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The Thickness of the Earth's Crust obtained from the Spectrum of P Waves at Charters Towers, Honiara, Port Moresby and Rabaul

by

D. Denham

RECORD 1971/97

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SUMMARY

The ground motion resulting from an earthquake recorded at the Earth's surface can be considered to be the result of the incident seismic energy, the elastic properties of the Earth's crust beneath the recording station, and the response characteristics of the recording instruments. Using a matched three-component station it is possible to eliminate the response of the instruments by dividing the spectrum of the vertical component $TW(\omega)$ of motion by the spectrum of the horizontal component $TU(\omega)$. The result is a single ratio, which depends on the angle of incidence of the ray and the system of layers beneath the recording station.

By using some simplifying assumptions about the crustal structure beneath the recording station, the ratios obtained can be compared with master curves, and estimates of the crustal structure beneath the station can be obtained.

In this study, large deep earthquakes recorded by the long-period instruments of the Worldwide Standard Seismograph systems at Charters Towers, Honiara, Port Moresby, and Rabaul were analysed. The results suggested depths to the top of the mantle of about 35 km at Charters Towers, 20 km at Honiara, and 30 km at Port Moresby. At Rabaul a three-layer case is indicated with discontinuties at 14 km and 52 km.

1. INTRODUCTION

As a first approximation, the crust of the Earth and upper mantle may be considered as a system of horizontal layers. When the system is excited by seismic energy, its frequency response can be expressed as a function of the elastic parameters and thicknesses of the layers.

Haskell (1953 & 1962), using a method introduced by Thomson (1950), developed a procedure for calculating the motion at a free surface when plane P waves are incident at any given angle at the base of a horizontally layered system. This method was applied by Phinney (1964) and Hannon (1964), who both studied the spectral behaviour of long-period body waves incident on particular crustal models.

Fernandez (1965, 1967 & 1968) developed a set of curves for the transfer functions of the vertical and horizontal components of longitudinal waves. From these he developed a set of theoretical master curves in terms of the tangent of the apparent angle of emergence and a dimensionless parameter depending on frequency, P wave velocity, and layer thickness.

By comparing these master curves of Fernandez with the results obtained from selected seismograms recorded at Charters Towers (CTA), Honiara (HNR), Port Moresby (PMG), and Tabaul (RAB) an estimate of the crustal structure was made at each of these stations. At the time this work was carried out, no crustal explosion work had been completed near any of these sites and this represented a first estimate of the crustal structure near each recording station.

The details of development of the method used can be found in the references given above, but for completeness a brief outline of the procedures involved will now be described. Using the notation of Haskell, the transfer functions for the horizontal and vertical components of ground motion at a given frequency (ω) are respectively:

$$TU(\omega) = 2c\,(J_{42} - J_{32})/\alpha_n D \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (1)$$

$$TW(\omega) = 2c\,(J_{41} - J_{31})/\alpha_n D \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

where c is the apparent surface velocity; α_n is the P wave velocity in the half-space underlying the (n - 1)-layer system; D is given by:

$$D = (J_{11} - J_{21})\,(J_{32} - J_{42}) - (J_{12} - J_{22})\,(J_{31} - J_{41}) \; . \; . \; . \; (3)$$

and the J_{ij}'s are the elements of the matrix product obtained in solving the boundary value problem of the layered system. The matrix J is given by:

$$J = E_n^{-1} \, a_{n-1} \, a_{n-2} \; . \; . \; . \; a_1 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (4)$$

where each element or submatrix a_m depends on the parameters (thickness, density, rigidity, and velocities) of only the m th layer. The matrices E_n, D_n, and E_n^{-1} and the elements of the matrix product $a_n = D_n E_n^{-1}$ are given on pages 20 and 21 of Haskell's paper (1953).

To obtain the master curves equation (2) is divided by equation (1) and this ratio is plotted against a dimensionless parameter γ for different angles of incidence. γ is defined as $f.h/\alpha$ where f is frequency, h the layer thickness, and α the P wave velocity in the layer.

The calculations are simplified by making the following assumptions:

(1) The layers are isotropic and horizontally stratified.

(2) Poisson's ratio is equal to 0.25.

(3) The density changes linearly with the P velocity.

A fourth assumption, that the apparent surface velocity is greater than the P velocity in the top layers and that the S velocity shows the same relationship in any layer, is necessary to avoid total internal reflections in the system.

9 The master curves used in this work are one-layer models for different angles of incidence and velocity contrast. The master curves are plotted on logarithmic scales which provides ease of comparison with the observed curves obtained from the seismograms. Fernandez (1965 & 1967) gives the curves in detail. First results of the P wave analysis in the New Guinea/Solomon Islands region have been briefly given by Denham (1968). This report describes the results in more detail and presents plots of the actual observations.

2. APPLICATION OF METHOD

In order to compare the theoretical master curves with the observed curves, it is necessary to calculate the apparent angle of emergence at the recording station for a number of frequencies. This involves the following procedures:

(a) Selection of suitable seismograms

It is necessary to use an earthquake which is large enough to give a good signal-to-noise ratio for the initial P phase on each of the three-component long-period seismographs. In practice this restricts useful events to those having a magnitude greater than 6. Size is not the only criterion, however, and in order to avoid the influence of reflections at the crust near the source, or reflections from the core of the Earth, the earthquake has to be of intermediate or large focal depth and restricted to an epicentral distance of less than 50 degrees. By proper selection of size, depth, and distance it should be possible to obtain at least 60 seconds of usable P wave duration without the influence of unwanted phases.

(b) Digitization of seismograms

Having selected a suitable earthquake, the next step is to digitize the trace prior to the numerical analysis. In all cases the seismograms were obtained from matched long-period Worldwide Standard Seismograph systems with a drum speed of 30 mm/min. This resulted in the big advantage of not having to correct the seismograms for different instrumental frequency responses for each component.

To include the full frequency band of interest, it was decided to sample the seismogram at 0.5-second intervals. This was achieved by accurately enlarging the original record by a factor of 4 and tracing the resulting record onto standard millimetre/millimetre graph paper. In this arrangement 1 mm is equivalent to half a second.

(c) Numerical analysis

Before the digitized data are Fourier analyzed to obtain the transfer functions, they are smoothed and weighted. The smoothing procedure applies a baseline correction,removes any linear trend that could have been introduced in the records by mislocation of the zero line, and applied a linear digital smoothing filter to eliminate high-frequency scaling noise.

The smoothing procedure is followed by a time window operation which 'hams' the data (See Blackman & Tukey, 1958, pp. 14-15). This has the effect of emphasizing the early arrivals in the P wave train.

The final step is a Fourier analysis of the corrected data to calculate the coefficients in the transfer function ratios $TW(\omega)/TU(\omega)$ for each value of (ω). The ratios are then plotted against frequency and compared to the master curves.

(d) Method of comparison

The curve of the tangent of the apparent angle of emergence against frequency is plotted on log/log tracing paper on the same scale as that of the master curves. From the available hypocentral data a rough estimate is made of the angle of incidence of the ray at the surface of the Earth. This step is not critical but assists in selecting the correct set of master curves.

In the matching procedure, the observed curve is laid over the theoretical curve with the vertical and horizontal axes kept parallel. The observed curve is then moved until the best visual match between the two curves is obtained. No rotational movements are allowed and the axes must always be kept parallel.

When the curves are in the best matching position a value of the velocity contrast between the two layers is obtained - if necessary, by interpolating between the members of the families of the matched curves. The velocity contrasts are usually plotted in 0.1 increments from 0.7 to 1.0. Unless otherwise stated a velocity of 8.0 km/sec in the upper mantle (α_2) was assumed to calculate the velocity in the upper layer (α_1).

The next step is to read the value of γ (the dimensionless parameter) corresponding to the 0.1 Hz value. Then we have by definition:

$$\gamma = 0.1 \times h_1/\alpha_1 \quad \ldots\ldots\ldots\ldots (5)$$

and the thickness of the crust will be:

$$h_1 = 10 \times \gamma \times \alpha_1 \quad \ldots\ldots\ldots\ldots (6)$$

An example of the method presented in Plate 2 illustrates the results of analysing the recordings of the large December 1964 Fiji earthquake recorded at Charters Towers. The continuous line connecting the round dots represents the observed apparent angle of emergence as obtained from the seismograms. The dots are the actual measured values. The dashed curves represent two master curves for the case of a 25 degree angle of incidence and velocity contrasts of 0.8 and 0.9 between the two layers.

The observed curve was matched visually to provide the best fit with the master curves, ensuring that the axes remained parallel. The frequency response of the seismographs used is at a maximum between 0.02 and 0.1 Hz so this part of the curve is usually the most reliable, and particular attention was made to this section in the matching procedure.

For the case shown in Plate 2 approximately 75 percent of the trace energy was contained in the 0.02-0.1 Hz pass band. Above this range the amplitudes rapidly decrease and the range 0.16 to 0.51 Hz contains only 10 percent of the total trace energy. For this earthquake a value of $\gamma = 0.53$ on the master curves corresponds to a value of 0.1 on the observed curve. Using a velocity contrast of 0.8 and a velocity of 8.0 km/sec for the lower half-space, the depth to the base of the top layer is given by equation (6) as:

$$h_1 = 10 \times 0.53 \times 0.8 \times 8.0 = 34 \text{ km}$$

and the average P wave velocity for the top layer is 6.4 km/sec.

The errors involved in these values are difficult to assess quantitatively. For the example illustrated in Plate 2 the value 0.53 can probably be estimated to ± 0.01, and the velocity contrast to ± 0.05. Using these error values and an upper mantle velocity uncertainty of ± 0.2 km/sec, a value of ± 2 km is obtained for the error associated with the depth term.

3. RESULTS

Eleven sets of seismograms were analysed. These involved the examination of the results of six large earthquakes that occurred in the region of interest during 1963-1965. The record copies for the analysis were obtained from the USCGS data centre and enlarged photographically. Plate 1 shows the locations of the epicentres, the recording stations, and the schematic travel paths.

All the earthquakes analysed had long incident P wave trains, because the focal depths were all greater than 500 km. Table 1 lists the hypocentral details used for each earthquake examined. It was not possible to analyse all the earthquakes at all the stations owing either to malfunctions of one or more components at the time of the earthquake or to the signal-to-noise ratios being too low for reliable digitization.

The results obtained at each station will now be examined in an effort to match the observations with the plots of the master curves. On each diagram the continuous lines, whether axes or curves, refer to the observed results and the dashed lines refer to the master curves.

Charters Towers (CTA)

The results illustrated in Plate 2 have already been described previously. The best fit for a one-layer case gives a depth to the upper mantle of 34 km and an average P wave velocity of 6.4 km/sec in the upper layer. The fit between the master curves and the observed data is considered to be good and the match of the twin peaks between 0.1 and 0.2 Hz is very good.

Finlayson (1968) in his analysis of data from the Carpentaria region upper mantle project obtained by time-term analysis a three-layer model with a depth to the upper mantle of about 45 km. The intermediate upper layers had thicknesses of 21 and 24 km and velocities of 5.9 and 6.6 km/sec respectively. These results were based on unreversed profiles and contain all the uncertainties associated with this type of situation. If a horizontally layered crust is assumed, the refraction work gives thicknesses of 12 and 22 km by using the same velocities as those outlined previously.

It would appear from the refraction data that 34 km is a lower estimate of the depth to the top of the upper mantle. Final assessment of the crustal parameters will have to await further explosion work and the use of reversed profiles.

Plate 3 shows the results of the Flores Sea earthquake recorded at Charters Towers. The theoretical curves for the one-layer case with velocity contrasts of 0.7 and 0.8 and an angle of incidence of 25 degrees are plotted as comparisons with the observed results.

The fit between the theoretical curves and the observed results is poor, although the peaks at 0.05 and 0.17 Hz agree reasonably well with the master curves. Using a velocity contrast of 0.8 and a γ value of 0.59, a depth to the top of the upper mantle of 38 km is obtained. The fit is not as good as those shown in Plate 2, but the crustal thickness given by the results is roughly similar.

Honiara (HNR)

Three earthquakes recorded at Honiara were examined. Two were located in the Fiji region and one to the east of New Ireland. The results are shown in Plates 4, 5, and 6.

Plate 4 shows the August 1963 earthquake. The observed curve consists of a single noisy hump peaking at about 0.1 Hz. It is difficult to find any master curve that matches these results. The best fit is obtained by using the curves for a 40 degree angle of incidence and with a velocity contrast of 0.7; γ is then given as 0.36 and the depth to the upper mantle is 20 km. With a contrast of 0.8 the depth would be 23 km.

The December 1964 earthquake gives a curve of similar shape for the observed angle of emergence. The fit with the master curve shown in Plate 5 is poor, but is a slightly better match than that shown in Plate 4. The peaks at 0.2 and 0.3 Hz have been used to fix the position of the curves. With a velocity contrast of 0.8 and a γ value of 0.30 a depth to the upper mantle of 19 km is obtained. This is similar to the value obtained in the previous example.

Plate 6 shows the results of the July 1965 shock. As can be seen, no fit was obtainable.

The crustal structure at Honiara is probably very complicated and the assumption that horizontal isotropic layers are present under the station probably does not hold. The work carried out by the Hawaiian Institute of Geophysics (Rose, Woollard & Malahoff, 1968) based on gravity and magnetic data suggested depths to the mantle of between 17 and 23 km in the Guadalcanal region. The results shown here in Plates 4 and 5 are in accordance with those observations.

Port Moresby (PMG)

The quality of fit for the two earthquakes recorded at Port Moresby is good. Plates 7 and 8 show the observed angles of emergence and the master curves used for comparison.

Plate 7 illustrates the results from the Fiji earthquake that occurred in August 1963. The master curves for a 30 degree angle of incidence are plotted and the peaks on the observed curve at 0.14, 0.19, and 0.32 Hz agree very well with the master curves. This match gives a γ value of 0.45 and a velocity contrast of 0.8. With these parameters a crustal thickness of 29 km is obtained.

The Java Sea earthquake gave a better match with the master curves, and good correlations are present throughout the entire frequency range. The velocity contrast was again assumed to be 0.8 and a γ equal to 0.46 was obtained. The depth to the upper mantle using these values is again 29 km.

The results are considered reliable because the same values are obtained from earthquakes having very different azimuths. They are also in general agreement with Brooks's work (1969) on surface waves in the New Guinea region. He obtained an average structure over a 1500 km path in the southern New Guinea area which gave a depth to the upper mantle of 33 km. He used P wave velocities of 6.1 km for the top layer and 7.9 km/sec for the mantle velocity.

Rabaul (RAB)

Four earthquakes recorded at Rabaul were examined. Three occurred in the Fiji region and the fourth was the Flores Sea event previously mentioned and examined at Charters Towers.

The results of the Flores Sea earthquake are shown in Plate 9. The data agree reasonably well up to about 0.17 Hz, but above this frequency no fit is possible. Using a velocity ratio of 0.85, obtained from visual interpolation between 0.8 and 0.9 curves, and a γ value of 0.6, a depth to the upper mantle of 41 km is obtained. The value is based on the assumption of an upper mantle velocity of 8.0 km/sec. Since this analysis was completed, it has become known from the crustal studies carried out by the Bureau of Mineral Resources in the Rabaul vicinity (Wiebenga, personal communication) that the velocity in the upper layer is about 6.0 km/sec. Using this value for the upper layer, a value of 7.1 km/sec is obtained for the top of the second layer and the depth is reduced correspondingly to 36 km. However, if an intermediate layer were present, this would alter the apparent average velocity of the layer above the mantle and the depth would be increased.

Plate 10 shows the results from the September 1964 earthquake. The fit is poor and the data above 2 Hz are questionable. The fit suggested by matching the lower-frequency parts of the curves is of a velocity contrast of 0.85 and a γ value of 0.5. These parameters lead to depths of 30 or 34 km depending on whether mantle velocities of 7.1 or 8.0 are assumed. In Table 2 the latter value is listed.

Plates 11 and 12 show the results from the August 1963 and December 1964 earthquakes. The remarkable fact about these events is that they give almost identical observed response curves. Two matching positions can be obtained for each curve. Using the high-frequency part of the curves and the master curves for a 25 degree angle of incidence, a velocity contrast of 0.8 and γ values of 0.24 fit well in the 0.2-0.4 Hz range. These parameters, coupled with a first-layer velocity of 6 km/sec, yield depths to the upper mantle of 14 km in both cases and a mantle velocity of 7.5 km/sec.

By matching the low-frequency end of the curves good fits are obtained between 0.02 and 0.2 Hz and in both cases velocity ratios of 0.9 were used. For the 1963 event, using a velocity of 8.0 km/sec for the lower layer and a γ value of 0.72, a depth of 52 km is obtained. The 1964 shock gives a depth of 50 km with a γ value of 0.70 while using the same velocity for the lower layer.

The information from these two earthquakes suggests that a three-layer model would be appropriate in the Rabaul area. The high-frequency part of the curve is controlled by the top layer and the low-frequency section responds to the thicker top two layers. The model indicated has a layer 14 km thick overlying a 7.5 km/sec layer, 36 km thick, which in turn overlies an 8 km/sec layer.

4. DISCUSSION AND CONCLUSIONS

Table 2 lists the preferred solution for each earthquake together with an assessment of the quality of fit. At this stage it is appropriate to discuss the errors involved and to obtain some estimate of the uncertainties of each value.

In the first place, each fit is based on the assumption that the crustal layers in the region beneath the station are isotropic and horizontally stratified. This assumption is usually impossible to verify, and although it may hold in the vicinities of Port Moresby and Charters Towers, it almost certainly will not be valid in the Honiara and Rabaul regions because of their proximity to the ocean and the disturbed situations revealed by the gravity anomalies. Furthermore it is not known how the invalidity of this assumption will affect the observed curves.

Secondly each fit between the theoretical curves and the observed curves is based on a subjective appraisal of the results. The shapes of the theoretical curves are such that a least-squares error analysis is not applicable so it is necessary to make fits by inspection. The error in the depth estimate is therefore a function of the errors associated with the values assigned to γ , the velocity ratio α_1/α_2, and the value of one of the velocities. The first two values are estimated subjectively from the shape of the observed curve, and the third value is usually an intelligent guess based on crustal or mantle velocities obtained from other parts of the world. It is therefore felt appropriate to assess qualitatively the suitability of the fit.

Four categories of fit are used - good, fair, poor, and unobtainable. Only in the examples where the fits are classified as good can the results be relied on. Results classified as fair can probably be used with caution, but the poor results should not be depended on.

In the case of a good fit, a subjective estimate of the error associated with the velocity ratio value is about 6 percent, the error in γ about 2 percent, and the error in the velocity value used for α_1, or α_2 is about 6 percent. These figures give an error of about 9 percent in the final depth estimate. This is therefore a minimum error estimate because of the unknown effects caused by any failure in the assumption that the layers are isotropic and horizontally stratified.

In spite of the high errors associated with the final values, it is felt that the method is useful in areas where no data on crustal structure are available. The Port Moresby results give consistent values for velocity and depth from two earthquakes of very different azimuths. However, most of the Rabaul and Honiara solutions are of poor quality. The similarities between the observed results at Rabaul for earthquakes 1 and 5 are encouraging, but as is shown in Table 2 there is ambiguity in fitting the observed results to the theoretical curves.

In conclusion, it is felt that the method of estimating crustal parameters by analysing the spectra of P waves cannot be used in all localities; this applies particularly in complicated regions of recent tectonic activity. The work by Fernandez (1968) confirms this conclusion. His results obtained using data from St Louis, in continental United States, are much superior to those obtained at La Paz in the high Andes. Further crustal study work in the Rabaul region will be useful in obtaining further evaluation of the method. In the meantime an examination of Mundaring long-period records of large Banda Sea events would prove valuable, since the crustal structure in this vicinity is comparatively well known.

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TABLE 1

EARTHQUAKES STUDIED

No.	Date	Origin Time	Lat°	Long°	Depth(km)	Magnitude (USCGS)	Region
1	Aug. 25, 1963	12 18 12.5	17.5 S	178.8 W	565	6.1	Fiji Islands
2	Dec. 15, 1963	19 34 45.5	4.8 S	108.0 E	650	6.4	Java Sea
3	Sep. 12, 1964	15 19 22.3	17.4 S	179.9 E	561	5.8	Fiji Islands
4	Oct. 18, 1964	12 32 24.9	7.2 S	123.9 E	574	5.8	Flores Sea
5	Dec. 28, 1964	16 16 11.0	22.1 S	179.6 W	611	6.2	Fiji Islands
6	Jul. 6, 1965	18 36 47.3	4.5 S	155.1 W	510	6.5	Bougainville Island

TABLE 2

SUMMARY OF RESULTS FROM EARTHQUAKES ANALYSED

Station	Earthquake No.	Distance Degrees	α_1/α_2	Preferred Model h, km	γ	angle of incidence	Quality of fit
CTA	5	31.9	0.8	34	0.53	25	good
CTA	4	25.2	0.8	38	0.59	25	poor
HNR	1	22.2	0.7	20	0.36	40	poor
HNR	5	22.3	0.8	19	0.30	30	poor
HNR	6	6.9		no fit obtainable			
PMG	1	34.2	0.8	29	0.45	30	fair
PMG	2	39.1	0.8	29	0.46	30	good
RAB	1	31.7	0.8 0.9	14 51	0.24 0.72	 25	fair good *
RAB	3	30.6	0.85	34	0.50	25	poor
RAB	4	28.3	0.85	41	0.60	25	poor
RAB	5	32.6	0.8 0.9	14 52	0.24 0.70	 25	fair good *

* See text for explanation of two solutions

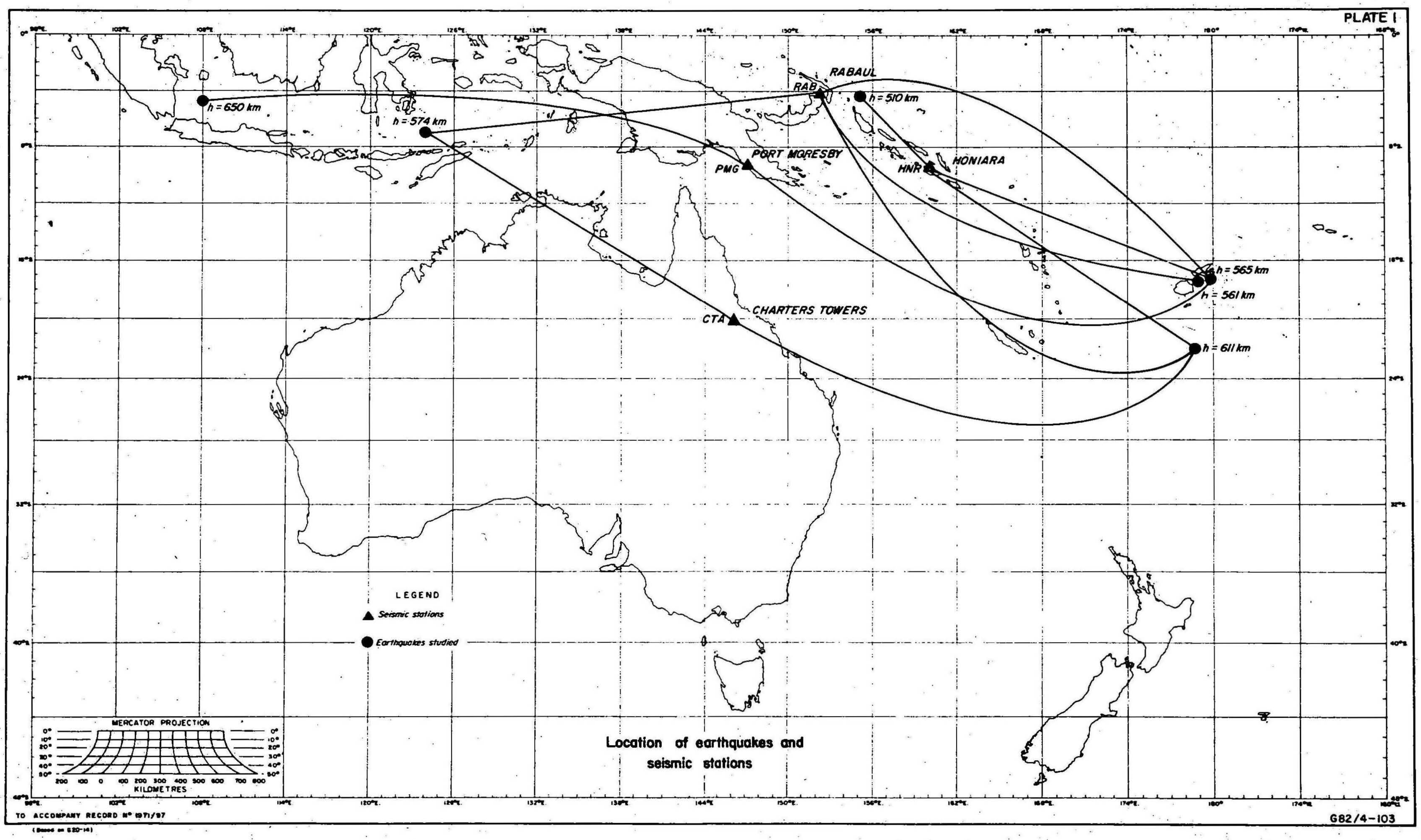
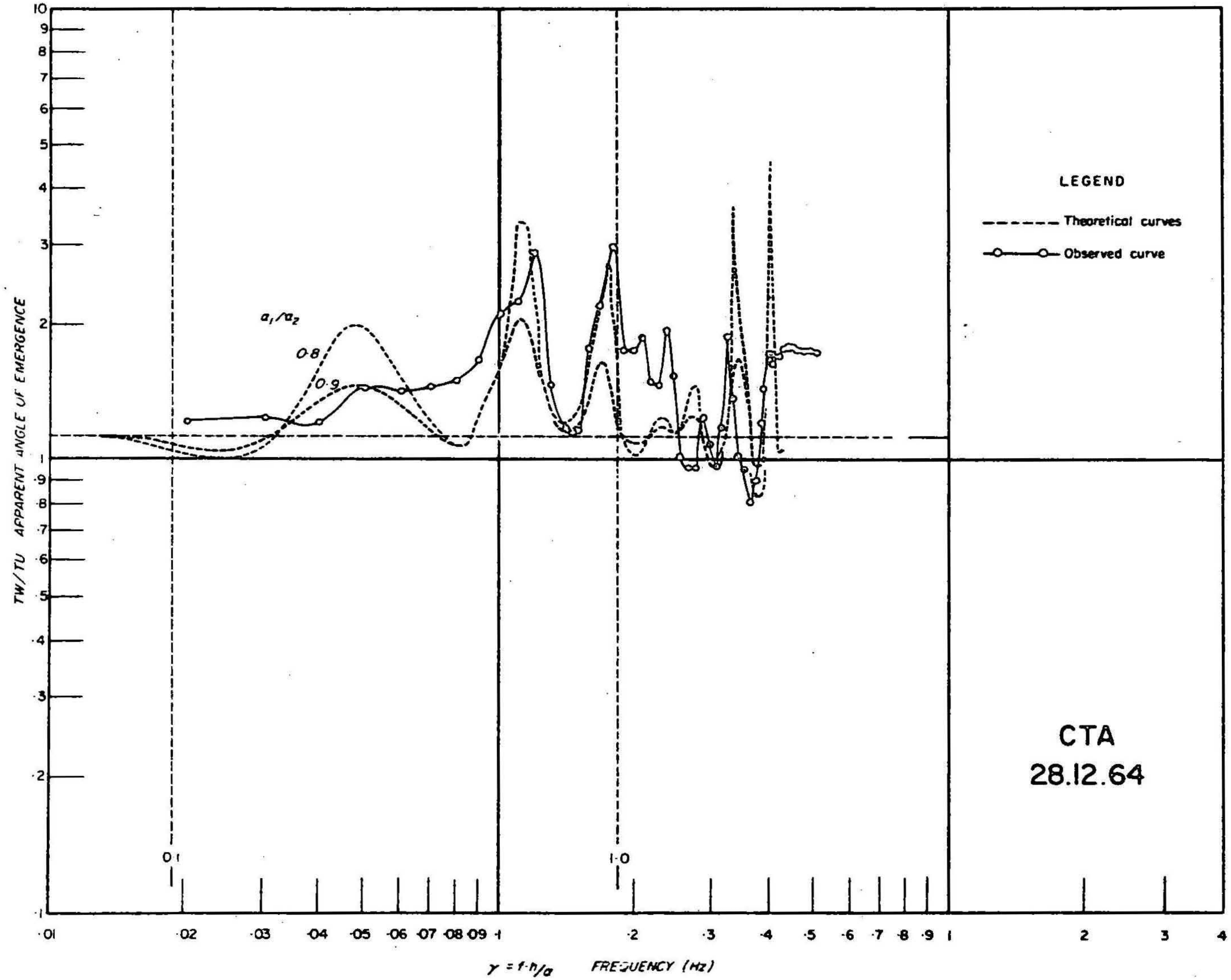


PLATE I
RABAUL
RAB
h = 510 km
h = 650 km
h = 574 km
PORT MORESBY
PMG
HONIARA
HNR
h = 565 km
h = 561 km
CHARTERS TOWERS
CTA
h = 611 km
LEGEND
Seismic stations
Earthquakes studied
MERCATOR PROJECTION
KILOMETRES
Location of earthquakes and seismic stations
TO ACCOMPANY RECORD Nº 1971/97
(Based on G20-14)
G82/4-103

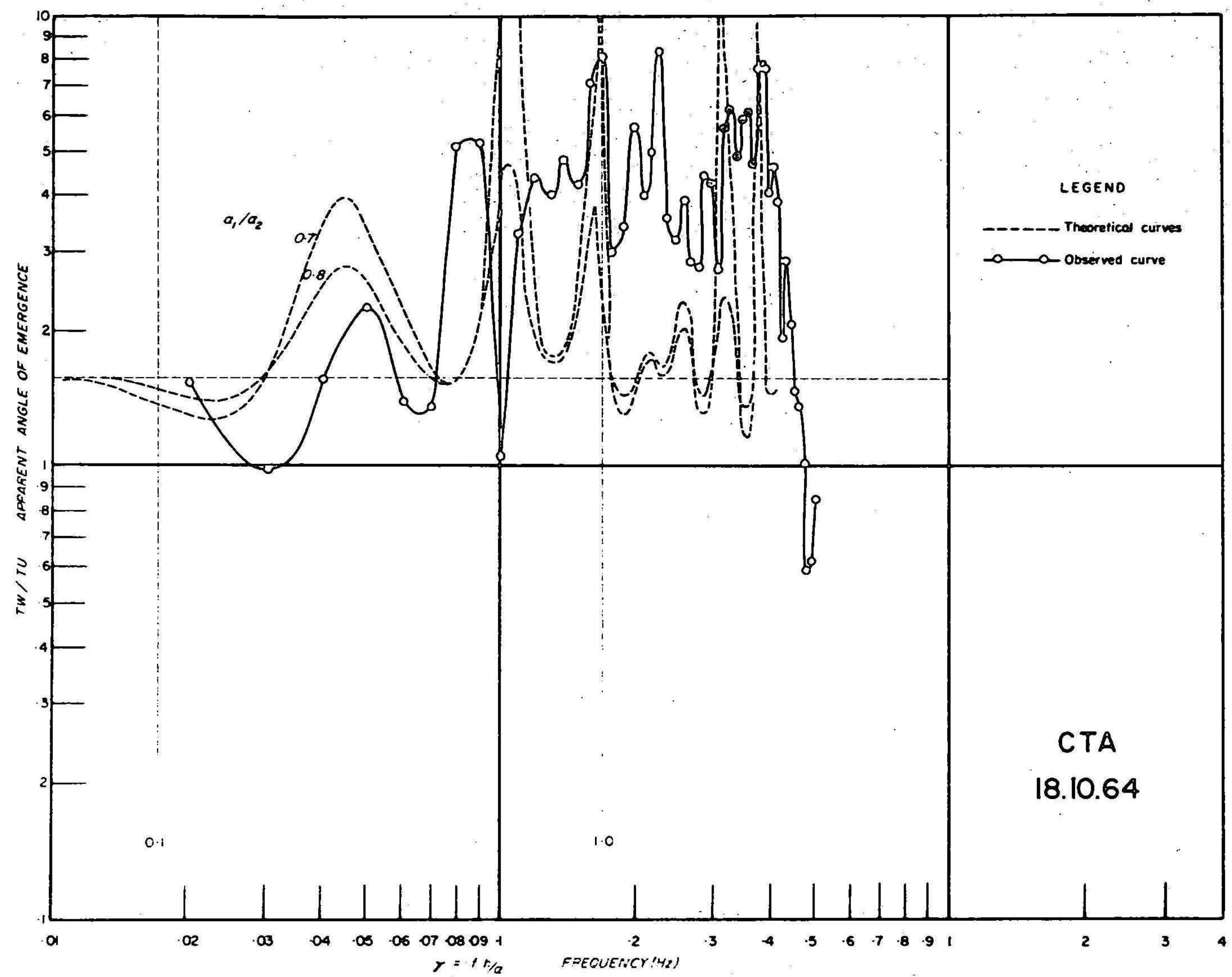


Crustal solution at CHARTERS TOWERS from the
FIJI EARTHQUAKE of December 1964
An example of good fitting

PLATE 2

TO ACCOMPANY RECORD Nº 1971/97

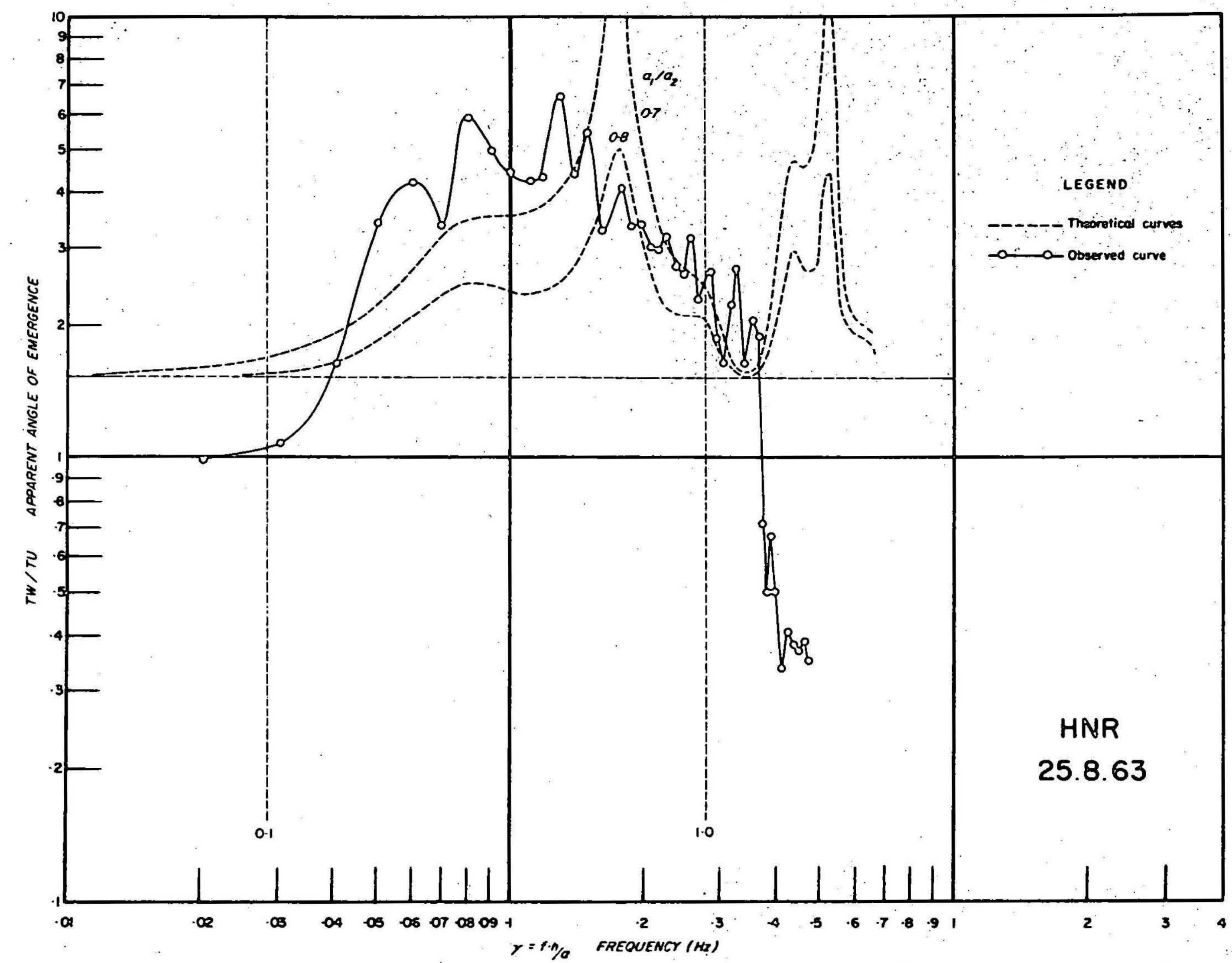
G82/4-113



Crustal solution at Charters Towers from the Flores Sea earthquake of 18 October 1964

An example of poor fitting

PLATE 3

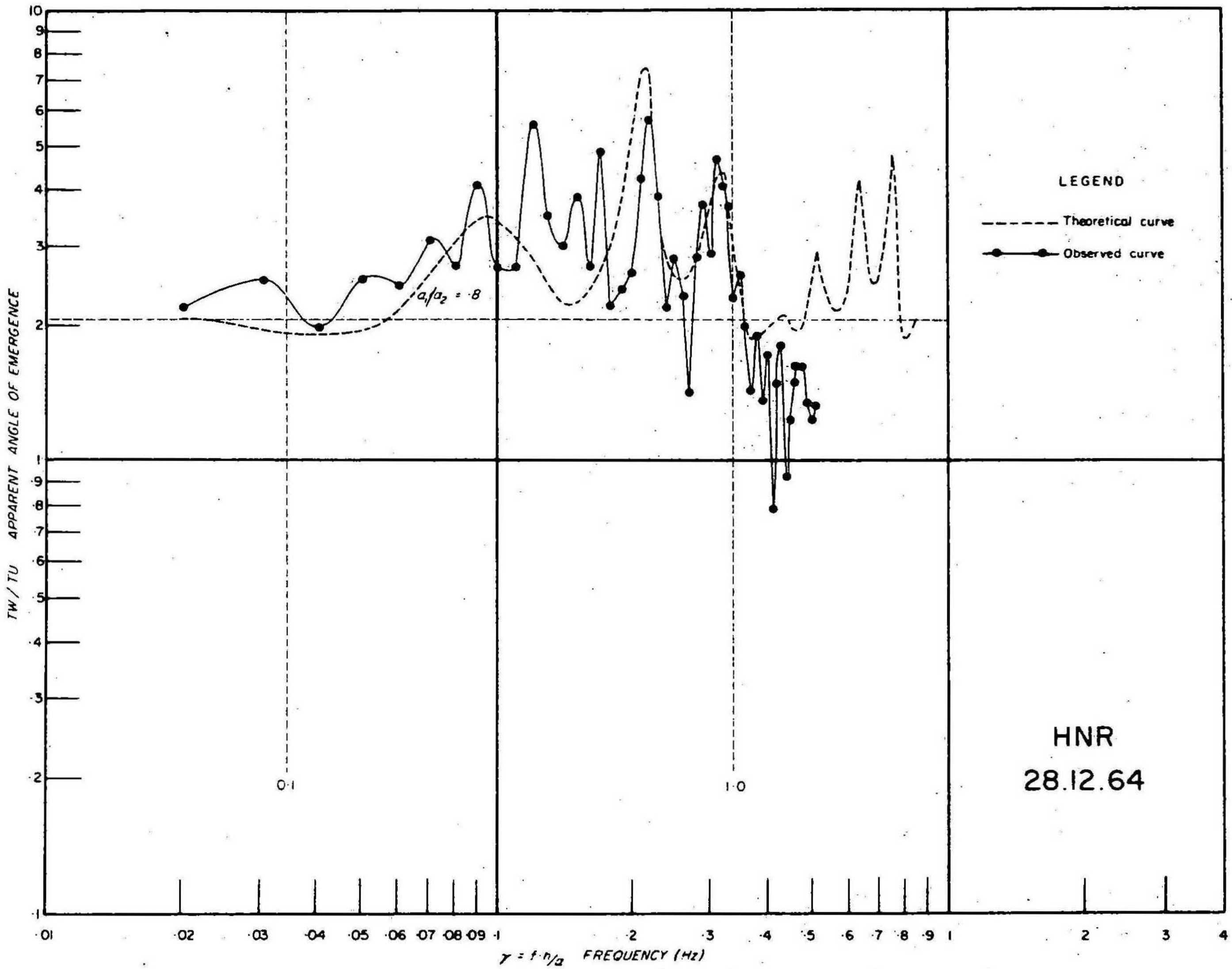


Crustal function obtained at Honiara from the Fiji earthquake of 25 August 1963
The fit is very poor

TO ACCOMPANY RECORD No 1971/97.

G82/4-109

PLATE 4

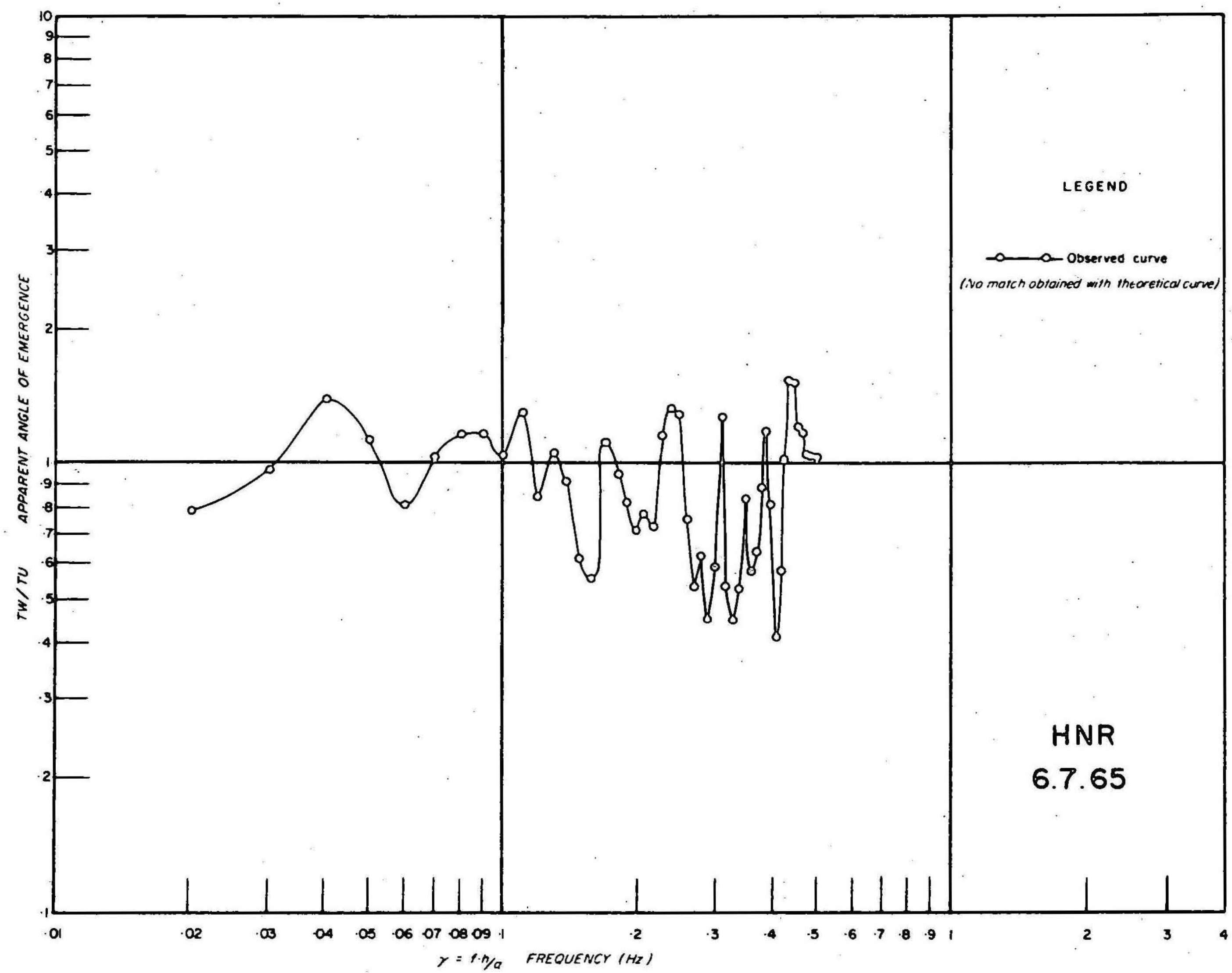


Crustal function obtained at Honiara from the
Fiji earthquake of 28 December 1964
The fit is poor

PLATE 5

TO ACCOMPANY RECORD Nº 1971/97

G82 / 4-108



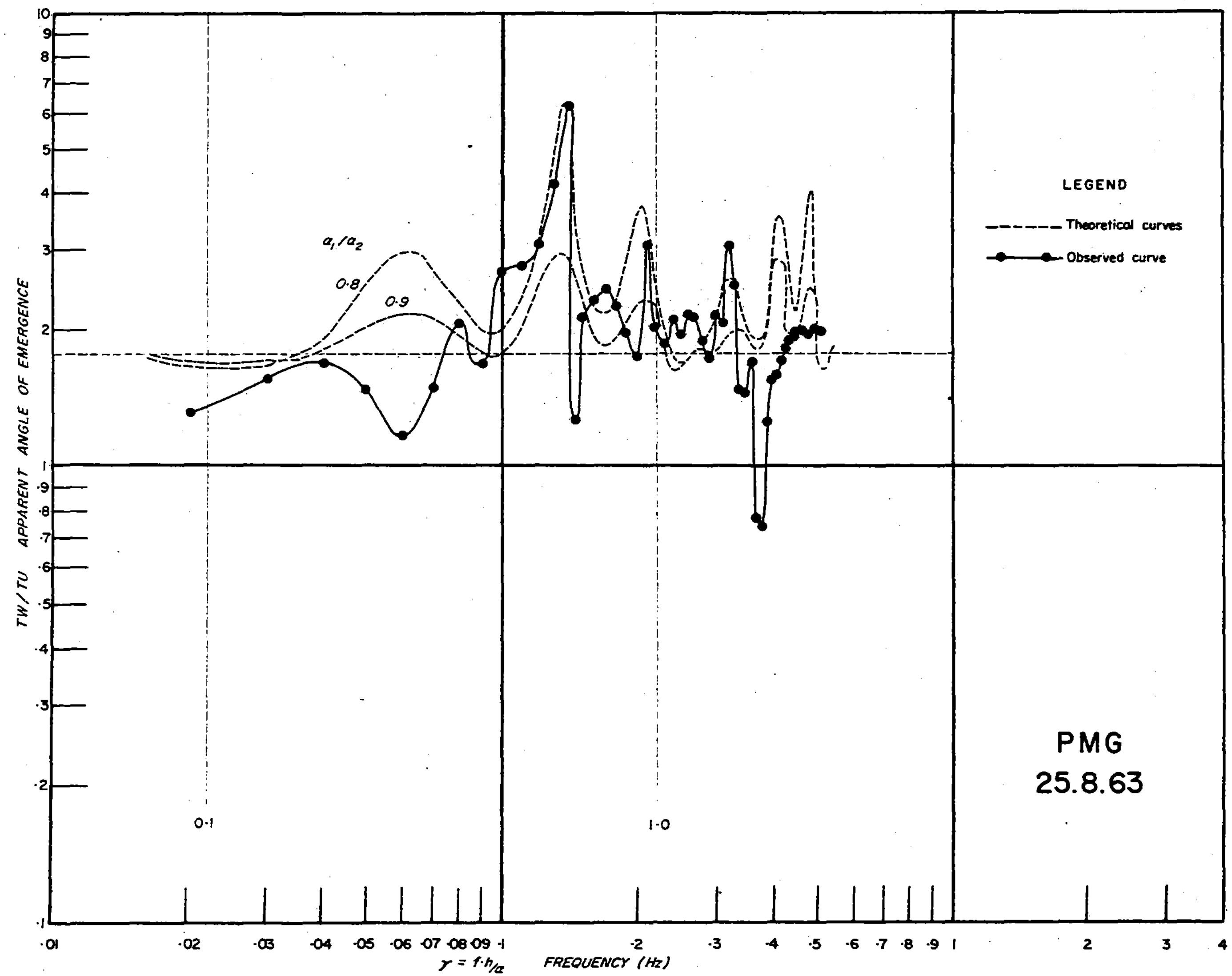
Crustal function obtained at Honiara from the Bougainville Island earthquake of 6 July 1965

No solution was obtained

PLATE 6

TO ACCOMPANY RECORD Nº 1971/97

G82/4-107

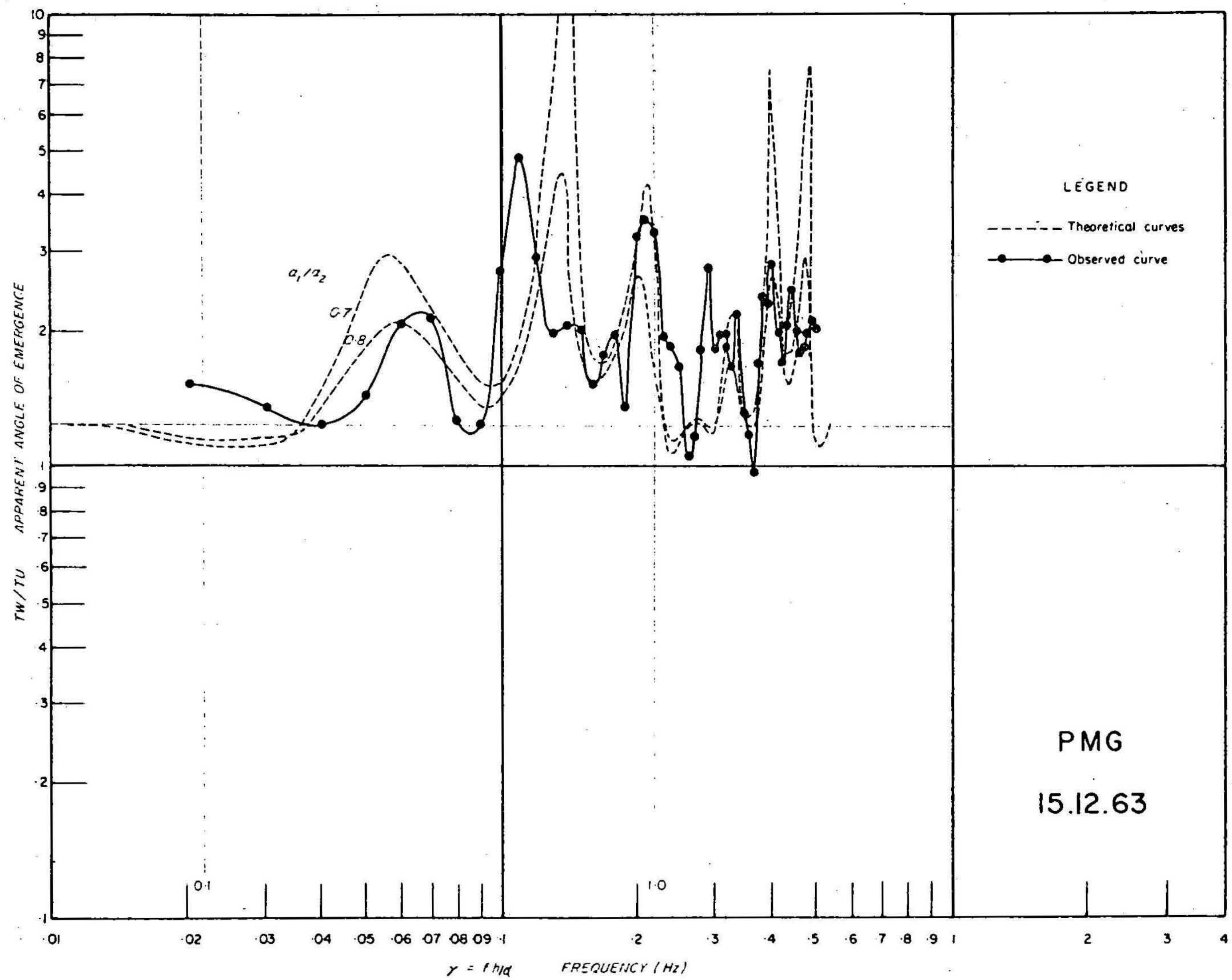


Crustal solution at Port Moresby from the
Fiji Islands earthquake of 25 August 1963
An example of a fair fit

PLATE 7

TO ACCOMPANY RECORD Nº 1971/97

G82/4-106

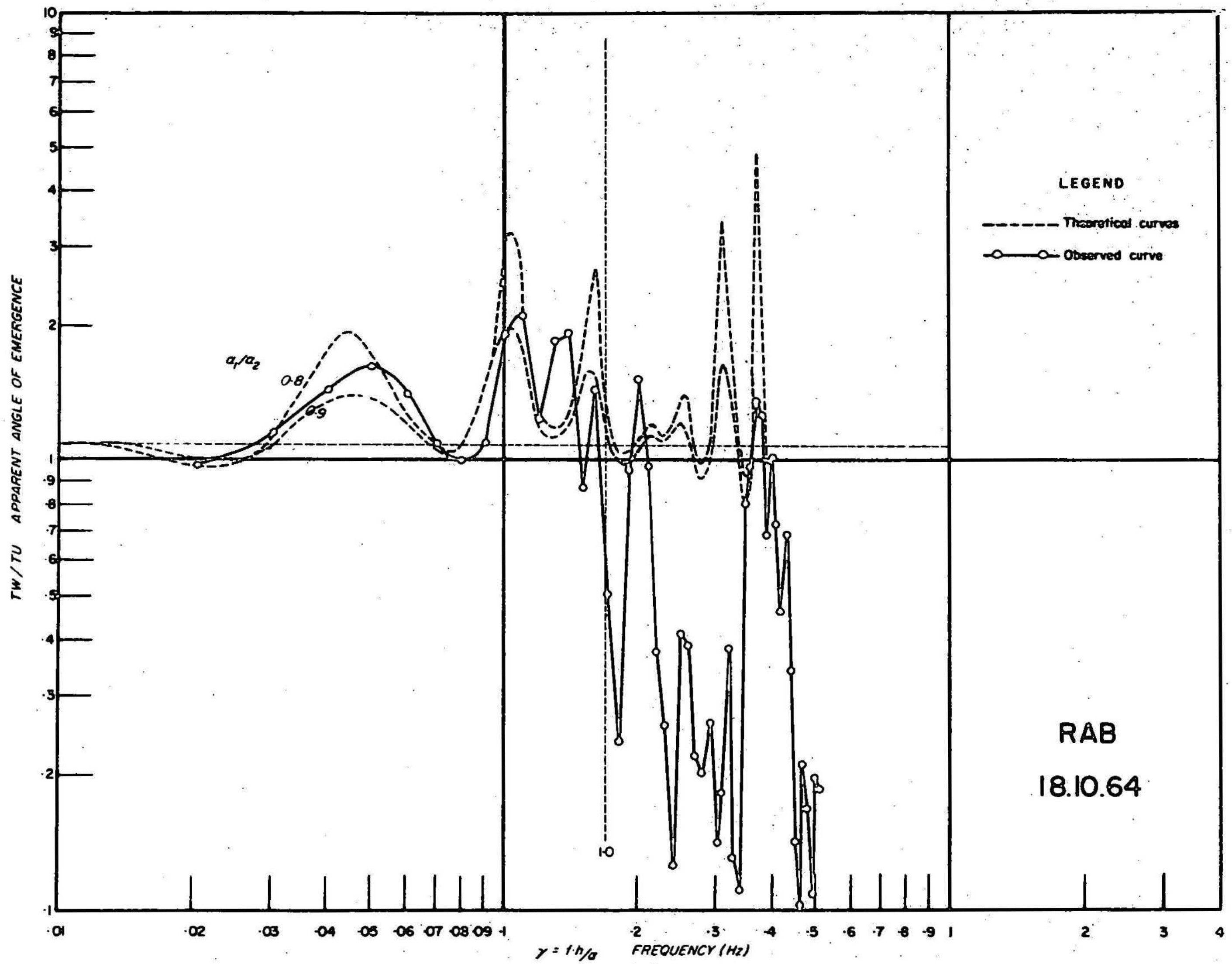


Crustal solution at Port Moresby from the
Java Sea earthquake of 15 December 1963
An example of a good fit

PLATE 8

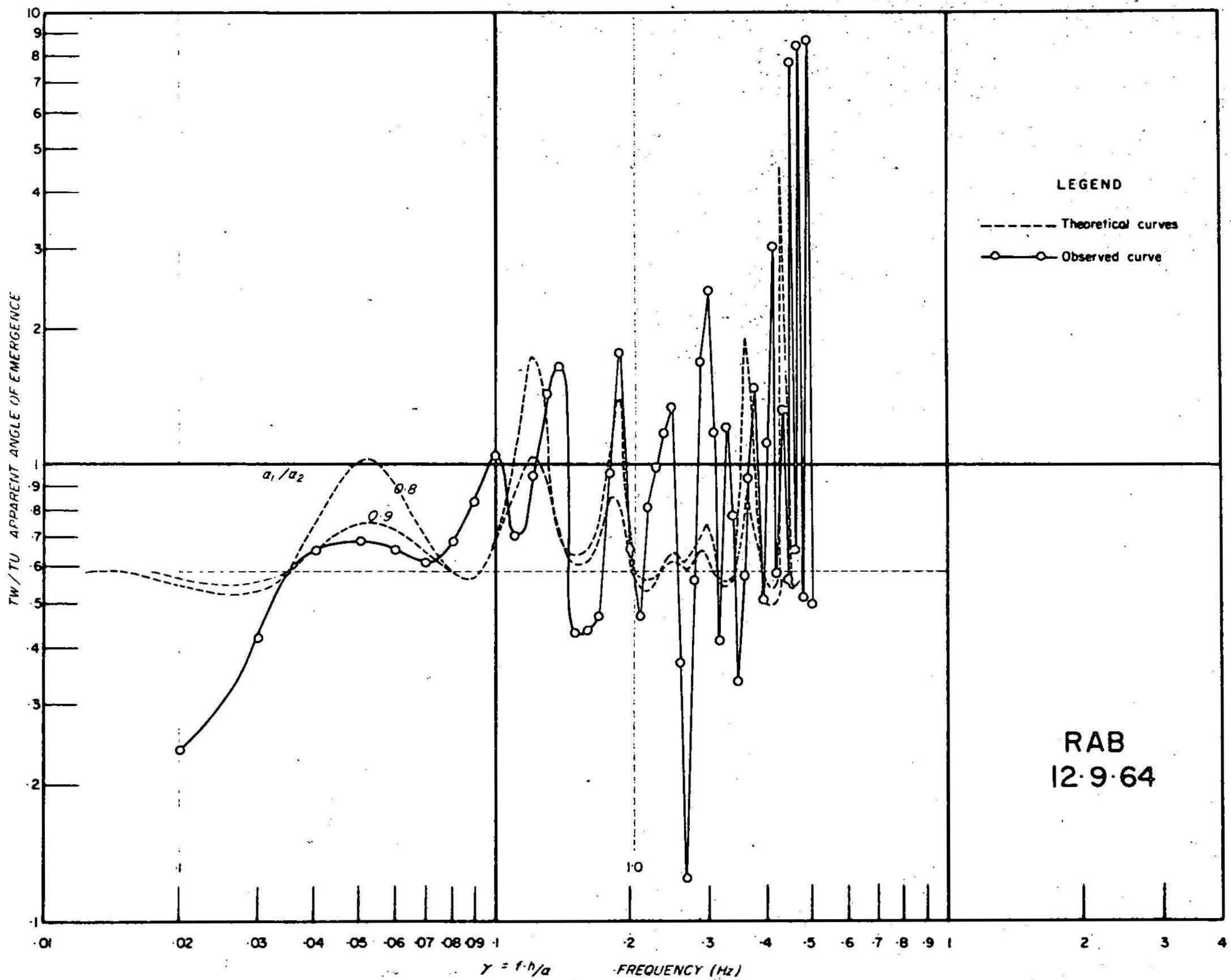
TO ACCOMPANY RECORD Nº 1971/97

G82/4-104



Crustal solution at RABAUL from the
FLORES STRAIT EARTHQUAKE of 18 October 1964
The fit is poor

PLATE 9

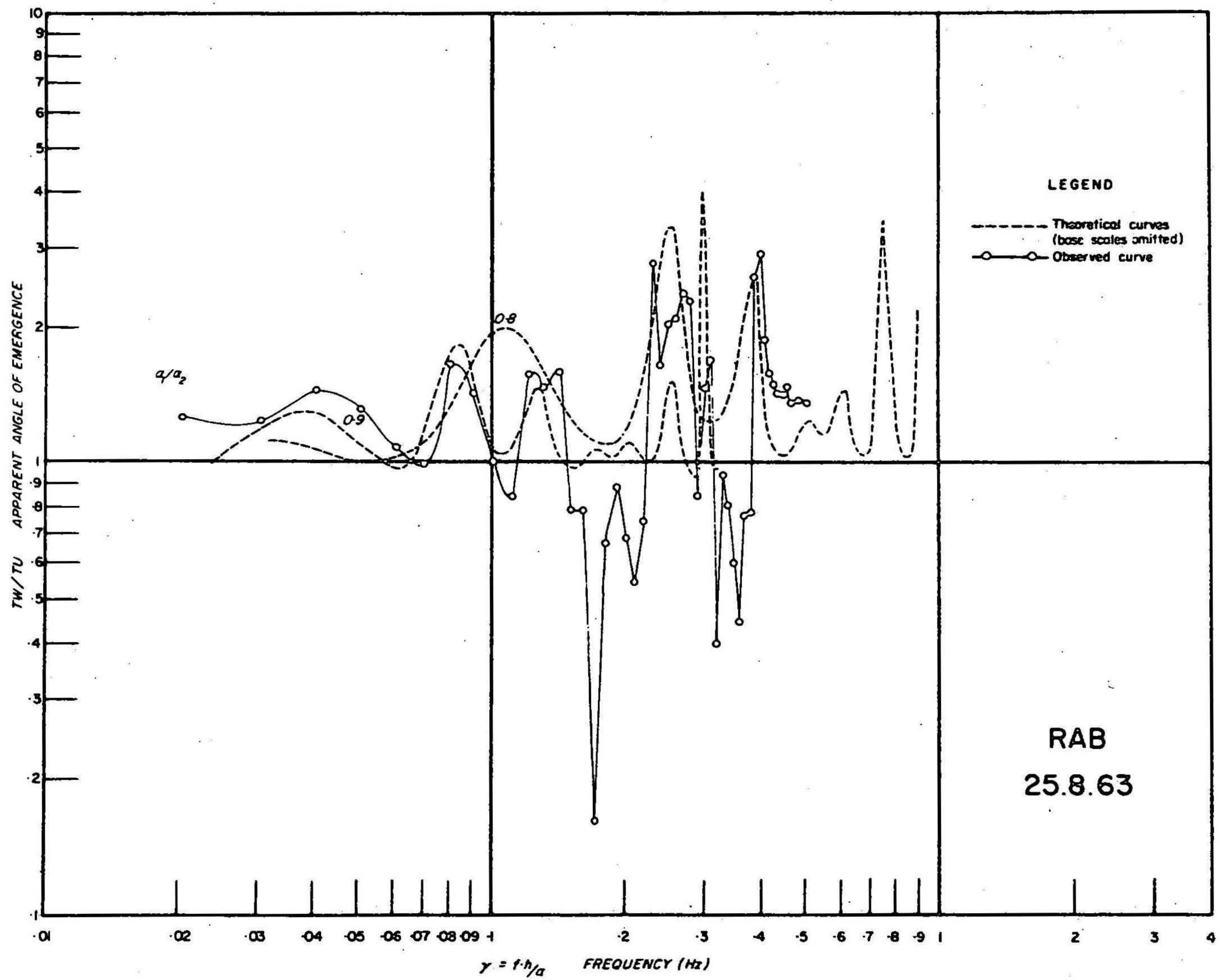


Crustal function obtained at RABAUL from the FIJI ISLAND EARTHQUAKE of 12 September 1964 The fit is poor

TO ACCOMPANY RECORD Nº 1971/97

G82/4-114

PLATE 10



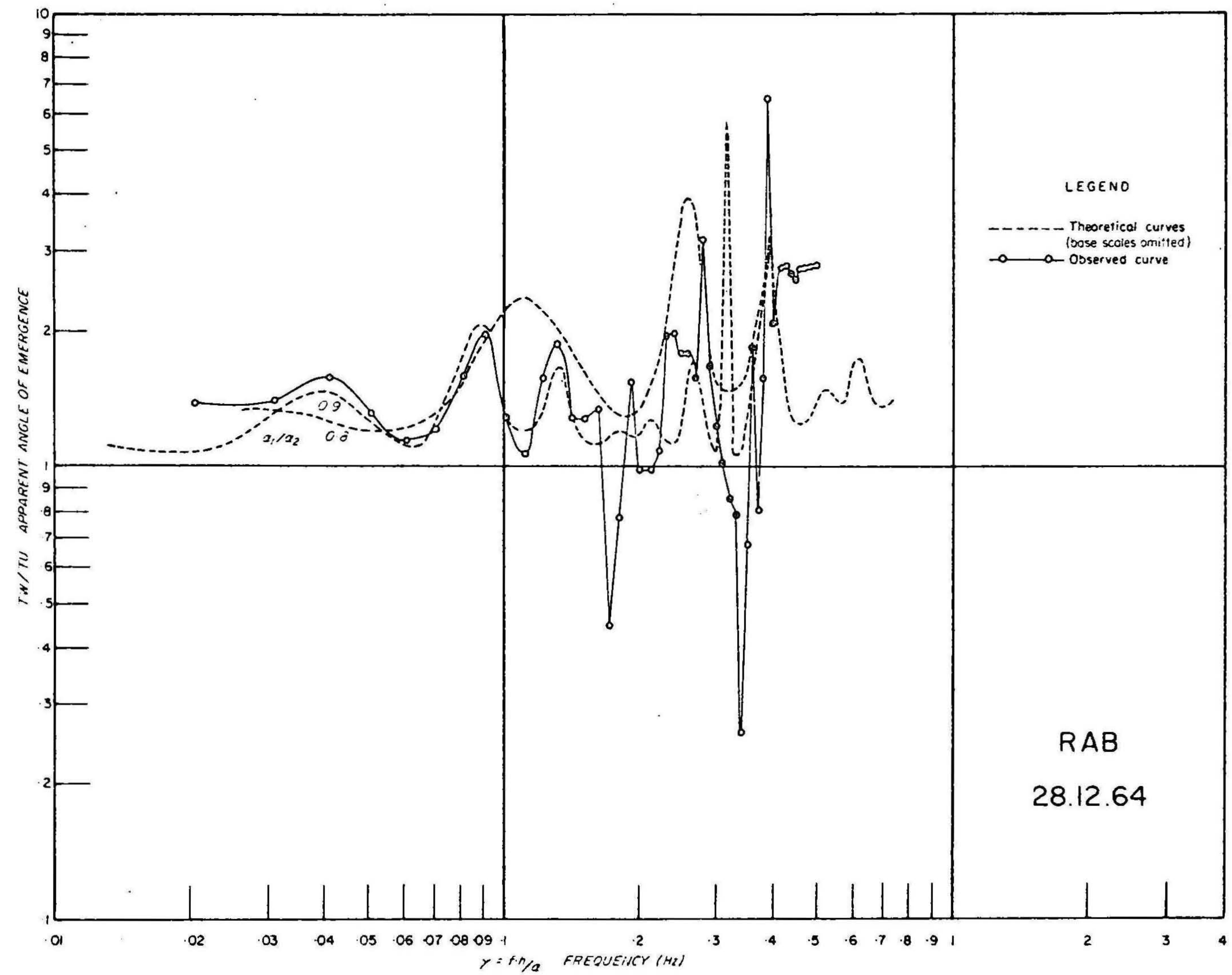
Crustal function obtained at RABAUL from the FIJI EARTHQUAKE of 25 August 1963

See text for explanation of the two fits

PLATE 11

TO ACCOMPANY RECORD Nº 1971/97

G82/4-110



Crustal function obtained at RABAUL from the
FIJI EARTHQUAKE of 28 December 1964
See text for explanation of the two fits

PLATE 12

TO ACCOMPANY RECORD Nº 1971/97

G82/4-112