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STRUCTURE INFERENCES BASED ON TWO AFTERSHOCKS IN THE MEXICALI-IMPERIAL VALLEY.

ABSTRACT

A study of S-wave arrival-time residuals for the aftershocks of the Victoria earthquake (June 9, 1980) and the Mexicali earthquake (October 15, 1979) make it possible to detect the existence of a phase that arrives a few seconds prior to the S-wave and may be confused with it. This phase is recorded at the stations located in the Mexicali-Imperial Valley. If it is interpreted as being the result of a conversion between P and S-waves at the base of the consolidated sediments, the velocity values required in the sedimentary layers would be too low to match observations. A more plausible interpretation is to consider the phase as a P-wave converted into an S-wave within a gap between the basement (VP= 6.0 km/s) and materials with velocities on the order of 4.4 - 5.0 km/s. This interpretation indicates that the velocities in the Mexicali-Imperial Valley gradually increase with depth, from the unconsolidated sediments to a point in the basement, at some 8.5 km, where there must be a very strong gap in order to produce the conversion. An analysis of the aftershocks distributed in different regions of the Mexicali-Imperial Valley indicates lateral variations in the model. The preceding interpretation is based on a series of numerical experiments, contrasting observations of differences in arrival time with values predicted through ray theory and making qualitative comparisons of observations synthetic seismograms and calculated refraction coefficients. A discussion is also included on the distribution of station corrections for P-wave arrival times and the implications of the previous results in conjunction with the tectonics of the zone.

1. INTRODUCTION

This study attempts to define a local structure on the basis of the first arrival times of waves produced by earthquakes. From a mathematical point by view, this is an inherently ill-posed problem. On one hand, such times are only an overall measurement of the structure through which they travel and it is thus difficult to estimate the details of the structure. On the other hand, a large part of the information obtained is used in the necessary task of determining the four hypocentral parameters. Thus, the ill-posed problem indicated above implies a lack of resolution for measuring details, that is, a lack of unicity in results and, consequently, poor conditioning in the related algebraic problem.

In this process, it is common to use a method of successive approximations. We start out with provisional values for the model and station corrections and, with them, we determine hypocenters. With an adequate azimuthal distribution of stations, we are always able to make a good epicenter determination. This location will depend on the provisional station corrections, but will be almost independent of the structure used. Good control of depth may be obtained with data from stations near the hypocenter. In the absence of such data, the determination of depth will be strongly correlated with the determination of origin time. Thus, our estimates of station corrections, depth and origin time of hypocenters depend both on the provisional model and on the relative position of epicenters and stations.

Inversion of the new station corrections and of the residuals of observations may be used to improve the structural model, in addition to all other information from geologic and geophysical studies of the region in question.

Determining the hypocenters and structure together does not solve the ill-conditioning of this situation, but it does offer the advantage of inversion explicitly showing the correlations between estimates of the unknowns. The price paid for this advantage is an increase in the magnitude of the computational problem.

The most natural way to break through the ill-conditioning referred to is to use some information that is specifically sensitive to structural details. Thus, for example, the phases resulting from reflection, refraction or trapping in the gaps of the environment are sensitive to the physical properties surrounding the gap and to the related thicknesses.

In our previous paper (Wong and Frez, 1982) we reported the existence of a phase that appears prior to the arrival of the

S-wave in the local logs of the Mexicali-Imperial Valley. An interpretation of this phase on the basis of lateral heterogeneity is not consistent with its characteristics (Figures 5 and 6). In contrast, an interpretation of the phase as a converted wave in a gap seems to be more suitable.

In this paper, we make a preliminary study of the spatial distribution of the station corrections (P-wave) and the residuals of observations (S-wave) for the aftershocks of the Mexicali earthquake (October 15, 1979) and the Victoria earthquake (July 9, 1980); we identify the phase mentioned in the previous paragraph and we use the information on the different arrival times of this phase in relation to the P and S-waves to infer the structural characteristics of the Mexicali-Imperial Valley. Finally, we discuss the implications of a model obtained for the tectonics of the region.

2. HYPOCENTER DATA AND DETERMINATIONS

The data consists of P and S-wave arrival-time readings from stations belonging to the Caltech=USCGS Southern California network, from those installed by the IGPP of the University of California at San Diego, by the Universidad Nacional Autónoma de México and CICESE. We also used three stations of the RESNOR network that CICESE maintains to study the seismicity of the northwest of México. Times were collected to study the aftershocks of the Mexicali earthquake (October 15, 1979) and the Victoria earthquake (June 9, 1980).

The total number of aftershocks whose hypocenters were determined is on the order of 400 and these results have been used to study the seismicity associated with both events (Chávez and González, 1982; Wong and Frez, 1982). In order to estimate structures, it was necessary to edit the data, eliminating hypocenter determinations of insufficient quality, stations that produce high and oscillating residuals in signals and, in general, high residuals that seem highly unlikely to have been produced by lateral heterogeneity effects. Hypocenters of insufficient quality refer to those determined with fewer than six stations, with azimuthal gaps greater than some 130° and to low precision measurements in determining the focal parameters. Most of the final determinations were made with 10-25 P-wave arrival-time data, using the HYPO71 program (Lee and Lahr, 1975) for such purposes. The total number of locations used in this study is 130 and their distribution by depth is shown in Figure 2. In this figure, the data is classified according to four groups: NORTH, CENTRAL, SOUTH and VICTORIA, and the three first classifications apply to the Mexicali event. It may be observed that the number of earthquakes diminishes toward the south, which we believe is due both to the related decrease in the number of stations that report observations there and to the quality of their spatial distribution. The statistical behavior of the epicenters depends very little on the structure used, although the average depth values may vary a couple of kilometers. The models used in the different stages of our work are variations of the proposal made by Johnson and Hadley (1976) and of those obtained and summarized by Fuis et al (1979). Two models that were particularly useful in our numerical experiments are shown in Table 1; the VALLE-2 model was used to obtain Figure 2.

In general, we had no control over the components of the readings that we used and, only in some cases, did we obtain arrival times for both horizontal components.

Although Figure 2 is not presented for statistical analysis, it should be noted that almost all the hypocenters are found at a depth between 7 and 13 km; that the average depth varies along the faults and is at the minimum depth in spreading zones; and that the seismic gaps around the main earthquakes have been reported as being real (Chávez and González, 1982; Wong and Frez, 1982). The region's main characterisitics are highlighted in Figure 1 and the locations of the stations that report arrival times may be seen in Figures 1 and 3.

3. SPATIAL DISTRIBUTION OF THE STATION CHARACTERISTICS

We calculated the station corrections as average residuals of P-wave arrival times for each station that had more than 10 observations and in which the residuals appeared with little variation. Stations that show low consistency (standard deviations greater than 0.25 sec) were carefully examined and those that showed chaotic behavior, which could not be explained by lateral heterogeneity effects, were eliminated during the editing of data. The determination of station corrections was conducted through successive approximations, based on different initial values. In general, it was observed that estimates of these values matched well.

Figure 3 shows zones with positive,

negative and approximately null corrections, using a value of 0.15 sec to define the related limits. These calculations apply to the VALLE-2 structure.

The results show that the most outstanding zone of small corrections is the one that is approximately longitudinal lying along the northeast edge of the Imperial Fault and clearly associated with the related valley. The part of the Mexicali Valley that is covered by the network of stations that we have used also has small corrections. Negative corrections are found in the flanks of the Imperial Valley and also in the area of the Salton Trough. Spreading zones located between the ends of faults appear with positive corrections as do those to the west that are clearly correlated with the Peninsula Ranges. A few stations with positive corrections are found in the mountain ranges northeast of the Salton Trough (the Chocolate and Orocopia Ranges). Finally, going in the direction of the faults toward the northwest and beyond the Salton Trough, we found traces of small corrections.

The corrections mentioned indicate that VALLE-2 is a good model for describing the structure of the Mexicali-Imperial Valley and may even be suitable for the valleys that follow to the northwest. Positive corrections indicate greater average velocity and thus it is not difficult to interpret the positive corrections that we have found associated with mountain ranges and chains. The positive values in the spreading zones may be interpreted as the relative nearness of more basic material to the surface. The possible existence of material of lower average velocity under the Salton Trough may be important for its tectonic interpretation; however, both its interpretation and that of the negative anomalies of the regions that flank the Mexicali-Imperial Valley will not be attempted here.

A detailed investigation of the station corrections in this region, based on a greater number of data, would provide material for separate research.

4. IDENTIFICATION OF THE CONVERTED PHASE

Through a study of the residuals of S-wave arrival times, Wong and Frez (1982) determined the existence of a phase that is confused with the first arrival of S-waves in local earthquakes in the Mexicali-Imperial Valley. Hereinafter, we will refer to this phase as Sc and to both the phases and their arrival times as P, S and Sc.

A clear demonstration of the existence of the Sc phase may be found in Figures 7 and 5a, as well as in the Wadati diagram for the NORTH region (Figure 6). The Sc-P difference seems to be approximately constant (Figure 6), while the Sc-S difference increases linearly with distance until it reaches a value of -0.5 sec at some 50 km of epicenter distance (Figure 5a). The phase is not reported for distances greater than 50 km. The stations that report that phase are generally in the Mexicali-Imperial Valley; those that do not report it are on land that has very few or no sediments.

The characteristics shown in the figures mentioned above indicate a conversion of P into S in a gap that we consider to be flat and horizontal. A conversion of S into P would tend to show constancy in Sc-S and linear growth with the epicentral distance for Sc-P, that is, behavior just the opposite to that observed (Figure 4).

If the type of conversion proposed is correct, the Sc-S difference should be approximately equal to the S-P difference for the run in the substratum between the focus and the gap. The Sc-P difference should, however, the adjusted approximately to the S-P difference for the surface layer. These considerations are based on the pronounced contrast in velocities in the interphase implied by the existence of the converted wave and on the use of basic ray theory.

Figure 8 shows synthetic seismograms for a model of flat layers composed of sedimentary, granitic and basaltic strata in VALLE-2. The seismograms were constructed using the Apsel-Luco technique (Apsel, 1979). The existence of a converted wave that appears before the true S-wave may be noted. The determination of the S-wave arrival time is calculated in the tangential-horizontal component. At approximately 45 km, the clarity of the beginning of this phase (and, generally, of the S-wave train) deteriorates because the seismogram begins to fill up with arrivals of reflected and refracted waves (Figure 8b). This is one possible explanation for the lack of Sc observations beyond distances of 50 km.

Refraction coefficient calculations (Young and Braile, 1976) for amplitude shift (Zoepritz) yeild maximum values of 0.30 - 0.40 for typical gaps that occur within the crust. The figures that we have obtained do not differ greatly from those presented by McCamy et al (1962) for mantle/crust contrasts. The maximum coefficients appear at a value of 60° from the angle of incidence and gradually fall to both sides of the highest value.

A more quantitative verification of the type of conversion represented by Sc is shown in Figure 9 where we have plotted the calculated values of Sc-S, S-P and Sc-P as a function of the epicentral distance for the VALLE-2 model. The calculation was made using basic ray theory. The values calculated approximately replicate the observations in Figures 5a and 6.

The type of gap where the conversion takes place must still be established. We recall that Sc-P represents the approximate value of S-P in the upper layer, where the ray travels almost vertically. If we take the value Sc-P = 2.3 sec from Figure 6, then P-0 is equal to 3.2 sec for a Poisson module equal to 0.25. If the gap responsible for the conversion is at the base of the consolidated sediments, we can use a maximum value of 5 km of related thickness (Kovach et al., 1962; Peña et al., 1979; Fuis et al., 1979). For a vertical run time equal to 3.2 sec, we obtain a mean velocity for P of 1.6 km/sec, a value which is not realistic. We reject the possibility of changing the Poisson module, since it would imply very high values for the module, far beyond the actual geophysical conditions. Such considerations lead us to postulate that the conversion takes place in a deeper interphase.

In summary, we believe that there is firm evidence for interpreting the phase as P-wave converted into an S-wave in a gap deeper than that at the base of the consolidated sediments.

5. INVERSION AND DISCUSSION OF RESULTS

The quantitative data that we use in inversion belong to the NORTH set of observations, which consist of: a) a value of Sc-P = 2.3 (0.3) sec (Figure 6); b) a linear increase of Sc-S with epicentral distance until a value of -5.0 sec is reached at 50 km of distance (Figure 5a); and c) constrictions due to the extreme velocity values that P-waves may reach. In our numerical experiments, we decided not to vary the standard value of 0.25 for the Poisson module for two reasons. In the first place, the Waditi diagrams observed suggest 0.24 - 0.25 for this elastic coefficient. Although these values depend on the value included in the computation of hypocenters, we believe that are stable because of the range of distances for which we have observations. In the second place, we take into account the influence of this module on the numerical values that we wish to invert. Since this influence takes place through the VP/VS-1 factor, we need large variations in the coefficient in order to obtain significant changes in the dependence of Sc-S and Sc-P on epicentral distance.

We have conducted dozens of numerical experiments to find models that adapt to the requirements already mentioned. Here two factors should be stressed: a) the S-wave arrival times have <u>not</u> been included in the determination of hypocenters and b) our basic data are <u>differences</u> in arrival times and, therefore, do <u>not</u> depend on the locations we have determined for the focal centers. We also note that Sc-P constrains velocities in the upper layers of the gap, while Sc-S constrains them in the underlying layers. A focal depth of 9.5 km, which is the average value for the NORTH set of data, was chosen for the calculations.

As a result of these experiments, we present the VALLE-2 model, which approximately fits the data. Figure 9 was obtained with this model. The conversion has been placed in the interphase where the P-velocity contrast is 4.6/6.1 km/sec. The position of this interphase at 8.5 km from the surface corresponds to the minimum depth that fits the data. There is a balance between the depth estimates of this gap and the mean velocity in the layers above it; in particular, an increase in depth corresponds to a decrease in mean velocities.

The NORTH set of data are the only observations that clearly show the converted waves. There is evidence of such waves in the CENTER data (Figure 5b) and VICTORIA data (Figure 5a), while there are practically no observations for distances greater than 25 km in the SOUTH data (Figure 5c). Two factors should be borne in mind in interpreting these data. The first is an observational limitation. The NORTH data are of better quality and more numerous, because the related hypocenters were determined with a greater number of stations and with a better azimuthal distribution of such stations. As we move to the south, this situation deteriorates. As a result of this limitation, we can see that the S arrival residuals for distances less than 25 km show greater dispersion in the SOUTH and VICTORIA data than in the NORTH and CENTER data. This is not the only interpretation, however, since we should consider the possible influence of real regional factors. The SOUTH data, for example, would seem to have low residuals to the north, but to the southeast (azimuth from 90° to 190°) it seems to need lower velocities. The

VICTORIA residuals suggest that the conversion is received chiefly at azimuths between 110° and 200°, but the dispersion of the points prevents us from drawing definite conclusions. The NORTH data show points with a second negative tendency that arrive at approximately -1.2 sec at some 65 km. This may be due to a combination of the following factors: conversion at a shallower depth, greater mean velocity of the S-wave, or a lower value for the Poisson module, which could reach 0.20 in an extreme case. A similar situation appears in the CENTER data.

We can attempt to interpret the proposed model geophysically. The contrast responsible for the conversion indicates that there is basaltic material in the lower layer and granitic material, subject to transformations, in the upper layer. We believe that these transformations are those associated with the formation process of a spreading zone within the continent (Elder et al., 1972). In this process, the crust becomes thinner, is heated, rises and is subject to tensional stresses in a zone that is filled with sediments on a base subject to normal faults, fracturing, heating and metamorphism. We suggest that this highly fractured thin granite rock forms the third rock of the VALLE-2 model. This rock would have a velocity lower than the original, that is, lower than the velocity of the purely continental crust. Toward the sides of the basin and underneath the layer that is subject to fracturing, there may be another thin granite layer which would gradually grow thicker until it crops out in the ranges that surround the Mexicali-Imperial Valley.

Although the VALLE-2 model is composed of layers, the numerical values suggest a continous variation in velocities from the surface to the interphase that produces the conversion, where there must be a contrast in the properties of the environment. Our experiments also suggest a slow increase in velocities in the material underlying the gap. We have too little resolution to observe the properties of the materials at depths greater than 10-13 km; however, the nonexistence of seismicity for depths greater than 14 km (Figure 2) indicates a major change in the properties of the materials in these regions. Our model of the deepest part of the crust is based approximately on the model of Fuis et al. (1979).

6. CONCLUSIONS

For local earthquakes, the stations located in the Mexicali-Imperial Valley record an Sc phase that appears between the arrival times of P and S. The differences in Sc arrival times with the differences in the first arrivals of P and S enable us to interpret it as P-wave converted into an S-wave in an interphase situated at a depth of some 8-9 km. These differences limit modeling in both the upper layers and deep layers between the gap and the seismic focal centers. As a result of trial and error inversion, we have obtained the VALLE-2 model, with velocity values in the upper layers that are significantly lower than those presented by Fuis et al. (1979). These authors obtained their results on the basis of refraction measurements. The model fits the S-wave arrival times for distances less than 25 km and for hypocenter determinations made only with P arrivals. At epicentral distances greater than 25 km, regional variations may be observed. We interpret the proposed gap as the separation between the basalt and granite that has been strongly modified by the formation of the graben in the Mexicali-Imperial Valley. Figure 2 indicates that the earthquakes in this region occur in the lower part of the fractured granite layer and, basically, in the relatively homogeneous basalt layer that lies immediately below it. We believe that the influence of high tempertures at greater depths prevents the generation of earthquakes. We also prevent a schematic distribution of the P-wave arrival-time residuals of the stations. This distribution also indicates that our model is suitable for describing the structure of the Mexicali-Imperial Valley. We also point out that our model presents similarities to the model presented by Biehler et al. (1964), which was obtained on the basis of refraction and gravity anomaly measurements.

These conclusions are important in at least three areas of geophysical research in the region. The converted wave arrival, which may be intepreted as a pure S-wave, may produce systematic errors in the calculation of seismic source spectrums and in the determination of attenuation, particularly for distances less than 25 km. Within this same range of distances, there may be problems in the interpretation of Wadati diagrams. Finally, the influence of the layers with velocities different from those of commonly-used models may produce systematic errors in estimating the depth of focal centers. Confusion created by the conversion of waves at the base of the crust have already been pointed out by Kanasewich et al. (1973).

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FIGURE TITLES

Figure 1. Schematic map showing the region of the study.

Figure 2. Distribution of aftershocks (edited data) projected onto a vertical plain in the direction of the Imperial and Cerro Prieto Faults. The origin is found approximately at the northwestern end of the Imperial Fault. The position of the main earthquakes of both aftershocks, indicated with diamonds, is taken from references cited in the text. The figure defines four sets of data.

Figure 3. Map of the region showing the places where positive residuals ($r>0.15$ sec), negative residuals ($r<-0.15$ sec) and approximately null residuals are recorded for P-wave arrival times. The limits are tentative, especially where the density of stations is low. The sign of the related correction has been used to distinguish the zones.

Figure 4. Path-time curves for the first arrivals of P and S-waves; the curves for two waves converted in the gap between the third and fourth layer of the VALLE-2 structure are also shown. The depth of the focus is 9.5 km. The arrows indicate the type of conversion.

Figure 5. Distribution of S-wave residuals by azimuth and distance for the four sets of data. The S-wave arrival times were not used in determining the hypocenters.

a) NORTH data
b) CENTER data
c) SOUTH data
d) VICTORIA data

Figure 6. Waditi diagram for the earthquakes located in the NORTH region. The P-wave time origin is taken from hypocentral determinations.

Figure 7. Seismograms observed showing the converted wave.

Figure 8. Synthetic seismograms (Apsel-Luco) showing the converted wave for the VALLE-2 model. The focal mechanism is a model of a transform fault; the azimuth of the station is 22.5 in relation to the trace line of the fault.

a) Three components at an epicentral distance of 65 km.

b) Vertical component at epicentral distances of 15, 25 and 65 km.

Figure 9. a) Wadati diagram using ray theory. The model used is VALLE-2.

b) S-residuals calculated using ray theory. The model used is VALLE-2.

T A B L A 1

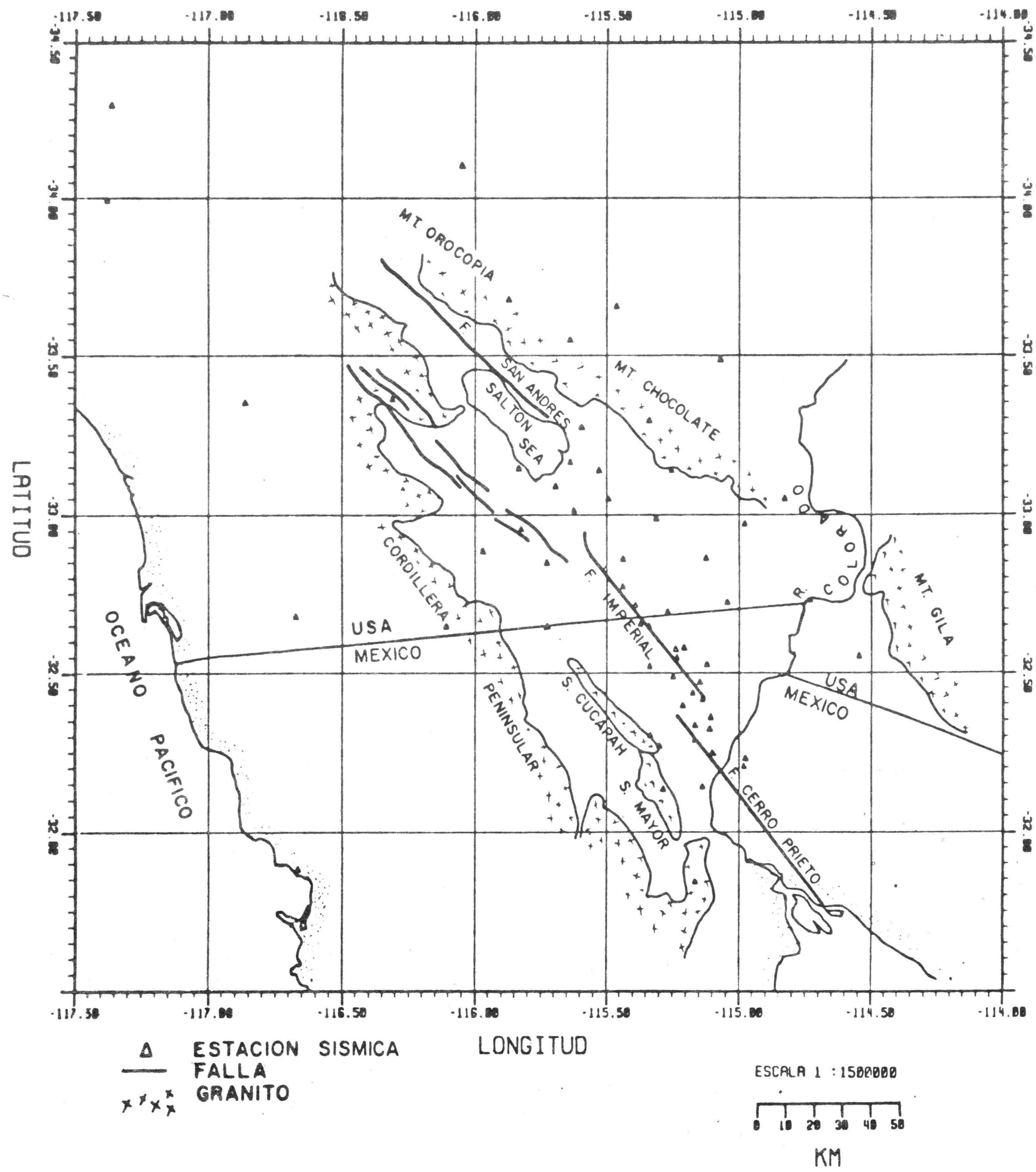
Estructuras usadas en este estudio
Structures used in this study

VALLE-1

Espesor Km	VP Km/seg	VS Km/seg	QP	QS	Densidad gr/cm^3
2.0	2.2	1.270	135	60	2.2
3.0	3.9	2.252	225	100	2.4
1.0	5.3	3.060	450	200	2.6
6.0	5.9	3.406	450	200	2.7
1.0	6.8	3.926	337.5	150	3.0
7.0	7.2	4.157	225	100	3.1
00	7.8	4.503	225	100	3.3

VALLE-2

Espesor Km	VP Km/seg	VS Km/seg	QP	QS	Densidad gr/cm^3
2.0	2.0	1.155	135	60	2.3
3.0	3.4	1.963	225	100	2.4
3.5	4.6	2.656	450	200	2.6
5.0	6.1	3.522	450	150	2.7
1.0	6.8	3.926	337.5	150	3.0
3.0	7.2	4.157	337.5	150	3.1
2.5	7.5	4.330	225	100	3.2
00	7.8	4.503	225	100	3.3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LATITUD
LONGITUD
MT OROCOPIA
F. SAN ANDRES
SALTON SEA
MT. CHOCOLATE
R. COLORADO
MT. GILA
CORDILLERA
PENINSULAR
USA
MEXICO
USA
MEXICO
F. IMPERIAL
S. CUCAPAH
S. MAYOR
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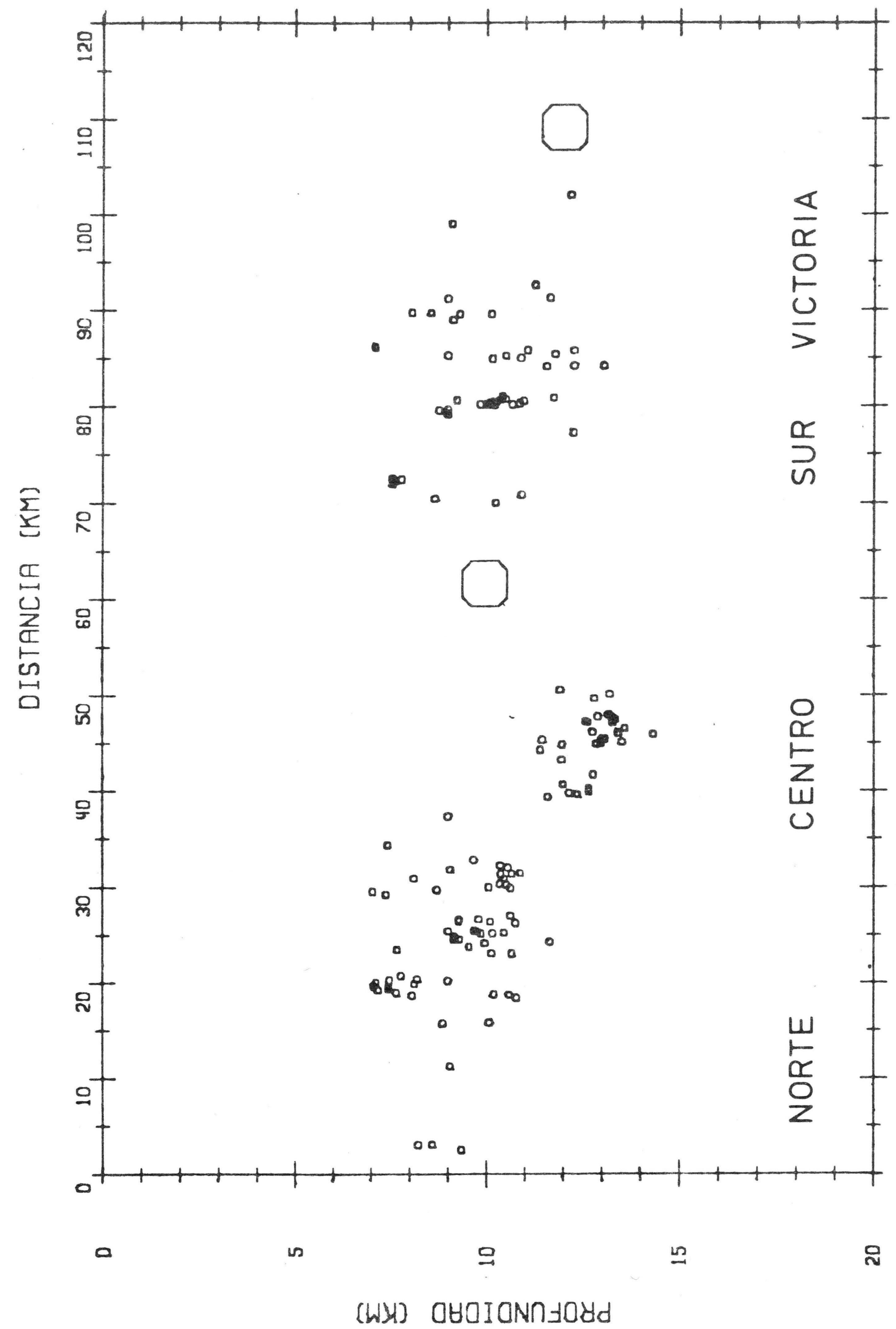
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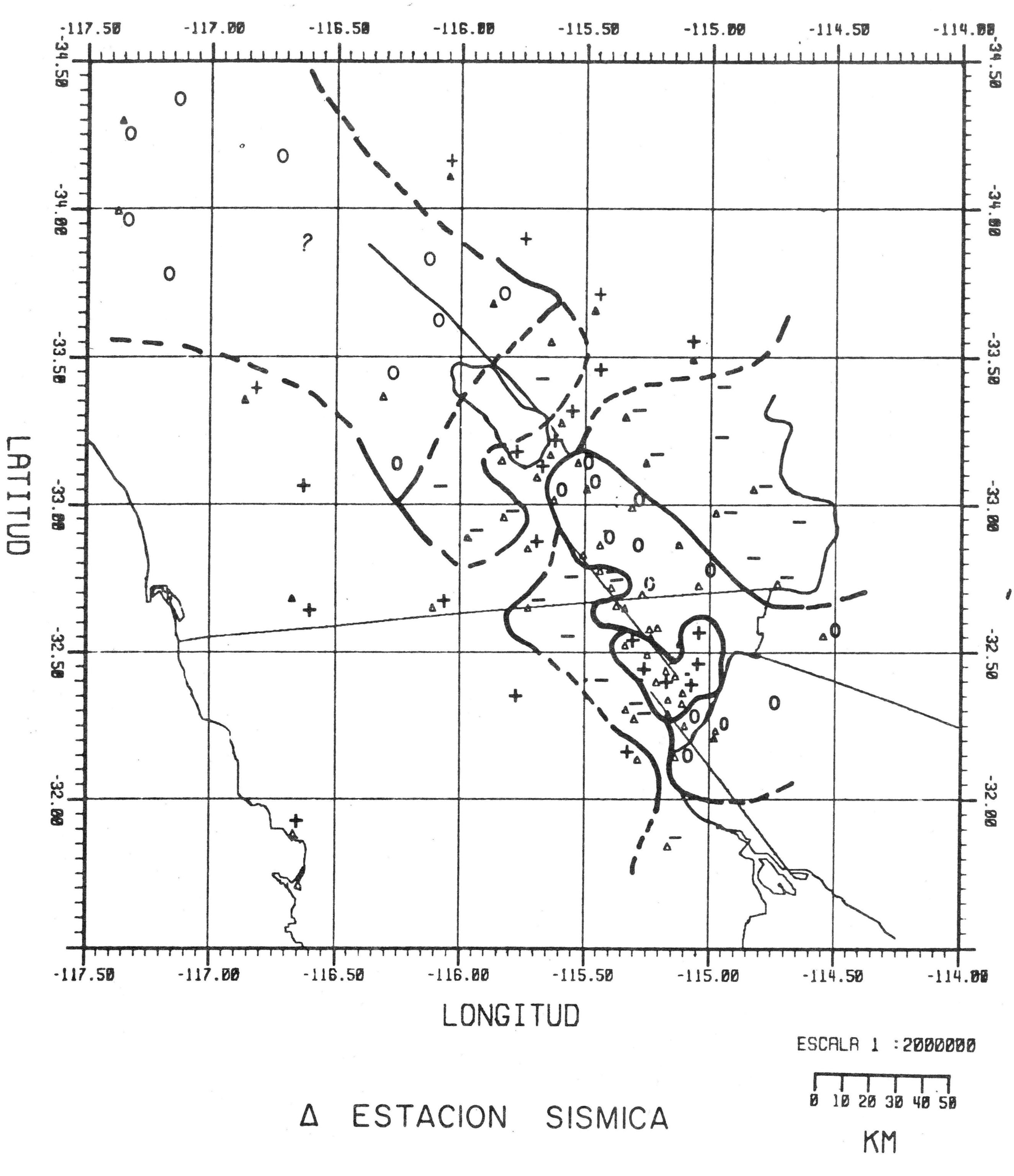

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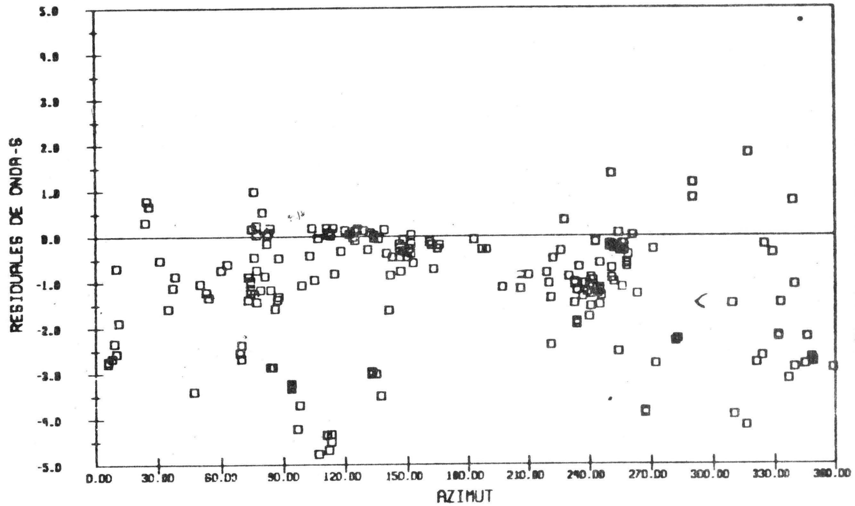

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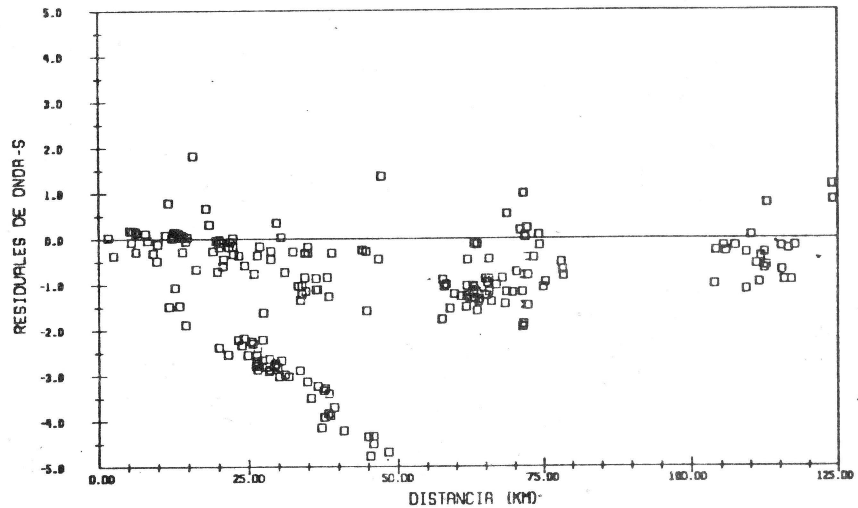

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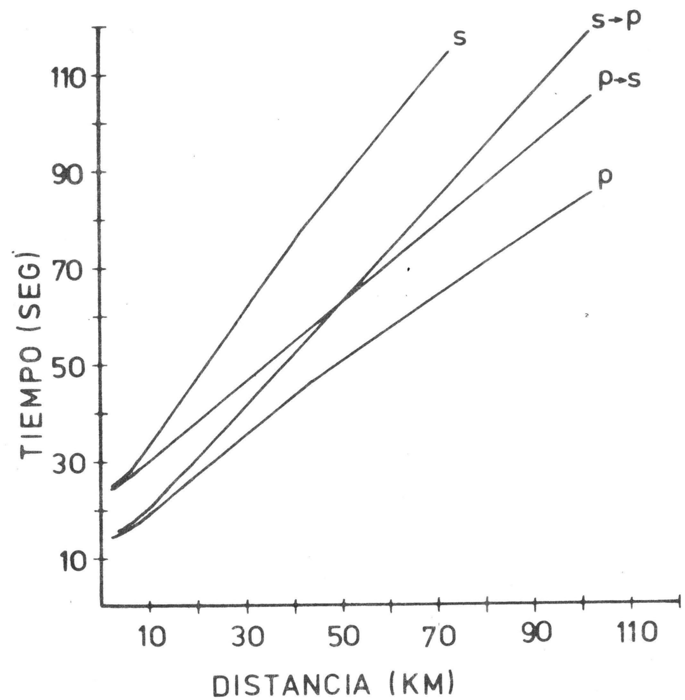

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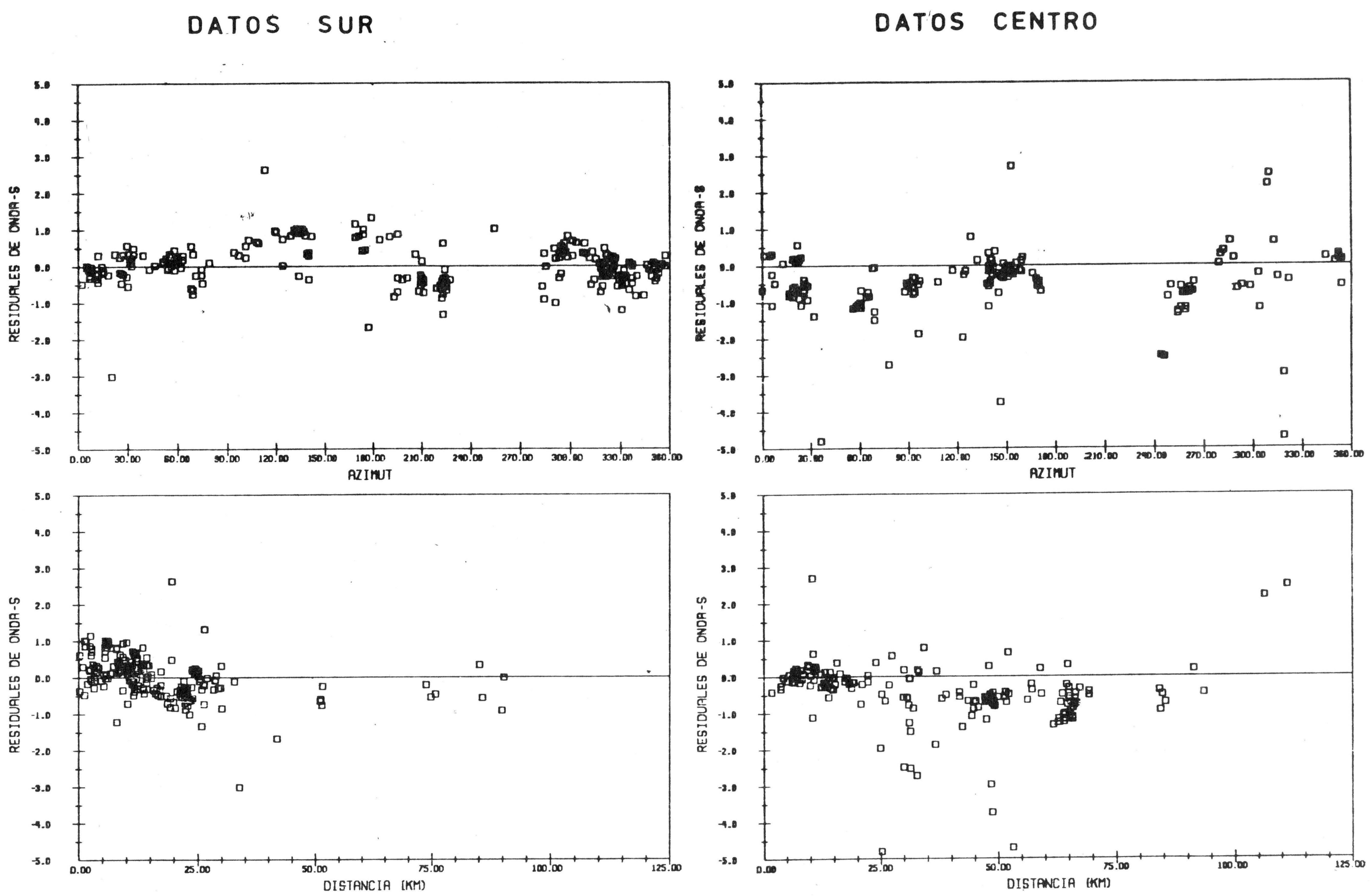
s→p
p→s
p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-5.0
0.00
30.00
60.00
90.00
120.00
150.00
180.00
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100.00
125.00

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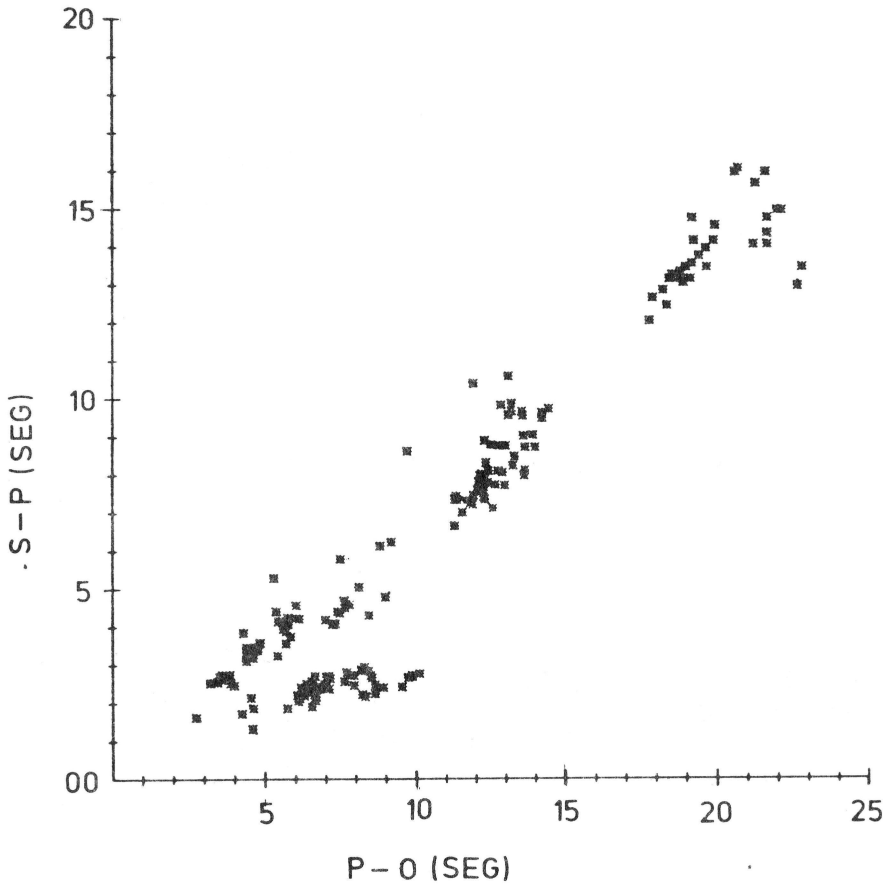

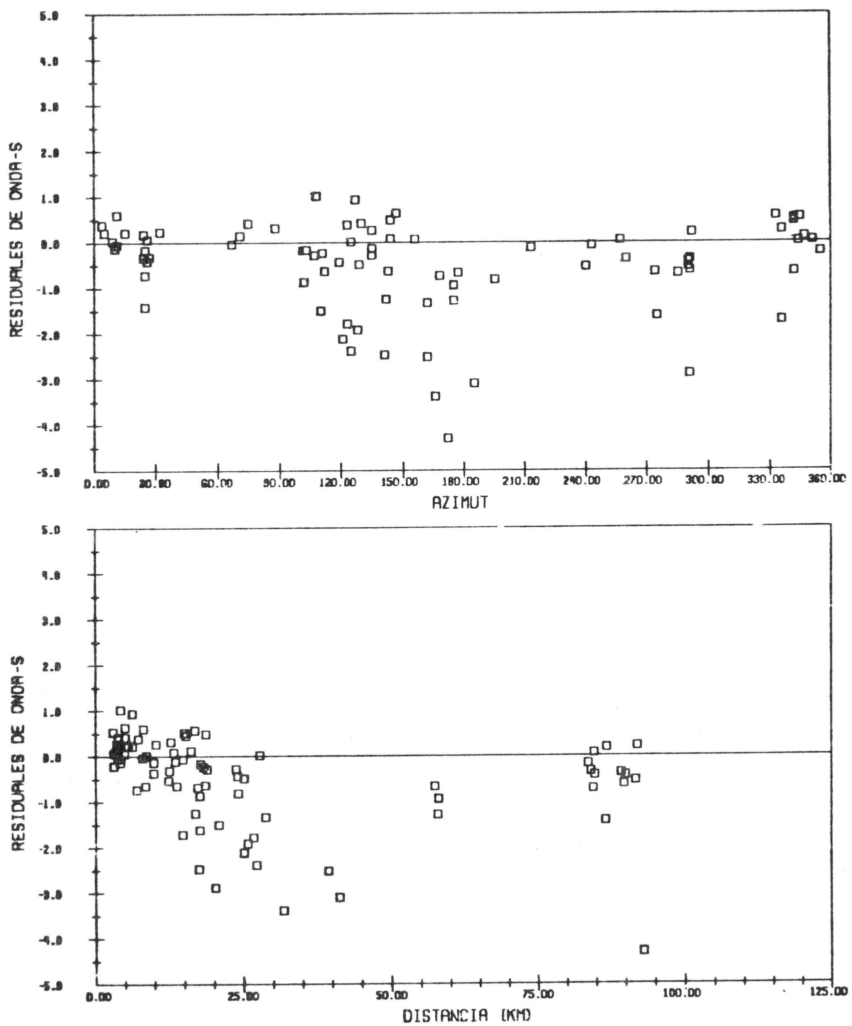

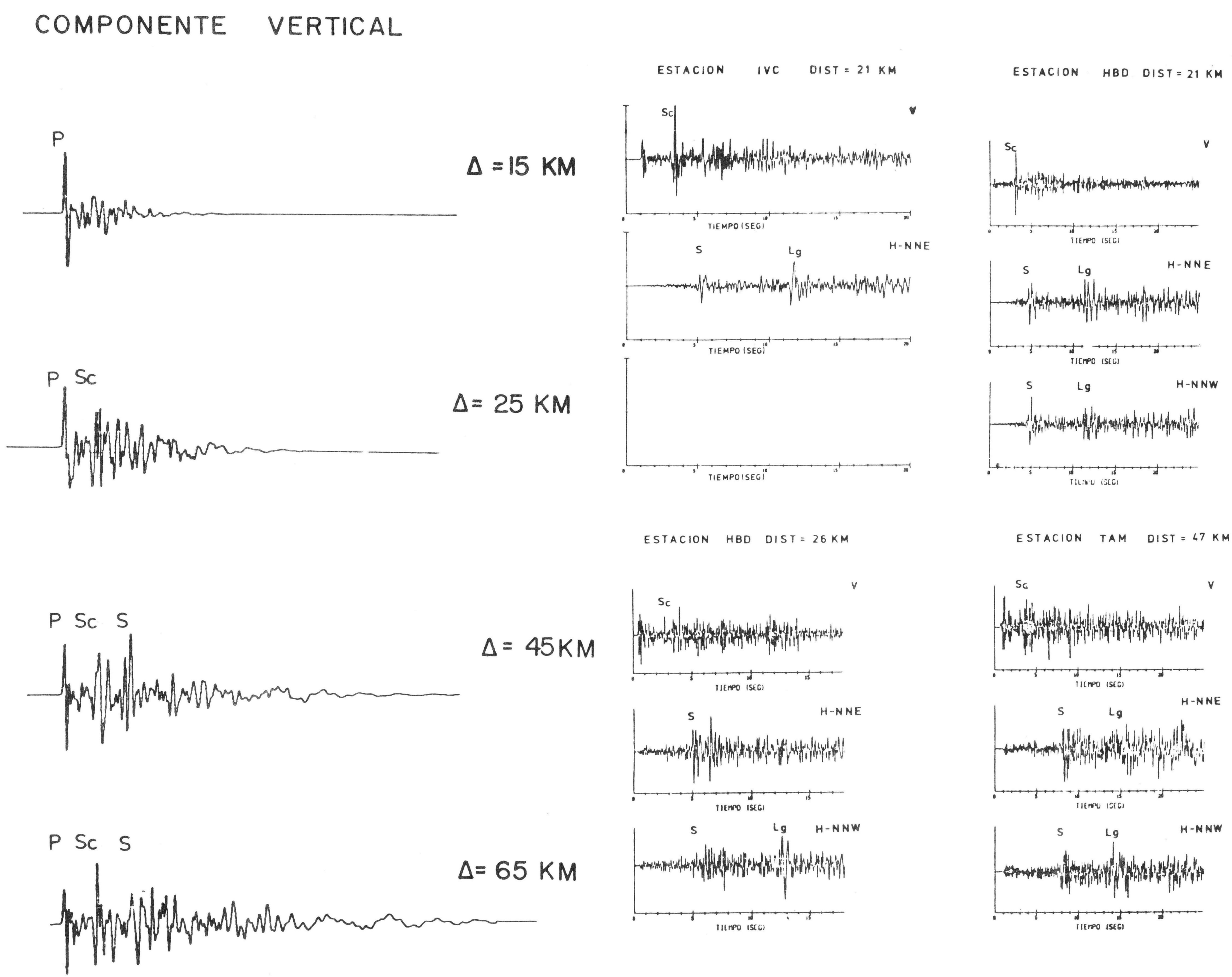
COMPONENTE VERTICAL
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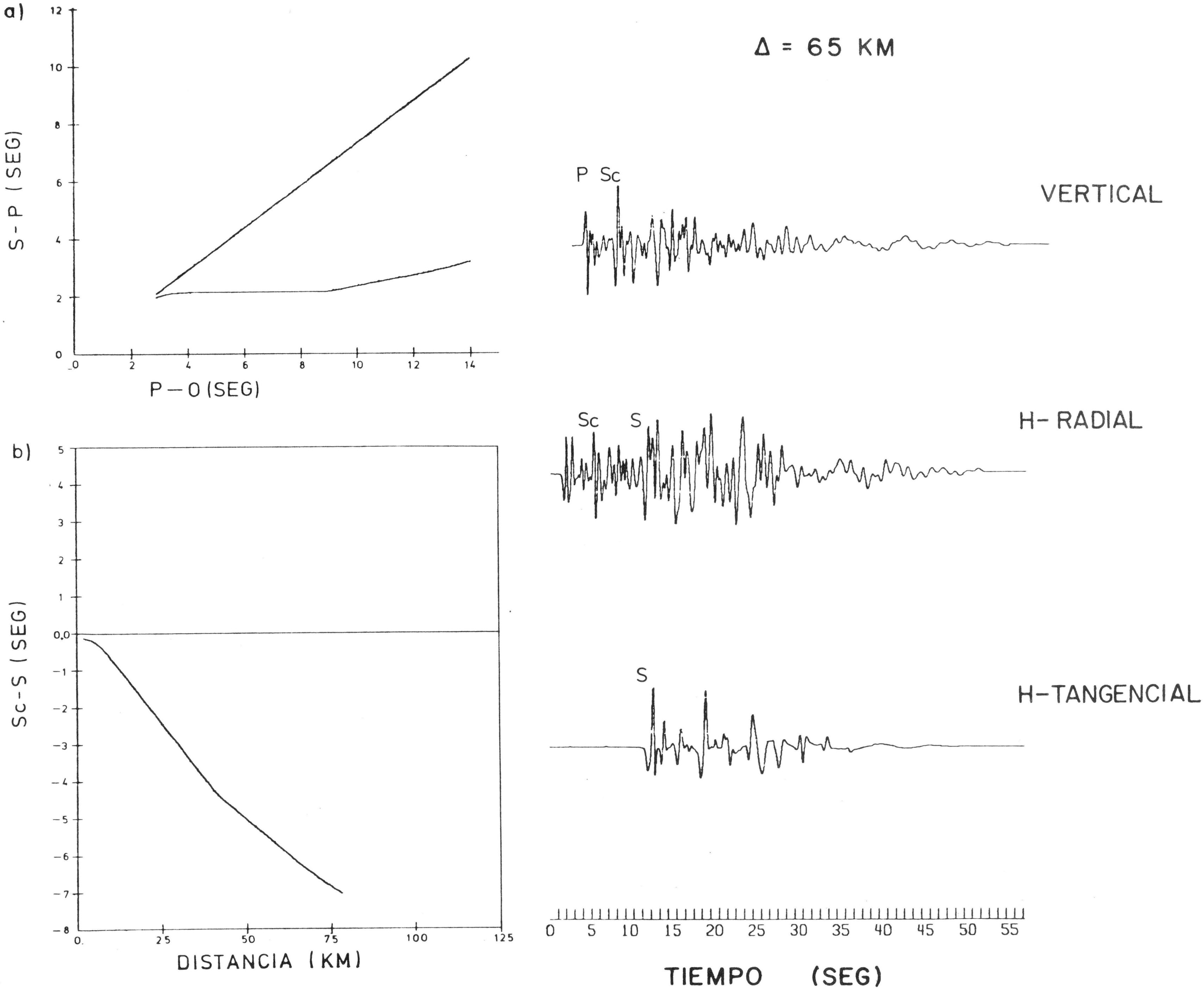
H-NNW
TIEMPO (SEG)


a)
S-P (SEG)
P — O (SEG)
b)
Sc-S (SEG)
DISTANCIA (KM)
Δ = 65 KM
P Sc
VERTICAL
Sc S
H- RADIAL
S
H-TANGENCIAL
TIEMPO (SEG)