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A REGIONAL MAGNITUDE SCALE FOR BRAZIL

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ABSTRACT

An empirical amplitude-distance curve is determined for earthquakes registered at regional distances in conterminous Brazil. This curve is the basis of a regional magnitude scale, m_R, using the maximum amplitude in the whole *P*-wave train with periods in the range 0.1 to 1.0 sec. In the distance range 200 $\leqq R \leqq$ 1500 km, we find

$$m_R = \log(A/T) + 2.3 \log R - 1.48.$$

This scale gives much better agreement with the teleseismic m_b magnitudes than the values calculated using the regional *Q* factors of Gutenberg and Richter (1956). It is shown that, despite using a wide range of periods, m_R should be a good estimate of the 1-sec teleseismic m_b in the range $2 \leqq m_b < 5$.

Introduction

The variation of *P*-wave amplitudes (A/T) with distance has been fairly well known since the development of the m_b magnitude scale (Gutenberg and Richter, 1956). More recent analysis of better quality data (Veith and Clawson, 1972; Booth *et al.*, 1974) have shown that the amplitude (A/T)-distance curve at teleseismic ranges ($\Delta > 20°$) has the same general shape as that determined by Gutenberg and Richter (1956), being perhaps a little smoother. However, at regional distances ($\Delta < 20°$), large differences have been found. (Hereafter, the ground amplitude divided by period, A/T, will be referred to as amplitude).

It is long known (e.g., Romney *et al.*, 1962; Jordan *et al.*, 1965, 1966) that seismic amplitudes, at regional distances, depend strongly on the propagation path, being much higher when the waves propagate in mid-plate regions (such as Central and Eastern North America) than when they propagate near active plate margins (such as Western North America). This means that appropriate amplitude-distance curves must be determined locally whenever accurate magnitudes are to be calculated using regional stations (McMechan and Workman, 1974).

The purpose of this paper is to determine a *P*-wave amplitude-distance curve for small to moderate earthquakes ($2 \leqq m_b \leqq 5$) occurring in conterminous Brazil and registered by Brazilian stations. This curve is the basis of a regional magnitude scale using *P* waves with periods in the range of 0.1 to 1.0 sec.

The Data

Since 1975, a large number of portable seismographic stations (peak amplifications around 10 Hz) have been installed in Brazil mainly for dam monitoring purposes. Many events have been recorded, and 32 were selected for this study (Figure 1 and Table 1). Only events with reliable trace amplitude readings from at least two stations at different distances in the range 200 to 2000 km were chosen. All hypocenters were assumed to be at a mid-crustal depth of 15 km, as this seems to be an average depth for mid-plate earthquakes. No evidence was found (either instrumental or macroseismic) for an event with focal depth below the crust. Therefore, the regional amplitude-distance curve here determined is supposed to represent the average amplitude attenuation of a mid-crustal event.

The earthquakes were located using *P* arrival times, *S-P* intervals, and sometimes macroseismic information as well. Epicenter uncertainties are mostly between 10 and 50 km. The effect of this error on the magnitude is very small: the maximum uncertainty in epicentral distance is usually about 10 per cent which would cause an error in magnitude of 0.10, well within the scatter of amplitude data. Each event

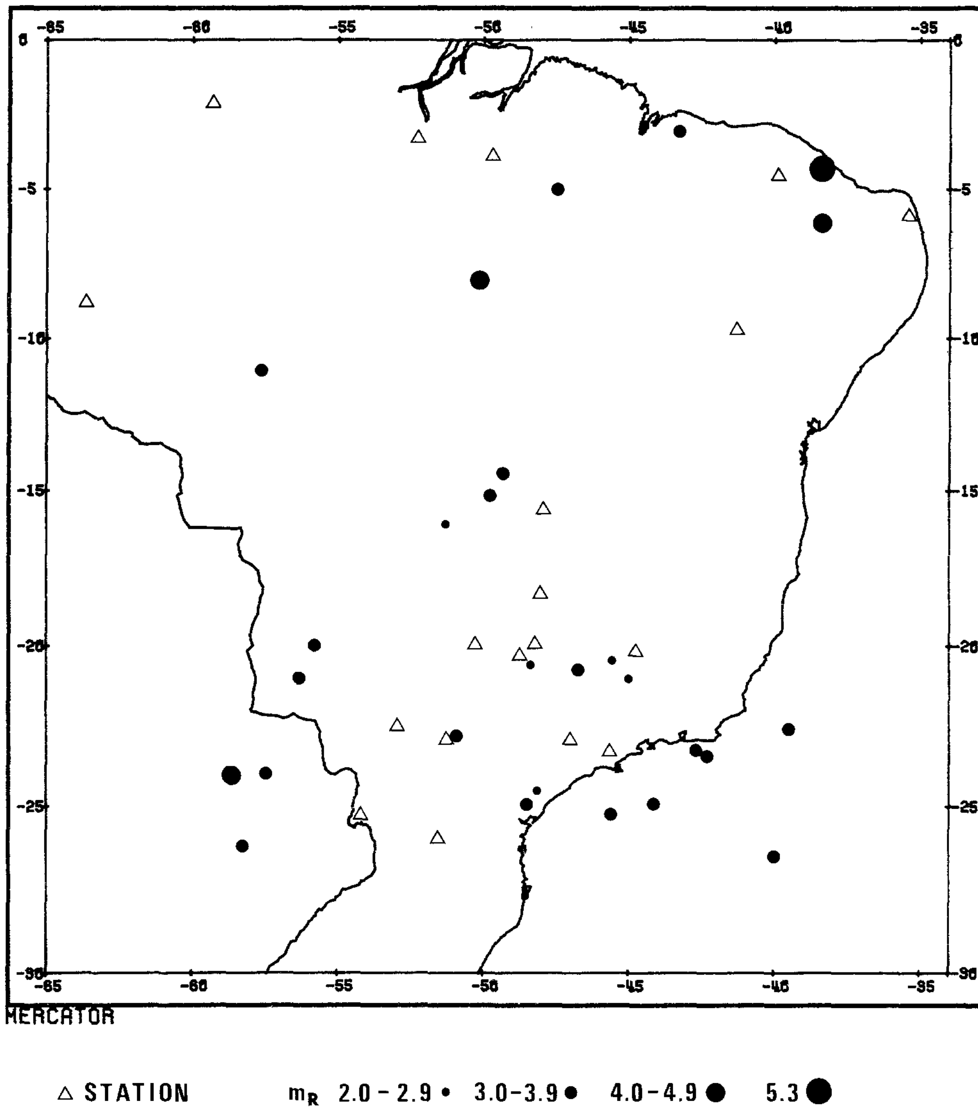

FIG. 1. Map of stations and events used to determine the shape of the amplitude distance curve. The events are listed in Table 1.

provided from 2 to 13 amplitude values (average of six per event) in the distance range 200 to 2300 km (average distance 800 km) producing a total of 187 data points.

As the main purpose of this work was to determine magnitudes of small events and not attenuation coefficients, the maximum trace amplitude in the whole P-wave train was picked regardless of the phase. Besides avoiding the problem of phase identification and emergent arrivals, the maximum P-wave amplitude is less dependent on possible variations of crust/upper mantle structure (McMechan and Workman, 1974). In this way, different phases were picked depending on the epicentral distance. For distances shorter than 500 km, the maximum *P*-wave trace amplitude in the seismogram is usually a crustal phase (such as *PmP*, *Pg*, etc.), whereas for longer distances a mantle phase (*Pn*) was usually picked. Occasionally, the maximum trace amplitude was registered up to 40 or 50 sec after the onset. All trace amplitudes and periods were read by the author.

As only 6 of the 32 events were recorded at teleseismic distances, the following procedure was adopted to establish the regional magnitude scale. First, the selected set of 32 events was used to determine the shape of the amplitude-distance curve

TABLE 1

EVENTS USED TO DETERMINE THE SHAPE OF THE AMPLITUDE-DISTANCE CURVE

No.	Date (d:m:y)	Time (UTC)	Latitude (°S)	Longitude (°W)	m_R
1	13.01.68	01:55:50	6.09	38.44	3.8
2	15.02.68	13:20:45	6.09	38.44	3.9
3	23.02.68	14:23:03	6.09	38.44	4.8
4	23.02.68	15:33:18	6.09	38.44	3.7
5	30.03.75	17:06:00	23.40	42.40	3.4
6	08.12.75	08:21:28	24.94	44.16	3.4
7	19.06.77	03:03:30	23.30	42.60	3.5
8	19.03.78	05:33:27	24.96	48.50	3.3
9	05.10.78	09:38:44	16.10	51.27	2.9
10	16.01.79	02:38:24	24.00	58.70	4.0
11	21.01.79	17:49:36	21.02	56.36	3.6
12	04.03.79	16:26:54	21.00	45.00	2.1
13	27.03.79	12:54:45	22.84	51.01	3.7
14	07.07.79	19:51:28	24.52	48.13	2.3
15	20.07.79	04:00:37	24.00	57.50	3.0
16	13.08.79	18:41:00	25.20	45.60	3.0
17	22.08.79	23:01:40	15.17	49.76	3.5
18	08.12.79	05:05:50	20.00	55.80	3.8
19	23.04.80	16:11:30	26.50	40.00	3.5
20	24.10.80	00:49:02	14.41	49.39	3.0
21	12.11.80	21:23:04	08.06	50.19	4.6
22	20.11.80	03:29:43	04.30	38.40	5.3
23	20.11.80	22:29:07	26.25	58.25	3.8
24	29.11.80	01:05:00	03.10	43.30	3.1
25	19.12.80	05:29:10	20.45	45.54	2.5
26	02.01.81	04:14:55	04.30	38.40	3.6
27	06.01.81	19:51:58	05.00	47.50	3.4
28	12.01.81	03:33:08	04.30	38.40	3.8
29	18.01.81	16:19:50	20.71	46.70	3.3
30	09.03.81	20:27:40	11.01	57.64	3.8
31	24.03.81	22:10:03	20.58	48.34	2.7
32	07.05.81	03:44:55	22.60	39.50	3.7

but not its absolute level. Accordingly, only relative magnitudes were determined at this stage. Another set of 11 events with teleseismic magnitudes in the range 4 to 5 m_b were used to find the absolute level of the amplitude-distance curve tying the regional Brazilian magnitude scale to the Gutenberg and Richter (1956) teleseismic m_b scale.

The Shape of the Amplitude-Distance Curve

A method similar to that of Veith and Clawson (1972) was used to determine the empirical $\log(A/T)$-distance curve. The $\log(A/T)$ data were normalized to a mag-

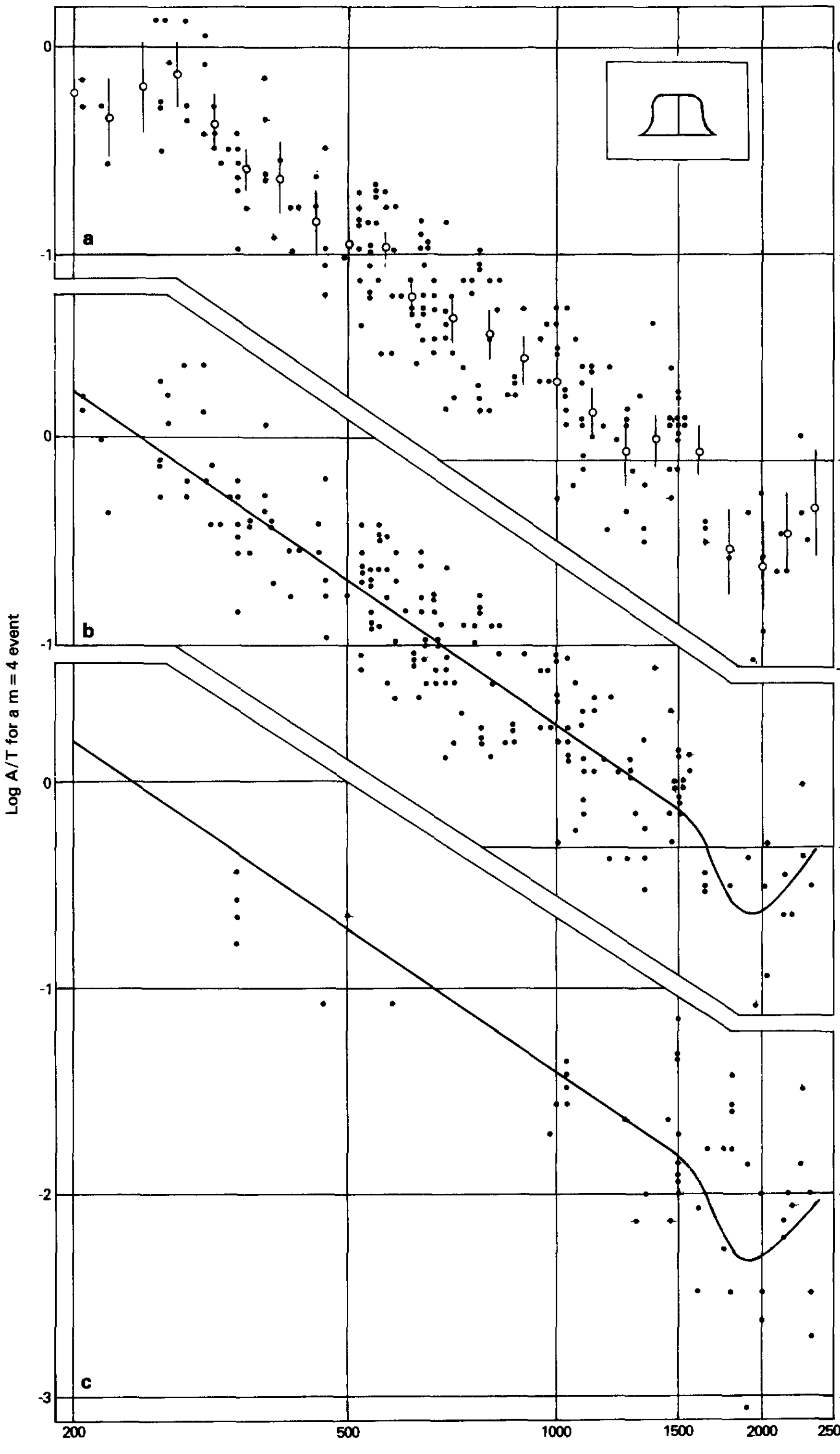

FIG. 2. Amplitude-distance curve. (a) Data with general curve defined by the moving averages. Circles are window centers used for averaging the normalized data. Vertical bars are ±2 S.D. of the mean. *Inset* shows window size and weight. (b) Shape of the final curve with a straight line fitted between 200 and 1500 km. (c) Level of the curve adjusted to best fit data normalized with known teleseismic magnitudes.

nitude of 4 using an initial preliminary amplitude-distance curve. An improved curve was obtained by averaging the normalized $\log(A/T)$ data within overlapping equally spaced windows. The data windows (whoses centers are shown in Figure 2a) were equally spaced in terms of log (distance) to compensate for the lower density of data points at longer distances. The data within the window were weighted with a cosine taper (Figure 2a, *inset*). This improved curve was then used to recompute the magnitudes and normalized $\log(A/T)$ data. The new amplitude data were then averaged, as described above, to modify the amplitude-distance curve. This iterative process was continued until the curve and relative magnitudes were stabilized. Although a large number of iterations may be necessary, this process is computationally very quick. Using the amplitude-distance curve of Gutenberg and Richter (1956) [extrapolated down to 2° by USCGS (unpublished data, 1963)] as the initial curve, the final curve was obtained after 16 iterations and the rms $\log(A/T)$ residual was decreased from 0.39 to 0.23. Of course the final curve is independent of the

TABLE 2

BRAZILIAN EVENTS, WITH m_b DETERMINED WITH TELESEISMIC STATIONS, USED TO ADJUST THE REGIONAL m_R SCALE

No.	Date (d:m:y)	Time (UTC)	Latitude (°S)	Longitude (°W)	m_b*		Regional Distance†		$m_R - m_b$
1	13.01.68	01:55:50	06.09	38.44	3.96	(2)	350–1480	(3)	−0.13
2	15.02.68	13:20:45	06.09	38.44	4.14	(5)	350–1480	(3)	−0.27
3	23.02.68	14:23:03	06.09	38.44	4.56	(18)	350–1480	(4)	+0.24
4	23.02.68	15:33:18	06.09	39.44	3.89	(3)	350–1480	(3)	−0.16
5	12.01.70	04:43:08	01.32	48.48	4.50	(8)	1580–1600	(2)	−0.30
6	24.10.72	15:36:36	21.72	40.53	4.84	(10)	1025–1035	(3)	+0.03
7	22.07.73	21:22:52	05.28	35.84	4.13	(2)	1750–1785	(5)	+0.55
8	24.02.74	03:19:40	20.04	48.47	4.11	(4)	500–2115	(2)	+0.16
9	02.08.77	17:45:52	00.03	50.06	4.75	(17)	1740	(1)	−0.13
10	12.11.80	21:23:04	08.06	50.19	4.92	(5)	460–2010	(14)	−0.28
11	20.11.80	03:29:43	04.30	38.40	5.15	(33)	1245–2150	(6)	+0.18

* Teleseismic m_b using Gutenberg and Richter's (1956) Q factors for 15 km depth. Number of stations used for m_b is in parentheses.

† Range of recorded distances in Brazil (kilometers) used to calculate m_R. Number of stations used is shown in parentheses.

choice of the initial curve, which only affects the number of iterations. Different window sizes and intervals were tried but no significant differences were noticed in the final curve.

Figure 2a shows the final $\log(A/T)$ averages defining the general shape of the amplitude-distance curve. As can be seen from the scatter of the data points, the irregularities of the curve, especially between 200 and 1500 km, do not represent actual data trends but are the result of data concentrations. For this reason, a straight line was fitted to the data between 200 and 1500 km as follows

$$\log(A/T)_{ki} = m_k - (a \cdot \log R_{ki} + b) \qquad (1)$$

where m_k is the magnitude of the kth event ($k = 1$ to 32), and R_{ki} is the ith epicentral distance (km) for the kth event.

The parameter a and the 32 magnitudes were determined with least squares. Of course the absolute magnitudes cannot be determined as the coefficient b is indeterminate: only relative magnitudes $(m_k - b)$ can be determined at this stage. The result was

$$a = 2.29 \pm 0.12.$$

Having found the slope of the amplitude-distance curve up to 1500 km, the rest of the curve was determined with the iterative procedure described above, maintaining the segment from 200 to 1500 km fixed (a slope of 2.3 instead of 2.29 was adopted). The resulting curve, shown in Figure 2b has a variance slightly smaller than the general curve of Figure 2a confirming that those irregularities were not significant. The final curve (Figure 2b) has a rms residual in the log(A/T) data of 0.24.

TABLE 3

Q_R FACTORS: $m_R = \log(A/T) + Q_R(\Delta)$*

Δ(°):	2	3	4	5	6	7	8	9	10	
Q_R:	3.92	4.32	4.61	4.83	5.01	5.17	5.30	5.42	5.52	
Δ(°):	11	12	13	14	15	16	17	18	19	20
Q_R:	5.61	5.71	5.79	5.91	6.07	6.21	6.32	6.28	6.22	6.14

*A, center-to-peak ground amplitude in microns; T, period in seconds.

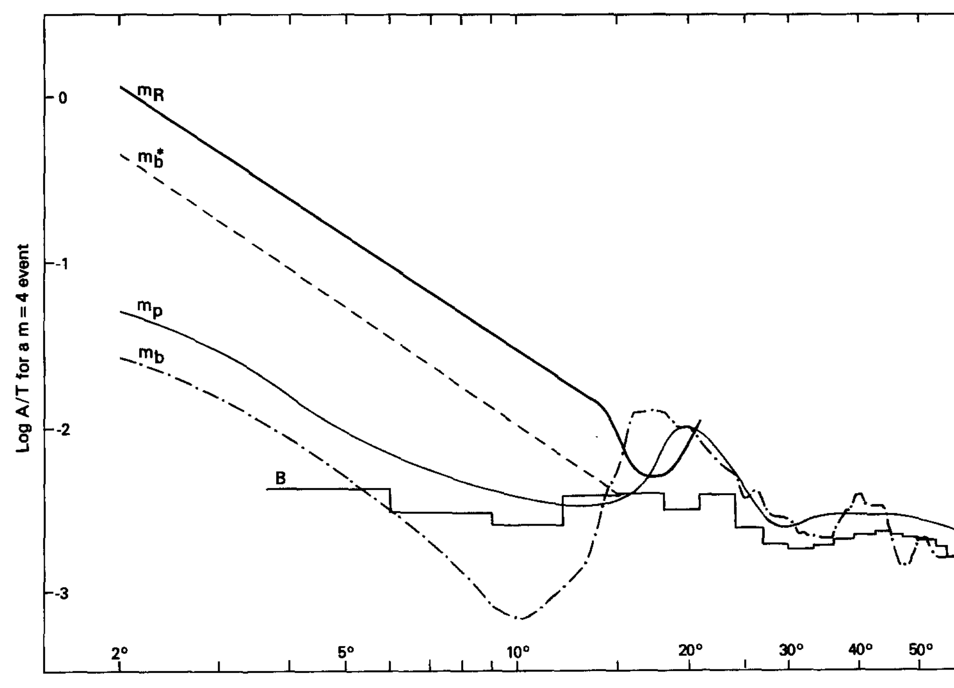

FIG. 3. Amplitude-distance curves. m_R, this study; m_b^*, Jacob and Neilson (1977), $h = 0$ km; m_p, Veith and Clawson (1972), $h = 15$ km; m_b, Gutenberg and Richter (1956), $h = 15$ km; B, Booth *et al.* (1974).

THE LEVEL OF THE AMPLITUDE-DISTANCE CURVE

Eleven events occurred in Brazil since 1968 (Table 2), recorded both at teleseismic and regional distances, that were used to adjust the level of the amplitude-distance curve so that the regional magnitudes would best agree with the teleseismic m_b values. The teleseismic m_b magnitudes were recalculated, using stations at $\Delta \geqq 20°$, with Gutenberg and Richter's Q factors for a mid-crustal depth of 15 km. (None of these events had its focal depth well constrained.) Data from ISC or NEIS bulletins and other WWSSN stations were used for the teleseismic m_b. These magnitudes were then used to normalize the regional log(A/T) data. The level of the curve was then adjusted to best fit the normalized log(A/T) data as shown in Figure 2c.

The level of the curve, expressed in terms of the coefficient b in equation (1), was

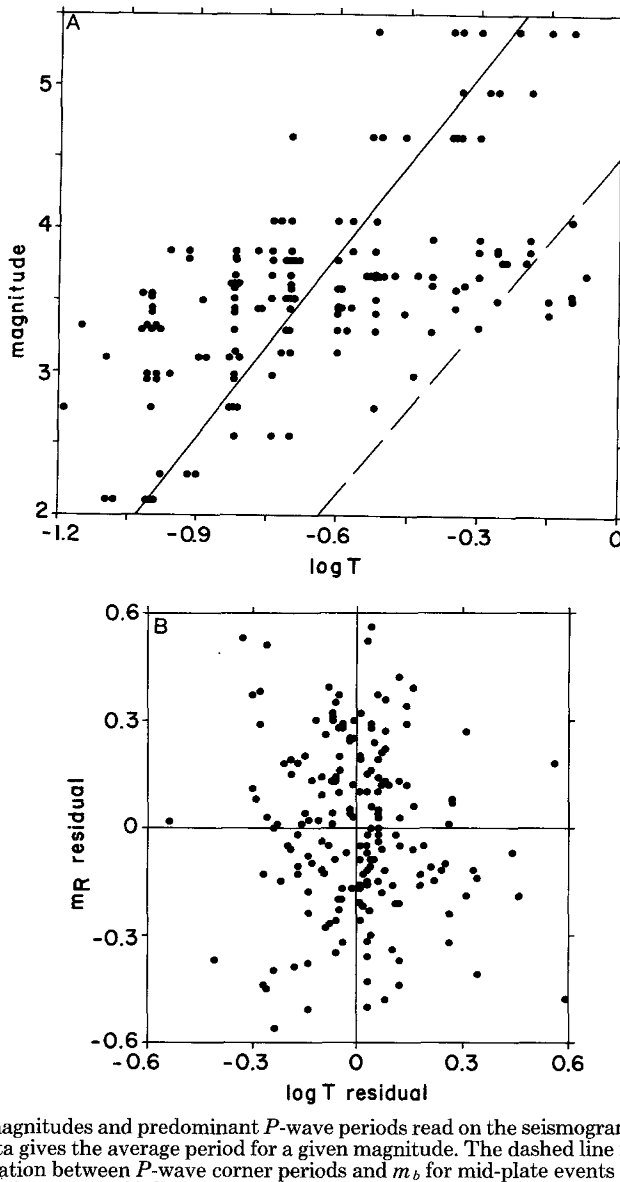

FIG. 4. (a) m_R magnitudes and predominant P-wave periods read on the seismograms. The continuous line fitted to the data gives the average period for a given magnitude. The dashed line is a semi-empirical, semi-theoretical relation between P-wave corner periods and m_b for mid-plate events according to Nuttli (written communication, 1982). (b) Scattergram of residuals of m_R and residuals of periods.

found to be

$$b = -1.48 \pm 0.05.$$

The rms residual of the log(A/T) data points in Figure 2c is 0.35. This amplitude-distance curve (Figure 2c) is the basis of a Brazilian regional magnitude scale, m_R, which can then be expressed, in the distance range 200 to 1500 km, as

$$m_R = \log(A/T) + 2.3 \log R \text{ (km)} - 1.48$$

where A is the ground displacement, in microns, corresponding to the maximum trace amplitude in the whole P-wave train with period T in the range 0.1 to 1.0 sec. As can be seen from Table 2, the differences $m_R - m_b$ are reasonably small indicating that m_R can be a useful estimate of m_b at regional distances. Table 3 shows the Q_R factors for calculating m_R.

Assessment of the Regional Magnitude m_R

The regional amplitude-distance curve derived here is plotted in Figure 3 together with other regional curves. A direct comparison of the various curves should be made with care because of the different criteria used to measure the amplitudes. For example, the original Gutenberg and Richter m_b was established picking the maximum trace amplitude in the entire P-wave train (McMechan and Workman, 1974) with periods around 5 to 10 sec (Geller and Kanamori, 1977). Booth *et al.*

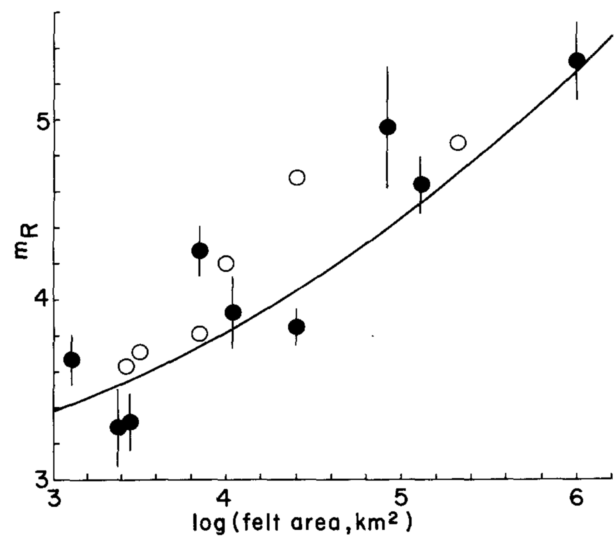

FIG. 5. Relation between m_R and felt area. Data on felt area were taken from Berrocal *et al.* (unpublished data, 1981) and Ferreira (in preparation, 1982). The curve is $m_b(Lg)$-felt area relation of Nuttli *et al.* (1979) for Central and Eastern North America. Error bars of full symbols are ±2 S.D. of the mean. Open symbols denote m_R values from a single station.

(1974) used 1-sec P wave in the first 3 or 4 cycles and Veith and Clawson (1972) also used amplitudes in the "first few cycles" (McMechan and Workman, 1974) as had been recommended by the USCGS (unpublished data, 1963). The m_R amplitude-distance curve is 0.4 to 0.5 units higher than the $m_b{}^*$ curve determined from two 10-ton explosions in Britain ($m_b = 4.4$) using the same criteria adopted here (Jacob and Neilson, 1977). The m_R curve seems to join the general teleseismic curve at about 20°. Despite picking the maximum trace amplitude in the whole P-wave train, the m_R magnitudes are, on average, 0.7 units lower than the values calculated with USCGS (1963) criteria and the Gutenberg and Richter's Q factors for regional distances.

The teleseismic m_b magnitude, as currently reported by USGS and ISC, is measured at periods close to 1 sec. However, due to the instrumental characteristics of the Brazilian stations, the dominant period of the maximum amplitude P wave is less than 1 sec (Figure 4a). Nevertheless, no correlation was observed beween residuals of m_R and period for the same earthquake (Figure 4b), indicating that in the range 0.1 to 1 sec, the A/T value gives about the same m_R magnitude whichever period is used. This is probably due to the fact that dividing the displacement amplitude A by the period T largely compensates for the higher attenuation and lower source spectral amplitude of the shorter period P waves. As m_R decreases, the average of the periods recorded by different stations also decreases (Figure 4a). However, the relation between this average period and m_R seems to be parallel to the relation between corner periods and m_b for mid-plate events (Figure 4a). This would indicate that the m_R magnitudes scale the same way as the 1-sec m_b for magnitudes lower than 4.5. As m_R was tied to m_b between 4 and 5, it is believed that m_R should be a reasonable estimate of the "true" teleseismic m_b for magnitudes down to 2.

Figure 5 shows the relation between m_R and felt area (intensity $\geqq$ II MM) of some Brazilian events together with the empirical relation between $m_b(Lg)$ and felt area determined by Nuttli *et al.* (1979) for Central and Eastern North America, where the $m_b(Lg)$ magnitude is a reliable estimate of m_b at regional distances. The data are not enough to draw definite conclusions but it seems that the relation between magnitude and felt area in Brazil is not substantially different from that of Central and Eastern North America.

Conclusions

Despite the scarcity of data, it has been possible to determine a P-wave amplitude-distance curve which is used to calculate magnitudes within regional distances in conterminous Brazil. This was done by using all events well recorded at regional distances to determine the shape of the amplitude-distance curve, and then using the few events with teleseismic m_b to fix the absolute level of the curve. Magnitudes calculated with the m_R scale are in better agreement with the teleseismic m_b value than those calculated with the regional Gutenberg and Richter's Q factors. Although m_R is calculated with a wide range of periods (0.1 to 1.0 sec), it should be equivalent, within the usual uncertainties in magnitude calculations, to the 1-sec teleseismic m_b in the range $2 \leqq m \leqq 5$.

It is assumed that, to a first approximation, this amplitude-distance curve represents P-wave attenuation in the whole of Brazil, although the events and stations were not evenly distributed. As more events are recorded, it will be possible in the future to improve the amplitude-distance curve, especially beyond 1500 km, and also to study differences in the P-wave attenuation between different parts of Brazil.

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