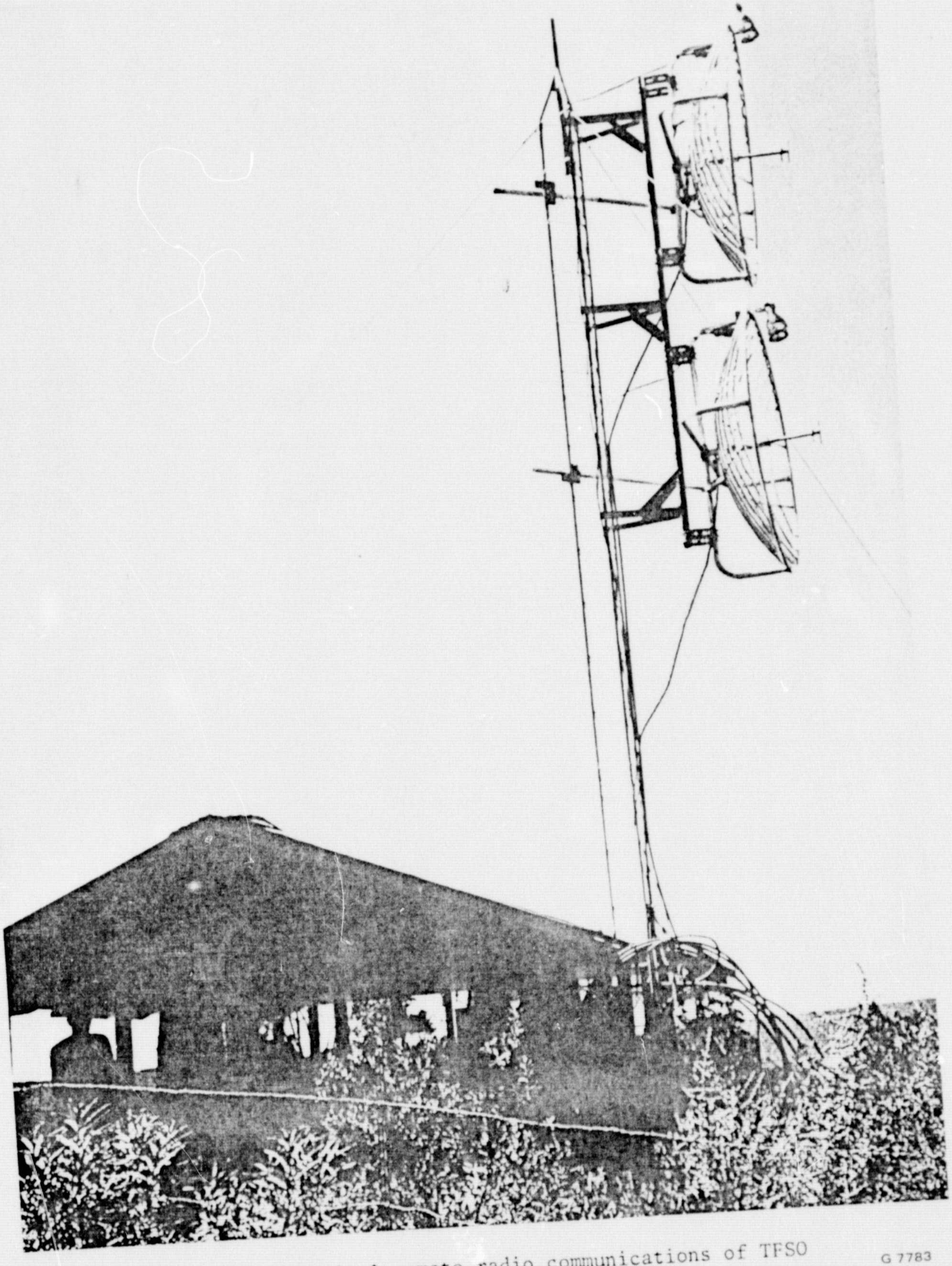

Figure 22. Typical remote radio communications of TFSO G 7783

Figure 23. Typical cable installation at TFSO

G 7784

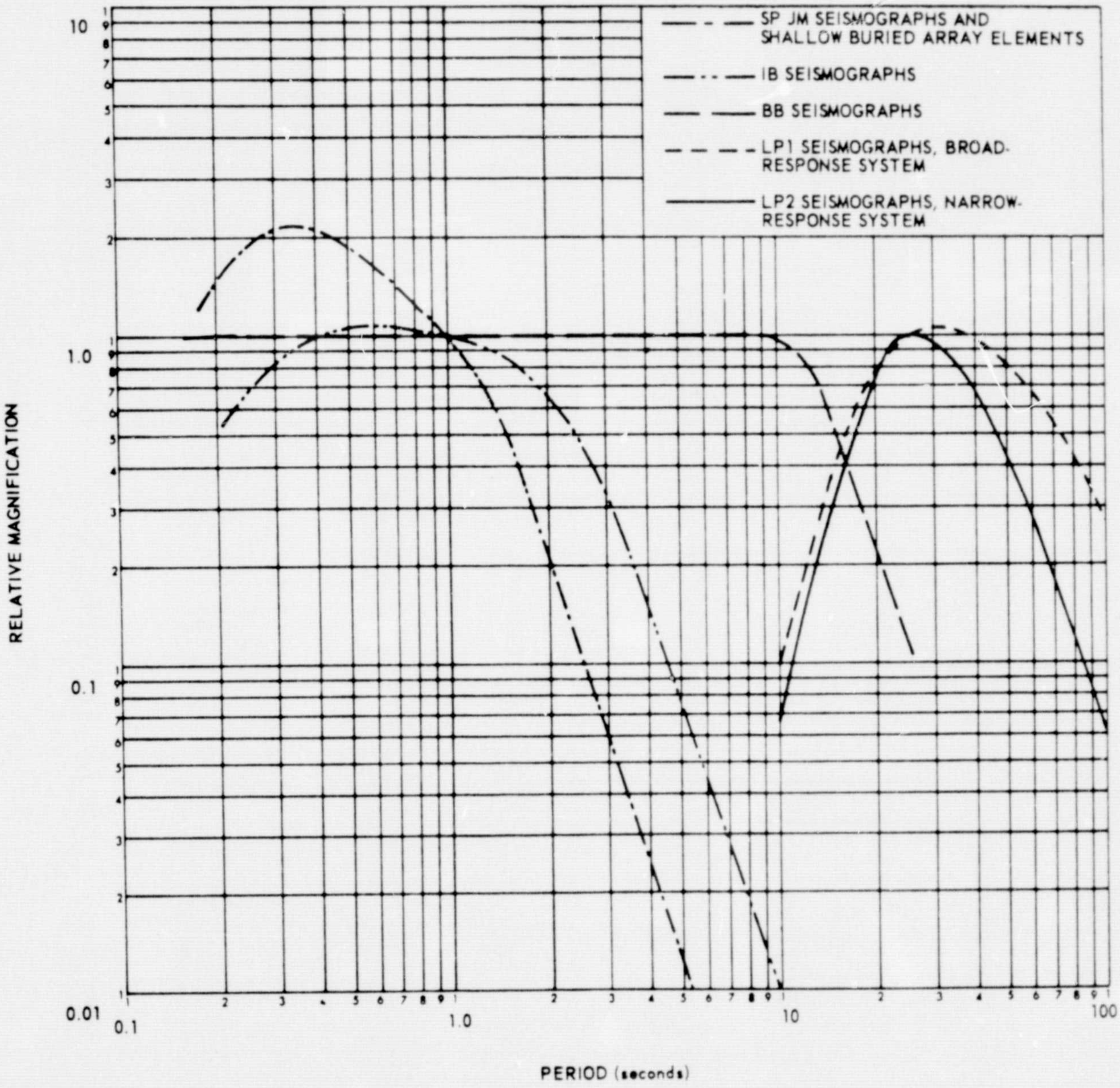

Figure 24. Normalized response characteristics of the routine seismographs at UBSO

G 7785

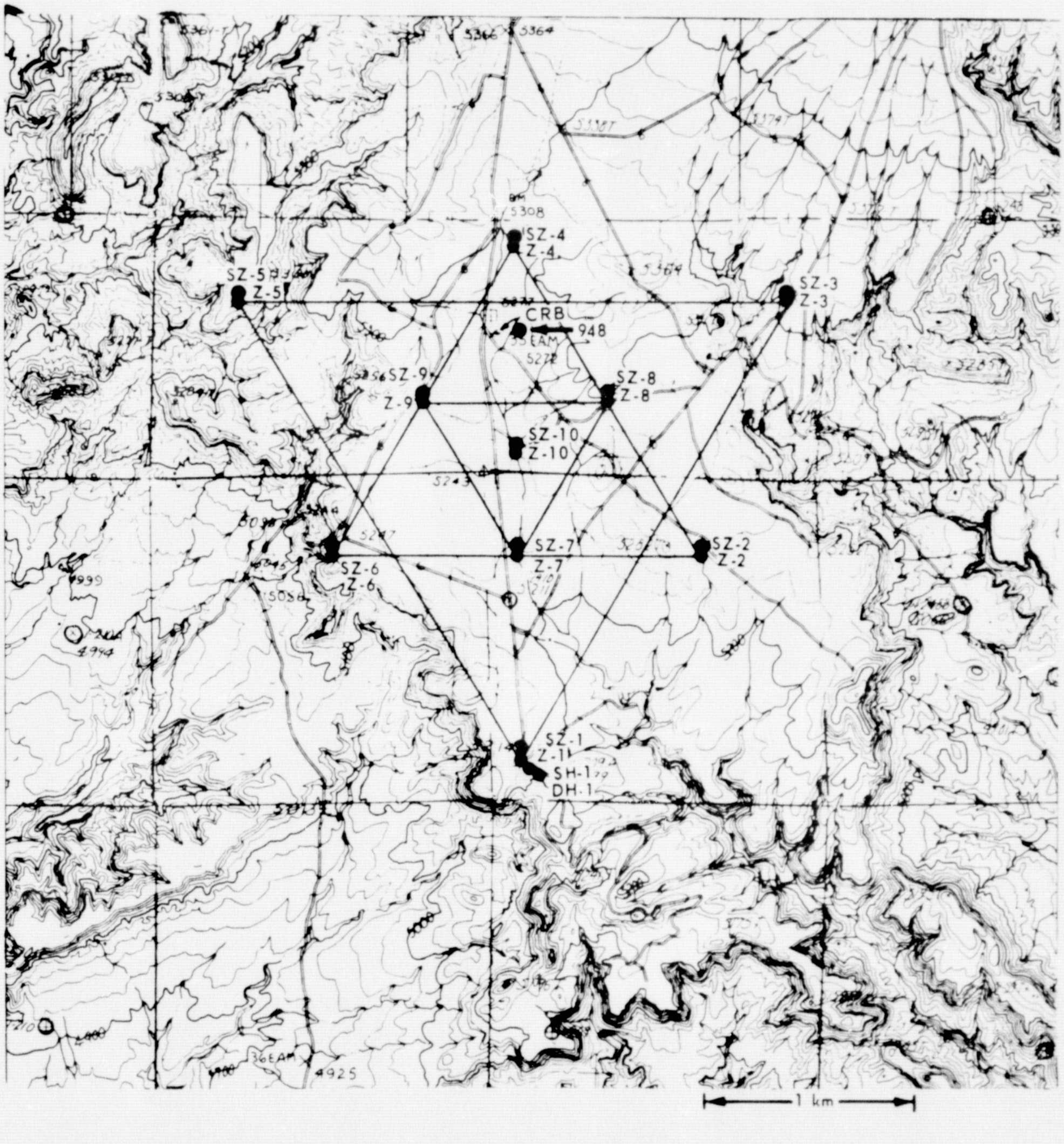

Figure 25. Orientation and configuration of UBSO short-period arrays
G 7786

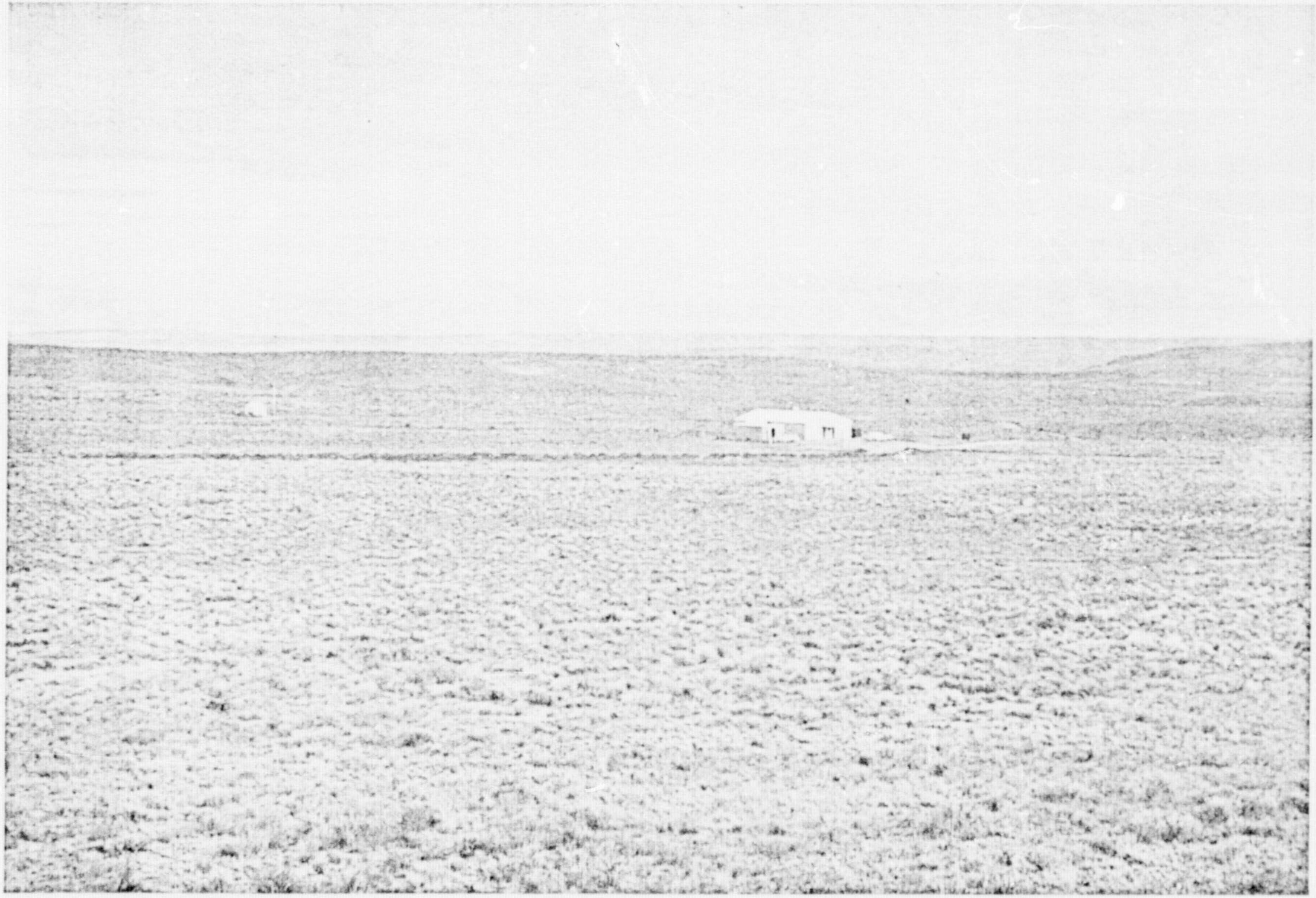

Figure 26. View of UBSO central recording building

G 7787

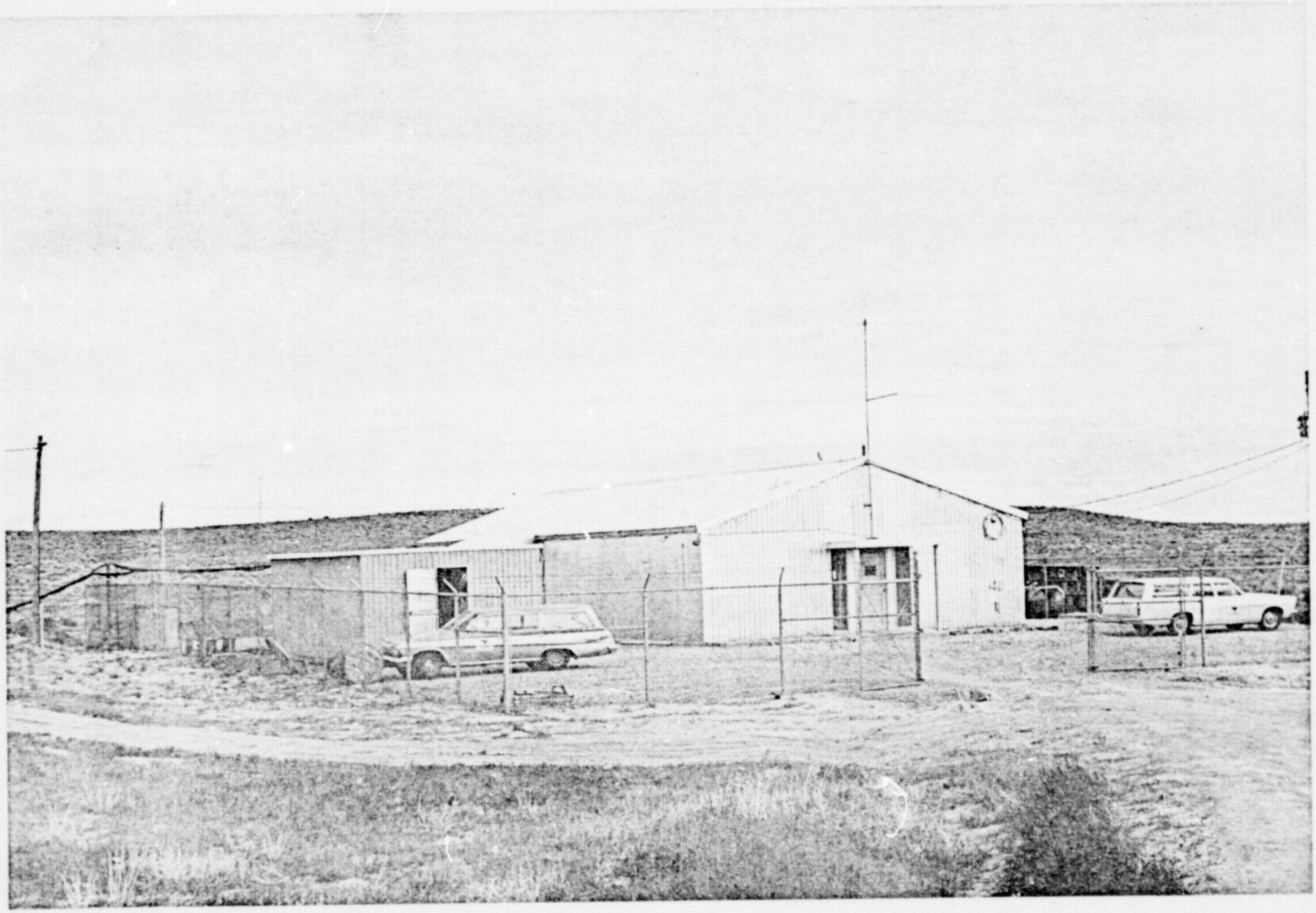

Figure 27. Central facility at UBSO

G 7788

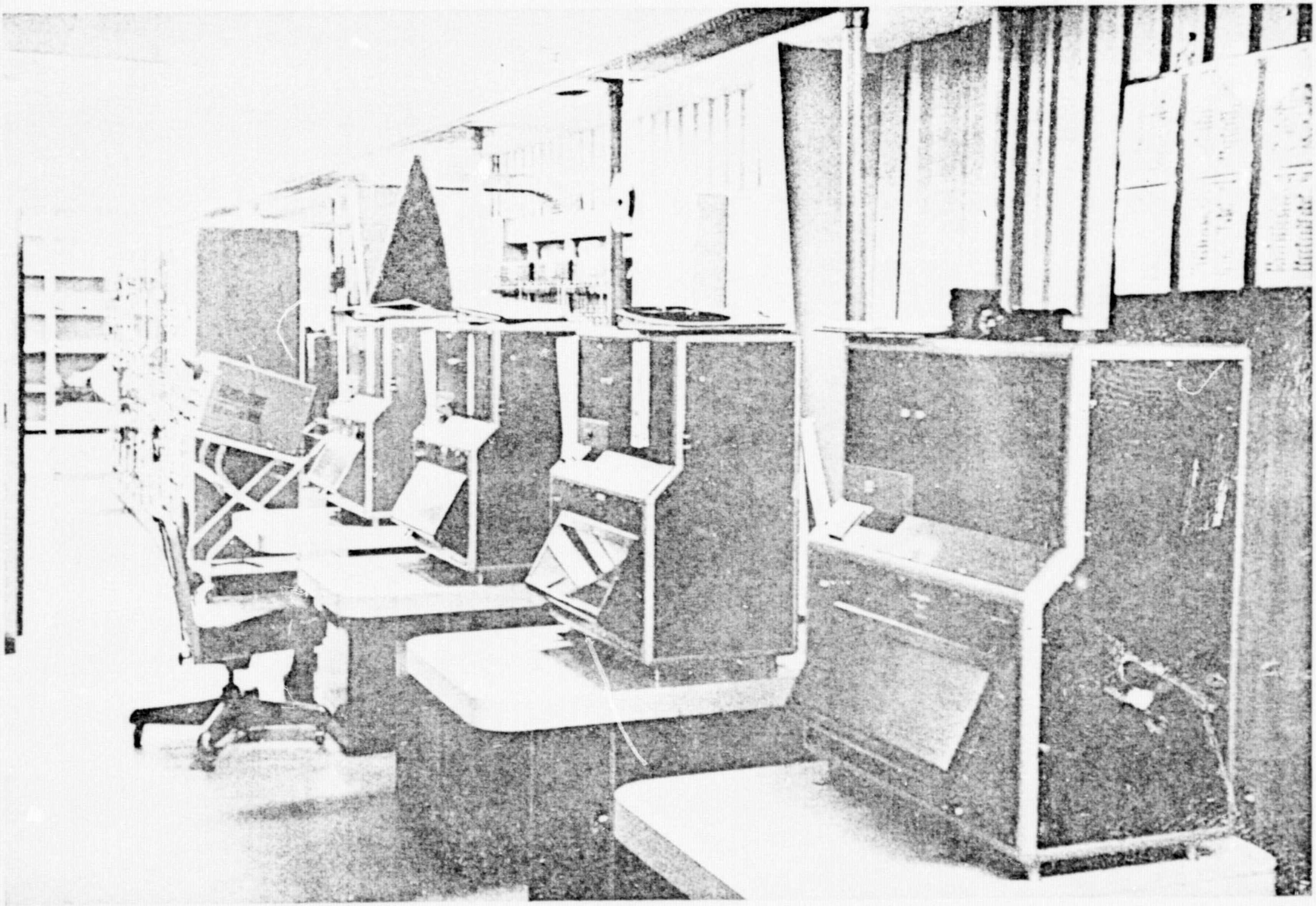

Figure 28. Film recorders and equipment at UBSO

G 7789

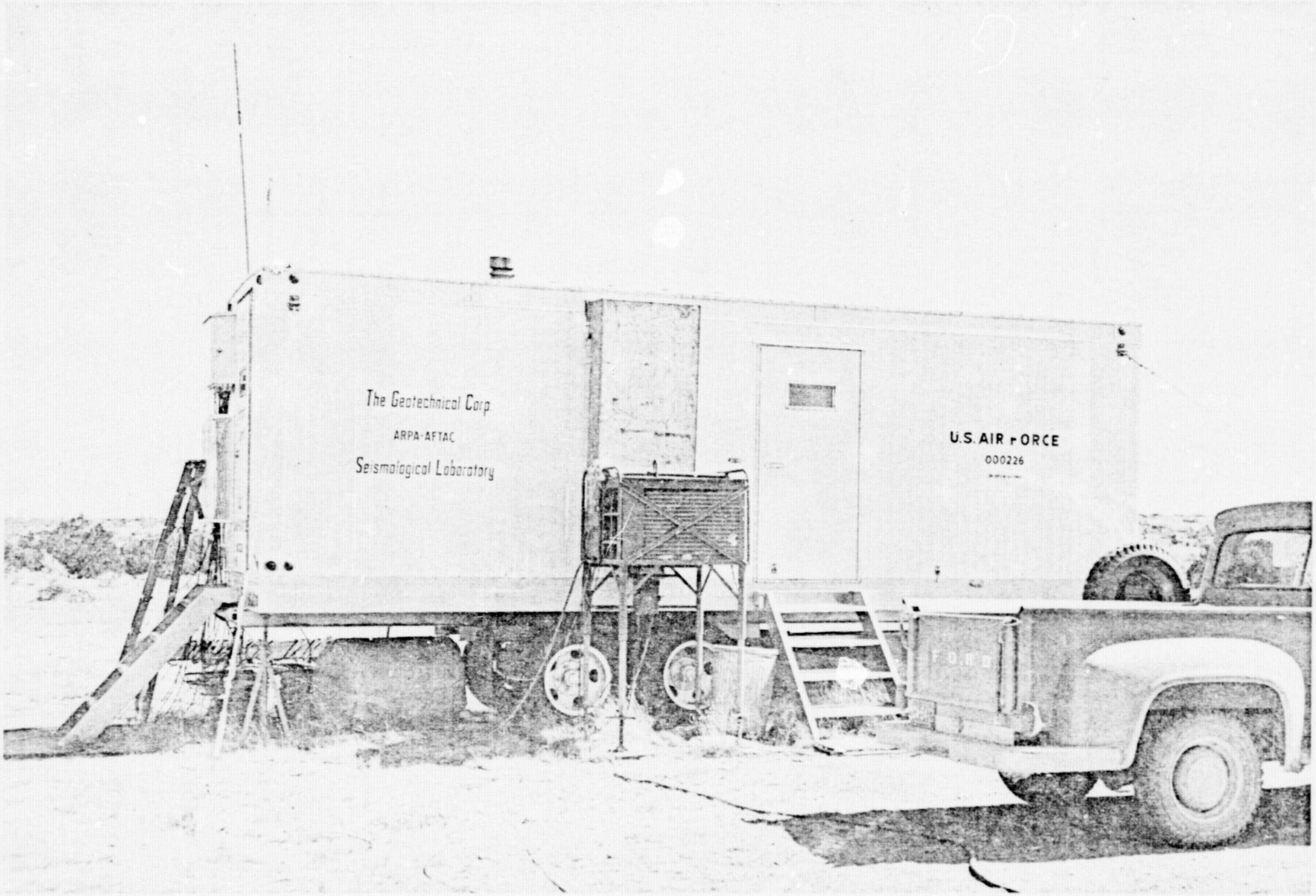

Figure 29. A mobile seismological van used to gather data during the 1960's

G 7790