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IMPROVED PROCEDURES FOR DETERMINING SEISMIC SOURCE DEPTHS FROM DEPTH PHASE INFORMATION

FINAL REPORT

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This work has been directed towards evaluating the utility of ENSCO's teleseismic source depth determination procedure as a nuclear discriminant, and also towards simplifying interpretation of the program output. This depth determination procedure, developed during four previous ARPA-sponsored projects, uses cepstrum analysis techniques to detect depth phases, converts delay times to depths using computed travel times, and combines results from

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different primary phases (P,PP,PPP,PcP) and stations to get a single depth estimate for an event. Thus, this technique automatically makes use of all available depth phase information in arriving at an estimated depth.

Evaluation of the technique was carried out using data from the discrimination experiment data set. To facilitate analysis of this data, the program was implemented at the Seismic Data Analysis Center (SDAC). The final implemented version contains three new program features designed to aid the analyst in interpreting the output.

Most events were analyzed using the unclassified discrimination experiment data set. This data had very sparse station coverage for almost all events, and it was concluded that this depth determination procedure is not suitable for such a data set. A total of 41 events were examined, but only 18 depth estimates could be made, and most of these were unreliable due to poor station coverage. Some analysis was also done using the complete discrimination experiment data set. This has much better coverage and promises to produce better results.

SUBJECT: Improved Procedures for Determining Seismic Source Depths from Depth Phase Information

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1.0 INTRODUCTION

This report describes program development work done on ENSCO's teleseismic source depth determination procedure, along with data analysis designed to evaluate its utility as a seismic discriminant. Source depth can be used to discriminate between earthquakes and explosions if events can be classified as being deeper or shallower than some limiting drilling depth. Then all events deeper than this depth must be earthquakes, and the use of other discrimination techniques may be confined to the shallower events.

ENSCO's depth determination procedure, developed during a series of ARPA-sponsored projects, applies cepstrum analysis techniques to depth phase detection for a set of stations and primary phases. The first project (VT-4710) showed that applying cepstrum techniques to the P-wave coda, including possible PP, PPP, and PcP arrivals, improves delay time estimates for "little p" and "little s" depth phases. Project VT-5710 demonstrated the use of travel time information to constructively stack cepstrums from different stations and primary phases, thus improving depth phase detectability. In Project VT-6710, this technique was automated to yield "depth plot" displays that can easily be interpreted by an analyst to get a source depth estimate. Finally, Project VT-7710 incorporated several improvements, including an algorithm to determine the significance of a depth estimate, and applied the depth determination procedure to approximately 10 new events. At the end of this project, it was concluded that this technique was ready for large scale testing.

The principal effort in this project has been directed toward this large scale testing - the discrimination experiment being run by the VELA Seismological Center (VSC). Work was performed in two phases: implementation of the depth determination procedure at the Seismic Data Analysis Center (SDAC), and analysis of events from the discrimination experiment data set.

Implementation at SDAC was started during Project VT-7710 and completed during Project VT-8710, and was intended to facilitate processing of discrimination experiment data. The basic structure of this program was described in the Final Report for VT-7710, but the final implemented version contains three new program features not previously described: cepstrum phase editing, an improved significance level algorithm, and computation of a significance threshold due to data bandwidth. Phase editing gives the analyst the option of editing cepstrums point-by-point, based on the phase of each cepstrum point, before generating depth plots. The new significance level algorithm improves the statistical base of the significance level estimates by making five random delay time passes of each cepstrum instead of just one. Finally, the bandwidth-based significance threshold gives the analyst a quantitative estimate of the shallowest depth that can be determined due to the bandwidth of the input seismograms.

In the data analysis portion of the project, events from the discrimination experiment data set were analyzed to evaluate the utility of this depth determination technique as a discriminant. A qualitative reliability grade was assigned to each resulting depth estimate. Assuming that events deeper than 80 km can easily be screened out using another technique (such as P arrival times), the estimated depth can be used to classify an event as a possible explosion. Most events have been analyzed using only an unclassified data set. The complete data set became available near the end of the project, but, since substantial program changes were necessary to handle this data, only three events were processed using this data set. Since the complete data set is much more suitable for this depth determination technique, further analysis of this data is really necessary for a final evaluation.

2.0 PROGRAM DEVELOPMENT

To facilitate processing of discrimination experiment data, the depth determination procedure has been implemented at SDAC. This version of the program contains three new features not described in the Final Report for Project VT-7710: phase editing, an improved significance level algorithm, and calculation of a narrow band threshold. After a brief general description of the operation of the SDAC program, the concepts behind each of these new features will be discussed. A detailed description of the actual algorithms is given in the computer documentation.

2.1 IMPLEMENTATION OF BASIC SYSTEM

Implementation of the basic seismic source depth determination system, including all Calcomp plot options, control parameter override capabilities, and RUN files for job submission, has been completed. Two RUN files have been set up: one for executing the entire depth determination procedure starting from the seismograms, and another for executing only the second part of the procedure with a new set of analysis parameters, starting from a set of previously computed cepstrums. In a "second pass" run, any control parameter may be changed, and different combinations of stations and analysis start and end times may be used. The basic output of the program is a set of Calcomp depth plots, shown in Figure 1. Seismogram plots (Figure 2) and plots of individual cepstrums (Figure 3) may also be obtained, if desired.

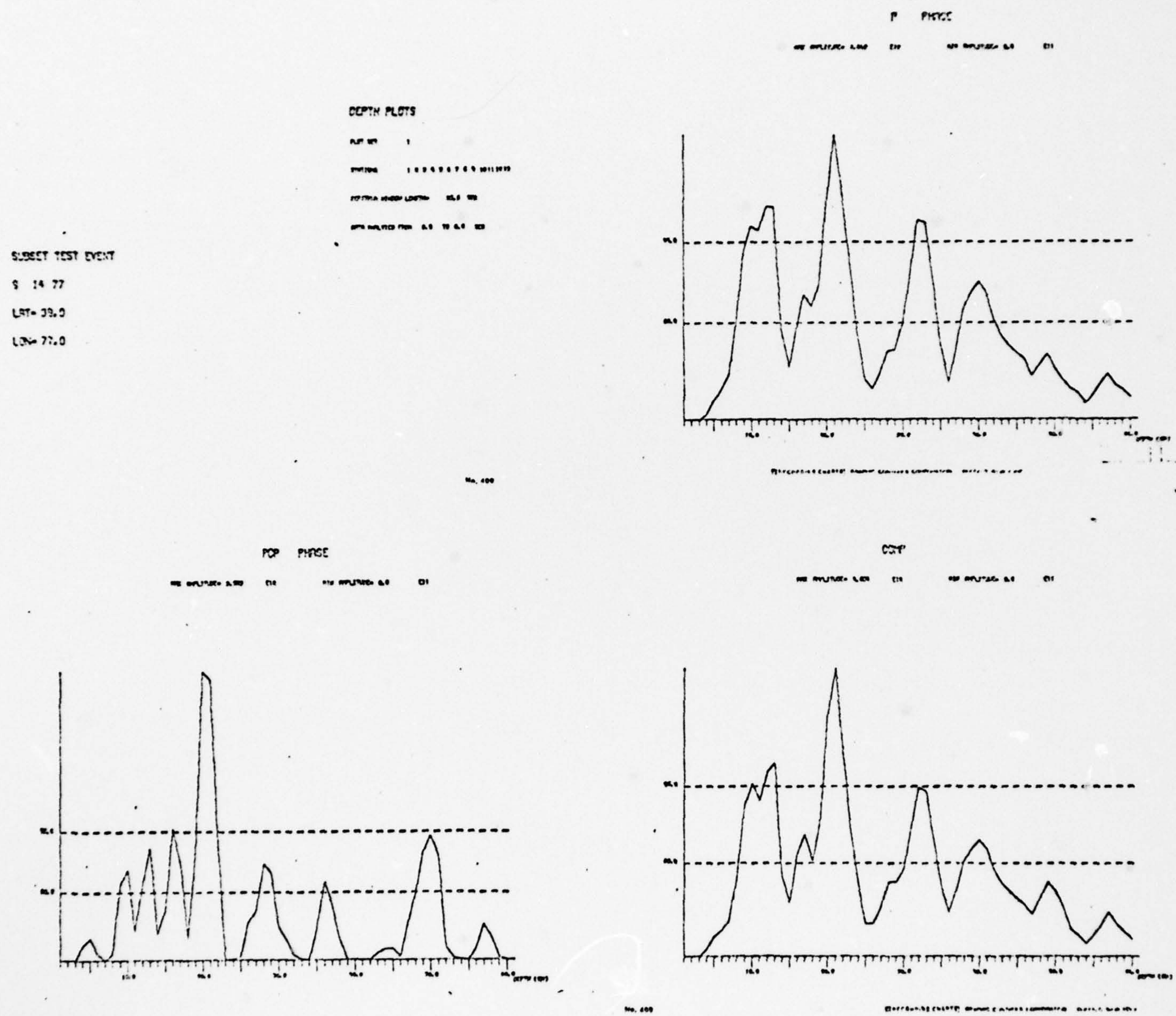

Figure 1. Depth Plots

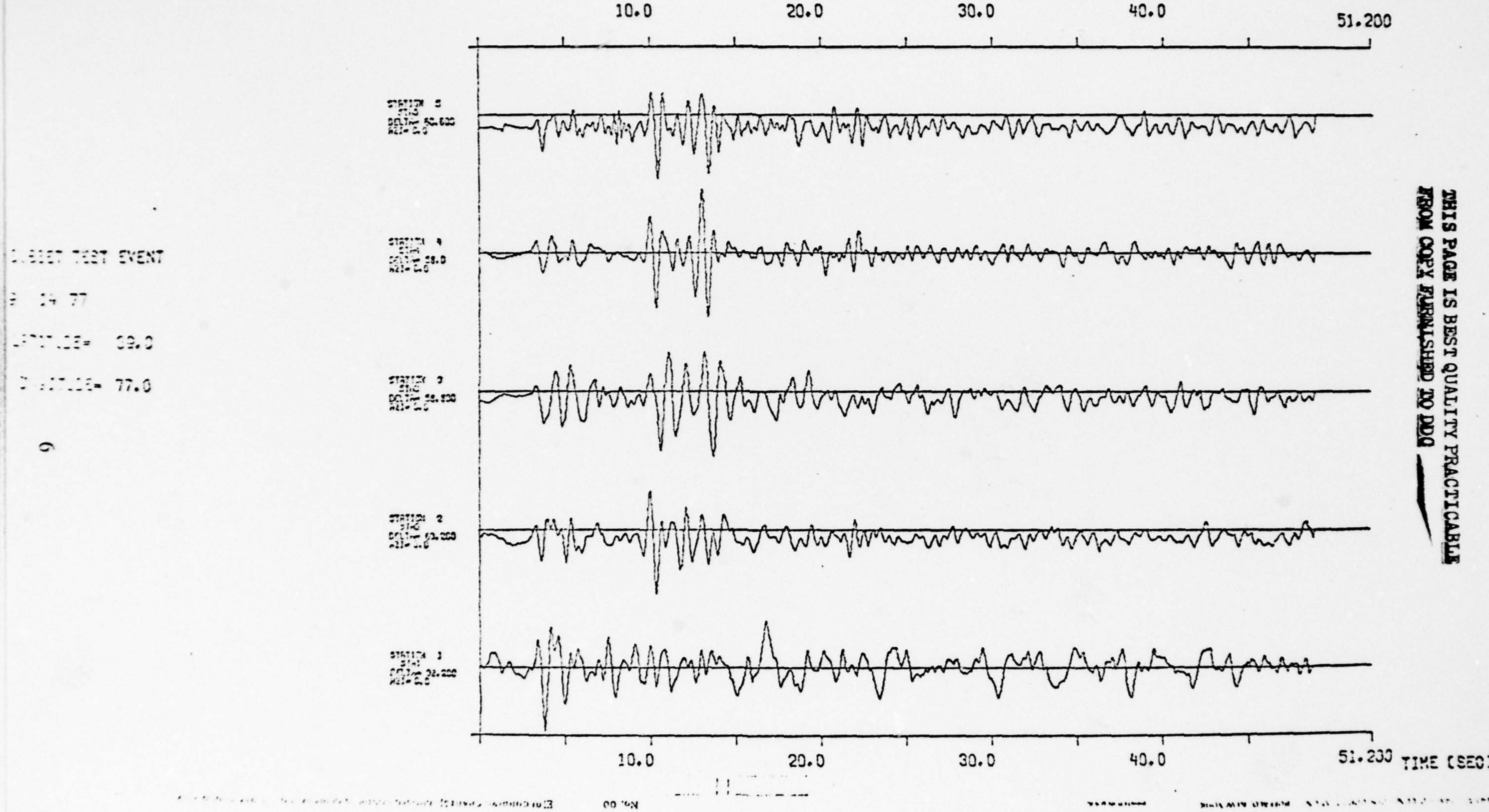

Figure 2. Seismogram Plot

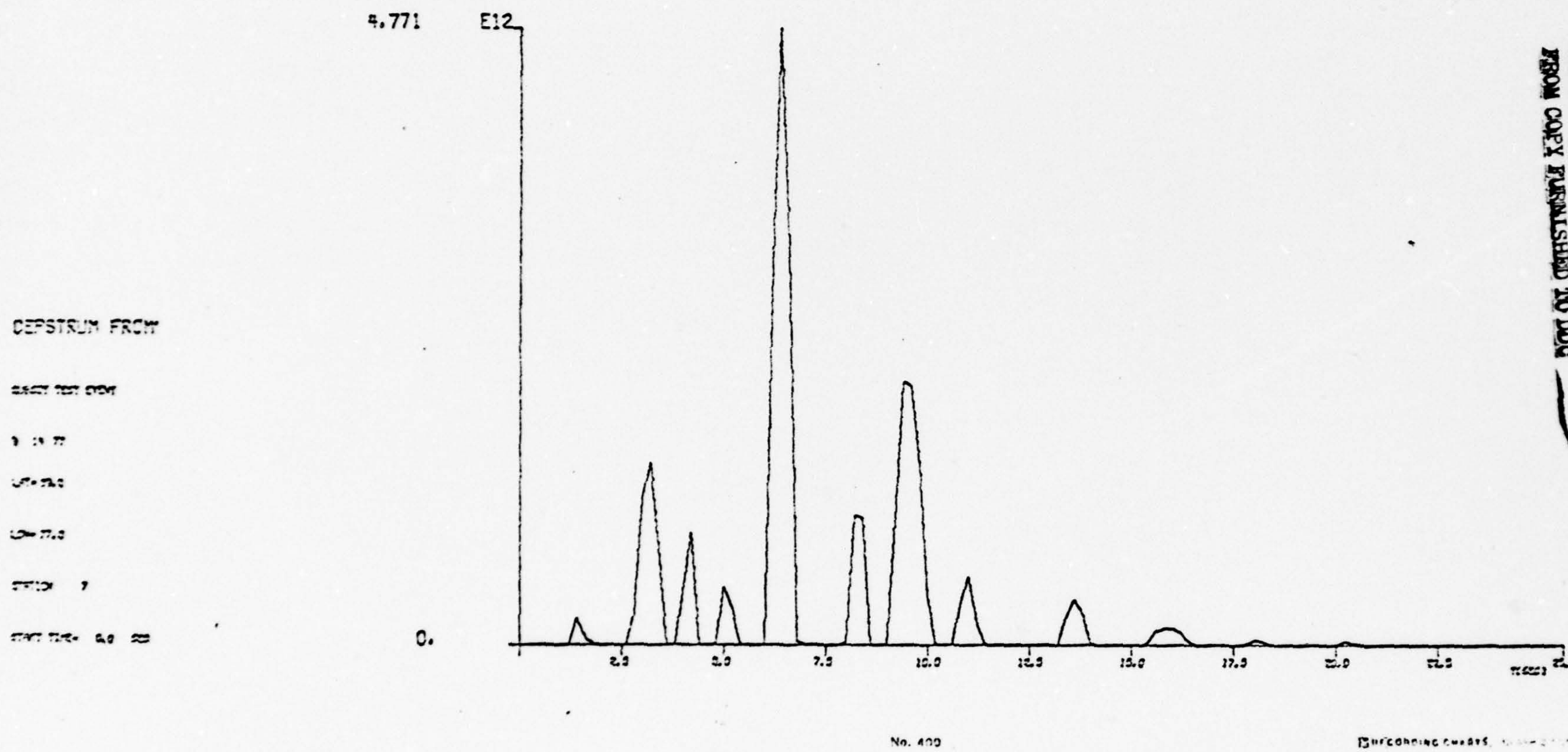

Figure 3. Cepstrum Plot

2.2 PHASE EDITING

The first new analysis feature allows the analyst to edit each cepstrum, based on phase, before generating depth plots. Since cepstrum peaks resulting from depth phases are expected to consistently have phases near 0° or 180°, phase editing should be useful in eliminating non-depth-phase cepstrum peaks. Phase limits are input to the program as phase angle intervals about 0° and 180°; all cepstrum points having a phase outside these limits are edited out.

Depth plots illustrating the application of phase editing to the Illinois event (11/9/68) are shown in Figures 4-6. Figure 4 is the composite depth plot obtained using no phase editing, Figure 5 used only cepstrum points having phases between -25° and 25° and between 165° and 205°, and Figure 6 accepted only phases between 165° and 205°. The best results are obtained using only those points with phases within 25° of 180°; when cepstrum points with phases within 25° of 0° are also used, the depth plot deteriorates. Phase editing promises to be a useful addition to the depth determination procedure, but, as this example illustrates, its behavior needs to be studied using a larger data base.

2.3 IMPROVED SIGNIFICANCE LEVEL ALGORITHM

The second new analysis feature is an improved version of the significance level algorithm. Briefly, the old significance level algorithm involves computing the distributions of depth plot amplitudes that result from picking cepstrum points at random times instead of the correct depth phase delay time. This distribution is used to determine the random depth plot amplitude that is greater than a specified percentage of the random depth plot points. Finally, this amplitude is marked on the final depth plot, to be used as an indication of the significance of depth plot peaks.

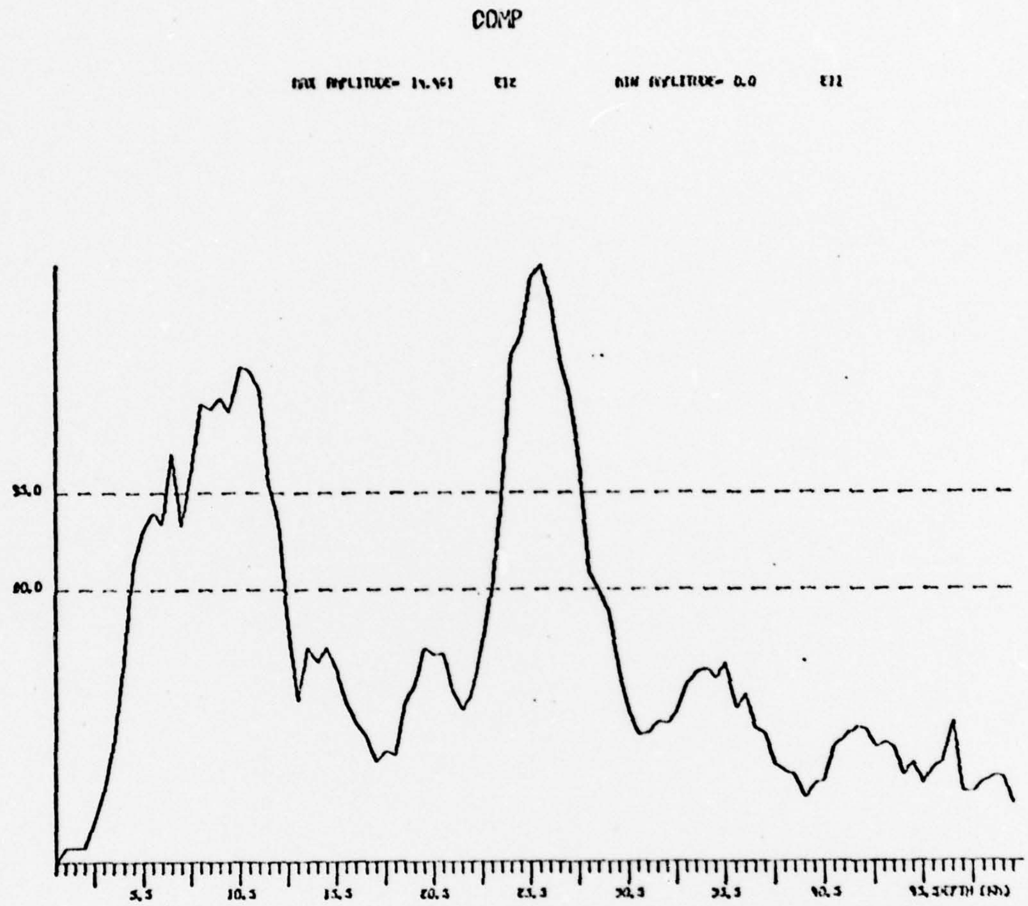

Figure 4. Illinois Event Composite Depth Plot. No Phase Editing.

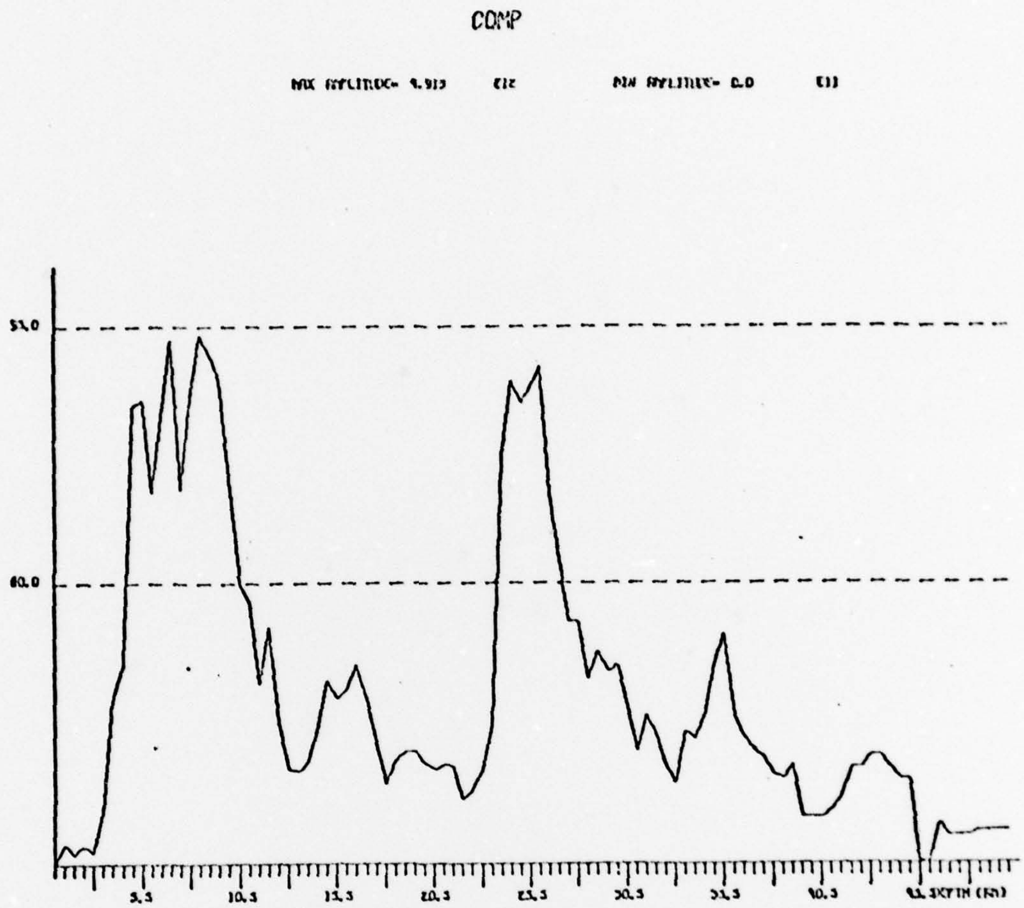

Figure 5. Illinois Event Composite Depth Plot
Phases Allowed: 0° ± 25°
180° ± 25°

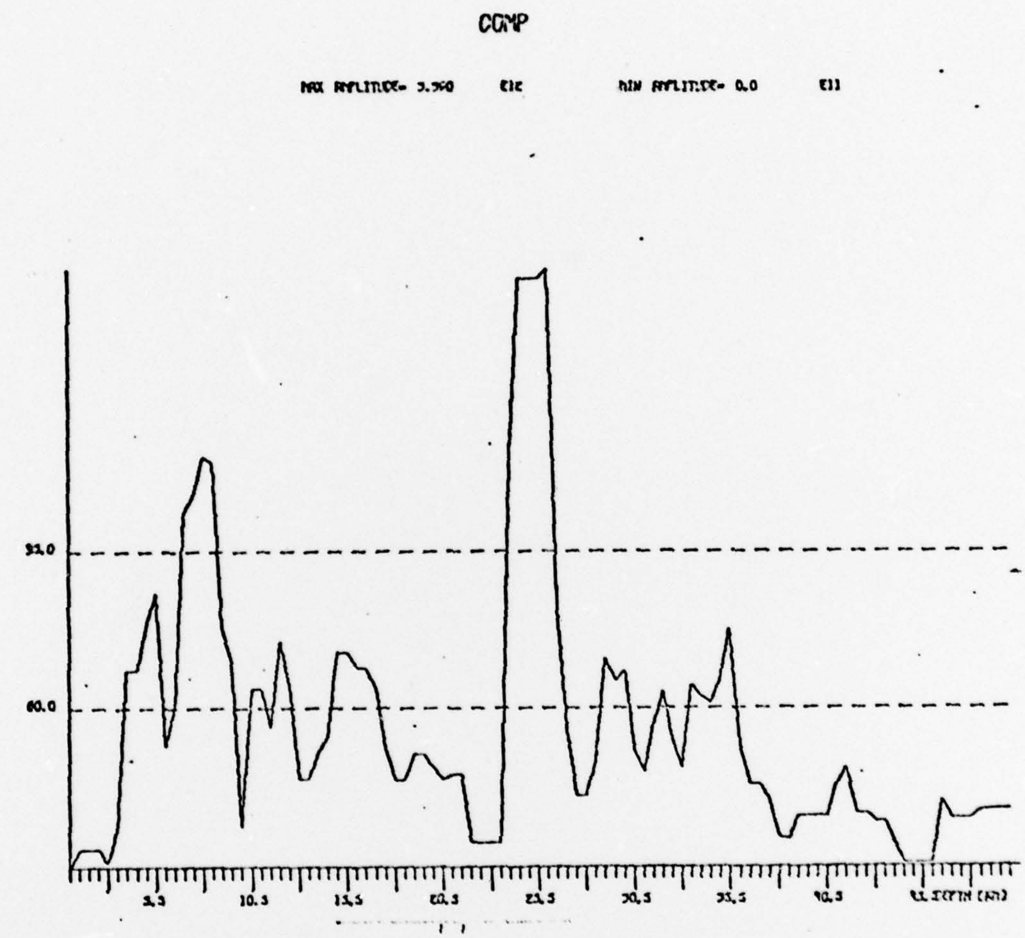

Figure 6. Illinois Event Composite Depth Plot
Phases Allowed: 180° ± 25°

The new significance level algorithm differs from the old one in that, instead of computing just one random depth plot amplitude distribution, five separate distributions are computed. These five distributions are computed from the same cepstrums, but with five different sets of uniformly distributed random delay times. Five sets of significance levels are then determined, and an average and standard deviation is computed from these five numbers and written on the final depth plot.

This technique results in two improvements over the previous method. First, the average significance level displayed on the final depth plot is a better estimate of the true significance level because it is computed from five estimates of the random amplitude distribution instead of just one. Second, since the central limit theorem implies that the five significance levels are normally distributed, the standard deviation provides a quantitative estimate of the reliability of the average significance level. Using this new algorithm, depth plots can be interpreted with greater confidence than previously possible.

2.4 BANDWIDTH-BASED SIGNIFICANCE THRESHOLD

The last of the new analysis features provides a quantitative estimate of the shallowest depth that can be determined from a given set of seismograms. This is necessary because of the way the general structure of the cepstrum is affected by the bandwidth of the original seismogram.

The depth determination program computes a cepstrum by taking the power spectrum of the one-sided version of the seismogram power spectrum. Consequenly, each cepstrum has low amplitudes at long lags, and, at short lags, a high amplitude central peak that becomes wider as the seismogram power spectrum becomes narrower. Unless the much smaller peak that corresponds to the echoed arrival falls outside this central peak, it will not be detected. Thus, the width of the central peak determines the shallowest depth (shortest delay) that can be detected from the original seismogram.

This effect is illustrated in Figure 7. A wide band seismogram has a power spectrum that is sufficiently broad for the modulation caused by the depth phase to be well defined. Consequently, the cepstrum has a narrow central peak and a distinct peak corresponding to the echoed arrival that dominates the final depth plot. In contrast, a narrow band seismogram has a power spectrum that is too narrow for any but very high frequency modulations to be detectable. The resulting cepstrum has a very broad central peak that would overwhelm any echo peaks occurring at short or moderate lags. Even when the depth phase has a sufficiently long delay time, interpretation of the final depth plot will still be complicated by the large, shallow depth peak that is produced by the wide central peak of the cepstrum. If an estimate of the central peak width were available, it could be used to determine the shallowest interpretable depth.

Figure 8 illustrates the technique developed to estimate the width of the cepstrum central peak. Since the final depth plot is produced from a large number of cepstrums, the first step is to calculate an average power spectrum from all the seismograms being analyzed. Next, this average power spectrum is smoothed to remove any depth-phase-generated modulation that hasn't already been eliminated by the averaging process. Finally, an average cepstrum is computed by taking the power spectrum of the positive frequency side of the smoothed average power spectrum. The time at which this average cepstrum first falls below 1% of its maximum value is used as the estimated shortest detectable delay time.

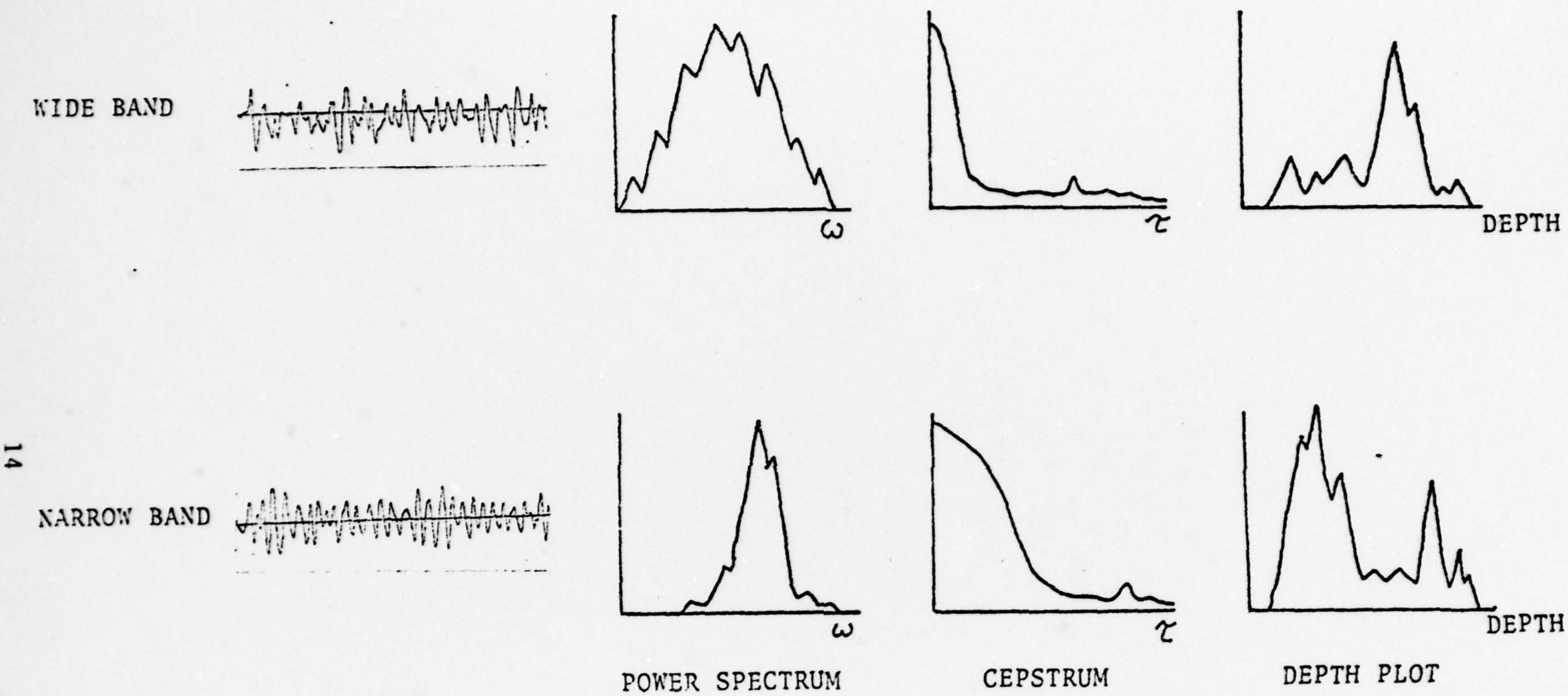

Figure 7. Effect of Narrow Band Data on Depth Plots

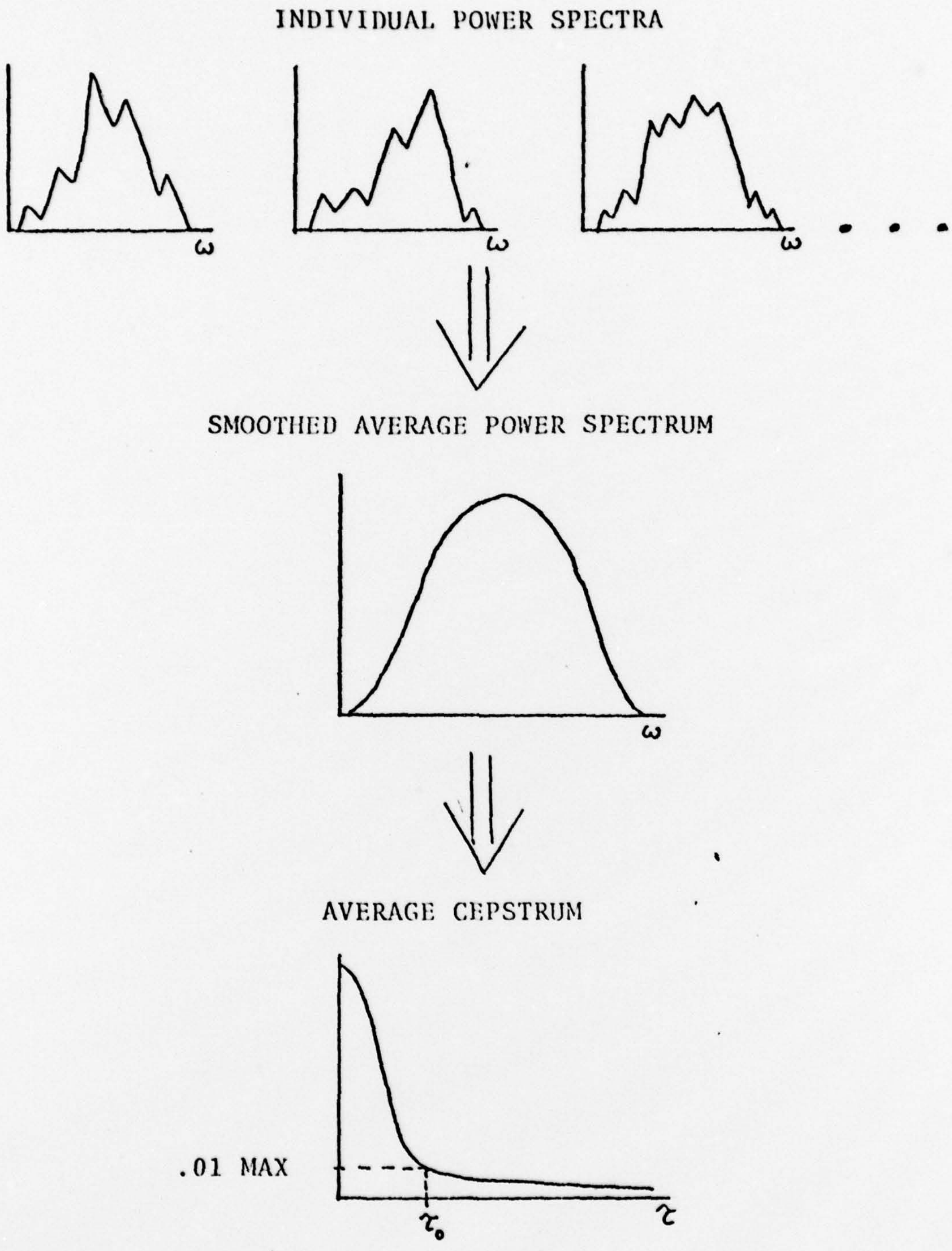

Figure 8. Computation of Narrow Band Threshold

The shortest detectable delay time estimate is converted to depth and written in the depth plot label. This warns the analyst that any depth plot peak shallower than this depth is likely to be a product of the seismogram spectra and not a true indicator of the source depth.

3.0 DATA ANALYSIS

The major portion of this work was concerned with analysis of discrimination experiment data. Results from the unclassified data set and the complete data set will be discussed in the following sections.

3.1 UNCLASSIFIED DATA SET RESULTS

Depth estimates were obtained for 18 events from the unclassified data set. A total of 41 events were examined, but 23 were not processed due to inadequate data. An event is considered to have inadequate data if it does not have a visible P wave arrival on at lease two stations at teleseismic distances. Close-in data is not acceptable because our depth determination technique is presently based on teleseismic phases; the use of close-in data may be valid with some modifications, but a whole new research project would be necessary to determine this. A minimum of two stations is required because the technique needs repeated depth phases to get a well-defined depth estimate -- even with two stations a significant depth plot peak can only rarely be obtained.

Results from analysis of the discrimination experiment data are listed in Table 1. Since a depth range of 10 km-80 km was searched, a depth estimate of "NONE" implies that the source depth is outside this range. For each event, a letter grade has been assigned for data quality and depth estimate reliability. The data quality grade is based on seismogram signal-to-noise ratio, the distribution of station deltas, and the total amount of time available for analysis after the P arrival. Factors considered in assigning the depth reliability grades are: data quality, appearance of depth plots, significance level of peaks, and consistency of depth plot peaks among different window lengths, station sets, and primary phases.

Table 1. Discrimination Experiment Results

EVENT NO.	NO. OF STATIONS	DATA QUALITY	DEPTH (km)	DEPTH ESTIMATE RELIABILITY
1	5	F	36	F
1*	8	G	NONE	P
3	7	P	21	VP
7	2	F	32	VP
14	4	P	20	F
16	3	P	31	Q
16*	7	F	NONE	P
17	2	F	32	F
18	4	F	NONE	P
19	7	G	34	G
20	6	G	NONE	F
21	2	F	NONE	Q
22	4	VP	NONE	Q
24	2	VP	19	Q
27	4	F	26	P
41	3	VP	NONE	Q
41*	5	P	22	F
47	8	P	32	VP
49	6	P	50	F
50	10	F	19	G
59	3	P	NONE	Q

Data Quality and Reliability Grades:

G = Good
F = Fair
P = Poor
VP = Very Poor
Q = Questionable

NONE = Depth Outside 10-80 km Search Range

* = Complete Data Set

It must be emphasized that these grades are totally qualitative. A "good" depth estimate is probably better than a "poor" one, and a "Q" depth is probably better than a guess, but anything like a comparison between adjacent grades is not very meaningful. The only way to get a good quantitative estimate of the reliability of this depth determination procedure is to analyze a large set of events with known depths.

3.2 COMPLETE DATA SET RESULTS

Near the end of the project, data from the complete discrimination experiment data set became available for some events. Substantial program modifications were needed to process this data (see Computer Documentation), and consequently only three events could be processed. Results for these events are listed in Table 1 with each event listing including data quality and depth reliability grades.

Comparison of the complete data set results with the corresponding results from the unclassified data set shows that different depth estimates have been obtained for all three events. This is not too surprising for Events 16 and 41, since the depth estimates for these events from the unclassified data set had very low reliabilities. The complete data set has better station coverage and better data quality than the original set, so the resulting depths are much more reliable.

The difference in depth estimates is more disturbing for Event 1, however, since the original depth had a relatively high reliability. As shown in Figures 9 and 10, the complete data set depth plots for this event still show the 36 km peak seen on the original plot, but a larger peak is present at 24 km, and neither peak can be picked as the correct one. Without further analysis, no explanation can be given for this result, which illustrates the need for a more quantitative and better based technique for determining the reliability of depth estimates.

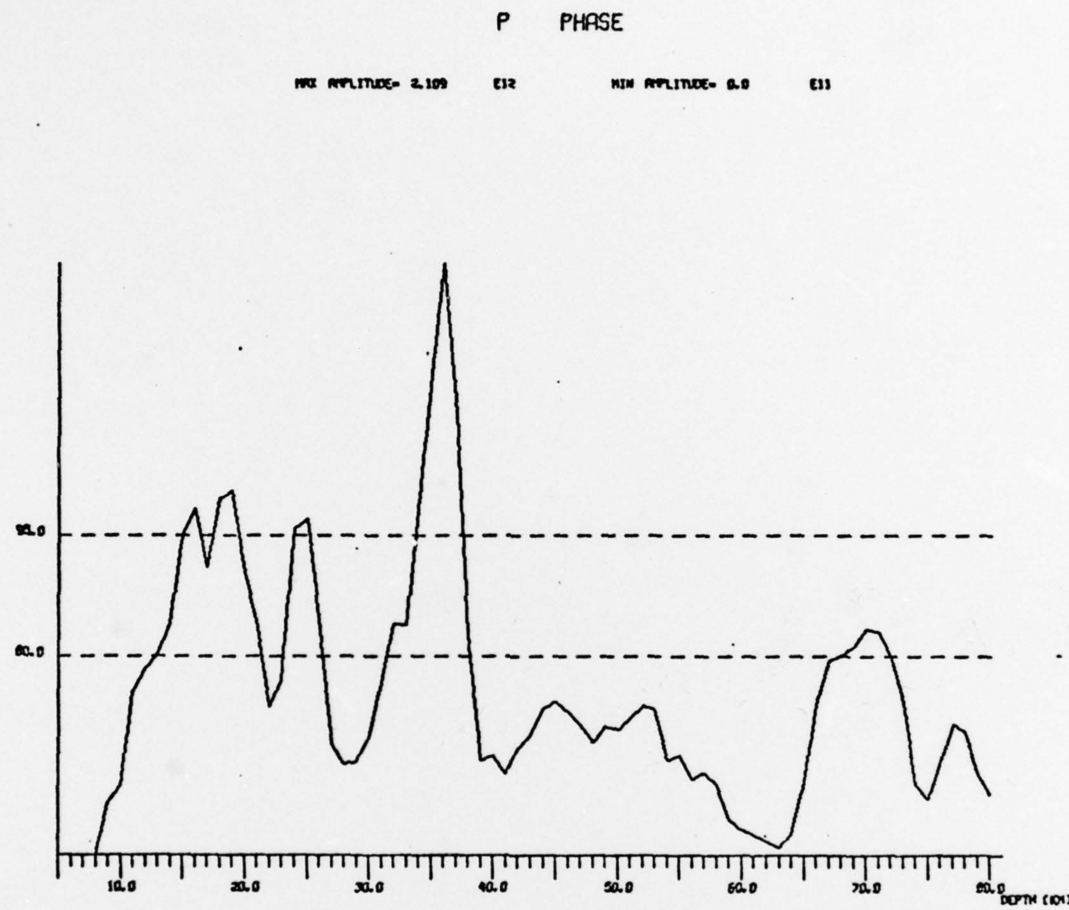

Figure 9. Unclassified Data Set P Wave Depth Plot for Discrimination Experiment Event #1, Window Length=25.6 sec.

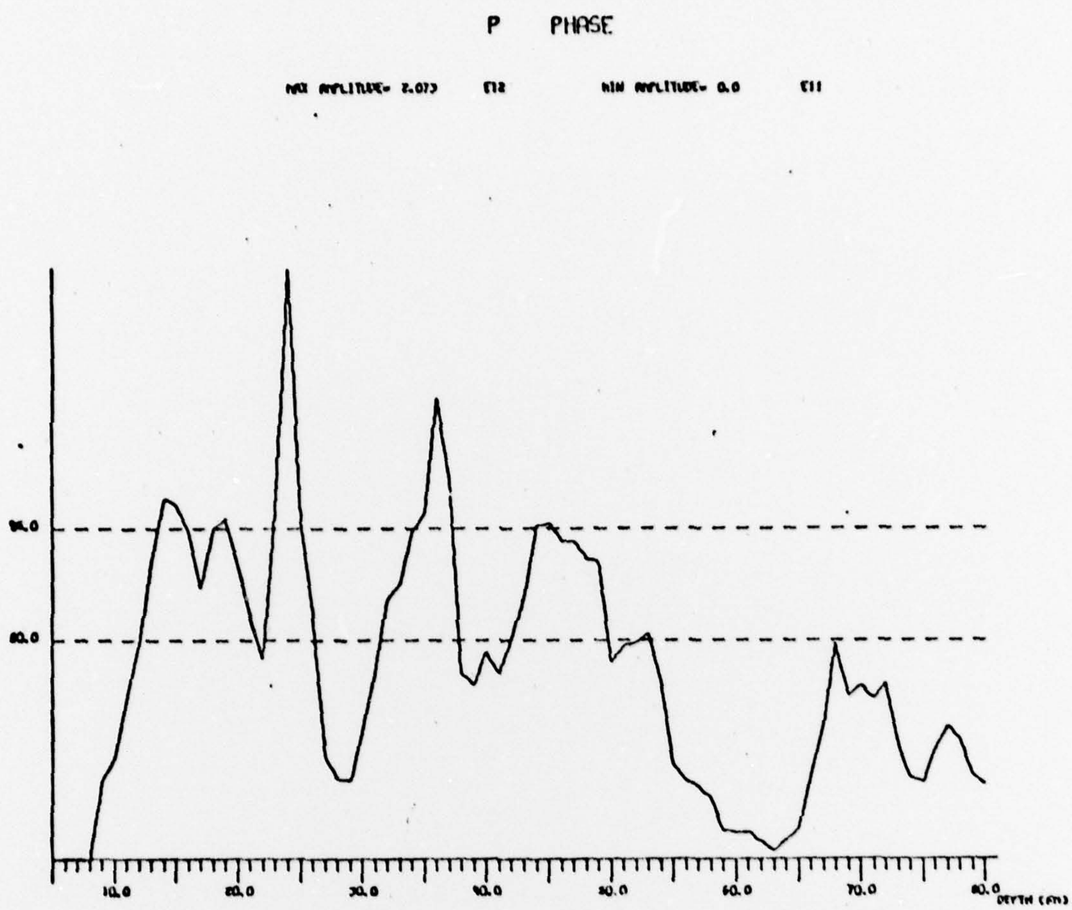

Figure 10. Complete Data Set P Wave Depth Plot for Discrimination Experiment Event #1, Window Length=25.6 sec.

4.0 CONCLUSIONS

The principal conclusion that can be drawn from the data analysis performed during this project is that this depth determination technique is not suitable for a data set like the original, unclassified one. This method keys on the repetition of depth phase cepstrum peaks at different delay times, but with the same equivalent depth, and this requires a large group of stations covering a range of deltas. Results from previous projects indicate that this technique works well when adequate station coverage is available, but, in general, results obtained using fewer than five stations are unreliable. Very few events from the original data set satisfy this condition - in fact, most of them had too few stations to be processible.

For the complete data set, a sufficient number of stations is available for most events, and the performance of the depth determination procedure would be expected to improve with this data. Too few events were analyzed with the complete data set, however, to reliably evaluate the technique's performance. Further analysis of discrimination experiment events using the complete data set is necessary before the utility of this technique as a nuclear discriminant can be determined.

One problem area that has become more evident in the course of this project is the need for an objective, quantitative technique for determining the reliability of a depth estimate. This is well illustrated by discrimination experiment Event #1, where the depth estimate obtained using the unclassified data set appeared to be a fairly reliable one, but it disagreed with later results obtained using the complete data set. The significance level algorithm is an attempt to provide an objective way of determining the reliability of a depth estimate, but this technique is not useful for fewer than five stations, or when there is little variation in delta. Even when it is working well, the significance level does not attach an actual numerical confidence level to a depth estimate, which, ideally, is what is desired. This kind of reliability estimate can probably be obtained only through a detailed analysis of results from a large set of events with known depths.