UNITED STATES
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TECHNICAL LETTER NUMBER 13

PRELIMINARY STUDY OF FIRST MOTION FROM NUCLEAR EXPLOSIONS RECORDED ON SEISMOGRAMS IN THE FIRST ZONE*

By

J. H. Healy** and G. B. Mangan**

DENVER, COLORADO

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Technical Letter
Crustal Studies-13
August 23, 1963

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defense
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

TECHNICAL LETTER NUMBER 13

PRELIMINARY STUDY OF FIRST MOTION

FROM NUCLEAR EXPLOSIONS

RECORDED ON SEISMOGRAMS IN THE FIRST ZONE*

By

J. H. Healy** and G. B. Mangan**

Sincerely,

David J. Stuart
Acting Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-61.

** U. S. Geological Survey, Denver, Colorado.

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PRELIMINARY STUDY OF FIRST MOTION FROM NUCLEAR EXPLOSIONS RECORDED ON SEISMOGRAMS IN THE FIRST ZONE*

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J. H. Healy** and G. B. Mangan**

Introduction. The U. S. Geological Survey has recorded more than 300 seismograms from more than 50 underground nuclear explosions. Most were recorded at distances of less than 1,000 km. These seismograms have been studied to obtain travel times and amplitudes which have been presented in reports on crustal structure and in a new series of nuclear shot reports.

This report describes preliminary studies of first motion of seismic waves generated by underground nuclear explosions. Visual inspection of all seismograms was made in an attempt to identify the direction of first motion, and to estimate the probability of recording detectable first motion at various distances for various charge sizes and in different geologic environments. In this study, a characteristic pattern of the first phase became apparent on seismograms where first motion was clearly recorded. When an interpreter became familiar with this pattern, he was frequently able to identify

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** U. S. Geological Survey, Denver, Colorado.

the polarity of the first arrival even though the direction of first motion could not be seen clearly on the seismogram. In addition, it was sometimes possible to recognize this pattern for secondary arrivals of larger amplitude.

These qualitative visual observations suggest that it might be possible to define a simple criterion that could be used in a digital computer to identify polarity, not only of the first phase, but of secondary phases as well. A short segment of recordings near the first motion on 56 seismograms was digitized on an optical digitizer. Spectral analyses of these digitized recordings were made to determine the range of frequencies present, and studies were made with various simple digital filters to explore the nature of polarity as a function of frequency. These studies have not yet led to conclusive results, partly because of inaccuracies resulting from optical digitization. The work is continuing, using an electronic digitizer that will allow study of a much larger sample of more accurately digitized data.

VISUAL INSPECTION FOR DETERMINATION OF THE DIRECTION OF FIRST MOTION

Instrumental frequency response. The frequency response of equipment used to make recordings will have an effect on the character of recorded first motion. Amplifiers in the equipment used by the Geological Survey have a flat response from 1 to 300 cps.

Adjustable bandpass filters permit use of a high-cut filter of 9 or 13 cps which was found effective for recording seismic waves from nuclear explosions. For almost all recordings, high-frequency noise requires the use of a high-cut filter of 37 cps or lower. A Hall-Sears 2-cps seismometer was used to make most of the recordings. The response of the combined seismometer-amplifier system with a 9 cps high-cut filter is shown in Figure 1.

Several nuclear explosions were recorded at AFTAC stations to compare performance of Geological Survey instruments with standard earthquake seismic instruments. In general, these recordings were similar, except that the Geological Survey instruments gave a slightly better high-frequency response than the AFTAC instruments. The AFTAC seismograms show more low-frequency energy, particularly on the later phases (Figure 2).

The pattern of the first arrival. A characteristic pattern of the first arrival is frequently observed on seismograms recorded from high-explosive charges. This pattern consists of a relatively weak up-break followed by a sharper, large amplitude down-break, and then by another upward motion roughly equal in amplitude to the first downward motion (Figure 3). A similar pattern occurs for nuclear explosions but at lower frequencies (Figure 4).

Visual estimation of first motion on the seismogram. Using the first-arrival pattern described above and a criterion based

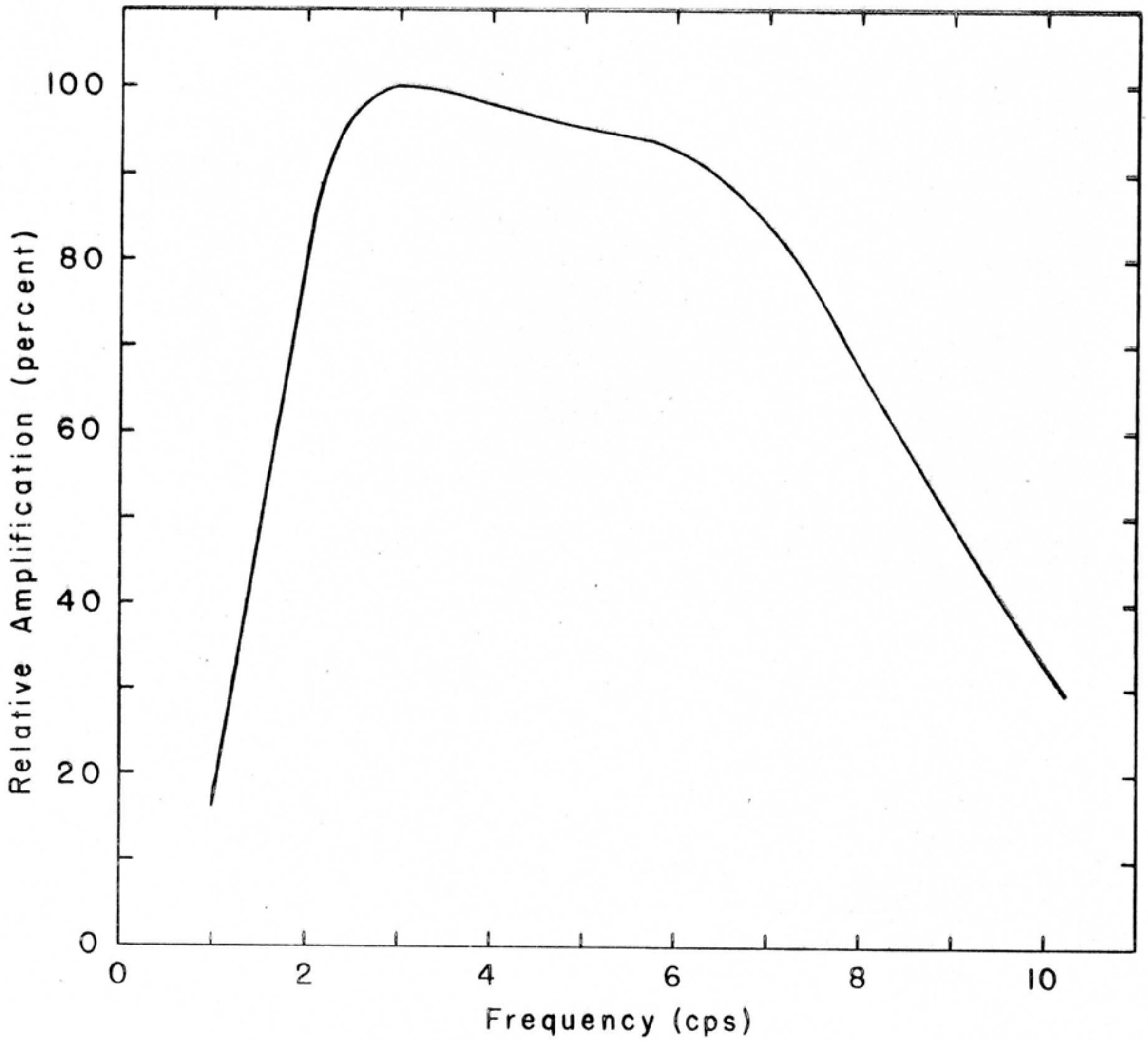

Figure 1.--Response of Geological Survey refraction instruments with a Hall-Sears 2-cps seismometer and a 9-cps high-cut filter.

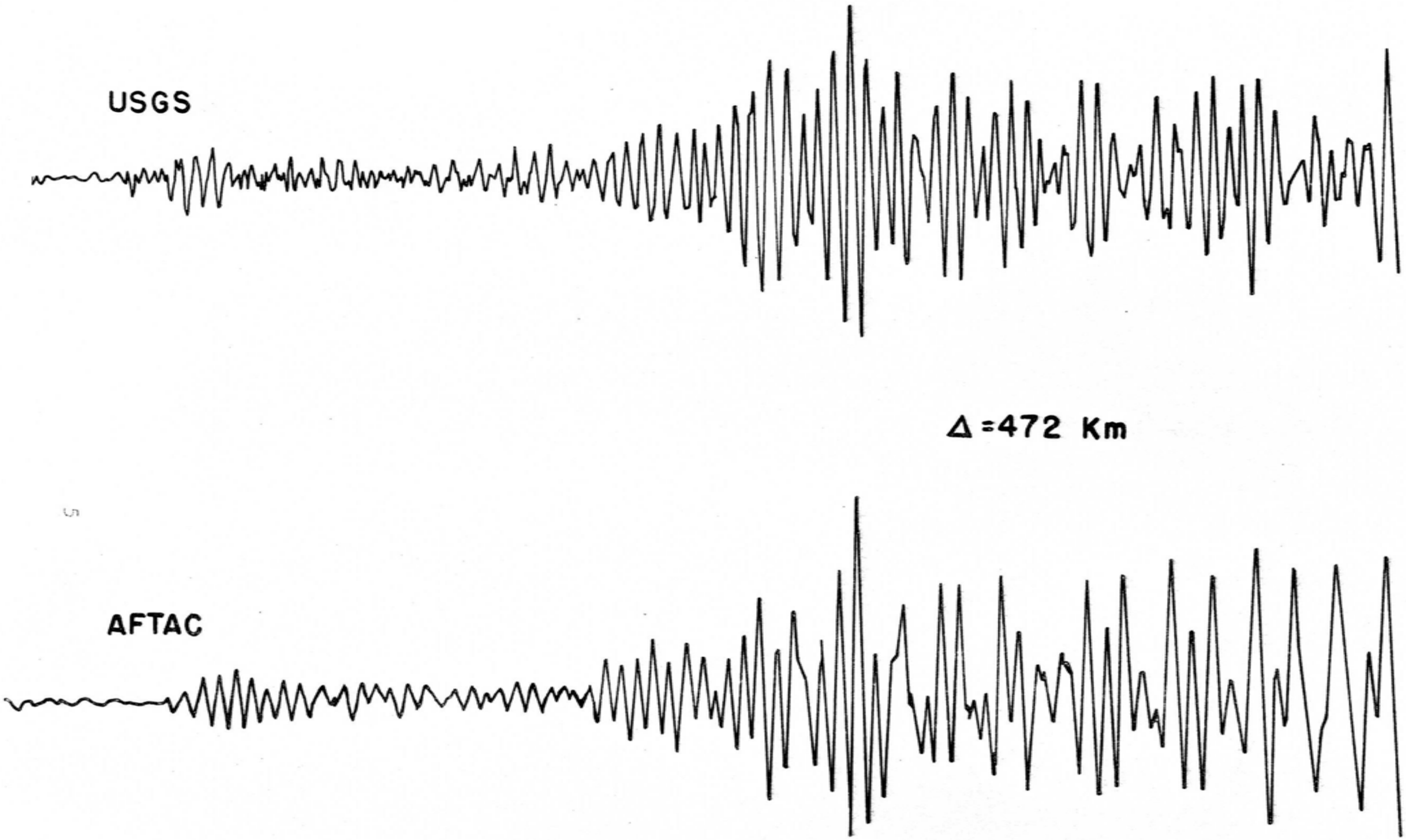

Figure 2.--Comparison of Geological Survey and AFTAC recordings at the same location.

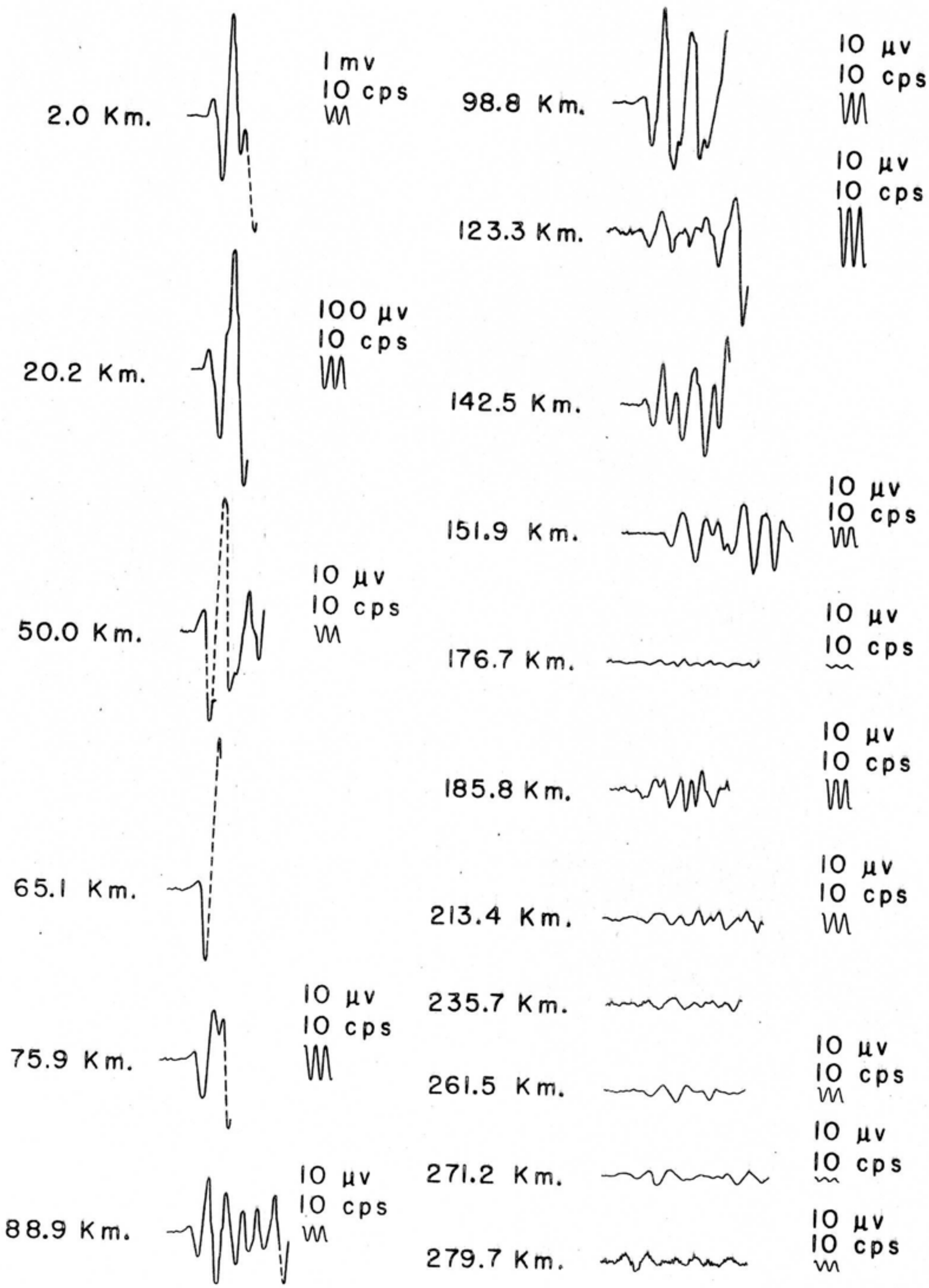

Figure 3.--First motion from high-explosive shots in Lake Mead.

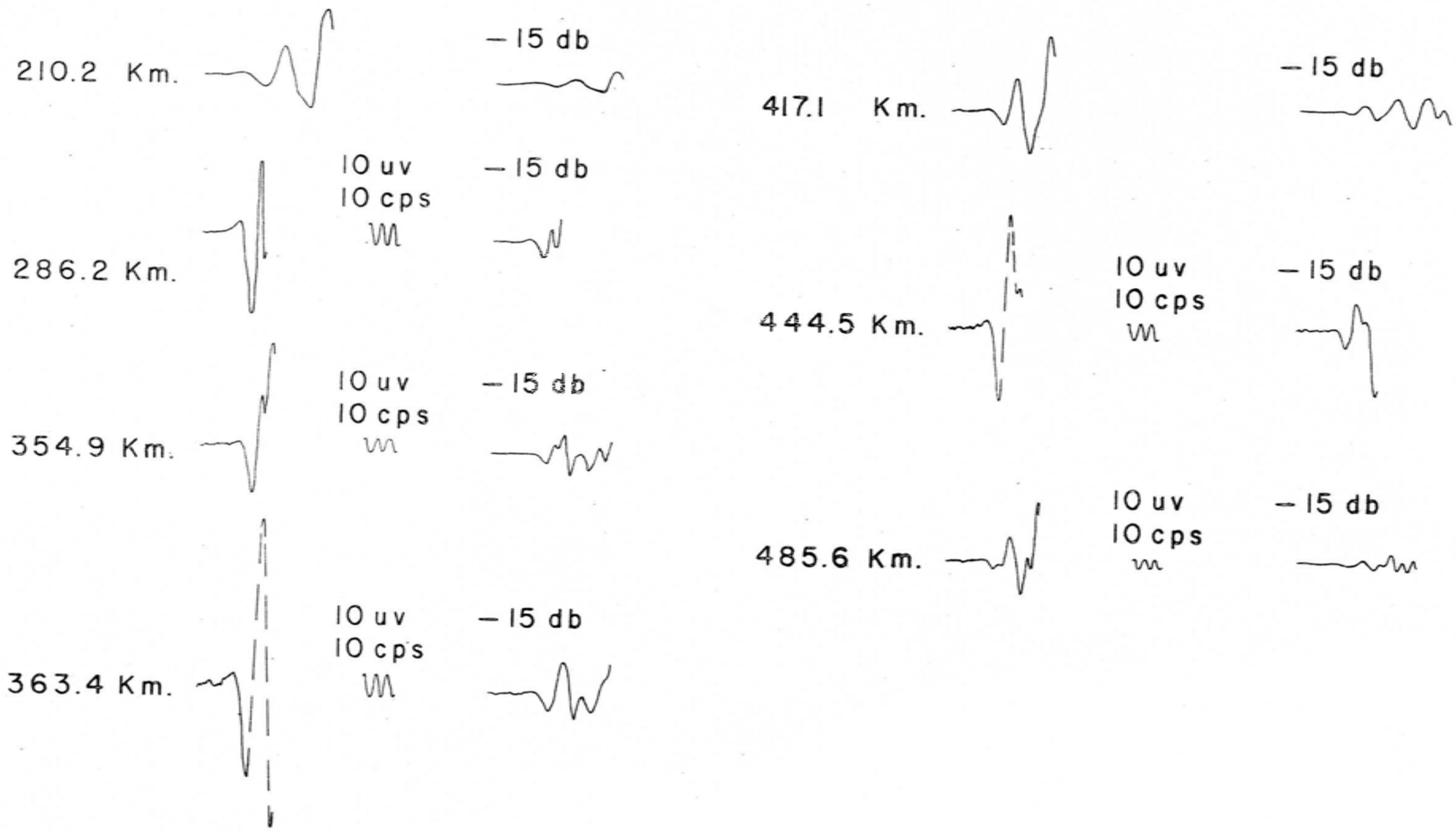

Figure 4.--First motion from ANTLER underground nuclear explosion.

on signal-to-noise ratio, three experienced seismic interpreters examined a large number of seismograms and graded them as follows:

Good - a seismogram on which the first motion is clearly defined,

Fair - a seismogram on which the first motion is indeterminate but on which, in the interpreter's judgment, the first energy recorded represented the first arrival,

Poor - a seismogram on which some arrivals were recorded but in the interpreter's judgment do not represent the first arrival,

NA - a seismogram on which no detectable phases were recorded.

Only the monitor seismograms were used to make this evaluation. When playbacks of the magnetic-tape recordings are made, it has sometimes been possible to recover the direction of first motion on "Fair" recordings. It is usually not possible to recover the direction of first motion on "Poor" recordings. Figure 5 shows all recording positions at which seismic waves from nuclear explosions were recorded, and the symbols indicate the grade for seismograms made at these locations. Figure 6 shows the record-quality distribution as a function of distance, and Figure 7 shows the record-quality distribution as a function of charge size.

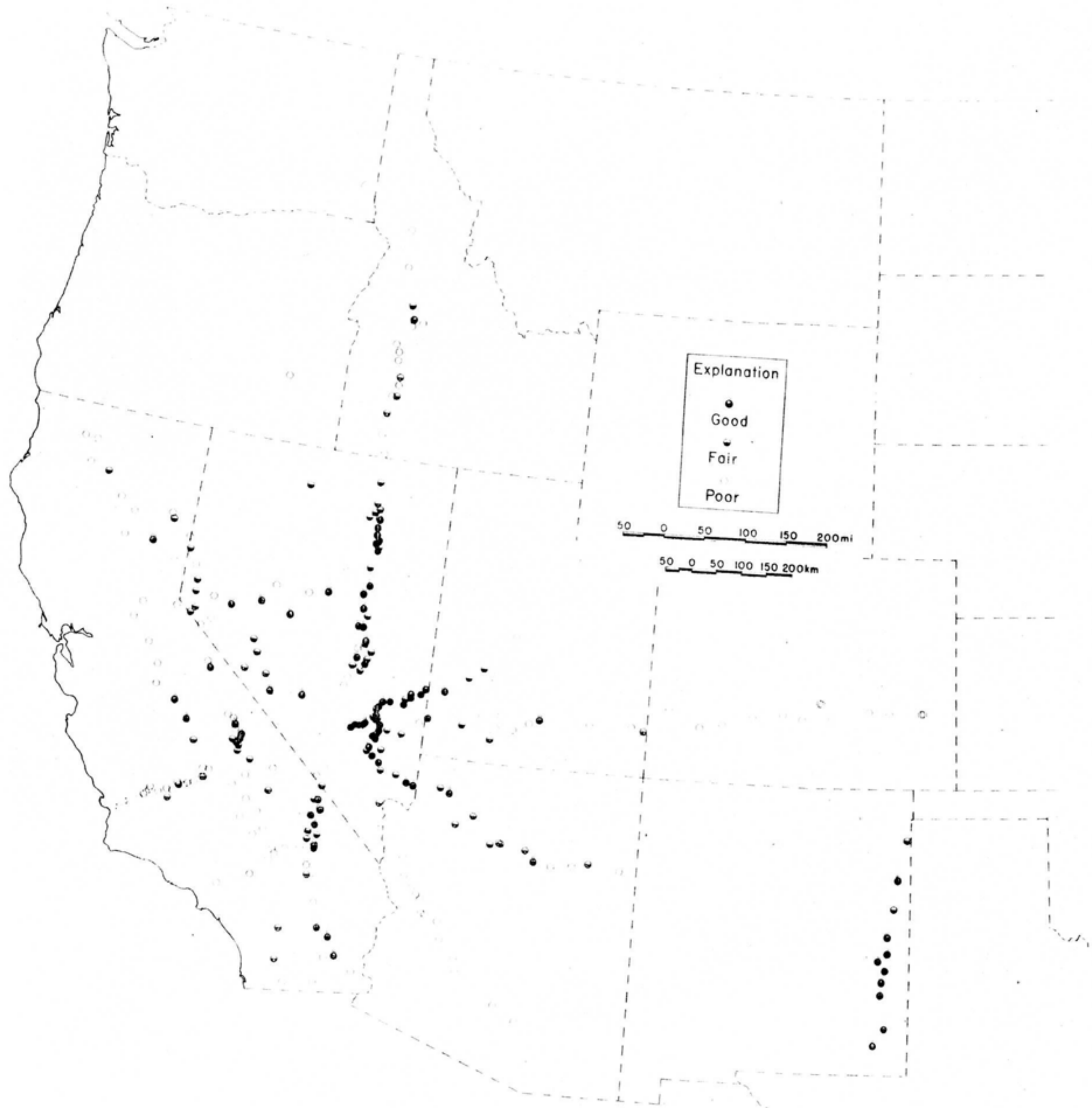

Figure 5.--Location of recordings of nuclear explosions.

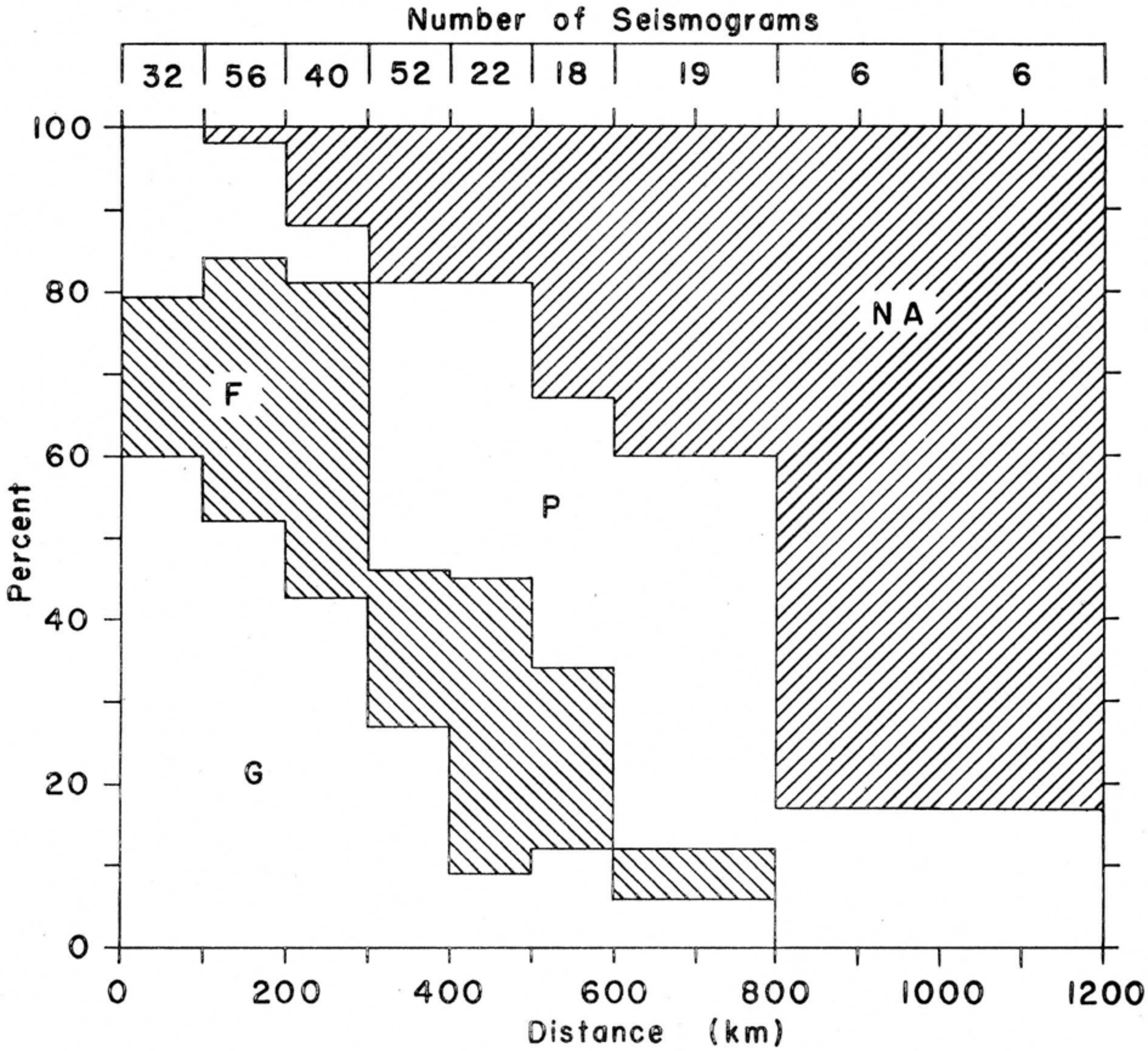

Figure 6.--Quality of seismograms as a function of distance. G - good recordings from which direction of first motion can be determined; F - fair recordings, clear first arrivals, but direction of first motion in doubt; P - poor recordings, first arrivals are below noise level, clear secondary arrivals; and NA - no clearly recorded arrivals apparent on the seismogram.

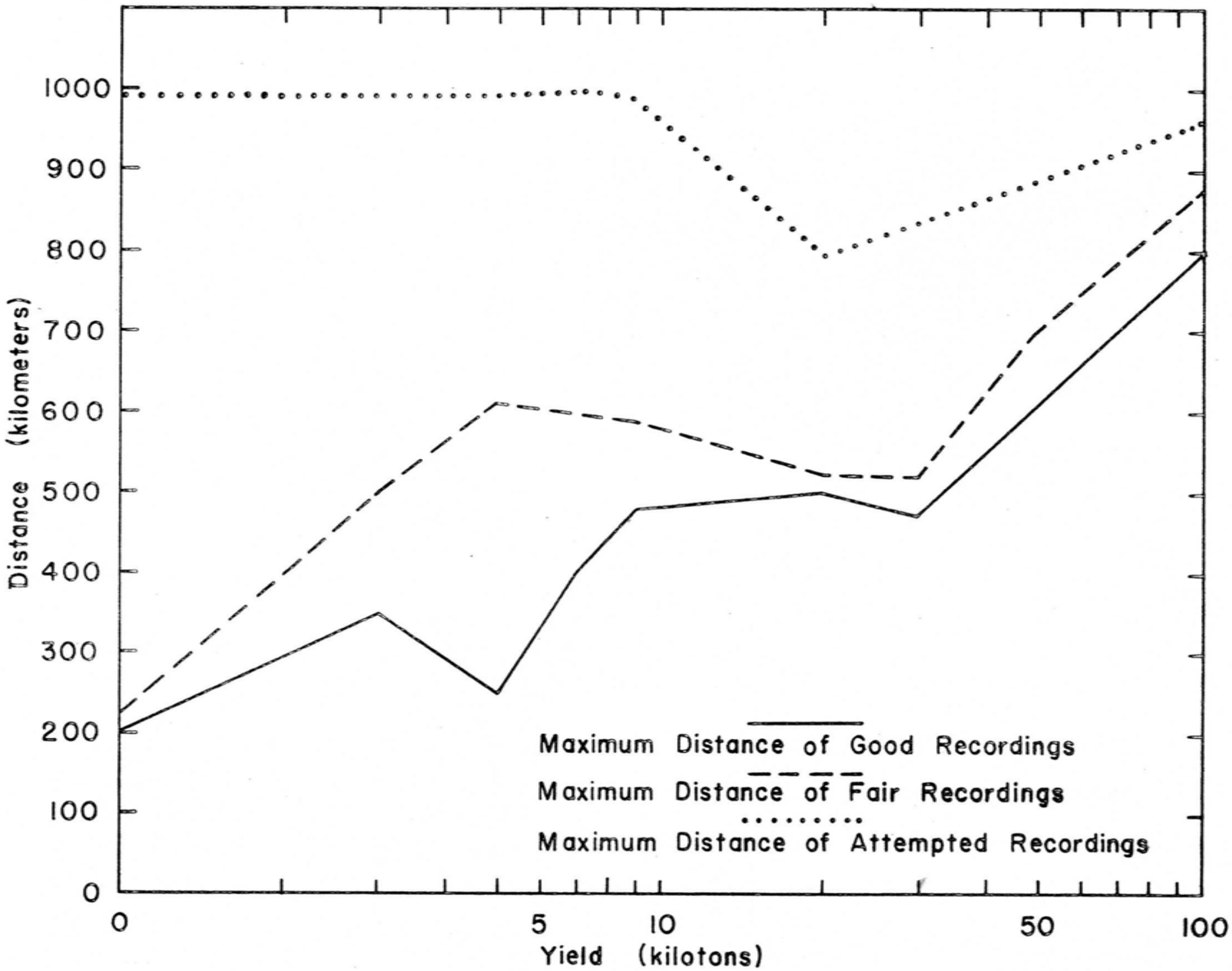

Figure 7.--Record quality as a function of charge size and distance.

It is interesting to speculate how these statistics might compare with the operation of a detection system. It would be extremely difficult to make a statistical evaluation of all factors that affect detection of first motion in a proposed detection system. The data presented here represent the recording of many sizes of shots in a number of different geologic environments. In general, no attempt was made to record shots smaller than 1 or 2 kt. The larger shots were recorded at the greater distances. Recording sites were selected by experienced observers, but in a relatively short period of time. The careful selection of recording sites after a very detailed regional study would improve the results. Considering these factors, and considering that no attempt was made to conceal these explosions, the authors feel that the statistics presented here represent an optimistic estimate of the probability of recording first motion in the first zone.

PRELIMINARY STUDIES OF DIGITIZED SEISMOGRAMS

Spectral analyses. The spectral distribution of seismic energy has an important effect on the detection of first motion. Of particular interest in this regard is the marked change in frequency content between first and third zone recordings. This effect is clearly illustrated in Figure 8, which shows magnetic-tape playbacks of recordings made, using Willmore 1-cps seismometers, of waves generated by HAYMAKER and by another nuclear event recorded 2800 km from the Nevada Test Site. These playbacks show no recorded

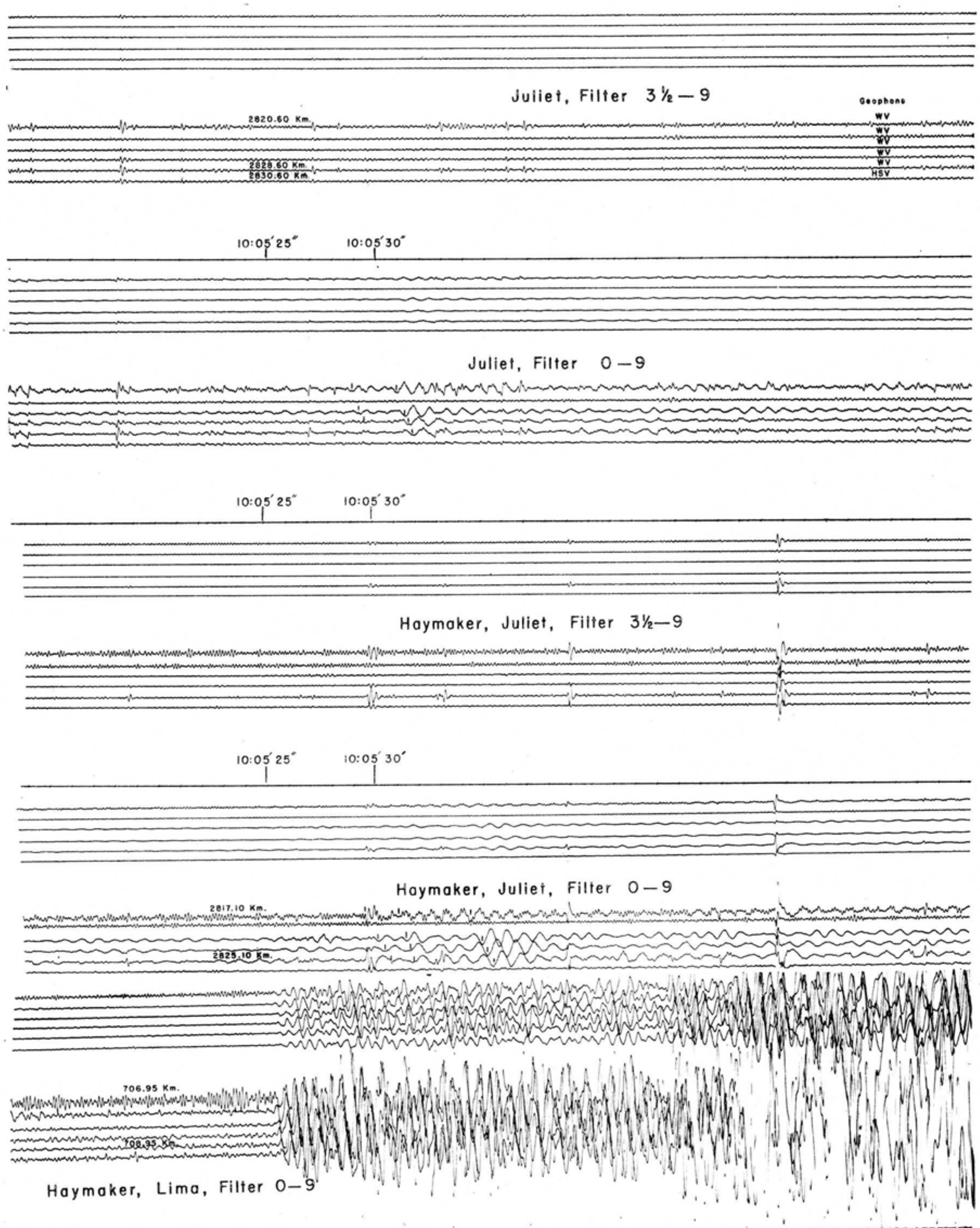

Figure 8.--Recordings of HAYMAKER and another nuclear event showing attenuation of high frequency with distance. Each recording is made at two levels separated by 15 db. WV refers to Willmore 1-cps vertical seismometers. HSV refers to Hall-Sears 2-cps vertical seismometers.

energy above 3.5 cps. The lower part of Figure 8, the HAYMAKER event recorded at 706 km, shows that most of the seismic energy is above 3 cps. Because of this extreme change in frequency content between the first and the third zones, it should be recognized that the problem of detecting the direction of the motion in the first zone is essentially different from the problem of detecting the direction of first motion in the third zone.

Spectral analyses were performed on digital samples that included the first motion from 56 seismograms. The digital sample consisted of 2 or 3 seconds of the recording, with the first recognizable energy approximately in the middle of the digitized window. Figures 9 and 10 show some typical results of these analyses. Because visual inspection of the seismograms had indicated that energy above 10 cps tended to obscure the first motion rather than clarify it, it was decided to pre-filter these data with a 9-cps high-cut filter. Consequently, no conclusions can be drawn about the spectrum above 9 cps. On the low-frequency side, the seismometer response begins to fall off at 2 cps. Because of the short length of the digitized sample, it was not considered possible adequately to de-trend the data. Conclusions about the spectrum below 2 cps must be limited to the observation that there seems to be significant energy below 2 cps on all samples.

<u>An attempt to discover the polarity of first motion by the use of digital filters</u>. In theory, an inverse filter can be

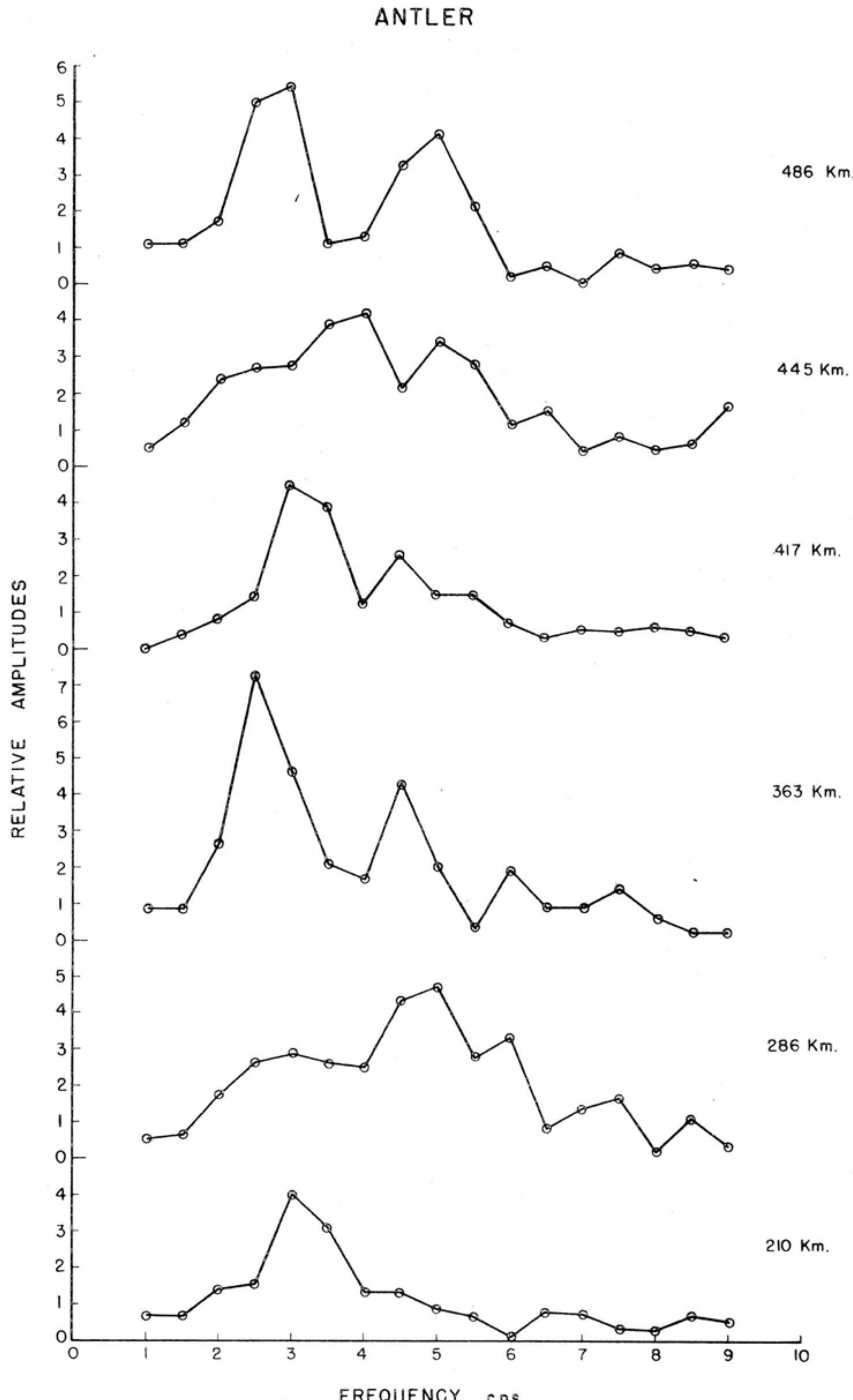

Figure 9.--Spectral analyses of six recordings of the underground-nuclear explosion ANTLER.

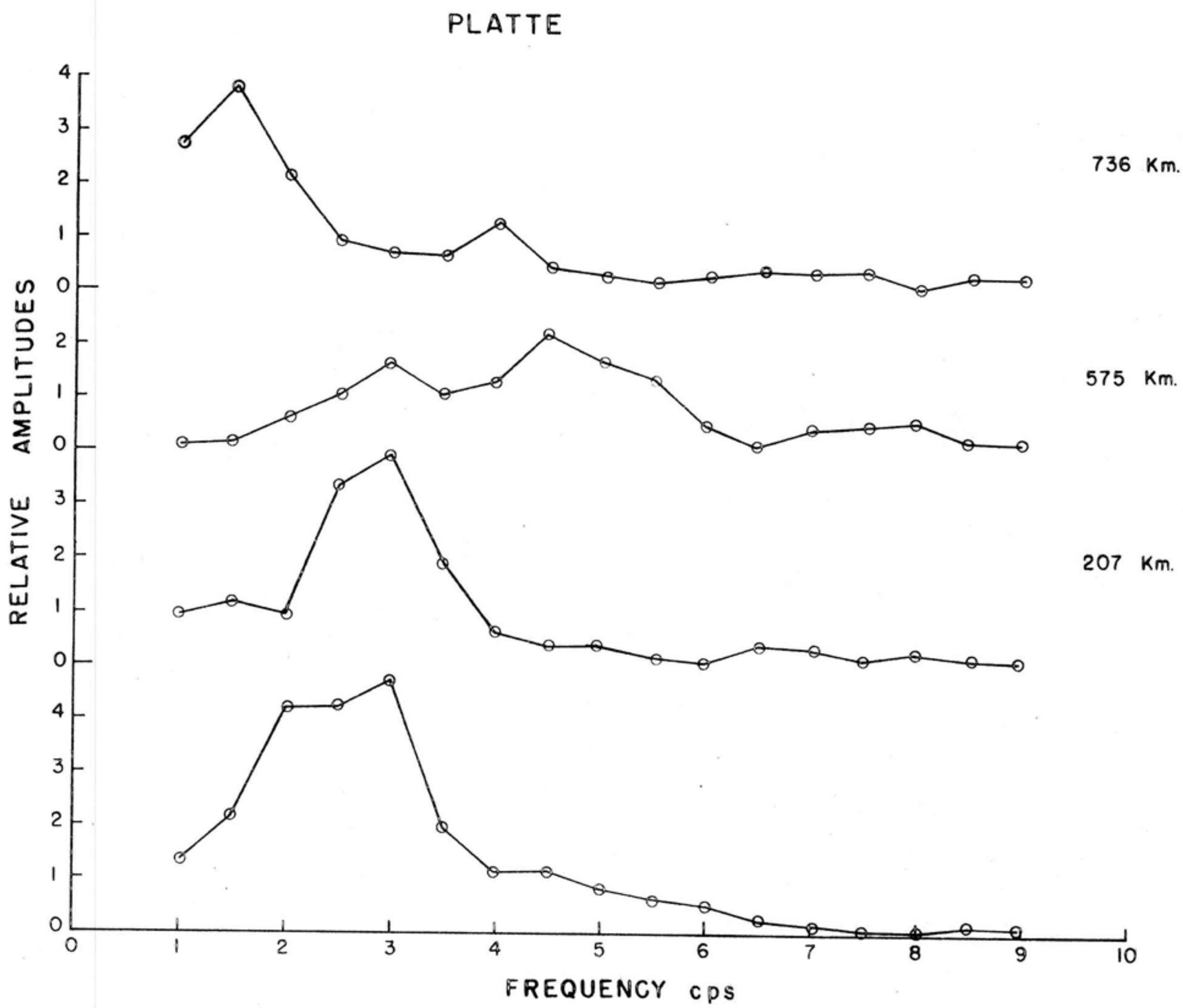

Figure 10.--Spectral analyses of four recordings of the underground-nuclear explosion PLATTE.

constructed that will reproduce the motion at the source and determine its polarity. In practice, this is usually impossible because of inadequate knowledge of earth structure and the interference of seismic noise. A number of lines of reasoning suggest that a low-pass digital filter consisting of a moving integration window might be useful in identifying first motion and polarity. From another viewpoint, one could say that looking at seismograms through a number of spectral windows might assist the interpreter in identifying the polarity of the seismogram when polarity had been obscured on the wide-band seismogram.

As a first attempt in exploring these possibilities, seismograms were passed through a digital filter which may be specified as follows:

$$\text{Filtered Trace (I)} = \sum_{J = I - 1/2\,W}^{I + 1/2\,W} \text{Recorded Trace (J)}$$

Window lengths of 1/2 and 1 second were used, and each trace was passed through the filter three times. This operation provides a zero-phase-shift low-pass filter with each pass through the filter giving an increasingly sharp cutoff for periods longer than the window length. Because of the short window available in the digitized data, and the low response of the instruments to frequencies below 1 cycle, the 1/2-cps window proved more effective than the 1 cps window. Figure 11 shows the results of this filtering process on several seismograms.

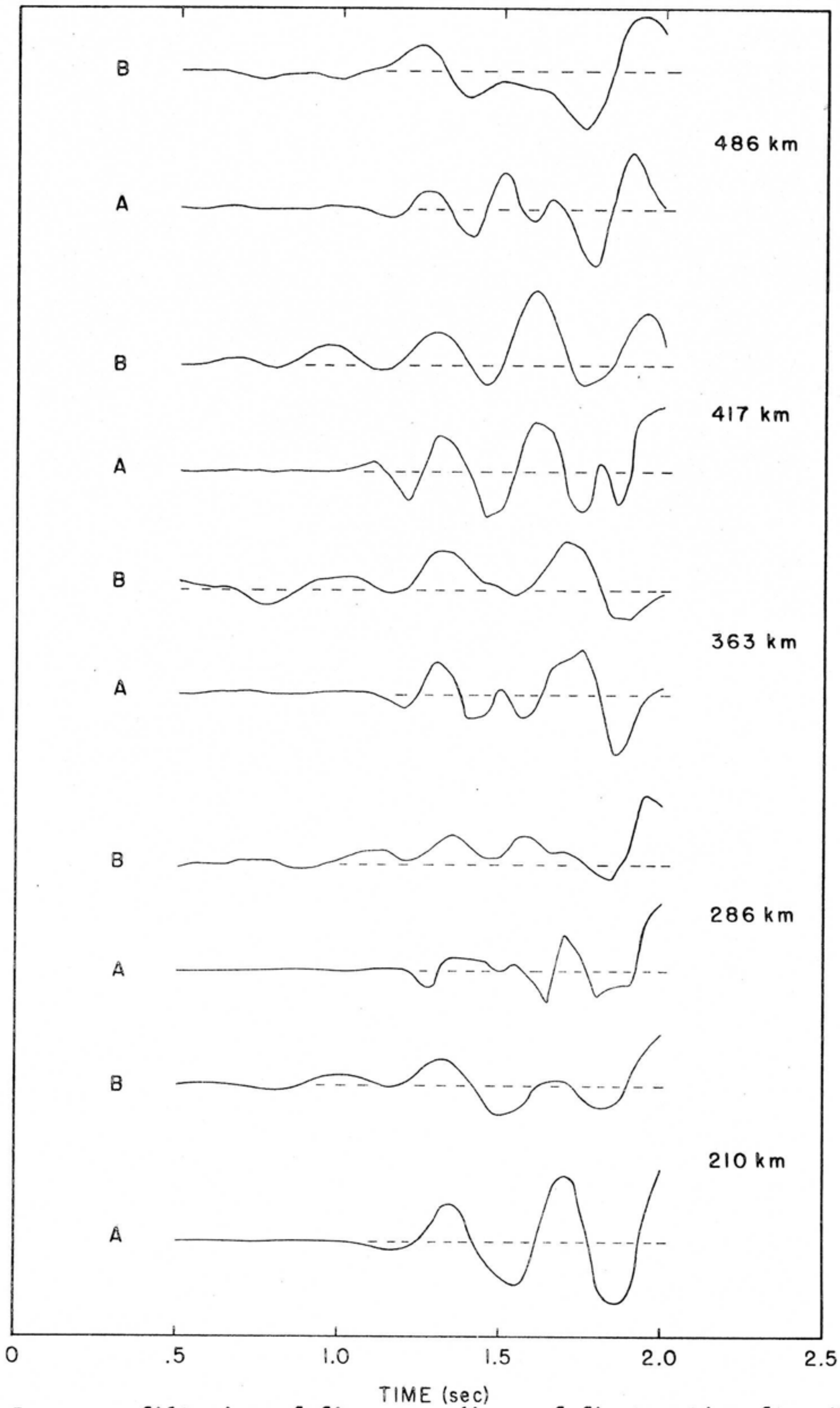

Figure 11.--Low-pass filtering of five recordings of first motion from ANTLER. A is original trace; B is the result of passing A through a digital low-pass filter.

The following procedure was used to estimate the polarity on the 56 samples: The trace consisting of a double pass through the 1/2-sec window filter was compared with the original seismogram. The time of the first arrival was picked from the original seismogram and the polarity of the filtered trace was recorded at this time. Thirty percent of the samples show a net positive polarity, 13 percent show a negative polarity, and 54 percent are inclusive. Although present results are inconclusive, they are encouraging enough to proceed with this type of analysis on a larger sample of data and with the more accurate digital process provided by new electronic-digitizing equipment. This analysis will consist of the following steps:

1. Identification of an arrival on the seismogram using the part of the spectrum above 5 cycles (high-frequency).
2. Examination of the polarity of the low-frequency part of the spectrum at the time of this arrival. If the low-frequency record is obtained by filtering through a zero-phase-shift filter, it should tend to show the net polarity of the arrival.