LEVEL II

SDAC-TR-78-8

DETECTION OF DEPTH PHASES USING COMPUTER GRAPHICS

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05 DECEMBER 1978

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SDAC-TR-78-8
2. GOVT ACCESSION NO.: AD-A071 158
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): DETECTION OF DEPTH PHASES USING COMPUTER GRAPHICS
5. TYPE OF REPORT & PERIOD COVERED: Technical Rept.
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): John H. Goncz, Brian W. Barker
8. CONTRACT OR GRANT NUMBER(s): F08606-78-C-0007, VO/ARPA Order-2551
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Teledyne Geotech, 314 Montgomery Street, Alexandria, Virginia 22314
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: T/8709/B/PMP
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, Nuclear Monitoring Research Office, 1400 Wilson Blvd., Arlington, Virginia 22209
12. REPORT DATE: 05 December 1978
13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): VELA Seismological Center, 312 Montgomery Street, Alexandria, Virginia 22314
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Author's Report Date 09/20/78

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Depth Phases
Depth Estimation
pP & sP
Interactive Graphics
m sub b

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

From a dataset of 116 earthquakes, all available SRO (Special Research Observatory) and PSWF (Preliminary Signal Waveform File) waveforms were presented on an interactive computer graphics screen and then examined for presence of depth phases pP, sP and PcP. Using the results, a focal depth for 66% of the total was postulated. About half of these, or 37%, agreed with depths published by NEP (Network Event Processor) or PDE (Preliminary Determination of Epicenter) bulletins. Earthquakes of magnitude m_b > 5 are likely to produce clear depth phases. Rapid routine processing of a large number of events by the aligned-on-

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

408258

P method can be achieved with interactive computer graphics.

DETECTION OF DEPTH PHASES USING COMPUTER GRAPHICS

SEISMIC DATA ANALYSIS CENTER REPORT NO.: SDAC-TR-78-8

AFTAC Project Authorization No.:	VELA-T/8709/B/PMP
Project Title:	Seismic Data Analysis Center
ARPA Order No.:	2551
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F08606-78-C-0007
Date of Contract:	01 October 1977
Amount of Contract:	$2,674,245
Contract Expiration Date:	30 September 1978
Project Manager:	Robert R. Blandford (703) 836-3882

P. O. Box 334, Alexandria, Virginia 22314

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ABSTRACT

From a dataset of 116 earthquakes, all available SRO (Special Research Observatory) and PSWF (Preliminary Signal Waveform File) waveforms were presented on an interactive computer graphics screen and then examined for presence of depth phases pP, sP and PcP. Using the results, a focal depth for 66% of the total was postulated. About half of these, or 37%, agreed with depths published by NEP (Network Event Processor) or PDE (Preliminary Determination of Epicenter) bulletins. Earthquakes of magnitude $m_b > 5$ are likely to produce clear depth phases. Rapid routine processing of a large number of events by the aligned-on-P method can be achieved with interactive computer graphics.

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INTRODUCTION

In the context of monitoring underground nuclear explosions, the ability to establish with certainty the depth of an event is an extremely powerful discriminant. Although depth estimation can be achieved by computer programs using only first arrivals, a more accurate and reliable depth estimation can be made if the depth phases pP and sP are observed. Body waves reflected back from the surface of the earth comprise pP or sP, and similar reflections from the core are called PcP. These phases arrive within 2 minutes after P, and are imbedded in the P-wave coda.

The primary factors that influence the appearance (or non-appearance) of a depth phase are thought to be:

- magnitude of earthquake
- depth
- focal mechanism
- source-to-receiver orientation
- signal to noise ratio at receiver
- structure around the hypocenter.

The seismological literature, to the author's knowledge, contains no information on the observability of depth phase and no work that systematically relates the above factors to actual observations. However, Dahlman's and Israelson's (1977) book includes a chapter on depth estimation. They cite two reports, one by Lacoss (1969) and the other by Yamamoto (1974), that have examined and reported on the frequency of observation of depth phases. The location of events in the Lacoss study is defined by the LASA beam, while

Dahlman, O. and H. Israelson, 1977, Monitoring Underground Nuclear Explosions: New York, Elsevier Scientific Publishing Co.

Lacoss, R. T., 1969, A large population LASA discrimination experiment: MIT Lincoln Laboratory, Technical Note 1969-24.

Yamamoto, M., 1974, Estimation of focal depth by pP and sP phases: National Defense Research Institute, Stockholm, Report A4505-A1.

Yamamoto's work was concerned with Japanese earthquakes. Chiburis and Ahner (1969) produced a third key report covering earthquakes in North and South America.

In our study, waveforms from a global network of seismometers are presented on a computer graphics screen and then examined by an analyst for evidence of depth phases. The goal is to obtain information on how frequently a sparse global network of seismic stations can observe earthquake depth phases. The data used consists of 116 events derived chiefly from the Network Event Processor (NEP) bulletin. Earthquake locations are worldwide, rather than limited to specific regions as in earlier studies.

While the three earlier studies, as well as this study, differ in fundamental design (e.g., Yamamoto's study did not utilize waveform data), they agree broadly in their conclusions. That is, that depth phases can be observed in about two thirds of all $m_b \approx 5$ events, and that half the implied depths agree with USGS depths. The major difficulty in observing depth phases is identifying a phase imbedded in the P-coda, particularly if its amplitude is equal to or less than the coda amplitude at the time the depth phase appears. Presenting available waveforms on a graphics screen, together with an interactive-predictor mark, helped the analyst make a decision.

Results from this project will be further analyzed with a computer program utilizing Pearce's (1977) ideas for establishing fault plane solutions using P-pP and P-sP amplitude ratios. While depth phases are not always observed at all network stations, their absence is as important as their presence because they act as a constraint on possible fault solutions.

Chiburis, E. F. and R. O. Ahner, 1969, The comparative detectability of pP at LASA, TSFO, UBSO and CPSO: Seismic Data Laboratory Report No. 231, Teledyne Geotech, Alexandria, Virginia.

Pearce, R. G., 1977, Fault plane solutions using relative amplitudes of P and pP: Geophys. J. R. Astr. Soc., 50, 381-394.

DETECTION OF DEPTH USING COMPUTER GRAPHICS

One method of enhancing the capability to detect and identify depth phases pP, sP and PcP is to arrange the short period signals from a network of seismometers so they are aligned on first motion of P onset. Presumably, secondary depth arrivals, if present, will form a coherent pattern with evidence of moveout of the depth phase with increasing epicentral distance, although the moveout may be slight. The moveout is slight because the time delays between the arrival of pP and P, as well as sP and P, are chiefly functions of focal depth. They are almost independent of epicentral distances for events less than 100 km deep, so the moveout is small, perhaps just 2 or 3 seconds, according to the range of epicentral distances covered by the available signals. However, producing this type of section with hard copy is time-consuming and not suitable for routine event analysis. This report describes an investigation into using computer graphics to build up the aligned-on-P section for 116 events, and expresses the results in terms of how frequently depth phases are seen, how they are identified and the level of confidence, as well as the implications for on-line discrimination between explosions and earthquakes.

The experiment was designed to use the PDP-15 computer to acquire all signals available at the SDAC for events listed in the NEP bulletin for the period 1 December 1977 to 15 December 1977, to then present these signals on the graphics screen so they could be aligned on P-onset, and to give the analyst a moveable vector for pP calculated arrivals. The signals are presented in order of increasing epicentral distance. The analyst shifts each signal left or right to align P-onsets to a vertical reference line, then enters a depth from teletype keyboard, and a series of vectors appear on the screen connecting the baselines of each signal at the point corresponding to the calculated arrival position of the pP phase. Also shown on the screen are the arrival positions for sP and PcP for the chosen depth. Computer response is essentially instantaneous for entry and display of a new depth vector.

Two data bases were used to acquire and present signals: the SRO network and the PSWF tape from NEP. At the time of the survey the SRO network consisted

of 11 reporting stations. Three Alaskan stations, plus LASA from the PSWF tape, gave a total of 15 potential signals for the display. However, the maximum number of signals seen for any one event was 9. The PDP-15 graphics screen can hold 11 signals. The SDAC bulletin reported a total of 116 events in the period 1 through 15 December 1977. Using the computer graphics scheme, we observed depth phases of sufficient clarity to postulate a focal depth for 77 of these events, or 66% of the total number of bulletin events.

The 116 events produced a total number of 658 signals at the network's reporting stations. Of these signals the analyst picked 312 signals, or ≈ 50% as containing a depth phase. The pick was not made on an individual signal, but rather it was made while the graphics screen presented all signals detected for that event, even though some of the signals there did not contain a depth phase, or might contain conflicting and extraneous phases.

The analyst recorded a confidence rating to the depth assignment ranging from 1 = (high confidence, numerous clear depth phases) to 4 = (unable to assign a focal depth). This rating was subjective; it depended upon the number of stations reporting, fraction of signals on the screen showing a depth phase, and non-ambiguity of the phase. The number of events and percentages of the total number in each of these categories are:

Confidence in Depth Assignment (1 = High)	Number of Events	Percentage of Total
1	12	10%
2	31	27%
3	34	29%
4 (no depth assignment possible)	39	34%
	116	100%

The 66% rate of depth postulation compared reasonably with the study of 150 Eurasia events that Lacoss (1969) recorded at LASA. Lacoss found that a secondary phase could be seen in about 60% of the events, and that of these,

about 80% could be associated with pP or sP. Thus, correctly identifying a depth phase was possible in about 50% of the events studied at LASA.

However, where only a single receiving station exists, such as the LASA beam, establishing whether a solitary secondary phase is pP or sP is virtually impossible if other information is unavailable. Still, it is statistically sound to consider an unassigned depth phase to be pP, because Yamamoto (1969) showed that for events in the Japan region the occurrence of pP was six times as great as the occurrence of sP.

Table I shows that this method's applicability and the confidence level of a depth assignment are strong functions of the magnitude of the 116 events. Only 40% of events with m_b less than 5.0 could be assigned a focal depth, while 83% of events with m_b greater than or equal to 5.0 showed sufficient evidence of depth phases to be assigned a focal depth. In addition, events with smaller magnitudes tended to cluster at the lower confidence levels of depth assignment, while the greater magnitude events tended toward a high confidence level of 1 in their depth assignment.

Depth Verification

Verification of the focal depths assigned by the analyst based on his interpretation of the information presented on the computer graphics screen is complicated by a number of factors. The NEIS depths do not necessarily agree with the NEP depths. Both NEP and NEIS compute focal depths in two ways. Restrained depth solutions (R) indicate that the NEP analyst fixed the depth during the reiterations of the location program based on additional information such as depth phases. The (R) solution, designated (D) in the NEIS bulletin, is considered to be more accurate than a free-running HYPO location solution, which is marked (F) in the NEP bulletin, and is without added notation in the NEIS bulletin.

In some cases the graphics screen showed that more than one focal depth interpretation could be made for a set of seismic traces. In these cases we attempted to use the depth with the greatest confidence, usually containing the most traces which showed evidence of a depth phase.

TABLE I

All 116 events according to magnitude and confidence assigned to postulated depth. A confidence of 4 means no depth could be assigned. Larger magnitude events m_b > 5.0 show clearer depth phases.

Confidence, m_b	0 - 4.5	4.6,4.7	4,8,4.9	5.0,5.1	5,2,5.3	5.4,5.5	5.6,5.7	5 8,5.9	m_b
1 (High)		1		5	1	2	2	1	
2	1	3	4	7	8	2	5	2	
3	1	5	3	12	7	3	2		
4 (No depth determination)	7	13	7	3	5	2	2		

Finally, the NEIS bulletin contains a third category of reported depths labeled 33N, which indicates that it was held at 33 km (normal depth), if at any point in the computation the depth became negative, or was otherwise unsatisfactory, and the earthquake probably had a shallow focus.

In Figure 1, the computer graphics depths are plotted against NEP depths for those events in the NEP bulletin with non-zero focal depth. These NEP depths contain both free and restrained depths, shown by different symbols on the graph. The agreement with the restrained NEP depths is excellent and is considerably better than the match with the unrestrained location solutions. All of the computer graphics depths which differ with NEP by more than 50% have been interpreted as shallow focus, 70 km or less. None of non-agreeing events have been interpreted as deep focus events.

Figure 2 shows a presentation similar to Figure 1 for NEIS events which also have a non-33R depth. There is only one restrained depth in this set, agreeing well with the computer graphics depth. This NEIS data set seems to show more scatter than the NEP data set; the explanation for this is not obvious.

Figure 3 is a histogram of computer graphics depths for 28 earthquakes reported as "33N" in the NEIS bulletin. It is significant that all the computer graphics depths are shallow ($\leq$ 70 km), and that the peak of the distribution occurs close to 20 km, thus tending to support the NEIS procedure of assigning 33N when the location program does produce a satisfactory depth, and it is a geophysicist's opinion that the focus is probably shallow. Nineteen of these twenty-eight earthquakes are contained in the NEP bulletin where they are restrained to surface focus, indicating also that the NEP computer location program produced unsatisfactory focal depths. Therefore, it is possible that the computer graphics approach has succeeded in assigning focal depths to shallow earthquakes when location programs using arrival times fail.

Unfortunately, there is no method readily available to verify these depth determinations in the cases where a location program fails to achieve a satisfactory depth. It is not surprising that stacking a number of aligned-on-P waveforms should help in recognizing any coherent pattern that

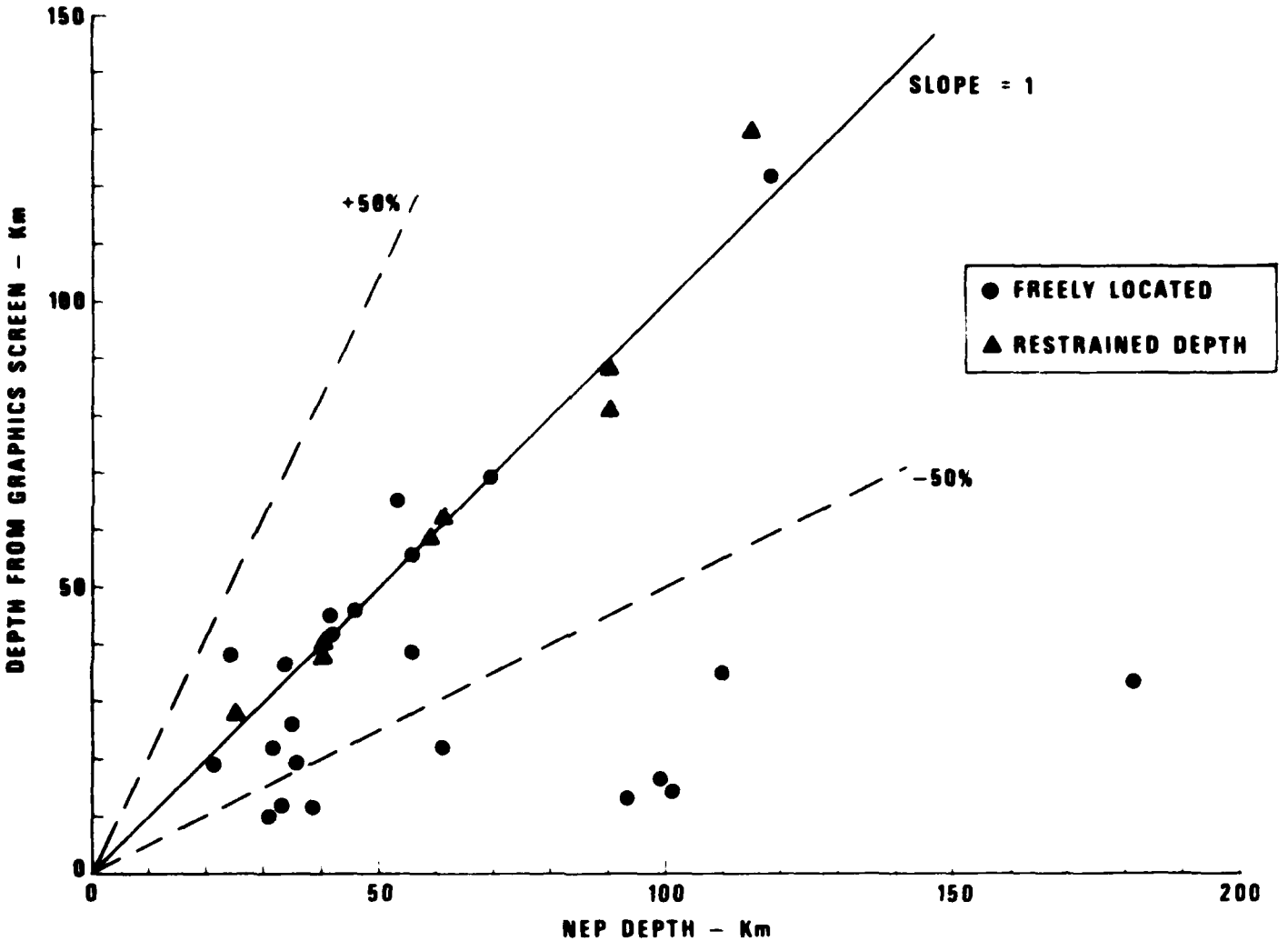

Figure 1. Depth determined with the aid of a computer graphics screen presentation of all P phases plotted against the depth for the same event in the NEP bulletin.

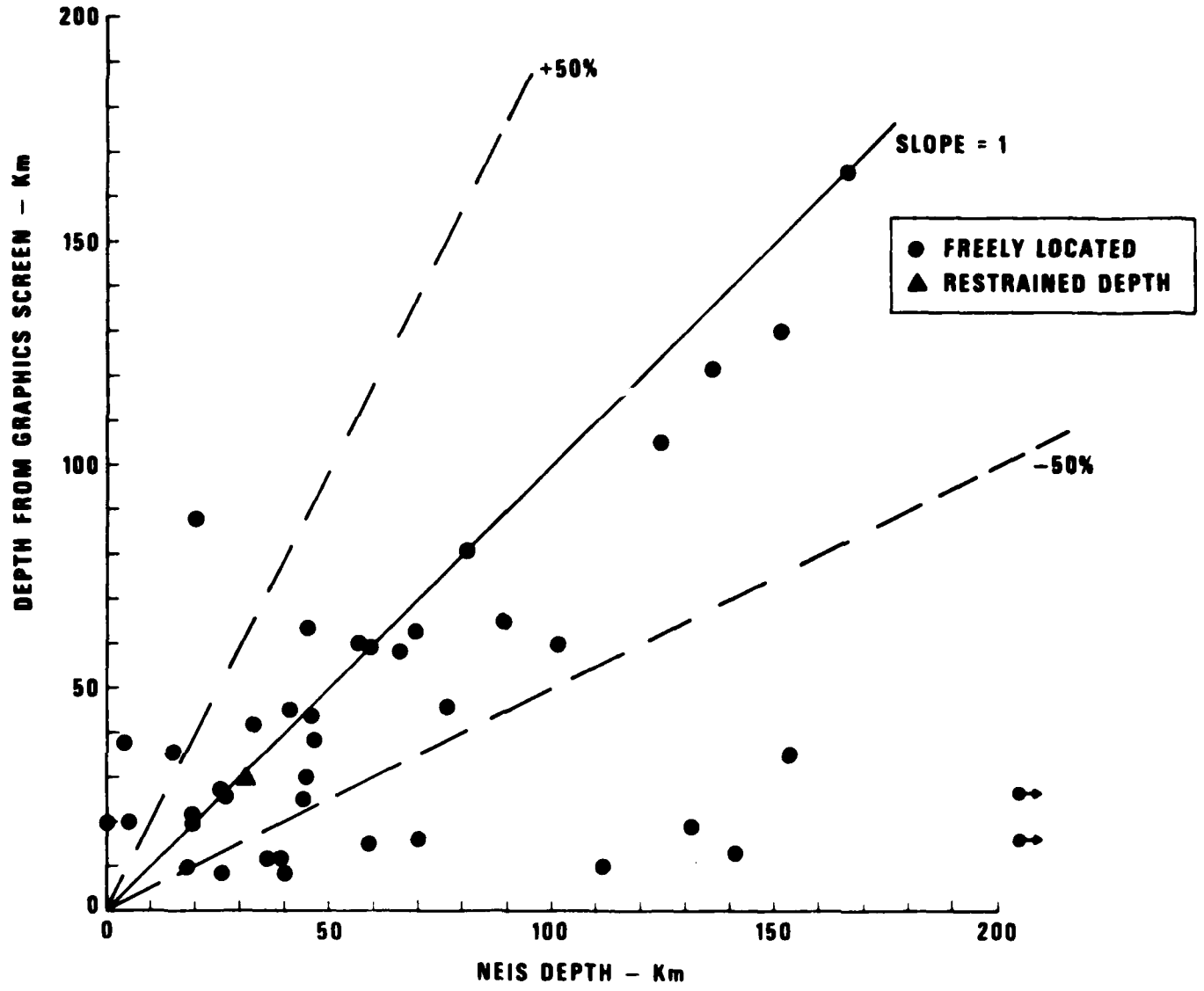

Figure 2. Depth determined with the aid of a computer graphics screen presentation of all P phases plotted against the depth for the same event in the NEIS bulletin.

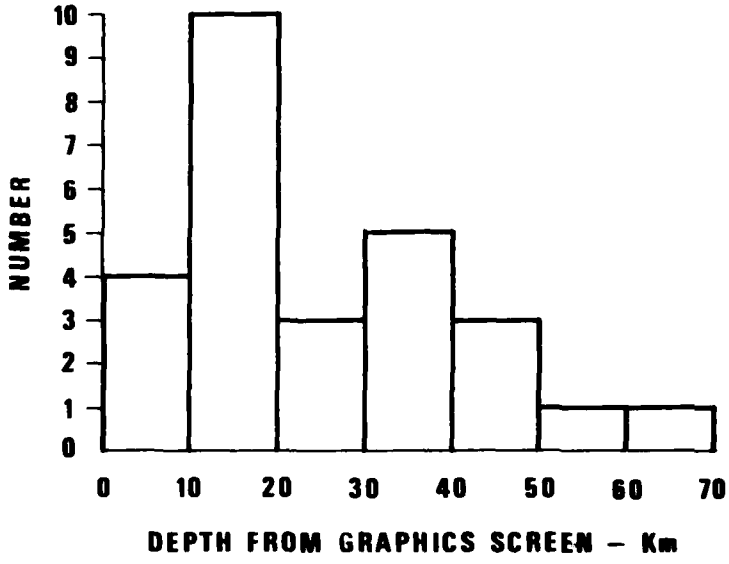

Figure 3. Histogram of number of depths versus depth for 28 earthquakes reported as "33N" in the NEIS bulletin.

may be presented, and the method would probably be more effective if more signals were available.

To get an overall picture of the performance of this project, we now look at how many depth determinations agree or disagree with NEP and NEIS. Lines corresponding to plus and minus 50% of bulletin depth are shown on Figures 1 and 2; these lines are used to arbitrarily class the events into those that are "verified" and those that are not. Furthermore, we make the assumption that all the "33N" events are "verified."

Counting in this way yields the following results:

Agree with NEP	28
Agree with NEIS	25
Agree with "33N"	28
No agreement	27
Total	102

Of course, this totals more events than the 77 events that were assigned a focal depth, because if an event is on both NEIS and NEP bulletins, it is counted twice in the above tabulation. However, the percentage, here 80%, of computer assisted focal depth determinations that have been "verified" is correct.

DISCUSSION AND CONCLUSIONS

Table II compares the results of this study with the studies of Lacoss, Yamamoto, and Chiburis and Ahner from the point of view of the number of earthquakes that have observable depth phases.

Chiburis and Ahner (1969) suggest that the large array is a better detector of pP and sP, but the information in a single beam is insufficient to choose between these two phases. They reached this conclusion in their study of the comparative detectability of later seismic phase arrivals of LASA and a small continental network of three observatories. However, several factors appearing in Table II make a comparative interpretation of these four studies difficult. These are: (1) a different geographical region is sampled in each case; (2) Chiburis and Ahner's data base must have been selected to eliminate events that did not show secondary arrivals, but they did not report how many events were discarded; and (3) Yamamoto's relatively low (32%) fraction of total number showing secondary arrivals stems from his requirement that at least 5 stations (out of 109) reported later phases.

An important seismological question raised in this report focuses on what percentage of earthquakes might show later depth phases. A later phase is easier to recognize in deep (> 100 km) earthquakes; the phases are better separated because the coda are generally more simple and die out more quickly than shallow earthquake coda. Both this report and Yamamoto's study show that for earthquakes with $m_b > 5.0$ the frequency of appearance of later depth phases is quite large; Yamamoto asserts that his method has an applicability of 70%, if m_b is greater than 5.0. This study found evidence of depth phases in 83% of events where m_b was greater than 5.0. Thus, 3 out of 4 earthquakes of magnitude 5.0 or larger may be expected to show a later depth phase. Presumably, the same ratio persists for earthquakes of smaller magnitude, but the number actually observed is less because of few reporting stations, less azimuthal coverage, and lower signal to noise ratio. An array, by itself, cannot verify if a phase is pP or sP, but it is more likely that a phase is pP rather than sP by about 6 to 1 (Yamamoto, 1969).

TABLE II

Comparison of former depth phases studies and verification of postulated depths.

	Region	Number of Events	Method	Percent of Total Showing Depth Phases	Verified Secondary Phases (%)	Verified Secondary Phases as Percent of Total Population
Lacoss	Eurasia	200	LASA beam	58%	78 (1)	48%
Chiburis & Ahner	N. & S. America	21	LASA Sub-array	100%	(Does Not Apply)	
This Study	Global	116	Waveform alignment	66%	54% (2)	36%
(Yamamoto)	Japan	279	Secondary phase picks (no waveforms)	32% (3)	(Not Applicable)	32%

(1) Consistent with USCGS reported depth for subject earthquake.

(2) Agreement with depths reported by NEIS or NEP.

(3) Five or more NEIS reporting stations give a depth phase.

Examples of Aligned Seismograms

The method employed in this study is as follows. Two tapes are mounted on the PDP-15 tape drives; the PSWF tape contains the NEP signals, and the SRO Day tape contains all reporting stations. For individual events, arrival times are computed and the SRO tape is searched; any signals present are windowed and merged with signals on the PSWF. The analyst studies the display and makes the best choice of a focal depth based upon the displayed data.

Some examples of the hard copy of the graphics screen are presented in the Figures 4 through 17. The upper number at the start of a seismogram is the epicentral distance in degrees, the lower smaller number is the azimuth in degrees. Station names are not shown on the graphics screen, but are available to the analyst on the print sheet accompanying each event.

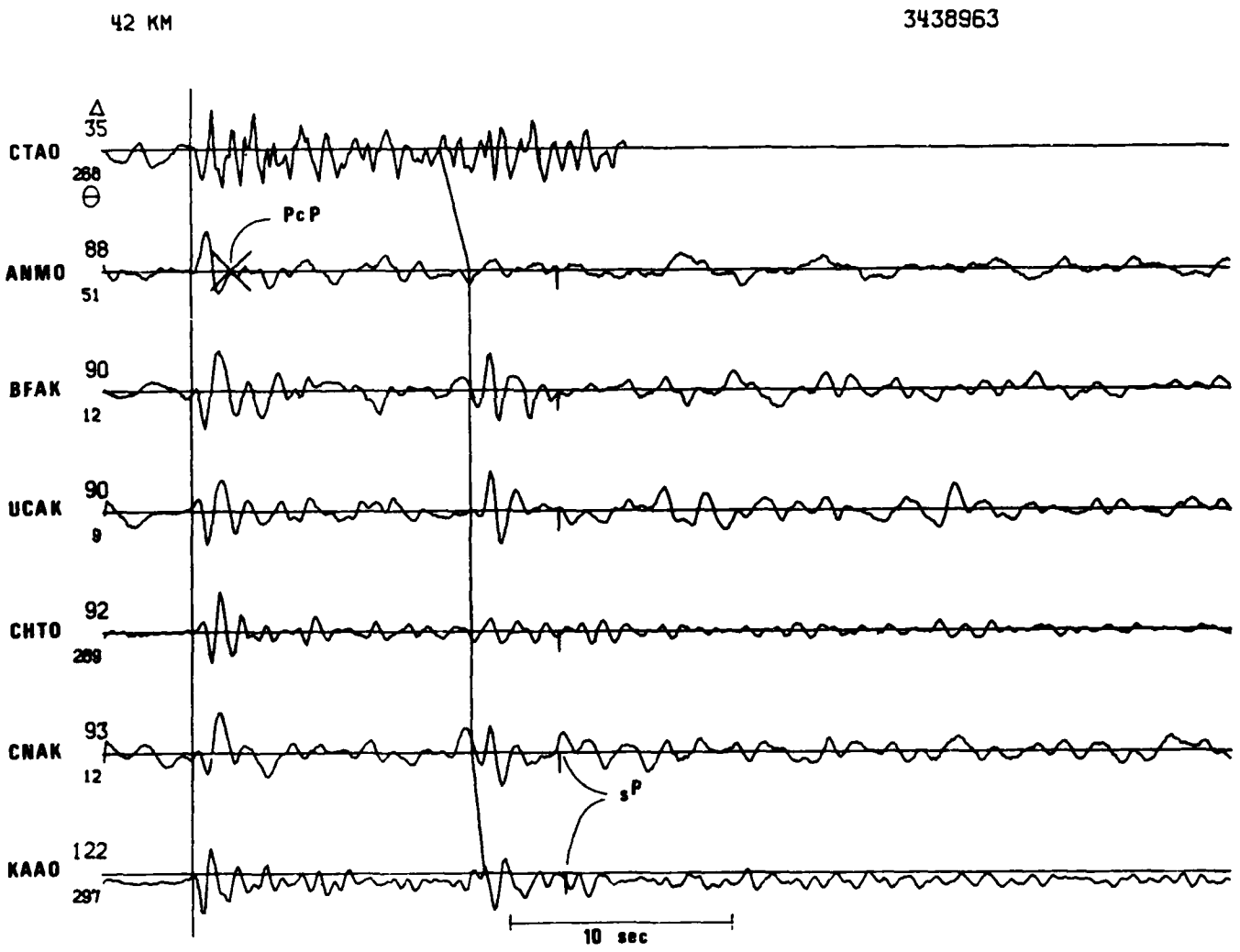

Figure 4. Event 3438963, 9 Dec. 1977, South of Fiji Islands. m_b = 5.1. Depth = 42 km, 42 (NEP), 33 (PDE). Good depth phase clarity.

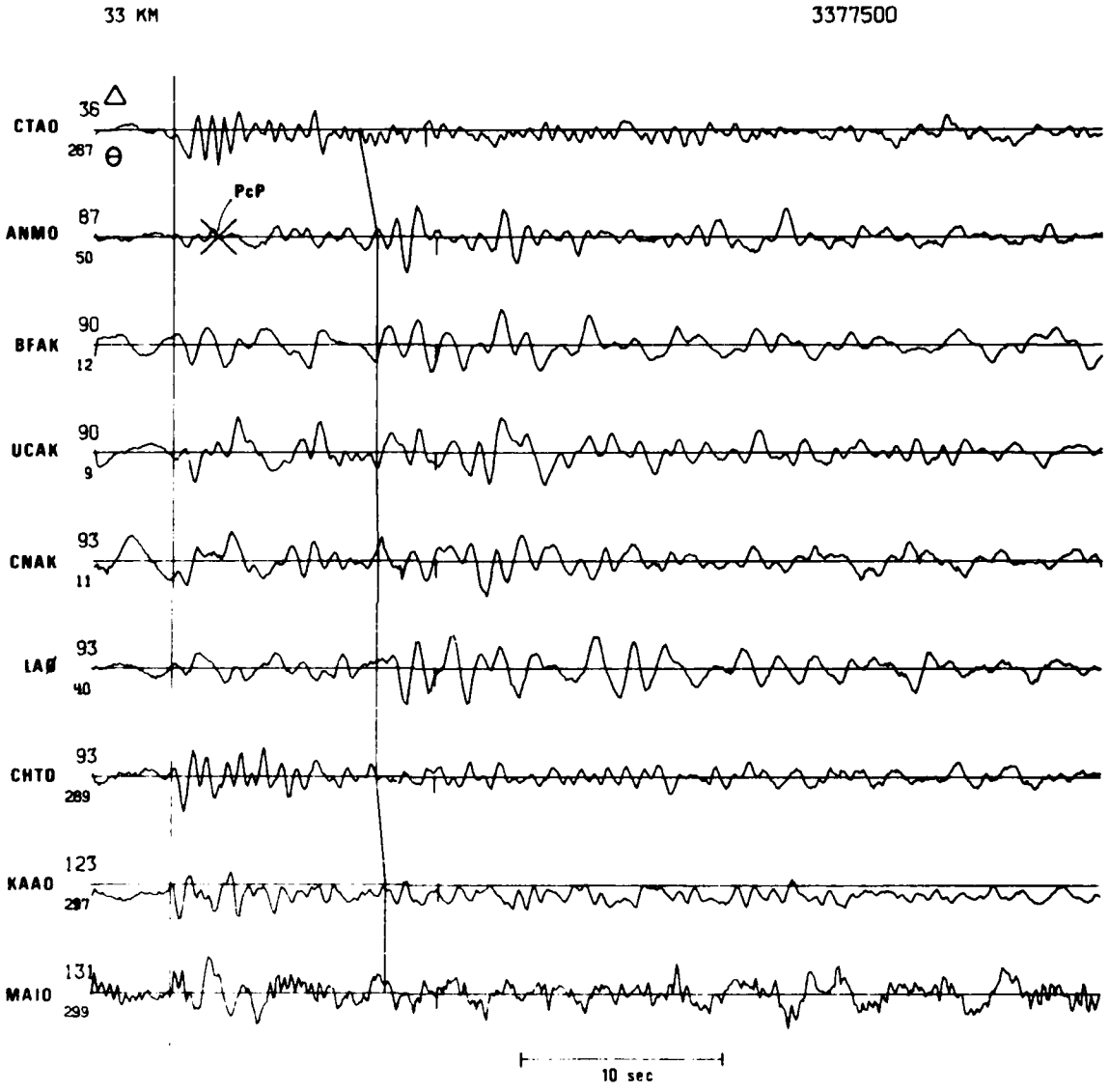

Figure 5. Event 3377500, 3 Dec. 1977, Tonga Islands Region. m_b = 5.3. Depth = 33 km, 363 (NEP), 33 N (PDE). Good phase clarity.

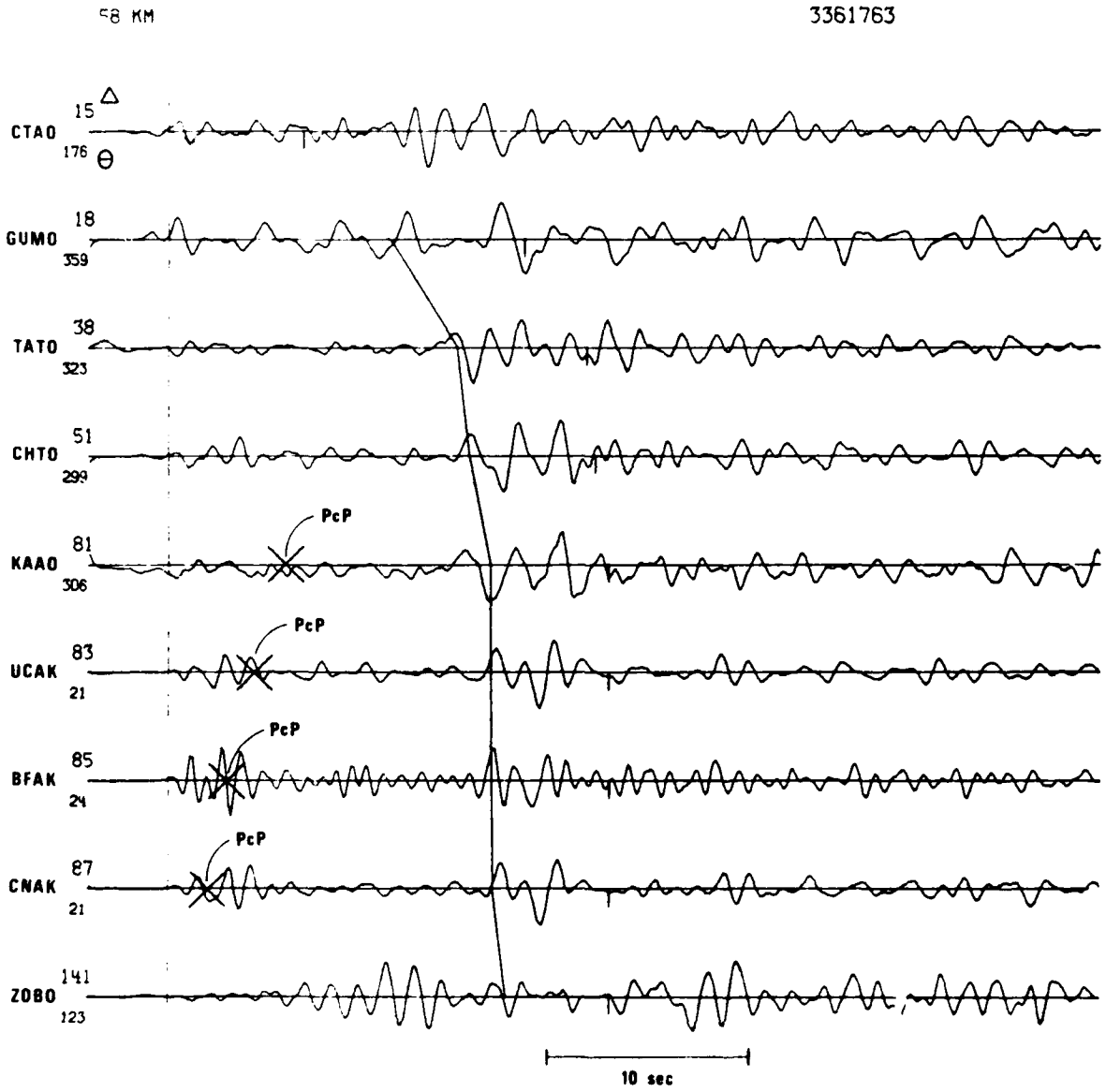

Figure 6. Event 3361763, 2 Dec. 1977, Near north coast of New Guinea. m_b = 5.7. Depth = 58 km, 58 (NEP), 66 (PDE). Good phase clarity.

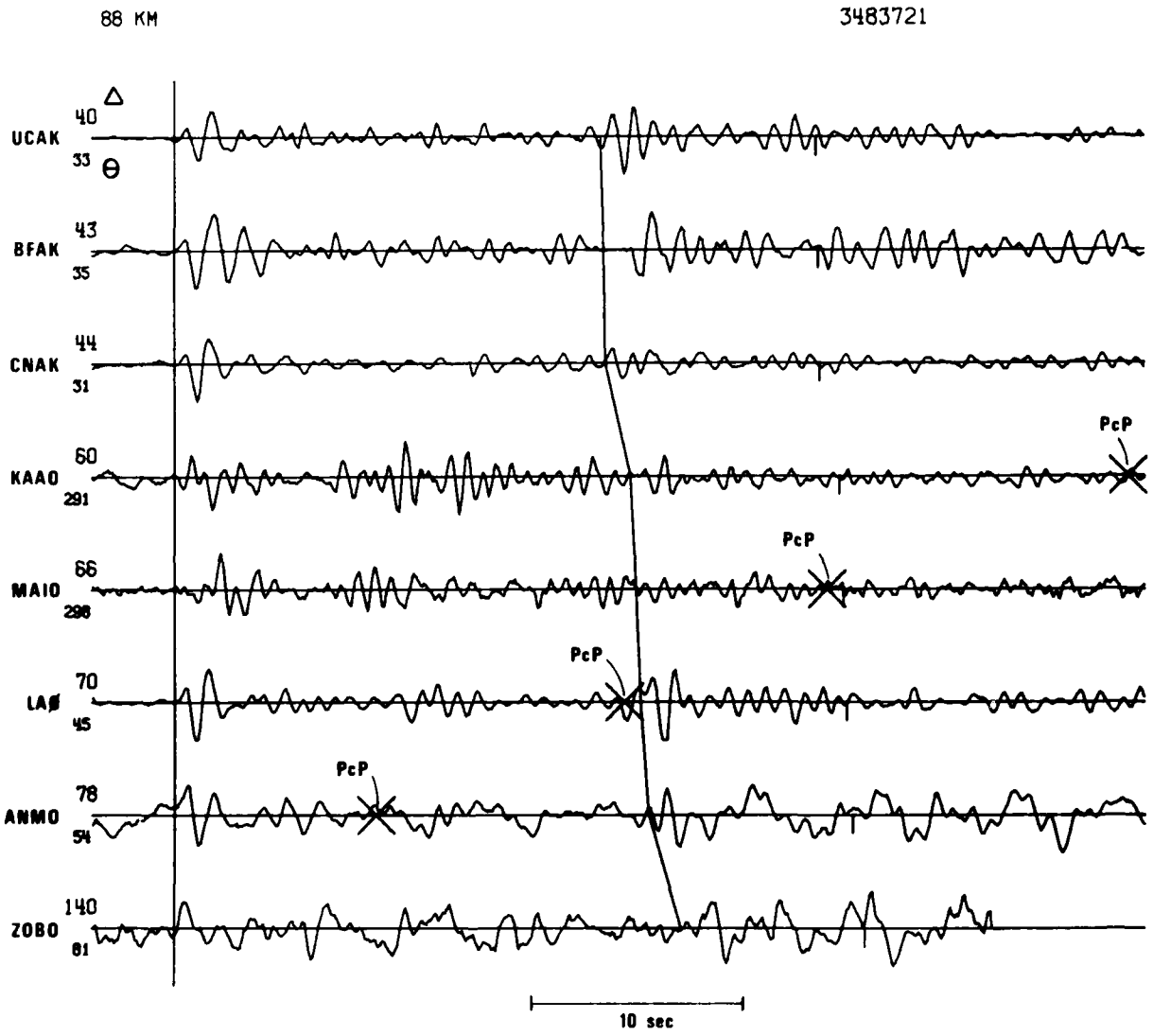

Figure 7. Event 3483721, 14 Dec. 1977, off coast of Hokaido, Japan. m_b = 5.1. Depth = 88 km. 90 (NEP). 20D (PDE). Good phase clarity. The PDE depth 20D indicates at least two confirming pP reports in the NOAA network.

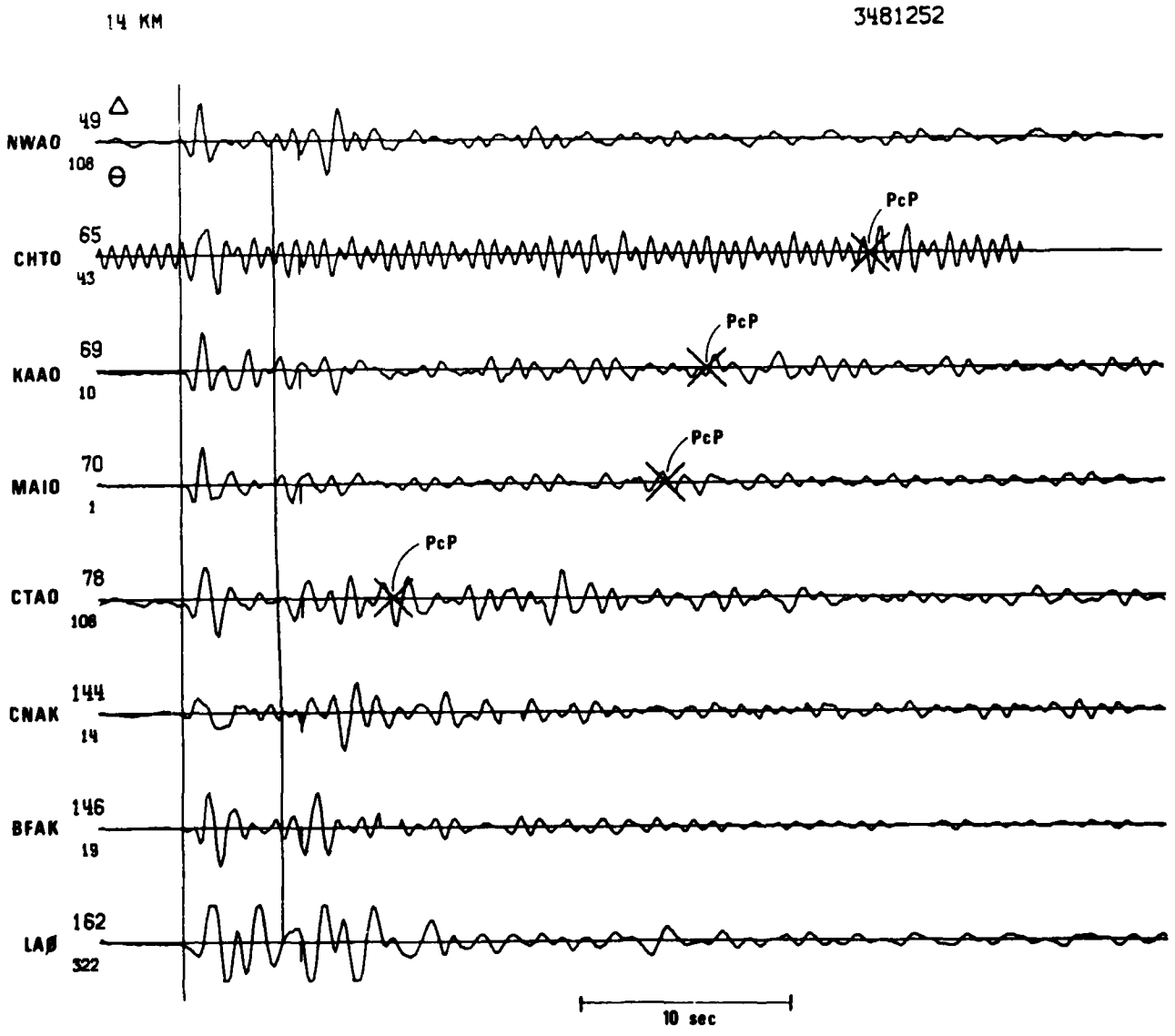

Figure 8. Event 3481252, 14 Dec. 1977, Atlantic-Indian Rise. m_b = 5.6. Good phase clarity. Depth = 14 km, 101 (NEP), 33 N (PDE).

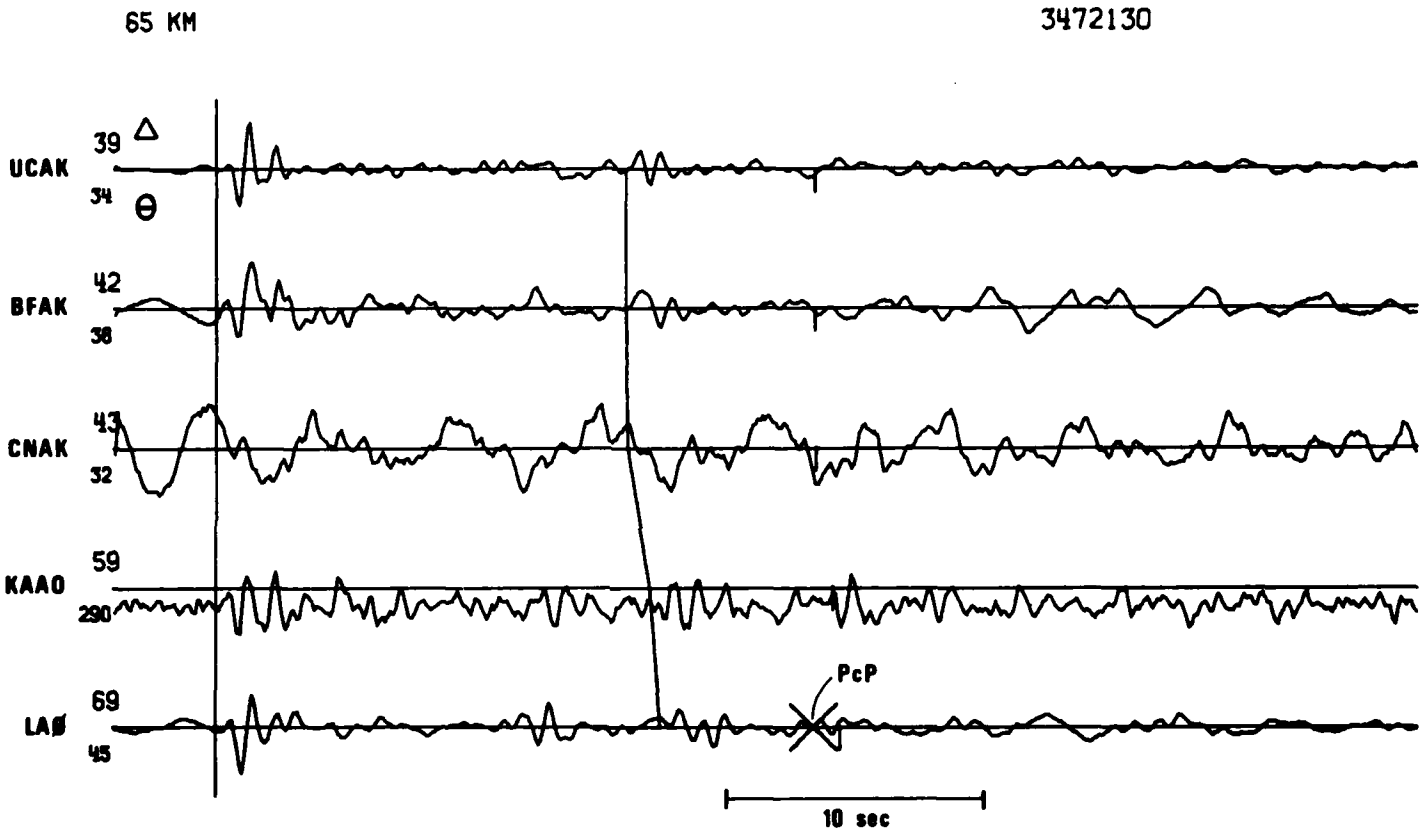

Figure 9. Event 3472130, 13 Dec. 1977, Kurile Islands. m_b = 4.6. Depth = 65 km, 54 (NEP), 89 (PDE). Fair phase clarity.

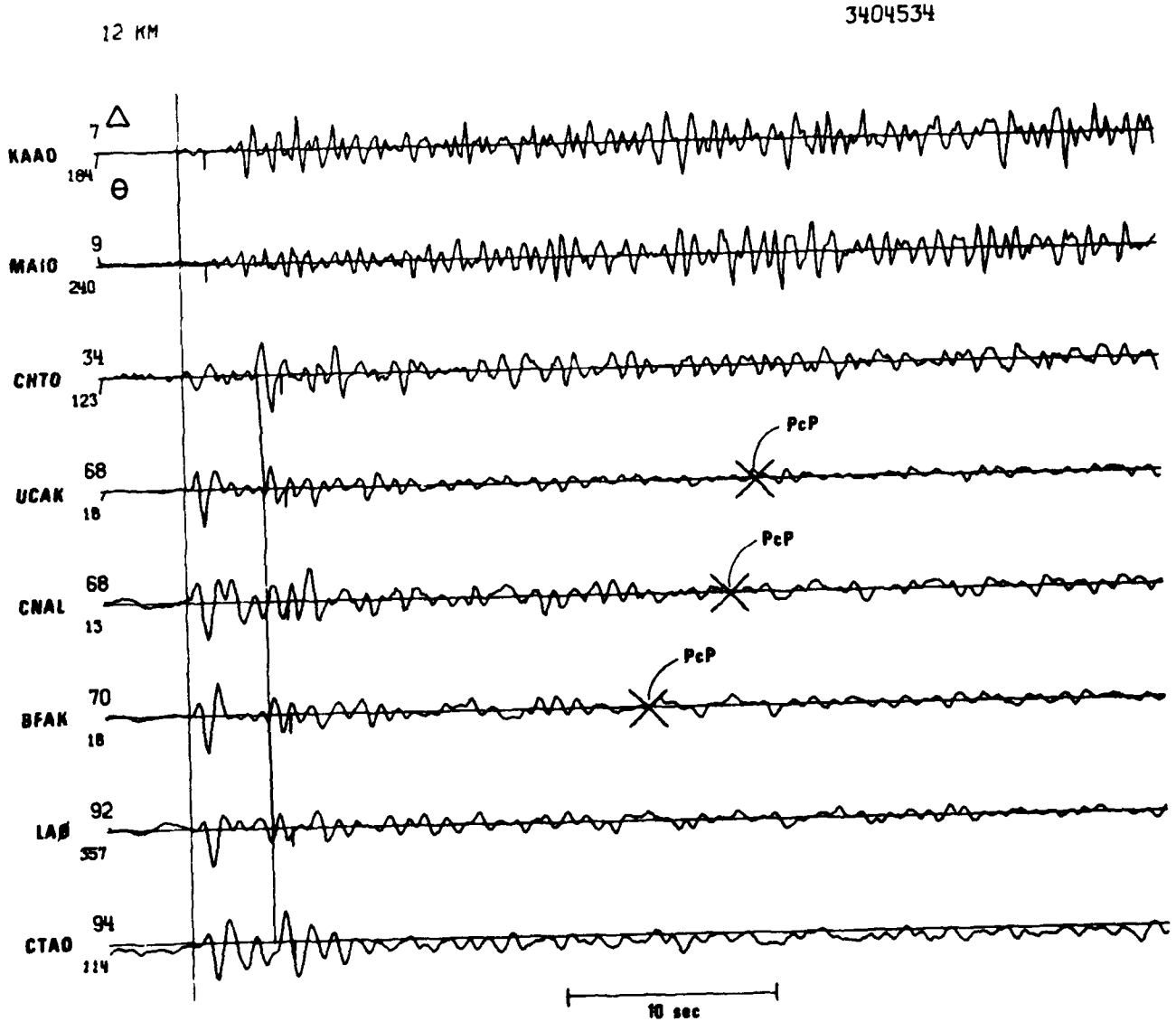

Figure 10. Event 3404534, 6 Dec. 1970, Kirgiz SSR. m_b = 5.2. Depth = 12 km, 33 (NEP), 33 N (PDE). Fair phase quality.

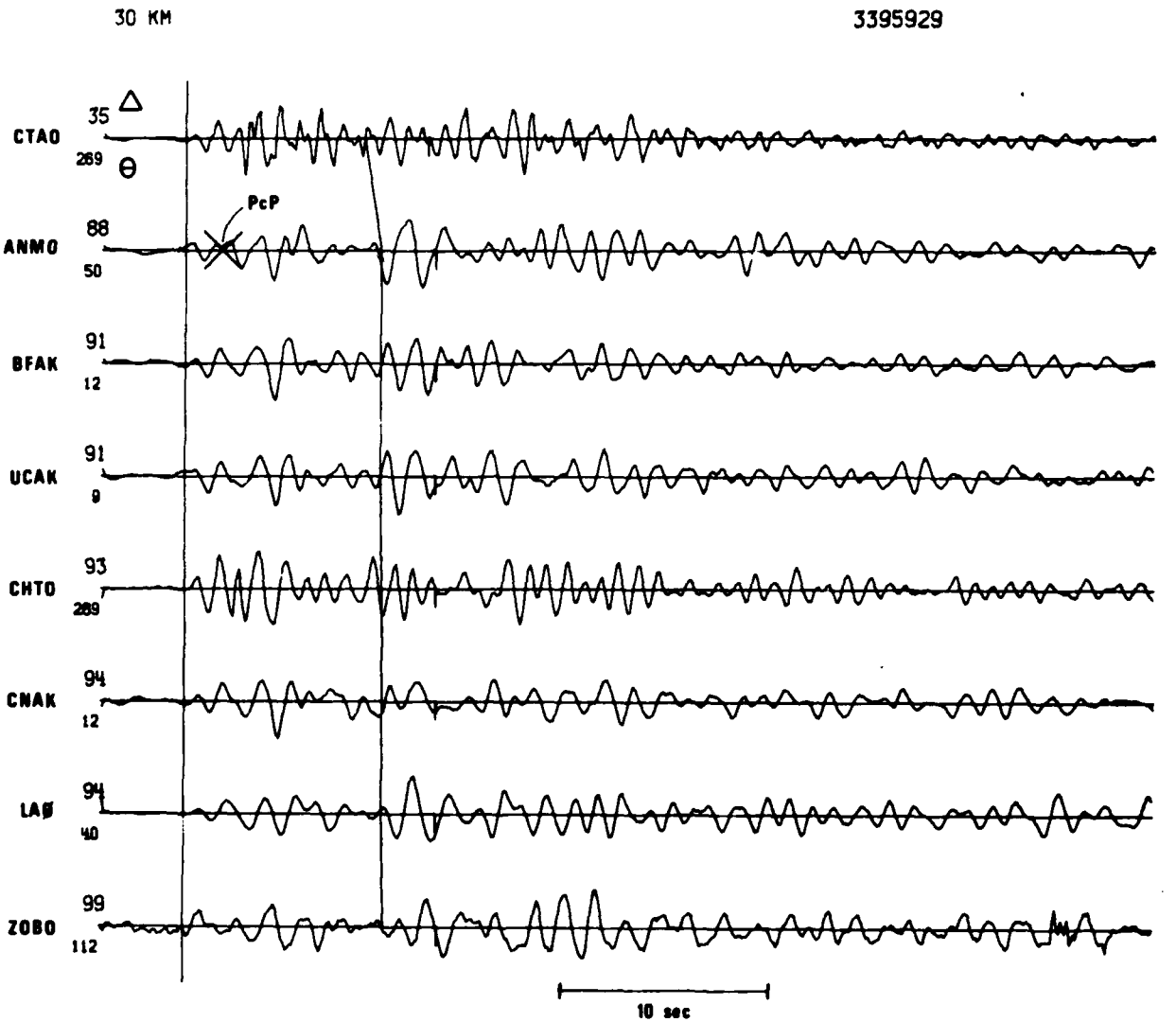

Figure 11. Event 3395929, 5 Dec. 1970, Tonga Islands Region. m_b = 5.5. Depth = 30 km, 0 (NEP), 33 N (PDE). Fair phase quality.

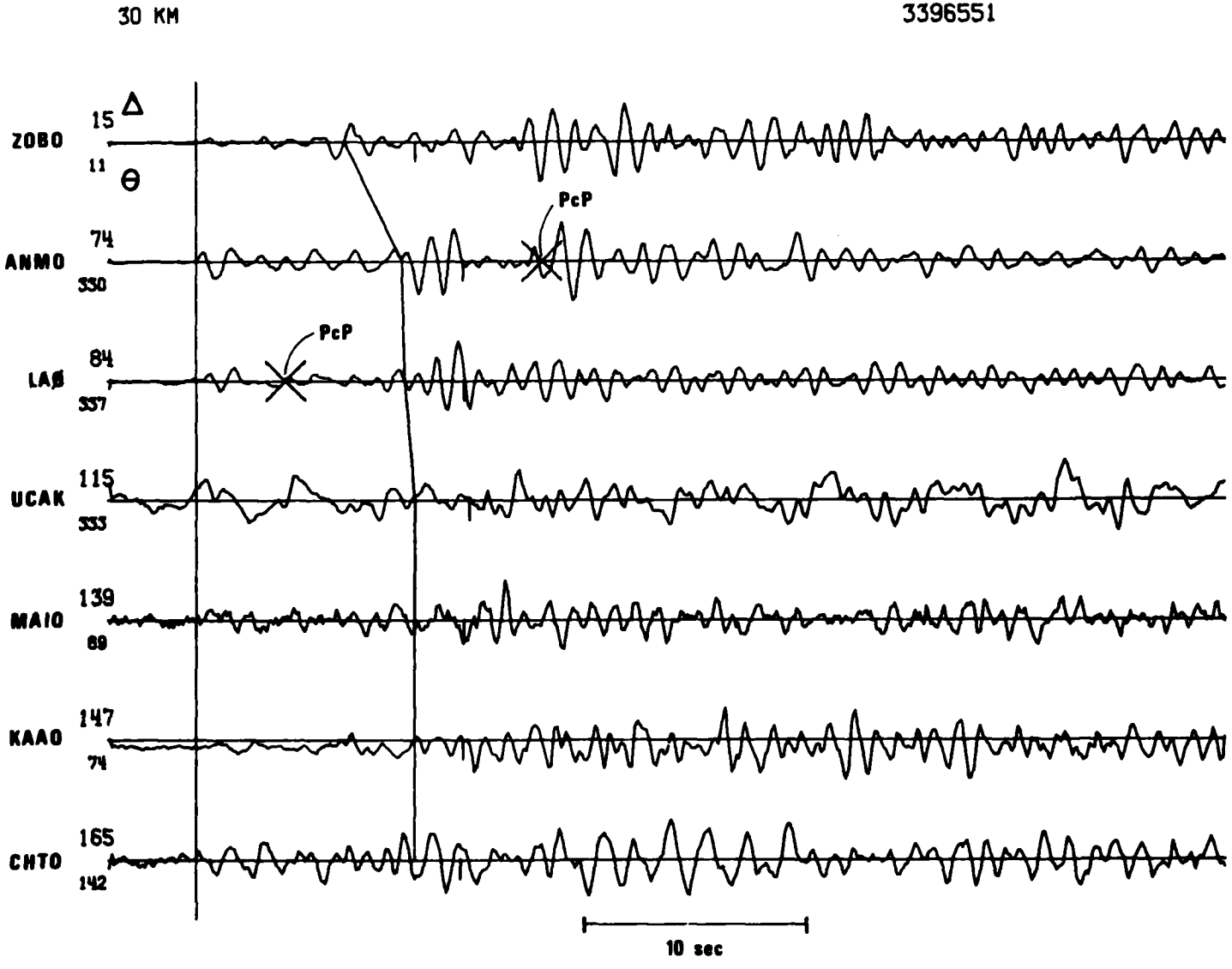

Figure 12. Event 3396551, 5 Dec. 1970, Near coast of Central Chile, m_b = 5.2. Depth = 30 km, 0 (NEP), 32D (PDE). Good agreement with PDE depth although phase quality is only fair.

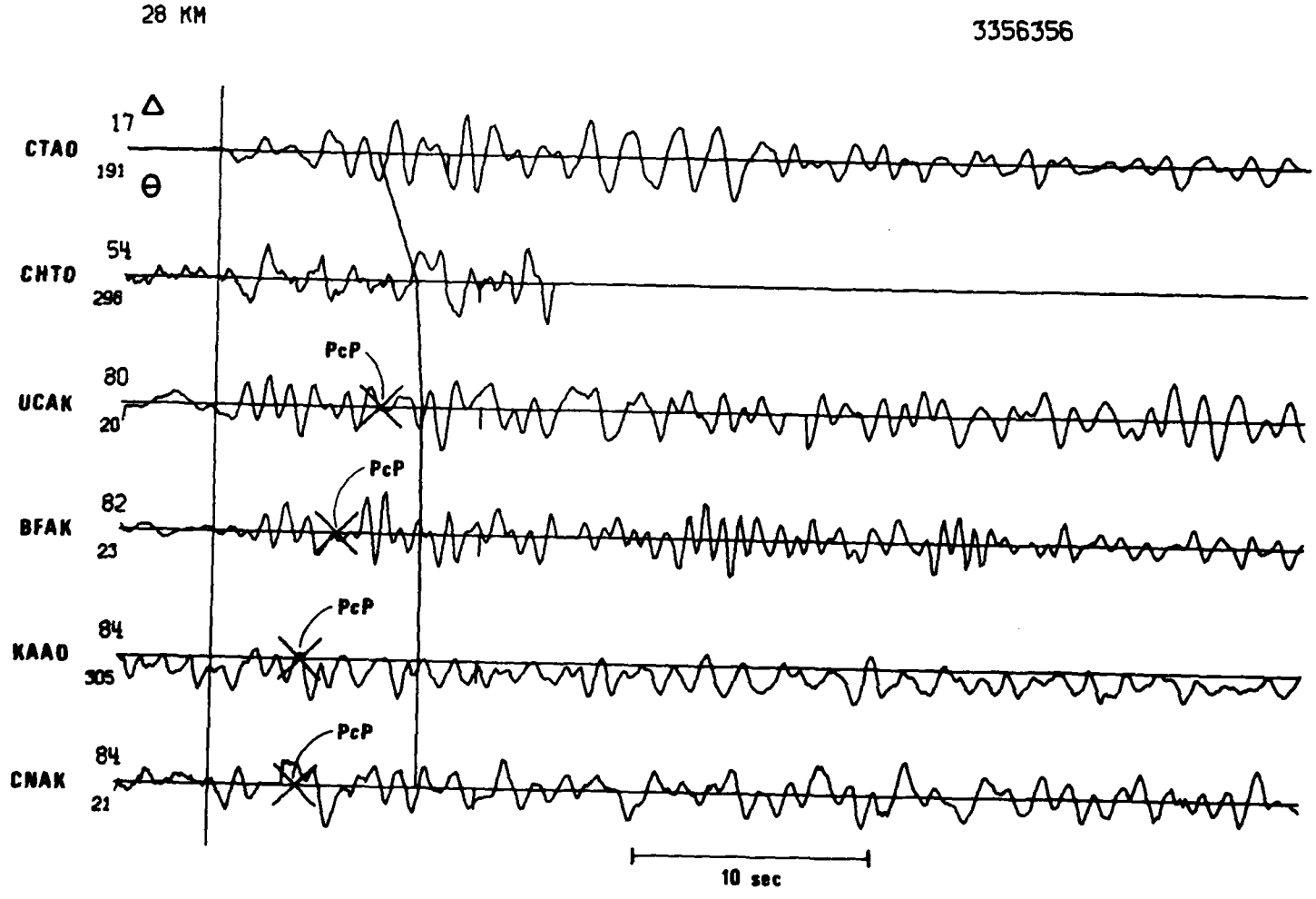

Figure 13. Event 3356356, 1 Dec. 1977, Bismarck Sea. m_b = 5.4. Depth = 28 km, 0 (NEP), 33 N (PDE). Poor phase quality.

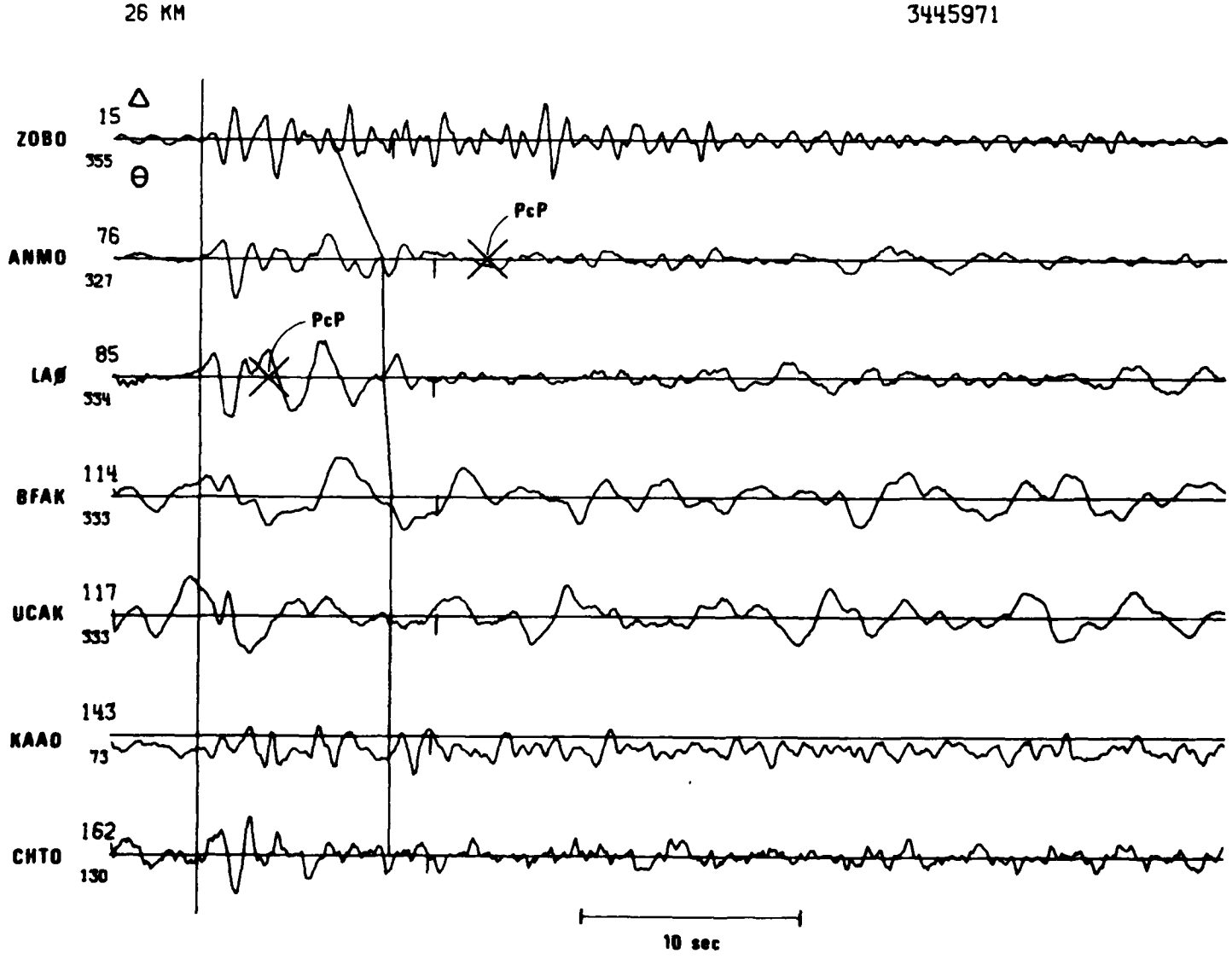

Figure 14. Event 3445971, 10 Dec. 1977, La Rioja Province, Argentina, m_b = 5.3. Depth = 26 km, 0 (NEP), 17 (PDE). Poor phase quality.

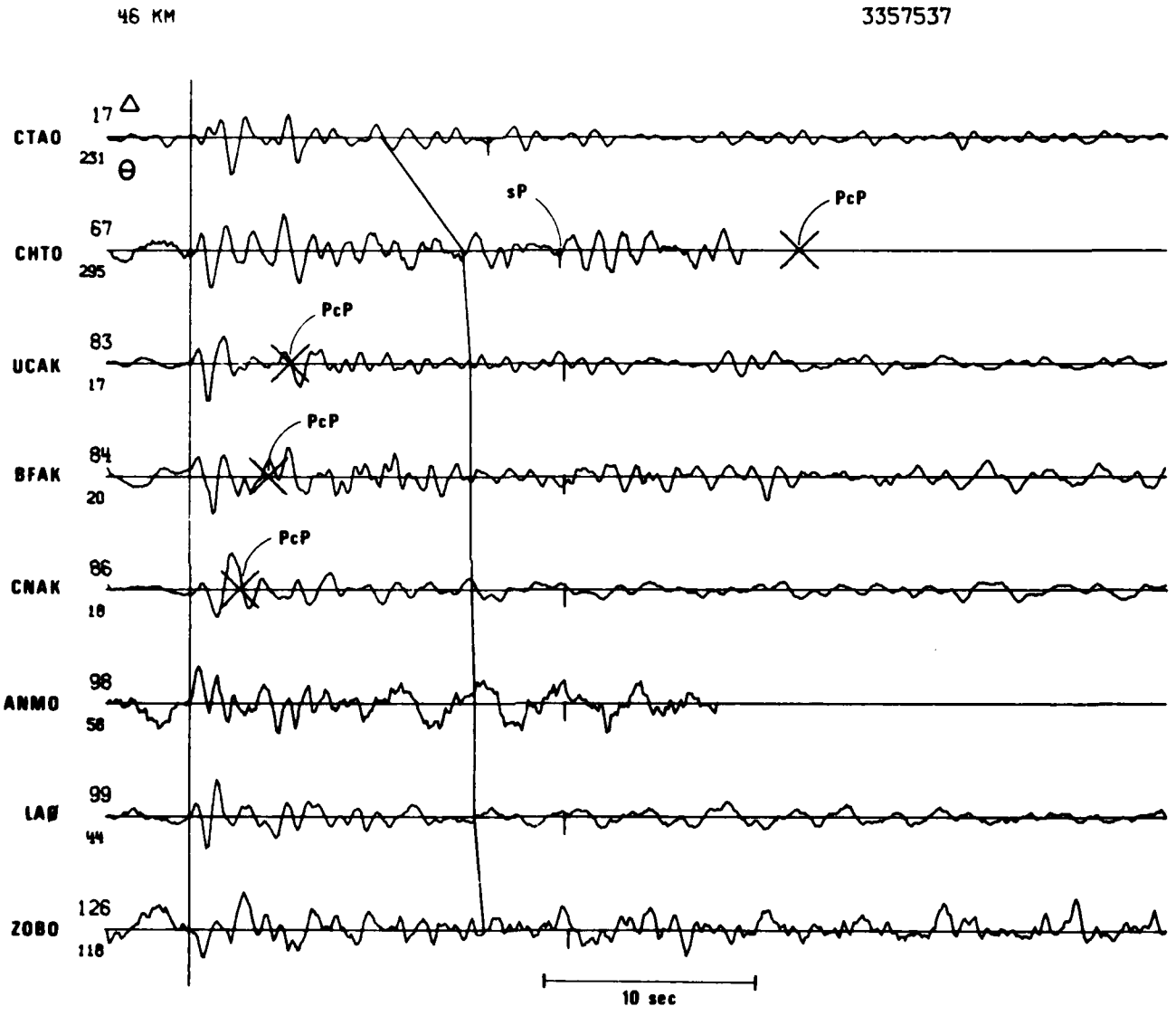

Figure 15. Event 3357537, 1 Dec. 1977, Solomon Islands. m_b = 5.2. Depth = 46 km, 46 (NEP), 77 (PDE). Poor phase quality. Possibly both pP and sP appear on second trace.

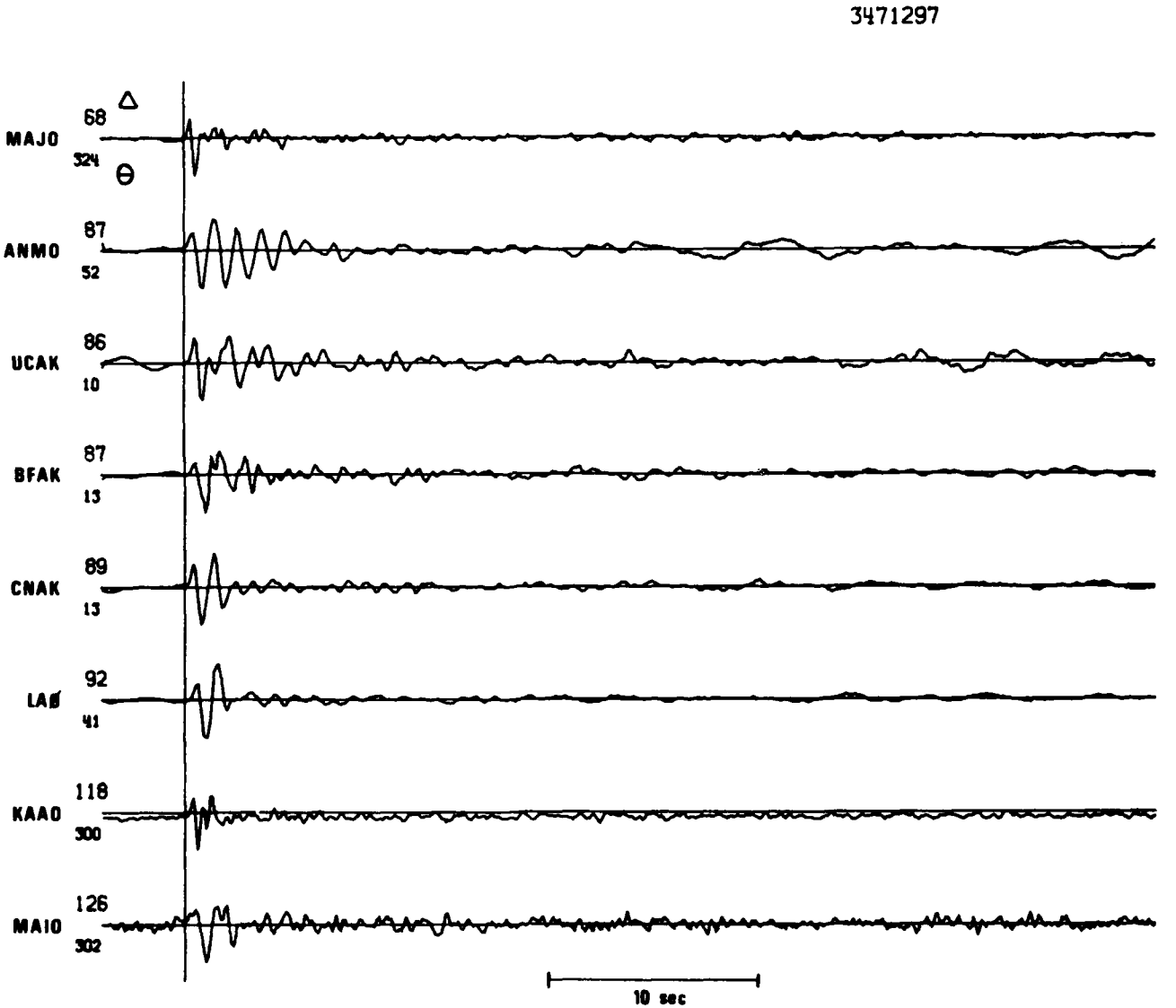

Figure 16. Event 3471297, 13 Dec. 1977, Fiji Islands Region. m_b = 5.3. Depth = 534 (PDE). The display screen holds 50 seconds of signal. If the focal depth is deeper than 200 km a depth phase is off the screen. Deep events show simple, explosion like P waveforms.

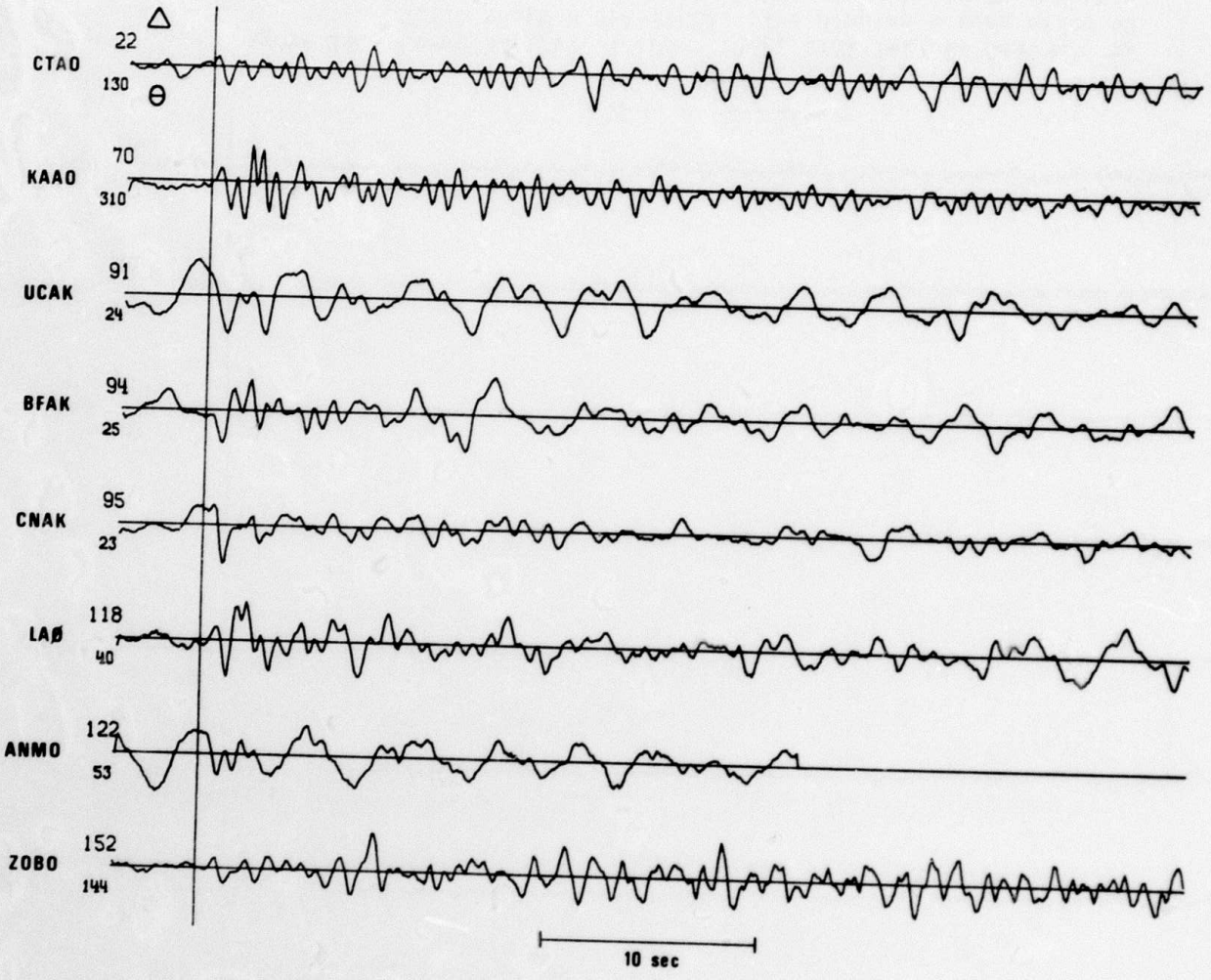

Figure 17. Event 3414766, 7 Dec. 1977, Banda Sea. m_b = 5.2. A well-recorded event, but no depth determination is possible. Depth = 0 (NEP), 33 N (PDE).

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APPENDIX

APPENDIX

Time delays of surface reflections (pP and sP) and the core reflection PcP, relative to the direct P wave as functions of epicentral distance, Δ, and focal depth, according to the travel-time table of Jeffrey & Bullen. The band for PcP covers the depth interval of 0 ~ 100 km.

DEPTH ESTIMATION

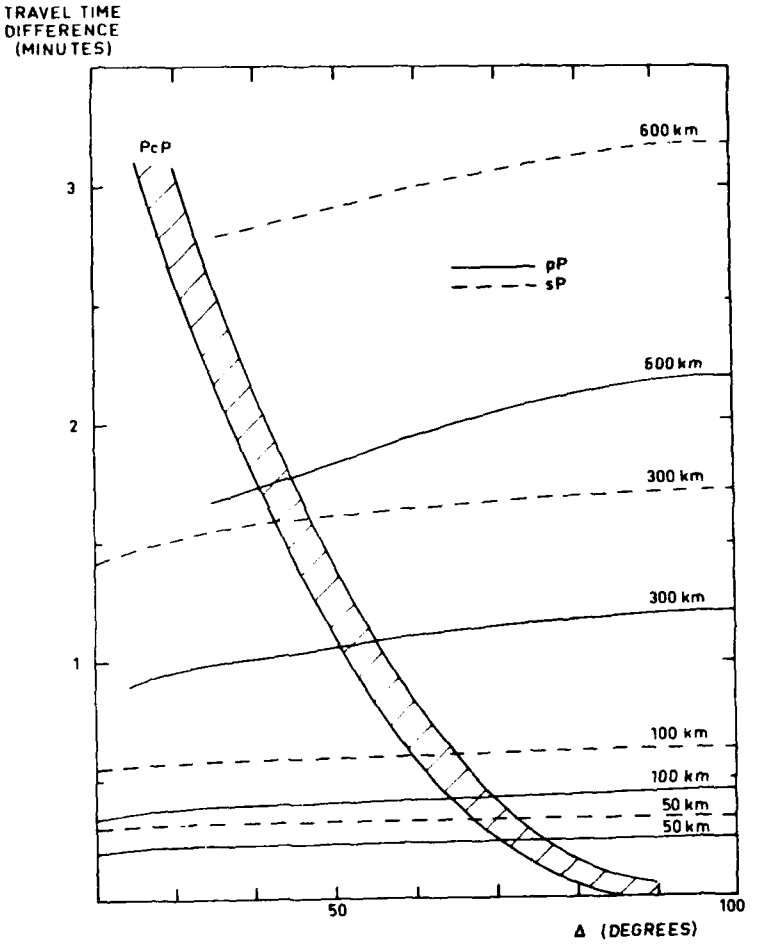

Figure A-1. Time delays of surface reflections (pP and sP) and the core reflection, PcP, relative to the direct P wave as functions of epicentral distance, Δ, and focal depth, according to the travel-time table of Jeffreys & Bullen (1967). The band for PcP covers the depth interval of 0-100 km. (After Yamamoto, 1974.)