THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

A STUDY OF LOCAL EARTHQUAKES IN OKLAHOMA RECORDED ON 1-3 HERTZ SEISMOGRAPHS

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

By

KEVIN LOWELL WOLLER

Norman, Oklahoma

1978

ACKNOWLEDGEMENTS

I would like to sincerely thank Dr. Jim Lawson of the University of Oklahoma Earth Sciences Observatory for the original idea behind this study and his continued help and interest in my work. Thanks also go to Dr. Robert L. Dubois and Dr. Charles Harper of the University of Oklahoma School of Geology and Geophysics for their critical comments in the writing and printing of this thesis. Special thanks go to my wife Pam for her moral support during my graduate work and the typing and printing of this paper.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Figure | Page

A STUDY OF LOCAL EARTHQUAKES IN OKLAHOMA USING 1-3 HERTZ SEISMOGRAPHS

CHAPTER I

Introduction

In the years previous to 1972, all the short period seismographs operating in Oklahoma were of the teleseismic type, operating on a band pass of about 1-3 hertz. Local earthquakes occurring in Oklahoma, typically having frequencies in the 2-10 hertz range, do not always appear clearly on the seismograms recorded on such seismographs. The effect of the filtering is such that local earthquakes cannot always be distinguished from other high frequency events such as quarry blasts.

In May, 1972, a high-pass vertical seismograph, HPZ, began operation at TUL, the seismic station of the University of Oklahoma Earth Sciences Observatory at 35.90°N., 95.79°W. near Leonard, Oklahoma. Early work with HPZ indicated that local earthquakes could easily be identified. Later work using a narrow band-pass very short period vertical seismograph, VSPZ, corroborates the earlier work, allowing reasonable identification of local earthquakes. Determination of local earthquakes in recent years is thus very dependable and allows work to be done to develop a method of detection of earlier earthquakes by studying the short period records of recent years.

Local earthquakes in Oklahoma occurring in 1976 are used as a "learning set" to determine the characteristics of local earthquakes on the short period teleseismic type seismographs SPZ, SPE, and SPN. The method of identification was not initially known, as no previous work of this explicit nature had been done. Methods of qualitative determination were known and had been applied by Tryggvason (1964) in a study of the seismicity of Oklahoma. His main criteria was to look for short period events with phases having a particular shape, much like that of an exponential decay. This worked for several events, but left some that were indeterminate in origin.

It thus seems desirable to employ some sort of quantitative discriminant between local earthquakes and other short period events. Measuring several variables such as Pg and Sg period, Pg to Sg amplitude ratio, duration, and coda length on the three seismographs and comparing the results for earthquakes and other events seemed a reasonable procedure, although the best method of applying the differences in variable values was at first unclear. In the above discussion, the subscript g indicates the P(longitudinal) and S(shear) waves traveled only in the upper crust.

After the variables listed above had been measured for most of the earthquakes in Oklahoma in 1976, variable measurements for many other short period events were also made. Initial attempts to find a discriminant involved making a large number of x-y graphs of one variable versus another. This work showed some improvement over the use of a single variable, but still left much to be desired. A method that would use all the variables to their fullest extent in a multidimensional space was thought to be better.

After some search a satisfactory way of discrimination was arrived upon and developed. This method, multivariate discriminant analysis, uses population samples to develop weights to be applied to the variables so as to arrive at a single weighted value for an event. A dividing value is also determined so that identification of an event depends on whether its weighted value is greater than or less than the dividing value. Use of multivariate discriminant analysis provides a maximum of approximately 94% chance of correctly identifying individual events in the categories of local earthquakes and other short period events.

CHAPTER II

Related Investigations

Although there have been no studies of earthquakes in Oklahoma that deal specifically with the problem of identification, there are related studies of earthquakes and seismicity in Oklahoma and the central United States. One of them, the aforementioned study by Tryggvason (1964), is more of a cataloging study in which the author observes trends of epicenters, magnitude ranges, and present tectonic activity. As mentioned before, Tryggvason gives some basic qualitative criteria for identifying local earthquakes. In fact, some particularly interesting notations on the events he studied are taped on the seismograms, which helped in early study to become familiar with the appearance of events on the short period seismograms.

Another cataloging effort of interest is the one done by James Zollweg (1974). Zollweg, in a preliminary study of the seismicity of the central United States, studied records from several seismic stations in the continental interior covering a period of time from January, 1963 to February, 1974. It is assumed that his criteria for classification of events as earthquakes is similar to Tryggvason's.

Study more relevant to the development of a discriminant has been done by Dr. James Lawson, geophysicist at the University of Oklahoma Earth Sciences Observatory (O.U.E.S.O.) in Leonard, Oklahoma. His work with seismograph filtering at TUL, the seismic station code for the observatory, was one of the principal reasons for suspecting that there have been many local earthquakes overlooked or unidentified over the years previous to 1972 (Lawson, 1975). His method of identification using filters, which will be discussed in more detail later, shows that local earthquakes occur with a frequency around 30 per year. Another study, by Lawson and Robert DuBois (1976), is a descriptive field study of felt earthquakes in Oklahoma over the years 1974-1976. A catalog of earthquakes with epicenters in Oklahoma through 1976 with an accompanying map has been prepared by Lawson, Du Bois, and Paul Foster (1977).

Another article, written by Bill Kalb (1964), is more of a laymen's guide to earthquakes in Oklahoma. This article is a little sensationalistic and scientifically inaccurate.

CHAPTER III

Theory

Source Considerations

A basic assumption used in this study is that local earthquakes are inherently different from other short period events and can be distinguished from other such events. One way to qualify such a statement is to study earthquakes and other short period wave generators such as explosions in the context of seismic sources to predict how their signals should appear on a seismic record.

As is discussed by Dahlman and Israelson (1977), a seismic source can be described by its strength and its spatial and temporal characteristics. An explosion should be a much simpler source as the size of the energy source is relatively small and the geometry of energy radiation should be symmetric, whereas an earthquake is usually of a more complex, asymmetric nature. Although the explosions discussed by Dahlman and Israelson are nuclear explosions, some or most of what they say should hold true for smaller, incendiary blasts of the type which occur with great frequency in quarry operations in Oklahoma.

Empirical and theoretical models of explosions have been made which indicate that most of the energy released by an underground nuclear explosion is thermal and exists only in the vicinity of the explosion. Only a small fraction of the explosion energy, estimated between

0.01 and 5% (Berg et al, 1964, Trembly and Berg, 1966, Haskell, 1967), is radiated as seismic energy. The geometry of an explosion source is usually described as the surface of the spherical boundary between the inelastic and elastic regions of the explosion. As the radial pressure of the explosion shock-wave acts on the surface of the elastic sphere, seismic waves are generated. If the sphere were truly symmetric, only compressional waves with constant amplitude in all directions would be generated. For such a model, the initial motion of earth materials should be compressional.

Complications in the above model for explosion sources in Oklahoma are that the explosions occur on or near the surface, as the explosions are usually quarry blasts. This complicates the signal in that large surface waves are usually generated which are not always discernible from the small shear waves on seismograms.

The amplitude spectra studies for most models indicates that the peak of the spectrum is shifted towards lower frequencies with an increase in explosion energy. Thus, although blast charge sizes probably vary, the frequency spectrum for blasts might be expected to be more uniform than that from a natural seismic event. A complication in studying blasts in this area is that they are usually conducted in the form of multiple charges, which complicate the apparent wave phases recorded on the seismogram.

Bollinger (1971) presents an analytic approach to studying blast seismograms, but is mainly directed toward engineering purposes. Some examples of blast seismograms comparable to those recorded at TUL are given in his book, and several references on blasts are listed in the appendix for further investigation.

Most models of earthquake sources are derived from radiated seismic waves. The process by which an earthquake occurs is usually described by strain accumulation and release in a narrow zone along a fault plane (Dahlman and Israelson, 1977). Since an active fault plane rarely breaks the surface of the earth, as is the case in Oklahoma, the geometry and dynamics of a fault plane are seldom known. Often the earthquakes occur along preexisting fault planes, or zones of weakness, of which Oklahoma has many.

Models of energy radiation for earthquakes usually have four quadrants of alternating compressional and dilatational initial P motion (Dahlman and Israelson, 1977). The polarity of the shear waves alternates in a similar way. This radiation pattern is in sharp contrast with that of the simpler explosion.

Amplitude spectrum studies (Aki, 1972, e.g.) have shown that an increase in the dimension of an earthquake leads to an increased amplitude at zero frequency and to a lower corner frequency above which amplitude drops off rapidly. This means that small magnitude earthquakes such as those that occur in Oklahoma radiate more energy at high frequencies than larger events.

A further distinguishing feature of earthquakes is that they have a larger temporal dimension than explosions, which should be more pulse-like(Dahlman and Israelson, 1977). If earthquakes occur due to movement along a fault the time it takes for the movement is apparently longer than the time it takes for an explosion to occur. This observation is more a result of empirical observation from seismograms than anything else. Aki and Chouet (1972) have suggested that the differences in coda length may arise as a result of differences in source spectra only.

Simple Discriminants

As was mentioned in the introduction, there are some simple ways to distinguish most earthquakes from other short period events. Tryggvason (1964) used a combination of the hour of occurrence, the apparent frequency of body waves, and the amplitude ratio of Pg and Sg waves to positively identify ten events as natural earthquakes. Richard Simons (1977) in a study of the seismicity of San Diego employed proximity of the event to known active quarries, signal characteristics at two recording stations, PLM and RVR, time of day, and presence of aftershocks to distinguish earthquakes from other events. The hour of occurrence is significant because blasts tend to be detonated at those times that are safest and most convenient. This means that most blasting occurs during the lunch hour at the site, or, more commonly, in the late afternoon shortly after all operations have been shut down for the day. Early morning detonations seem to prompt a large number of enquiries from nearby residents. Thus an event occurring outside the normal working hours in an area is probably an earthquake.

Simons found that the ratio of peak S-wave amplitude to P-wave amplitude always exceeds 2 and is generally 3 or more. Earthquakes, on the other hand, have a ratio that never exceeds 2 and is generally 1 or less. (Note: The way this relation is expressed above is the converse of the way it is listed in Simons' paper. A mistake was probably made, as is borne out by the accompanying figure, Figure 10, in the paper.)

Simons also used the presence of a long-period (about 0.8-1.0

sec.) ground roll following the S phase to distinguish blasts from earthquakes. The ground roll is a trapped Rayleigh mode in the low-velocity surface layers which doesn't usually appear for the relatively deeper earthquakes.

In addition to these above criteria it would seem that the day of the week might help classify some events, as little to no blasting is done on weekends. This would of course be limited in scope to those few events which occur on a weekend, and does not supply a discriminant with much flexibility.

Personal observation has shown that some of these simple discriminating criteria are indeed useful. Most local earthquakes recorded on the short period seismographs at TUL have relatively short periods in the range 0.1-0.4 sec. for both Pg and Sg phases. Most also seem to have a Pg to Sg maximum amplitude ratio of about one, and usually have well developed phase separation and good agreement on arrival times of the phases on the different seismograms.

There is no apparent dispersion in the wave pattern of the earthquakes, as opposed to the usual normally dispersed surface waves from a blast, in which the lower frequency signal travels faster and arrives before the higher frequency signal. However, in studying the earthquakes for the year 1976 it was found that some of the earthquakes deviate from this normal pattern. It thus seems reasonable that a more potent discriminational method should be developed that quantitatively combines several measurable characteristics of short period events.

Graphical Approach

A crude attempt at discrimination of local earthquakes from other short period events can be made by making x-y plots of two of the variables measured. The idea behind this is that a combination of variables expressed in such a graphical manner would allow visual discrimination by a simple geometric separation of groups of symbols representing the two types of events. The advantages of such a method are that many such plots can be made using a computer and visual inspection of the plots quickly assesses the validity of any proposed discriminant. The major drawbacks to this method are that it is limited to two dimensional comparisons and combinations and that the evaluation of a discriminant cannot be made quantitatively.

Quantitative Discriminants

A literature search on seismic discriminants showed that most techniques that have been developed are for distinguishing earthquakes from nuclear blasts. As the source characteristics and recorded character of both of these types of events are very much different from those studied in this paper, parallel logic and direct application of any of these methods was not possible. It is interesting and instructive to note, though, what methods have been applied by others.

Booker and Mitronovas (1964) used Anderson's statistical method for discrimination of blasts, collapses, and earthquakes using nine parameters computed from the ratios of integrals of the squared amplitude for vertical, radial, and tangential components for different velocity windows. Each of the ratios is a measure of the relative energy in a pair of the velocity windows. Their method involves the use of digital recording equipment, as do most of the other discriminants in the literature. Booker and Mitronovas approach the discrimination problem statistically, making significance tests on the means of the earthquake and blast groups. Discrimination was achieved by multivariate discriminant analysis, the method chosen for use in this paper. Booker and Mitronovas achieved about 85% probability of correctly classifying a given event either as an explosion or an earthquake.

Other discriminants that have been developed for nuclear explosions and earthquakes involve spectral analysis. Bakun and Johnson (1970) use the fact that explosion spectra are relatively richer in the high frequency band (1.35-2.0 Hz) than are the natural earthquake spectra. Evernden (1977) has developed an impressive discriminant based on use of the full spectral bandwidth of the P coda from 0.4 to 9 Hz that successfully distinguishes between all Eurasian explosions and shallow-focus earthquakes studied.

Some other discriminants are listed by Dahlman and Israelson (1977). One is the polarity of initial motion, in which all initial motions from an explosion should be compressive, regardless of azimuth. Another is the corner frequency, which uses the fact that the corner frequency above which amplitude rapidly drops is theoretically higher for explosions than for earthquakes having the same amplitude at zero frequency. The fact that explosions generally generate less shear-wave energy than earthquakes has been tried as a discriminant too, but little has been done with this method as it is difficult to detect S waves from weak seismic events.

The discriminational technique that has received the most success and attention in nuclear explosion work is that based on the $m_b(M_s)$ ratio. This method has been hampered in applicability by a lower limit around $m_b = 4.4$ and the fact that the m_b and M_s magnitudes cannot be calculated at a distance less than 20° central angle by their definition. The $m_b(M_s)$ discriminant is therefore not useful in a study of small magnitude earthquakes of the sort that occur in Oklahoma.

Multivariate Discriminant Analysis

Multivariate discriminant analysis is a distinguishing method that is mainly used by researchers in the social and biological sciences. The method's main feature is that it reduces multiple variable measurements to a single weighted composite. The multivariate problem is thus reduced to a simpler univariate problem, and classification of an event into a group depends on the single weighted value. Under appropriate conditions, the new composite score can be assumed to have a normal distribution with estimable mean and variance for each group. Probability tables for the unit-normal (z) distribution can thus be used to determine probabilities of misclassification and the likelihood with which an individual event belongs to each group. Using samples from a population and reducing the measurements made on each individual event to a single value, it is possible to determine a critical value, or cutting point, which will minimize errors of misclassification or which will yield known, but unequal probabilities of error within the two groups. Under appropriate assumptions, tests of significance of multivariate mean differences such as the F test can be used to analyze discriminant analysis results.

One of the clearest expositions on multivariate discriminant analysis and one which gives several good examples is given by Overall and Klett (1972). Their methods are the ones mainly used in this paper for such things as the evaluation of a proper cutting value, determination of the probability of properly classifying an event, and testing for a significant difference in the means of two groups. Other statistical sources used are Koch and Link (1971), Eisenbeis and Avery (1972), McCammon (1969), Spiegel (1975), and Lachenbruch (1975).

The solution to a discriminant analysis problem involves determining the weights to be given to each of the k variable measurements made on an event in order that the resulting composite value has maximum utility in distinguishing between members of groups. The method is applicable to any number of groups, but the scope of this explanation of the theory will be limited to the case where only two groups are under consideration.

If it is assumed that there exists some unknown set of linear weighting coefficients which will define a composite value providing maximum discrimination between two groups, the desired discriminant function will have the form

$$y = a_1x_1 + a_2x_2 + \dots + a_kx_k$$

where $a_1, a_2, \dots, a_k$ are the weighting coefficients to be applied to the k measured variables $x_i (i = 1,2,\dots,k)$ for each event. The problem is to derive optimal values for the weighting coefficients such that the difference between scores for the two groups will be maximized relative to the variation within groups. This is equivalent to saying that weighting coefficients are to be derived such that the t statistic or F ratio between groups will be maximum. The function to be maximized is the ratio of the between-groups variance to the within-groups variance. The between groups variance can be defined as the square of the sum of the weighted differences in arithmetic means of the k variables for the two groups:

$$s\ (\text{between groups}) = \frac{n_1 n_2}{n_1+n_2}\ (a_1 d_1 + a_2 d_2 + \ldots + a_k d_k)^2$$

where s (between groups) is the between groups variance and the d_1, d_2, ...d_k are the mean differences for the k variables for the two groups.

The within-groups variance is commonly computed using variance-covariance values, which are usually listed as matrix coefficients in a covariance matrix. Covariance, which is also sometimes referred to as dispersion, is a measure of the scatter of values about their means. The elements c_{ij} in a within-groups covariance k x k matrix C can be computed in several equivalent ways, two of which are:

1) $$c_{ij} = \frac{1}{n_1+n_2-g} \sum^{g} \sum^{n_g} (x_i-\bar{x}_i)(x_j-\bar{x}_j)$$ (Eisenbeis and Avery, 1972)

2) $$c_{ij} = \frac{1}{n_1+n_2-g} \sum^{g} \left(\sum^{n_g} x_i x_j - \frac{\sum^{n_g} x_i \sum^{n_g} x_j}{n}\right)$$ (Overall and Kleh, 1972)

where i and j are variable designations for each of the k variables, g is the group number, and n_g is the number in the group for which the covariance value is being computed.

The ratio of the between-groups variance to the within-groups variance is then

$$f(a_1, a_2, \ldots, a_k) = \frac{n_1 n_2}{n_1+n_2} \frac{(a_1 d_1 + a_2 d_2 + \ldots + a_k d_k)^2}{\sum^{i} \sum^{j} c_{ij} a_i a_j}$$

This function is not used in calculation, but defines the criterion function that is maximized when one computes optimal values for the unknown weighting coefficients.

The general form of the solution is obtained by applying calculus to the function and maximizing with regard to the $a_i (i = 1,2,\ldots,k)$. This yields a set of k equations with k unknowns that can be solved simultaneously to obtain values for the a_i. The equations obtained are:

$$a_1c_{11} + a_2c_{12} + \ldots + a_kc_{1k} = d_1$$

$$a_1c_{21} + a_2c_{22} + \ldots + a_kc_{2k} = d_2$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

$$a_1c_{k1} + a_2c_{k2} + \ldots + a_kc_{kk} = d_k$$

where the c_{ij} are elements of the within-groups variance-covariance matrix among the k variables.

In this solution it is assumed that the variances and covariances of the two groups are the same. This means that the earthquake data and other short period data in this study whould be scattered about their means in a similar manner. Linear weights have been derived for the case where no restrictions on the covariance with respect to equality is made (Anderson and Bahadur, 1962). These weights have so far been tested for only a few cases, but have not resulted in any significant improvement (Ericsson, 1973).

The number of observations in the samples must be appreciably larger than the number cf dimensions of the discriminant. Otherwise one might easily overestimate the capability of the discriminant (Sammon et al, 1970).

Once the weighting coefficients a_i have been determined, the mean value of the discriminant function for a group can be obtained by applying the weighting coefficients to the means scores for the group on the k variables:

$$\bar{y}(1) = a_1\bar{x}_1(1) + a_2\bar{x}_2(1) + \ldots + a_k\bar{x}_k(1)$$

$$\bar{y}(2) = a_1\bar{x}_1(1) + a_2\bar{x}_2(2) + \ldots + a_k\bar{x}_k(2)$$

where the number in parentheses represent the two groups.

The variance V(y) of the discriminant function within each group, which is assumed to be identical as a result of the preliminary assumption of equal variance-covariance matrices for the two groups, is given by

$$V(y) = \bar{y}(1) - \bar{y}(2).$$

If it is further assumed that the original x_i have a multivariate normal distribution within groups, then it is possible to consider the discriminant function variate as having a normal distribution within groups, with mean values $\bar{y}(1)$ and $\bar{y}(2)$ and that the deviation of an individual discriminant score from each of the group means can be regarded as a unit-normal deviate or z score

$$z_y = \frac{y-\bar{y}(i)}{\sqrt{V(y)}} .$$

If a critical or cutting value y_c is determined, the proportion of misclassifications can be found by converting y_c to a z score as above for both of the two group mean weighted values.

Let y_c be a particular value of the discrimination function falling between the two group means $\bar{y}(1)$ and $\bar{y}(2)$ as shown in Figure 1. If every individual event having a discriminant function value less than y_c were classified into group one, the proportion of events actually belonging to group two that would be misclassified by being assigned to group one would be represented by the shaded area under the curve left of y_c. To determine this proportion, y_c is transformed to z-score form by

$$z_y = \frac{y_c-\bar{y}(2)}{\sqrt{V(y)}}$$

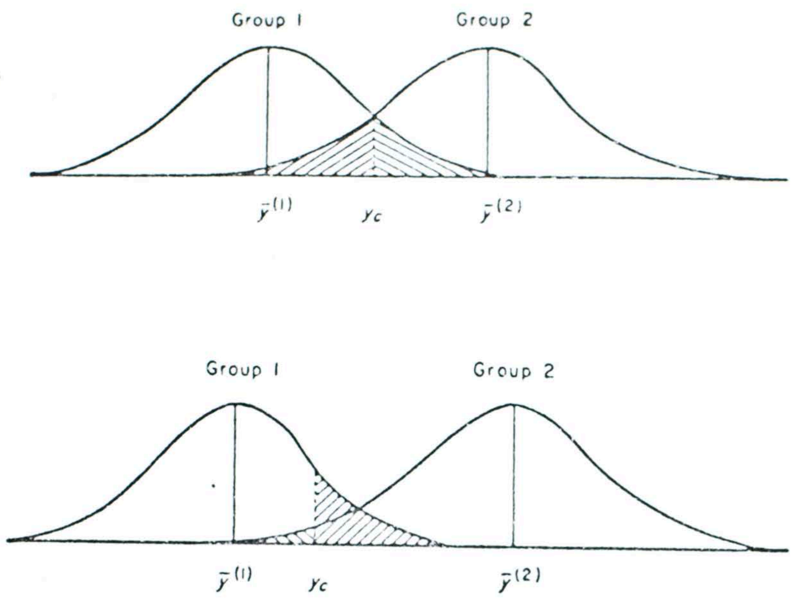


Figure 1. Schematic diagram of distribution of discriminant function scores in two groups showing errors of misclassification. (from Overall and Klett, 1972)

The area in the smaller portion of the unit-normal curve corresponding to z_y can be referenced in a z-score table found in most statistic books. The value of the smaller area provides an estimate of the proportion of events from group two that would be incorrectly classified as belonging to group one. If $p_e(2)$ represents the probability of misclassification for events in group two, then the probability of correctly classifying an event from group two by using y_c as a cutting point will be $1-p_e(2)$, or the area in the larger portion of the curve corresponding to z_y. The value of the area in the larger portion of the curve is also usually listed in z-score tables.

In a similar manner the probability of misclassifying an event from group one using the cutting value y_c can be calculated by using a new z_y

$$z_y = \frac{y_c - \bar{y}(1)}{\sqrt{V(y)}}$$

The probability of misclassifying an event from group one using y_c as a cutting value is the shaded area under the curve to the right of y_c, which can be found in the z-score tables. If this probability of misclassification is called $p_e(1)$, the probability of correctly classifying an event is equal to the area under the larger portion of the curve, or $1-p_e(1)$.

It is possible to mathematically calculate cutting points which are optimal in one sense or another. For practical purposes, y_c can often be determined by a trial and error method by which the probability of misclassification should be minimized. Further, the relative number of individuals expected to belong to the two populations studied may also be an important consideration, since the actual numbers of individuals misclassified will be equal to the probabilities of misclassification times the relative numbers in the two populations. Such considerations tend to be highly subjective, so that an estimate of the proportions correctly and incorrectly classified from each group should be available for any particular cutting point chosen by an investigator. Unless the samples are quite large, it is also unnecessary to attempt to place cutting points so as to absolutely minimize errors of classification in the particular samples, because this involves too much emphasis on a few extreme cases.

In view of the above discussion, the cutting point for earthquakes and other short period events was chosen midway between the two weighted group means $\bar{y}(1)$ and $\bar{y}(2)$. Although the probability that a short period event will not be an earthquake is much larger than that of it being an earthquake, the samples are perhaps too small to attempt affecting y_c with such considerations.

A test for significance of difference in mean discriminant-function scores can be made using the F test. The within groups variance V(y) can be used as what is known as the Mahalanobis D^2, which can be related to the F distribution under the assumption that the several original variable measurements have a multivariate normal distribution within the populations from which samples were drawn and that the variance-covariance matrices are equal for the two populations. These assumptions are multivariate generalizations of the usual parametric assumptions of normality and homogeneity of variance in the univariate analysis of variance. Given these assumptions,

$$F = \frac{n_1 n_2 (n_1+n_2-k-1)}{k(n_1+n_2)(n_1+n_2-2)} D^2$$

where $D^2 = V(y)$, n_1 and n_2 are sample sizes of the two groups, and k is the number of variables entering into the discriminant function. The statistic F is given in tables of the F distribution with k and n_1+n_2-k-1 degrees of freedom. The F distribution is usually listed at confidence levels of .95 and .99, the latter having a lower F score value. The F statistic is used by calculating the F score as above, finding the critical F value for the appropriate degrees of freedom and level of confidence, and seeing if the calculated F score is larger than or less than the critical value. If the calculated F score exceeds the critical score, the two means are not significantly different.

Another statistical measure that is useful is the sample correlation coefficient r. The correlation coefficient can be defined as

$$r = \frac{\overline{xy} - \bar{x}\,\bar{y}}{\sqrt{(\overline{x^2}-\bar{x}^2)(\overline{y^2}-\bar{y}^2)}}$$

The correlation coefficient measures how well a linear correlation fits two variables x and y. The maximum value for r is 1 for perfect correlation, and is 0 for no correlation whatsoever, or random scattering.

CHAPTER IV

Method

Outline

The basic method used in this study was to measure eighteen variables on several samples from the populations of earthquakes and other short period events. The eighteen variables, Pg period, Sg period, Pg amplitude, Sg amplitude, duration, and coda length measured on the three seismographs SPZ, SPE, and SPN, were reduced to fifteen by the computation of the Pg to Sg maximum amplitude ratio, and later increased back to eighteen by the computation of Pg to Sg amplitude ratio, coda length, and duration for SPH, a horizontal vector summed component of the individual horizontal variables calculated by the square root of the sum of squares of the variable values on SPE and SPN. The variables for SPE and SPN were kept for the possibility that direction might be an important component of discrimination, and SPH was used for the possibility that a non-directional variable might be better.

Duration and coda length were measured using the position at which the event signal last dropped below twice the average noise level determined within two minutes before the first arrival. These measurements are perhaps subjective as it has to be decided by the measurer if the position being measured is actually part of the event being measured or if it is a high amplitude random or unrelated signal. Coda length was measured after the arrival of the Sg phase; duration was measured after the first arrival of any P phase.

The P and S amplitude measurements were restricted to the Pg and Sg phases, as these are the only phases to be found on most of the short period events that are not earthquakes. Although the designated Pg and Sg phases have not traveled in or been refracted from the granitic crust, this term was used to signify travel in all layers above the Mohorovicic Discontinuity. The amplitude measured was the maximum peak-to-trough amplitude for both the P and S phases. Possible error in this measurement results from long period noise present on some days.

The period measured for the P and S phases is the one that seems dominant. Of course the dominant period can only be accurately determined from a Fourier spectrum analysis, but the periods measured should reflect the actual value. In the case where a dispersed wave was present, the average period was used.

Due to the proximity of many of the short period events and the usually small amplitude of the S phase for the short period events that were not in the earthquake group, the maximum S amplitude measured was usually actually the amplitude of the surface waves. Period measurements on the S phase were done in a similar manner.

It may at first seem that in making a vector sum of the horizontal seismograph measurements for coda length and duration that only time is being summed and that this sum has no physical meaning. These vector sums were done with the thoughts that the measurements of coda length and duration were made using amplitude criteria and the north-south and east-west seismographs measure only orthogonal parts of the total horizontal amplitude that would be measured on a theoretical seismograph with its seismometer oriented in the direction of maximum amplitude, that is, either in line with the horizontal direction line to an event for compressional waves or perpendicular to such a line for shear waves. If random noise is assumed, the noise measured on this theoretical horizontal seismometer would have the same average amplitude as the noise on the individual north-south and east-west seismometers. Signal amplitudes from the north-south and east-west seismograms should add vectorally to the value on the theoretical seismogram. Thus, although the units being added in the vector-sum are time units, the concept of coda length and duration being functions of the amplitude give the summation some physical basis.

The SPZ, SPE, and SPN seismographs all use 15 kg. Benioff seismometers with a natural period of 1.0 seconds. Their galvos have a natural period of 0.75 seconds. The seismograms are made on 60 mm./sec. photo paper. Magnification is 100,000 at 1.0 seconds, and 160,000 at 0.6 seconds, as is seen in Figure 2. Only the magnification curve for SPZ is shown, but the responses of SPN and SPE are very similar. The high pass characteristics of the seismometer and the low pass characteristics of the galvanometer filter the signal so that the response of the short period seismographs emphasize teleseisms, meaning the pass band for the seismographs is mainly for 1-3 Hz signals.

The data for the earthquakes and other events is listed in Appendix A. Although the arrival times for all discernible phases were recorded on the original data sheets, space limitations do not permit listing of all data. The times that are listed will permit location of the event being measured on the TUL records.

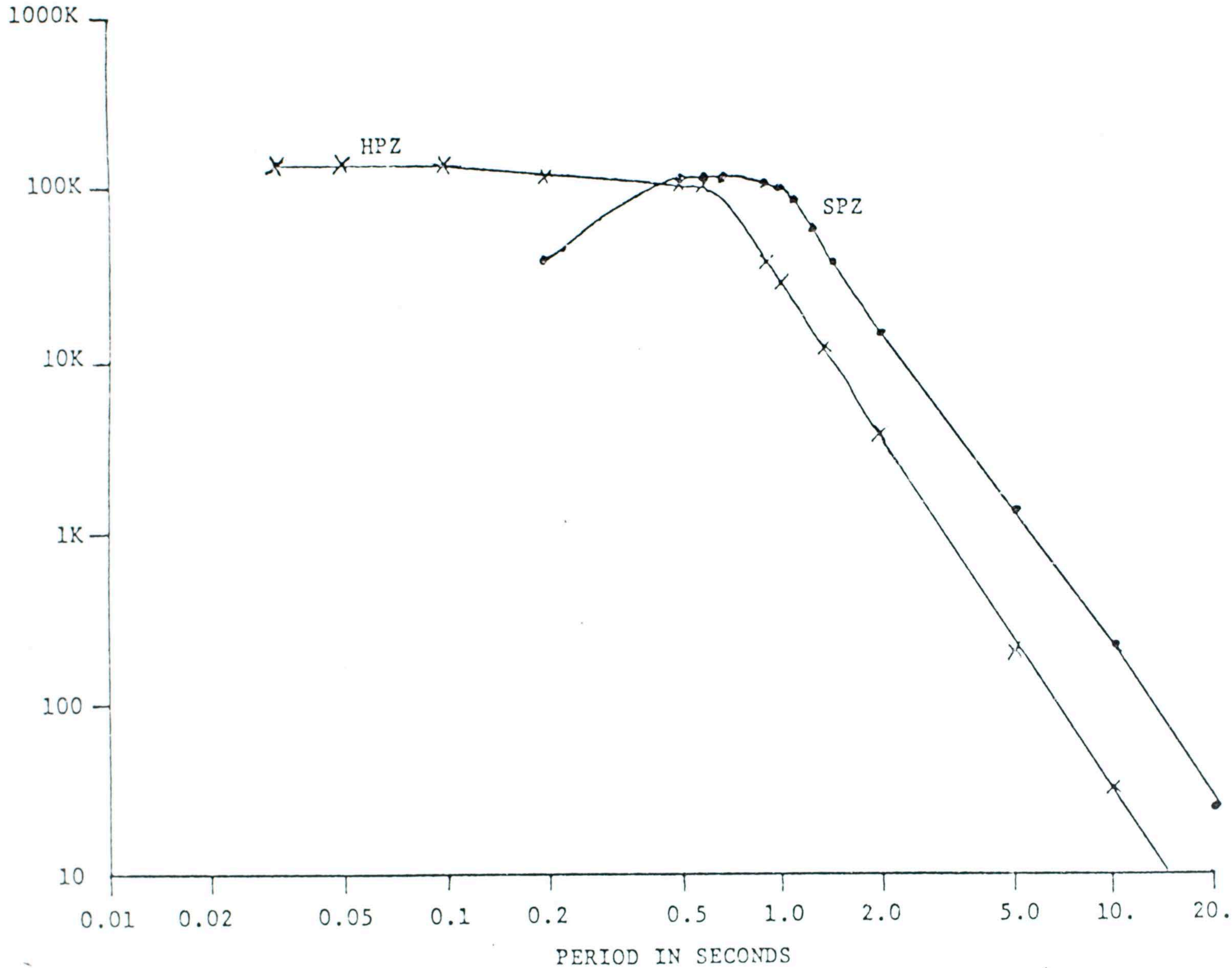


Figure 2. Displacement magnification of the University of Oklahoma Earth Sciences Observatory (TUL) short period vertical (SPZ) and high-pass vertical (HPZ) seismographs.(from Lawson and DuBois, 1975)

After data had been gathered, it was recorded on magnetic tape for use with a Hewlett-Packard 9825A desktop computer, so that efficient and repeated access of the data would be possible. Initial work with the data involved plotting one variable versus another using a computer controlled plotter in an attempt to derive some sort of bivariate discriminant. The results of this attempt were not totally satisfactory, but some interesting data features were observed which will be discussed in the Results section.

A tailored program was written for this study utilizing the Hewlett-Packard 9825A. After the multivariate discriminant program was developed, various discriminants were derived as is discussed in the Results section. Other secondary features, such as correlation coefficients for different variables, were also derived, as is also discussed in the Results section. All computer programs used in this study are listed in Appendix B.

Other factors involved in performing this study are the method by which the earthquakes studied were originally determined, the method of selection of other short period events measured, and the problems encountered in data measurement. A description of these factors follows.

Determination of Earthquakes

Identification of the 1976 local earthquakes in Oklahoma used in this study was done by Dr. Jim Lawson. An elaboration of his methods follows, and was given in a personal communication. It is assumed throughout this study that these events are true natural earthquakes.

Identification of the earthquakes in Oklahoma occurring in 1976 that were used in this study was done mainly by their appearance on the

HPZ seismograms. The HPZ, or high pass vertical, seismograph is run from a similar seismometer as the one for SPZ, but records at 90 mm./sec. by a visible heatwriting method. Magnification is 35,600 at 1.0 sec., and 250,600 at 0.33 sec. as is seen on Figure 2.

The signals recorded by HPZ emphasize the short period differences between blasts and earthquakes. The amplitudes of shorter periods are increased by about an order of magnitude. Earthquake codas are much longer due to their frequency content. On HPZ, the amplitude of a 5 Hz signal is about 5-6 times as large as that of a 1 Hz signal. The ratio of a 5 Hz signal to a 1 Hz signal on the regular short period seismographs is only about 2. Felt earthquakes have exhibited all these characteristics.

A very short period vertical (VSPZ) seismograph started operation at TUL in February, 1976. This is a narrow pass band seismograph centered at about 16 Hz. If the phases of an event are very clear on VSPZ, the event is probably an earthquake. Comparison of the results using VSPZ with concurrent HPZ seismograms indicates that the reliability of former designation of earthquakes using HPZ only is high.

Other subsidiary methods for a few of the earthquake identifications have been used also. One is that the epicenters of earthquakes, when they can be located, do not occur near quarries. Two of the earthquakes in 1976 were not used in the study as they appeared too small on the seismogram to be accurately measured. These earthquakes were known only from felt reports from reliable sources. This suggests that some earthquakes in Oklahoma may go unnoticed as they are too small to appear on the seismograms and occur in sparsely populated areas. The average frequency of earthquakes in Oklahoma may thus be substantially larger than the round figure of 30 that is suggested by 1976 earthquake figures.

Selection of Other Short Period Events

Short period events other than earthquakes, referred to in this study as random events, pseudo-random events, and other events, were selected in a pseudo-random fashion. Random hour numbers between 0 and 23 (inclusive) were generated using a Hewlett-Packard 9825A desktop computer pseudo-random number generator function. The program works using a "seed" upon which the random number generation begins. Seven sets of random numbers to be used for hours in a day were made using seed numbers of 623, 4893, 21, 53, 5376, 453, and 108.

Pseudo-random numbers from 1 to 12 were also generated for month selection. The seed number was 253.

The pseudo-random hours were used on 30 consecutive days in a pseudo-random month. The first event having measurable parameters occurring after the random hour was used for data. If no event occurred within the day after the designated hour, no data was taken for that day. If an event appeared measurable on one of the short period seismograms, the event was searched out and measured when possible on the other seismograms.

It was decided that the data from two months would be sufficient for study. As the first two random month numbers generated were 9 and 5, the months of September and May were used. In addition, six events of interest were used in the list of short period events other than earthquakes; these events are called additional events elsewhere in this paper.

Examples and Problems in Data Measurement

Some of the 1976 earthquakes measured were clearly identifiable as earthquakes due to high frequency content, shape of signal, and separation of phases. An example of this type of event is the earthquake occurring on December 19, 1976. The SPE record of this event appears in Figure 3. Even though there is high amplitude low frequency noise present on this day, the high frequency signal clearly shows this event to be an earthquake. The HPZ record of this event as recorded at TUL is shown in Figure 4. The low frequency noise is filtered out on this seismogram, and the event is even more clearly identifiable as an earthquake. Note the long coda length and duration of this event on HPZ.

Another example of a good earthquake is shown in Figure 5. This earthquake occurred on March 16, 1976 in McIntosh County, Oklahoma at an origin time of 07:39:45.3 UTC (Lawson et al, 1977). Again, note the high frequency content and clear separation of phases. Also typical of earthquakes is the shape of the Pg and Sg coda, which appear to have an inverse exponential decay. (See also Herrmann, 1975)

One earthquake which showed anomalous variable measurements was the one occurring on March 30, 1976, whose SPZ record is shown in Figure 6. Note the low, irregular frequencies and irregular shape of the signal. This event occurred quite a distance away from TUL, but the labelling of this event as an earthquake is substantiated by felt reports.

The record shown in Figure 7 is one of the pseudo-random events, this one occurring on September 6, 1976, during low noise conditions. This event clearly shows the typical appearance of surface waves and their normal dispersion. The Pg wave has a low amplitude compared to the larger surface wave amplitude, resulting in a low P/S amplitude ratio.

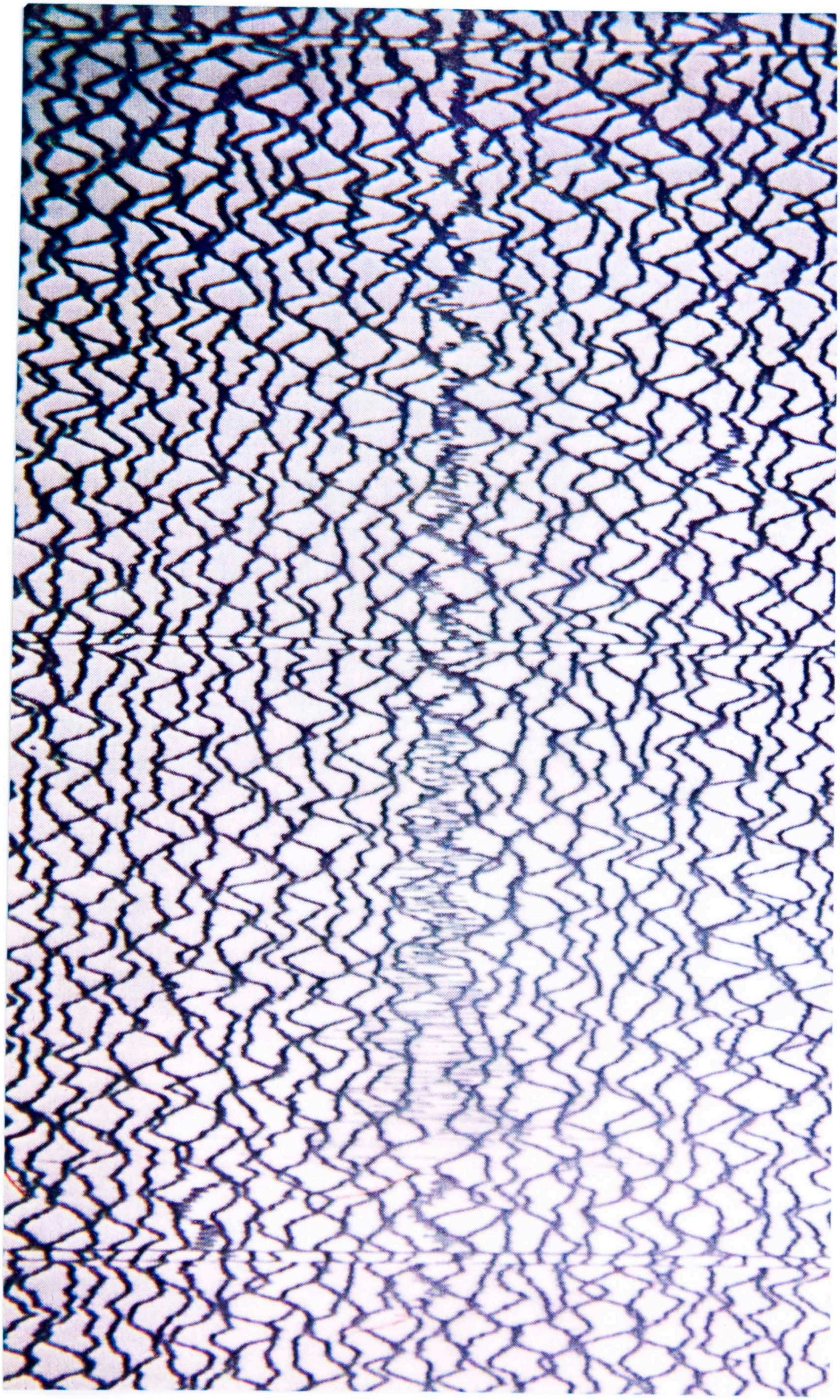


Figure 3. SPE seismogram recorded at TUL of earthquake occurring on Dec. 19, 1976. Origin time 08:26:36.7 UTC.

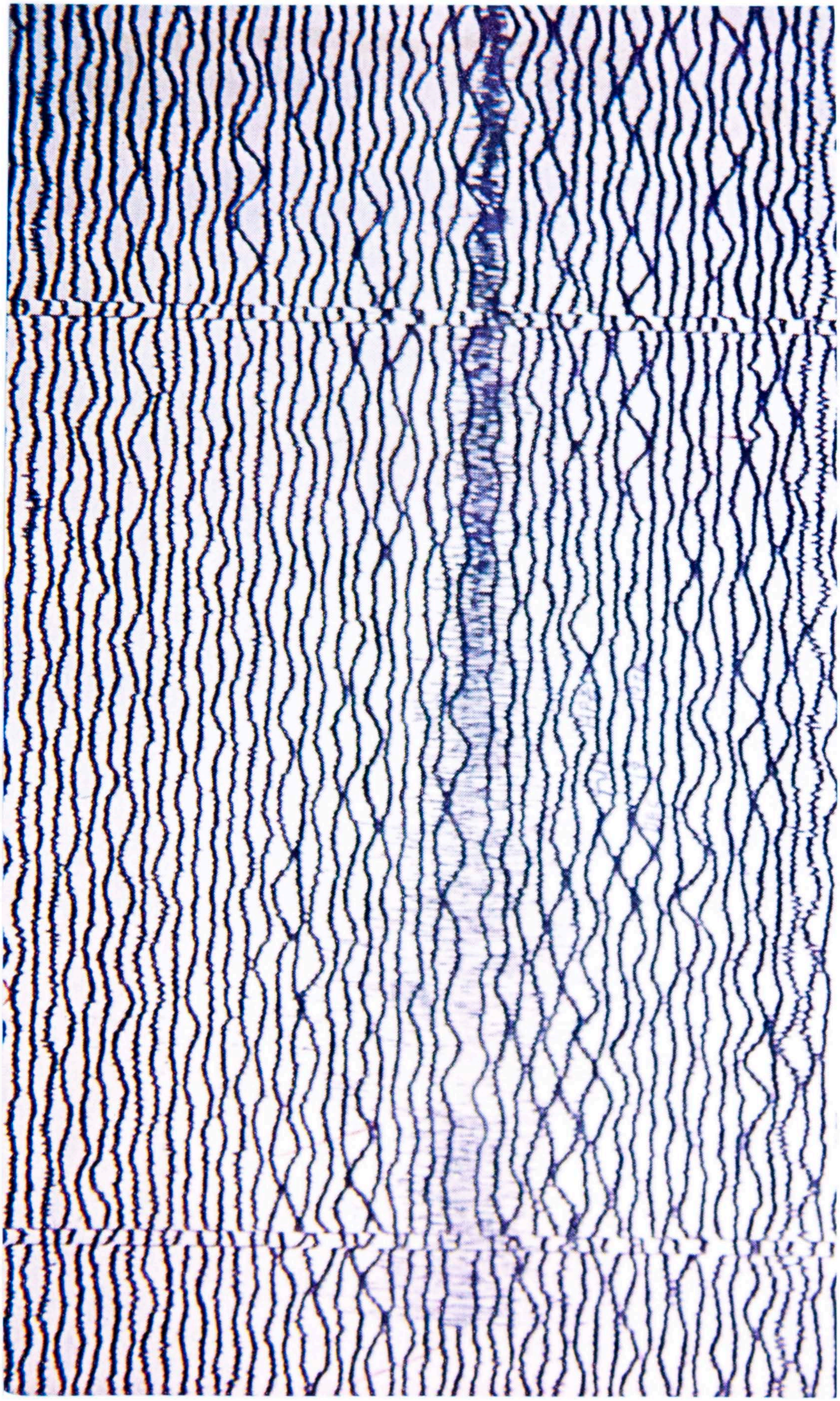


Figure 4. HPZ seismogram recorded at TUL of earthquake occurring on Dec. 19, 1976. Origin time 08:26:36.7 UTC.

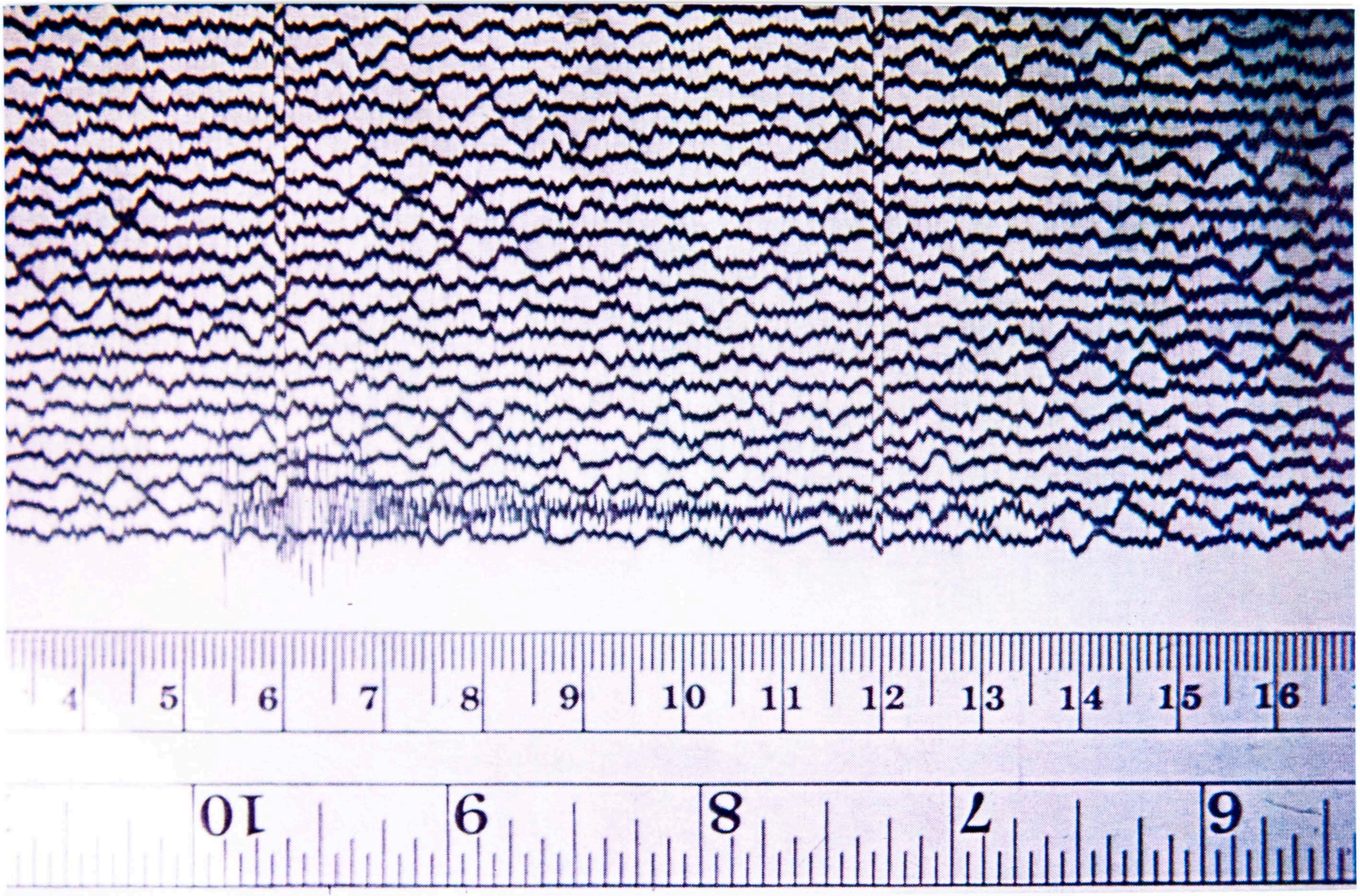


Figure 5. SPZ seismogram recorded at TUL of earthquake occurring on March 16, 1976. Origin time 07:39:54.2 UTC.

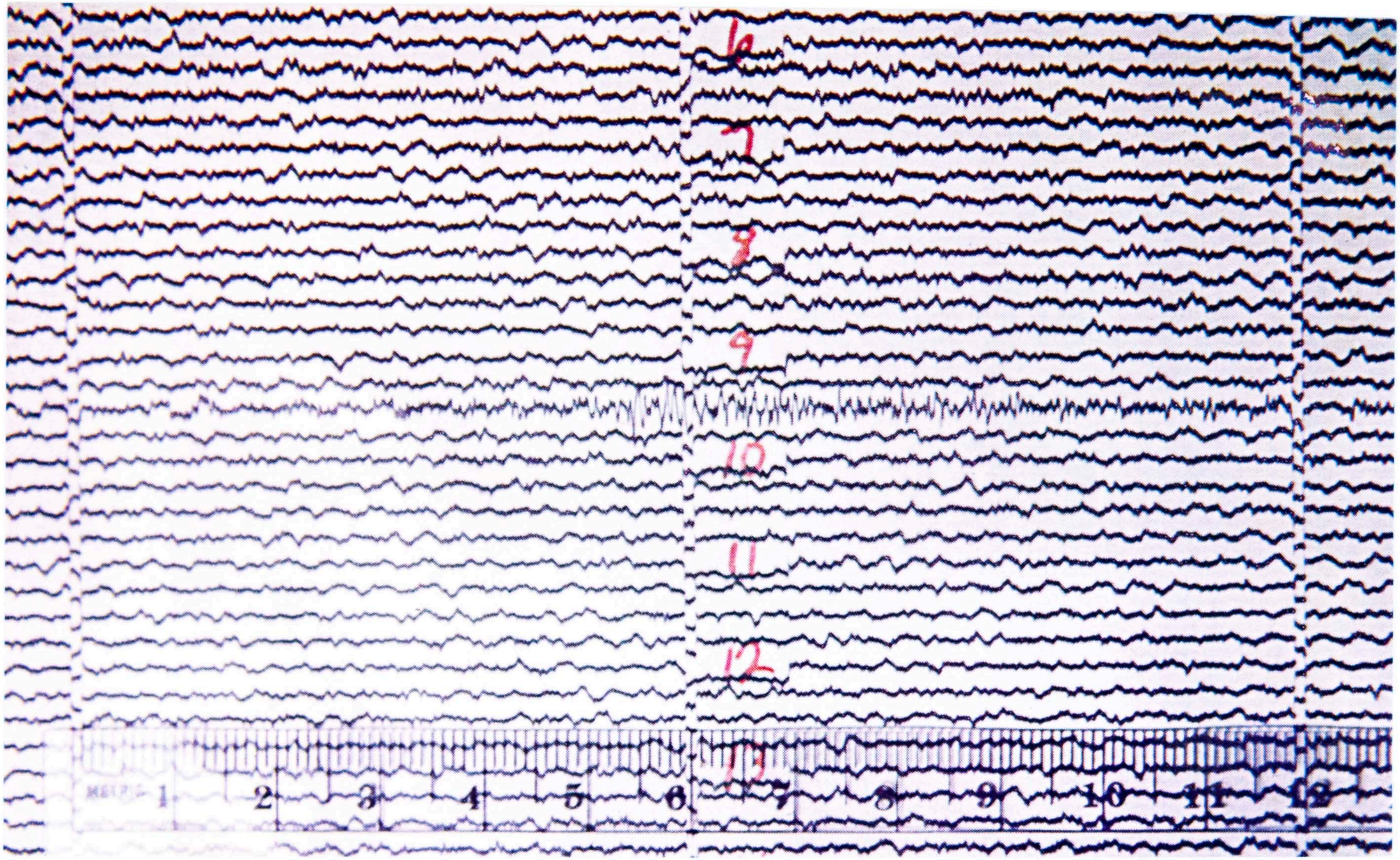


Figure 6. SPZ seismogram recorded at TUL of earthquake occurring on March 30, 1976. Origin time 09:27:02.0 UTC.

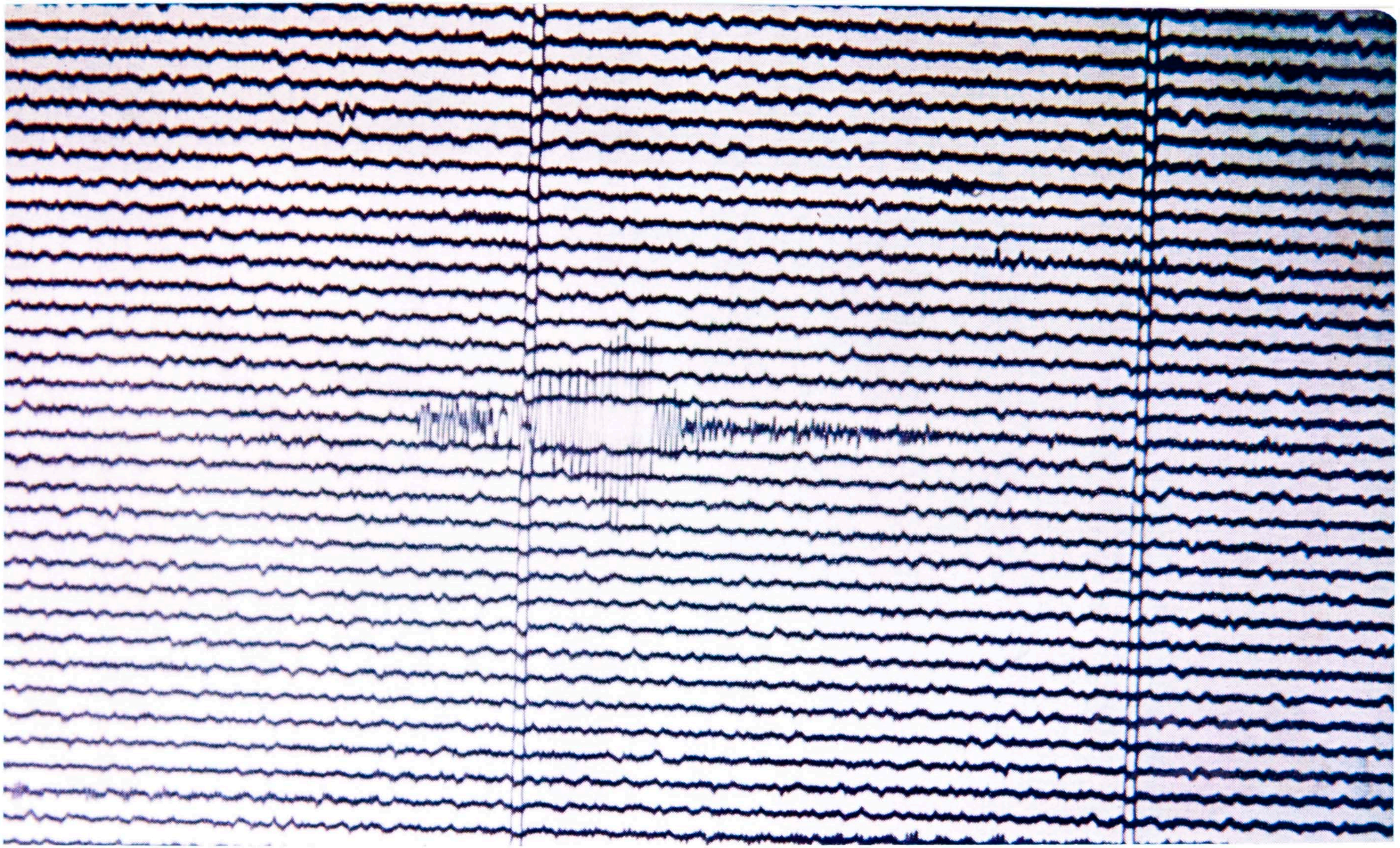


Figure 7. SPE seismogram recorded at TUL of event occurring on Sept. 6, 1976. First arrival at 21:26:39.7 UTC.

Figures 8 and 9 show two different short period seismograms of an event, probably a quarry blast. The SPZ record, shown in Figure 8, also shows high amplitude, normally dispersed surface waves. Note the irregular shape of the signal. Figure 9 shows the SPN record of the same event. The appearance of the surface waves is similar to that in Figure 8, but the shape of the signal is different. A low Pg to Sg amplitude ratio is also apparent from these two figures.

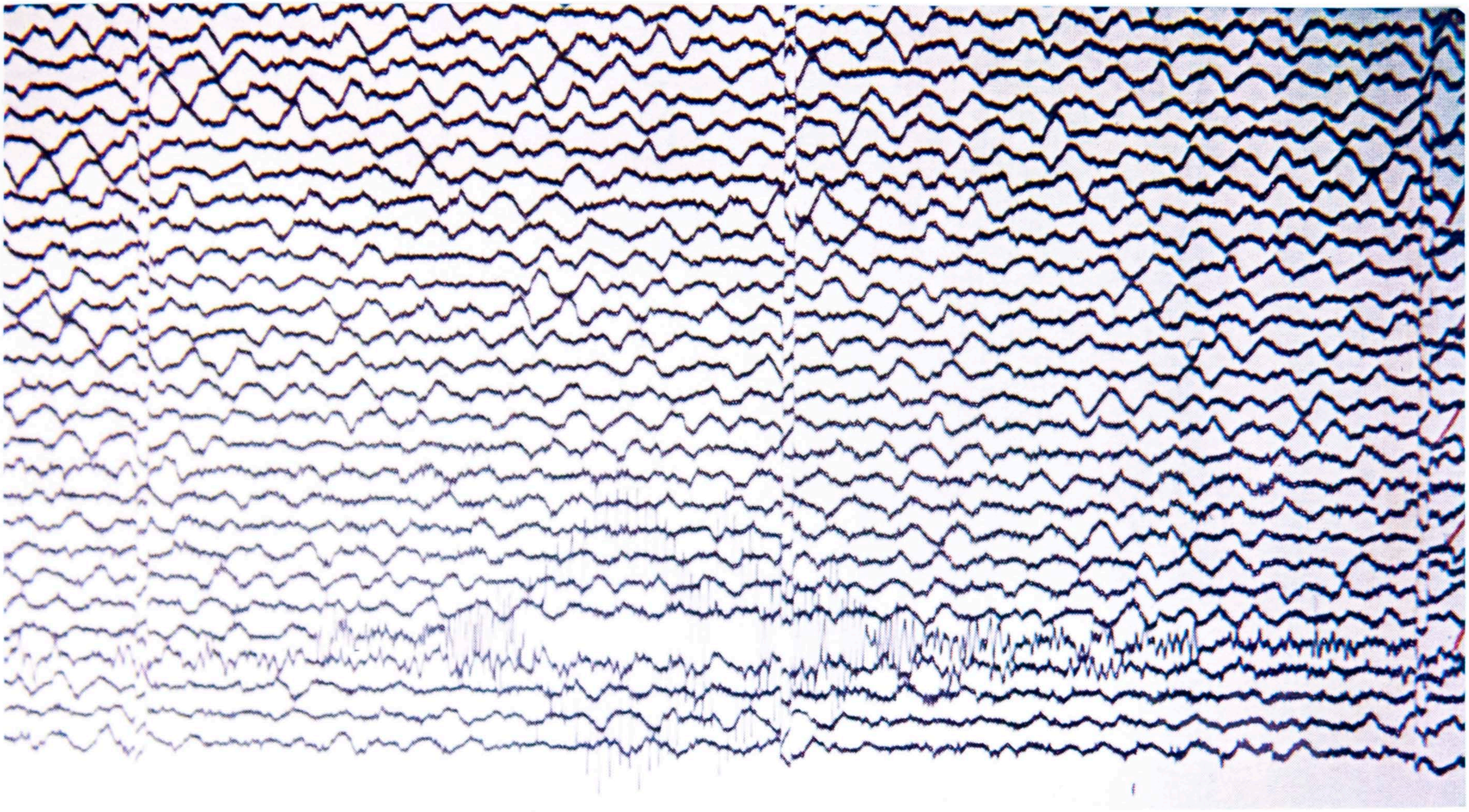


Figure 8. SPZ seismogram recorded at TUL of event occurring on Sept. 25, 1976. First arrival at 13:58:16.6 UTC.

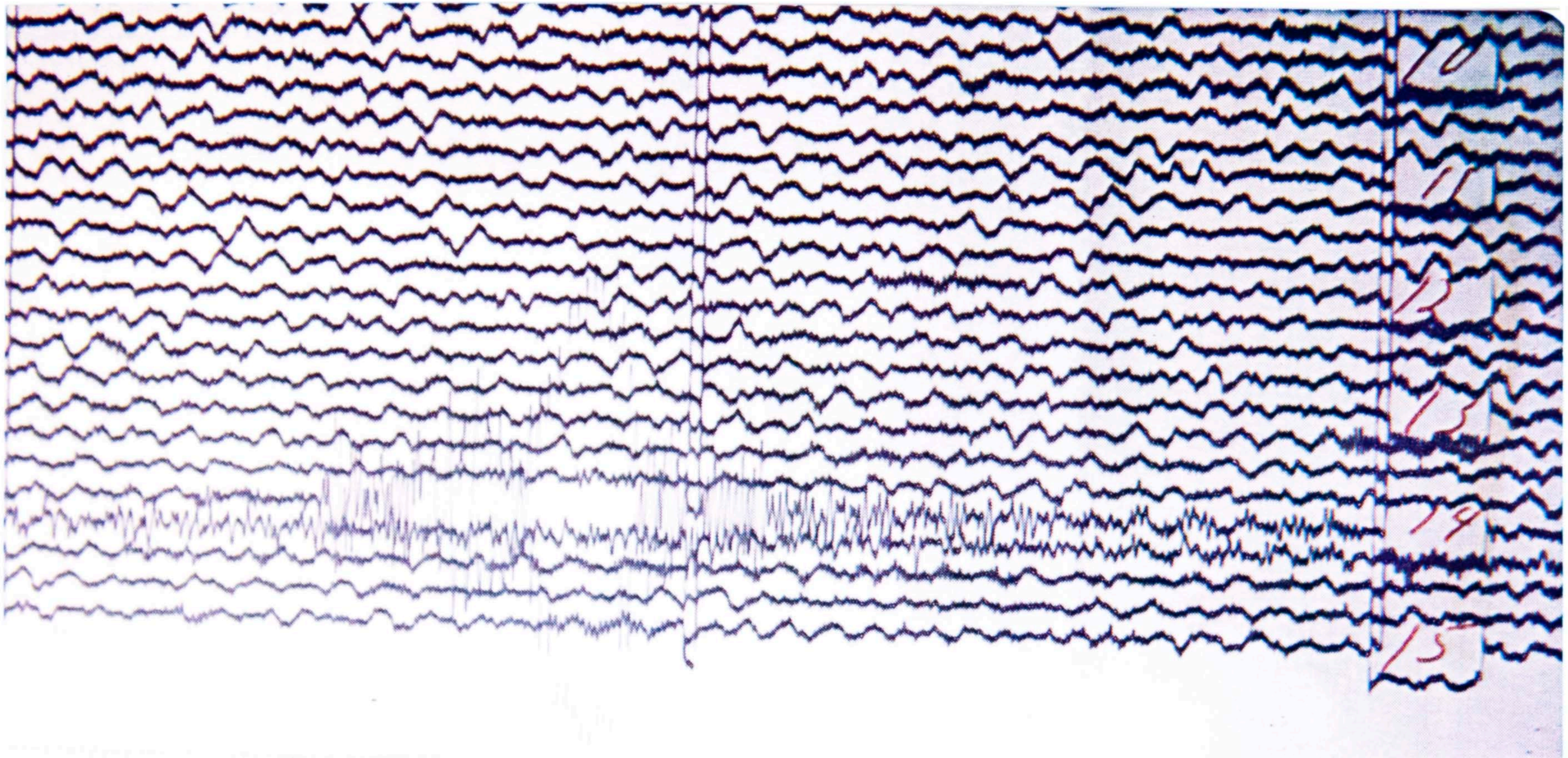


Figure 9. SPE seismogram recorded at TUL of event occurring on Sept. 25, 1976. First arrival at 13:58:17.2 UTC.

CHAPTER V

Results

Discriminants

The computer program used in discriminant function computation was designed such that the function could be calculated with (1) missing variable values replaced by variable group means and (2) events with one or more missing variable values deleted from computations. In either case, the means used in calculations were computed using the maximum number of obersvations possible, since the arithmetic mean approaches the true population mean as the number of samples gets larger.

F scores that will be useful for comparison with computed values are given in Table 1.

Table 1

F Scores Used in Study

F_{k,n_1+n_2-k-1}	95% Confidence	99% Confidence
$F_{1,78}$	3.96	6.97
$F_{2,77}$	3.12	4.89
$F_{3,76}$	2.73	4.06
$F_{4,75}$	2.49	3.58
$F_{5,74}$	2.34	3.27
$F_{6,73}$	2.22	3.06
$F_{9,70}$	2.01	2.67
$F_{10,69}$	1.97	2.59

As a preliminary test for finding which of the eighteen variables under consideration were the best individual discriminants, the discriminant program was run on each variable. The results of this test are shown in Tables 2A and 2B. Based on this test, the rank of the variables as a single discriminant, in descending order of importance, are shown in Table 3.

Table 3

Rank of Single Discriminants

Replaced with means list	Deletions list
1. Ts, SPE	1. Ts, SPE
2. Ts, SPZ	2. Ts, SPZ
3. Ts, SPN	3. Ts, SPN
4. Tp, SPN	4. Tp, SPE
5. Tp, SPE	5. Tp, SPN
6. Tp, SPZ	6. Tp, SPZ
7. Dur., SPN	7. Dur., SPN
8. Dur., SPH	8. Dur., SPH
9. Dur., SPE	9. Dur., SPE
10. P/S, SPZ	10. Coda, SPH
11. Coda, SPH	11. P/S, SPZ
12. Coda, SPE	12. Coda, SPE
13. P/S, SPN	13. P/S, SPN
14. Coda, SPN	14. Coda, SPN
15. P/S, SPH	15. P/S, SPH
16. P/S, SPE	16. P/S, SPE
17. Dur., SPZ	17. Dur., SPZ
18. Coda, SPZ	18. Coda, SPZ

The combination of the top ten variables (ten being the maximum number of variables allowed in the discriminant program by memory limitations) on the replaced with means list gives $z=1.48$ and 13.92. This

TABLE 2A

STATISTICAL RESULTS USING REPLACED WITH MEANS METHOD

	Earthquakes		Other Short Period Events			
Variable	Mean	Standard Deviation	Mean	Standard Deviation	z	F
Tp, SPZ	0.37	0.16	0.59	0.19	0.60	25.44
Tp, SPN	0.29	0.11	0.56	0.18	0.83	49.38
Tp, SPE	0.32	0.14	0.55	0.14	0.81	46.92
Ts, SPZ	0.34	0.20	0.77	0.26	0.90	58.08
Ts, SPN	0.30	0.12	0.64	0.22	0.85	52.21
Ts, SPE	0.29	0.15	0.65	0.20	0.97	67.07
P/S, SPZ	0.61	0.33	0.36	0.21	0.48	16.67
P/S, SPN	0.19	0.17	0.41	0.30	0.41	12.28
P/S, SPE	0.16	0.10	0.34	0.35	0.30	6.60
P/S, SPH	0.18	0.18	0.35	0.27	0.33	7.60
Coda, SPZ	62.8	60.2	49.3	21.6	0.18	2.29
Coda, SPN	83.0	62.0	52.3	23.9	0.39	10.85
Coda, SPE	97.3	76.8	54.8	27.2	0.44	14.04
Coda, SPH	128.2	82.0	76.4	35.2	0.48	16.55
Dur., SPZ	82.9	71.5	57.4	21.9	0.29	6.19
Dur., SPN	105.7	58.6	60.8	25.3	0.58	24.31
Dur., SPE	121.0	85.9	64.0	27.8	0.54	20.98
Dur., SPH	155.1	88.9	89.1	36.5	0.57	23.45

TABLE 2B

STATISTICAL RESULTS USING DELETION METHOD

	Earthquakes		Other Short Period Events			
Variable	Mean	Standard Deviation	Mean	Standard Deviation	z	F
Tp, SPZ	0.37	0.16	0.59	0.20	0.57	23.20
Tp, SPN	0.29	0.12	0.56	0.19	0.77	42.10
Tp, SPE	0.32	0.14	0.55	0.15	0.77	42.45
Ts, SPZ	0.34	0.20	0.77	0.27	0.87	53.95
Ts, SPN	0.30	0.12	0.64	0.23	0.82	48.18
Ts, SPE	0.29	0.15	0.65	0.21	0.94	63.31
P/S, SPZ	0.61	0.35	0.36	0.25	0.43	13.40
P/S, SPN	0.19	0.19	0.41	0.31	0.39	11.07
P/S, SPE	0.16	0.10	0.34	0.36	0.29	6.08
P/S, SPH	0.18	0.19	0.35	0.29	0.31	6.81
Coda, SPZ	62.8	64.2	49.3	22.6	0.17	2.07
Coda, SPN	83.0	64.6	52.3	24.9	0.37	10.02
Coda, SPE	97.3	80.0	54.8	28.6	0.42	12.83
Coda, SPH	128.2	89.5	76.4	37.0	0.45	14.69
Dur., SPZ	82.9	73.0	57.4	23.2	0.28	5.65
Dur., SPN	105.7	67.2	60.8	26.3	0.54	21.2
Dur., SPE	121.0	91.5	64.0	29.4	0.51	18.67
Dur., SPH	155.1	101.9	89.1	38.6	0.53	20.01

means that there is a 93.1% chance of correctly classifying an event. The weighted means for the two groups of earthquakes and other short period events are significantly different since 13.92 exceeds both 1.97 and 2.59. This discriminant will be called the Maximum Discriminant in ensuing discussion. The weighting coefficients for the Maximum Discriminant are: Ts, SPE: -4.8748, Ts, SPZ: -2.2731, Ts, SPN: -1.4274, Tp, SPN: -6.8903, Tp, SPE: -2.1963, Tp, SPZ: -1.2892, Dur., SPN: 0.0785, Dur., SPH: -0.0398, Dur., SPE: 0.0139, and P/S, SPZ: 4.6935. The weighted group mean for earthquakes is 0.8988 and for other short period events the mean is -7.8092. The cutting value for no a priori expectations is the midpoint -3.4552. A graph of the weighted values for the Maximum Discriminant versus Tp, SPZ, Tp, SPZ being arbitrarily chosen and used only to make a two-dimensional plot to allow easier visual separation of the weighted values for the two groups, is shown in Figure 10. In this and all following graphs the x-axis is the horizontal axis and the y-axis is the vertical.

A discriminant based on the top ten discriminating variables from the deletions list has z=1.96 and F=24.50. This yields 97.5% chance of correctly classifying events. This discriminant will be called the Maximum2 Discriminant. Weighting values for the Maximum2 Discriminant are: Ts, SPE: -8.3850, Ts, SPZ: -1.9184, Ts, SPN: -2.6279, Tp, SPE: -4.8696, Tp, SPN: -3.1891, Tp, SPZ: -3.3624, Dur., SPN: 0.5200, Dur., SPH: -0.4693, Dur., SPE: 0.4996, and Coda, SPH: -0.2507. The weighted group mean for earthquakes is 2.8789 and for the other short period events the mean is -12.4506. The cutting value for no a priori assumptions is -4.7858. A plot of the Maximum2 Discriminant versus Tp, SPZ is shown in Figure 11.

Since the correlation coefficients for SPE and SPN are large (the exact value of these and other correlation coefficients is given

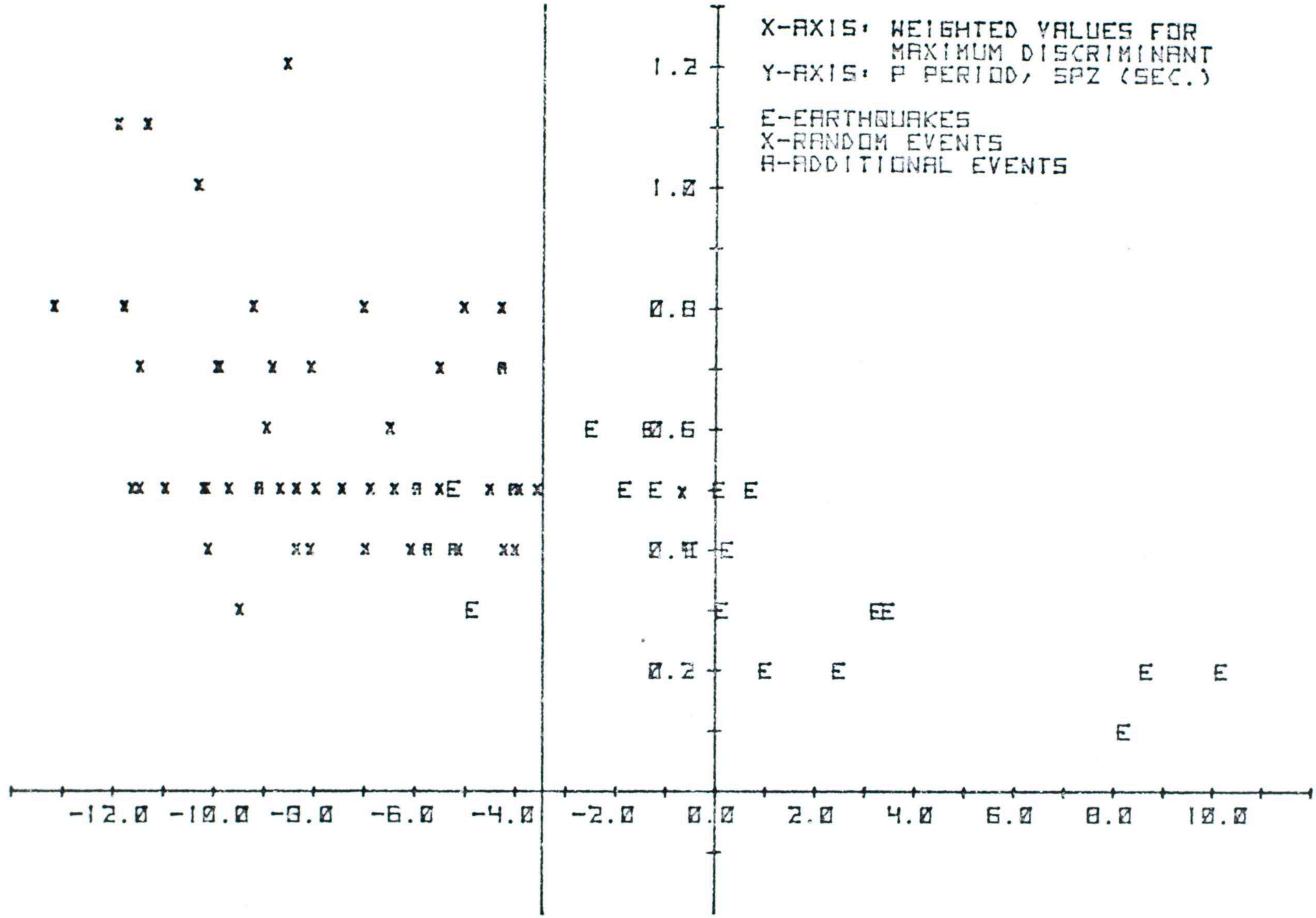

X-AXIS: WEIGHTED VALUES FOR MAXIMUM DISCRIMINANT
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.2
-12.0
-10.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0

Figure 10

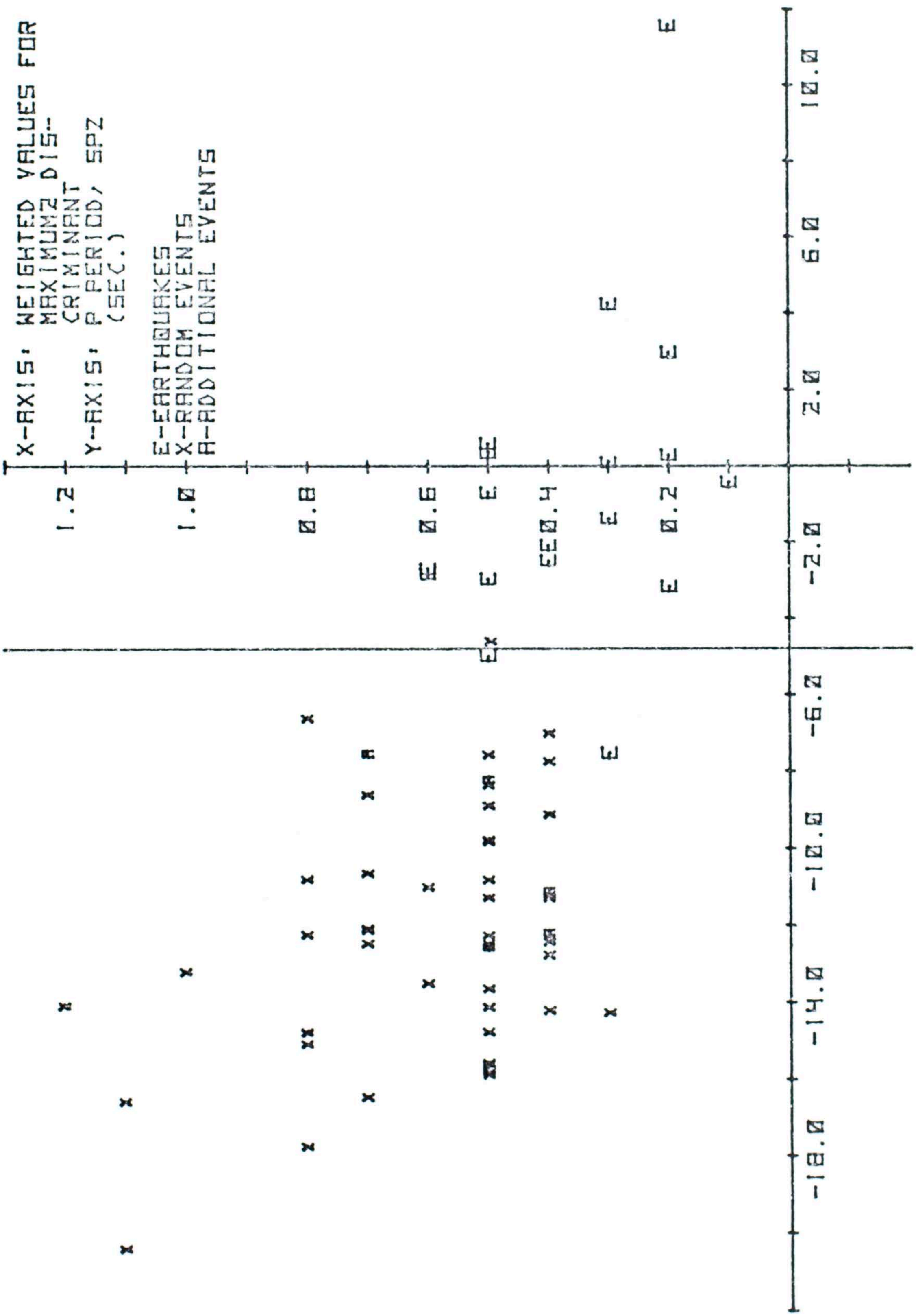

X-AXIS: WEIGHTED VALUES FOR MAXIMUM2 DIS-CRIMINANT
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
0.2
-18.0
-14.0
-10.0
-6.0
-2.0
2.0
6.0
10.0

Figure 11

later in the paper) for Tp, Ts, coda length, and duration, values for both seismographs and for SPH are perhaps redundant. Thus a discriminant for just one seismograph might be determined. For SPN, a discriminant, which will be called Discriminant A, using the variables Ts, SPN, Tp, SPN, Coda, SPN, and Duration, SPN has a z-score of 1.31 and F=29.46. This gives 90.5% chance of correctly classifying an event. Discriminant A2, calculated using only those events with full variable measurements for those variables used in Discriminant A, has z=1.63 and F=46.22 for 94.8% chance of correct event classification. Other discriminants computed for SPN and their resultant test values are listed in Table 4.

Weighting coefficients for Discriminant A are: Tp, SPN: -8.9811, Ts, APN: -7.2043, Coda, SPN: -0.0549, Dur., SPN: 0.0813. The weighted group mean for earthquakes is -0.6968 and for other events -7.5094. The cutting value midway between these two means is -4.1031. A graph of the weighted values from the original data for Discriminant A is shown in Figure 12, where Tp, SPZ is once again used for the y-axis.

Weighting coefficients for Discriminant A2 are: Tp, SPN: -9.6613, Ts, SPN: -8.4926, Coda, SPN: -0.3658, and Dur., SPN: 0.3668. The earthquake weighted group mean is 3.0882 and for the other short period events the mean is -7.6005. The cutting value is thus -2.2562. A graph of weighted values for Discriminant A2 versus Tp, SPZ is shown in Figure 13.

Applying the same procedure as outlined above for SPE and using Ts, SPE, Tp, SPE, Coda, SPE, and Dur., SPE for the variables, z=1.34 and F=30.97, for 91.0% chance of correctly classifying an event. This discriminant will be called Discriminant B. Weighting coefficients for

TABLE 4

DISCRIMINANTS FOR SPN

Variables	z	F	% Correctly Classified	Weighting Coefficients	Earthquake Mean	Other Mean	Cutting Value
Ts, SPN, Tp, SPN, Coda, SPN, Dur., SPN, P/S, SPN	1.33	24.12	90.8	-6.8124 -9.6429 -0.0543 0.0751 -2.1057	-1.7697	-8.8314	-5.3006
Ts, SPN, Tp, SPN, Dur., SPN	1.21	34.45	88.7	-6.8688 -8.1573 0.0309	-1.1344	-7.0344	-4.0844
Tp, SPN, Ts, SPN,	1.06	39.73	85.5	-7.9535 -6.9370	-4.3587	-8.8396	-6.5991
Ts, SPN	0.85	52.21	80.2	--	0.3000	0.6352	0.4676
P/S, SPN, Coda, SPN, Dur., SPN	0.68	10.77	75.2	-1.5442 -0.0327 0.0559	2.9072	1.0625	1.9848

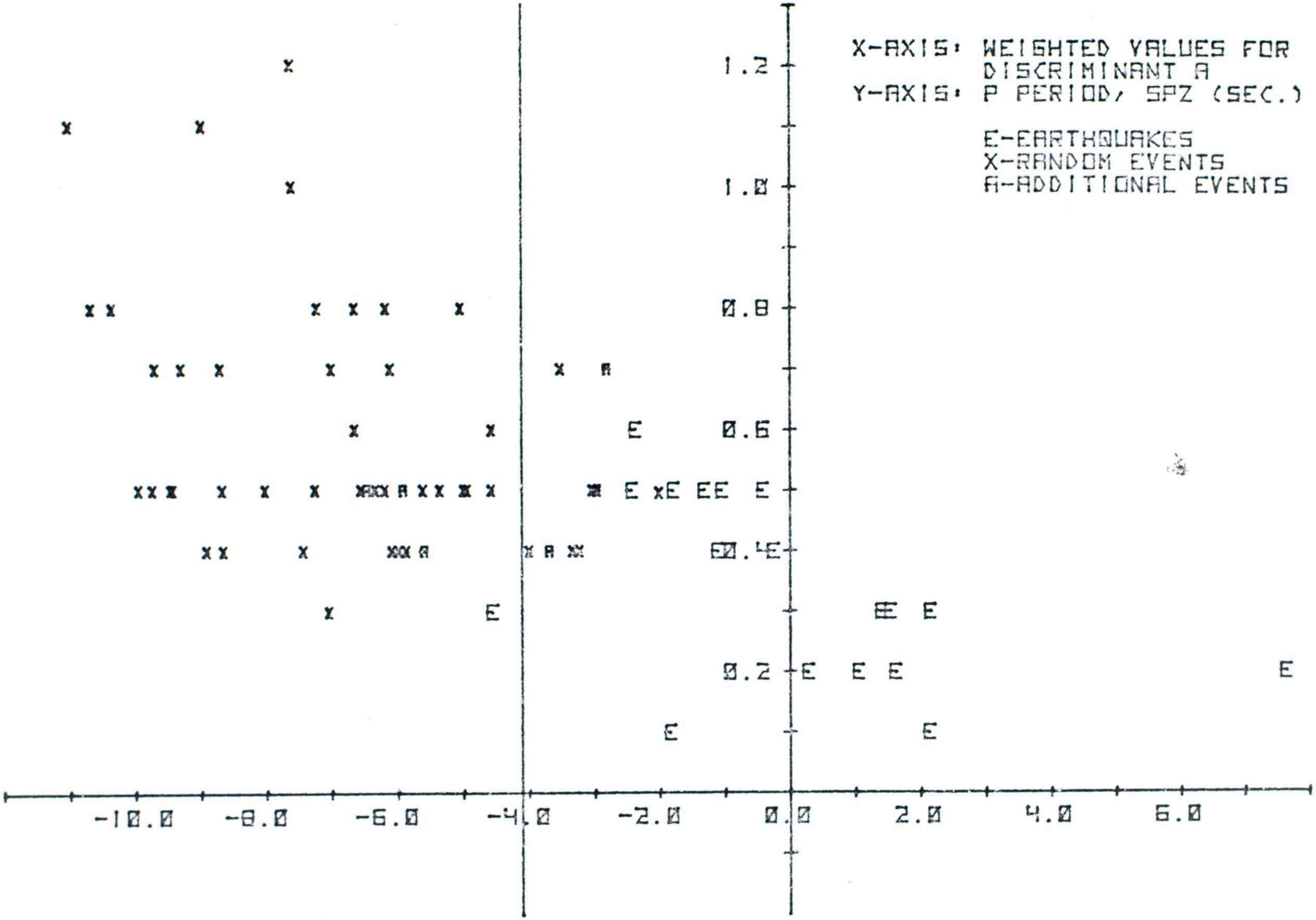

X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT A
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.2
-10.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0

Figure 12

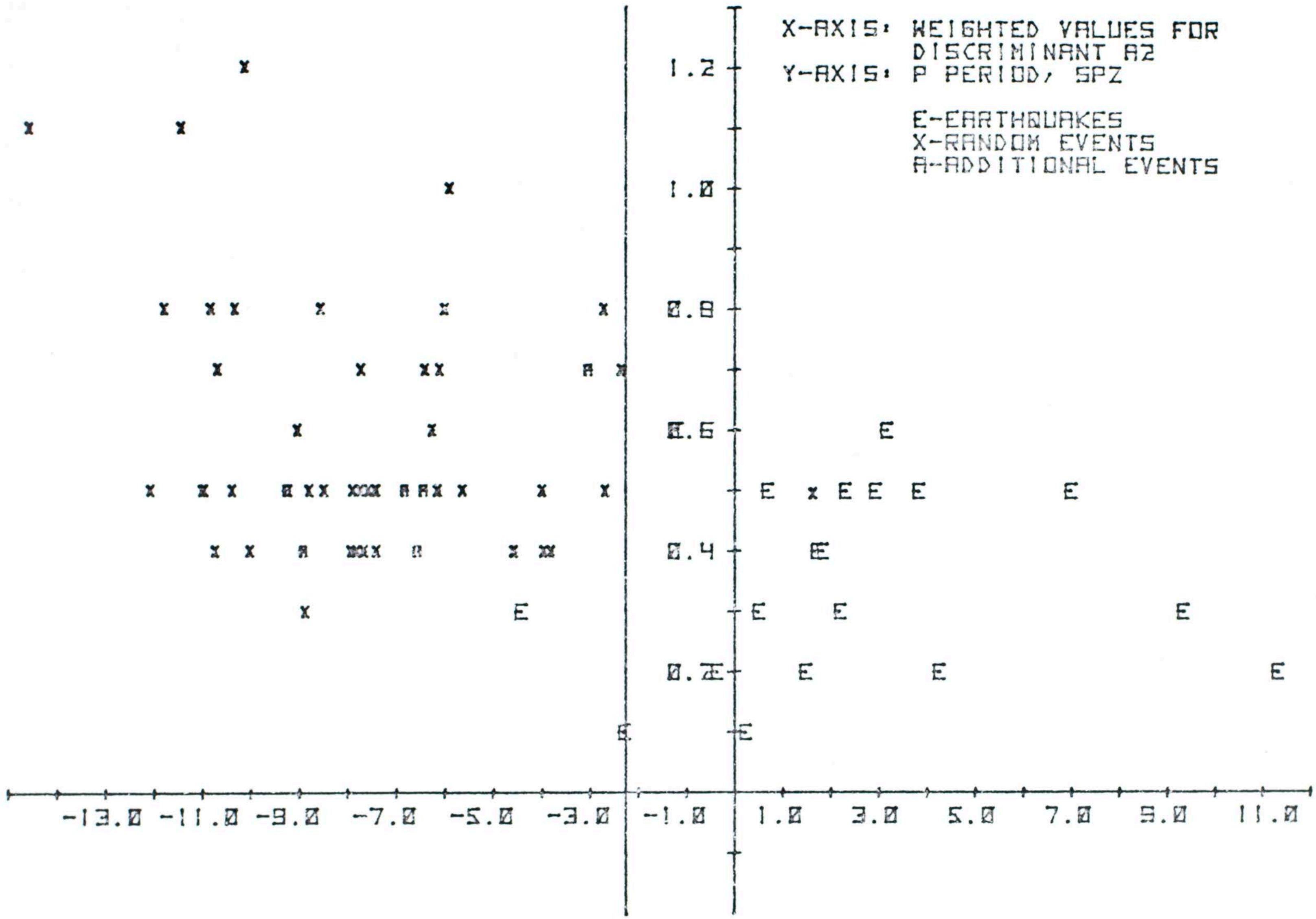

X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT A2
Y-AXIS: P PERIOD, SPZ
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
0.2
-13.0 -11.0 -9.0 -7.0 -5.0 -3.0 -1.0 1.0 3.0 5.0 7.0 9.0 11.0

Figure 13

this discriminant are: Tp, SPE: -9.8458, Ts, SPE: -9.5955, Coda, SPE: -0.0719, and Dur., SPE: 0.0793. The weighted group mean for earthquakes is -3.3212 and for other short period events it is -10.4845. The cutting value for no a priori expectations is -6.9028. A plot of Discriminant B versus Tp, SPZ is shown in Figure 14.

Discriminant B2, based on variable values for the events with full variables readings has z=1.58 and F=43.35. This yields an estimate of correctly classifying an event of 94.3%. The weighting coefficients for Discriminant B2 are: Tp, SPE: -9.1462, Ts, SPE: -11.6417, Coda, SPE: -0.3225, and Dur., SPE: 0.3061. The weighted mean for the earthquake group is -0.6206 and for the other short period events the mean is -10.6463. The cutting value for Discriminant B2 for no a priori assumptions is the midpoint -5.6334. A graph of the weighted variable observations for Discriminant B2 versus Tp, SPZ is shown in Figure 15.

Running discriminant tests for more or less than the above four variables has not been done. This is due to the example of the tests for SPN, where it was seen that Tp, Ts, coda length and duration compose the best compact discriminant.

As P/S, SPZ exhibits a relatively good discriminating power in contrast to the horizontal seismographs' P/S amplitude ratios, it will be considered necessary in forming Discriminant C for seismograph SPZ. Using Ts, SPZ, Tp, SPZ, P/S, SPZ, Dur., SPZ, and Coda, SPZ, z=1.26 and F=21.66. This gives an 89.6% chance of correct event classification.

The weighting coefficients for Discriminant C are: Tp, SPZ: -7.1299, Ts, SPZ: -6.3221, P/S, SPZ: 3.5204, Dur., SPZ: 0.1041, and Coda, SPZ: -0.1074. The weighted group mean for earthquakes is

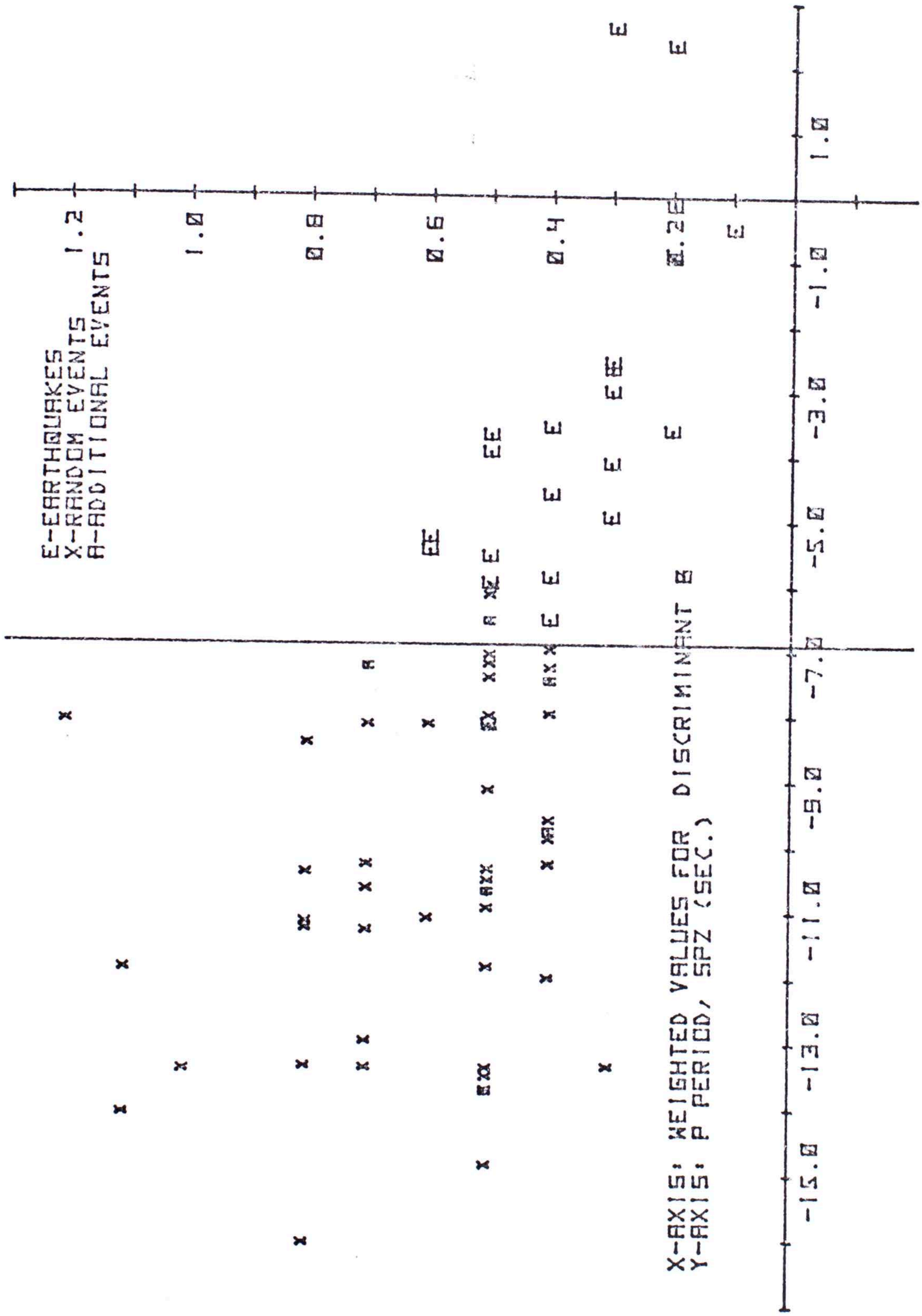

E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
0.2
1.0
-1.0
-3.0
-5.0
-7.0
-9.0
-11.0
-13.0
-15.0
X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT B
Y-AXIS: P PERIOD, SPZ (SEC.)

Figure 14

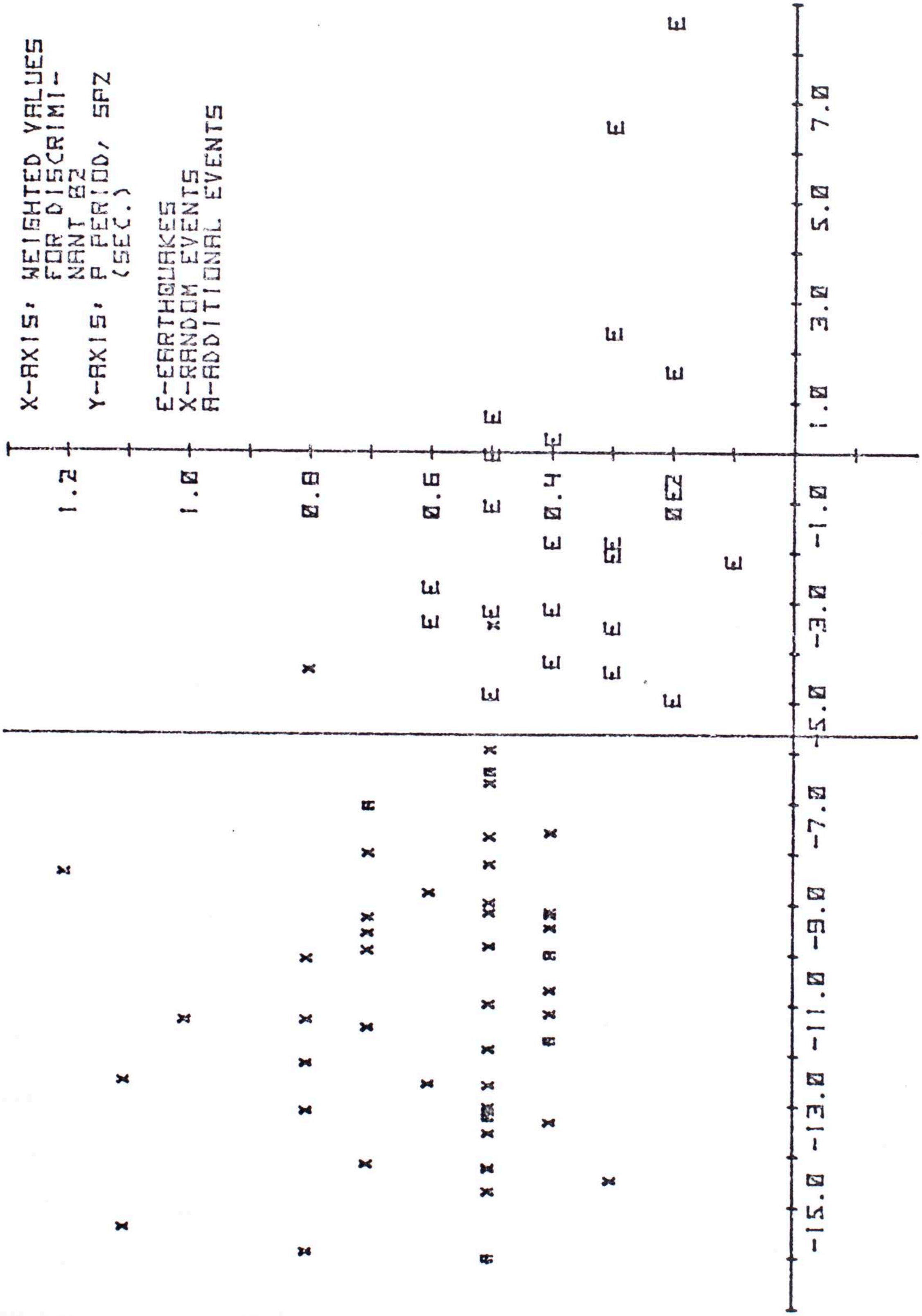

X-AXIS, WEIGHTED VALUES FOR DISCRIMI- NANT B2
Y-AXIS, P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
-15.0 -13.0 -11.0 -9.0 -7.0 -5.0 -3.0 -1.0 1.0 3.0 5.0 7.0

Figure 15

-0.7637 and for other short period events, -7.1058. The midpoint of these two means, and thus the dividing point, is -3.9348. A graph showing the efficiency of Discriminant C is shown in Figure 16.

Other combinations of SPZ variables used in forming discriminants using the replaced with means method for missing variable measurements are shown in Table 5. From observing these discriminants it seems that all five of the variables used in Discriminant C are necessary for forming a good discriminant.

A discriminant based on the method of deleting events with one or more missing variables using the same variables as used in Discriminant C will be called Discriminant C2. Discriminant C2 has z=1.32 and F=23.72 for 90.7% chance of correct event classification. The weighting coefficients for Discriminant C2 are: Tp, SPZ: -7.2817, Ts, SPZ: -6.1930, P/S, SPZ: 2.3475, Coda, SPZ: -0.2155, and Dur., SPZ: 0.1971. The weighted earthquake group mean is -0.5649 and the mean for other short period events is -7.5108. The cutting value is -4.0379. A graph of Discriminant C2 versus Tp, SPZ is shown in Figure 17.

It was thought that since dominant period measurements are perhaps the most subjective of the variable measurements, although relative differences between earthquakes and other short period events are undisputable, that a discriminant, herein called Discriminant D, based on less subjective variables could prove interesting and might be more meaningful quantitatively. Discriminant D, based on P/S, SPZ, P/S, SPE, P/S, SPN, Coda, SPZ, Coda, SPE, Coda, SPN, Dur., SPZ, Dur., SPE, and Dur., SPN has a z-score of 1.04 and F=7.85 for 85.1% correct classification of events. The weighting coefficients for Discriminant D are: P/S, SPZ:

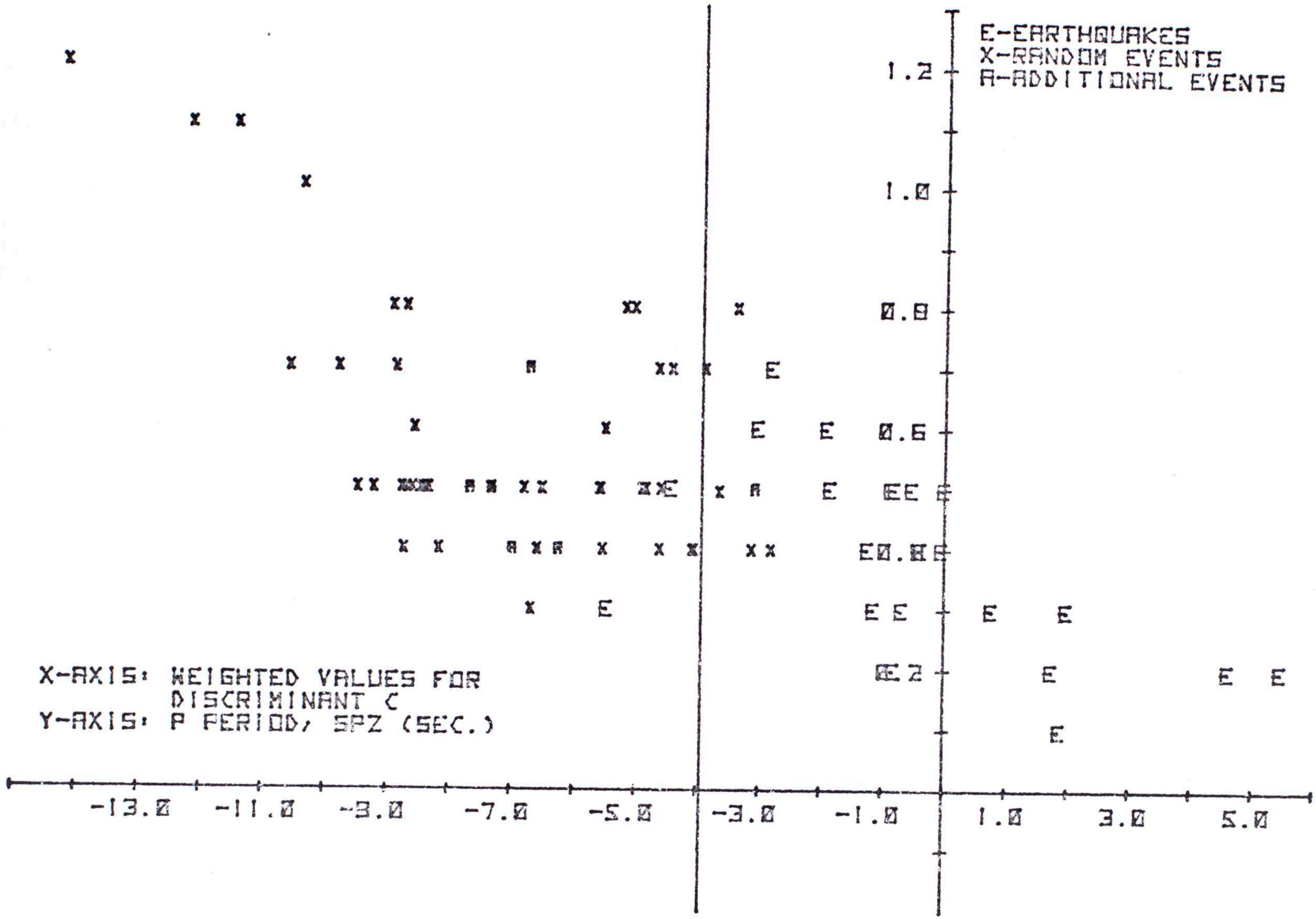

E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT C
Y-AXIS: P PERIOD, SPZ (SEC.)
1.2
1.0
0.8
0.6
-13.0
-11.0
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0

Figure 16

TABLE 5

DISCRIMINANTS FOR SPZ

Variables	z	F	% Correctly Classified	Weighting Coefficients	Earthquake Mean	Other Mean	Cutting Value
Tp. SPZ, Ts, SPZ, P/S, SPZ, Dur., SPZ	1.13	22.17	87.08	-5.5185 -5.8248 4.1180 0.0159	-0.1997	-5.3260	-2.7628
Tp, SPZ, Ts, SPZ, P/S, SPZ, Coda, SPZ	1.09	20.71	86.2	-5.2935 -6.0350 3.7433 0.0088	-1.1822	-5.9715	-3.5769
Tp, SPZ, Ts, SPZ, P/S, SPZ	1.08	27.39	86.0	-5.3481 -6.2843 3.3424	-2.0832	-6.7748	-4.4290
Tp, SPZ, Ts, SPZ, Coda, SPZ, Dur., SPZ	1.19	24.34	88.3	-6.7849 -7.0021 -0.1181 0.1071	-3.4267	-9.0571	-6.2419
P/S, SPZ, Dur., SPZ, Coda, SPZ	0.71	11.78	76.1	4.4069 0.0649 -0.0535	4.6994	2.6821	3.6908

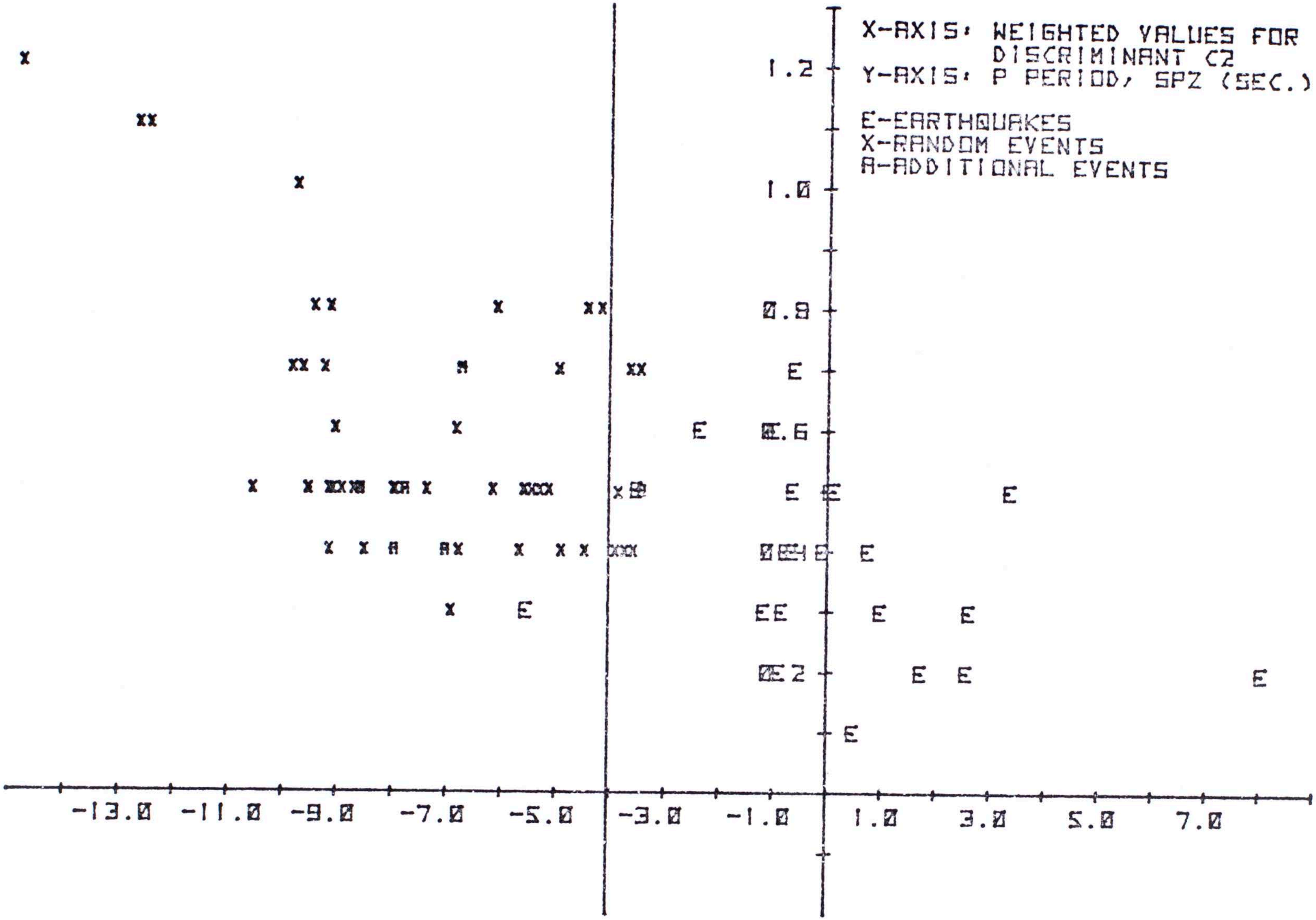

X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT C2
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
.2
-13.0
-11.0
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0

Figure 17

5.7621, P/S, SPE: -2.4644, P/S, SPN: -0.7557, Coda, SPZ: -0.0364, Coda, SPE: 0.0181, Coda, SPN: -0.0352, Dur., SPZ: 0.0083, Dur., SPE: 0.0198, and Dur., SPN: 0.0400. The weighted group mean for earthquakes is 6.8440 and for other short period events the mean is 2.4847. The midpoint derived cutting value is 4.6643. A graph of Discriminant D versus Tp, SPZ is shown in Figure 18.

A discriminant based on the variables used in Discriminant D but using only events with full variable measurements has z=1.47 and F=15.59. This discriminant, called Discriminant D2, has an estimated efficiency of 92.9% in correctly classifying individual events. The weighting coefficients for Discriminant D2 are: P/S, SPZ: 2.9908, P/S, SPE: -2.5711, P/S, SPN: -0.0017, Coda, SPZ: 0.2796, Coda, SPE: 0.2345, Coda, SPN: -0.8175, Dur., SPZ: -0.3643, Dur., SPE: -0.1440, and Dur., SPN: 0.8103. The weighted group mean for earthquakes is 11.9078 and for other short period events, 3.2453, giving a cutting value for no a priori expectations of 7.5765. The efficiency of this discriminant is demonstrated visually in the graph of the weighted values for Discriminant C2 versus Tp, SPZ shown in Figure 19.

Other combinations of less subjective variables in forming discriminants are shown in Table 6. From this table it is seen that only the combination of nine variables used in forming Discriminant D has any real usefulness in practical work.

Other Results

Some of the graphical discriminants did seem to show signs of reasonably good discrimination. For example, Figure 20 shows a graph

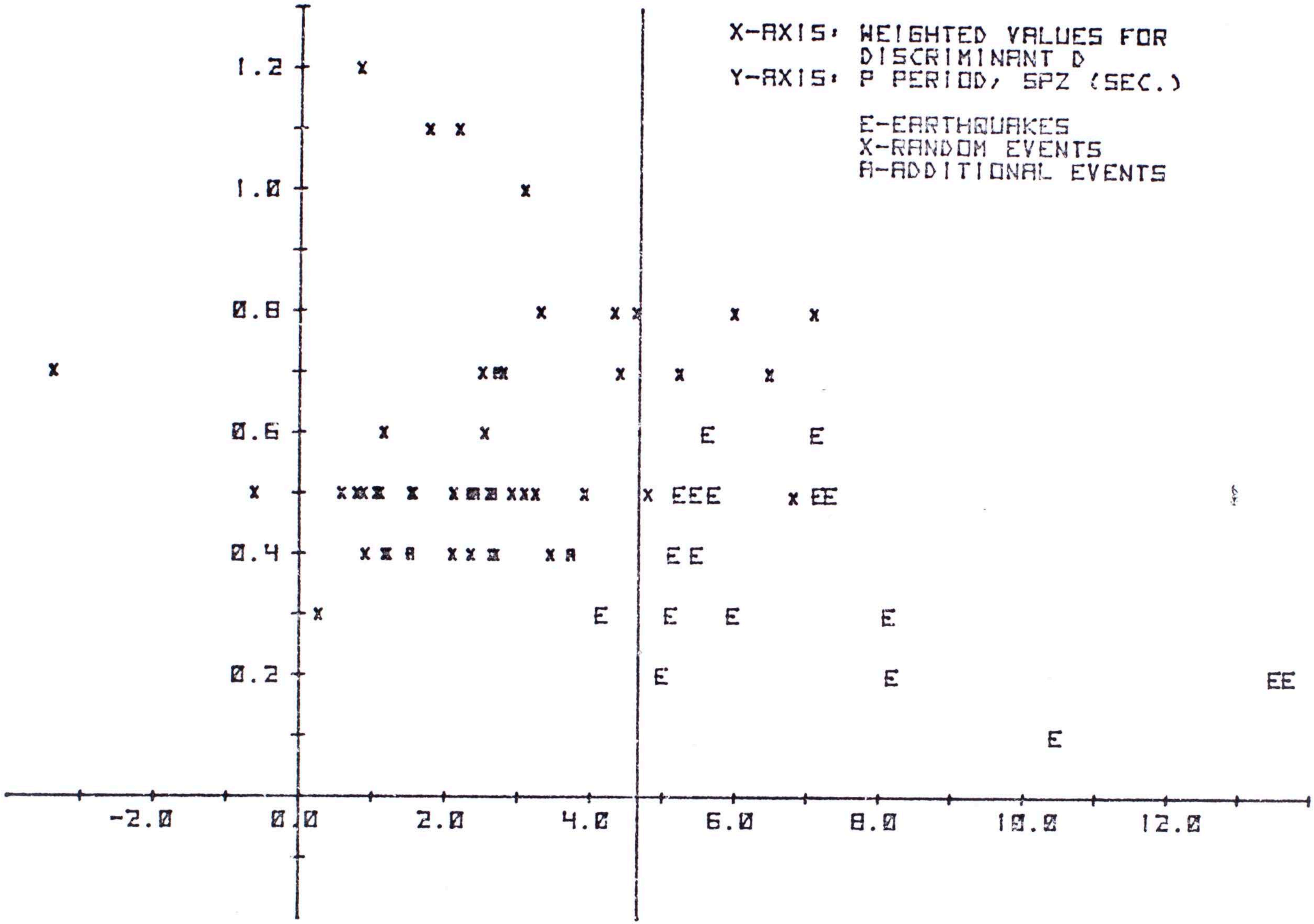

X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT D
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
0.2
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0

Figure 18

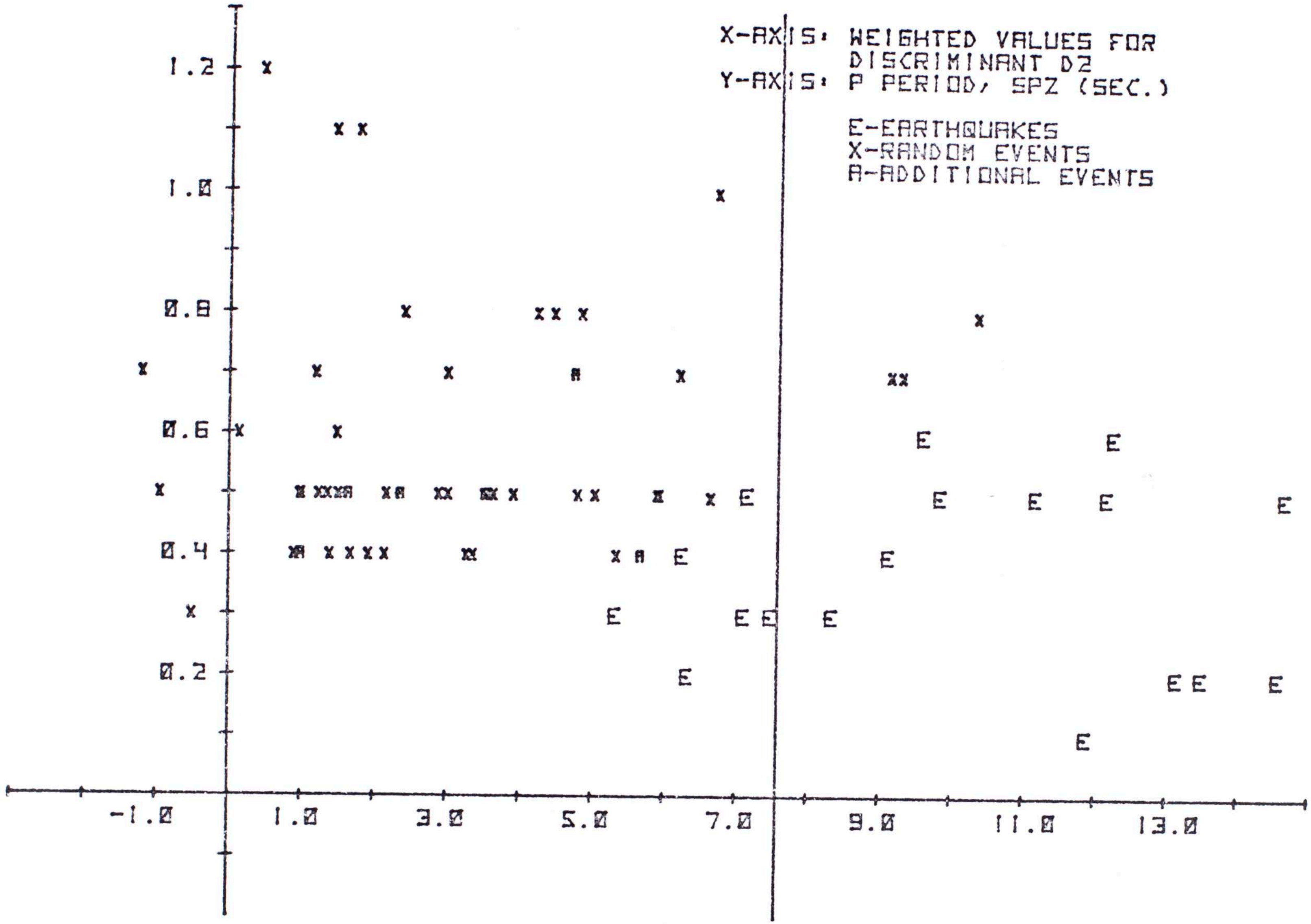

X-AXIS: WEIGHTED VALUES FOR DISCRIMINANT D2
Y-AXIS: P PERIOD, SPZ (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.2
1.0
0.8
0.6
0.4
0.2
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0

Figure 19

TABLE 6

DISCRIMINANTS FOR LESS SUBJECTIVE VARIABLES

Variables	z	F	% Correctly Classified	Weighting Coefficients	Earthquake Mean	Other Mean	Cutting Value
P/S, SPZ, P/S, SPE, P/S, SPN	0.73	12.31	76.7	4.7416 -1.7144 -2.9032	2.0683	-0.0402	1.0141
Coda, SPZ, Coda, SPE, Coda, SPN	0.60	8.49	75.3	-0.0411 0.0426 0.0065	2.0983	0.6443	1.3713
Dur., SPZ, Dur., SPE, Dur., SPN	0.68	10.91	75.2	-0.0331 0.0360 0.0146	3.1648	1.2964	2.2306
P/S, SPZ, P/S, SPN, Dur., SPN, Dur., SPE	0.91	14.17	81.9	5.3323 -2.2455 0.0108 0.0173	6.0616	2.7849	4.4232
Dur., SPN, Dur., SPE, P/S, SPZ, Coda, SPE	0.88	13.25	81.1	0.0158 0.0325 5.0583 -0.0174	6.9855	3.9184	5.4520
Dur., SPZ, Dur., SPE, Coda, SPZ, Coda, SPE, P/S, SPZ, P/S, SPE	1.01	11.39	84.4	0.0003 0.0481 -0.0374 -0.0010 5.4781 -2.8132	6.2887	2.2338	4.2613

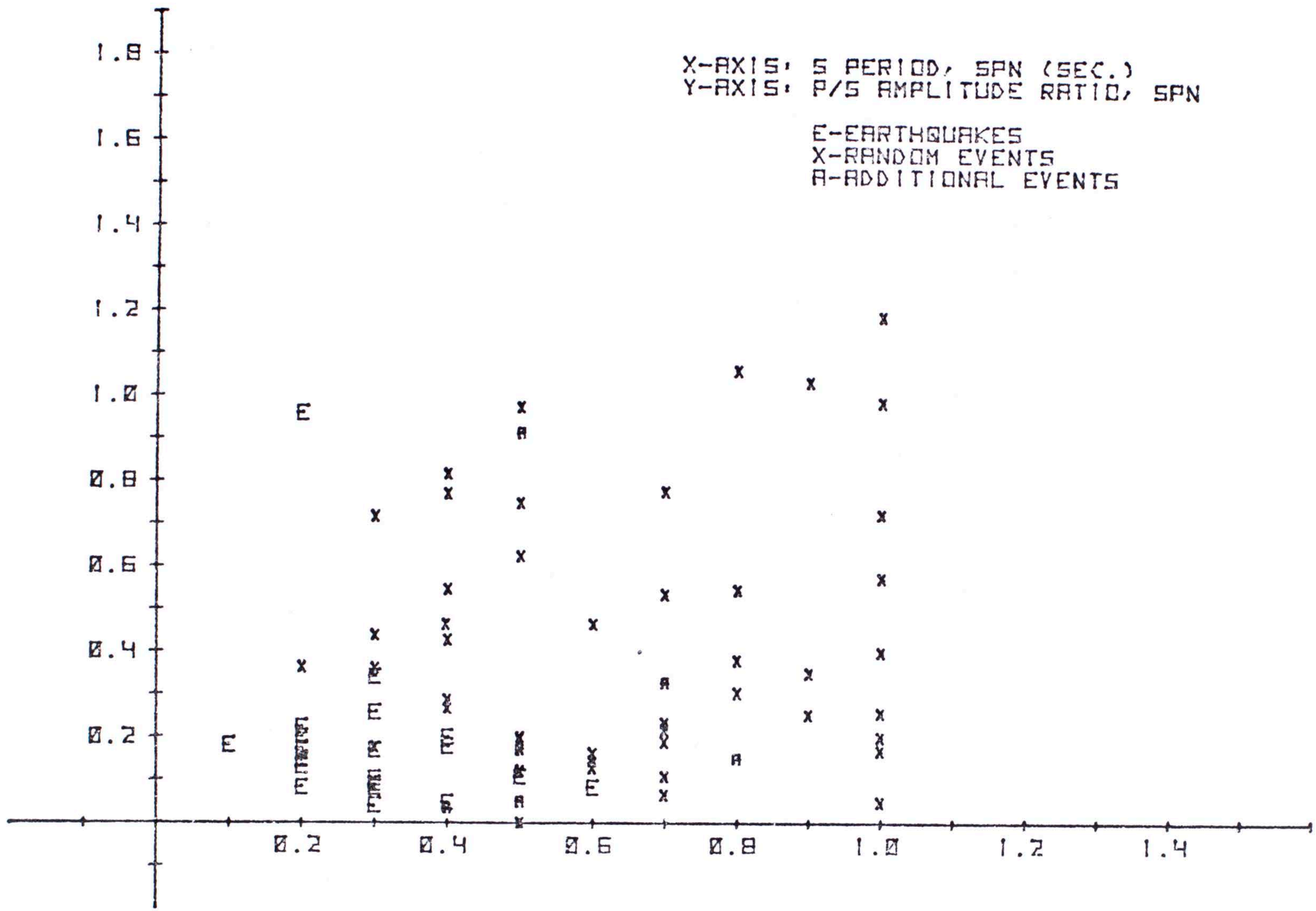

X-AXIS: S PERIOD, SPN (SEC.)
Y-AXIS: P/S AMPLITUDE RATIO, SPN
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
1.2
1.4

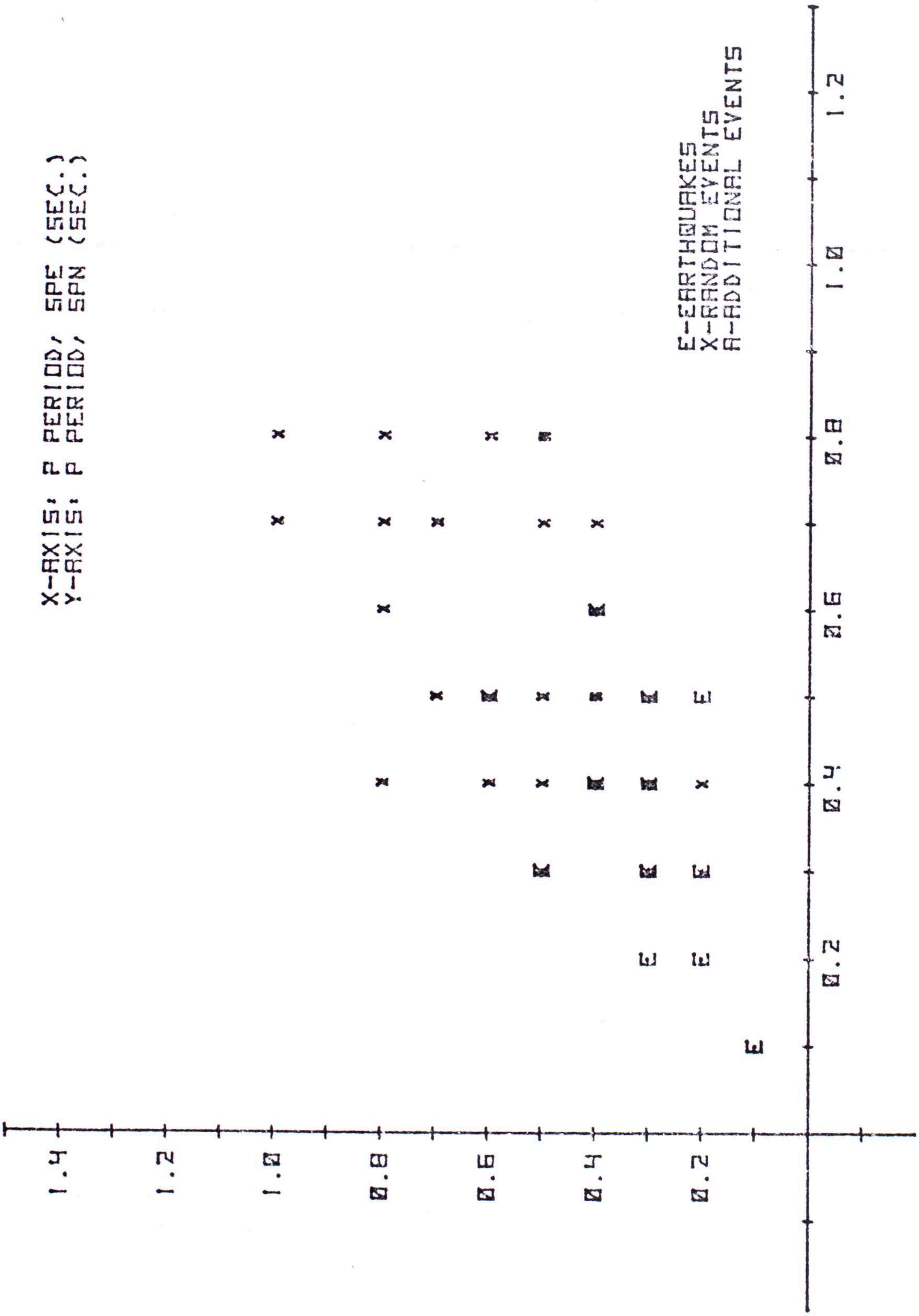
Figure 20

of S period, SPN versus P/S amplitude ratio, SPN. A line drawn from the 0.6 second mark on the period axis to the 0.6 amplitude ratio mark would capture most of the earthquakes in the lower left part of the graph. Most of the better discriminants involved the usage of a period, and the main separation of events seemed to be linear perpendicular to the period axis. A horizontal line drawn at the 0.3 second P period, SPN mark on Figure 21 would capture most of the earthquakes in the lower part of the graph, for example.

Another trial discriminant is shown in Figure 22. This involves the plotting of a heuristic variable called the total product, which is the product of the Pg period, Sg period, P/S amplitude ratio, and coda length on a particular seismograph. It was thought at the time this type of graph was first made that Pg period, Sg period, P/S amplitude ratio, and coda length were the only variables expected to have any significance in discrimination, a false presumption according to the quantitative results already shown. As is seen in the graph, earthquakes seem to cluster in the lower left portion of the graph. One can see that this and the other graphical discriminants discussed above provide some discrimination but is not as selective as the quantitative discriminants eventually derived.

Table 7 lists the correlation coefficients computed in this study. Some of these relations are shown graphically in Figure 21 and Figures 23-27.

Coda length, SPE versus coda length, SPN shows good correlation with r=0.88. This is not too surprising, and suggests that the coda length for one seismograph could substitute for the other in case of



X-AXIS: P PERIOD, SPE (SEC.)
Y-AXIS: P PERIOD, SPN (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Figure 21

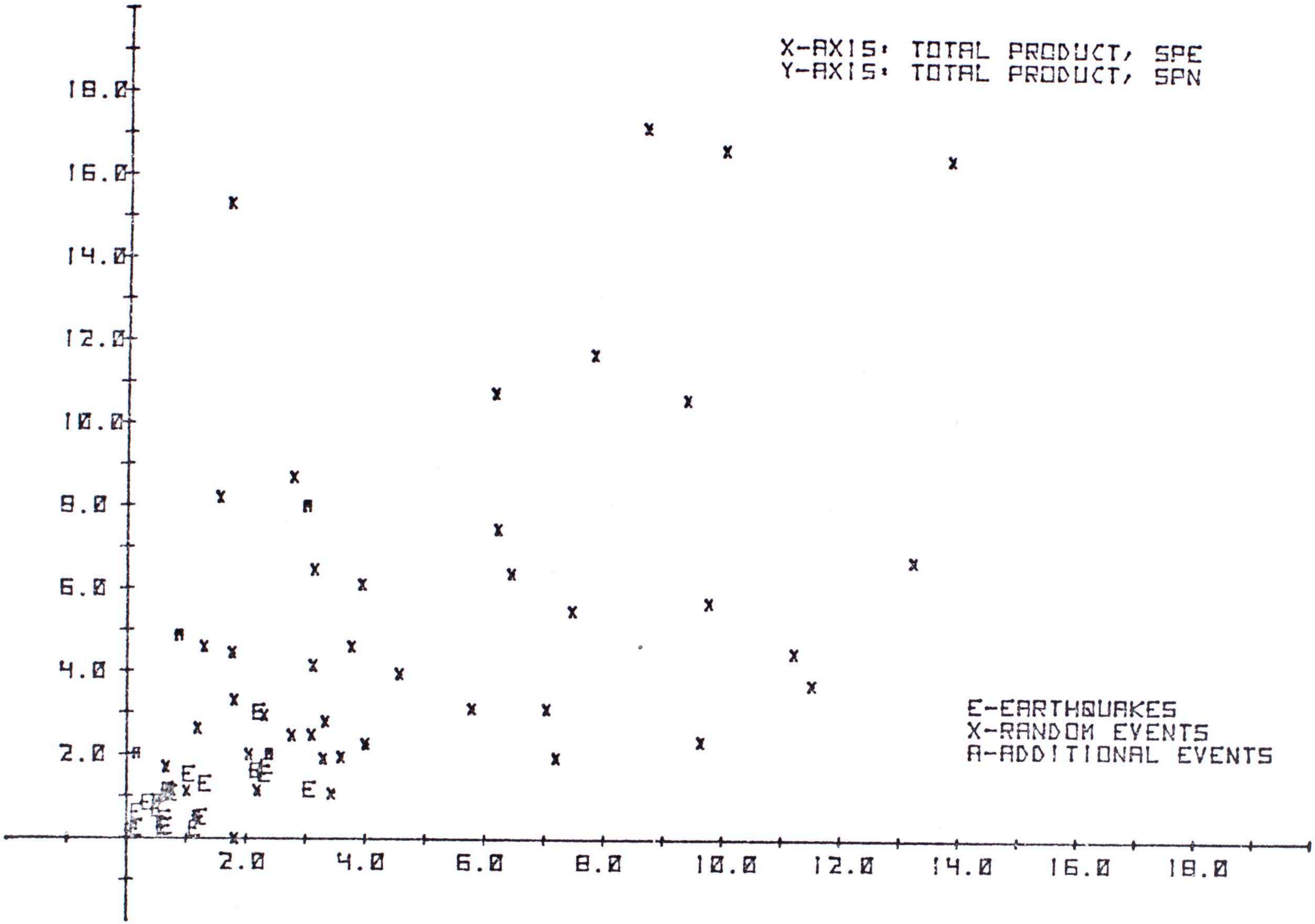

X-AXIS: TOTAL PRODUCT, SPE
Y-AXIS: TOTAL PRODUCT, SPN
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0

Figure 22

TABLE 7

VARIABLE CORRELATION COEFFICIENTS

Variable 1	Variable 2	Correlation Coefficient
Tp, SPE	Tp, SPN	0.81
Ts, SPE	Ts, SPN	0.89
Coda, SPE	Coda, SPN	0.88
Dur., SPE	Dur., SPN	0.98
P/S, SPE	P/S, SPN	0.67
P/S, SPZ	P/S, SPH	0.31
Tp, SPE	Tp, SPZ	0.60
Tp, SPN	Tp, SPZ	0.69
Ts, SPE	Ts, SPZ	0.74
Ts, SPN	Ts, SPZ	0.69
Coda, SPZ	Coda, SPE	0.85
Coda, SPZ	Coda, SPN	0.81
Dur., SPZ	Dur., SPE	0.89
Dur., SPZ	Dur., SPN	0.86

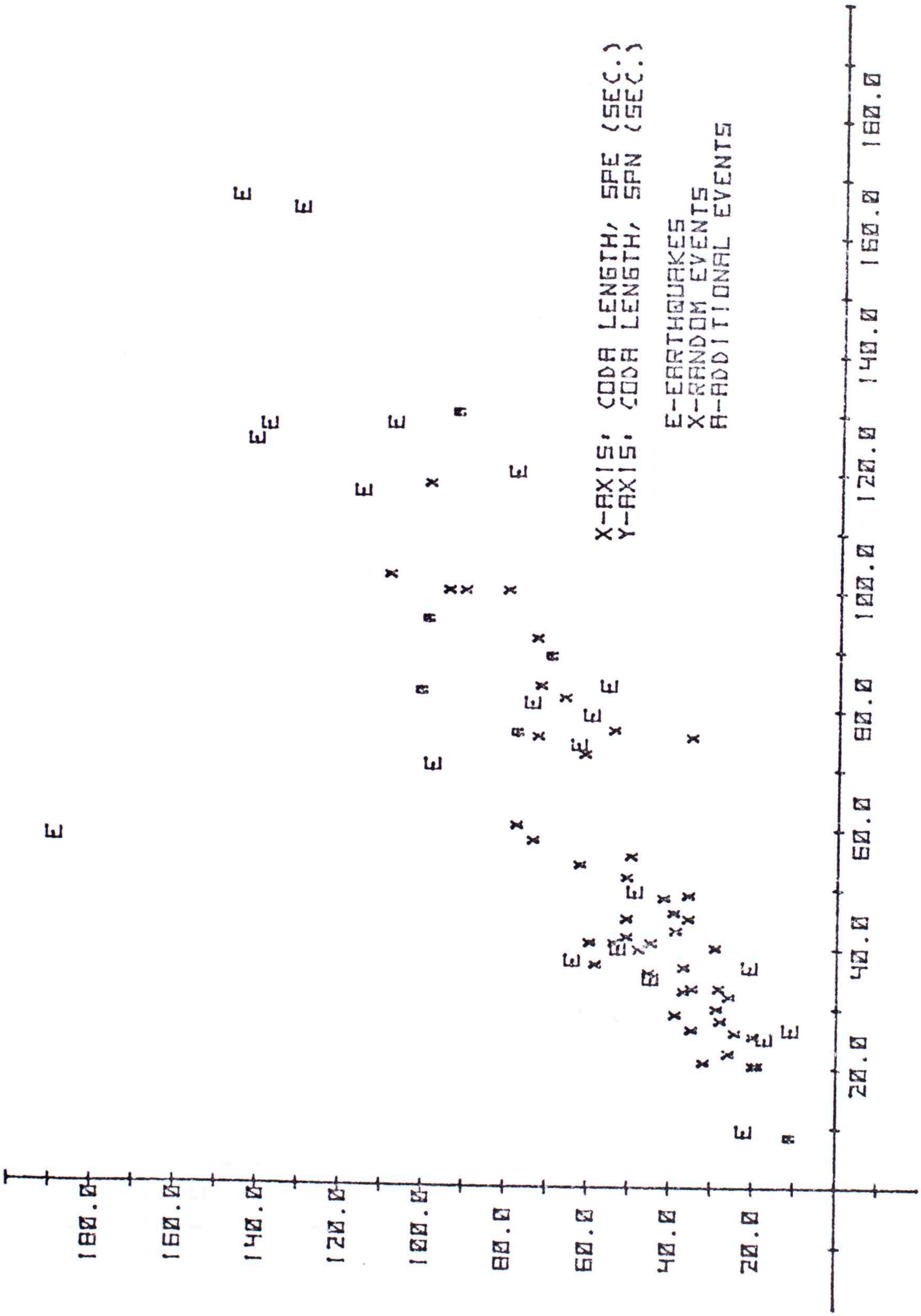

X-AXIS, CODA LENGTH, SPE (SEC.)
Y-AXIS, CODA LENGTH, SPN (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0

Figure 23

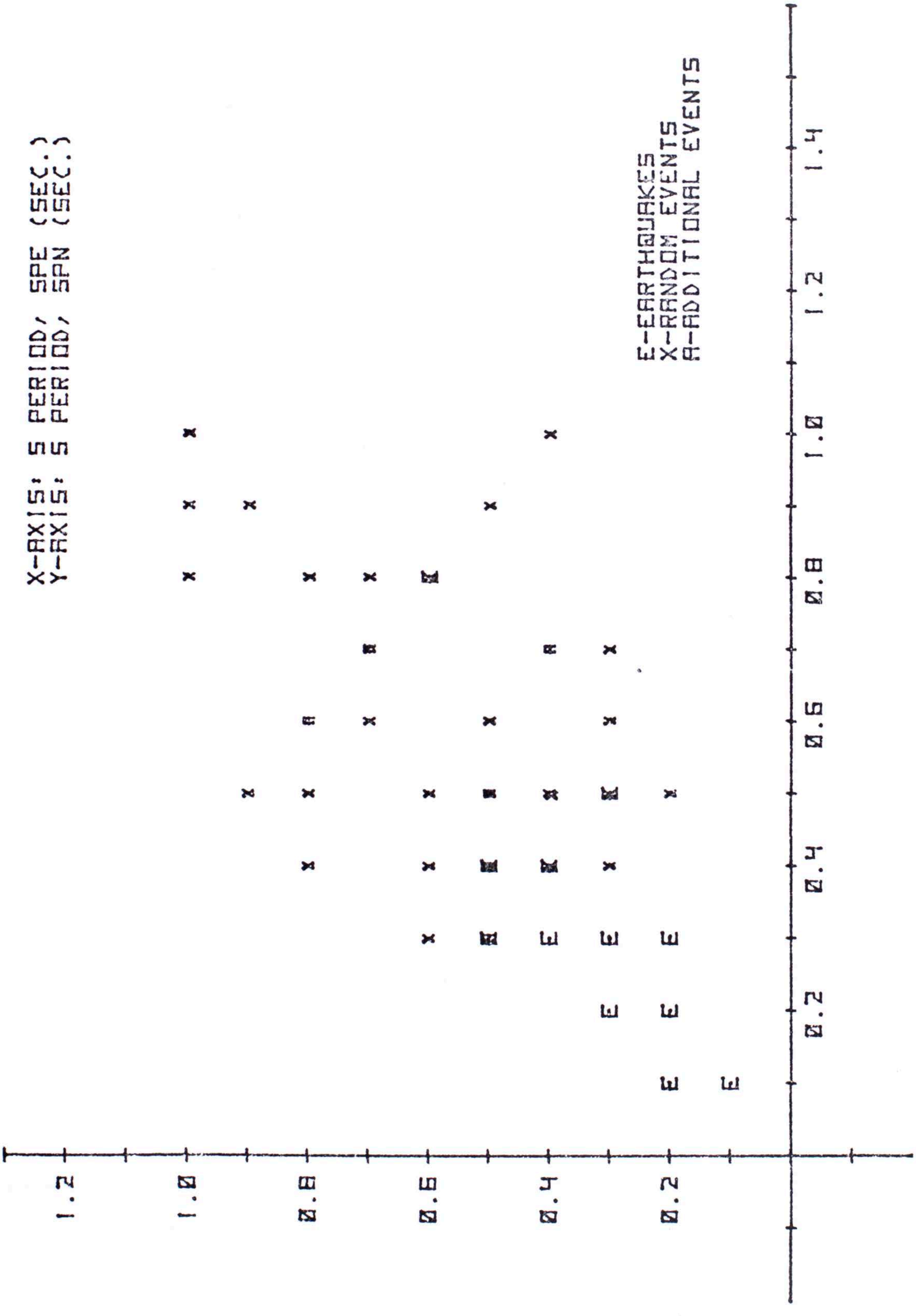
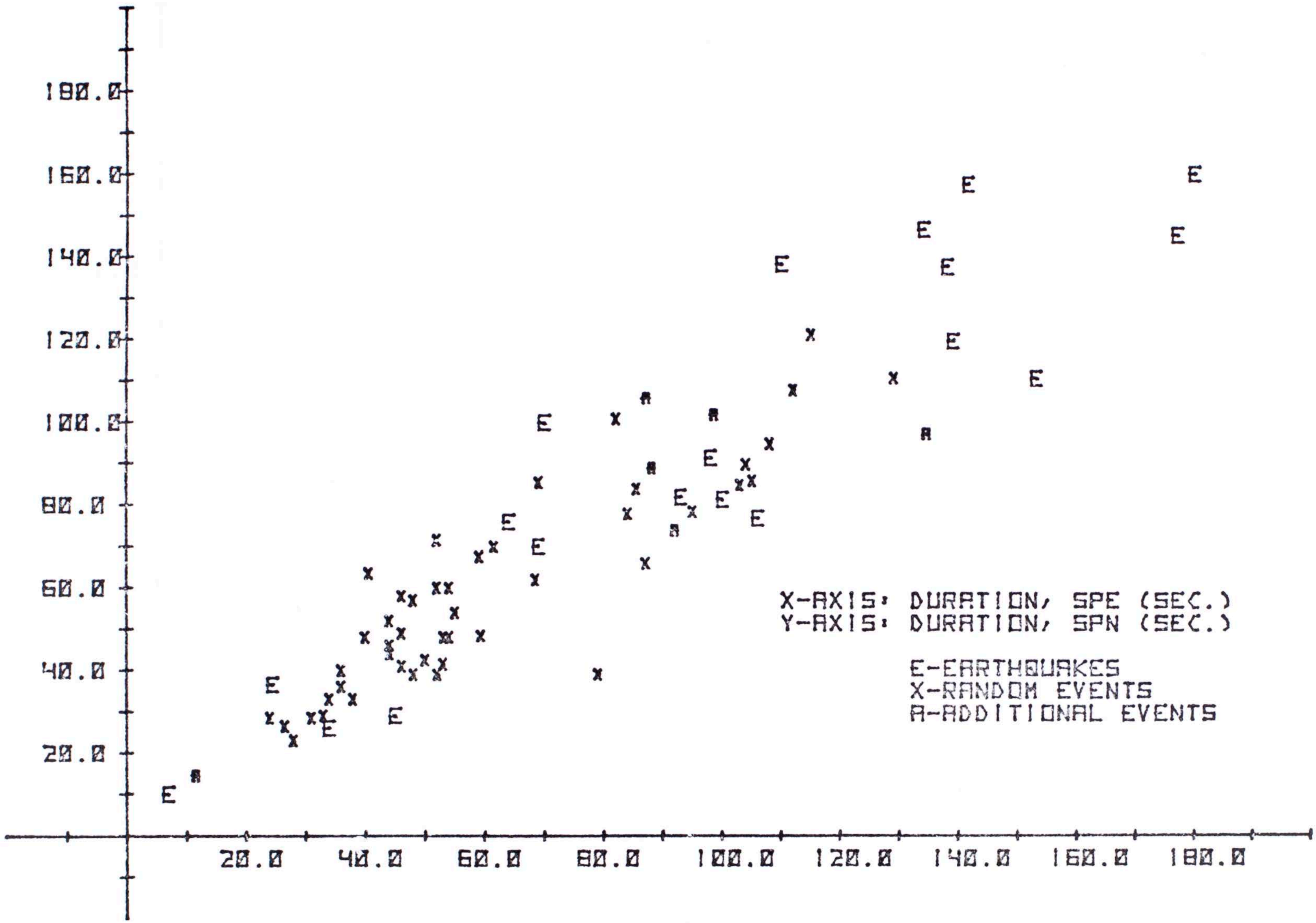

X-AXIS: S PERIOD, SPE (SEC.)
Y-AXIS: S PERIOD, SPN (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.2
0.4
0.6
0.8
1.0
1.2

Figure 24



180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
X-AXIS: DURATION, SPE (SEC.)
Y-AXIS: DURATION, SPN (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS

Figure 25

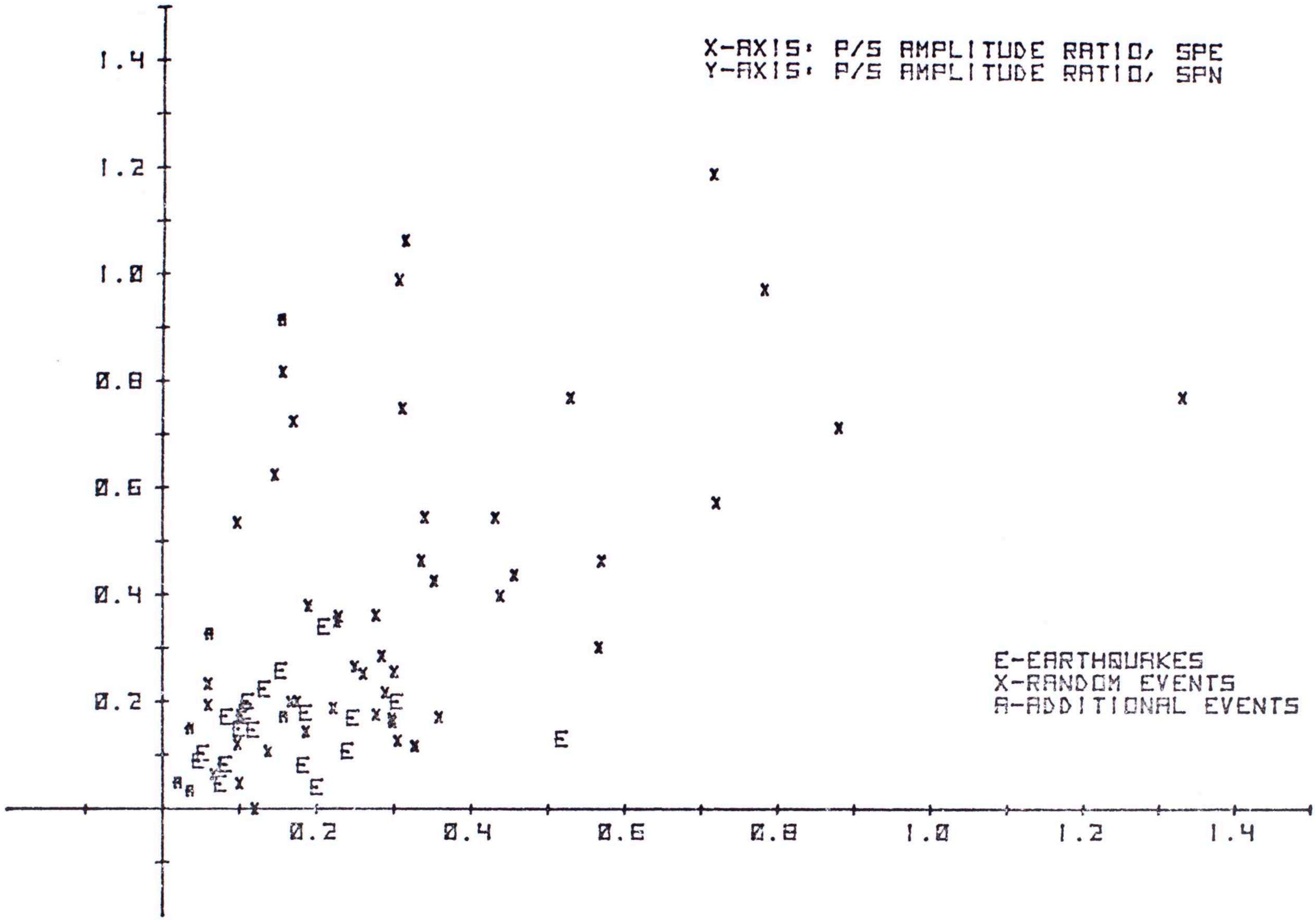

X-AXIS: P/S AMPLITUDE RATIO, SPE
Y-AXIS: P/S AMPLITUDE RATIO, SPN
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Figure 26

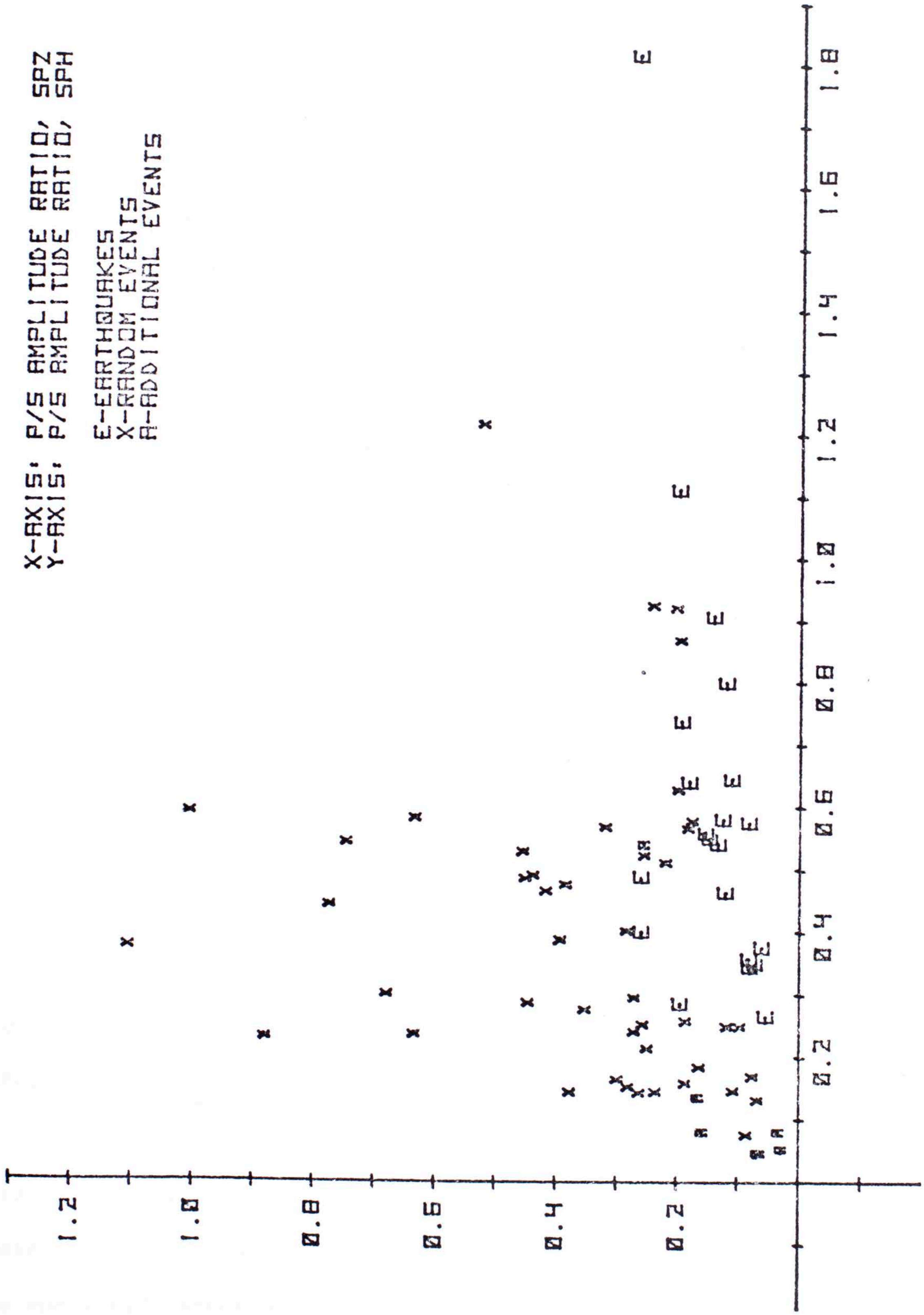

X-AXIS: P/S AMPLITUDE RATIO, SPZ
Y-AXIS: P/S AMPLITUDE RATIO, SPH
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS

Figure 27

destroyed or missing records. The correlation coefficient for P period on the same two seismographs is 0.81, which suggest a similar substituting capability for P period. S period, with a correlation coefficient of 0.89, also exhibits a high substitutive power. These relations are shown in Figures 21 and 24.

The highest correlation coefficient computed was for Duration, SPE versus Duration, SPN where r=0.98. This result strongly shows the similarity of the variable on the seismograph and reinforces the argument for not using SPH. A graphical depiction of this relation is shown in Figure 25.

P/S amplitude correlation on SPN versus SPE, shown in Figure 26, has r=0.67, which is relatively low when substitution capability is considered. This low correlation is perhaps reflective of the effect direction has on the horizontal seismographs, with larger amplitudes occurring when the seismometer is oriented in line with or perpendicular to the azimuth vector to a seismic source.

The relation between P/S amplitude, SPZ and P/S amplitude, SPH is shown graphically in Figure 27. The correlation for these two variables is rather low, as r=0.31. The graph does however suggest a trend for earthquakes to have a higher P/S ratio on SPZ than on the computed SPH, and the trend does appear to be somehow linear.

More correlation coefficient results of interest not shown graphically are the high correlations between the vertical and horizontal seismographs for coda length and duration. This is not too surprising as one would expect an event of long duration on one seismograph to also be of long duration on the other. The relations between periods measured on the vertical and each of the horizontal seismographs show relatively high correlation coefficients, but not high enough for any possible substitution.

Some other relations resulting from graphical investigations are shown in Figures 28 and 29. Figure 28 is a plot of coda length, SPZ and coda length, SPH. The interesting feature of this plot is that the trend of the points, although apparently linear, is not one to one, and shows graphically that almost all of the events have a shorter coda length on the SPZ seismograph than on the vector-summed SPH. A satisfactory explanation for this trend cannot be found, but factors such as a lower noise level on the horizontal seismographs could be causative. Another possible explanation is that coda length, SPH has no real meaning.

A very conjectural relation can be seen in Figure 29. This plot of duration, SPN versus P/S amplitude ratio, SPN best exhibits a trend seen on each of the three seismograph records for the P/S amplitude ratio to decrease as the duration increases. Explanations for this trend are again not known.

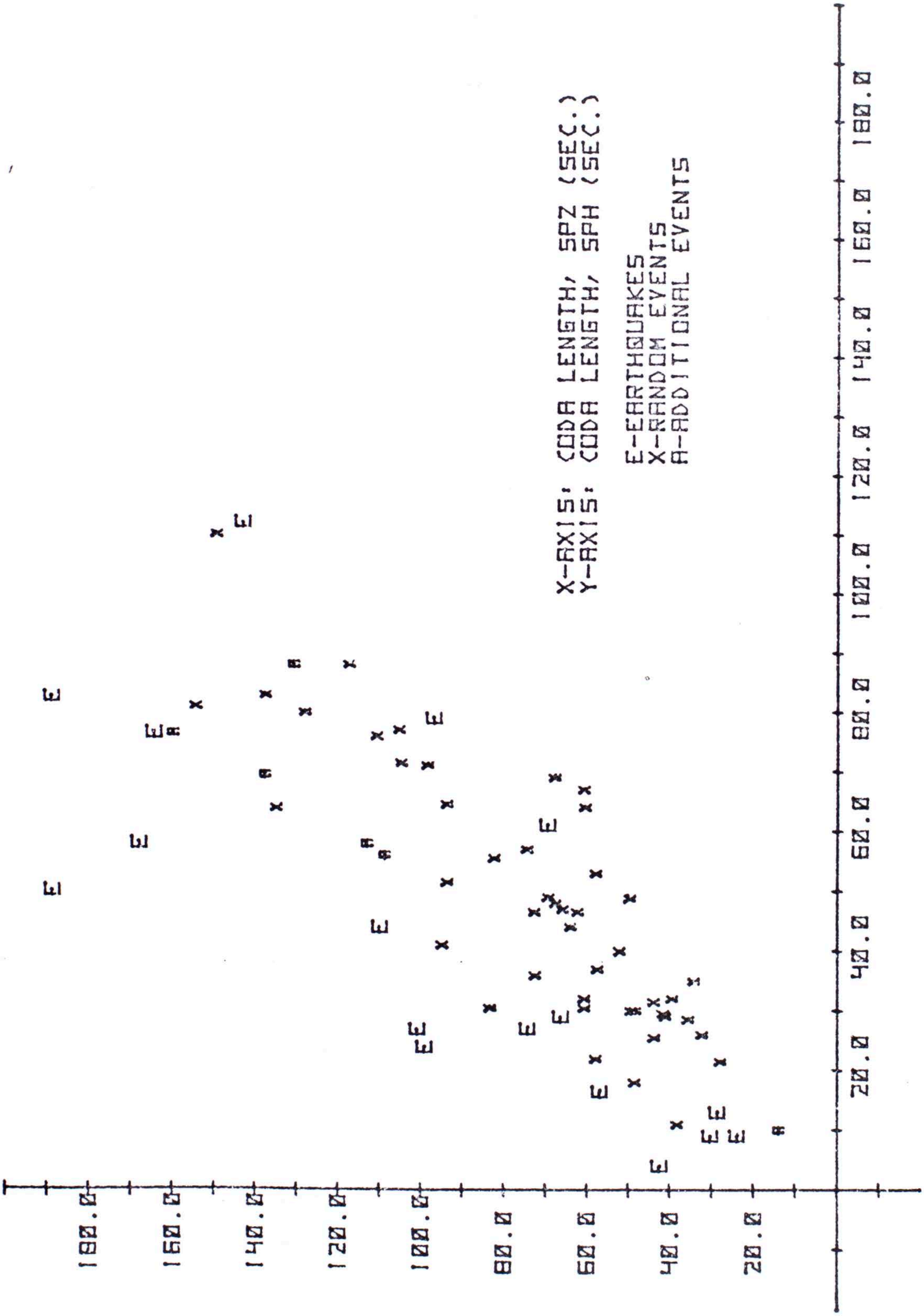

X-AXIS: CODA LENGTH, SPZ (SEC.)
Y-AXIS: CODA LENGTH, SPH (SEC.)
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0

Figure 28

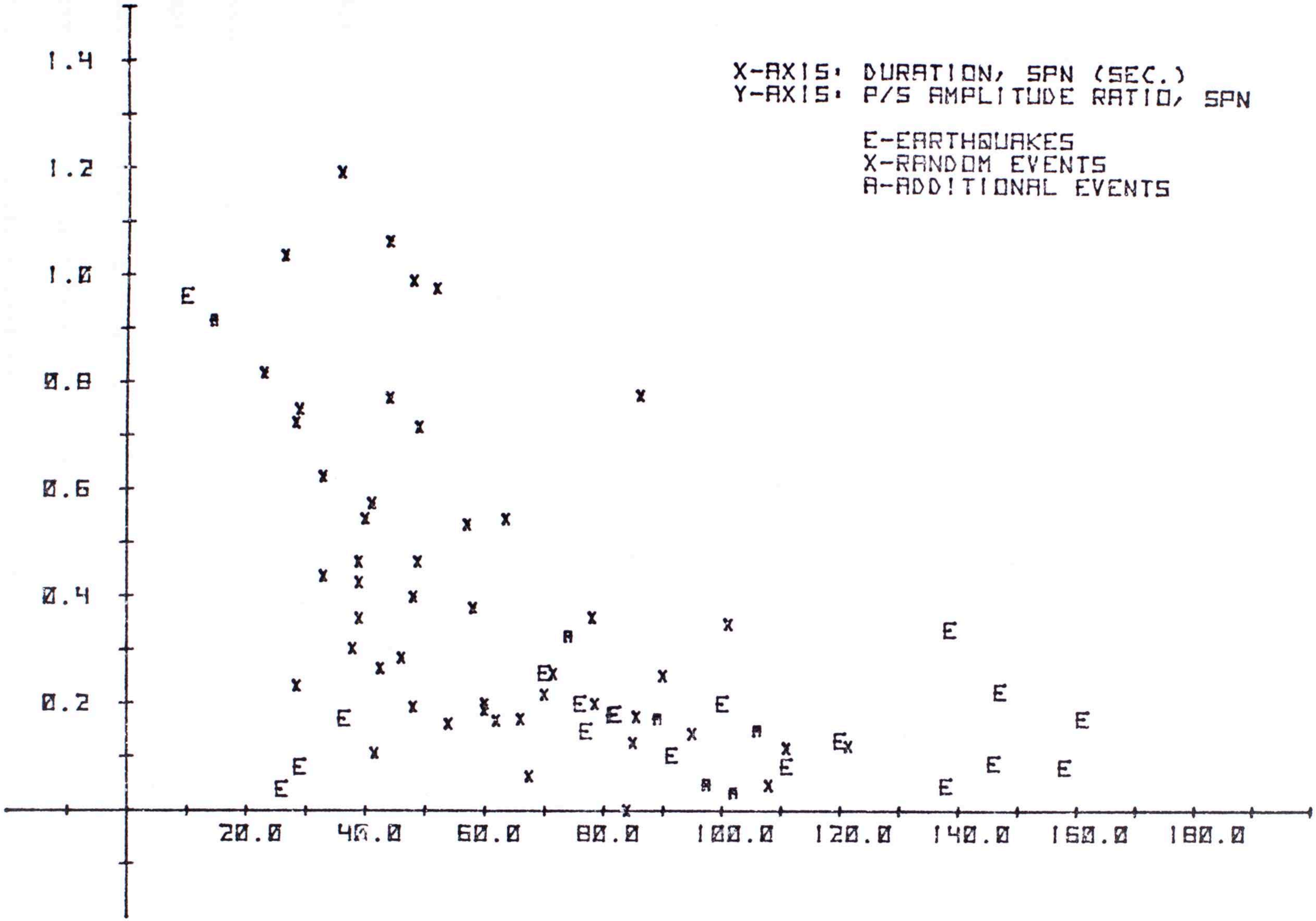

X-AXIS: DURATION, SPN (SEC.)
Y-AXIS: P/S AMPLITUDE RATIO, SPN
E-EARTHQUAKES
X-RANDOM EVENTS
A-ADDITIONAL EVENTS
1.4
1.2
1.0
0.8
0.6
0.4
0.2
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0

Figure 29

CHAPTER VI

Discussion

In applying the discriminant method as developed one must consider actual validity of the method and decide if the assumptions made in discriminant development are acceptable. One of the the first assumptions made in applying the multivariate method was that the two populations of earthquakes and other short period events have normal distributions about their means for the variables measured. It would seem that these assumptions are reasonable, as the events showed scatter above and below means with frequency decrease both ways. The other main assumption, that the variance-covariance matrices of the two groups are equal, is probably more suspect although it is widely assumed in multivariate analyses. As the group of other short period events constitutes a wide range of possible sources, the variance might be expected to be larger in relation to the closed group of events called earthquakes. As was pointed out in the Theory section, however, studies making allowances for unequal covariance have not as yet shown any improvement over those not making such allowances. Further, the discriminants resulting from assuming equal covariance in this study show very good discrimination between the groups, suggesting that either the assumption that the covariances are equal is valid or at least it is not critical in discriminant development.

One point about the discriminants developed that is perhaps disturbing is that the discriminants determined from events having a full set of variable measurements consistently had higher z-score values and thus a higher expectation of correct classification of events than those discriminants developed with variable means substituted for missing values. This could be indicative of two things. One is that the sample of events with full variable measurements is so small that not enough variance is introduced to cause overlap in the two groups. The other is that by replacing the missing values with means so much variance is introduced that a reduction of efficiency in discrimination by more variable overlap in the two groups is caused. It cannot be easily decided which of these two explanations is correct. Replacing missing values with means, however, does allow the use of more variable measurements, and might thus give more realistic or significant population description.

Another point to be considered is the validity of the z-scores and the probability of correct classification that come from them. It should be realized that the z-scores are measures of the area underneath the standard normal, or Gaussian, curve for ordinates determined from the discriminants by assuming that the discriminant function weighted values have a normal distribution within the two groups, that the two groups have group means, and that the standard deviations of the two groups are equal and defined as the difference in group means, since it has been assumed that the variance-covariance matrices of the two groups are equal. Thus the z-score is an estimate of the effectiveness of discrimination, and not an absolute figure. This is the best that can be done with a population sample; increasing the sample number should give a better estimation of the population's true characteristics.

CHAPTER VII

Test of Method

A short test of the multivariate discriminant method was performed on some possible natural earthquakes as determined by E. Tryggvason (1964). Most of the events were recorded only on SPZ and SPE with intermittent use of SPN. Discriminants based on the population samples from SPZ and SPE were therefore used in the test. The data for the events is listed in Appendix C.

The specific discriminants used in the test were Discriminant B, Discriminant C, and the last discriminant in Table 6, which will be called Discriminant D3. This last discriminant is based on P/S amplitude ratio, coda length, and duration as measured on SPZ and SPE, and is designed to test the classification of an event into the class of earthquakes on criteria other than period.

The list of weighted values for the nine events Tryggvason called possible natural earthquakes is shown in Table 8. Earthquakes have weighted values above the cutting value for all three discriminants. It can be seen that all but one of the events is classified as an earthquake by all three discriminants, and that one event which fails the test under Discriminant D3 passes the earthquake identification test for the other discriminants. A decision would have to be made by investigators whether to include this one event as an earthquake for further consideration in seismicity studies.

TABLE 8

WEIGHTED VALUES FOR DIFFERENT DISCRIMINANTS

Date	Discriminant B	Discriminant C	Discriminant D3
Aug. 11, 1962	-2.1824	1.3151	6.6239
Sep. 7, 1962	-1.2135	3.1565	7.8371
Oct. 23, 1962	-1.4740	-2.0105	7.2247
Nov. 23, 1962	-0.4364	1.6247	5.8662
Nov. 24, 1962	-3.6046	0.8587	2.7719
Feb. 2, 1963	-0.0820	2.7355	5.5414
May 7, 1963	-2.2059	-1.5957	5.2388
May 9, 1963	-2.0872	1.6816	6.2075
Jun. 5, 1963	-1.1891	1.4328	6.8576

Cutting value for Discriminant B: -6.9028
Cutting value for Discriminant C: -3.9348
Cutting value for Discriminant D3: 4.2613

CHAPTER VIII

Conclusions

First and foremost of the conclusions reached in this study is that earthquakes and other short period events can successfully be discriminated using simple measured variables. That the two groups of events are significantly different is evident from the figures in Tables 2A 2B. Only one of the variables, coda length, SPZ, fails the F test at both 95% and 99% confidence levels. Only three of the variables, P/S amplitude ratio, SPE, P/S amplitude ratio, SPH, and duration, SPZ fail the F test at the 99% confidence level, but not the 95% confidence level. Discriminantion can be achieved at at least a 90% probability of correctly classifying an event by measuring a minimum of four variables, Pg period, Sg period, coda length, and duration, on either of the seismograms from the two horizontal short period seismographs.

Although higher estimates of correct classification can be obtained by using more variables, the significance of such an increase, which is on the order of a few percent, is not very high, as the assumptions made in discriminant development cannot be rigidly supported. This suggests that a practical working discriminant to be applied to the short period seismograms recorded before HPZ started operation at TUL could be one developed for one of the horizontal seismographs,using four or, with the possible inclusion of P/S amplitude ratio, five variables.

Some important facts brought out by this study are that the variables that were thought most important in qualitative identification of earthquakes are also the most important in quantitative classification. Pg and Sg periods on the three short period seismographs are the most effective discriminants and are the main difference in earthquake and other signals. P/S amplitude ratio on the vertical short period seismograph is also important, as was suspected before quantitative evaluations, but it is much less so than the periods. The fact that the coda lengths and durations as measured on the horizontal seismograms are significantly different between the two groups whereas the coda length and duration for the vertical seismometer are not is also worth noting, as many stations operate using only vertical seismometers. This also suggests that in starting a seismic observatory it would be desirable to acquire and use one horizontal seismograph over the alternative of waiting for both or none at all. These findings are also important as seismic station TUL sometimes had in operation only one horizontal seismograph during its early days.

CHAPTER IX

Future Work

One of the first studies that would proceed where this study ends is to apply the discriminants to the seismograms recorded previous to May, 1972, when the HPZ seismograph started operation. Accumulation or cataloging of information on earthquakes found by such a study would greatly increase the knowledge of seismic activity in Oklahoma and the central United States.

Another possibility for future work is for more measurement of variables for earthquakes and other short period events to sharpen and strengthen the discriminants. Any studies into an alternate method of discrimination would also be an appropriate topic for study.

The use of multivariate discrimant analysis and statistics in general in this study has shown the desirability of such methods in geological and geophysical studies. Any other endeavor using these techniques is encouraged, as the benefits of quantitative analysis are such that they help shape the descriptive concepts widely used in the geosciences.

BIBLIOGRAPHY

Aki, K. 1972. Scaling law of earthquake source time function. Geophys. J. Roy. Astron. Soc. 31:3-25.

Aki, Keiiti, and Chouet, Bernard, 1975. Origin of coda waves: source, attenuation, and scattering effects. Jour. Gphys. Res. 80:3322-3342.

Anderson, T. W., and Bahadur, R. R. 1962. Classification into two multivariate normal distributions with different covariance matrices. Ann. Math Stat. 33:420-431.

Bakun, William H., and Johnson, Lane R. 1971. Short period spectral discriminants for explosions. Geophys. J. Roy. Astron. Soc. 22:139-152.

Berg, J. W., Trembly, L. D., and Laun, P. R. 1964. Primary ground water displacements and seismic energy near the Gnome explosion. Bull. Seis. Soc. Amer. 54:1115-1126.

Bollinger, G. A. 1971. Blast vibration analysis. Carbondale and Edwardsville: Southern Illinois University Press.

Booker, Aaron, and Mitronovas, Walter 1964. An application of statistical discrimination to classify seismic events. Bull. Seis. Soc. Amer. 54:961-971.

Dahlman, Ola, and Israelson, Hans 1977. Monitoring underground nuclear explosions. New York: Elsevier Scientific Publishing Company.

Eisenbeis, Robert A., and Avery, Robert B. 1972. Discriminant analysis and classification procedures. Lexington, Mass.: D. C. Heath and Co.

Ericsson, U. 1973. Multivariate and strength independent discrimination between underground explosions and earthquakes. Paper presented at the IASPEI meeting in Lima.

Evernden, J. F. 1977. Spectral characteristics of the P codas of Eurasian earthquakes and explosions. Bull. Seis. Soc. Amer. 67:1153-1171.

Haskell, N.A. 1967. Analytic approximation for the elastic radiation from a contained underground explosion. J. Geophys. Res. 72:2583-2587.

Hermann, Robert B. 1975. The use of duration as a measure of seismic moment and magnitude. Bull. Seis. Soc. Amer. 65:899-913.

Kalb, Bill 1964. Earthquakes that shook Oklahoma. Oklahoma's Orbit. September 27, 1964. pp. 4-7.

Koch, George S., Jr., and Link, Richard F. 1971. Statistical analysis of geological data, Volumes I and II. New York: John Wiley and Sons.

Lachenbruch, Peter A. 1975. Discriminant analysis. New York: Hafner Press.

Lawson, J. E. 1975. Detection of small local earthquakes in Oklahoma with a high-pass vertical seismograph. Geo. Soc. Amer. Abstr. Programs. 7:182. (South-Central Section 9th Annual Meeting.)

Lawson, Jim, and DuBois, Robert L. 1976. Recent field studies of felt earthquakes in Oklahoma. Oklahoma Geology Notes. 36:135-139.

Lawson, James E., Jr., DuBois, Robert L., and Foster, Paul 1977. Catalog of Oklahoma earthquakes through 1976. Oklahoma Geological Survey Open File Report. 9 pp., 1:1,000,000 scale epicenter map.

Lawson, Jim, and DuBois, Robert L. 1975. Outline of seismic facilities, Bulletin No. 15. University of Oklahoma Earth Sciences Observatory.

McCammon, R. B. 1969. Multivariate processes in geology. In: Fenner, Peter, ed. Models of Geologic Processes. RM-B-1-RM-F-6.

Overall, John E., and Klett, C. James 1972. Applied multivariate analysis. New York: McGraw-Hill Book Company.

Sammon, J. W., Foley, D., and Proctor, A. 1970. Considerations of dimensionality versus sample size. In: Proc. 1970 IEEE symposium on adaptive processes, decision, and control. IX:2.1-2.9. Austin, Texas: The University of Texas at Austin.

Simons, Richard S. 1977. Seismicity of San Diego. Bull. Seis. Soc. Amer. 67:809-826.

Spiegel, Murray R. 1975. Theory and problems in probability and statistics. New York: McGraw-Hill Book Company.

Trembly, L. D., and Berg, J. W. 1966. Amplitude and energies of primary seismic waves near the Hardhat, Haymaker, and Shoal nuclear explosions. Bull. Seis. Soc. Amer. 56:643-654.

Tryggvason, Eysteinn 1964. Seismicity of Oklahoma. Unpublished paper presented at the Seismological Society of America national meeting, 1964.

Zollweg, James E. 1974. A preliminary study of the seismicity of the central United States (1963-1974). Unpublished undergraduate report, St. Louis University.

APPENDIX A

Data for Earthquakes, Pseudo-Random Events, and Additional Events

Following is a list of the data used in developing the multivariate discriminants. It should be noted that this is not a complete list of the 1976 earthquakes occurring in Oklahoma, as some were too small to be effectively measured for variables and one occurred on a day for which the records were accidentally exposed. Data such as Pn and Sn arrival times were also measured, but space limitations do not permit their listing. Also, arrival times were measured on the SPZ, SPE, and SPN seismograms for Pg and Sg for all events. Due to space limitations this data cannot be listed either, but the listing of the earliest first arrival for the other short period events should permit anyone to find the event that has been measured.

EARTHQUAKES

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Jan. 15, 1976	02:30:54.8	SPZ	--	.1	.1	2.0	--
		SPE	--	.1	.1	7.0	--
		SPN	.96	.1	.2	10.0	9.0
Jan. 20, 1976	00:05:25.4	SPZ	.58	.3	.3	17.5	9.0
		SPE	.20	.2	.2	34.0	25.0
		SPN	.04	--	.3	26.0	17.2
Jan. 28, 1976	16:15:34.6	SPZ	156	.2	.1	98.9	78.9
		SPE	.11	.2	.1	93.0	74.0
		SPN	.18	.2	.1	82.0	63.0
Feb. 16, 1976	06:09:49.1	SPZ	1.81	.2	.2	68.5	58.0
		SPE	.52	.1	.1	139.0	128.0
		SPN	.13	.1	.2	120.0	109.0
Mar. 9, 1976	06:00:32.5	SPZ	.29	.5	.3	59.5	16.5
		SPE	.25	.2	.3	--	35.0
		SPN	.17	.3	.3	--	45.0
Mar. 16, 1976	07:39:45.3	SPZ	1.11	.1	.3	57.0	50.0
		SPE	.13	.1	.1	134.0	127.5
		SPN	.22	.1	.2	147.0	139.5
Mar. 30, 1976	09:27:02.0	SPZ	.40	.3	.5	72.0	--
		SPE	.21	.3	.5	110.0	70.5
		SPN	.34	.3	.3	138.5	98.5
Apr. 15, 1976	09:15:18.9	SPZ	--	--	.3	--	--
		SPE	--	--	.3	--	--
		SPN	--	--	.4	--	18.0

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Apr. 16, 1976	18:59:46.1	SPZ	.46	.2	.1	236.0	174.0
		SPE	.12	.2	.3	370.0	308.0
		SPN	.15	.2	.2	315.0	275.0
Apr. 17, 1976	02:48:05.7	SPZ	.49	.5	.5	58.0	27.0
		SPE	.30	.5	.4	70.0	38.0
		SPN	.20	.3	.4	100.0	64.0
Apr. 19, 1976	04:42:43.9	SPZ	.14	.3	.2	346.0	290.0
		SPE	.12	.2	.2	373.0	321.0
		SPN	--	--	--	--	--
Apr. 19, 1976	12:13:22.7	SPZ	.70	.4	.4	43.0	18.5
		SPE	.17	.3	.3	76.0	52.0
		SPN	--	.3	--	--	--
Jun. 7, 1976	01:30:49.6	SPZ	.98	.5	.4	113.0	92.0
		SPE	.21	.5	.4	81.0	58.0
		SPN	--	--	.5	--	190.0
Jun. 23, 1976	08:21:17.8	SPZ	.34	.5	.8	144.0	112.0
		SPE	.08	.4	.8	153.0	120.0
		SPN	.08	.3	.6	111.0	79.0
Jun. 23, 1976	13:51:42.2	SPZ	.64	.3	.1	11.0	4.0
		SPE	.18	.3	.3	45.0	37.0
		SPN	.08	.5	.3	28.0	21.0
Aug. 30, 1976	22:30:38.0	SPZ	.74	.5	.3	82.5	61.0
		SPE	.15	.3	.3	69.0	49.5
		SPN	.26	.3	.3	70.0	49.0
Sep. 6, 1976	18:15:26.5	SPZ	.91	.5	.4	52.5	29.0
		SPE	.11	.4	.2	64.0	40.0
		SPN	.20	.4	.2	76.0	53.0

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Sep. 20, 1976	09:40:16.2	SPZ	.55	.7	.5	46.0	13.0
		SPE	.24	.6	.3	--	26.5
		SPN	.11	.4	.5	--	11.0
Sep. 22, 1976	16:04:14.2	SPZ	.58	.6	.3	49.0	27.0
		SPE	.10	.5	.3	106.0	84.0
		SPN	.15	.3	.2	77.0	56.0
Oct. 3, 1976	16:31:08.8	SPZ	.80	.4	.3	24.0	9.0
		SPE	.08	.3	.3	24.5	9.5
		SPN	.17	.2	.2	36.5	22.0
Oct. 20, 1976	04:05:39.8	SPZ	.35	.4	.2	61.0	44.0
		SPE	.05	.5	.3	98.0	81.0
		SPN	.10	.2	.3	91.5	74.5
Oct. 22, 1976	17:15:50.5	SPZ	.36	.3	.2	99.0	82.5
		SPE	.08	.3	.2	141.5	125.0
		SPN	.08	.2	.2	158.0	142.5
Nov. 11, 1976	16:12:21.9	SPZ	.64	.5	.3	47.0	24.0
		SPE	.19	.4	.4	100.0	79.0
		SPN	.18	.4	.4	81.5	60.0
Nov. 11, 1976	19:41:35.9	SPZ	.27	.6	.3	100.0	76.5
		SPE	.08	.5	.3	138.0	--
		SPN	.05	.6	.4	138.0	--
Nov. 19, 1976	05:52:24.8	SPZ	.54	.3	.2	117.0	92.5
		SPE	.10	.3	.2	180.0	166.0
		SPN	.17	.3	.2	161.0	147.5

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Dec. 19, 1976	08:26:36.7	SPZ	.38	.2	.3	68.0	55.0
		SPE	.05	.3	.3	177.0	164.0
		SPN	.09	.3	.3	146.0	132.5

PSEUDO-RANDOM EVENTS

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
May 1, 1976	18:49:41.0	SPZ	1.22	.5	1.0	69.5	49.0
		SPE	.57	.3	.5	59.5	40.5
		SPN	.47	.2	.4	49.0	30.0
May 2, 1976	19:58:11.1	SPZ	.58	.8	.4	100.5	88.0
		SPE	.30	.8	.5	103.0	92.0
		SPN	.13	.8	.6	85.0	73.5
May 3, 1976	22:15:18.1	SPZ	.93	.8	.8	46.5	22.0
		SPE	.29	.5	.6	61.5	36.0
		SPN	.22	.6	.7	70.0	45.5
May 5, 1976	21:05:14.4	SPZ	.54	.4	1.0	25.0	18.0
		SPE	.31	.8	.5	--	29.0
		SPN	1.06	.6	.8	44.0	39.0
May 6, 1976	17:02:11.4	SPZ	.53	1.1	.9	53.0	49.0
		SPE	.43	.7	.8	40.5	37.5
		SPN	.55	1.0	.8	63.5	58.5
May 7, 1976	16:42:30.0	SPZ	.25	.7	1.0	39.5	32.0
		SPE	.14	.7	.7	53.0	49.0
		SPN	.11	.7	.7	41.5	36.0
May 8, 1976	18:02:17.8	SPZ	.15	.4	.4	121.0	110.0
		SPE	.10	.3	.6	115.0	102.5
		SPN	.12	.5	.5	121.5	109.5
May 9, 1976	19:54:36.2	SPZ	.51	.7	.7	63.5	51.5
		SPE	.36	.7	.7	87.0	76.5
		SPN	.17	.8	.8	66.0	54.5

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
May 10, 1976	17:49:15.3	SPZ	.18	.8	.7	71.5	64.0
		SPE	.19	.5	.8	108.0	100.0
		SPN	.14	.8	.6	95.0	91.0
May 11, 1976	19:38:53.7	SPZ	.38	.5	1.0	84.5	80.0
		SPE	1.33	.4	.8	105.0	100.0
		SPN	.78	.4	.7	86.0	80.5
May 12, 1976	17:56:51.0	SPZ	.24	.5	1.1	50.0	44.0
		SPE	.31	.5	.8	54.0	48.5
		SPN	.99	.6	1.0	48.0	42.0
May 13, 1976	13:02:16.7	SPZ	.58	.4	.9	48.0	29.0
		SPE	.72	.3	.9	46.0	32.0
		SPN	.58	.5	1.0	41.0	26.0
May 15, 1976	17:36:05.4	SPZ	.52	.6	.5	67.0	64.0
		SPE	.25	.5	.4	50.0	46.0
		SPN	.27	.7	.4	42.5	39.5
May 17, 1976	15:38:22.8	SPZ	.29	.4	.4	33.5	29.5
		SPE	.46	.4	.4	34.0	30.0
		SPN	.44	.3	.3	33.0	29.0
May 20, 1976	18:10:33.8	SPZ	.23	.5	.5	51.0	46.5
		SPE	.78	.5	.5	44.0	40.0
		SPN	.98	.5	.5	52.0	48.0
May 22, 1976	15:13:27.4	SPZ	.47	.5	1.0	28.0	11.0
		SPE	.44	.5	1.0	40.0	21.0
		SPN	.40	.5	1.0	48.0	32.0
May 24, 1976	12:57:57.0	SPZ	.15	.5	.9	49.5	46.5
		SPE	.30	.5	.4	55.0	52.0
		SPN	.16	.5	.6	54.0	51.0

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
May 25, 1976	12:34:03.2	SPZ	.17	.6	.8	40.0	37.0
		SPE	.23	.5	.7	48.0	45.0
		SPN	.36	.5	.3	39.0	36.0
May 26, 1976	21:49:18.4	SPZ	.40	.7	1.4	49.0	30.0
		SPE	.28	.7	.5	44.0	33.5
		SPN	.29	.7	.4	46.0	35.0
May 27, 1976	12:57:57.0	SPZ	.49	.5	.5	33.5	28.5
		SPE	.31	.4	.4	33.0	26.0
		SPN	.75	.5	.5	29.0	24.5
May 28, 1976	11:31:51.0	SPZ	.26	1.1	.9	53.0	47.0
		SPE	.10	.6	.7	48.0	42.0
		SPN	.54	.8	.7	57.0	51.0
May 29, 1976	17:55:48.2	SPZ	.30	.5	1.1	48.0	40.0
		SPE	.53	.5	1.0	44.0	37.0
		SPN	.77	.5	.4	44.0	37.0
Sep. 1, 1976	22:01:15.2	SPZ	.87	.7	.8	51.0	25.5
		SPE	.22	.8	.8	52.0	26.5
		SPN	.19	1.0	.7	60.0	35.0
Sep. 3, 1976	17:08:45.3	SPZ	.14	1.2	1.0	51.5	48.0
		SPE	.19	.5	.4	46.0	41.0
		SPN	.38	.5	.8	58.0	54.0
Sep. 4, 1976	20:31:31.6	SPZ	.25	.8	1.0	--	76.0
		SPE	.26	.7	.9	104.0	84.0
		SPN	.25	1.0	.9	90.0	72.5
Sep. 5, 1976	19:39:57.6	SPZ	.57	.7	.4	58.0	41.0
		SPE	.28	.7	.5	84.0	72.5
		SPN	.36	.7	.2	78.0	61.5

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Sep. 6, 1976	21:26:39.7	SPZ	.25	.4	.7	63.0	53.0
		SPE	.06	.5	.6	53.0	43.0
		SPN	.19	.3	.5	48.0	39.0
Sep. 7, 1976	19:00:44.7	SPZ	.08	.3	.8	38.5	35.0
		SPE	.06	.7	.7	24.0	22.5
		SPN	.23	.4	.7	28.5	26.0
Sep. 8, 1976	15:11:43.8	SPZ	.28	.5	1.0	29.0	26.0
		SPE	.16	.6	.5	28.0	25.5
		SPN	.82	.4	.4	23.0	20.0
Sep. 9, 1976	13:46:31.0	SPZ	--	--	.8	--	--
		SPE	.17	.8	1.0	21.0	20.5
		SPN	.73	.6	1.0	28.5	20.0
Sep. 10, 1976	16:00:12.7	SPZ	.15	.5	.5	30.0	23.0
		SPE	.57	.8	.9	--	--
		SPN	.30	.5	.8	38.0	31.5
Sep. 11, 1976	14:24:57.3	SPZ	.21	.4	1.0	35.0	31.5
		SPE	.15	.4	.9	38.0	33.5
		SPN	.63	.5	.5	33.0	28.5
Sep. 12, 1976	19:48:45.2	SPZ	.63	.8	1.0	69.5	57.0
		SPE	.30	.8	1.0	68.5	55.5
		SPN	.17	.8	1.0	62.0	50.0
Sep. 13, 1976	13:38:22.8	SPZ	.49	.4	.3	33.0	30.0
		SPE	.34	.7	.4	36.0	33.0
		SPN	.55	.5	.4	40.0	37.0
Sep. 14, 1976		SPZ	.44	.8	.8	71.0	67.0
		SPE	.88	.4	.5	46.0	41.0
		SPN	.72	.2	.3	49.0	45.0

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Sep. 16, 1976	18:07:50.1	SPZ	.15	.5	1.0	47.0	36.0
		SPE	.30	.5	1.0	52.0	41.0
		SPN	.26	.7	1.0	71.5	60.0
Sep. 17, 1976	18:11:30.0	SPZ	.13	.5	1.0	95.0	83.0
		SPE	.10	.5	.8	112.0	100.0
		SPN	.05	.5	1.0	108.0	95.0
Sep. 19, 1976	19:54:33.7	SPZ	.92	.8	.3	76.0	64.5
		SPE	.28	.6	.6	69.0	58.0
		SPN	.18	.8	.3	85.5	74.0
Sep. 20, 1976	22:46:03.9	SPZ	.05	.4	1.0	60.0	55.5
		SPE	.07	.4	.7	59.0	54.0
		SPN	.06	.4	.7	67.5	62.5
Sep. 21, 1976	13:40:27.0	SPZ	.40	.7	.9	26.0	21.5
		SPE	2.29	.4	.5	26.5	20.5
		SPN	1.04	.6	.9	26.5	19.0
Sep. 22, 1976	17:12:20.8	SPZ	.17	.5	1.0	82.5	71.5
		SPE	.12	.4	.5	85.5	75.5
		SPN	.11	.8	.5	84.0	73.0
Sep. 23, 1976	19:33:54.0	SPZ	.16	.5	1.0	70.0	69.0
		SPE	.18	.5	1.0	54.0	45.0
		SPN	.20	.6	1.0	60.0	51.0
Sep. 24, 1976	13:49:30.9	SPZ	.48	.5	.5	33.5	30.5
		SPE	.35	.4	.4	52.0	49.0
		SPN	.43	.4	.4	39.0	36.0
Sep. 25, 1976	13:58:16.4	SPZ	.24	.5	.5	93.0	81.0
		SPE	.33	.5	.5	.29.0	118.0
		SPN	.12	.4	.5	111.0	100.0

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Sep. 26, 1976	13:58:16.4	SPZ	.30	1.0	1.0	93.0	71.0
		SPE	.23	.7	.9	82.0	60.5
		SPN	.35	.7	.9	101.0	78.0
Sep. 27, 1976	22:23:55.0	SPZ	.57	.5	1.0	90.0	77.0
		SPE	.17	.3	.5	95.0	82.0
		SPN	.20	.3	.5	78.5	66.5
Sep. 28, 1976	17:57:17.6	SPZ	.59	.5	1.0	37.5	32.0
		SPE	.71	.5	1.0	36.0	28.0
		SPN	1.19	.5	1.0	36.0	28.0
Sep. 29, 1976	13:33:03.0	SPZ	.39	.4	.3	34.0	30.5
		SPE	.34	.6	.3	79.0	75.5
		SPN	.46	.4	.6	39.0	35.5

ADDITIONAL EVENTS

Date	Earliest First Arrival(UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Sep. 18, 1976	21:57:51.4	SPZ	.54	.5	.3	15.0	10.0
		SPE	.15	.8	.3	11.5	8.5
		SPN	.91	.4	.5	14.5	11.0
Sep. 15, 1976	22:02:08.9	SPZ	.08	.5	.7	63.5	58.0
		SPE	.06	.5	.7	92.0	89.0
		SPN	.33	.5	.7	74.0	70.0
Nov. 16, 1976	23:04:50.3	SPZ	.05	.4	.6	81.0	76.5
		SPE	.02	.5	.4	134.5	130.0
		SPN	.05	.4	.5	97.5	93.5
May 3, 1976	22:16:44.9	SPZ	.08	.5	.7	72.0	69.5
		SPE	.04	.4	.7	98.5	95.0
		SPN	.03	.4	.4	102.0	100.0
May 3, 1976	19:58:24.4	SPZ	.14	.7	.5	67.0	56.0
		SPE	.16	.5	.5	88.0	76.0
		SPN	.17	.3	.5	89.0	78.0
May 3, 1976	21:07:06.6	SPZ	.05	.4	.7	92.0	88.0
		SPE	.03	.4	.6	87.0	83.0
		SPN	.15	.4	.8	106.0	101.5

APPENDIX B

COMPUTER PROGRAMS USED

Following is a list of the computer programs used in this study. Some of these programs, such as the data loading and data listing programs, are quite simple and can easily be tailored to the preferences of the user. It should be noted that some of the programs have been designed specifically for use with the number of events used in this study, while others have not. Any adaptation of these programs will thus require a change in this respect.

Some remarks on the DISCRIMINANT programs are in order:

(1) Means computed from all possible values are used in computations where events having one or more missing variable values are done. This is done to better approximate the population mean. The number of events in each group, n_1 and n_2, are adjusted for event deletion.

(2) The method of covariance computation used in the program is

$$c_{ij} = (1/(n_1 + n_2 - k))(\sum_{g=1}^{2} \Sigma(x_i - \bar{x}_i)\ (x_j - \bar{x}_j)).$$

This is used to avoid problems with keeping track of the number of replaced values that is required by the method

$$c_{ij} = (1/(n_1 + n_2 - k))\sum_{g=1}^{2} (\Sigma\ x_i x_j - \Sigma x_i\ \Sigma x_j / n_g)$$

where n_g is the number of events in a group, x_i and x_j are variable measurements for variables i and j, and k is the number of variables. When no values are missing, the above two forms of covariance computation are exactly equal. Error may be introduced when x_i or x_j have been summed over different numbers with each group g.

(3) The program has been designed specifically for the 80 event observations made in this study. To alter the program for more general use a parameter E could be introduced, where E would be the last number in group one. Replacement throughout the program would be done as follows:

E replaces 26 in for, next loops, mean calculations, covariance, F test,etc.

N replaces 84 in all similar uses

E+1 replaces 27 in all similar uses

N-E replaces 58 in all similar uses.

(4) The "SOLVE" subroutine for solving simultaneous equations was adapted from the Hewlett-Packard software package that comes with the HP-9825-A computer. The "SOLVE" subroutine uses a modified Gauss-Jordan method for solving simultaneous equations. Use of the "SOLVE" subroutine involves the following parameters and variables:

<u>INPUT</u>

K   number of equations (unknowns)

C[K,K+1]   matrix of coefficients where the first subscript is the row

<u>OUTPUT</u>

K   unchanged

X[K]   vector of solutions X_i for i = 1 to K

flg 4   set if the determinant of the matrix of coefficients is zero, indicating that the system is unsolvable

DESTROYED

B	current largest (in magnitude) element in search for pivot; also used for pivot
I	loop counter used as row subscript
J	loop counter used as column subscript
L	loop counter
R	row which contains largest pivot available
S	partial sum used in backsolve process
T	temporary storage
C[K,K+1]	matrix of coefficients

```
0: "DISCRIMINANT":
1: "BY KEVIN WOLLER":
2: "MARCH, 1978":
3: ent "Number of variables?",K
4: ent "Number of observations?",N
5: dim V[K,N],F[K],C[K,K+1],D[2,K],M[2,K],K$[K,10],X[N]
6: dim S[2,K],Q[2,K,K],W[2]
7: for A=1 to K
8: ent "Variable name?",K$[A]
9: ent "Variable file number?",F[A]
10: ldf F[A],X[*]
11: for B=1 to N
12: X[B]→V[A,B]
13: next B
14: next A
15:
16: "Mean computation":
17: for A=1 to K
18: 0→X;0→Y
19: for B=1 to 26
20: if V[A,B]=99999;X+1→X
21: if V[A,B]=99999;jmp 2
22: S[1,A]+V[A,B]→S[1,A]
23: next B
24: for C=27 to 84
25: if V[A,C]=99999;Y+1→Y
26: if V[A,C]=99999;jmp 2
27: S[2,A]+V[A,C]→S[2,A]
28: next C
29: S[1,A]/(26-X)→M[1,A]
30: S[2,A]/(58-Y)→M[2,A]
31: M[1,A]-M[2,A]→C[A,K+1]
32: next A
33:
34: ent "Do you want missing values replaced with means?",O
35: ent "1=YES,0=NO",O
36: if O=1;cll 'Replace'
37: if O=0;cll 'Delete'
38:
39: "Covariance Matrix":
40: for A=1 to K
41: for B=1 to A
42: for C=1 to 26
43: if V[A,C]=99999;jmp 3
44: if V[B,C]=99999;jmp 2
45: Q[1,A,B]+(V[A,C]-M[1,A])(V[B,C]-M[1,B])→Q[1,A,B]
46: next C
47: for C=27 to 84
48: if V[A,C]=99999;jmp 3
49: if V[B,C]=99999;jmp 2
50: Q[2,A,B]+(V[A,C]-M[2,A])(V[B,C]-M[2,B])→Q[2,A,B]
51: next C
```

```
(Q[1,A,B]+Q[2,A,B])/(84-X-Y-2)→C[A,B]
C[A,B]→C[B,A]
next B
next A

"Standard Deviations":
prt "List of means and standard deviations for groups
spc 2                                              one and two:"
for A=1 to K
√(Q[1,A,A]/(26-X-1))→D[1,A]
√(Q[2,A,A]/(58-Y-1))→D[2,A]
prt "     For",K$[A]
prt "Mean for group one:",M[1,A]
prt "Standard deviation:",D[1,A]
prt "Mean for group two:",M[2,A]
prt "Standard deviation:",D[2,A];spc 2
next A
spc 4

prt "List of covariance matrix coefficients:";spc 2
for A=1 to K
for B=1 to K
fxd 0
prt "              I=",A
prt "              J=",B
fxd 4
prt "C[I,J]=",C[A,B]
next B
next A
spc 4

cll 'SOLVE'

prt "The weighting coefficients are:";spc 2
for A=1 to K
prt "Weight for",K$[A]
prt X[A];spc 1
next A
spc 4.
spc 4
prt "The weighted group means are:";spc 2
for A=1 to K
X[A]M[1,A]+W[1]→W[1]
X[A]M[2,A]+W[2]→W[2]
next A
prt "For Group One:",W[1]
prt "For Group Two:",W[2]
(W[1]+W[2])/2→P
prt "Discriminant value for no a priori expectation:",P
W[1]-W[2]→V
prt "Z(1)=",(P-W[1])/√abs(V)
prt "Z(2)=",(P-W[2])/√abs(V)
```

```
104: spc 3
105:
106: "F test":
107: prt "F test value forthe K variables:";spc 1
108: (26)58(26+58-K-1)V/K(26+58)(26+58-2)→F
109: prt "     F=",F
110: spc 4
111:
112: end.
113:
114: "SOLVE":cfg 4;0→I
115: if (I+1→I)=K;gto +16
116: I-1→L;0→B
117: if (L+1→L)>K;gto +3
118: if (abs(C[L,I])→T)>B;T→B;L→R
119: gto -2
120: if B=0;sfg 4;dsp "DET=0";ret
121: I→J;if I=R;gto +2
122: C[I,J]→T;C[R,J]→C[I,J];T→C[R,J];jmp (J+1→J)>K+1
123: I+1→J;C[I,I]→B
124: C[I,J]/B→C[I,J];jmp (J+1→J)>K+1
125: I→L
126: if (L+1→L)>K;gto -11
127: I+1→J
128: C[L,J]-C[L,I]C[I,J]→C[L,J];jmp (J+1→J)>K+1
129: gto -3
130: if C[K,K]=0;0→B;gto -10
131: C[K,K+1]/C[K,K]→X[K];K→I
132: if (I-1→I)<1;ret
133: 0→S;K→L
134: C[I,L]X[L]+S→S;jmp (L-1→L)<=I
135: C[I,K+1]-S→X[I];gto -3
136:
137: "Replace":
138: for A=1 to K
139: for B=1 to 26
140: if V[A,B]=99999;M[1,A]→V[A,B]
141: next B
142: for C=27 to 84
143: if V[A,C]=99999;M[2,A]→V[A,B]
144: next C
145: next A
146: 0→X;0→Y
147: prt "Missing values replaced with means.";spc 2
148: ret
149:
150: "Delete":
151: for A=1 to K
152: 0→X;0→Y
153: for B=1 to 84
154: if V[A,B]≠99999;jmp 6
155: for C=1 to K
```

```
156: 99999→V[C,B]
157: next C
158: if B<=26;X+1→X
159: if B>26;Y+1→Y
160: next B
161: next A
162: prt "Values for observations with missing values deleted."
163: spc 2
164: ret
*29864
```

Program for Weighting Observations

```
0: "Weighted observations":
1: ent "Number of variables?",K
2: ent "Number of observations?",N
3: dim V[K,N],K$[K,10],F[K],X[N],W[K],Z[N]
4: for A=1 to K
5: ent "Variable name?",K$[A]
6: ent "Variable file no.?",F[A]
7: ldf F[A],X[*]
8: ent "Variable weight?",W[A]
9: for B=1 to N
10: W[A]X[B]→V[A,B]
11: if X[B]=99999;99999→V[A,B]
12: next B
13: next A
14:
15: for A=1 to N
16: for B=1 to K
17: Z[A]+V[B,A]→Z[A]
18: next B
19: for L=1 to K
20: if V[L,A]=99999;99999→Z[A]
21: next L
22: next A
23:
24: ent "File no.for weighted sets?",G
25: rcf G,Z[*]
26: prt "Weighted observations for variables:"
27: for C=1 to K
28: prt K$[C]
29: next C
30: prt "Stored in file",G
31: end
*28788
```

X-Y Plotting Program

```
0: ent "N=",N
1: dim X[N],Y[N]
2: ent "File no. for data set 1?",F
3: ent "File no. for data set 2?",G
4: ent "Smallest X value?",A
5: ent "Largest X value?",B
6: ent "Smallest Y value?",C
7: ent "Largest Y value?",D
8: ent "X tic division?",T
9: ent "Y tic division?",V
10: ent "X origin location?",O
11: ent "Y origin location?",P
12: if A>=0;O-2T→A
13: if C>=0;P-2V→C
14: scl A,B,C,D
15: if A+2T=0;0→A
16: if C+2V=0;0→C
17: axe O,P,T,V
18: csiz 1.5
19: "yaxis":
20: fxd 1
21: C+2*V→C
22: plt 0,C,1
23: cplt -5,-.3
24: lbl C
25: if C<D-2*V;gto "yaxis"
26: "xaxis":
27: fxd 1
28: A+2*T→A
29: plt A,0,1
30: cplt -2.5,-1.3
31: lbl A
32: if A<B-2*T;gto "xaxis"
33: fxd 2
34: ldf F,X[*]
35: ldf G,Y[*]
36: for J=1 to N
37: if X[J]>200;gto "cont"
38: if Y[J]>200;gto "cont"
39: if J<=26;gto "earth"
40: if J>=79;gto "extra"
41: plt X[J],Y[J]
42: cplt -.3,-.3
43: csiz 1
44: lbl "x"
45: pen
46: gto "cont"
47: "earth":
```

```
48: plt X[J],Y[J]
49: cplt -.3,-.3
50: lbl "e"
51: pen
52: gto "cont"
53: "extra":
54: plt X[J],Y[J]
55: cplt -.3,-.3
56: csiz 1
57: lbl "a"
58: pen
59: "cont":
60: next J
61: csiz 1.5
62: prt "Label plot.";ptyp
63: end
*9072
```

Correlation Coefficient Program

```
0: "Correlation Coefficient":
1: dim A$[10],B$[10]
2: ent "Name of first set?",A$
3: ent "Name of second set?",B$
4: ent "Number of observations?",N
5: dim X[N],Y[N]
6: ent "File no. for first set?",F
7: ent "File no. for second set?",G
8: ldf F,X[*]
9: ldf G,Y[*]
10: for J=1 to N
11: if X[J]=99999;K+1→K
12: if X[J]=99999;jmp 5
13: if Y[J]=99999;L+1→L
14: if Y[J]=99999;jmp 3
15: A+X[J]→A
16: B+Y[J]→B
17: next J
18: A/(N-K)→A
19: B/(N-L)→B
20: for I=1 to N
21: if X[I]=99999;99999→Y[I]
22: if Y[I]=99999;jmp 4
23: Q+(X[I]-A)(Y[I]-B)→Q
24: S+(X[I]-A)↑2→S
25: T+(Y[I]-B)↑2→T
26: next I
27: Q/√(ST)→R
28: prt "Correlation coefficient between",A$,B$
29: prt "R=",R
30: end
*26169
```

Data Loading Program

```
0: "Data Loading":
1: ent "File number?",F
2: ent "N=",N
3: dim V[N]
4: for J=1 to N
5: ent "Variable?",V[J]
6: next J
7: rcf F,V[*]
8: beep
9: end
*27095
```

Data Editing Program

```
0: dim V[84]
1: ent "File number?",F
2: ldf F,V[*]
3: ent "N=?",N
4: ent "Variable=?",V
5: V→V[N]
6: ent "Do you want more corrections?",Y
7: ent "1=YES,0=NO",D
8: if D=1;gto 3
9: rcf F,V[*]
10: beep
11: end
*15556
```

Data Listing Program

```
0: ent "File No.?",F
1: rew
2: ent "N=",N
3: dim V[N]
4: ldf F,V[*]
5: for L=1 to N
6: prt "No.",L,"V=",V[L]
7: next L
8: end
*8332
```

Program for Computing P/S Ratios

```
0: ent "N=",N
1: dim A[N],B[N],C[N]
2: ent "File no. for P cmp.?",P
3: ent "File no. for S cmp.?",S
4: ldf P,A[*]
5: ldf S,B[*]
6: for J=1 to N
7: A[J]/B[J]→C[J]
8: next J
9: ent "File no. for P/S ratio?",T
10: rew
11: rcf T,C[*]
12: end
*21743
```

Program for Computing Products of Two Variables

```
0: ent "N=?",N
1: dim A[N],B[N],C[N]
2: ent "File no. for first data set?",F
3: ent "File no. for second data set?",G
4: ldf F,A[*]
5: ldf G,B[*]
6: for J=1 to N
7: if A[J]>1000;gto "skip"
8: if B[J]>1000;gto "skip"
9: A[J]*B[J]→C[J]
10: "cont":
11: next J
12: gto "store"
13: "skip":
14: 99999→C[J]
15: gto "cont"
16: "store":
17: ent "File no. for new data set?",H
18: rcf H,C[*]
19: end
*23962
```

APPENDIX C

List of Data for Events Used in Discriminant Test

Following is a tabulation of the data for events listed by Tryggvason (1964) as possible natural earthquakes. Use of the SPN seismograph was sporadic at this time, accounting for the numerous omissions of data for SPN.

DISCRIMINANT TEST DATA

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Aug. 11, 1962	20:47:19.0	SPZ	.20	.3	.2	98.0	74.0
		SPE	.17	.2	.3	127.0	103.0
		SPN	--	--	--	--	--
Sep. 7, 1962	22:53:44.0	SPZ	.57	.2	.2	73.0	35.0
		SPE	.14	.3	.2	135.0	98.0
		SPN	.24	.4	--	93.0	61.0
Oct. 23, 1962	17:55:58.0	SPZ	.56	.6	.5	91.5	56.5
		SPE	.22	.2	.3	145.0	113.0
		SPN	.22	.4	.5	137.0	108.0
Nov. 23, 1962	12:35:11.5	SPZ	.80	.2	.2	34.0	19.0
		SPE	.20	.1	.1	58.0	43.0
		SPN	--	--	--	--	--
Nov. 24, 1962	21:03:04.0	SPZ	.40	.2	.1	31.0	16.0
		SPE	.10	.3	.2	30.5	16.0
		SPN	--	--	--	--	--
Feb. 2, 1963	16:57:39.0	SPZ	.67	.2	.2	112.0	80.0
		SPE	.24	.2	.2	116.0	75.0
		SPN	--	--	--	--	--
May 7, 1963	20:03:29.0	SPZ	.56	.6	.2	150.0	127.0
		SPE	.10	.3	.2	151.5	130.0
		SPN	--	--	--	--	--
May 9, 1978	21:19:27.5	SPZ	.60	.1	.2	52.0	36.0
		SPE	.88	.2	.2	102.5	88.0
		SPN	--	--	--	--	--

Date	Origin Time (UTC)	Seismograph	P/S Amplitude Ratio	Tp(sec.)	Ts(sec.)	Duration (sec.)	Coda Length (sec.)
Jun. 5, 1963	17:02:08.0	SPZ	.61	.2	.2	101.0	79.5
		SPE	.24	.2	.2	151.0	129.0
		SPN	--	--	--	--	--