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NOTES ON EARTHQUAKE MAGNITUDE SCALES

by

P.M. McGREGOR & I.D. RIPPER

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SUMMARY

The 'magnitude' of an earthquake is intended to provide an instrumental, quantitative measure of the relative 'size' of the earthquake.

Because recorded ground-motion varies widely, depending amongst other things on the seismograph characteristics, and the distance and depth of the earthquake, several magnitude scales (and modifications of them) are required. The main scales are: the Richter, applied to shallow earthquakes at distances up to 600 km; the surface-wave, applied to shallow earthquakes at distances beyond 2000 km (20°); and the body-wave, applied to any earthquake beyond 600 km. All scales are logarithmic and open-ended.

The scales in general do not give the same numerical magnitude when applied to a given earthquake. But they are related, though with some uncertainity, by empirical formulas.

In the literature magnitude symbols have been used indiscriminately and confusion has arisen. Recommended symbols for use by BMR are given.

1. INTRODUCTION

In order to study effectively some aspects of earthquakes it is necessary to have a scale which will rate the earthquakes in terms of their 'size' at the hypocentre, and which will be independent of other factors (e.g. epicentral distance, place of origin, depth). That is, a scale based on instrumental recordings is required.

In 1935 Richter (q.v.) introduced the expression 'magnitude' for this objective rating, and devised a magnitude-scale based on the recordings at a network of standardized seismographs (Wood-Anderson torsion seismometers) in southern California. His scale is logarithmic and the larger the magnitude value the larger the earthquake. Richter's basic assumption was that the ratios of recorded amplitudes were measures of the relative magnitudes of the local earthquakes. The scale-zero was chosen arbitrarily, as it was realized that data were inadequate to allow the derivation of an absolute scale, i.e. one in which the numbers referred directly to shock energy measured in joules.

More recently it has become increasingly apparent that magnitudes based on recorded energy may not be adequate to define the earthquake 'size'; a better measure may be the seismic moment (Mo) which takes into account the area and displacement of the fault, and the modulus of rigidity (Duda & Nuttli, 1974; Chinnery & North, 1975). However, moments have been determined for very few earthquakes, and magnitudes will continue to be the rating parameter for a long time yet.

The Richter scale has intrinsically a limited application, being designed to cope with local, shallow earthquakes. To assign magnitudes to distant events Gutenberg & Richter (1936) applied a similar technique to recorded surface waves with periods near 20 s. They obtained internally consistent results but the magnitudes differed from those given by the Richter scale where both could be determined.

Deep earthquakes do not always produce surface waves with period 20 s and so a third scale based on body waves became necessary to describe other distant events (Gutenberg & Richter, 1956b).

Subsequently empirical relations were established between these scales, and between magnitude and energy; other workers have devised scales to suit local or regional circumstances. As a result confusion has arisen in the reporting of magnitudes, in their application, and in the use of symbols.

The objects of these notes are to specify how each magnitude is determined in practice, and to list the preferred scales and symbols.

It should be noted that all magnitude-scales are open-ended (in contrast to the subjective intensity scales which rate the relative effects of earthquakes at particular places). Thus micro-earthquakes may have negative magnitudes. Nevertheless there is a physical upper limit set by the maximum strain the rocks can support before yielding, and statistical earthquake frequency/magnitude relations indicate an upper magnitude limit of about 8.6 (Chinnery & North, 1975).

Units in current use have been used throughout this report and no attempt has been made to convert formulas to their SI equivalents. Common logarithms are used throughout. Unfortunately the term 'amplitude' is not used consistently in its correct sense in the literature, and care is necessary in using the definition accompanying each formula.

2. RICHTER MAGNITUDE M_L

Origin.

Richter (1935)

Definition and procedure

$$M_L = \log A - \log Ao$$

where

A = maximum trace amplitude (mm) measured from mean-to-peak on a standard Wood-Anderson seismogram;

Ao = trace amplitude of the reference earthquake (magnitude zero) at the same distance.

The standard Wood-Anderson seismograph has period 0.8 s, static magnification Vw = 2800 and damping factor h = 0.8 (Anderson & Wood, 1925). Its response curve is given in Plate 1, and is reproduced from the ISC Manual of Seismological Observatory Practice.

The reference earthquake was assumed to produce an amplitude of 1 micron (10^{-6} m) at 100 km. Values of -log Ao derived by Richter (1958, p. 342) are given in Table 1.

If two components of ground motion are recorded (e.g. North-South (n) and East-West (e)), the arithmetic mean trace amplitude is used to give A; the amplitudes are not combined vectorially because they may occur at different times and relate to different waves.

To compute M_L, obtain the tabulated value of -log Ao for the known epicentral distance and add the value of log A. Alternatively use the nomogram (Pl. 2) derived by Nordquist (Gutenberg & Richter, 1942) or the version of Eiby & Muir (1961) in Plate 3. The latter uses S-P intervals on the distance scale.

(Note: determinations of the magnifications of all Wood-Anderson seismometers owned by BMR have yielded a result of about 2040. It is unknown whether the magnification of the original instruments (2800) is erroneous or whether the BMR instruments are not standard).

Limitations and adaptations

M_L was devised for local Californian earthquakes which occur at a depth of roughly 16 km, recorded by standard Wood-Anderson seismographs. Strictly it should be derived from Wood-Anderson seismograms only and is limited to earthquakes in the distance range 0 - 600 km and of shallow depth (about 16 km). Even then discrepancies may arise because the curve of Ao (for California) may not apply elsewhere.

Use of non-standard seismographs. Provided they have characteristics similar to the standard Wood-Anderson, and amplitudes of S waves only are measured, other types of instruments may be used. In these circumstances convert trace amplitudes (An, Ae) to equivalent Wood-Anderson amplitudes (A) by allowing for the differences in magnifications (V).

$$\begin{aligned}\log A &= \log ((An\ Vw/Vn + Ae\ Vw/Ve)/2) \\ &= \log ((An/Vn + Ae/Ve)/2) + \log Vw\end{aligned}$$

If the seismometers are a reasonably matched pair (i.e. $Vn = Ve \pm 10\%$)

$$\log A = \log \bar{A} + \log Vw - \log \bar{V}$$

where $\bar{A}$ = mean trace amplitude in mm
$\bar{V}$ = mean seismometer magnification

A magnitude determined in this fashion should be labelled M_L (XYZ) where (XYZ) is the station code symbol, because it has not been derived in accordance with the definition.

Extension to SV waves. In order to determine magnitudes of weak, local earthquakes in South Australia, White (1968) devised a scale based on the S wave trace amplitude recorded on Benioff vertical seismographs. This has the advantages of producing consistent local results, and avoids labelling them (erroneously) as M_L. He labelled his scale m_L and derived:

$$m_L = 2.07 + \log Up + 1.31 \log \Delta + 0.08 \Delta + c$$

where Up = maximum peak-peak vertical ground velocity in microns/s.

Δ = epicentral distance in degrees ($\Delta \leq 3.6^o$)

c = station correction

The relation to M_L, determined over a very narrow range of magnitudes, was:

$$m_L = 0.7 + 0.71 M_L$$

More recently Stewart (1975) produced a further-refined scale for South Australian earthquakes. His magnitude M_n is defined by

$$M_n = 4.85 + \log Ag + 0.84 \log \Delta + 0.0003 f \Delta /2.3$$
$$-2.89 \log f + 2.45 (\log f)^2 + c$$

where

Ag = ground amplitude in mm

f = frequency

This formula is restricted to the frequency range 1-10 Hz and to the magnitude range 1.5^o - 3.5^o in South Australia. According to Sutton (pers. comm.) a tentative relation between Mn and M_L is:

$$M_L = 1.33 M_n - 0.73$$

Deep earthquakes. In New Zealand the method has been applied to deep earthquakes by using the slant distance from hypocentre to station instead of the epicentral distance (Eiby & Muir, 1962).

3. SURFACE WAVE MAGNITUDE M_S

Origin

Gutenberg & Richter (1936)

Definition and procedure

$$M_S = \log A - \log A_o$$

where

A = maximum combined horizontal <u>mean-to-peak</u> ground amplitude in microns (10^{-6} m) of surface waves with period near 20 s;

A_o = ground amplitude of the reference earthquake (magnitude zero) at the same distance.

Table 2 gives values of $-\log A_o$ and is taken from Richter (1958, p. 346); a more detailed table is given by Gutenberg (1945a).

Note the introduction of ground amplitudes in place of trace amplitudes (used in the determination of M_L). This is to allow the use of seismograms from any type of instrument. The ground amplitude is derived by vectorially combining the amplitudes of the two horizontal components.

<u>Limitations and adaptations</u>

Determinations are restricted to earthquakes of shallow depth (h   35 km) at distances greater than 20° (2000 km); a 'matched' pair of long-period seismographs is required to adequately record signals at 20 s period from the majority of events. Note that a seismograph mismatch of 25% causes an error of only 0.1 in M_S.

<u>IASPEI recommendation</u>. In the range $20^\circ \leqslant \Delta \leqslant 130^\circ$, the definitive formula (i) is approximated closely by:

$$M_S = \log A + 1.656 \log \Delta + 1.87 \qquad \text{(ii)}$$

where Δ is the epicentral distance (see Table 3). Several workers have estimated the parameters in formula (ii) (cf. Bath, 1966); and in October 1967 the International Association of Seismology and Physics of the Earth's Interior (IASPEI) recommended the following formula which is representative of the various results:

$$M_S = \log (A/T) + 1.66 \log \Delta + 3.3 \qquad \text{(iii)}$$

where T = the wave period (seconds) and $18 \leqslant T \leqslant 22$

This yields magnitudes which are about 0.2 higher than those given by the original formula (i) for $20^\circ \leqslant \Delta \leqslant 130^\circ$ (Table 3).

Working formulas. In terms of trace amplitudes the IASPEI formula is:

$$M_S = \log Amm/T - \log Vt + 1.66 \log \Delta + 6.3 \qquad (iv)$$

where

$Amm = (An^2 + Ae^2)^{\frac{1}{2}}$

An = trace amplitude of N-S component in mm

Ae = trace amplitude of E-W component in mm

Vt = magnification at period T

= (Vn + Ve)/2 provided Vn = Ve $\pm$ 10%

Further, if it is assumed that T is 20 s:

$$M_S = \log Amm - \log V20 + 1.66 \log \Delta + 5.0 \qquad (v)$$

with a maximum error of 0.04 (provided T is in the specified range).

Extension to shorter distances. Marshall & Basham (1973) have devised an extension of the scale to cover distances less than 20°. It allows for the higher frequency of Rayleigh waves in these distances, and normalizes the results to long distance/20s values. Their formula is

$$M_s' = \log A + B'(\Delta) + P(\Delta)$$

where

$B'(\Delta)$ = distance-correction term (given in Table 4)

$P(\Delta)$ = path-correction term (given in Table 5)

The path-correction term includes the allowance for variation of wave-period with distance, and the formula gives magnitudes which agree within 0.1 of those given by (i) and (iii) in the range ($T = 20, \Delta \geqslant 25°$).

This scale was presented to the IASPEI Commission on Practice at the Moscow Assembly of IUGG (1971), but it has not yet been adopted officially.

Extension for use on vertical component and for depths to 100 km. Bath (1952) extended the surface-wave magnitude concept to allow application to vertical-component (Benioff) seismographs. His formula also allows for greater than normal focal depths, and includes corrections for an observed variation with magnitude of the ratio of vertical to horizontal amplitudes; and for the region of occurrence. His formula is:

$$M = \log Az - \log Ao + \delta(h) + m_R + c\,(Mo-Mc)$$

Az = vertical ground amplitude (microns) at 20s

A_o = Gutenberg's distance term

$\delta(h)$ = depth term (= 0.008 h for $h \leqslant 100$)

m_R = regional correction term

c = amplitude variation coefficient

Mo = 7.1

$M_c = (\log A_z - \log A_o + \delta(h) + M_R)$

The mean value of c is 0.2 but in the southwest Pacific c ranges from 0.0 to 0.2 (loc. cit. p. 87).

The values of m_R for the Australian-New Guinea region are (loc. cit. p. 85):

Australia	:	+0.3
New Guinea	:	-0.3 ($h \leqslant 40$)
	:	+0.1 ($40 < h \leqslant 100$)
Solomon Is	:	+0.3 ($H \leqslant 40$)
	:	-0.4 ($40 < h \leqslant 100$)

4. BODY-WAVE MAGNITUDE, m_B

Origin

Gutenberg 1945b and 1945c.

Definition and procedure

$$m_B = \log (A/T) + Q$$

where

A = maximum mean-to-peak ground amplitude in microns of P, PP, or S wave train.

T = corresponding wave-period (seconds)

Q = depth/distance factor

Plates 4, 5, and 6 show the Q factors derived by Gutenberg, and re-presented by Richter (1958, p. 688-689). (In the original, 'A' was used for Q which has been retained here to accord with current usage.) The Q factors were derived empirically to make $m_B = M_S$ near magnitude 7 but it was found subsequently that the two scales diverged at other magnitudes (see Chapter 5).

Note the introduction of the wave-period (cf. IASPEI formula for M_S) to cope with the large variations in period of the different phases and the diversity of seismographs in use. The quantity (A/T) is related theoretically to the kinetic energy of the wave.

Limitations and adaptations

The method is limited to distances greater than: 5^o (600 km) for P waves; 10^o (1100 km) for S waves; and 25^o (2800 km) for PP waves. There is no depth restriction, and any type of seismogram may be used.

Extrapolation to short distances. The method has been extended for PZ to cover the epicentral range between 1^o and 5^o by several groups (cf. Hofmann & Romberg, 1963). They derived a curve 'A_2' equivalent to the Q data for surface focus. For studies of seismicity in Western Australia and using data from recordings at Mundaring observatory (MUN), Everingham (1968) evaluated a curve of 'A_2' for use on WA earthquakes. He found that

$$m_B = m_B \text{ (MUN)} + 0.4$$

USERL body-wave magnitude. The World Wide Standardised Seismograph Network (WWSSN) was set up by the US Coast and Geodetic Survey (CGS) between 1961 and 1964. (In July 1970 CGS became the National Ocean Survey (NOS), and in July 1971 NOS became the Environmental Research Laboratories (ERL) of the National Oceanic and Atmospheric Administration; in 1973 the seismological function was transferred to the US Geological Survey (GS)). The WWSSN instruments included carefully calibrated and standardized Benioff short-period seismographs, and stations were required to report body-wave magnitudes defined on the same lines as m_B. However the CGS instruction was to measure the 'maximum amplitude in the first few cycles of P', not the maximum amplitude in the entire P wave-train. Amplitude data are reported either as ground amplitudes in millimicrons (10^{-9}m), or as trace ranges (peak-peak) in millimetres together with the corresponding magnification.

Because the amplitude is measured in a different way the US body-wave magnitude is not m_B, and because it generally appears on a computer print-out (with no lower case letters) it is designated MB (cf Earthquake Data Reports). To be completely unambiguous these terms should be used, depending on the epoch of the data: MB (CGS), MB(NOS), MB(ERL), MB(GS). In some of the literature the symbol m_b has been used, but in September 1971 ERL confirmed that this usage is erroneous.

Several writers have compared MB(ERL) with m_B (e.g. Fisher et al., 1964; Evernden, 1970) with the following mean result

$$m_B = MB(ERL) + 0.7$$

for $5 \leqslant MB(ERL) \leqslant 6$.

IASPEI recommendation. In 1967 IASPEI endorsed the original formula for determining body wave magnitudes, viz

$$m_B = \log (A/T) + Q$$

ISC body wave magnitude. The International Seismological Centre (ISC) has adopted for data since 1964 the 'unified' magnitude (m) defined the same as MB. The ISC receives data direct from some stations and in collated form from the USGS for other stations. It is likely that most stations report amplitudes on the ERL basis, not the ISC basis, because Willmore, (in Båth, 1968 p. 88) has shown that, generally: m (ISC) = MB(ERL). If amplitude data were reported correctly to ISC we should have: m(ISC) = MB(ERL) + 0.7, so it appears that ISC magnitudes are not true unified magnitudes.

5. MAGNITUDE AND ENERGY RELATIONS

Relations between main magnitude scales

The definitive magnitude scales are M_L, M_S, and m_B. Ideally all scales should give the same values for corresponding earthquake sizes, but in general this does not happen. The reasons for this unfortunate result lie in the scale definitions, in the recording systems, in the wave spectra, in crustal and mantle structure, and in the earthquake mechanism. Therefore it is essential that (a) it is clearly stated how magnitude results were obtained; and (b) how magnitudes on one scale have been converted to those in another.

After the introduction of M_S and m_B, Gutenberg & Richter (1956a) determined that the empirical relation between them was:

$$m_B = 0.63\ M_S + 2.5 \qquad \text{(i)}$$

or correspondingly,

$$M_S = 1.59\ m_B - 4.0 \qquad \text{(ii)}$$

Båth (1966) lists the results of several other investigators. IASPEI has recommended that the relation should be

$$m_B = 0.56M_S + 2.9 \qquad \text{(iii)}$$

(which is the mean of the results referred to by Bath) i.e.

$$M_S = 1.79m_B - 5.2 \qquad \text{(iv)}$$

When magnitudes are converted by these formulas from one to the other scale the subscripts are dropped, so we have:

Body wave magnitude from surface waves:

$$m = 0.56\ M_S + 2.9 \qquad \text{(v)}$$
$$= 0.56\ (\log A/T) + 1.66 \log\Delta + 3.3) + 2.9 \qquad \text{(vi)}$$
$$= 0.56 \log (A/T) + 0.93 \log\Delta + 4.7 \qquad \text{(vii)}$$

Surface wave magnitude from body waves:

$$M = 1.79\ m_B - 5.2 \qquad \text{(viii)}$$
$$= 1.79\ (\log (A/T) + Q) - 5.2 \qquad \text{(ix)}$$

According to the recommended relation (iii) the scales coincide at $m = M = 6.6$. (Note in passing that symbols such as m_S (for *m*) and M_B (for M) have been used, but they do not clarify the terminology and should be abandoned).

An empirical relation between the Richter magnitude and the body-wave magnitude is (Gutenberg & Richter, 1956b):

$$m = 1.7 + 0.8\ M_L - 0.01M_L^2 \qquad \text{(x)}$$

In the range $1 \leq M_L \leq 6$ this is approximated closely by

$$m = 1.8 + 0.73M_L \qquad \text{(xi)}$$

(White, 1968). The scales coincide at $m = M_L = 6.4$

The relation (x) is, in the authors' words, "... not yet on a definitive basis ....." (loc. cit., p. 14), but it is still referred to in a definitive way almost 20 years later (e.g. Båth, 1973). A recent study of earthquakes in New Zealand by Gibowicz (1972) gave these significantly different relations, over the range $4.6 \leq M_L \leq 7.3$:

(a) Shallow ($h \leqslant 100$ km)

$$m = 0.37 + 0.86\ M_L \qquad \text{(xii)}$$

(b) Deep ($h > 100$ km)

$$m = -0.10 + 0.85\ M_L \qquad \text{(xiii)}$$

However, Gibowicz used USCGS data (or data converted to USCGS equivalent) so his m is in fact MB(CGS) (= m - 0.7). That is, (xii) and (xiii) should be

$$m = 1.07 + 0.86\ M_L \quad \text{(shallow)} \qquad \text{(xiv)}$$

$$m = 0.80 + 0.85\ M_L \quad \text{(deep)} \qquad \text{(xv)}$$

Over the range for which these relations were determined, the maximum discrepancy between (xiv) and (x) is 0.3 in m, so the recent results indicate that Gutenberg and Richter's initial formula is surprisingly good. Gibowicz's finding that the M_L values of the deeper earthquakes are consistently higher than those for the shallower earthquakes may have more than local significance. Obviously, the relation between M_L and the other scales needs further investigation.

Plate 7 shows the relations between the main scales (and MB(ERL)).

<u>Relations between magnitude and energy</u>

The first magnitude scale (M_L) was devised to provide a rough separation of large, medium, and small shocks (Richter, 1958), i.e. to provide measures of the relative energies released in different earthquakes.

Subsequently estimates of the actual energies released in particular earthquakes were made from field observations of fault displacements and theoretically from seismograms. From these estimates, empirical relations between energy (E, ergs) and magnitude were established. Gutenberg & Richter (1956b) determined

$$\log E = 5.8 + 2.4\ m \qquad \text{(i)}$$

$$= 11.8 + 1.5\ M \qquad \text{(ii)}$$

$$= 9.9 + 1.9\ M_L - 0.024\ M_L^2 \qquad \text{(iii)}$$

(It should be noted that the constant in formula (ii) is incorrectly shown as 11.4 by Richter (1958, p. 366), an error which tends to be perpetuated by other authors (e.g. Brooks, 1965, p. 24; Lomnitz, 1974, p. 24)).

Applying the IASPEI relation ($m = 0.56M + 2.9$) to (i), the energy formulas become

$$\log E = 5.8 + 2.4\ m \qquad \text{(iv)}$$

$$= 12.8 + 1.34\ M \qquad \text{(v)}$$

Bath determined the relation

$$\log E = 12.24 + 1.44\ M \qquad \text{(vi)}$$

and applying the IASPEI magnitude relation (iii)

$$\log E = 4.78 + 2.57\ m \qquad \text{(vii)}$$

Also from (x)

$$\log E = 9.15 + 2.06\ M_L - 0.026\ M_L^2 \qquad \text{(ix)}$$

IASPEI has made no recommendation on an energy formula, but (iv) and (v), and (vi) and (vii) preserve the approved magnitude relation and either pair should be used until international agreement is reached.

Table 6 shows the relations between the magnitude scales and energy, and Plate 8 illustrates the magnitude scales in relation to energy according to formula (vi). On this scale an M5 earthquake corresponds to an energy release equivalent to that from 600 tons of TNT (2.5×10^{19} ergs).

The energy formulas (v) and (vi) agree at $M = 7.3$, and differ by a factor of 2 (in energy) at $M = 3$ and $M = 8$. They give factors of 22 and 28 for the ratio of energy per unit increase in magnitude and are the basis for statements in the literature such as "...a magnitude increase by one unit... corresponds to an energy increase by 25-30 times" (Båth, 1973, p. 116). It must be noted that such statements hold only with respect to the surface-wave relation.

6. Recommendations

It is probable that attempts to rate earthquakes in terms of the energy at the source by a single number derived from seismograph recordings is a forlorn endeavour. The descriptions of the principal magnitude scales and reference to some of their derivatives indicate the limited application of each, and the complexity of the problem; their relations to energy (Plate 8) should emphasize the care and caution needed in using magnitude statistics. We note the 1968 IASPEI recommendation that the surface-wave magnitude is at present the best parameter for statistical purposes, because it has the advantage that there is little lateral variation in the attenuation of 20s period waves anywhere in the world, so the formula is valid everywhere (Duda & Nuttli, 1974, p. 433).

Nevertheless, the magnitude parameter will continue in use for a long time yet because (with care) it is easily derived and (again with care) it does provide a reasonable relative rating of earthquake size. But to avoid confusion and ambiguity a self-consistent set of symbols and formulas which accord with original definitions or international agreements is essential; furthermore, local symbols must be clearly distinguished from those more generally adopted, and formulas should accompany results to allow conversion from one scale to another.

The following recommendations are made for use within BMR:

(a) Richter magnitudes (M_L) should be determined from

$$M_L = \log A - \log Ao$$

defined in Chapter 2.

(b) Surface-wave magnitudes (M_S) should be determined from

$$M_S = \log (A/T) + 1.66 \log \Delta + 3.3$$

defined in Chapter 3.

(c) Body-wave magnitudes (m_B) should be determined from

$$m_B = \log (A/T) + Q$$

defined in Chapter 4

(d) The symbols for derived magnitudes are m (from body waves) and M (from surface waves); they are related by:

$$m = 0.56M + 2.9$$

$$M = 1.79m - 5.2$$

(e) M_s or M should be used in statistical studies

(f) M_L is related to m by

$$m = 1.7 + 0.8\, M_L - 0.01\, M_L^2$$

$$\simeq 1.8 + 0.73 M_L \quad (1 \leqslant M_L \leqslant 6)$$

(g) Energy/magnitude formulas are

$$\log E = 5.8 + 2.4\ m \qquad)$$
$$= 12.8 + 1.34\ M \qquad)$$
$$= 9.9 + 1.9\ M_L - 0.024\ M_L^2 \qquad)$$

OR

$$\log E = 12.24 + 1.44\ M \qquad)$$
$$= 4.78 + 2.57\ m \qquad)$$
$$= 9.15 + 2.06\ M_L - 0.026 M_L^2 \qquad)$$

(h) In texts of BMR Records in order to simplify typing and avoid errors the approved symbols may be written:

Approved	BMR
M_L	ML
M_S	MS
m_B	mB (or MB in computer printouts)

(i) US body-wave magnitudes should be written: MB (CGS : NOS : ERL : GS) according to the epoch of the data

(j) MB (ERL) = m_B - 0.7 ca in the range 5 MB 6

(k) Non-standard magnitudes should show the source (e.g. M_L (PMG)); if the magnitude is not determined according to one of the definitions (a), (b) or (c), the formula used must be shown, or the method described.

(l) Magnitudes should be derived on as many different scales as possible in order to allow the accumulation of statistics for studies of scale-interrelations; in particular instruments suitable for directly determining Richter and surface-wave magnitudes should be used wherever possible.

(m) The question of the 'standard' Wood-Anderson magnification should be resolved; the response curve of recently manufactured Wood-Anderson needs to be determined.

(n) A program to determine seismic moments should be started with the aim of providing better statistics on seismicity.

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Addendum

The Richter distance term, log Ao

It can be useful to have the distance term in the form of a numerical expression rather than having to refer to tabular values (c.f. the surface-wave magnitude formula). In the distance range 50 to 600 km the tabular values are approximated closely by the parabolic function:

$$- \log Ao'' = 2.26 + 7.46 \Delta .10^{-3} - 0.51 \Delta^2 .10^{-5}$$

And in the range 100 to 500 km they are approximated, less closely, by the linear function:

$$- \log Ao' = 2.7 + 4.0 \Delta .10^{-3}$$

The table shows the values given by the functions and the discrepancies they produce.

Δ	Distance terms			Differences	
km	-log Ao	-log Ao"	-log Ao'	d"	d'
45	2.5	2.59		-0.09	
50	2.6	2.62	2.9	-0.02	-0.3
100	3.0	2.96	3.1	+0.04	-0.1
200	3.5	3.55	3.5	-0.05	0.0
300	4.0	4.05	3.9	-0.05	+0.1
400	4.5	4.44	4.3	+0.06	+0.2
500	4.7	4.74	4.7	-0.04	0.0
600	4.9	4.94	4.1	-0.04	-0.2

TABLE 1

Distance term (log Ao) in the formula for Richter magnitude

Δ(km)	- log Ao	Δ(km)	- log Ao	Δ(km)	- log Ao
0	1.4	150	3.3	390	4.4
5	1.4	160	3.3	400	4.5
10	1.5	170	3.4	410	4.5
15	1.6	180	3.4	420	4.5
20	1.7	190	3.5	430	4.6
25	1.9	200	3.5	440	4.6
30	2.1	210	3.6	450	4.6
35	2.3	220	3.65	460	4.6
40	2.4	230	3.7	470	4.7
45	2.5	240	3.7	480	4.7
50	2.6	250	3.8	490	4.7
55	2.7	260	3.8	500	4.7
60	2.8	270	3.9	510	4.8
65	2.8	280	3.9	520	4.8
70	2.8	290	4.0	530	4.8
80	2.9	300	4.0	540	4.8
85	2.9	310	4.1	550	4.8
90	3.0	320	4.1	560	4.9
95	3.0	330	4.2	570	4.9
100	3.0	340	4.2	580	4.9
110	3.1	350	4.3	590	4.9
120	3.1	360	4.3	600	4.9
130	3.2	370	4.3		
140	3.2	380	4.4		

TABLE 2

Distance term (log Ao) in the surface-wave magnitude formula.

Δ(degrees)	-log Ao	Δ(degrees)	-log Ao
20	4.0	90	5.05
25	4.1	100	5.1
30	4.3	110	5.2
40	4.5	120	5.3
45	4.6	140	5.3
50	4.6	160	5.35
60	4.8	170	5.3
70	4.9	180	5.0
80	5.0		

TABLE 3

Comparison of distance terms in surface-wave magnitude formulas

Δ°	$-\log A_o$	$-\log A'_o$	d'	$-\log A''_o$	d''
20	4.0	4.02	0.02	4.16	0.16
30	4.3	4.32	0.02	4.45	0.15
40	4.5	4.52	0.02	4.66	0.16
50	4.6	4.68	0.08	4.82	0.22
60	4.8	4.81	0.01	4.95	0.15
70	4.9	4.93	0.03	5.06	0.16
80	5.0	5.02	0.02	5.16	0.16
90	5.05	5.11	0.06	5.24	0.19
100	5.1	5.18	0.08	5.32	0.22
110	5.2	5.25	0.05	5.39	0.19
120	5.3	5.31	0.01	5.45	0.15
140	5.3	5.42	0.12	5.56	0.26
160	5.35	5.52	0.17	5.66	0.31
170	5.3	5.56	0.26	5.70	0.40
180	5.0	5.60	0.60	5.74	0.74

$-\log A'_o = 1.656 \log \Delta + 1.87$ (Approximate G & R factor)

$d' = \log A_o - \log A'_o$

$-\log A''_o = 1.66 \log \Delta + 2.0$ (IASPEI distance factor)

$d'' = \log A_o - \log A''_o$

TABLE 4

Distance-correction (B'(Δ), surface-wave magnitudes
(Marshall and Basham formula)

Δ	B (Δ)	Δ	B (Δ)	Δ	B (Δ)	Δ	B (Δ)	Δ	B (Δ)
		20	1.25	40	1.57	60	1.85	80	2.08
1	0.17	21	1.27	41	1.59	61	1.87	81	2.09
2	0.35	22	1.29	42	1.61	62	1.89	82	2.10
3	0.57	23	1.31	43	1.62	63	1.90	83	2.11
4	0.67	24	1.32	44	1.64	64	1.91	84	2.12
5	0.78	25	1.34	45	1.65	65	1.92	85	2.13
6	0.84	26	1.36	46	1.66	66	1.93	86	2.14
7	0.90	27	1.38	47	1.68	67	1.94	87	2.15
8	0.95	28	1.40	48	1.70	68	1.95	88	2.16
9	0.98	29	1.41	49	1.71	69	1.96	89	2.17
10	1.02	30	1.43	50	1.72	70	1.97	90	2.18
11	1.05	31	1.44	51	1.74	71	1.98	91	2.18
12	1.08	32	1.45	52	1.75	72	1.99	92	2.19
13	1.11	33	1.47	53	1.76	73	2.01	93	2.20
14	1.13	34	1.48	54	1.77	74	2.02	94	2.21
15	1.15	35	1.50	55	1.78	75	2.03	95	2.22
16	1.17	36	1.52	56	1.80	76	2.04	96	2.23
17	1.19	37	1.54	57	1.82	77	2.05	97	2.24
18	1.21	38	1.55	58	1.83	78	2.06	98	2.25
19	1.23	39	1.56	59	1.84	79	2.07	99	2.26

TABLE 5

Path-correction term P (Δ), surface-wave magnitudes
(Marshall & Basham formula)

North America (Totally continental)		Eurasia (Totally continental)	Mixed Path (Oceanic and continental)	Oceanic
T secs	Correction	Correction	Correction	Correction
10	-.75	-.30	.00	+.50
11	-.67	-.27	+.01	+.45
12	-.61	-.24	+.03	+.38
13	-.53	-.21	+.04	+.33
14	-.46	-.18	+.05	+.27
15	-.38	-.15	+.07	+.20
16	-.30	-.13	+.08	+.15
17	-.24	-.10	+.09	+.09
18	-.16	-.07	+.10	+.03
19	-.08	-.04	+.12	-.03
20	.00	.00	+.13	-.09
21	+.01	+.03	+.15	-.08
22	+.03	+.05	+.16	-.07
23	+.04	+.07	+.17	-.06
24	+.05	+.11	+.18	-.05
25	+.07	+.14	+.20	-.04
26	+.09	+.18	+.21	-.03
27	+.11	+.22	+.22	-.03
28	+.13	+.24	+.23	-.02
29	+.14	+.27	+.24	-.01
30	+.16	+.30	+.25	.00
31	+.17	+.32	+.26	+.01
32	+.18	+.33	+.27	+.02
33	+.20	+.34	+.28	+.03
34	+.21	+.35	+.29	+.04
35	+.23	+.36	+.30	+.05
36	+.25	+.37	+.31	+.06
37	+.27	+.38	+.32	+.07
38	+.28	+.39	+.33	+.08
39	+.29	+.40	+.34	+.09
40	+.31	+.41	+.35	+.10

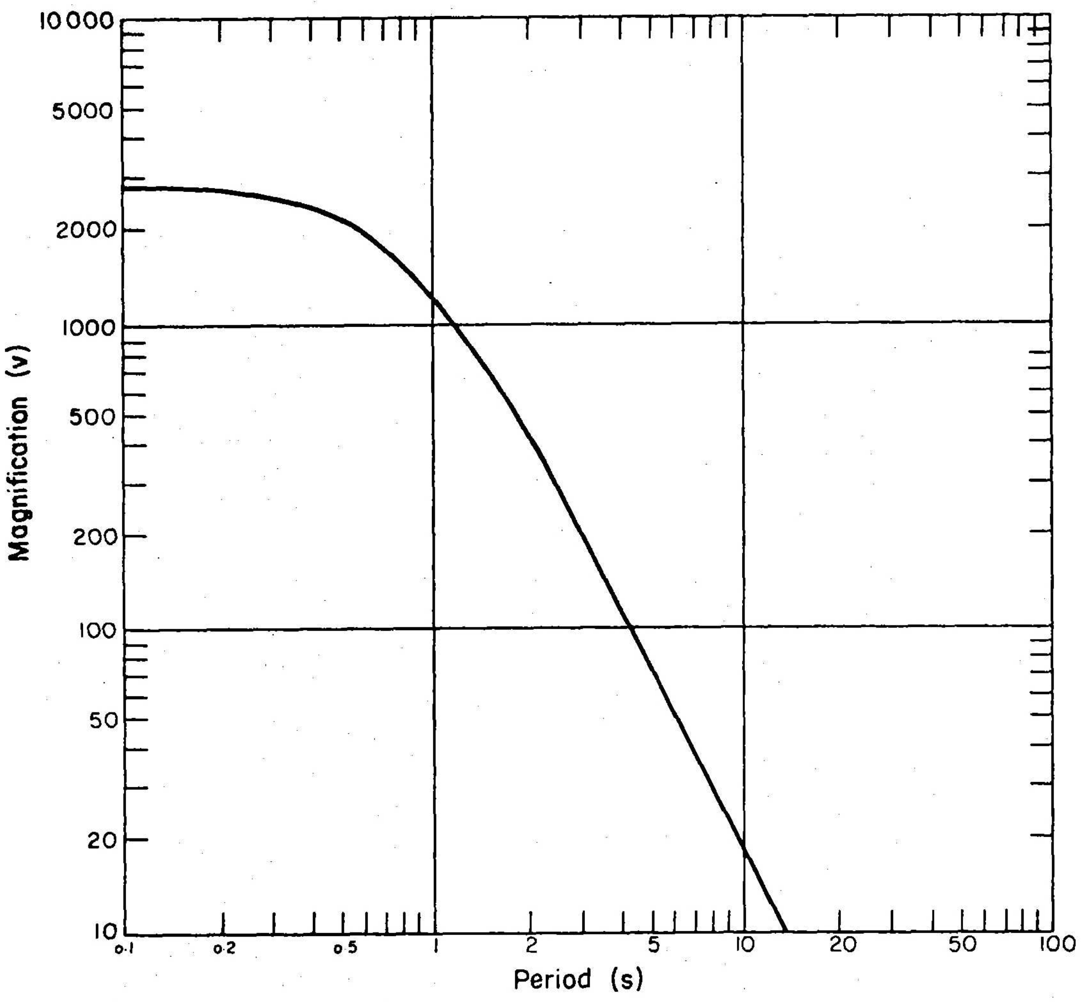
TABLE 6

Comparison of the magnitude scales and energy

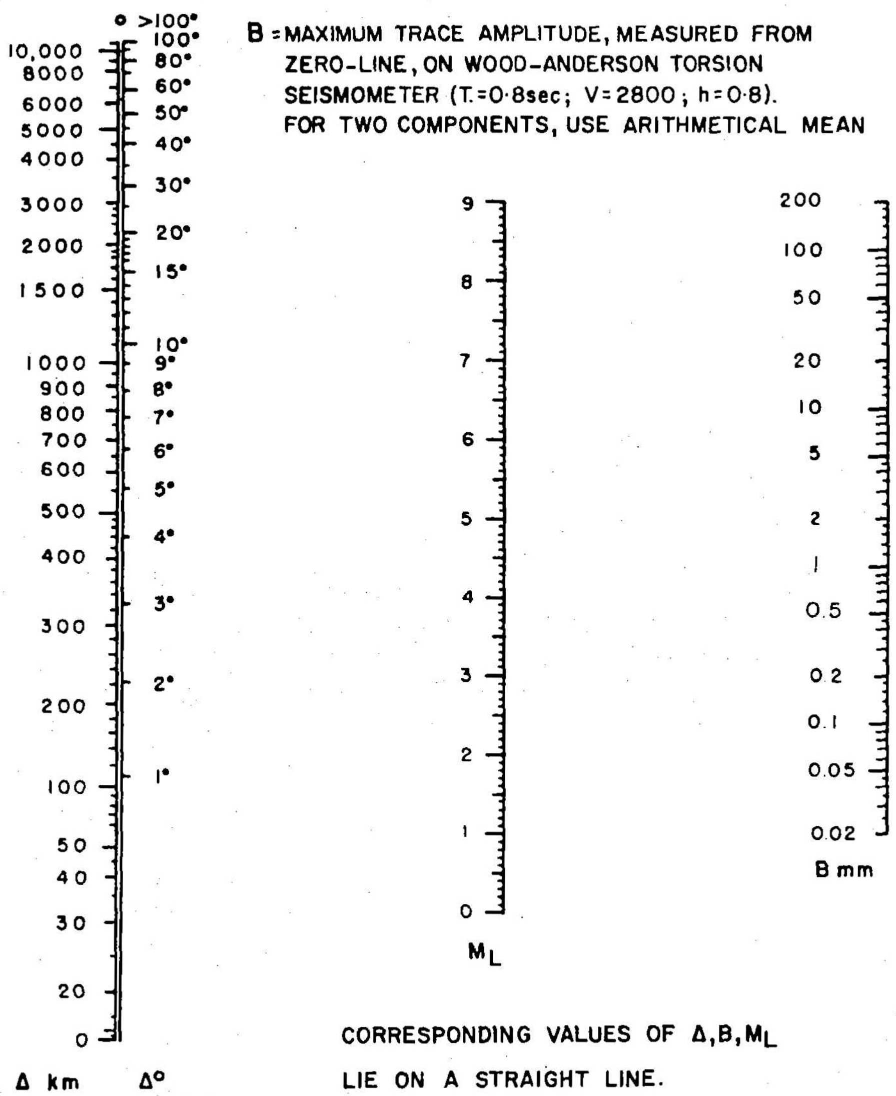
M	m	M_L	MB(ERL)	log E (m)	log E (M)	M	m	M_L	MB(ERL)	log E (m)	log E (M)
3.0	4.6	3.8		16.8	16.6	5.5	6.0	5.8	5.3	20.2	20.2
3.1	4.6	3.9		16.9	16.7	5.6	6.0	5.8	5.3	20.3	20.3
3.2	4.7	4.0		17.1	16.8	5.7	6.1	5.9	5.4	20.4	20.4
3.3	4.7	4.0		17.2	17.0	5.8	6.1	6.0	5.4	20.6	20.6
3.4	4.8	4.1		17.3	17.1	5.9	6.2	6.1	5.5	20.7	20.7
3.5	4.9	4.2		17.5	17.3	6.0	6.3	6.2	5.6	20.8	20.9
3.6	4.9	4.3		17.6	17.4	6.1	6.3	6.3	5.6	21.0	21.0
3.7	5.0	4.3		17.7	17.6	6.2	6.4	6.3	5.7	21.1	21.2
3.8	5.0	4.4		17.9	17.7	6.3	6.4	6.4	5.7	21.2	21.3
3.9	5.1	4.5		18.0	17.9	6.4	6.5	6.5	5.8	21.4	21.5
4.0	5.1	4.6		18.1	18.0	6.5	6.5	6.6	5.8	21.5	21.6
4.1	5.2	4.7		18.3	18.1	6.6	6.6	6.7	5.9	21.6	21.7
4.2	5.2	4.7		18.4	18.3	6.7	6.6	6.8	5.9	21.8	21.9
4.3	5.3	4.8		18.5	18.4	6.8	6.7	6.8	6.0	21.9	22.0
4.4	5.4	4.9		18.7	18.6	6.9	6.8	6.9	6.1	22.0	22.2
4.5	5.4	5.0		18.8	18.7	7.0	6.8	7.0	6.1	22.2	22.3
4.6	5.5	5.0		19.0	18.9	7.1	6.9	7.1	6.2	22.3	22.5
4.7	5.5	5.1		19.1	19.0	7.2	6.9	7.2		22.4	22.6
4.8	5.6	5.2		19.2	19.2	7.3	7.0	7.3		22.6	22.8
4.9	5.6	5.3	4.9	19.3	19.3	7.4	7.0	7.4		22.7	22.9
5.0	5.7	5.4	5.0	19.5	19.4	7.5	7.1	7.4		22.8	23.0
5.1	5.8	5.5	5.1	19.6	19.6	7.6	7.2	7.5		23.0	23.2
5.2	5.8	5.5	5.1	19.8	19.7	7.7	7.2	7.6		23.1	23.3
5.3	5.9	5.6	5.2	19.9	19.9	7.8	7.3	7.7		23.2	23.5
5.4	5.9	5.7	5.2	20.0	20.0	7.9	7.3	7.8		23.4	23.6
5.5	6.0	5.8	5.3	20.2	20.2	8.0	7.4	7.9		23.5	23.8

$m = 2.9 + 0.56\ M$; $m = 1.7 + 0.8\ M_L - 0.01\ M_L^2$; $MB(ERL) = m - 0.7$

$\log E(m) = 5.8 + 2.4\ m$; $\log E(M) = 12.24 + 1.44\ M$

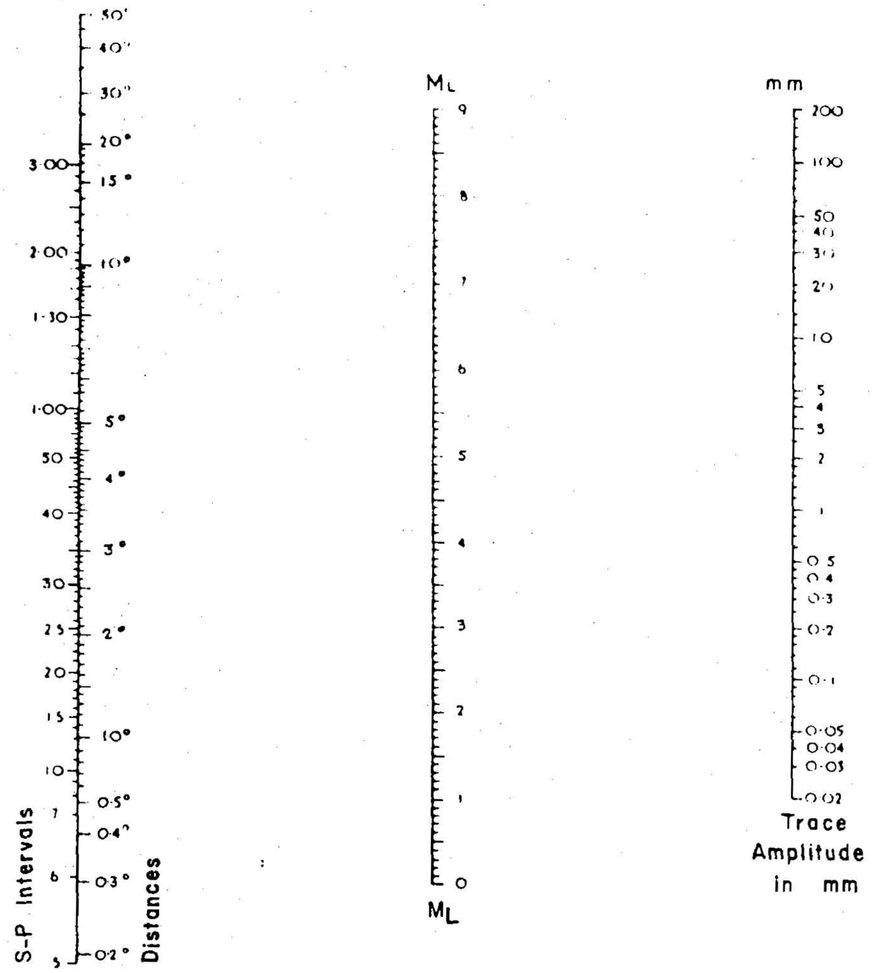


RESPONSE CURVE FOR STANDARD WOOD-ANDERSON SEISMOGRAPH



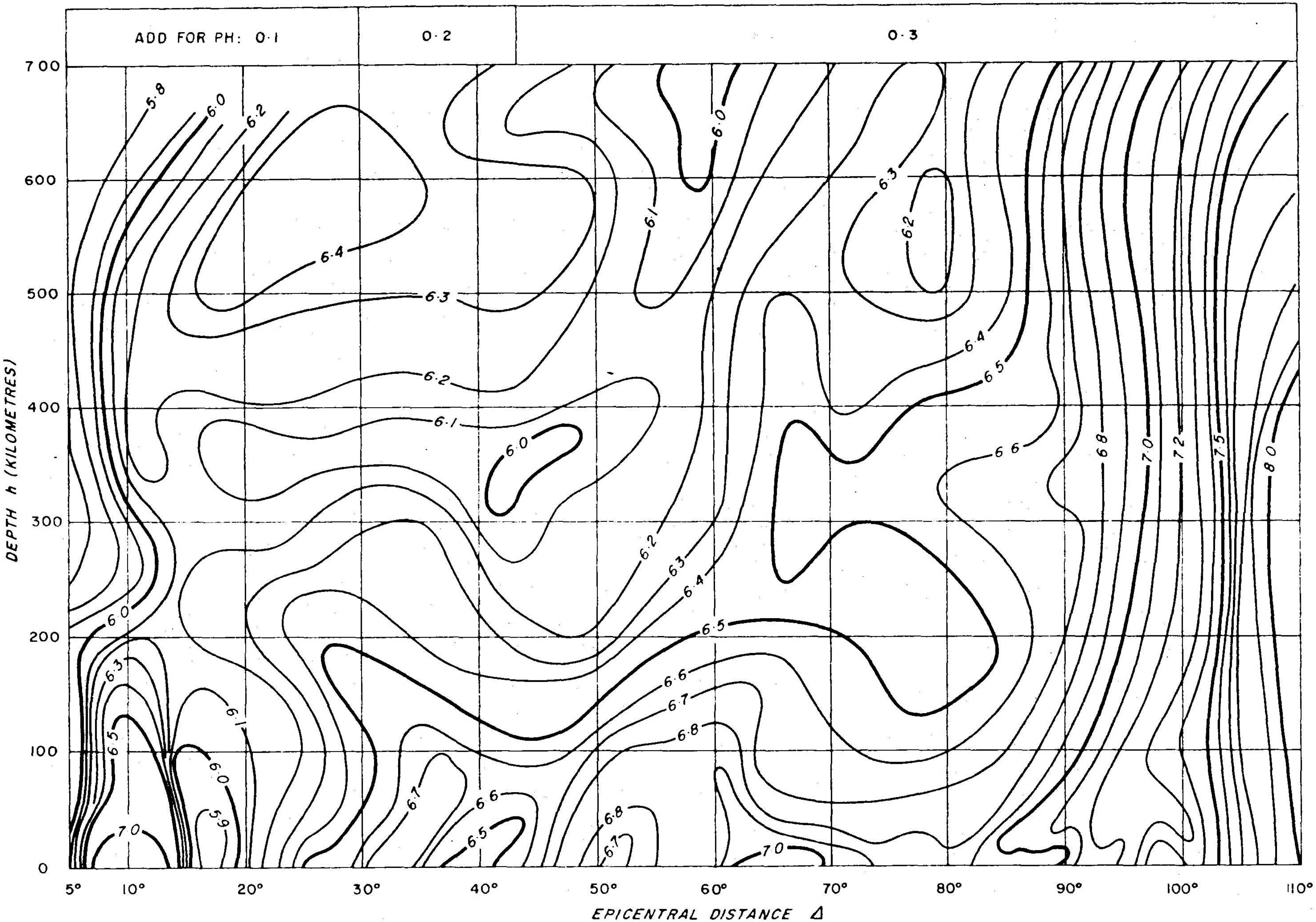
B = MAXIMUM TRACE AMPLITUDE, MEASURED FROM ZERO-LINE, ON WOOD-ANDERSON TORSION SEISMOMETER (T.=0·8sec; V=2800; h=0·8). FOR TWO COMPONENTS, USE ARITHMETICAL MEAN

CORRESPONDING VALUES OF Δ, B, M_L LIE ON A STRAIGHT LINE.



For use only with Wood-Anderson Torsion Seismographs having standard constants (Period 0·8 sec, Magnification 2800, Damping h=0·8). The maximum trace amplitude is measured from the zero line. When two components are available use the arithmetic mean. Corresponding values of distance, amplitude and magnitude lie on a straight line. S-P intervals shown are those for a focal depth of 0·00r.

REVISED VALUES OF Q FOR PZ, 1955



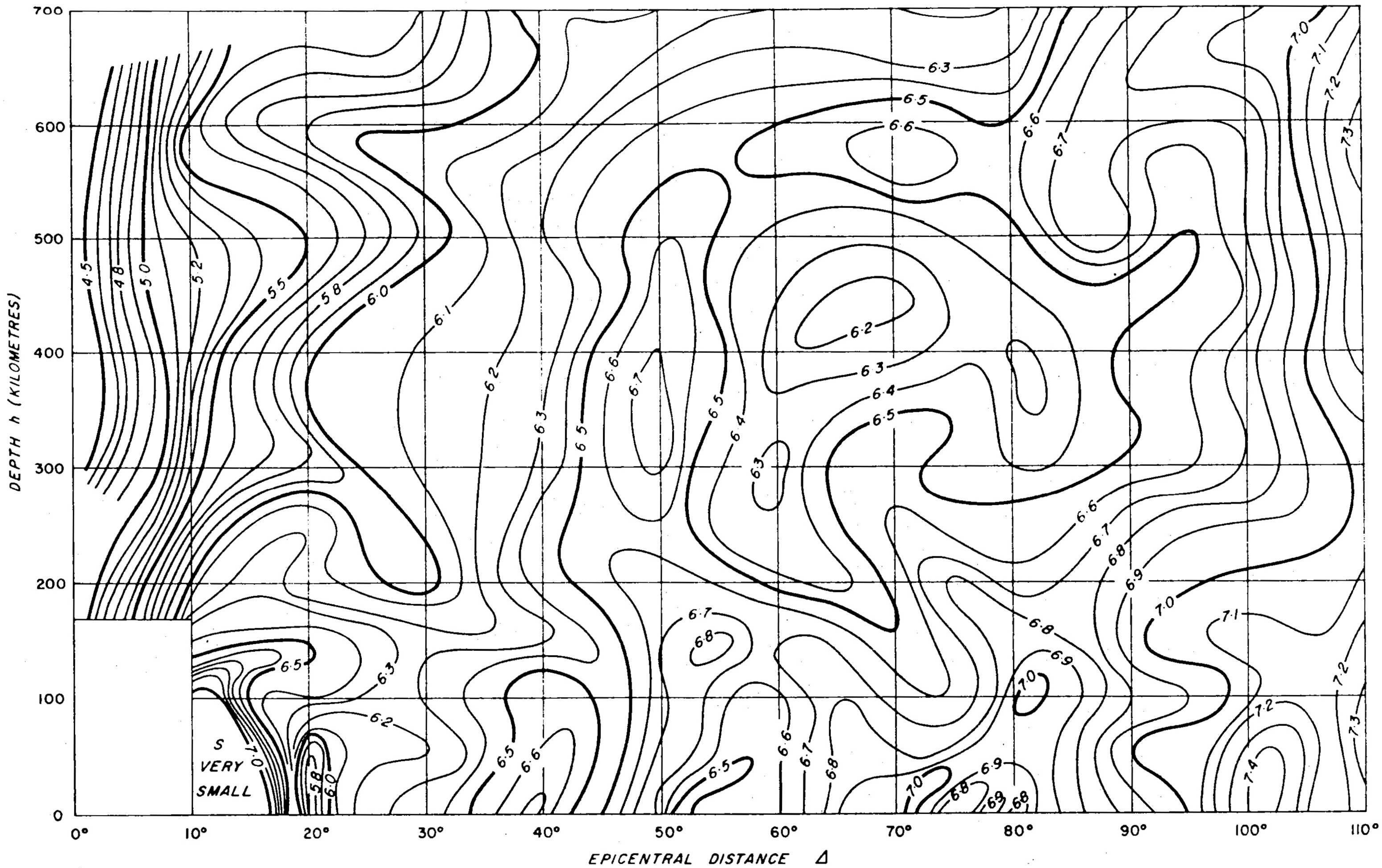
Record No. 1976/56

G82/2-158A

PLATE 4

Record No.1976/56

REVISED VALUES OF Q FOR SH, 1955



G82/2-159A

PLATE 5

REVISED VALUES OF Q FOR PPZ, 1955

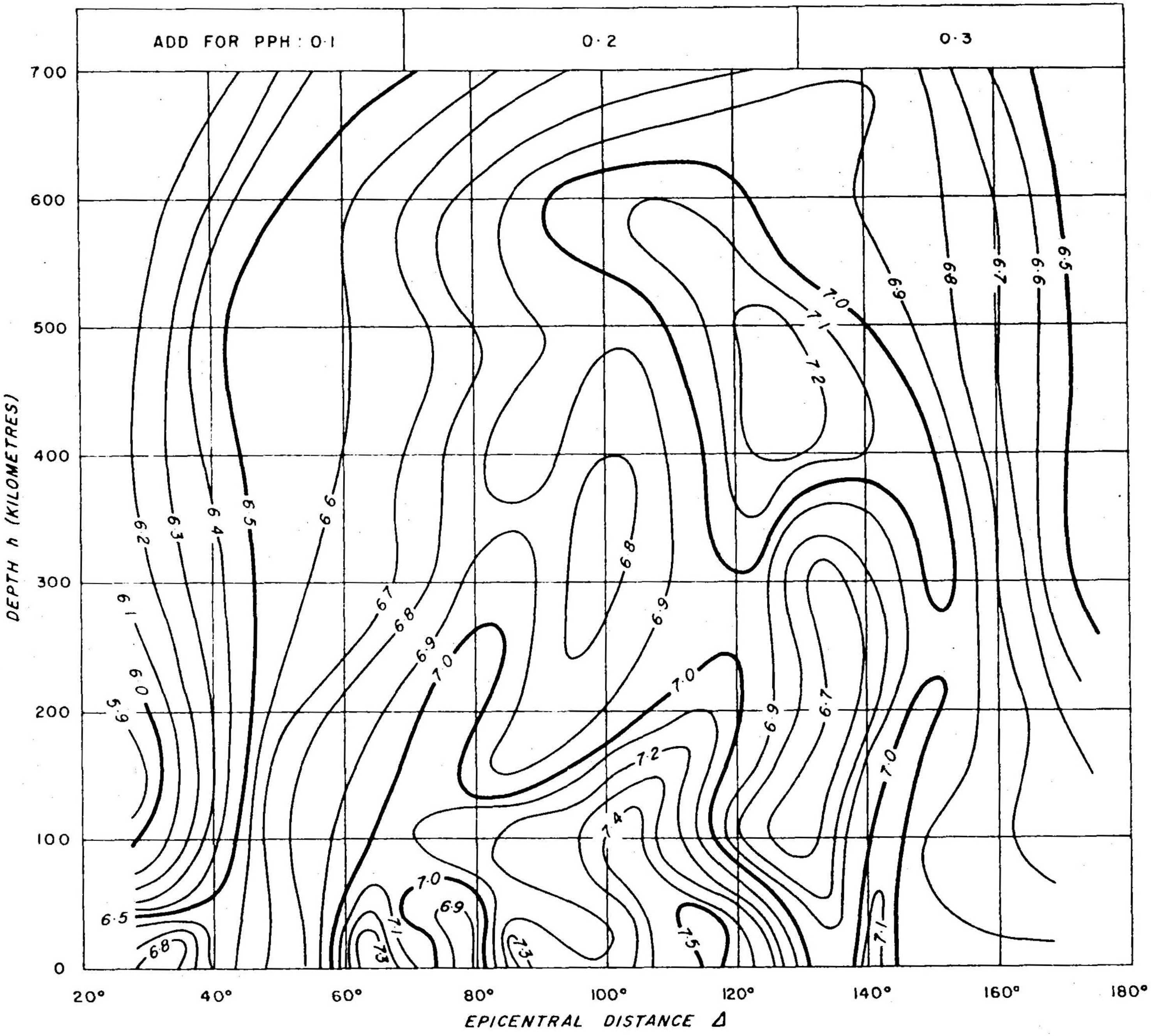
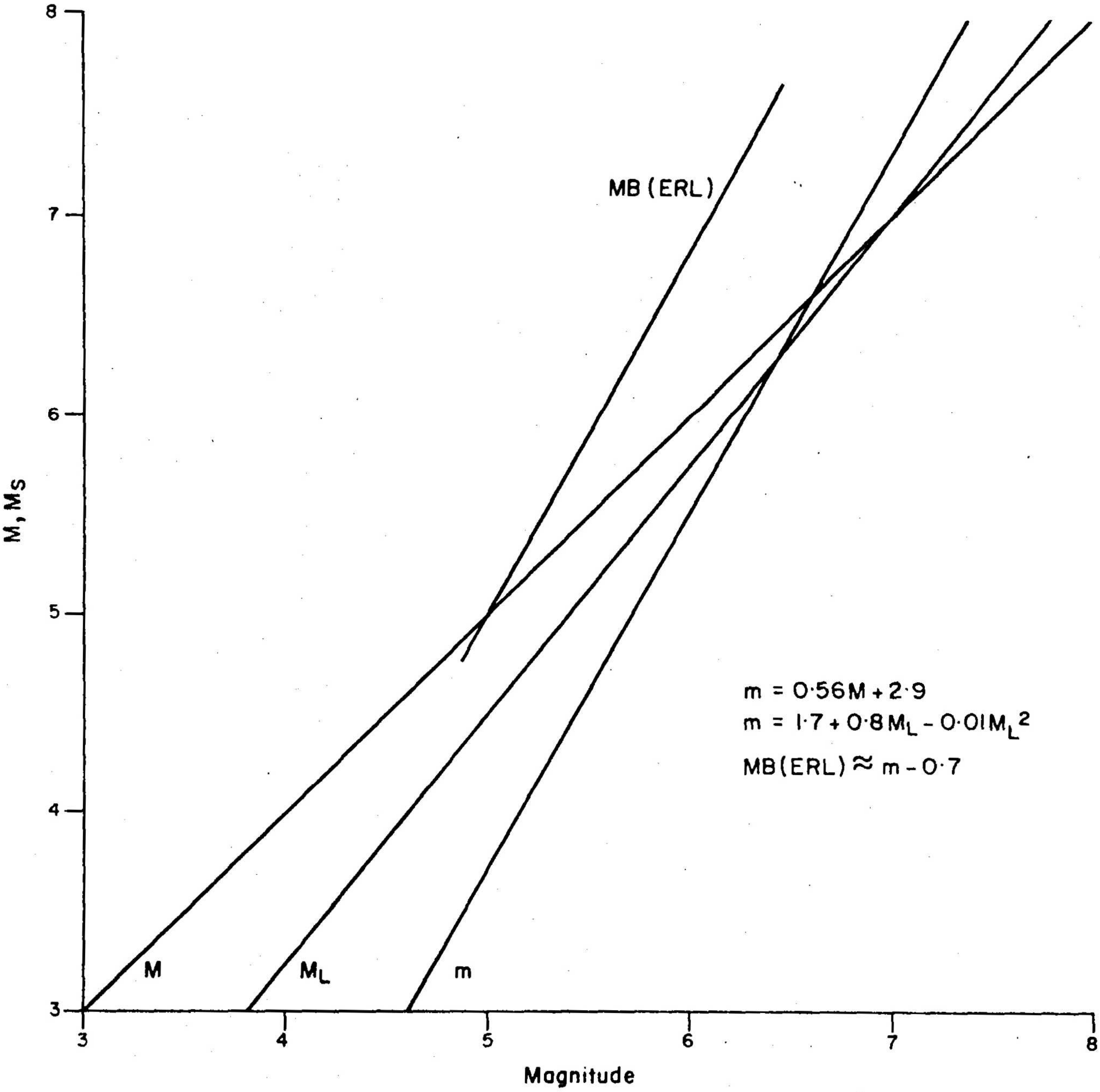
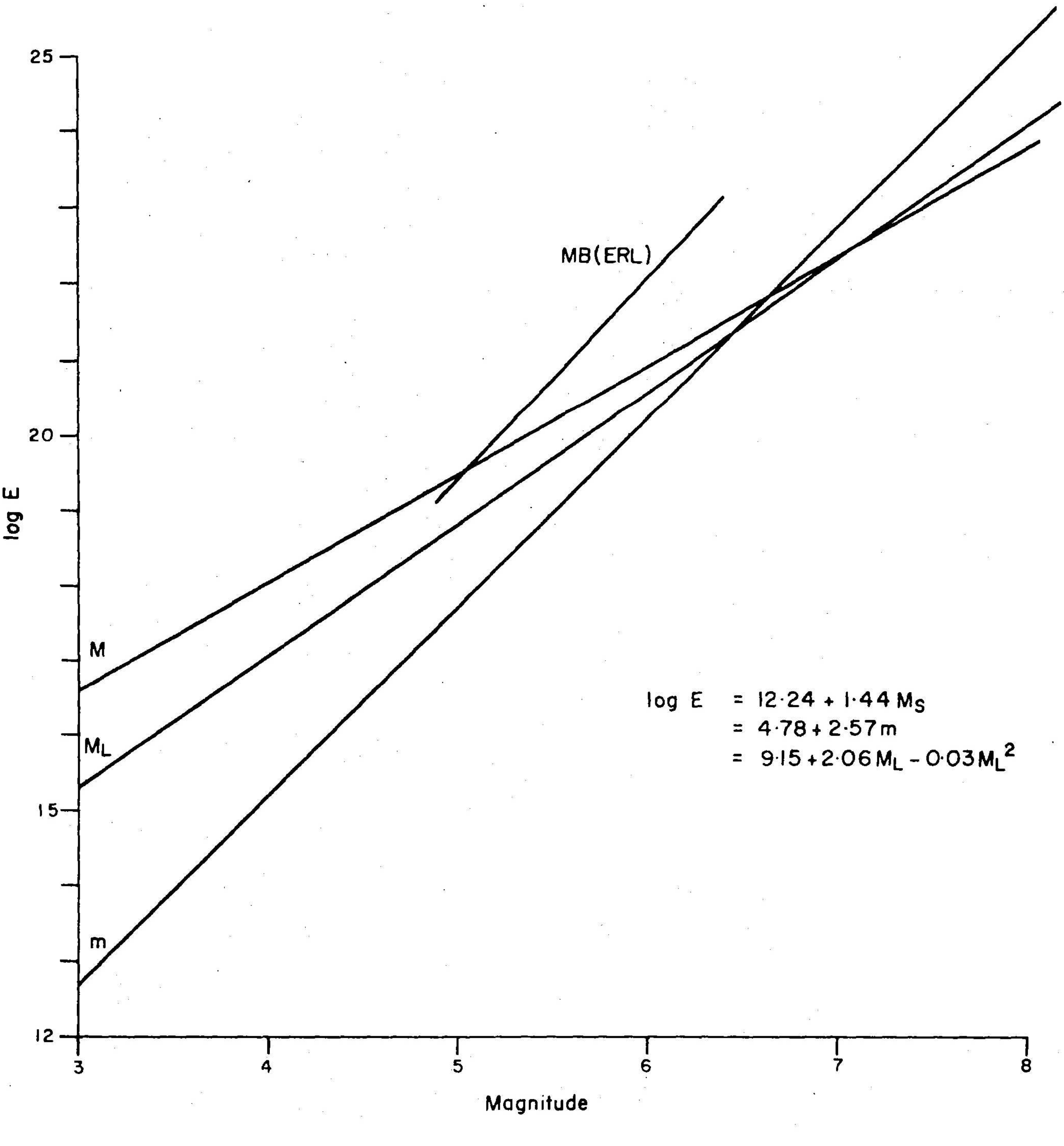


PLATE 6

GR22-160A



RELATIONS BETWEEN THE MAGNITUDE SCALES



MAGNITUDE & ENERGY RELATIONS