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Search for P_dP phases and doublet earthquakes using the Yellowknife, N.W.T. array

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ABSTRACT

Data from the recently upgraded short-period Yellowknife array (NWT, Canada) were searched over the period from November 1989 to July 1990 for the distance range from about 70° to 85° for evidence of P_dP phases (Davis and Weber, 1990 and Weber and Davis, 1990). The search resulted in 51 seismograms for earthquakes from three widely separated geographical regions: Peru, Mariana Islands and Hindu Kush. None of the events had seismograms that exhibited a phase that is broadly consistent with the earlier reported P_dP phase (Weber and Davis, 1990) in respect to both travel time and slowness and with respect to the JB travel time tables and a discontinuity 243 km above the core mantle boundary (cmb). Although several other seismograms in the set did show apparent secondary arrivals shortly following P, either their travel-time or their slowness were inconsistent with the P_dP hypothesis. For the Peru events the average delay was 5 s and 50% showed doublets. A doublet earthquake is here defined as an aftershock that has essentially (within a few tens of km) the same epicenter as the mainshock but that occurs between 2 and 15 seconds after. For the Mariana Islands events the average delay was 6.5 s and 63% had doublets. Of the Hindu Kush earthquakes in the data set, 37% were followed by doublets with an average delay of 4 s. The secondary arrivals for these events are identified as aftershocks based on the fact that they had slownesses that were insignificantly different from those of the initial P phases. The doublet interpretation is confirmed for two cases by identification of a phase with the same time delay at other Canadian seismic stations.

RÉSUMÉ

Des données du réseau à courte période de Yellowknife, T.N.-O., (récemment mis à jour), furent examinées pour la période de novembre 1989 à juillet 1990 pour les distances de 70° à 85° afin de trouver des évidences pour les phases PdP (Davis et Weber, 1990 et Weber et Davis, 1990). La recherche procura 51 séismogrammes de séismes de trois régions géographiquement éloignées:

Pérou, Iles Mariannes et Hindu Kush. Aucun de ces événements n'a montré une phase grossièrement en accord avec la phase PdP rapportée précédemment (Weber et Davis, 1990) en ce qui concerne les temps de parcours, le slowness et par rapport aux tables de temps de parcours JB et une discontinuité de 243 km au-dessus de la transition manteau-noyau. Quoique plusieurs autres séismogrammes de cette série ont montré des arrivées secondaires apparentes suivant de peu le P, leur temps de parcours et leur slowness ne correspondent pas avec l'hypothèse PdP. Pour les événements du Pérou, le retard moyen était de 5 s et 50% montraient des doublets. Les séismes doublets sont ici définis comme une réplique qui a essentiellement le même épicentre que le choc principal (à l'intérieur de quelques dizaines de km) mais qui se produit entre 2 et 15 s après le choc principal. Pour les événements des Iles Mariannes, le retard moyen était de 6.5 s et 63% étaient doublets. De ceux de l'Hindu Kush, 37% étaient suivis de doublets avec un retard moyen de 4 s. Les phases secondaires de ces événements furent identifiées comme répliques sur la base d'un slowness très semblable à la phase P initiale. L'interprétation du doublet est confirmée par deux cas d'identification d'une phase avec le même retard sur d'autres stations seismographiques canadiennes.

INTRODUCTION

Previous work (Baumgardt, 1989; Davis and Weber, 1990; Weber and Davis, 1990) has suggested that a lower mantle velocity discontinuity produces a triplication that results in the P_dP phase. The question of whether this is correct or not, and the nature of the lower mantle structure in the D" region in particular are important issues for seismologists. This study suggests a different mechanism and interpretation for some of the seismic phases that are observed to arrive after the P phase. The purpose of this paper is threefold: first to attempt to find P_dP phases with the Yellowknife Array (YKA) data; second, to show that P_dP is not observed in any of the regions studied in this experiment; third, to suggest the existence of doublet earthquakes.

Weber and Davis (1990) presented a paper showing the existence of the P_dP phase by the use of slowness and azimuth data from the GRF array. The P_dP phase is believed to be generated by refraction from a hypothetical velocity increase of about 3% situated about 290 km above the core-mantle boundary. Their work was inspired by Baumgardt (1989) whose work was done with WWSSN stations, which cannot provide slowness information. It becomes rapidly obvious that such studies can only be done with an array. Fortunately during the latter part of 1989 the refurbished YKA became operational.

Earthquake Doublets

A doublet earthquake is an aftershock occurring soon after the mainshock. More specifically, it is defined here as an aftershock that has essentially (within a few tens of km) the same epicenter as the mainshock, but that occurs between 2 and 15 seconds after. Frankel (1982) discusses doublets that occur spacially in close proximity to small earthquakes in the Virgin Islands with time separations of 5 minutes. More recently Simila et al. (1990) discussed the 18 October 1989 California, Loma Prieta, earthquake of $m_b \approx 6.9$. Here 25 aftershocks occurred within 34 minutes after the mainshock, the earliest being 32 s after. Doublets with large time separations as described above are readily detected and located because the P phases for both are well separated in time and are reported separately by station operators. P phases for doublets with time separations of a few seconds, as discussed here, were not read by the operators because these later phases may be any one of a multitude of theoretically possible phases that may be generated near the source, such as pP or sP, to name just two.

While some earlier studies purporting to show the existence of multiple source time functions could be disputed because they had little or no azimuthal coverage, recently Tajima and Kikuchi (1991) and Ruff (1991) obtained multiple source time functions with azimuthal distribution of stations around the source, which were quite acceptable. Singh and Mortera (1991) determined source time functions for large Mexican earthquakes and showed that 14 out of 24 earthquakes had multiple source time functions.

Whether the doublets discussed here are truly earthquake doublets or P phases generated by other means, such as S to P conversions or reflection from discontinuities near the source, their mere existence requires discussion. Whatever their origin, they have slownesses and azimuths of arrival at the YKA that make them virtually indistinguishable from the P phases of the initial event.

In the upcoming International Seismological Observing Period (ISOP), when phases other than P are to be read on a large worldwide distribution of seismograph stations, it is very important to be aware of the existence of these second phases, regardless of their true origin. During that experiment timely data from arrays could help elucidate which earthquakes are followed by phases that approximate the slowness and azimuth of the initial P phase. Those events should not be included in the ISOP study or appropriate caution should be exercised when including them.

Data Collection

From the period of November 1989 to August 1990 YKA waveforms from 51 events in the distance range from 70° to 85° were collected. The parameters of all the events are listed in Table I. For a description of the array see Munro et al. (1990). These earthquakes have accurate focal depths to within a few tens of km.

The locations of the 51 events are shown by squares in Fig. 1; they are (broadly-speaking) in Peru, the Mariana Islands and the Hindu Kush. The three numbered diamonds represent 1) the reflection point for the average of the P_dP type phases from the Hindu Kush; 2) the reflection point of the Kurile earthquakes of Weber and Davis (1990); and 3) the reflection point for the average of the Peru events. The difference in the reflection points 1 and 2 is about 5°, this shows that in these two studies the same area of the mantle was not studied.

The data were analyzed by a program referred to here as CFKE that uses the broad-band fk analysis routine of Kvaerna and Doornbos (1986). The slowness and azimuth values computed from this will be referred to as the fk values. One important change that was undertaken here was to alter the program so as to line up all the seismic traces in order to have equal arrival times before undertaking the fk analysis (pers. com., Anglin, 1990). Another addition to the program permits one to analyze up to 5 time intervals, where the starting and stopping times of the windows may be arbitrarily selected.

In Fig. 2 are shown the center traces of the YKA for five earthquakes that were studied here. Events 25 and 57 are from the Hindu Kush, events 39 and 63 from the Mariana Islands region and event 37 from Peru. The seismograms shown have been band-pass filtered from 1.0 to 3.0 Hz. For each earthquake two time windows were analyzed by the fk method. The windows are indicated above the seismograms by arrows. The slowness values that were determined are given in Table I together with epicentral distance and depth of the events. Although not shown in Fig. 2, the program also provides a number of parameters that were determined for each window that are of interest here. From the fk analysis the slowness value is given to one hundredths of a second per degree, the azimuth value to one tenths of a degree, and finally the power level of each window is given in db. The principal advantage of this output is that the numerical values of slowness and azimuth can be read directly and accurately from the output of CFKE, rather than estimated from the contour plots of energy as used by Davis and Weber (1990).

I analyzed the first one or two cycles of the waveform, which amounts to a 1 to 2 s time window, because I wanted a consistently short time frame that corresponds as closely as possible to the source time function so that any later phases are excluded. To test the precision of the method, I analyzed the slowness values of a P phase twice by the fk routine by trying to use the same starting time and length of the window, the variation in slowness is about ± 0.02 seconds/degree (s/d) for a good signal to noise ratio and about ± 0.05 s/d for a poor signal to noise ratio. This changed the starting time and window length only slightly. This variation in slowness is a measure of the repeatability of the method. However the resolution of the fk routine is much better than the values given above (pers. comm., F. Anglin, 1991). For an event with a good signal to noise ratio, the resolution is ± 2 degrees in azimuth and a few ms/degree in slowness. In contrast, for a secondary phase of any sort, particularly when it follows the P phase within a few seconds and when it has a poor signal to noise ratio, the resolution in slowness is worse than for the P phase and may reach 0.5 s/d. Therefore the CFKE program was well suited to distinguish particularly the slowness differences between the phases that are of interest here.

From Weber and Davis (1990) it emerges that the difference in slowness between P and P_dP is 0.8 s/d and the delay 5.3 s between 80 and 90 degrees; and from Davis and Weber (1990) the P_dP phase arrive 3-5 s after P and have slowness smaller by 0.7 - 0.8 s/d for epicentral distances around 75 degrees. However, because of the strong distance dependence of both the slowness and the time differences these values were also computed theoretically from the JB velocity model with an added 3% velocity discontinuity at 2648 km depth or 243 km above the cmb. These theoretical values will be compared with the values observed in this study.

The data necessary for our study can be obtained either from or with the help of the PDE sheets, such as depth of focus and epicentral distance, or from the output of the program CFKE where the time difference between successive phases can be read.

Discussion of Data and Interpretation

For the Peru earthquakes the time differences between the doublet P phase and the P phase of the initial earthquake are shown at the top of Fig. 3, and the corresponding slowness differences are shown at the bottom of Fig. 3. The theoretical values, calculated from the JB velocity model using the depth to the discontinuity from the SYLO model (Young and Lay, 1990) with a discontinuity in velocity 243 km above the cmb are also shown in the figure (the top curve is for earthquakes with a focal depth of 4 km and the bottom one for those at 600 km depth). Of the data in Fig. 3, none of the earthquakes have both time and slowness differences that are in agreement the theoretical values. Of these earthquakes, 50% were followed by doublet earthquakes. The average time delay was 5 s.

The corresponding time and slowness differences for the Hindu Kush earthquakes are shown in Fig. 4 together with the same theoretical values as described above; none of the data points are compatible with both the theoretical values. Of these earthquakes, 37% were followed by doublet earthquakes, and the average time delay was 4 s. For the Mariana Islands earthquakes, the observed and the theoretical values are shown in Fig. 5. In this data set there are again no earthquakes that have both the time and slowness differences to satisfy the theoretical values. For these earthquakes 67% were followed by doublet earthquakes and the average time delay was 6.5 s. Since at least for part of the Mariana Islands zone a subducting slab is present, the second arrivals may be explained as a reflection from the top of the slab for earthquakes near the bottom of the slab.

In Fig. 6 are shown the travel time differences between the P phase of the doublet and the mainshock. For all three areas studied here the time differences exhibit a large amount of scatter. If the P phases of the doublet had been reflected from some subsurface discontinuity they would have shown a regular variation with depth at least for the Hindu Kush where the earthquakes have a small geographical distribution.

For two of the earthquakes in the Hindu Kush the time difference between the doublet P phase and that of the mainshock could also be read on two Canadian Seismograph Stations. In all cases the time differences there were equal to that observed at YKA. This observed equality of the time differences argues in favour of their interpretation as doublet earthquakes. The details are as follows.

The first event of February 5, 1990 with $\Delta = 80.33°$ and h=95 km had a time delay for the doublet of 4.5 s on YKA and the same delay was also read at IGL $\Delta = 71.71°$ and at FCC $\Delta = 83.39°$.

The second event of February 6, 1990 with $\Delta=80.95°$ and h=91 km had a time delay for the doublet of 4.5 s on YKA and the same delay was read at FRB $\Delta=74.92°$ and FCC $\Delta=84.03°$.

For these two events the theoretical pP-P times are 25 s and 24 s respectively at YKA so that the second phase can not be pP. Finally the theoretical PcP-P times for these two events are 7.2 s and 6.7 at YKA so that the second phases might be identified as PcP since that is within 3 s of the observed time difference at YKA. However, for the first event the distance difference between IGL and FCC is 11.7° and for those stations the theoretical time difference of PcP-P between the two stations amounts to 14.1 s. Since the observed time difference between the two phases at the two stations is 4.5 s, their difference is 0.0 s and therefore that phase can not possibly be PcP. A very similar argument can be made for the second event mentioned above.

It is interesting to consider the magnitude of the earthquakes and then their source dimensions, which are related to rupture time. In this study the m_b values vary from 6.1 to 4.0 but most fall between 5.0 and 5.5. From Kanamori and Anderson (1975) the source area for $M_s=5.5$ is about 40 km^2 and the fault length about 6.3 km, which corresponds to a rupture time of about 2 s. Because of their small magnitudes the majority of the earthquakes considered here should have small source rupture times. Therefore the sources considered here have short rupture times and would not be expected to be of the complex sources types of large near surface earthquakes that give rise to multiple events as the earthquake propagates along the fault.

In the interpretation of the doublet phases we have at least three choices. The first one is the path chosen by Weber and Davis (1990) where the later phases are interpreted to be PcP and P_dP. This requires that the observed travel time differences and slowness differences fit the earth model reasonably well. In their study this is corroborated by time and slowness measurements, the latter read from contour plots of energy. The data from our study used a different technique to measure slowness, involved a different array and source zone from those of Weber and Davis (1990) and yielded results that <u>do not support</u> the P_dP hypothesis for any of the data when compared to theoretical values based on the JB velocity model and a discontinuity 243 km above the cmb. However, because of these three differences between these two studies we are not in a position to duplicate their results and therefore we suggest a different interpretation for the data obtained here.

It should be noted that the theoretical values of the slowness and time differences are very model dependent. While it has been shown here that none of the data points agree with both the theoretical slowness and time differences of the model used here, other models may well fit some of the data. However, because of the shape of the theoretical changes in slowness and time, no other model can fit all the data. But three different models, one for each region may accomplish that. The theoretical changes in time and slowness shown in Figs. 3, 4 and 5 demonstrate the kind of distribution that must be exhibited by the observational data before their interpretation as P_dP phases is acceptable. Finally, since there is considerable uncertainty in both the P and S velocity distributions in layer D", and the height of the discontinuity varies from 200 km to 350 km above the cmb. The combination of both changes in height to the discontinuity and changes in velocity in or above D" results in a very large number of possible models. Therefore here we limited the comparison to only one model. Finally, we cannot predict with any degree of certainty what the theoretical variations of the time and slowness difference for the real Earth are.

Another choice involves interpreting the secondary phase as distinct earthquakes and leads to at least two possible interpretations. If we assume that the secondary phases are due to P phases of earthquakes with their slowness and azimuth values containing only little error that then leads us to earthquakes up to several degrees away from the primary ones because of the observed time and slowness differences. Also since the amplitudes of some of the secondary phases are comparable to the initial one that means that the secondary events should have been large enough to have been located by the international networks by themselves. Since there is no evidence in the Bulletins that they were reported or located one may argue that they did not in fact occur. This was tested by inspection of the epicenters listed in the PDE bulletin for the events larger than

$m_b=5$. This involved three events from Peru, 7 from the Marianas and 4 from the Hindu Kush. The result was that no known events occurred that could give rise to doublets. Furthermore, because of their magnitude these earthquakes should be in the bulletin, if their P phases had been read. It is, however, most unlikely that the P phases of the doublet earthquakes were read because station operators have no information on the depth of the earthquakes and therefore attribute the later phases to be "noise" generated by the earthquake or to be depth phases, particularly for phases arriving within 15 s of the P phases.

The third choice is that the secondary phases are P phases of earthquake doublets originating very near to the mainshock. The calculated slowness and azimuth (which is not used in this study) values calculated by the fk routine, except for Peru Fig. 3, often are not significantly different from the mainshock, which is in support of the hypothesis of them being doublets.

CONCLUSIONS

Of 51 earthquakes that were studied with YKA, from Peru, the Hindu Kush and the Mariana Islands, none have a phase that could be associated with the hypothesized P_dP phase (Davis and Weber, 1990) because neither the travel time nor the slowness agreed with the JB velocity model. About half of the initial P phases were followed by secondary phases within a few seconds. These secondary phases had slownesses and azimuths that were insignificantly different from the mainshocks. Here the argument is advanced that the secondary phases for all of the earthquakes studied are doublet earthquakes. It has also been pointed out that the theoretical changes in slowness and time are very model dependent, and that therefore models other than the one used here may well account for some of the observed data being P_dP phases. Regardless of their interpretation, P_dP or doublet earthquake, these phases must be considered in the interpretation of secondary phases reported in the BISC based on travel time differences alone as evidence for lower mantle complexity (Weber and Köring, 1990). We are in agreement with Weber and Köring

(1990) that the areas of the world that they find to be anomalous should be studied in more detail by analyzing the seismograms, ie. the amplitude and waveform information. Furthermore, Davis and Weber (1990) found that their P_dP phases were unubiquitous, in agreement with this investigation. From our study, it can be concluded that in at least three regions of the world doublet earthquakes are common and relatively frequent. Their existence complicates any tabulation of secondary phases being performed by the ISC and ISOP. For unambiguous identification use of array data such as that used in the present study is preferable.

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REFERENCES

Baumgardt, D.R., 1989, Evidence for a P-wave velocity anomaly in D", Geophys. Res. Let., 16, 657-660.

Davis, J.P. and M. Weber, 1990, Lower mantle velocity inhomogeneity observed at GRF array, Geophys. Res. Let., 17, 187-190.

Frankel, A., 1982, Precursors to a magnitude 4.8 earthquake in the Virgins Islands: Special clustering of small earthquakes, anomalous focal mechanisms and earthquake doublets, Bull. Seism. Soc. Am., 72, 1277-1294.

Kanomori, H. and D.L. Anderson, 1975, Theoretical basis of some empirical relations in seismology, Bull. Seism. Soc. Am., 65, 1073-1095.

Kvaerna, T. and D.J. Doornbos, 1986, An integrated approach to slowness analysis with arrays and three-component stations, Semiann. Tech. Summary, 1 Apr - 30 Sept 1986, NORSAR Sci. Rep. No 2-85/86, Kjeller, Norway.

Munro, P.S., R.J. Halliday, W.E. Shannon and D.R.J. Schieman, 1990. Canadian Seismograph Operations - 1987, Geological Survey of Canada Paper 88-25, Seismological Series Number 99.

Ruff, L., 1991, Large earthquakes in subduction zones: a simple model of asperity interaction that produces variable recurrence times and rupture mode, Abstract, page 62, AGU 1991 spring meeting, Baltimore, Mld.

Simila, G.W., K.C. McNally, E. Nava, M. Protti-Qusada and J. Yellin, 1990, Evidence of very early aftershock activity along the northwest portion of the 18 October 1989 earthquake rupture zone, Geophys. Res. Let., 17, 1785-1788.

Singh, S.K. and F. Mortera, 1991, Source time functions of large Mexican subduction earthquakes, morphology of the Benioff Zone, age of the plate and their tectonic implications, J. Geophys. Res., 96, 21,487-21,502.

Tajima, F. and M. Kikuchi, 1991, Recovery of source signals from apparently complex waveforms using an interactive deconvolution method, Abstract, page 89, AGU spring meeting, Baltimore, Mld.

Weber, M. and J.P. Davis, 1990, Evidence of a laterally variable lower mantle structure from P- and S- waves, Geophys. J. Int., 102, 231-255.

Weber, M. and M. Körnig, 1990, Lower mantle inhomogeneities inferred from PcP precursors, Geophys. Res. Let., 17, 1993-1996.

Young, C.J. and T. Lay, 1990, Multiple phase analysis of the shear velocity structure in the D" region beneath Alaska, J. Geophys. Res., 95, 17,385 - 17,402.

FIGURE CAPTIONS

1. The geographical distribution of earthquakes (squares) used in this study. The center of the map is at YKA and the outer circle is of 90°. Diamonds are reflection points: 1) Hindu Kush from this study, 2) Weber and Davis (1990), and 3) Peru.

2. Filtered center traces of earthquakes recorded at YKA. The amplitude in nm/s is given for each event at the left. The relative time scale is given at the top and bottom of the figure. The first pair of arrows represents the analysis window for the P phase and the second pair that for the doublet earthquake. The number on the right refers to the value in the No. column in Table I.

3. At the top are shown the time differences between the P phases of the doublet and the P phase of the mainshock and at the bottom are shown the corresponding slowness differences for the Peru events. The dashed curves represent the theoretical time differences and the solid curves the theoretical slowness differences calculated for the JB velocity model with a discontinuity in velocity 243 km above the cmb. The upper curve is for focal depth of 4 km, and the lower curve is for focal depth of 600 km.

4. Similar to Fig. 3 for the Hindu Kush events.

5. Similar to Fig. 3 for the Mariana Islands events.

6. Time differences between the P phases of the doublets and the P phases of the mainshocks against the depth of the events for the three areas.

TABLE I

EARTHQUAKE PARAMETERS

PDE	LAT	LONG	NO	DLT	H KM	AZM	S1	S2	DT	DIFS	DATE
	HINDU KUSH										
6	+35.629	+ 69.372	12	81.83	104.00	356.70	5.27	5.27	4.50	0.00	17/12/89
20	36.368	70.791	3	81.85	136.00	355.60	5.54	5.16	2.00	0.38	01/02/90
22	37.069	71.273	4	80.35	95.00	355.20	5.47	4.91	2.50	0.56	05/02/90
23	36.483	70.450									05/02/90
24	36.442	71.438	25	80.95	91.00	355.10	5.35	5.39	4.50	-0.04	06/02/90
38	36.910	71.290	13	80.45	108.00	355.20	5.43	5.36	3.50	0.07	25/02/90
39	36.390	71.440	26	81.00	149.00	355.00	5.38	5.38	5.00	0.00	27/02/90
46	36.352	70.436									30/03/90
47	35.751	70.803	44	81.66	96.00	355.60	5.33	5.38	4.00	-0.05	01/04/90
49	33.077	68.237	14	84.40	53.00	357.60	5.20	5.21	4.00	-0.01	02/04/90
60	36.950	71.406	54	80.44	96.00	355.10	5.40	5.45	2.50	-0.05	28/04/90
62	36.796	71.410									30/04/90
63	36.490	71.252	57	80.90	244.00	355.20	5.34	5.44	5.50	-0.10	02/05/90
67	35.986	70.443									15/05/90
71	38.372	74.376									17/05/90
72	36.483	70.424	66	80.94	220.00	355.90	5.28	5.38	6.00	-0.10	30/05/90
73	36.079	70.545									12/06/90
74	36.480	70.627									23/06/90
77	36.461	70.798									13/07/90
	PERU										
3	- 4.213	- 76.430	9	72.73	115.00	139.80	6.00	6.22	15.50	-0.22	07/12/89
40	- 8.339	-74.185	18	77.33	141.00	138.90	5.85	5.20	5.50	0.65	15/01/90
41	-16.547	- 69.944	24	86.43	186.00	137.50	5.13	4.48	2.00	0.65	27/01/90
32	- 3.184	- 80.867	10	70.48	56.00	143.90	6.13	5.36	5.50	0.77	10/02/90
42	- 3.421	- 76.908	37	71.83	117.00	140.00	6.11	5.75	8.00	0.36	13/03/90
43	-11.752	- 76.186	38	80.00	111.00	141.80	5.61	5.08	3.00	0.53	20/03/90
51	-16.275	- 73.299	15	85.15	56.00	140.50	5.48	5.10	2.00	0.38	04/04/90
59	-15.084	- 72.972	53	84.12	49.00	139.80	5.18	4.83	2.00	0.35	16/04/90
65	-15.242	- 72.061	59	85.54	146.00	139.00	5.29	4.72	2.00	0.57	02/05/90
79	- 8.583	- 74.576									26/07/90
	MARIANA ISLANDS										
11	+23.654	+141.902									08/11/89
13	18.843	145.586	3	77.76	209.00	287.40	5.46	5.33	6.50	0.13	25/11/89

4	17.974	146.461	10	78.14	80.00	286.20	5.52	5.53	6.50	-0.01	07/12/89
5	18.506	145.898	11	77.92	154.00	286.90	5.44	5.50	2.50	-0.06	10/12/89
6	35.629	69.372	13	83.11	147.00	285.80	5.20	5.11	8.50	0.09	17/12/89
7	15.775	147.249	1	79.74	50.00	284.50	5.36	5.35	4.50	0.01	13/01/90
8	21.578	143.148	2	76.40	299.00	290.80	5.68	5.71	7.50	-0.03	23/01/90
28	31.765	121.017	7	75.81	10.00	313.60	5.40	5.31	13.00	0.09	09/02/90
29	26.977	140.278									09/02/90
36	15.847	147.127	11	79.73	44.00	284.60	5.39	5.37	3.50	0.02	17/02/90
37	25.49	124.45									23/02/90
44	29.455	131.592	39	74.11	60.00	304.10	5.42	5.52	7.50	-0.10	01/03/90
48	24.360	141.186									01/04/90
52	16.423	145.922									04/04/90
54	15.558	147.536	48	79.80	46.00	284.10	5.47	5.50	3.00	-0.03	05/04/90
56	20.209	145.046									09/04/90
58	11.611	142.992	52	85.33	44.00	286.30	5.09	5.09	8.50	0.00	13/04/90
61	18.125	145.405	55	78.48	319.00	287.20	5.44	5.46	4.50	-0.02	29/04/90
66	13.231	143.798	60	83.53	187.00	286.30	5.14	5.03	3.50	0.11	10/05/90
69	15.044	147.378	63	80.33	10.00	284.00	5.38	5.47	11.50	-0.09	16/05/90
75	25.372	124.504									04/07/90
76	15.673	146.861									08/07/90

PDE are the numbers of the earthquakes in the PDE sheets.
NO are the numbers of the earthquakes from the CFKE program.

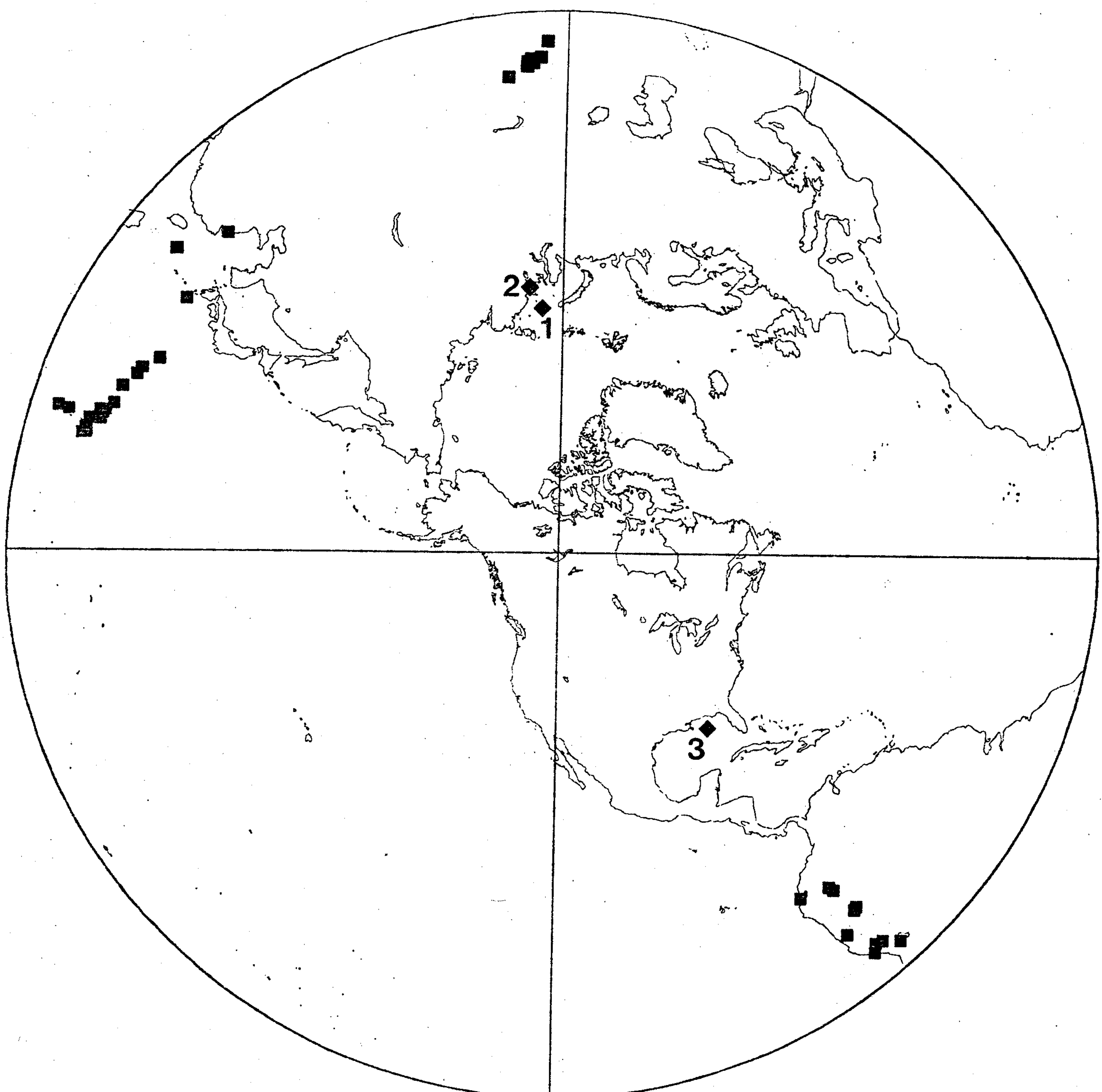


Fig. 1

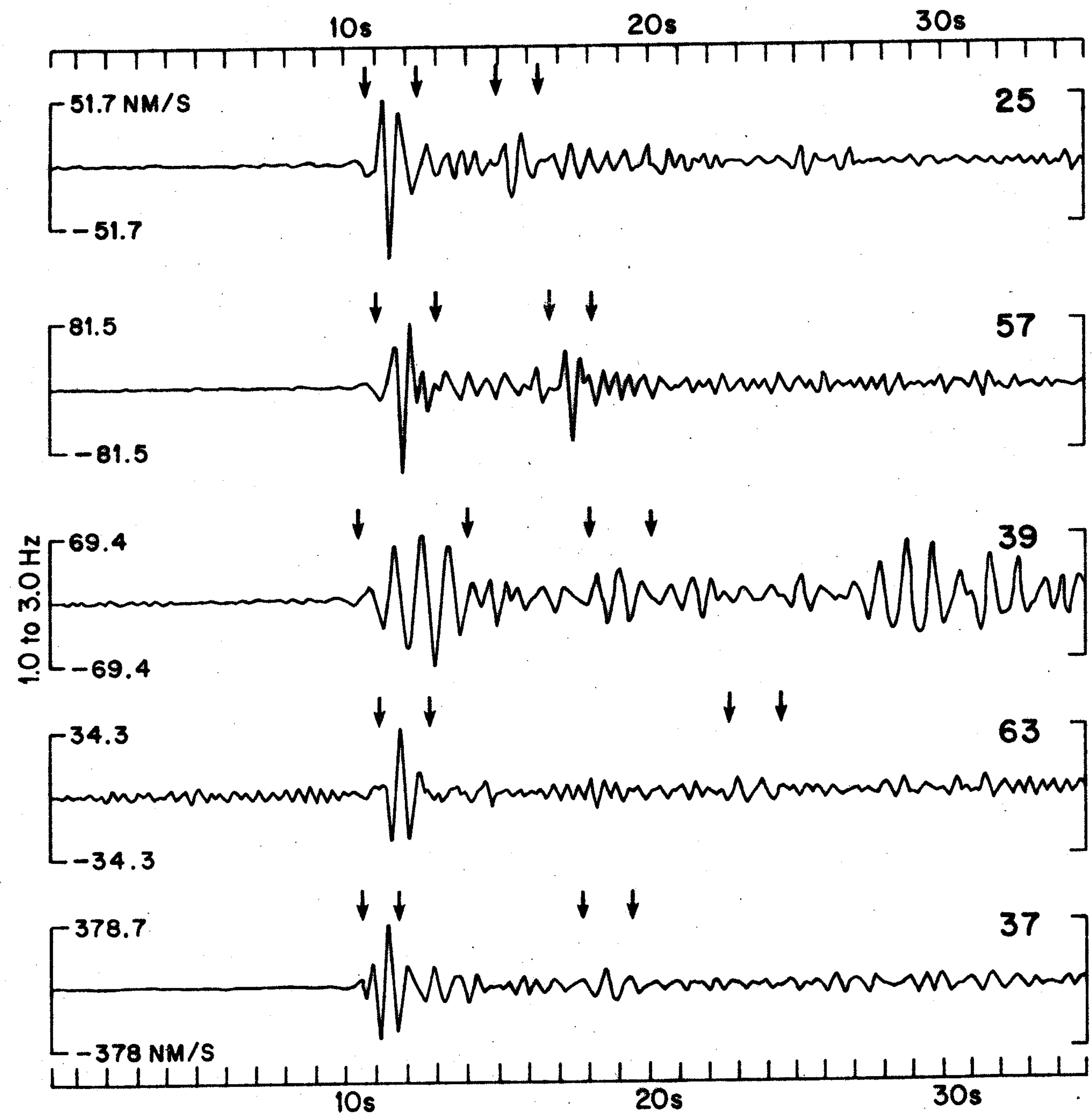
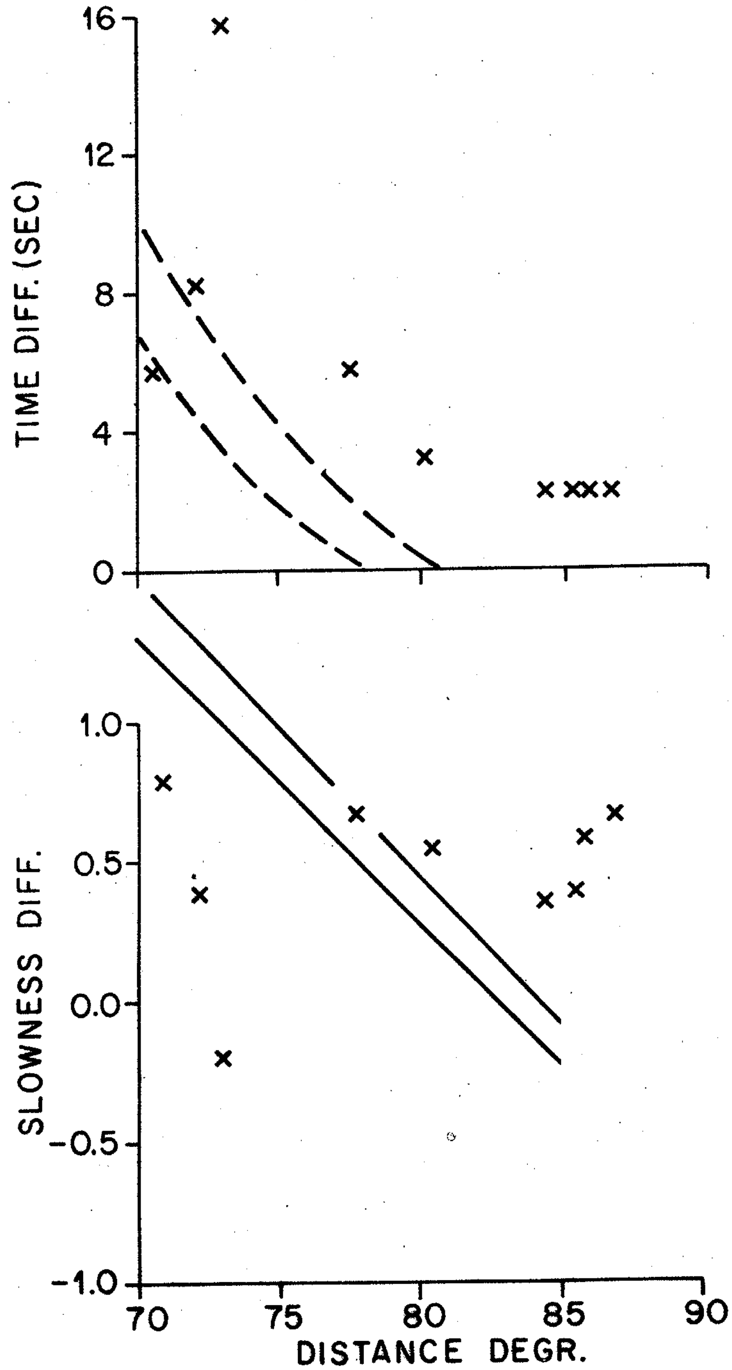
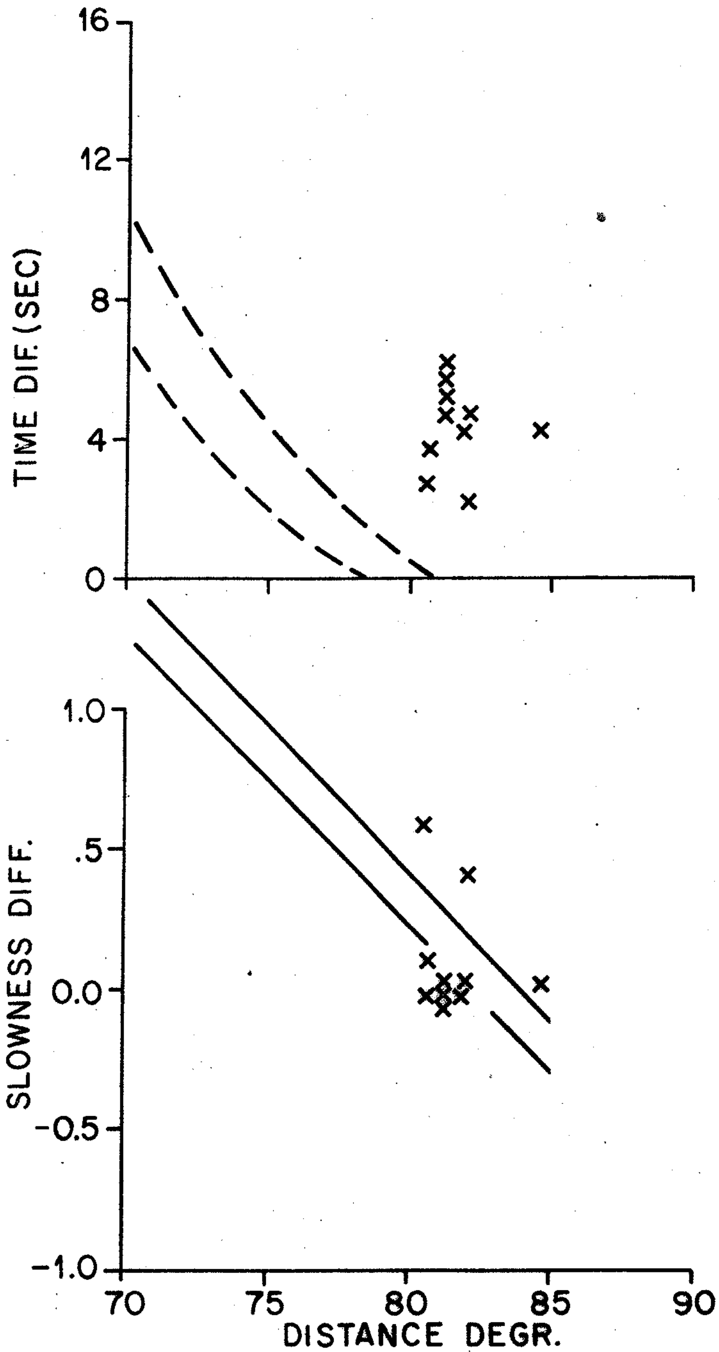

10s
20s
30s
51.7 NM/S
-51.7
25
81.5
-81.5
57
1.0 to 3.0 Hz
69.4
-69.4
39
34.3
-34.3
63
378.7
-378 NM/S
37
10s
20s
30s

Fig. 2



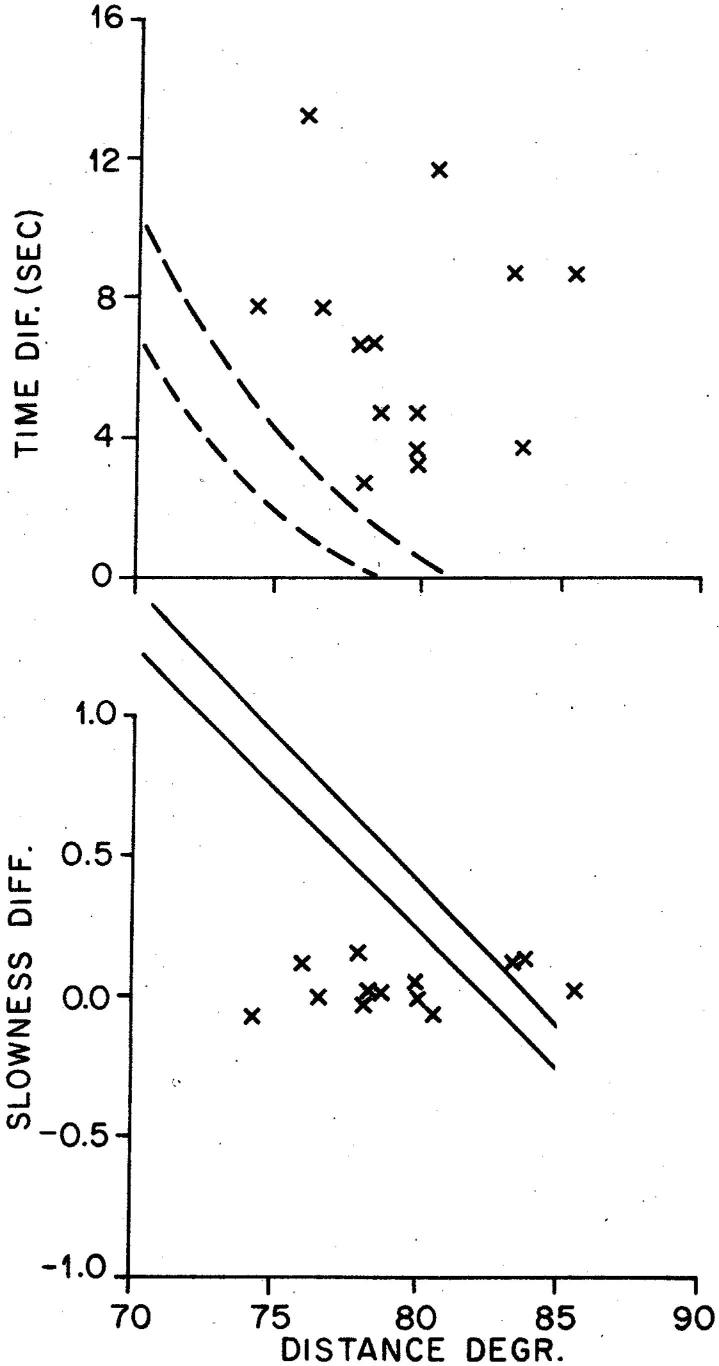
PERU DOUBLETS

Fig. 3



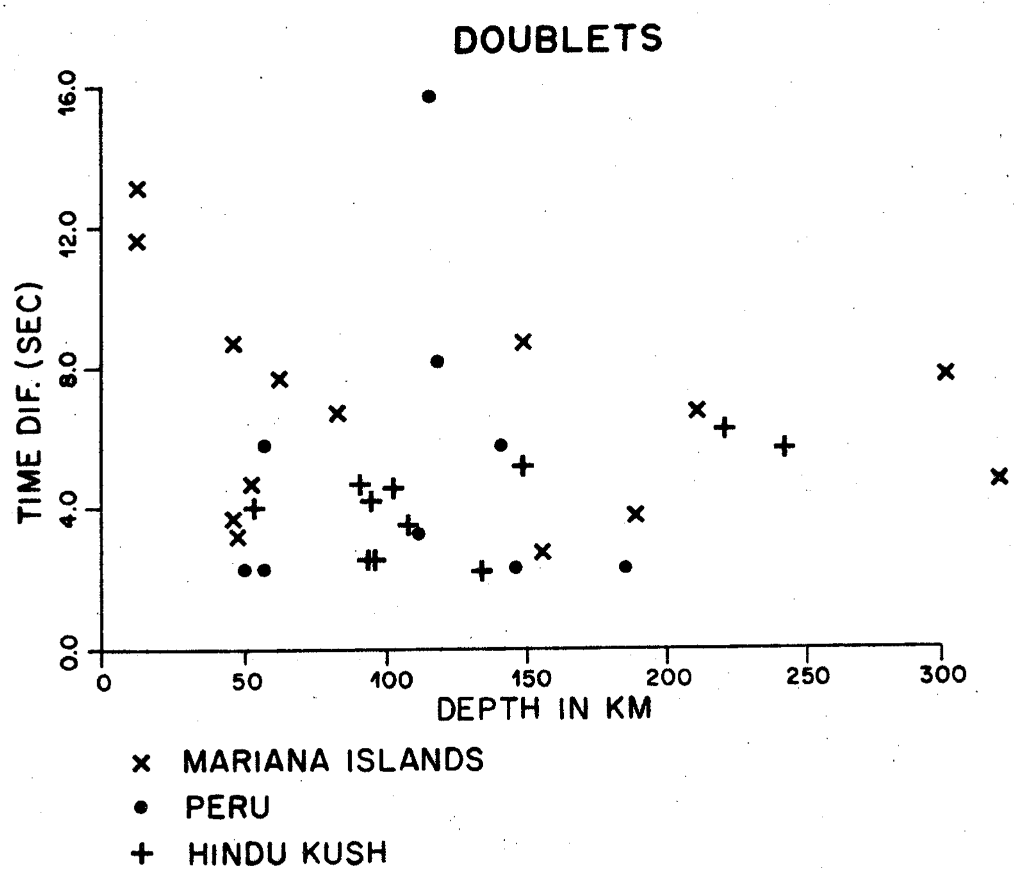
HINDU KUSH DOUBLETS

Fig. 4



MARIANA ISLANDS DOUBLETS

Fig. 5



DOUBLETS
TIME DIF. (SEC)
0.0
4.0
8.0
12.0
16.0
0
50
100
150
200
250
300
DEPTH IN KM
× MARIANA ISLANDS
• PERU
+ HINDU KUSH

Fig. 6