

A TRAVEL TIME STUDY OF P WAVES  
USING DEEP-FOCUS EARTHQUAKES

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A revision of the Jeffreys-Bullen (J-B) travel  
time table has been made using data from deep (450-  
600 km) earthquakes in order to reduce errors caused by  
heterogeneities in the upper mantle. The absolute values  
of travel-time have been determined from Nevada Test  
Site explosion data, for which the upper mantle velocity  
structure near the source is known and could be corrected  
for.

In this analysis, station errors and the sys-  
tematic error of the J-B table are, in general, similar  
to those found in other works, but the scatter of the

data is only about half as large, suggesting that the results of this study are probably more reliable.

Residual sphere plots of data suggest that anomalous, high velocity structures of the mantle in island arcs may extend beneath the region of deep earthquakes (e.g., in the Solomon Islands). Also, there is an anomalous travel-time variation between different source zones beyond  $80^\circ$  of distance, suggesting lateral velocity variations in the deep mantle. Stations in western North America were found to show different residuals for source regions in different azimuths reflecting a complicated velocity structure underneath the stations.

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## CHAPTER I.

## Introduction

Knowledge of the travel times of seismic waves is of great importance both for determining the internal structure of the earth and for accurately locating earthquakes. The experimental determination of travel times, however, is complicated by the mutual coupling between travel times and calculated hypocenter locations. Lateral inhomogeneity in the mantle causes bias in the travel times which in turn affects the hypocenter locations calculated from the observed times. This bias may be conveniently separated into i) source bias associated with the downgoing rays in the vicinity of the source, ii) station or network bias associated with the upgoing rays near the receiving stations, and iii) regional bias produced by the path through the deep mantle where most of the rays bottom. Source bias has a particularly severe effect upon travel-time studies because the seismicity of the world is concentrated along the high velocity

lithospheric slabs beneath island arcs (Isacks, Oliver and Sykes, 1968). This inhomogeneity introduces large systematic errors into the calculated locations of shallow and intermediate-depth earthquakes (Davies and McKenzie, 1969; Mitronovas and Isacks, 1971; Toksöz, Minear and Julian, 1971).

A large number of studies have been undertaken in the last decade or so with the aim of refining our knowledge of travel times (Husebye, 1965; Freedman, 1966a, 1967; Carder, Gordon and Jordan, 1966; Cleary and Hales, 1966; Herrin, et al., 1968; Konderskaya and Slavina, 1969; Gibowicz, 1970; Lilwall and Douglas, 1970). Most of these have been unable to properly account for the source bias. This includes the extensive project undertaken by Herrin, et al. (1968) and also the travel-time studies of Lilwall and Douglas (1970) who applied the technique of joint epicenter determination (Douglas, 1967). Only explosion studies are free from source mislocation errors, but the geographical distribution of explosions is severely limited.

For very deep events, however, it seems likely (though not certain) that source bias will be much less severe than for shallow events. There is also evidence



that the effects of network bias and regional bias are small compared to the effect of source bias (Mitronovas and Isacks, 1971). Therefore, this study of travel times of P waves is based on data from very deep events in different seismic regions throughout the world. In the treatment of this problem we discuss in Chapter 2 the selection of earthquakes and first arrival data and their analysis in terms of different error components after proper relocation of the events. In Chapter 3 we discuss the results of our study in light of the reliability of the relocation parameters and other correction terms. We also draw attention to the implications of the revised travel times with regard to understanding the deep structure of the earth. In Chapter 4 we summarize our principal findings.

## CHAPTER II.

## Methods

## 2.1 Introduction

First arrival times of P waves from deep events are the raw data for this study. Using the Jeffreys-Bullen (J-B) table (1940) as the starting point, the present method attempts to explain the data (residual) in terms of three effects: 1) The difference between the "true" world-wide average time curve and the J-B table as a function of distance -- which will be referred to as "systematic error", 2) "station error" caused by the local structure at the station, and 3) observational error (reading error). Two effects have been left out of this analysis: 1) Lateral variation in the deep mantle and 2) azimuthal variation of the station terms, which would reflect the effect of complex structure in the upper mantle beneath the stations. The results of this analysis will establish the extent to which these omissions are justified.

The determination of the different error terms depends on the residuals found from the starting table, for which the correction is also sought. Hence, the iterative Seidel process (Tucker et al., 1968) was employed (Fig. 1). The solution of the iterative process corresponds to the least square estimate (or to maximum likelihood estimate on the assumption of normal error) of the travel time correction and the station correction.

Apart from the main process of iteration, a single step of the Seidel process may also contain subsidiary iterations (e.g., the non-linear relocation problem also involves iteration). Other features of the method include 1) selection of data free from gross reading error by requiring that residuals should be consistent for events within a small region and 2) the utilization of first-arrival times from explosions of known origin time and position and occurring in a place of known upper mantle velocity structure to find the mean J-B error (d.c. component of systematic error) since the true origin times of deep events are unknown.

The method is illustrated in the form of a flow chart in Fig. 1. A supplementary description and discussion also follows.

## 2.2 Relocation and Estimation of Residuals

Cisternas (1963) and Aki (1965) have shown that the use of data from local stations in a region with known structure gives more accurate hypocenter locations than does the use of teleseismic data and standard tables. But the lack of appropriate data and lack of knowledge of the local structure in seismic regions compelled us to base our locations on the use of standard travel times (e.g. Bolt, 1960). Our relocation model is as follows:

$$\delta\mu_{ij} + e_{ij} = \left[ \frac{\partial T(\Delta, h)}{\partial \Delta} \Big|_{ij} + \frac{\partial F(\Delta, h)}{\partial \Delta} \Big|_{ij} \right] d\Delta_{ij} + z_i \frac{\partial T}{\partial h} \Big|_{ij} + \tau_i \quad [1]$$

where

$$\delta\mu_{ij} = t_{ij} - T_{ij}(\Delta, h) - F_{ij}(\Delta, h) - C_j - E_{ij} \quad [2]$$

and

$$d\Delta_{ij} = -x_i \cos \delta_i \sin AZ_{ij} - y_i \cos AZ_{ij}$$

where

$\delta\mu_{ij}$  = travel time residual for the  $i$ th event and  $j$ th station

$\Delta_{ij}$  = distance for  $i$ th event and  $j$ th station

$AZ_{ij}$  = azimuth for  $i$ th event and  $j$ th station

$T_{ij}$  = J-B time for  $i$ th event and  $j$ th station

$t_{ij}$  = observed travel time for  $i$ th event and  $j$ th station

$F_{ij}(\Delta, h)$  = systematic correction for J-B time for  $i$ th event and  $j$ th station

$E_{ij}$  = ellipticity error for  $i$ th event and  $j$ th station

$e_{ij}$  = random error for  $i$ th event and  $j$ th station

$x_i$  = correction to longitude of epicenter of  $i$ th event (east positive)

$y_i$  = correction to latitude of epicenter of  $i$ th event (north positive)

$\tau_i$  = correction to origin time for  $i$ th event

$z_i$  = correction of depth of  $i$ th event

$\delta_i$  = initial latitude for  $i$ th event

$C_j$  = station error for  $j$ th station

The Gauss-Newton process of iteration involved in the relocation was started with the initial location parameters (i.e., origin time, depth, latitude, and longitude) given by the International Seismological Centre (ISC) or the U. S. Coast and Geodetic Survey (USCGS). Cubic spline functions (Greville, 1960) were used for table interpolation. Ellipticity corrections (Bullen, 1937; 1938) have been applied to the data. Except during the starting cycle, data were also corrected for the systematic error and the station errors found in

the previous cycle. Following a process similar to Flinn's (1965) we estimated the standard errors of the determination of focal coordinates and the joint confidence regions for the epicentral coordinates. There has been some doubt raised about the validity of the probabilistic interpretation of these confidence regions (Evernden, 1969a). But, in any case, the area of the 95% confidence ellipse will be a measure of the internal consistency of the data. Data from events for which the area of the 95% confidence ellipse was greater than  $500 \text{ km}^2$  have been omitted from the analysis, since it is likely that they are contaminated by some type of large errors.

We note that a non-uniform geographical station distribution can contribute an artificial error into the calculated locations due to the increased weight given to regions with a high density of seismic stations. A weighting scheme was introduced to handle this problem such that regions of  $10^\circ$  length in distance and  $10^\circ$  width in azimuth were weighted equally irrespective of the number of stations in each region. Using two test events - one from west Tonga (event number 3 in table 1) with a typical concentration of teleseismic stations and the other from the Japan Sea (event number 35 in table 1) with a great number of local stations, it was found that the weighting scheme changed the values of residuals in

the least square location and also determined the location parameters with higher precision (table 2).

### 2.3 Consistency Check

It is probable that a significant number of data will contain gross errors (human reading and copying errors, clock error, etc.) To check easily for such bad data in a voluminous collection of nearly 4,000 of them, we imposed a requirement of consistency of residuals among the events from a small region. This check is valid only if the relative locations of these events are correct. Often, however, different sets of station reading were used for the location of events from almost the same place. In this case the relative locations for nearby events may not be correct, so the master event method (see for example Evernden, 1969b) was used to achieve correct relative location. The event with the largest number of observations was chosen as the master event of a region. After standard relocation of the master event, the residuals for each station were used as station corrections for the relocation of other events from the same region. In this relocation process, only those stations for which the station corrections were available

were used. With the new location parameters we obtained a set of residuals which were presumably biased in the same way as those from the master event. For each station we then had a set of residuals for earthquakes in a given source zone, which, barring gross errors, should be consistent within about a second, taking into account the small difference in the location of different events and unavoidable reading error. To discard bad data, a check was made first whether the difference between the maximum and the minimum residuals for a station-source zone pair is less than one second. If not, the datum lying farthest from the median was deleted and the cycle was repeated until the difference was less than a second. If the process continued until only one observation was left, it was discarded.

#### 2.4 Systematic Error

As the J-B table stands for the world-average earth, the error in the J-B table must be determined from world-average data. Included in the present analysis are not all possible deep events in different seismic regions. The travel-time table being a function of both



distance and depth, its error must also depend on both variables. The deepest events in different seismic regions do not occur at the same depth throughout the world. We therefore included in the analysis only events occurring within the depth range from 450 to 650 km (except one at 423 km and a few at more than 650 km) and to assume that for all data from these events, the systematic error is independent of the depths of the events. With this assumption, all data were corrected, with the help of the Jeffreys-Bullen model, to correspond to a source depth of 550 km. To check our assumption, the error which would result from three recently proposed upper mantle models (e.g. Kanamari, 1967; Green and Hales, 1968; Julian, 1972) was calculated. It was found that one would underestimate the systematic error in Jeffreys-Bullen times (depth=550 km) by 0.2-0.3 sec in this way. Since the reading error is of about this magnitude and since the correction varies for different models, the noted assumption was preferred. In the analysis, maximum and minimum distance corrections were observed to be only  $3.52^\circ$  and  $-2.43^\circ$ , respectively.

Next, all residuals were grouped in  $2^\circ$  intervals of distance, starting from  $20^\circ$  and ending at the maximum available distance of direct P arrivals. Strong regional variation in travel times to distances less than  $20^\circ$  makes it impractical to estimate the systematic error at

short distances (Herrin et al., 1968). Residuals in each cell were averaged giving equal weight to each source zone and through those averages a smooth curve was drawn by hand. Data and the smoothed curve are shown in Fig. 6.

## 2.5 Station Error

After correcting for the systematic error, the residuals for each station were averaged, giving equal weight to each source zone. Lack of data, however, do not permit us to do better than to take the average (independent of distance and azimuth) as station error.

## 2.6 Criteria for the Convergence in the Seidel Process

A decision on convergence of the Seidel process was made by examining the change in location parameters in different cycles of iteration and by noting the change in the standard deviation of residuals from all data after relocation in each cycle. In both cases we found a major change in the second cycle of iteration, when, for the first time, systematic corrections and station correc-

tions were introduced. In cycle number three, however, no significant changes were observed. As further improvement in the estimation of the systematic error and the station errors became doubtful at this stage, we claimed convergence. Final estimation of the systematic error and the station errors were made from the fresh residuals (corrected for elliptic error only) after using the location parameters of the third cycle.

## 2.7 Determination of Mean J-B Error

The procedure used so far can determine only the shape of the travel time curve, not its absolute value. We could clearly add any constant to the travel times and subtract it from the earthquake origin times without affecting our results. Data from explosions with precisely known shot position and blast time would be suitable for determining the d.c. part in the systematic error. Before finding the mean error, however one needs to correct travel times for surface explosions to correspond to a depth of 550 km, as our systematic error is determined for this depth. One can no longer assume that for this reduction only distance terms need a correction as the J-B upper mantle velocity differs greatly from the

present state of knowledge of the upper mantle (Knopoff, 1971). To introduce the corrections to explosion residuals, it was necessary to use explosions in places of known upper mantle velocity structure. Only Nevada Test Site explosions satisfy this criterion. We chose the WNA model of Julian (1972) and NTS1 model of Green and Hales (1968), both claimed to be valid for upper mantle structure of western North America. Consideration of these two models, which were derived independently, would enable us to judge the uncertainty in the determination of the mean J-B error.

After correction to 550 km depth, the explosion data were also corrected for the systematic error and the station errors found in this work.

The final residuals were averaged giving equal weight to each 2°-cell. This average presumably represents the d.c. component of the systematic error.

## 2.8 Data Base

All events in this analysis were selected from the period 1964-1970, when the reliability of reported times was high. To ensure the accuracy of first-arrival data, events were chosen with magnitudes ranging from 5.0 to 7.0. From the times reported in the bulletins of ISC

and USCGS, only those associated with 'i' (impetus)-type first-arrivals were accepted as they are likely to be read with better precision and are reported also to the nearest tenth of a second. During this selection, all reported times with residuals greater than four seconds were rejected. They were few in number and most of them were inconsistent with other events in the neighborhood and thus accountable by large reading error. Some of them were, however, consistent, especially at near distances, but still were discarded since they could reflect the near-source heterogeneity. Epicenter determination was found to be in error when simultaneous use was made of remote stations and near station which were affected by near-source heterogeneity, whereas introduction of near stations unaffected by near-source heterogeneity improved the location (Mitronovas, Isacks, and Seeber, 1969; Slavina, 1971). Times with small residuals also may contain large reading error since it is not rare to see residuals of +2 seconds and -2 seconds for the same station from two close events. Also, there are frequent misidentification of arrivals as 'i'-type (Freedman, 1966b). Errors in data arising from these two causes could largely be avoided by checking the consistency of residuals (see Section 2.3). Almost 8% of the data were rejected this way and almost the same

figure was true for five NTS explosions. Twelve events were also eliminated (out of 59) because either the number of good data was less than 30, or the data had a bad distribution around the epicenter, or the events were suspected to be multiple events, or finally if the confidence ellipse area was greater than  $500 \text{ km}^2$ . The decisions were helped through the equal area projection of the focal sphere made by the residual data. The WNA model of Julian (1972) was used for this plot to find the required take-off angle. Similar plots of "station sphere" (station at the center of the projected sphere) were also made. From station sphere plots, slightly more than 100 anomolous data were discarded.

Final analysis of very deep-focus travel times were thus performed using 3,294 carefully selected arrival times from 47 events and 487 data from five NTS explosions (see Table 1a and b and Fig. 2) recorded throughout the world by 559 and 214 stations, respectively.

## CHAPTER 3.

### Results

#### 3.1 Introduction

Our analysis of travel-times from deep events results in three sets of output: (1) relocated hypocenters; (2) the systematic error of J-B table; and (3) station errors. The success with which one can predict travel-times and make other inferences about the structure of the earth depends on estimating first the reliability of these parameters.

#### 3.2 Relocation Parameters

The following three assumptions were made in the analysis concerning the relocation of events. First, that there is no source bias for the deep-event arrival time data. Second, that network bias is small, causing no

severe systematic error in location (so station error could be found from the residual values of each station). And finally, that there is a stationary point to which the Guass-Newton process of iteration converges for the location of deep events.

### 3.2.1 Evidenc of Source Bias for Deep Events

Source bias includes predominantly the effects from downgoing slabs and will, in general, cause the calculated hypocenters to be systematically in error. It is then hard to detect any source error from the residuals. Despite this fact one still finds a sign of this error for a few of the deep events. The best examples come from the Solomon Islands events (see Fig. 3b). In Figure 3b the residual sphere centered at the focus of a Solomon Island event is shown as a representative plot from this region. In this plot are shown travel time residuals after correction for systematic error and station errors. Even after these corrections, the prominent appearance of negative residuals in the SW and NW quadrant makes one suspect that data have been affected by the complicated structure of this island arc (Denham, 1969 and Santo, 1970). From the orientation of island arcs, it is easily seen that the data in the two quadrants (SW and NW) are likely to be contaminated by the "plate structure" beneath the arcs. Further evidence for the contamination comes from the fact that events in the New Hebrides region, which is



close to the Solomon Islands, have a dissimilar appearance on the focal sphere plots (Fig. 3c). This dissimilarity would oppose any arguments in favor of either lateral heterogeneity of deep mantle or anomalous structure beneath the stations. The arguments for source error receives support from the station sphere plots (Fig. 4) of two stations, Mundaring (MUN) in Australia and Nhatrang (NHA) in South Vietnam. Data from both stations are likely to be affected by any source error in the Solomon Island data. And, in fact, negative residuals are found for events in the Solomon Islands but quite different values are found for events in the New Hebrides. However, the magnitude of this source error is found to be of the order of -1.0 sec which is considerably smaller than that from surface events. Even though source errors are probably present in our data, their effect is not expected to be large. It is also interesting to note that the presence of source error was not very evident until the data were corrected for both systematic and station error (for example, compare the Figs. 3a and 3b). This may show the importance of the results of this study in detecting a small plate-effect on travel time data.

### 3.2.2 Network Bias

Douglas and Lilwall (1968) and Douglas (1970) consistently argued for the importance of network bias. If it is really important, travel-time studies from deep earthquakes cannot be of great use as the hypocenters will still have systematic error. In order to test the strength of network bias, we relocated our two test events (see Table 1) in a special way. Each of these two events were relocated by using two different subsets of stations and correcting the travel times for systematic error and the station error found in this study. No appreciable change in the locations was found. This justifies our neglect of network bias (see table 3).

### 3.2.3 Are Location Parameters Unique?

The assumption that the mean-square error has a single absolute minimum may not be correct, especially if the depth is not known. For deep events, error caused by this assumption may not be large (James et al., 1969). To test the magnitude of error in our assumption, we relocated the same two test events (see Table 1) without prescribing any initial solution (i.e., putting all initial values as zero). The only constraints imposed were that the origin time must be within 1,000 sec (which is roughly equal to the travel-time for a ray grazing the core-mantle boundary) of the earliest arrival time

and that the depth must lie between zero and 700 km. Application of the systematic correction, station corrections and the weighting scheme were withdrawn for obvious reasons. The solutions (see Table 4) were found to be very close to the bulletin parameters which were used as initial solutions for this study. The presence of nearby stations is found to have a strong effect on the relocation, causing faster convergence. This result might ensure us about the uniqueness of calculated location parameters for deep events. However, there are some instances (e.g., an event in the Bali Sea and one in the Okhotsk Sea) for which even in the last cycle of iteration, depths changed by +14 and +10 km and origin times changed by +1.3 sec and +0.8 sec, respectively. Though these events had very good azimuthal station distributions, they lacked nearby stations (Fig. 5). The event in the Bali Sea had the nearest station at a distance of  $22.19^\circ$  and the Okhotsk Sea event at a distance of  $32.71^\circ$ . This fact may have caused this large change in origin time and depth. The change in origin time and change in depth, however, were found to be largely compensatory, except for stations at small distances. For large depth of focus, depth determination by depth phase is not of much help as error involved in this process is of the order of 2-3%.

The number of cases showing great changes of depth and origin time was in any case small.

### 3.3. Systematic Error

As the systematic error (Fig. 6) is determined from averages of all the data, it is imperative to inquire how well each source zone conforms to overall pattern. In fact, the agreement from almost all source zones is more than satisfactory. One example of the quality of the fit is shown by the data from the Okhotsk Sea (Fig. 9).

There are a few prominent exceptions to the fit of our systematic error curve as exemplified by the data from source region Argentina at a distance of  $40^\circ$  (Fig. 9). These data were from stations in northern South America and were presumably affected by the interference of ray paths with the underthrusting slab (Santo, 1969), on their way to those stations.

### 3.4 Absolute Value of Travel-Times.

The determination of the absolute value of the travel times remains ambiguous. The data from the NTS explosions in conjunction with two different upper mantle

models for western North America produced two different values for the mean J-B error, though the standard deviations remained comparable. The mean value of the J-B error was found to be -1.49 sec with a standard deviation of 0.92 sec using the WNA model of Julian (1972) whereas values of -2.35 and 0.86 were obtained using the NTS1 model of Green and Hales (1968). Even after applying the systematic correction, station corrections and the the correction for the upper mantle, the data still are quite scattered. This might be due to complicated crustal and upper mantle heterogeneity in this area which could not be corrected for. For comparison, similar reduction was made using the Herrin table with the station corrections of Herrin and Taggart (1968). The average value and standard deviation in this case were -0.27 sec and 1.03 sec after using the WNA model for upper mantle correction and -1.77 sec and 0.98 sec respectively when the upper mantle correction was applied through NTS1 model. The Herrin table and the associated station corrections are not quite as good as ours at reducing the scatter. Also, from the NTS explosion data it is found that both the J-B model and the Herrin model are slow for a source depth of 550 km. However, the problem of determining the absolute travel-time uniquely could not be solved because the two chosen models for western North America were significantly different.

### 3.5 Travel-times for Zero Depth

Travel-times from a source depth of 550 km are not very useful for surface events or explosions unless one knows the upper mantle structure for the source region. It is, however, not reliable to construct corrections for the Jeffreys-Bullen upper mantle on an average basis. For example, we selected eight reliable models for the upper mantle from different parts of the world. They were i) the WNA model (see Section 3.4), ii) the NTS1 model (see Section 3.4), iii) a preliminary model of Kanamori (1967) for Japan, iv) the HWNE model (proposed for the midwestern United States) of HelMBERGER and Wiggins (1971), v) the Australian shield model of White (1971), vi) the ERI model of the Canadian shield and the central United States of Green and Hales (1968), vii) the Pamir and Hindu Kush upper mantle model of Matveyeva and LUKK (1968) and viii) the upper mantle model of Carder (1964).

It was seen that the average correction for Jeffreys-Bullen upper mantle model (in the depth range of 0 to 550 km) bore little resemblance to that for any particular model. By all confidence measurements, the magnitude of this average correction also was close to zero.

An illustration of the ability to predict travel-times for surface events is provided by the 120 selected

data for Marshall Island explosions from Carder (1964). Application of our station correction and systematic correction with its d.c. values of +1.49 sec produces final residuals having an average value of -0.46 sec and a standard deviation of 0.81 sec. In comparison, after using Herrin's tables (1968) and the station corrections of Herrin and Taggart (1968), the remaining residuals were found to have an average value of +0.63 sec and standard deviation of 0.88 sec. The average value of -0.46 sec found with our times may mean that velocity structure in the Marshall Islands' upper mantle is on the average higher than that in Nevada, but this interpretation is dubious because of ambiguity of the d.c. component of our systematic correction. Using the value of +2.35 sec for the d.c. component of our systematic error changes the above average value of -0.46 sec to +0.40 sec which would then convey the opposite interpretation.

It is also worth noting that though Herrin's lower mantle model was found to be slow, the upper mantle in Herrin's model is very fast causing positive residuals from the Marshall Island data. Herrin's upper mantle model is even faster than two recently proposed shield models (Green and Hales, 1968; White, 1972) for different regions of the world where velocity structures are notably fast and which have large negative station residuals.

### 3.6 Comparing Systematic Error of this Study with Other Works

Figure 7a shows the systematic error relative to the J-B times, from four other works (Carder, Gordon and Jordan, 1966; Cleary and Hales, 1966; Herrin et al., 1968; and Lilwall and Douglas, 1970) in comparison with our values. Our systematic error has been reduced to zero depth after proper distance correction and d.c. values for this error were added. It is found that there is similarity in the broad shape of the curves but considerable uncertainty in the absolute values. Beyond about 85° of distance, our curve differs significantly from others (except the curve of Cleary and Hales, 1966, which bends down slightly beyond 90°). This deviation is real, as the majority of the source zones especially those from Indonesian Arc, Philippines and the Bonnin Island show this trend very convincingly (Figure 8). As some other source zones do not reveal this trend very well (see, for example, Figure 9), this peculiarity of the systematic error may very well be due to lateral variations in the deep mantle (see Section 3.9).

Also, comparing our systematic error with that of Herrin et al. (1968) we see that scatter of our data around



the systematic error curve is smaller. After correcting the data for station error, the standard deviation of a single residual about the systematic error curve was found to be  $\pm 0.57$  sec and without station corrections, it was  $\pm 0.91$  sec. On the other hand, the standard deviation of a single residual from the Herrin table is  $\pm 1.5$  sec (Herrin et al., 1968). This fact suggests that the effects of near-source heterogeneity have been substantially reduced in this study.

### 3.7 Station Residuals

Station errors found in this study are shown for North America in Figure 10. Only stations with more than three data were included in this plot. Positive station errors are, in general, found in tectonically active areas and negative ones in stable areas.

### 3.8 Comparison of Station Errors with Other Studies

Our station errors have been compared with those from three recent studies (Cleary and Hales, 1966; Herrin

and Taggart, 1968, and Lilwall and Douglas, 1970). For this comparison only mean corrections from other studies (neglecting their proposed azimuthal components) have been used. North American stations, because of their number and suitable coverage were chosen as standards for comparison (Figure 11a, b and c). It is seen that positive station residuals (presumably from the western part) are more negative compared to the values given by Herrin and Taggart (1968). Lilwall and Douglas (1970) also observed the similar correlation of their station residuals with those of Herrin and Taggart. In fact, our station residuals correlate best with those of Lilwall and Douglas because of the absence of definite bias. Scattering, however, is present. As Lilwall and Douglas (1970) made their study with a technique of joint epicenter determination (Douglas, 1967), it is quite likely that they will have in their analysis smaller systematic error due to source bias from surface events than other noted works. On the other hand, station errors found in the study of Cleary and Hales (1966) are systematically smaller than our values and correlation is the worst of the three. Cleary and Hales (1971) themselves found that station residuals from PKIKP observations are higher for North American stations than those from P observations.

### 3.9 Lower Mantle and its Regional Variation

The error in the J-B lower mantle also was studied independently by Hales, Cleary and Roberts (1968), Chinnery (1969), Johnson (1969) and Vinnik and Nikolayev (1970). Comparing the systematic error found in this study with those calculated from the lower mantle models of other studies, we find an overall similarity in the shape (Figure 7b). Although the values from Chinnery (1969) were too negative compared to the values of this study, values from other studies were comparable to ours excepting around  $60^\circ$  of distance. However, the most noted thing is the striking similarity of the shape of our curve beyond about  $85^\circ$  of distance with those of Johnson (1969). This gives one more convincing evidence of the reality and reliability of our systematic error beyond about  $85^\circ$  of distance.

Toksöz, Chinnery and Anderson (1967) have shown some evidence for regional variation in the lower mantle. Here we provide two other pieces of evidence. Figure 12 shows the focal sphere plots of the residuals from source zones of south Fiji and west Tonga after the residuals were corrected for systematic error and the station error. It is seen that the appearance of the residuals is not random

in nature (see, for example, NE quadrant), though it would have been expected from the presence of reading error alone in these plots. The regularity of the remaining residuals from two nearby source regions suggests the presence of lateral heterogeneity of the lower mantle. This evidence of lateral heterogeneity could be refuted on the basis of similar source bias for these regions. But this possibility is, however, small because selected events are very deep from these source regions.

The strongest evidence of the regional variation comes from the anomalous variation of travel-time from different source regions beyond  $80^\circ$  of distance. It was found that travel-times (corrected for station correction) from source zones of Indonesia (Bali Sea, Java Sea, Banda Sea and Celebes Sea), the Philippines, and the western Pacific (Bonnin Islands, South Marianas, and Okhotsk Sea) are consistently earlier (Figure 8) than travel-times from other source regions (e.g., Argentina in Figure 9) at corresponding distances. It is worth noting that Carder, Gordon and Jordan (1966) also reported a similar discrepancy of travel-times beyond  $80^\circ$  of distance for explosions in the Marshall Islands (which happen to be in the same general area of the sources for which this discrepancy is found in this study) com-

pared to the travel-times from Semipalatinsk and Sahara explosions. Carder et al. (1966) concluded that the anomaly is due to variation of station error from west to east in the United States. But even after the application of station correction of this study, the anomalous trend is seen to persist, suggesting that large-scale lateral inhomogeneity might be occurring at the base of the mantle. Proper delineation of this inhomogeneity is in the process. Lateral heterogeneity is, however, expected not to cause any severe bias in our analysis because of our world-wide station distribution.

### 3.10 Azimuthal Variation of Station Error

As noted earlier, this effect was not considered in our analysis. Here we show some evidence that azimuth-dependent station corrections are necessary for at least the western United States. It was found that station in the western United States show different travel-time residuals for three different azimuths, e.g., for source regions at Okhotsk Sea, Argentina and South Fiji (Figures 13, 14 and 15). In the figures, the average of the travel-time residuals were plotted separately for the events in three different source regions, after correcting the

residuals for the systematic error. The behavior of residuals possibly reflects the complicated structure beneath the Basin and Range Province, Sierra Nevada, and the mountainous regions of Washington. Bolt and Nuttli (1966) and Otsuka (1966a) noted a cyclic dependence of travel-time on azimuth from their observations of the Berkeley array. Otsuka (1966b) proposed a multi-interface model of the upper mantle while Nuttli and Bolt (1969) forwarded the idea of undulations of the mantle's low velocity layer. Cyclic dependence of station residuals on azimuth was not evident in our analysis for the western coast of the United States. However, we would agree that the transition zone between ocean to continent might play a great part in causing this residual variation. Further work is warranted toward this direction to unravel the structure beneath this region.

Inclusion of the azimuthal component in station error in the analysis, however, raised an obvious problem of deciding the nature of this function. Herrin and Taggart (1968) adopted a cyclic function for the station error as was suggested by Bolt and Nuttli (1966). Shimshoni and Pekeris (1966) and Davies and McKenzie (1969) suggested on the other hand low-order (one or two) spherical harmonics in distance and azimuth for delineation of station error for our spherical earth.

In order to test the relative merits of different ways to find station error, we found the station error for some selected stations (with good number of data) in three different ways -- first, by finding the average; second, by fitting the residual by a similar sinusoidal form as was applied by Herrin and Taggart (1968); and third, by fitting the residuals by a first-order spherical harmonics in distance and azimuth. It is found that the standard error of estimates for station error is not consistently the smallest for any particular model (Table 5). A complicated model is thus necessary to predict station errors.

### 3.11 Confidence Level for the Prediction of Times

After correcting the residuals for systematic error and the station error, it was found from all data that standard deviation of a single residual is  $\pm 0.57$  sec. However, considering each source zone separately, maximum standard deviation was found to be  $\pm 0.74$  sec from the residual residuals of the source region in Argentina. Our maximum standard deviation corresponds to the lower bound for the prediction of travel-times by Herrin's table and associated station corrections. Their maximum standard deviation

reached even  $\pm 1.4$  sec (Tucker et al., 1968). It is also worth to note that the standard deviation of our remaining residuals is only a little large compared to the reading error. By pooling the  $\sigma^2$  (variance) of the residuals for each source zone-station pair and then extracting the square root, we could get an estimate of the standard deviation for the reading error to be  $\pm 0.33$  sec. In this calculation, variance for each source zone-station pair was corrected by a factor given by Freedman (1966b) for the truncation of any data from the above pair during our "check for consistency" (see Section 2.3). Similar calculations for residuals from five NTS explosions whose origin times and positions are known very precisely show the standard deviation for the reading error to be  $\pm 0.30$  sec. Part of the largeness in the standard deviation of final residuals could certainly be accounted for by the omission of azimuthal term in our station error. Another part may be due to the lateral heterogeneity near the source and in the deep mantle which could not be corrected for.

Plotting the histogram of the remaining residuals, we find that distribution of residuals look more "normal" than that of uncorrected residuals right after the first relocation (Figure 16). Also the standard deviation is smaller. This fact also supports the reliability of our travel-times and other correction.



At this stage, it is worth pointing out that Lomnitz (1971a, b) objected to any revision of travel-times at the present state-of-the-art. His criticism is based on the fact that none of the tables, so far proposed, could reduce the standard deviation of data to the level of reading error. We, in fact, have almost approached the same range of reading error by careful selection of data in our analysis. Future work relating to the azimuth-dependent correction possibly will reduce further the standard deviation of final residuals.

## CHAPTER 4.

## Conclusions

The conclusions can be summarized as follows:

1. There is some evidence for source error even for the deep events (e.g., in the Solomon Islands) that could mean that anomalous high velocity structures in island arc regions continue beyond the depth of the Benioff zone. The magnitude of the source error for deep events is about four to five times smaller than for surface events, however.

2. Analysis of travel-times from several deep seismic regions have shown a systematic trend of the J-B residual. This finding was similar with other works involving surface events up to  $80^\circ$  distance. Beyond  $80^\circ$ , there is a pronounced discrepancy in the slope of the curves. Our curve, however, has a similarity with the calculated J-B residuals from the CIT 208 (or CIT 206) model of Johnson (1969). In terms of the standard deviation of

the data, our curve is also better determined than other works like Herrin et al. (1968).

3. Our station residuals were found to be positive (+1.0 sec) in the western United States and negative (-1.0 sec) in the central and eastern United States. Our station residuals agree well with those of Lilwall and Douglas (1970). However, there is a definite bias between our station residuals and those of Herrin and Taggart (1968) and Cleary and Hales (1966).

4. Even after applying systematic correction and station correction, focal sphere plots of residuals from some source regions (like South Fiji and West Tonga) show some regularity which may suggest lateral inhomogeneities. Also, it was noted that arrivals of P waves beyond  $80^\circ$  were earlier from some seismic zones (the Indonesian Arc and the Western Pacific) compared to other seismic zones (Argentina). This provides another evidence for regional heterogeneity.

5. From three different approaches of P waves, e.g., from Okhotsk Sea, Argentina and South Fiji, the stations in the Basin and Range Province and in the Sierra Nevadas show different residuals after correcting them for systematic error. This reflects the complicated structure beneath these stations. For these stations azimuthal terms in the "station error" are necessary.

6. Prediction of travel-times for deep events with

our systematic error and station error (excluding a d.c. term) shows a standard deviation of only 0.57 sec which is a little large compared to the reading error of the order  $\pm 0.3$  sec.

## REFERENCES

- Aki, K., Accuracy of origin time, epicenter and focal depth of local earthquake determined routinely by the Japan Meteorological Agency, Bull. Earthquake Res. Inst., 43, 23-38, 1965.
- Arnold, E.P., Smoothing Travel Times, Bull. Seism. Soc. Amer., 58, 1345-1351, 1968.
- Bolt, B.A., The revision of earthquake epicenters, focal depths, and origin times using a high-speed computer., Geophys. J. R. Astr. Soc., 3, 433-440, 1960.
- Bolt, B.A. and O.W. Nuttli, P wave residual as a function of azimuth, J. Geophys. Res., 71, 5977-5985.
- Bullen, K.E., The ellipticity correction to travel times of P and S earthquake waves, Monthly Notice R. Astron. Soc., Geophys. Suppl., 4, 143-157, 1937.
- Bullen, K.E., The ellipticity correction and deep focus earthquakes, Monthly Notice R. Astr. Soc., Geophys. Suppl., 4, 1938.

Carder, D.S., Travel times from Central Pacific Nuclear explosions and inferred mantle structure, Bull. Seism. Soc. Amer., 54, 2271-2294, 1964.

Carder, D.S., D.W. Gordon and J.N. Jordan, Analysis of surface foci travel times, Bull. Seism. Soc. Amer., 56, 815-840, 1966.

Chinnery, M.A., Velocity anomalies in the lower mantle, Phys. Earth Planet. Interiors, 2, 1-10, 1969.

Cisternas, A., Precision determination of focal depths and epicenters of local shocks in California, Bull. Seism. Soc. Amer., 53, 1075-1083, 1963.

Cleary, J. and A.L. Hales, An analysis of the travel times of P waves to North American stations in the distance range of 32° to 100°, Bull. Seism. Soc. Amer., 56, 467-489, 1966.

Cleary, J. and A.L. Hales, PKIKP times and station anomalies, J. Geophys. Res., 76, 7249-7259, 1971.

Curtis, A.R. and M. Shimshoni, The smoothing of seismological travel time tables using cubic splines, Bull. Seism. Soc. Amer., 60, 1077-1087, 1970.

Davies, D. and D.P. McKenzie, Seismic travel time residuals and plates, Geophys. J. R. Astr. Soc., 18, 51-61, 1969.

Denham, D., Distribution of earthquakes in the New Guinea-Solomon Islands region, J. Geophys. Res., 74, 4290-4299, 1969.

Douglas, A., Joint epicenter determination, Nature, 215, 47-48, July 1, 1967.

Douglas, A., How accurate are the 1968 P tables?, Earth Planet. Sci. Lett., 8, 250-252, 1970.

Douglas, A. and R.C. Lilwall, Does epicenter source bias exist?, Nature, 220, 469-470, November 20, 1968.

Evernden, J.F., Precision of epicenters obtained by small numbers of world-wide stations, Bull. Seism. Soc. Amer., 59, 1365-1398, 1969.

Evernden, J.F., Identification of earthquakes and explosions by use of teleseismic data, J. Geophys. Res., 74, 3828-3856, 1969.

- Evernden, J.F. and D.M. Clark, Study of teleseismic P  
I. travel time data, Phys. Earth Planet. Interiors,  
4, 1-23, 1970.
- Fitch, T.J. and P. Molnar, Focal mechanism along inclined  
earthquake zones in the Indonesia-Phillipines  
Region, J. Geophys. Res., 75, 1431-1444, 1970.
- Flinn, E.A., Confidence regions and error determinations  
for seismic event locations, Rev. Geophys., 3,  
157-185, 1965.
- Freedman, H.W., The "little variable factor": a sta-  
tistical discussion of the reading of seismograms,  
Bull. Seism. Soc. Amer., 56, 593-604, 1966a.
- Freedman, H.W., A statistical discussion of  $P_n$  residuals  
from explosions, Bull. Seism. Soc. Amer. 56,  
677-695, 1966b.
- Freedman, H.W., A statistical discussion of P residuals  
from explosions, Part II., Bull. Seism. Soc. Amer.,  
57, 545-561, 1967.
- Gibowicz, S., P wave travel time residuals from the  
Alaskan aftershocks of 1964, Phys. Earth Planet.



Interiors, 2, 239-258, 1970.

Green, R.W. and A.L. Hales, The travel times of P waves to 30° in the central United States and the upper mantle structure, Bull. Seism. Soc. Amer., 58, 267-289, 1968.

Greville, T.N.E., Spline functions interpolation and numerical quadrature, Mathematical Methods for Digital Computers, ed. A. Ralston and H.S. Wilf, John Wiley and Sons, Ltd. 1970, pp. 156-168.

Gutenberg, B. and C.F. Richter (1954), Seismicity of the earth and associated phenomena, Princeton Univ. Press, Princeton, New Jersey.

Hales, A.L., J.R. Cleary and J.L. Roberts, Velocity distribution in the lower mantle, Bull. Seism. Soc. Amer., 58, 1975-1989, 1968.

HelMBERGER, D. and R.A. Wiggins, Upper mantle structure of midwestern United States, J. Geophys. Res., 76, 3229-3245, 1971.

- Herrin, E. and J.N. Taggart, Regional variation in P travel times, Bull. Seism. Soc. Amer., 58, 1325-1337, 1968.
- Herrin, E. W. Tucker, J.N. Taggart, D.W. Gordon, and J.L. Lobdell, Estimation of surface focus P travel times, Bull. Seism. Soc. Amer., 58, 1273-1291, 1968.
- Husebye, E.S., Correction analysis of Jeffreys-Bullen travel time tables, Bull. Seism. Soc. Amer., 55, 1023-1038, 1965.
- Isacks, B., J. Oliver and L.R. Sykes, Seismology and the new global tectonics, J. Geophys. Res., 73, 5855-5899, 1968.
- James, D.E., I.S. Sacks, Eduardo Lazo L, and Pablo Aparicio G., On locating local earthquakes using small networks, Bull. Seism. Soc. Amer., 59, 1201-1212.
- Jeffreys, H. and K.E. Bullen, Seismological tables, Brit. Assoc. Advancement of Sci., Gray-Milne Trust, London, 1940.

Johnson, L.R., Array measurements of P velocities in the lower mantle, Bull. Seism. Soc. Amer., 59, 973-1008, 1969.

Julian, B.R. and D.L. Anderson, Travel times, apparent velocities and amplitudes of body waves, Bull. Seism. Soc. Amer., 58, 339-366, 1968.

Julian, B.R., The regional variation of upper mantle, in draft, 1972.

Kanamori, H., Upper mantle structure from apparent velocities of P waves recorded at Wakayama Micro-earthquake Observatory, Bull. Earthquake Res. Inst., 45, 657-678, 1967.

Katsumata, M. and L.R. Sykes, Seismicity and tectonics of the western pacific Izu-Mariana-Caroline and Ryukyu-Taiwan ridge, J. Geophys. Res., 74, 5923-5948, 1969.

Knopoff, L., The upper mantle of the earth -- a review, United States Program Final Report, Upper Mantle Project, 7-25, 1971.

- Kondorskaya, N.V. and L.B. Slavina, Some results of a study of the travel time of longitudinal waves, Izv. Earth. Physics, 2, 19-36, 1969.
- Lilwall, R.C. and A. Douglas, Estimation of P wave travel times using joint epicenter method, Geophys. J. R. Astr. Soc., 19, 165-181, 1970.
- Lomnitz, C., What is the accuracy of P travel time tables? Earth. Planet. Sci. Lett., 10, 193-195, 1971a.
- Lomnitz, C., Travel time errors in the laterally inhomogeneous earth, Bull. Seism. Soc. Amer., 61, 1639-1654, 1971b.
- Matveyeva, N.N. and A.A. Lukk, Estimates of the accuracy in constructing travel time curves for the Pamir-Hindu Kush zone and in the computer determination of the velocity profile in the upper mantle, Izvestia, 8, 12-24, 1968.
- Mitronovas, W., B. Isacks, and L. Seeber, Earthquake locations and seismic wave propagation in the upper 250 km of the Tonga Island Arc, Bull. Seism. Soc. Amer., 59, 1115-1135, 1969.

- Mitronovas, W. and B.L. Isacks, Seismic velocity anomalies in the upper mantle beneath the Tonga Kermadec Island Arc, J. Geophys. Res., 76, 7154-7180, 1971.
- Miyamura, S., The seismicity of Japan and the surrounding area, Izv. Earth Physics, 7, 420-437, 1969.
- Nuttli, O.W. and B.A. Bolt, P wave residuals as a function of azimuth 2. undulations of the mantle low-velocity layer as explanation, J. Geophys. Res., 74, 6594-6601, 1969.
- Otsuka, M, Azimuth and slowness anomalies of seismic waves measured on the central California seismographic array Par 1, observations, Bull. Seism. Soc. Amer., 56, 223-239, 1966a.
- Otsuka, M., Azimuth and slowness anomalies of seismic waves measured on central California seismographic array Part 2, interpretation, Bull. Seism. Soc. Amer., 56, 655-675, 1966b.
- Santo, T., Characteristics of seismicity in South America, Bull. Earthquake Res. Inst., 47, 635-672, 1969.

- Santo, T., Regional study on the characteristic seismicity of the world Part II. New Britain Island region, Bull. Earthquake Res. Inst., 48, 127-143, 1970.
- Shimshoni, M. and C.L. Pekeris, The seismic crustal function of the earth, Geophys. J.R. astr. Soc., 11, 1-4, 1966.
- Slavina, L.B., The dependence of the determination of the position of an earthquake epicenter on the station location and on the features of P wave travel times, Izv., 3, 77-87, 1971.
- Sykes, L.R., Deep focus earthquakes in the New Hebrides region, J. Geophys. Res., 69, 5353-5355, 1964.
- Sykes, L.R., The seismicity and deep structure of island arcs. J. Geophys. Res., 71, 2981-3006, 1966.
- Sykes, L.R., B.L. Isacks, J. Oliver, Spatial distribution of deep and shallow earthquakes of small magnitudes in the Fiji-Tonga region, Bull. Seism. Soc. Amer., 59, 1093-1113, 1969.
- Toksöz, M.N., M.A. Chinnery, and D.L. Anderson, Inhom-

geneities in the earth's mantle, Geophys. J. R. Astr. Soc., 13, 31-59, 1967.

Toksoz, M.N., J.W. Minnear and B.R. Julian, Temperature field and geophysical effects of a downgoing slab, J. Geophys. Res., 76, 1113-1138, 1971

Tucker, W., E. Herrin and H. Freedman, Some statistical aspects of the estimation of seismic travel times, Bull. Seism. Soc. Amer., 58, 1243-1260, 1968.

Vinnik, L.P. and A.V. Nikolayev, The velocity profile of the lower mantle from direct measurements of  $dT/d\Delta$ , Izv. Earth Phys., 11, 699-708, 1970.

White, R.E., P wave velocities in the upper mantle beneath the Australian shield from earthquake data, Geophys. J. R. Astr. Soc., 24, 109-118, 1971.

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Table 1.  
List of Earthquakes and Explosions

(a) Earthquakes

Source Region	Event No.	Date	Origin Time	Lat	Lon	Depth	Mag	Ref. of data	Reported maximum depth
West Tonga	1	12/09/65	13h 12m 55.3s	18.12S	178.12W	649	5.4	ISC	680 km (Gutenberg, 1954) 650 (Sykes, 1966; Sykes, Isacks & Oliver, 1969)
	2	12/25/65	02h 57m 58.2s	18.14S	179.13W	624	5.5	ISC	
	x†3	7/21/66	18h 30m 15.0s	18.85S	178.56W	589	5.6	ISC	
	4	12/25/65	19h 20m 45.6s	18.21S	179.13W	631	5.2	ISC	
	5	12/30/66	01h 00m 24.4s	18.06S	179.16E	650	5.1	ISC	
South Fiji	6	12/28/64	16h 16m 08.7s	22.13S	179.62W	577	5.7	ISC	680 km (Gutenberg, 1954) 650 km (Sykes, 1966; Sykes, Isacks & Oliver 1969)
	x7	3/17/66	15h 50m 32.3s	21.08S	179.15W	627	5.9	ISC	
	*	3/14/64	04h 45m 51.9s	21.96S	179.62E	627	5.0	ISC	
	8	10/17/66	18h 20m 07.0s	22.32S	179.21E	620	5.2	ISC	
Colombia	9	09/21/64	04h 23m 18.9s	21.96S	179.46W	603	5.2	ISC	650 km (Gutenberg, 1954; Santo 1969)
	10	7/31/70	17h 08m 05.4s	1.5S	72.6W	651	7.1	USCGS	
Peru- Brazil Border	x11	11/03/65	01h 39m 03.2s	9.04S	71.32W	587	5.9	ISC	650 km (Gutenberg, 1954; Santo 1969)
	12	12/22/64	00h 24m 48.8s	9.48S	71.21W	6615	5.2	ISC	
	*	11/28/64	16h 41m 34.3s	7.90S	71.32W	651	5.3	ISC	
	*	11/28/64	16h 49m 30.5s	7.87S	71.32W	651	5.3	ISC	
South Bolivia	*	02/18/65	22h 32m 19.1s	9.99S	71.08W	593	5.2	ISC	660 km (Gutenberg, 1954)
	13	5/13/65	02h 23m 24.2s	19.24S	63.84W	602	5.0	ISC	
Argentina	14	12/09/64	13h 35m 41.9s	27.46S	63.23W	578	5.8	ISC	660 km (Gutenberg, 1959)
	*	09/19/67	10h 06m 44.1s	27.7S	63.1W	578	5.8	ISC	
	15	03/05/65	14h 32m 17.9s	26.89S	63.25W	555	5.6	ISC	
	x16	12/20/66	12h 26m 53.6s	26.06S	63.10W	571	5.8	ISC	
	17	07/25/69	06h 06h 42.4s	25.6S	63.3W	579	5.5	USCGS	
Java Sea	x18	04/29/65	15h 48m 58.9s	5.65S	110.24E	524	5.7	ISC	660 km (Gutenberg 1954) 650 km (Santo, 1969; Fitch & Molner, 1970)
	*	03/24/67	09h 00m 19.5s	6.0S	112.3E	600	6.0	UUSCGS	
	19	01/30/68	03h 44m 24.4s	6.1S	113.3E	594	6.2	USCGS	
Bali Sea	20	02/13/70	15h 43m 28.7s	5.9S	113.0E	636	5.8	USCGS	600 km (Gutenberg, 1954)
	21	03/26/68	00h 41m 56.9s	6.6S	116.1E	520	5.9	USCGS	
Philippines	*	01/23/65	23h 24m 30.1s	7.43N	123.86E	628	5.2	ISC	610 km (Gutenberg, 1954)
	x22	12/22/65	00h 52m 56.8s	6.67N	124.11E	552	5.2	ISC	
	23	12/18/70	23h 50m 12.2s	5.1 N	123.5E	511	5.5	USCGS	
Celebes Sea Flores Sea	24	11/25/64	09h 24m 08.9s	4.34S	122.14E	607	5.8	ISC	670 km (Gutenberg, 1954)
	*	01/06/65	00h 55m 27.7s	7.13S	122.84E	554	5.3	ISC	
	x*	05/13/69	14h 30m 19.6s	7.2S	120.9 E	616	5.6	USCGS	
Banda Sea	25	08/17/66	19h 54m 11.1s	5.01S	125.15E	555	5.5	ISC	720 km (Gutenberg, 1954)
	26	06/14/66	16h 39m 47.9s	5.39S	124.41E	616	5.4	ISC	
	*	10/18/64	12h 32m 24.9s	7.17S	123.86E	585	5.8	ISC	



TABLE 2.

Effect of weighting scheme for relocation of events

NOTE: Normal weight refers that each data is given equal weight (=1.0).  
 Reduced weight is calculated from the weighting scheme.  
 (see Section 2.2)

## A) Effect on residual

Test Event Region	Quality of Station Distribution	Station	Distance	Azimuth	Reduced Weight	Residuals	
						Normal Weight	Reduced Weight
W. Tonga	Dense at large distance	MNW	30.12	199	1.71	0.4	0.2
		BUT	87.06	39	0.21	0.7	0.9
Japan Sea	Dense at small distance	ABU	6.20	127	0.24	0.7	1.0
		CTA	60.57	162	2.19	-2.5	-2.1

Table 2. continued

## B) Effect on location parameters

Test Event Region	Description of Location	Origin Time hms	Depth km	Lat.	Long.	Area of Confidence Ellipse (sq km)	Standard Error of Esti. of Residuals
West Tonga	1. Bulletin (ISC)	18:30:15.0 ±0.33s	589.0 ±4.6	17.85S ±0.026°	178.56W ±0.027°	-	1.07
	2. Normal Weight	18:30:15.2 ±0.59s	591.0 ±8.1	17.89S ±0.031°	178.58W ±0.032	239	1.06
	3. Reduced Weight	18:30:15.2 ±0.47s	591.0 ±6.4	17.85S ±0.026°	178.57W ±0.028°	178	1.02
Japan Sea	1. Bulletin (ISC)	17:17:46.7 ±0.08s	557.0 ±2.4	38.75N ±0.011°	129.54E ±0.026	-	1.21
	2. Normal Weight	17:17:46.7 ±0.15s	555.0 ±2.4	38.76N ±0.025°	129.50E ±0.028°	164	1.1
	3. Reduced Weight	17:17:46.7 ±0.16s	558.0 ±2.0	38.74N ±0.021°	129.55E ±0.026°	127	1.1

Table 3.  
 Test of network bias (see section 3.2.2)

Test Event Region	Location Description	No. of Stn. used	Origin Time h m s	Depth km.	Lat.	Lon.	Area of Confidence Ellipse	Standard Error of Estimate of Residuals
West Tonga	1.Final relocation with all stations	87	18.30.15.2 ±0.39	596.0 ±5.3	17.82S ±0.021°	178.51W ±0.023°	122	0.85
	2.Relocation with subset 1 of stations	40	18.30.15.2 ±0.56s	598.0 ± 7.3	17.83S ±0.039°	178.50W ±0.039°	360	0.98
	3.Relocation with subset 2 of stations	60	18.30.15.0 ±0.34s	594.0 ± 4.9	17.84S ±0.02°	178.46W ±0.022°	109	0.69
Japan Sea	1.Final relocation with all stations	151	17.17.46.7 ±0.1s	559.0 ±1.4	38.70N ±0.012°	129.53E ±0.016°	46	0.58
	2.Relocation with subset 1 of stations	92	17.17.46.5 ±0.1s	558.0 ±1.8	38.68N ±0.017°	129.50E ±0.018°	75	0.60
	3.Relocation with subset 2 of stations	104	17.17.46.8 ±0.09s	560.0 ±1.4	38.70N ±0.012°	129.58 ±0.015°	44	0.57

Table 4.  
Test for uniqueness of location parameters

Test Event Region	Location Description	No. of iterations to reach convergence	Origin Time h m s	Depth km	Lat	Lon	Area of confidence ellipse	Standard error of estimate for residuals
West Tonga	1. Bulletin (ISC)	-	18.30.15.0 ±0.33s	589.0 ±4.6	17.85S ±0.026°	178.56W ±0.027°	-	1.07
	2. Location from blank input solution	20	18.30.15.2 ±0.59s	591.0 ±8.1	17.89S ±0.031°	178.58W ±0.032°	239	1.06
Japan Sea	1. Bulletin (ISC)	-	17.17.46.7 ±0.08s	557.0 ±2.4	38.75N ±0.011°	129.54E ±0.026°	-	1.21
	2. Location from blank input solution	9	17.17.46.7 ±0.015s	555.0 ±2.50	38.76N ±0.025°	129.50E ±0.028°	164	1.1

Table 5.

Standard error of the estimate of 'station-residuals' found  
in 3 different ways  
(see section 3.10)

Station	No. of data	Standard error of estimate for 'station-residual'		
		*1	*2	*3
BKS	20	0.55	0.52	0.40
EUR	31	0.43	0.46	0.46
PAS	27	0.68	0.67	0.69

\*1 'station residual' is found from the average of all residuals at the station.

\*2 'station-residual' is given in the form of  $A + B \sin Az + C \cos Az$  where  $Az$  is the azimuth from the station to the epicenter. Values of  $A, B,$  and  $C$  are found by linear regression.

\*3 'Station-residual' is given in the form of  
 $a_0 + a_1 \cos \Delta + a_2 \sin \Delta \cos Az + a_3 \sin \Delta \sin Az$

## LIST OF FIGURES

1. Flow chart of the method.
2. Distribution of events. Earthquakes are marked by +, and explosions by x.
3. Evidence of source error from residual sphere plots of a Solomon Island event (number 40 in table 1) shown in a and b. For comparison is shown the same for a New Hebrides event (number 45 in table 1) in c. For b and c, residuals were corrected for systematic error in J-B table and station errors. For a, uncorrected residuals are shown. (see section 3.2.1).
4. Evidence of source error in Solomon Island events from station sphere plots at Mundaring (MUN) and Nhatrang (NHA) (see section 3.2.1).
5. Station distribution on the focal sphere plot of a Bali Sea event (a) and Okhotsk Sea event (b) (see section 3.2.3.)



6. Systematic error in the Jeffreys-Bullen travel times curve for a depth of 550 km. "x" represents averages of residuals in 2° cells with their standard error shown as vertical lines.
7.
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  - b) Lower mantle J-B residuals of this study in comparison with other works.
8. J-B residuals (shown as +), corrected for station error, for an Okhotsk sea event are shown against the systematic error curve (see section 3.3).
9. J-B residuals (shown as +), corrected for station error, for an Argentina event are shown against the systematic error curve (see section 3.3).
10. Station error for North America (see section 3.7).
11. Comparison of station errors (for North America) of this study with other works (see section 3.8).

- a) Herrin and Taggart
- b) Cleary and Hales
- c) Lilwall and Douglas

12. Evidence of lateral heterogeneity from focal sphere plots of residuals (corrected for systematic error in J-B table and station error) for an event in West Tonga (a) and South Fiji (b) (see section 3.9).
13. Evidence of azimuth dependent station error for western North American stations. Compare figures 13, 14, and 15. Note: Residuals were corrected for systematic error and were averaged for all events in the North Okhotsk Sea (see section 3.10).
14. See caption in figure 13. Events here are from Argentina.
15. See caption in figure 13. Events here are from South Fiji.
16. Histogram of residuals.  
Solid line: Final residuals with all corrections.  
Broken line: Starting residuals after first relocation without any systematic or station correction.

Figure 1.

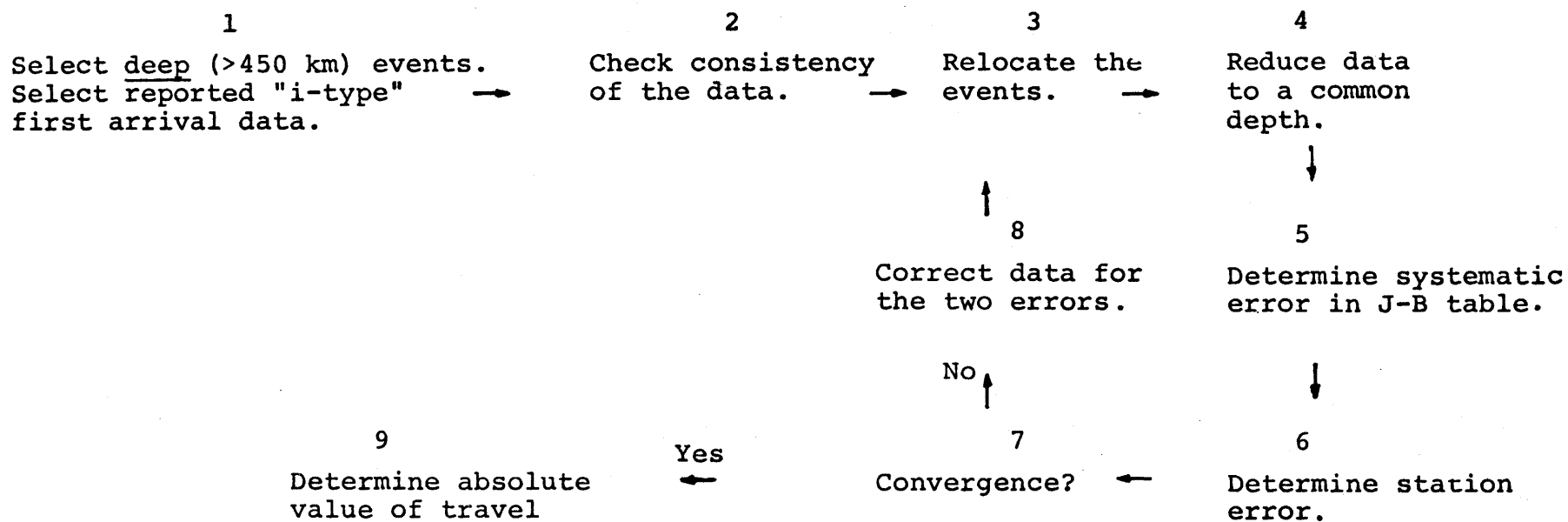
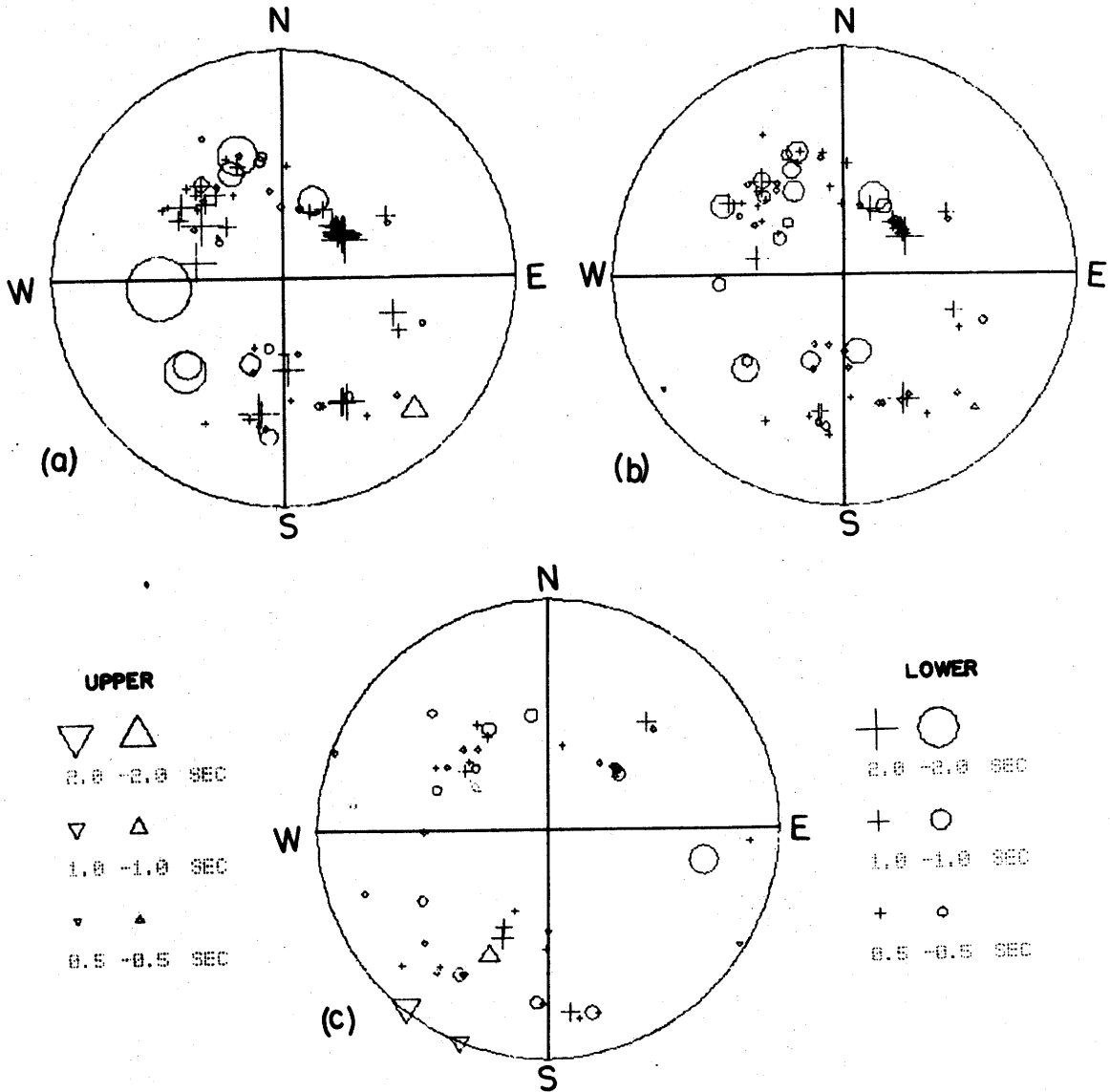


Figure 2.



Figure 3.



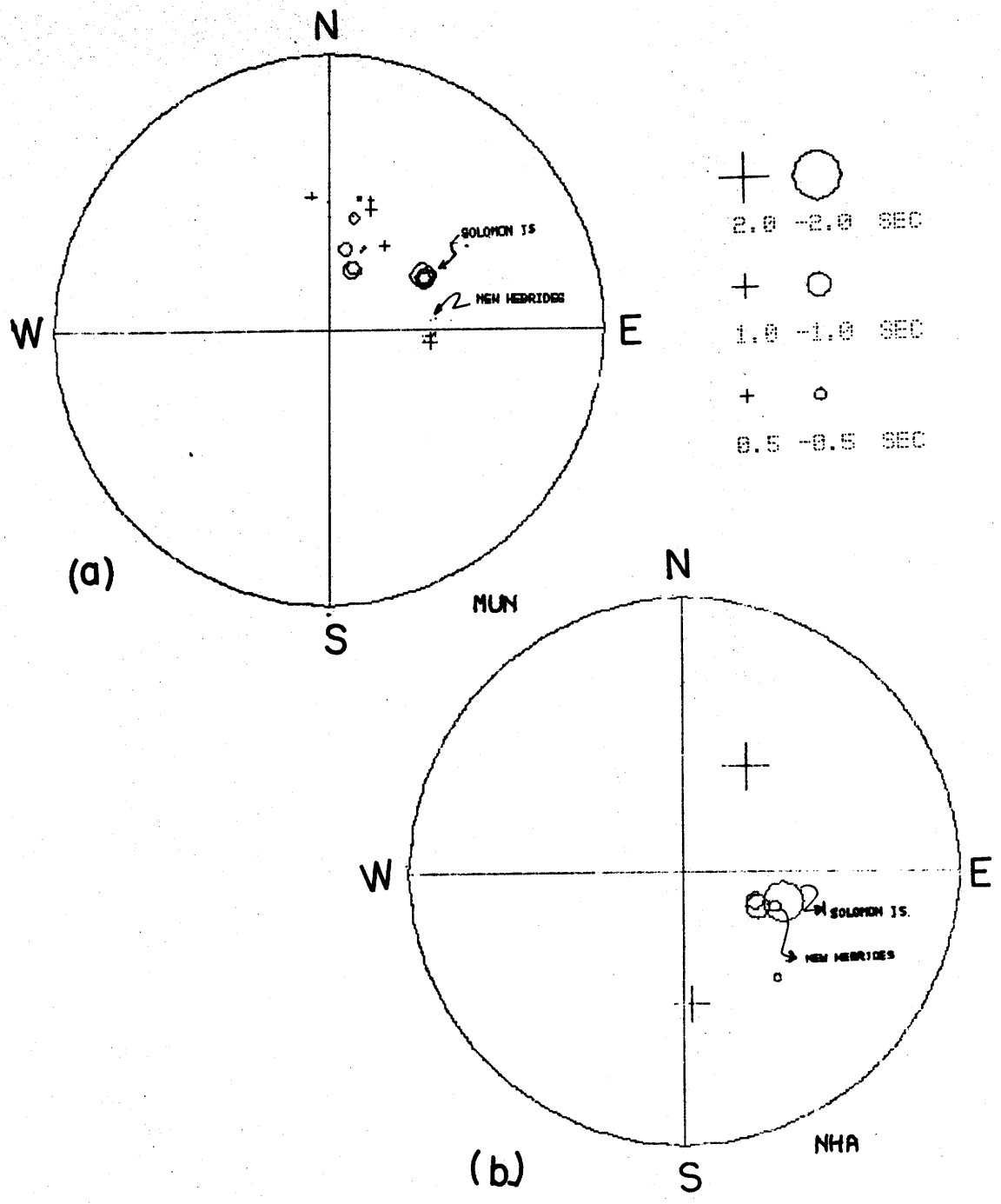


Figure 4.

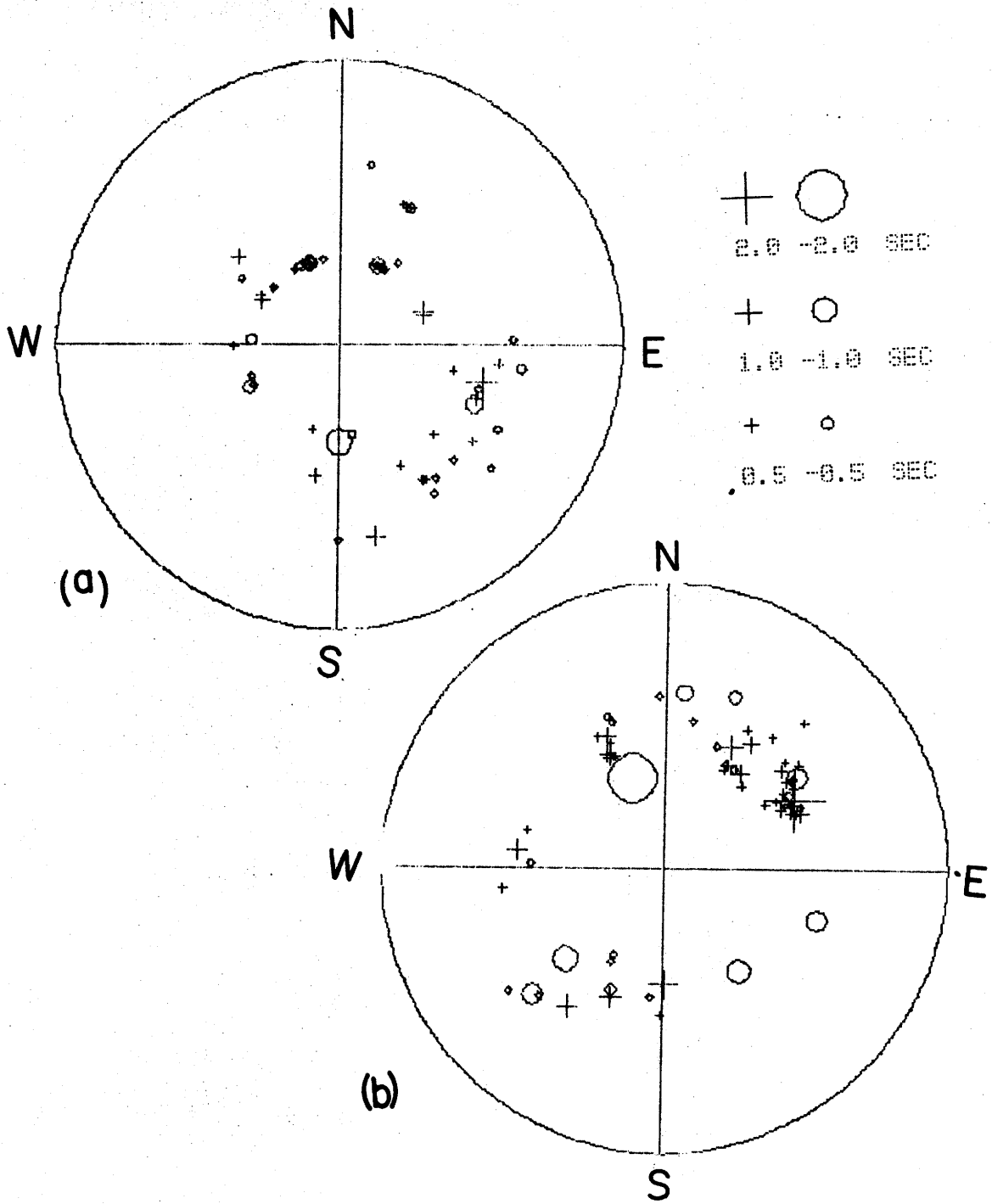


Figure 5.

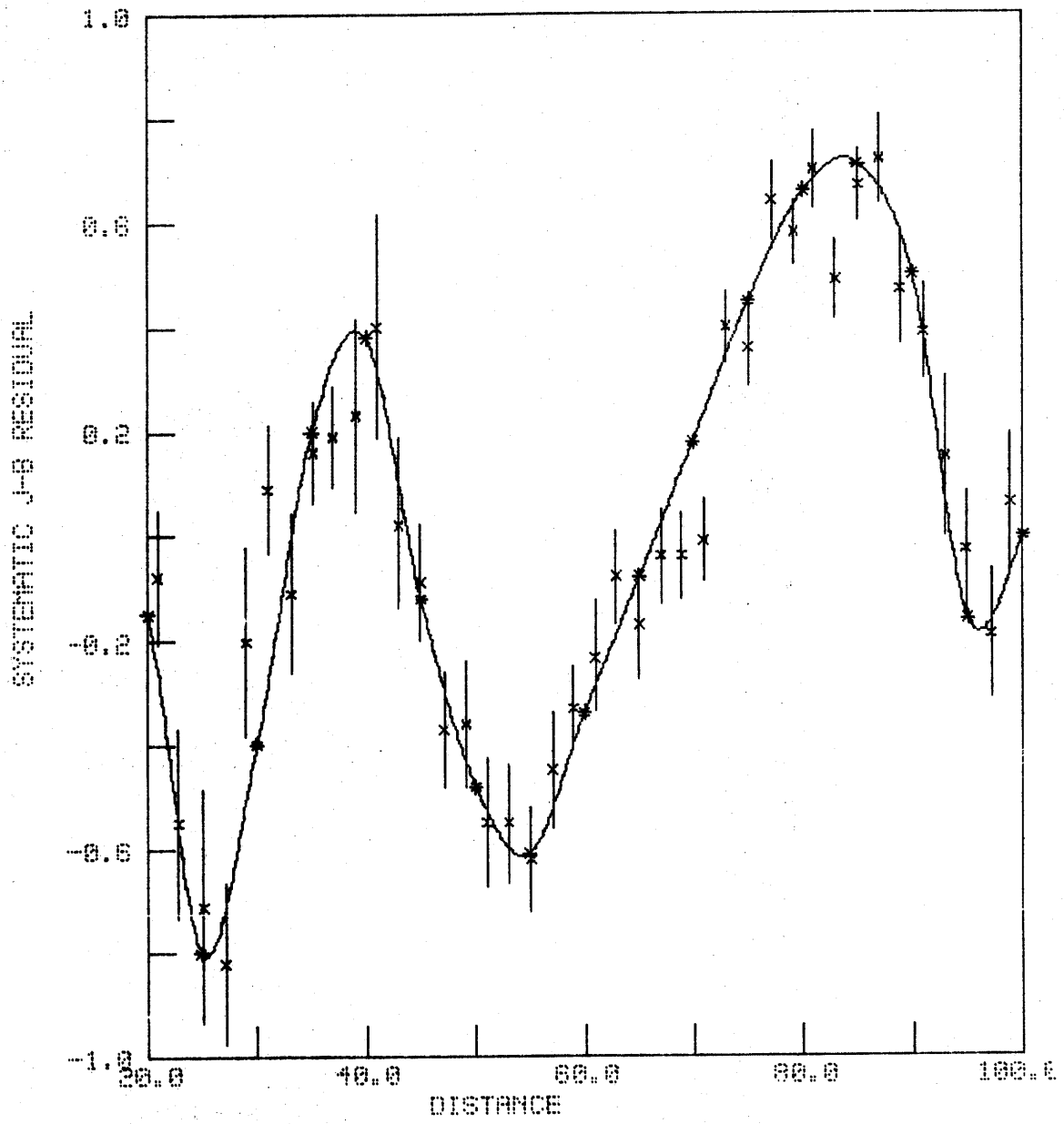
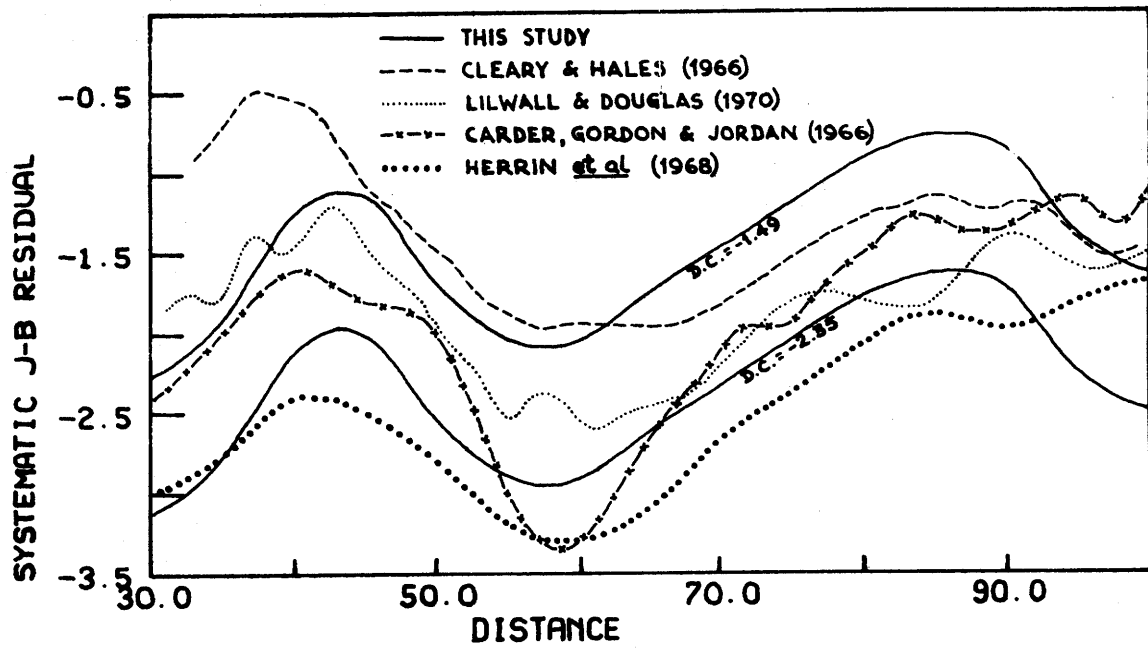
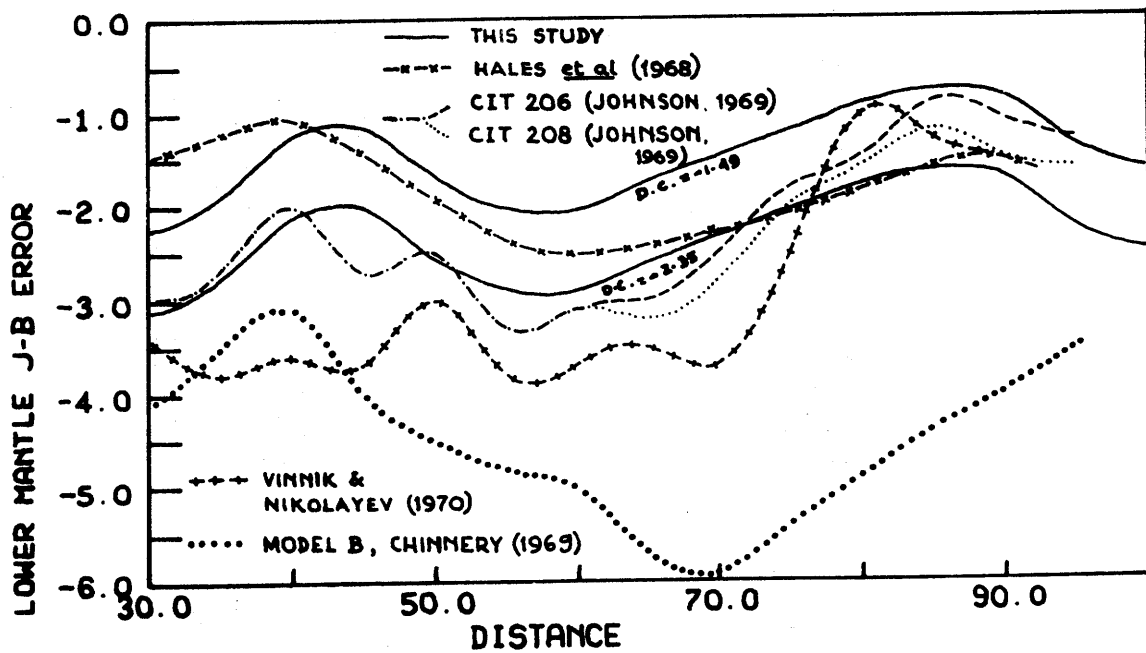


Figure 6.





(a)



(b)

Figure 7.

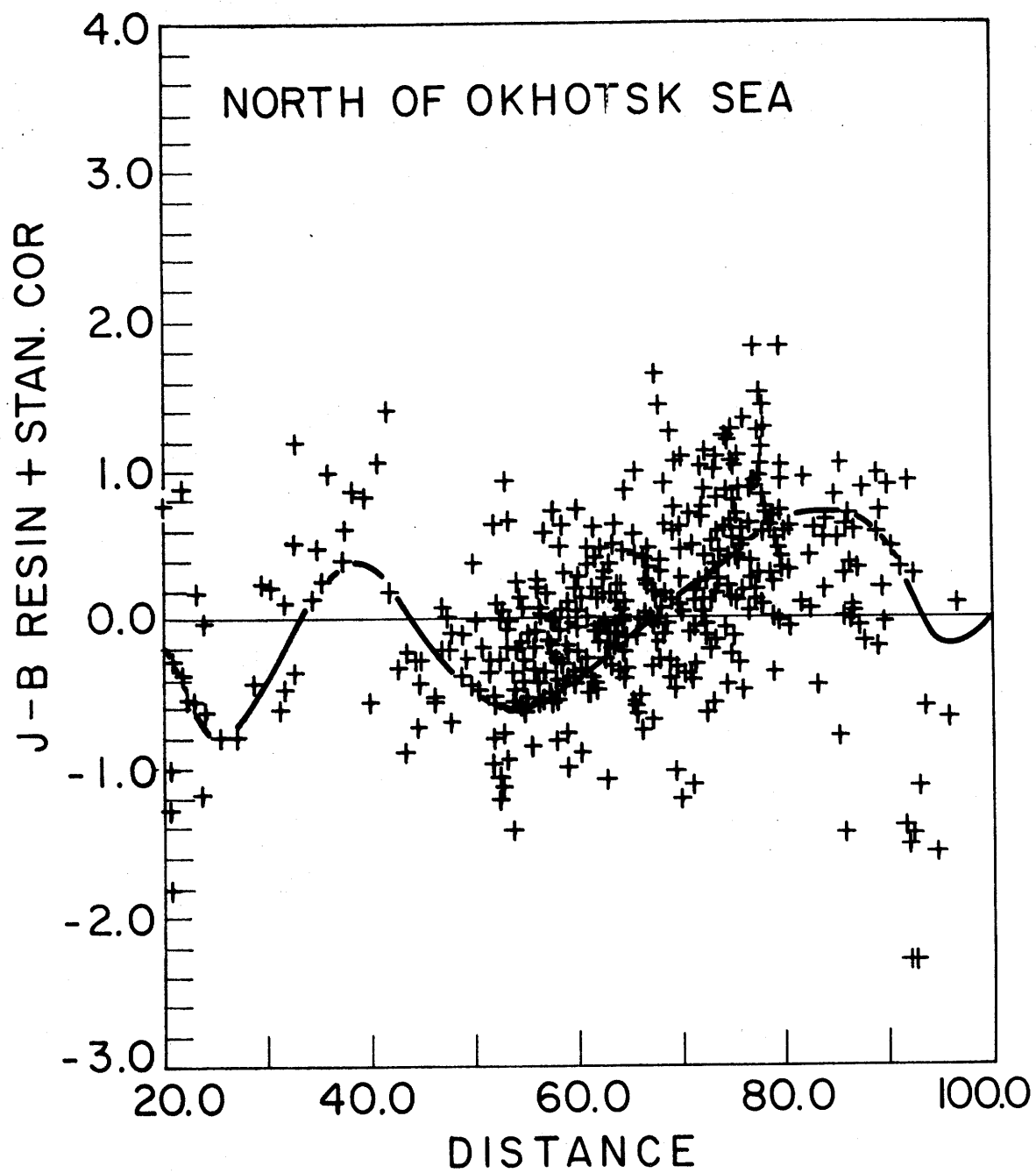


Figure 8.

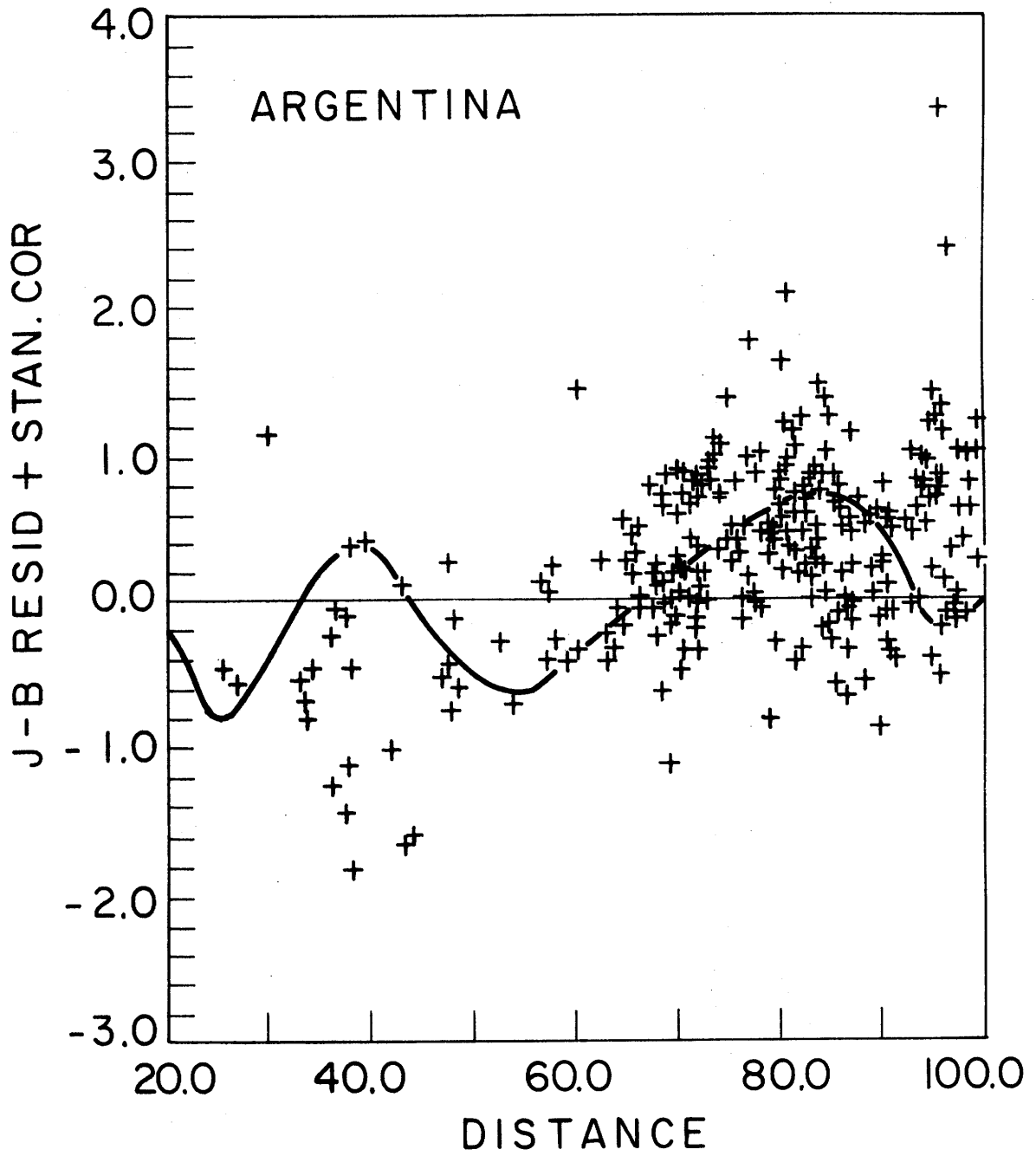


Figure 9.

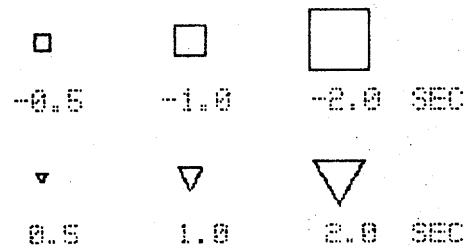
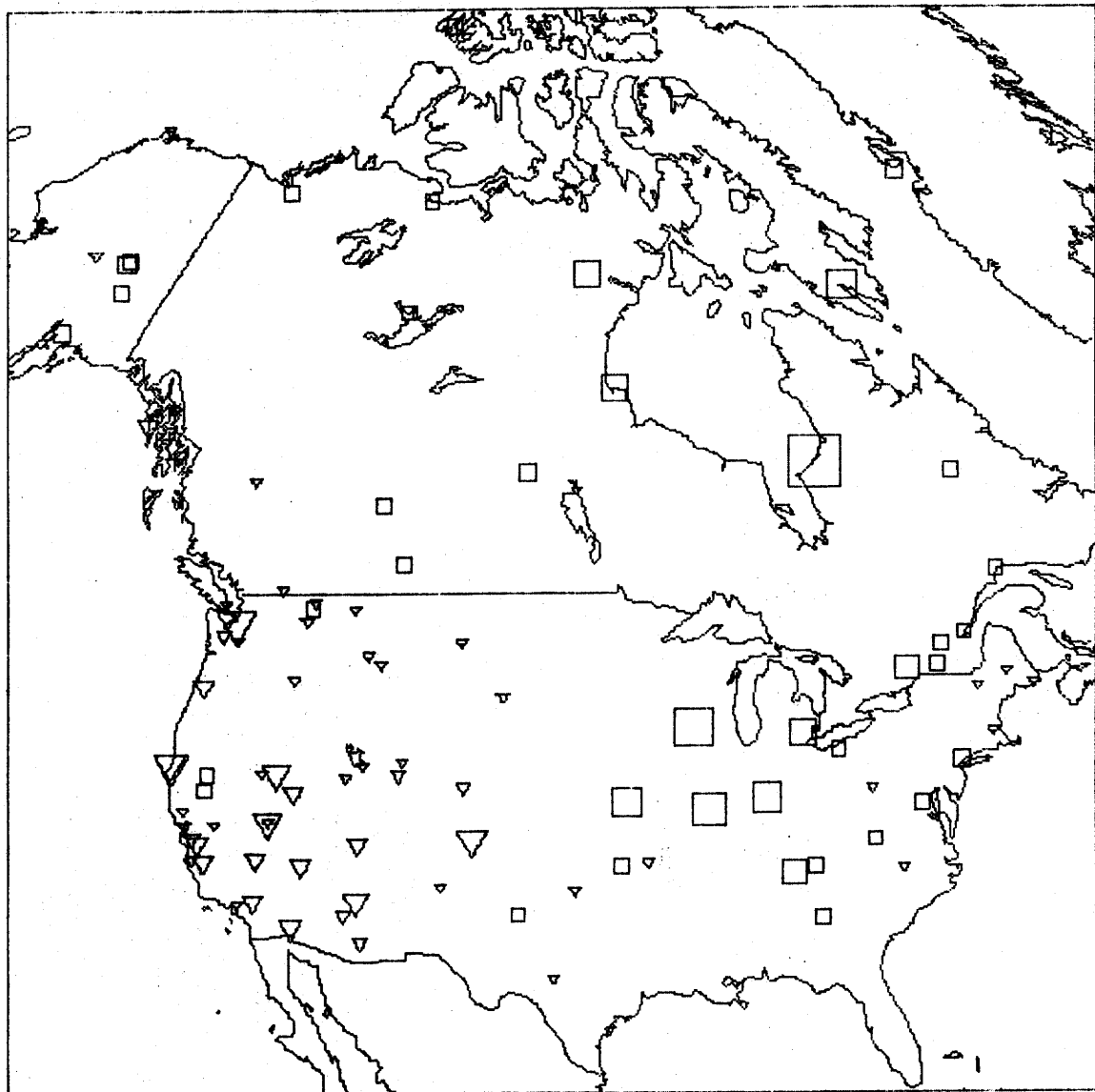


Figure 10.

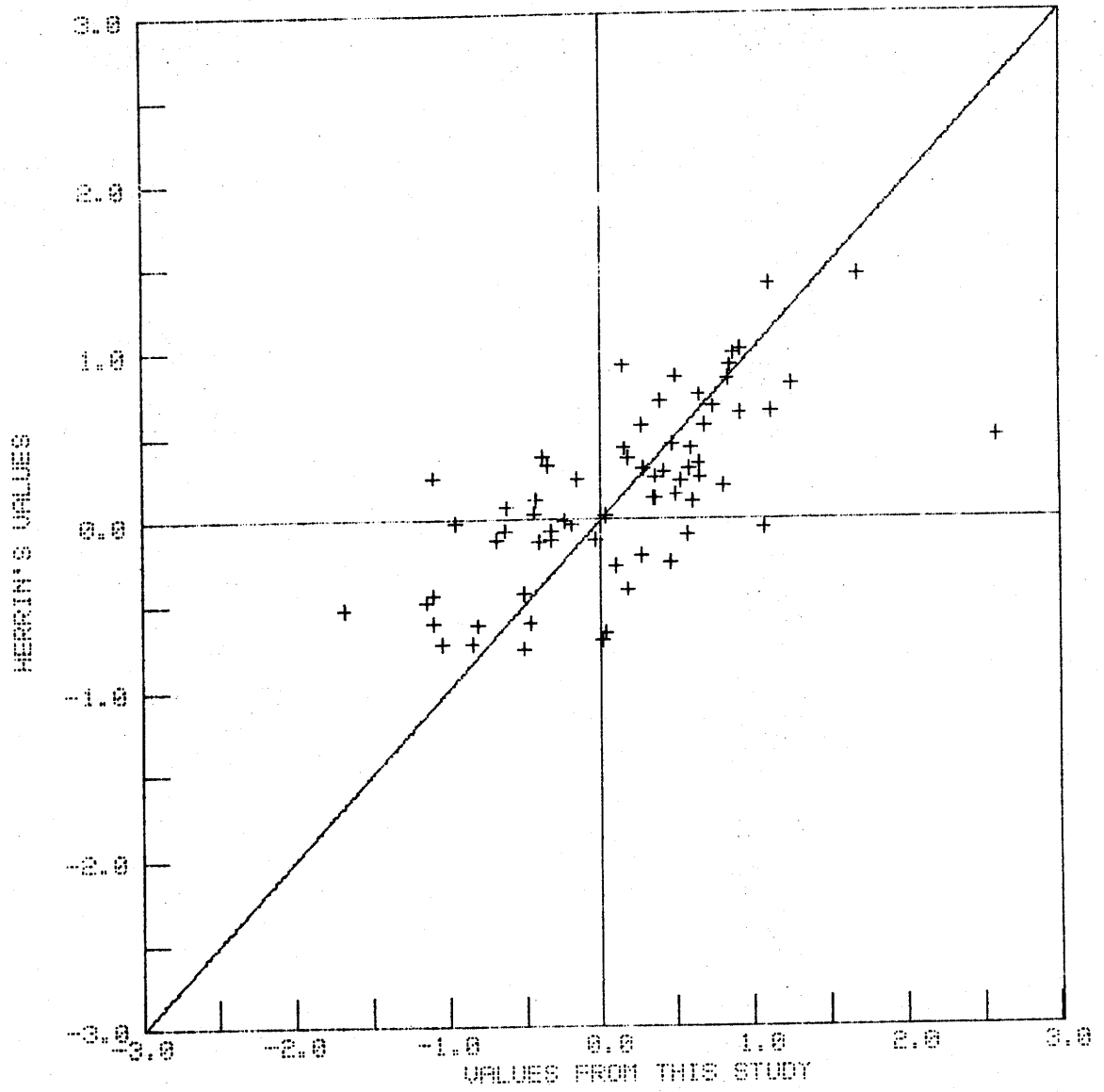


Figure 11.a

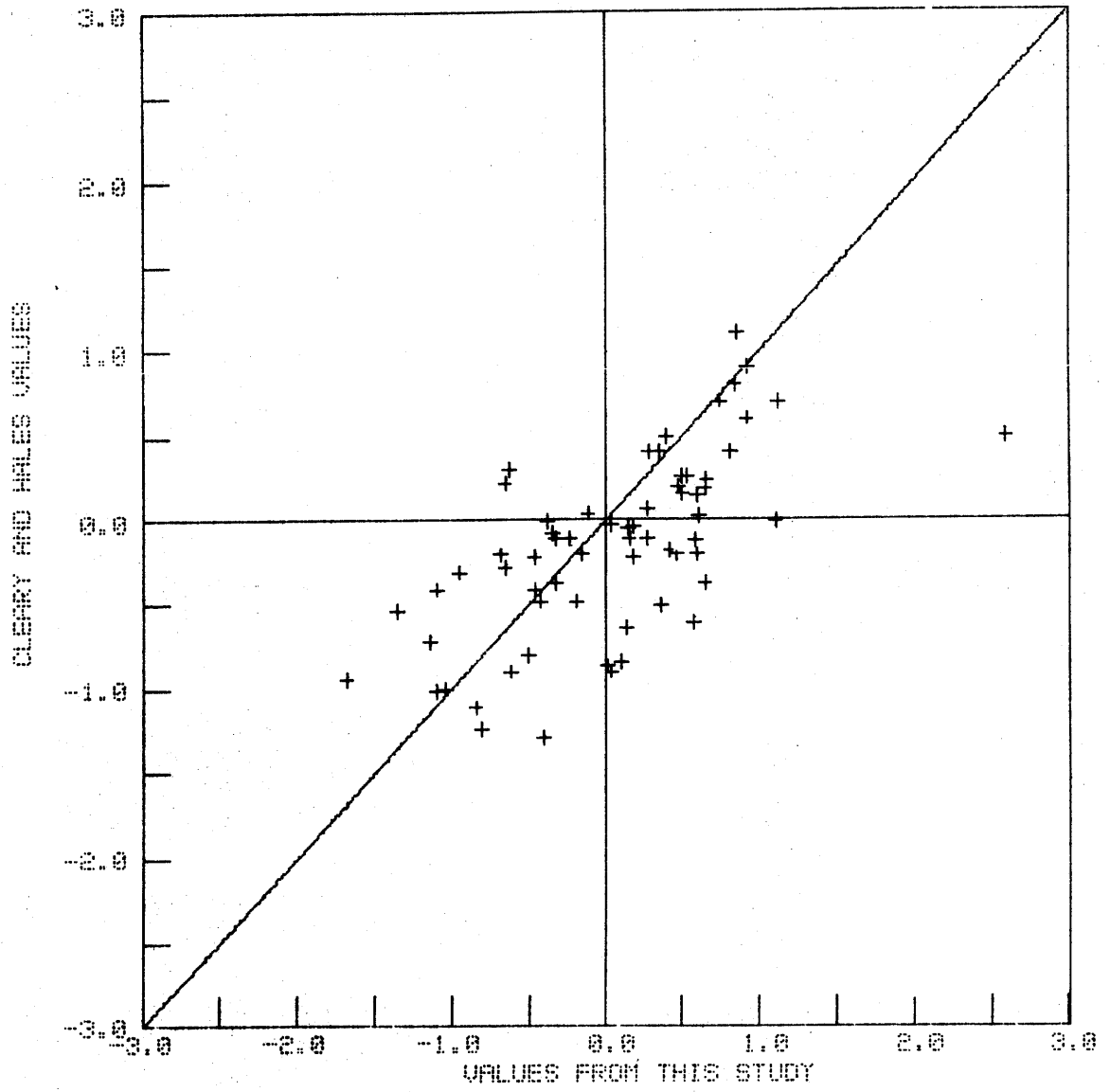


Figure 11.b

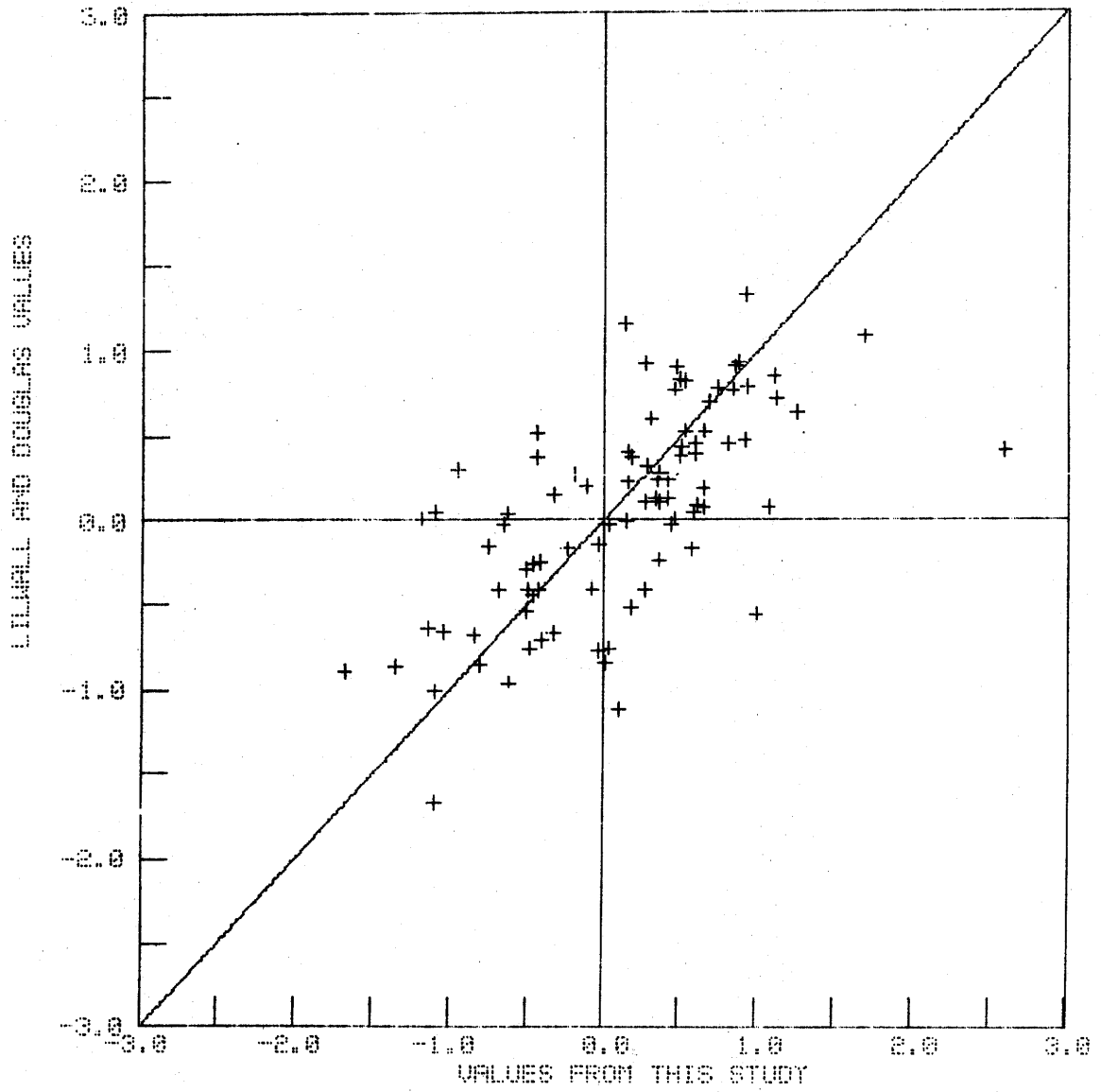


Figure 11.c

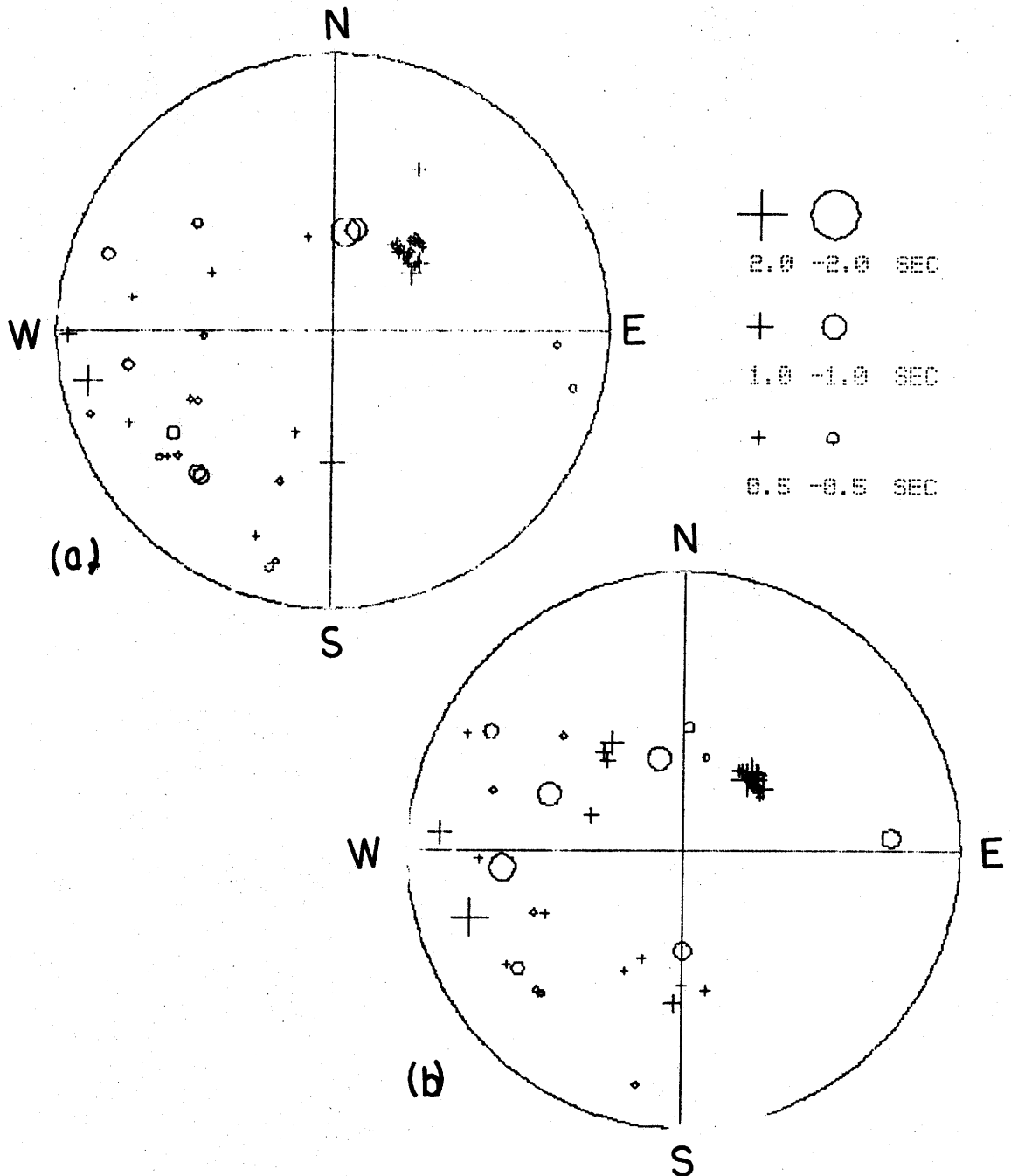
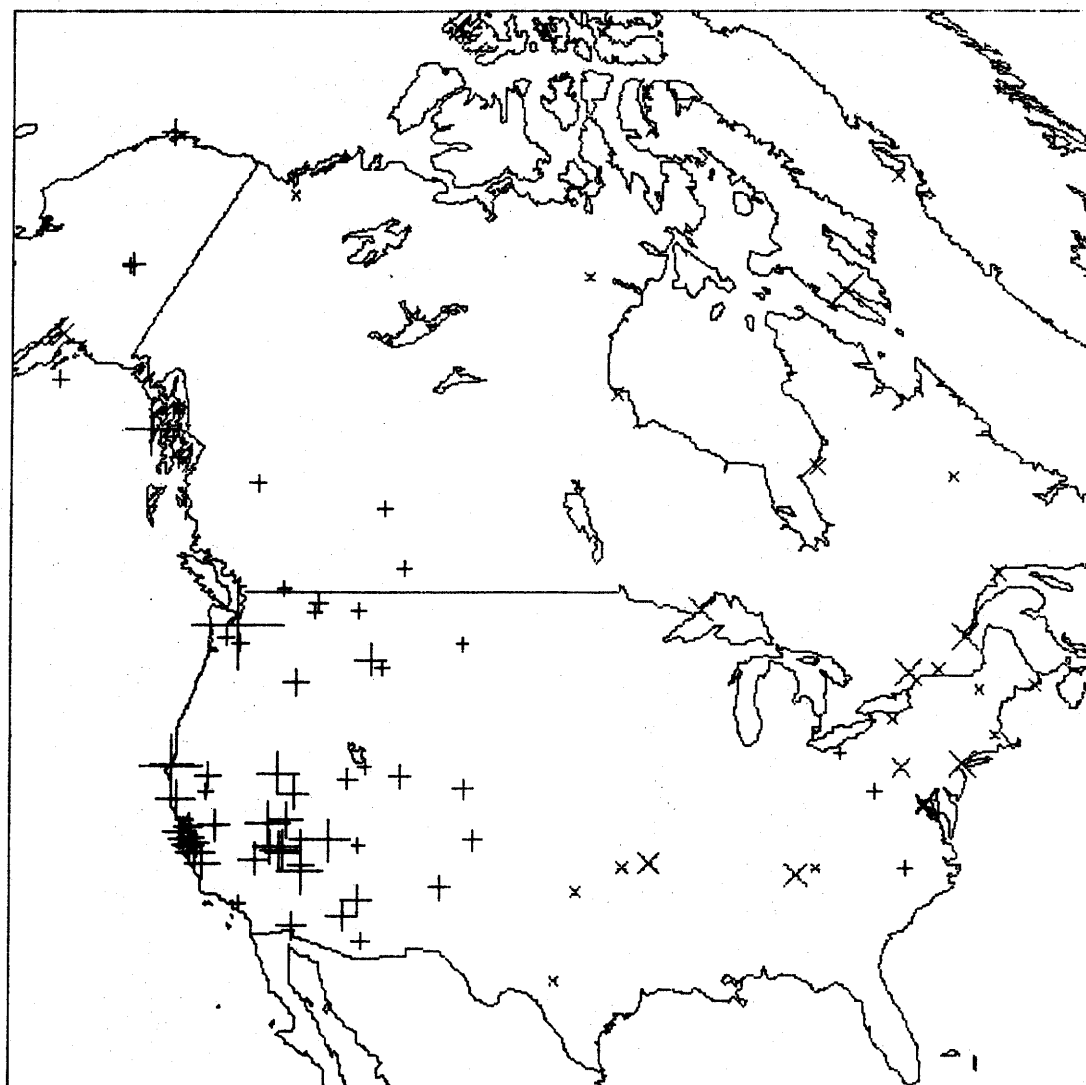


Figure 12.



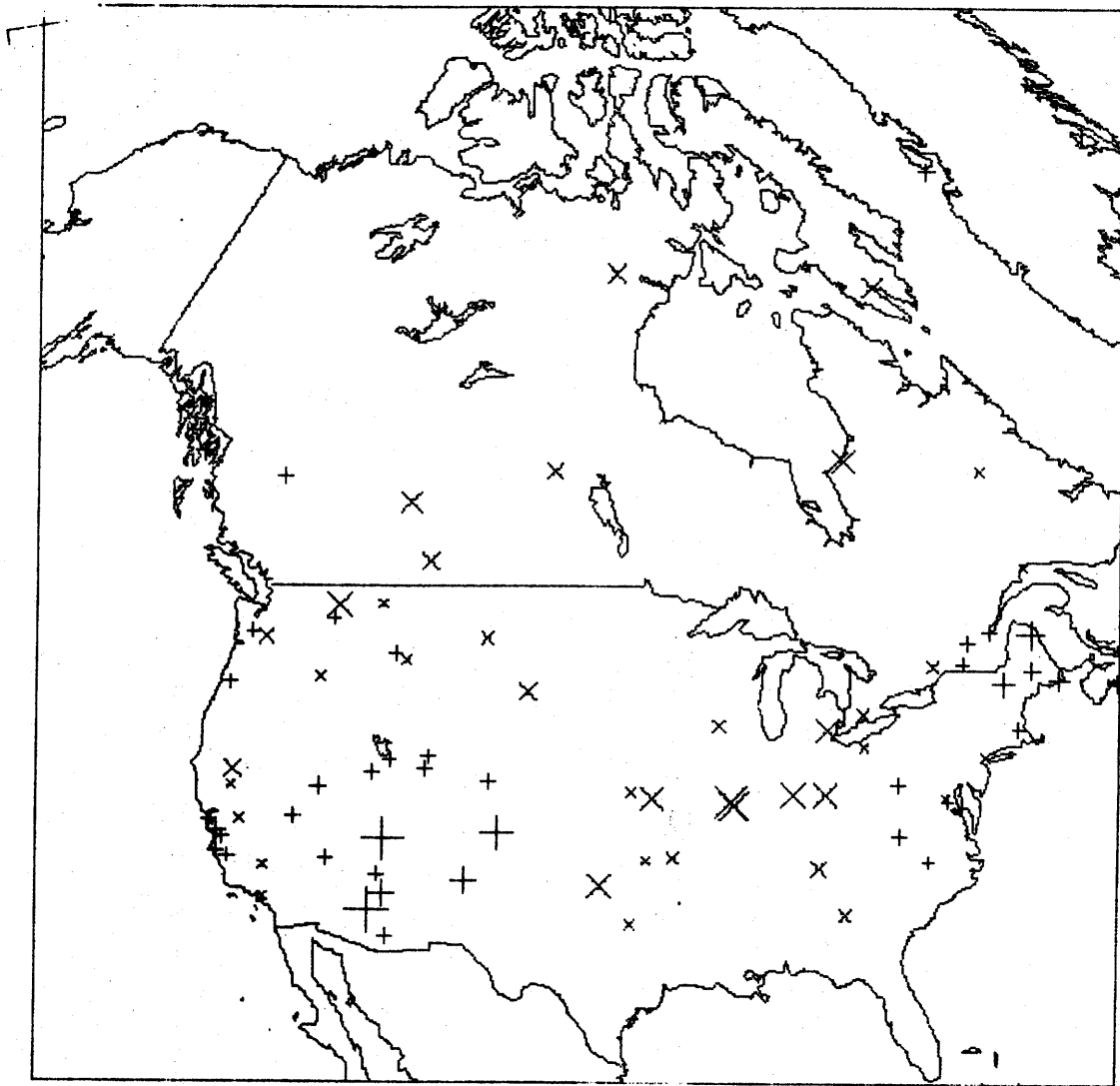


N. OKHOTSK SEA EVENTS

x	X	X	
-0.5	-1.0	-2.0	SEC

+	+	+	
0.5	1.0	2.0	SEC

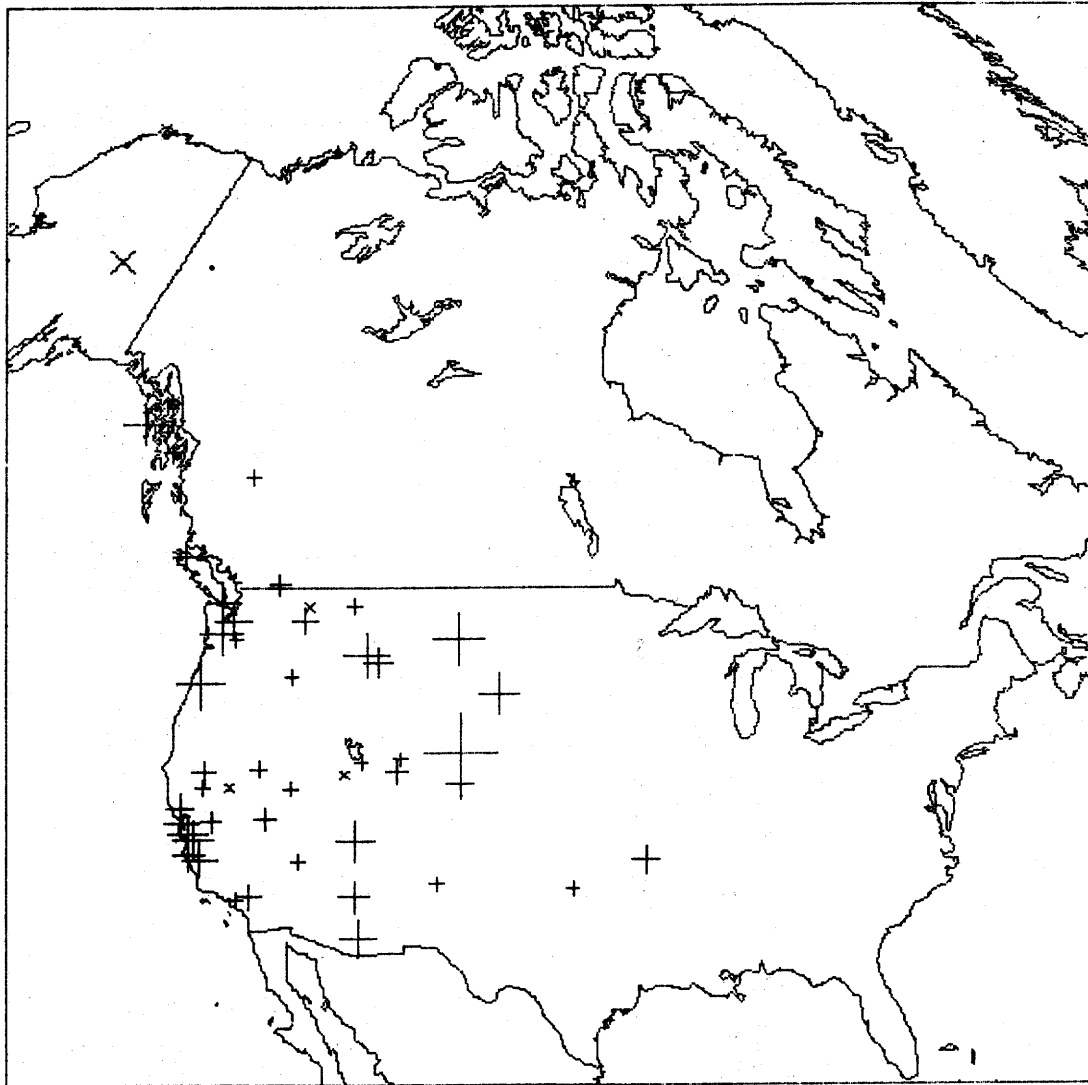
Figure 13 .



ARGENTINA EVENTS

x	X	⊗	
-0.5	-1.0	-2.0	SEC
+	+	+	
0.5	1.0	2.0	SEC

Figure 14.



S. FIJI EVENTS

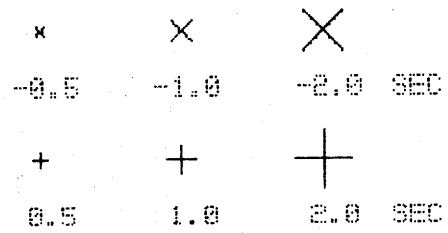


Figure 15.

Figure 16.

