Tectonophysics, 93 (1983) 185–199
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

MAGNITUDE SCALE AND QUANTIFICATION OF EARTHQUAKES

HIROO KANAMORI

Seismological Laboratory, California Institute of Technology, Pasadena, Calif. 91125 (U.S.A.)

(Received September 23, 1982)

ABSTRACT

Kanamori, H., 1983. Magnitude scale and quantification of earthquakes. In: S.J. Duda and K. Aki (Editors), Quantification of Earthquakes. *Tectonophysics*, 93: 185–199.

Despite various shortcomings, the earthquake magnitude scale is one of the most fundamental earthquake source parameters to be used for catalogs. Although use of a uniform scale is desirable, it is not always possible because of changes in instrumentation, the data reduction method and the magnitude formula, the station distribution, etc. As a result, various magnitude scales have been developed and are currently in use. Recent developments in seismometry and earthquake source theories provide more quantitative source parameters than the magnitude. In order to maintain continuity and uniformity of the data, it is important to relate these magnitude scales and the new parameters. In view of this importance, relations between different magnitude scales are examined with an emphasis on the difference in the period of the waves used for the magnitude determination. Use of several magnitude scales determined at different periods provides a convenient method for characterizing earthquakes. The moment magnitude can be used to quantify both shallow and deep earthquakes on the basis of wave energy radiated, and provides a uniform scheme.

INTRODUCTION

One of the ultimate goals of earthquake-source studies is to understand the physical processes of a seismic source in as much detail as possible. There are two possible approaches to this problem. In the first approach, we make very detailed analyses of all the data available including those on seismic body waves, surface waves, near-field data, foreshocks and aftershocks, static displacement field, and macro-seismic data. For many important earthquakes, this type of study has been made and the results have contributed a great deal to a better understanding of the physics of earthquake process. However, this type of study is time consuming and is not possible for every earthquake.

In the second approach we use a relatively simple method, and process a large number of events in a very short time. Since we use a relatively small number of parameters in this case, we cannot expect a very complete description of the source.

However, this approach provides the public with quick information on the earthquake. More importantly, it provides fundamental data to be included in earthquake catalogs which are the basis of a variety of scientific research. The earthquake magnitude scale, M_L, introduced by Richter (1935) is one of the important parameters to be used in the second approach. The magnitude can be determined quickly from the seismograms without detailed analyses. Yet it serves the major purposes of the second approach, public information service and cataloging of earthquakes. However, for the sake of simplicity and speed, the approach is inevitably empirical and the value of M_L does not directly represent any physical parameter of the source.

Earthquakes can be quantified with respect to various physical parameters such as the fault length, fault area, fault displacement, particle velocity and acceleration of fault motion, duration of faulting, amount of radiated energy, complexity of fault motion and a combination of these. It is impossible to represent all of these parameters by a single number, the magnitude. Obviously there is a limitation in the use of the magnitude scale for quantification of earthquakes. As mentioned earlier, the main purpose of the magnitude scale is to provide a parameter which can be used for the first-cut reconnaissance analysis of earthquake data (catalog) for various geophysical and engineering investigations; special caution should be exercised in using the magnitude beyond the reconnaissance purposes.

The problem of the magnitude scale became very complex as many different scales were introduced to accommodate different situations such as use of teleseismic surface and body waves, extension of the scale to intermediate and deep earthquakes, change in the seismic instrumentation, extension of the scale to very small and very large earthquakes and introduction of new seismological concepts.

Recent developments in seismometry and earthquake source theories provide more quantitative source parameters than those available in the past. However, in order to maintain continuity and uniformity of the data as much as possible, it is important to relate these new parameters to the old ones. In this paper we briefly review the relations between different magnitude scales and discuss several approaches towards uniform and useful earthquake catalogs.

Since very excellent reviews on various magnitude scales were recently published (e.g., Miyamura, 1978; Chung and Bernreuter, 1981; Båth, 1981; Abe, 1981), here I concentrate on some fundamental problems underlying this subject rather than make an exhaustive review of the literature.

RELATIONS BETWEEN DIFFERENT MAGNITUDE SCALES

Most magnitude scales currently in use are empirical. Usually a magnitude M is determined from the amplitude A and the period T of a certain type of seismic waves through a formula which contains several constants. These constants are determined in such a way that the magnitudes on the new scale agree with those of an existing one, at least over a certain magnitude range. In some cases, the duration of seismogram, macro-seismic data (e.g., intensity, tsunami source area) and geodetic data are used for the determination of magnitude. In this case too, the new scale is regressed against existing ones.

The first magnitude scale introduced to seismology is the local magnitude M_L, (Richter, 1935). Then the surface-wave magnitude M_s was introduced and was adjusted to agree with M_L (Gutenberg, 1945a). Since most of the events used for the calibration were around $M_L = 6$, these two scales approximately agree at $M_L \sim 6$. The dot-dash closed curve in Fig. 1 indicates the range of the data points. Since M_L is determined from the maximum amplitude on a Wood-Anderson seismogram, the predominant period of the waves used is usually 0.1–3 sec. In contrast, M_s is usually determined from the maximum amplitude of surface waves with a period of about 20 sec. Since the wave types and the period are different between these two scales, there is no *a priori* reason for these two scales to agree completely over a large range. As can be seen in Fig. 1, $M_L \gtrless M_s$ for $M_s \lessgtr 6$. Also, for a given M_L, M_s varies over a range of one magnitude unit.

Later, Gutenberg (1945b) introduced a body-wave magnitude, m_B, which is computed from the amplitude and the period of seismic body waves. In this scale, the maximum amplitude of a wave group corresponding to various seismic phases such as P, PP, and S are used for the determination of the magnitude. For this measurement, various types of seismographs including short- and long-period mechanical instruments and some electro-magnetic instruments were used. Usually the period of the waves used ranges from 0.5 to 12 sec. The main merit of m_B is its applicability to both shallow and deep (including intermediate depth) events. Again

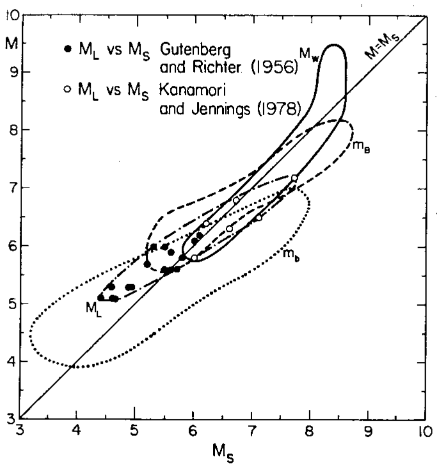

Fig. 1. Relations between various magnitude scales. M_L vs. M_s: Gutenberg and Richter (1956), Kanamori and Jennings (1978); m_B vs. M_s: Abe and Kanamori (1980); m_b vs. M_s: Noguchi and Abe (1977); M_w vs. M_s: Kanamori and Anderson (1975), Singh and Havskov (1980), Purcaru and Berckhemer (1978).

the constants in the formula were determined so that m_B agrees with M_s over a magnitude range of the events used for the calibration. Since the average of the magnitude of these events is about 6.5–7, m_B and M_s agree approximately in this magnitude range. However, m_B deviates from M_s systematically as m_B increases or decreases from this range. This is again due to the difference in the period and the wave type used in these scales. The trend is shown in Fig. 1 by a dashed curve.

TABLE I

Magnitude scales

Scale	T (sec)	λ_{max} (km)	Related scales
M_L	0.1 ~ 3	10	m_{bLg}
M_s	~ 20	70	M_{GR}, M_R, M_D, M_Z, M_V, M_{JMA}
m_B	0.5 ~ 12	70	
m_b	~ 1	10	m_{bLg}
Moment magnitude	10 ~ ∞	∞	M_M, M_w, M_E, M_t
M_C	–	–	
M_I	–	–	M_K

Notation

T	Period
λ_{max}	Maximum wave length
M_L	Local magnitude, Richter (1935)
M_s	Surface-wave magnitude, Gutenberg (1945a)
m_B	Body-wave magnitude, Gutenberg (1945b), Gutenberg and Richter (1956)
m_b	Short-period body-wave magnitude reported in "Earthquake Data Reports" and "Bulletin of International Seismological Center"
m_{bLg}	Lg-wave magnitude, e.g., Nuttli (1973)
M_{GR}	Magnitude used in Gutenberg and Richter (1954)
M_R	Magnitude used in Richter (1958)
M_D	Magnitude used in Duda (1965)
M_Z	Surface-wave magnitude determined from the vertical-component seismograms (e.g., Earthquake Data Reports)
M_V	Surface-wave magnitude defined by Vaněk et al. (1962)
M_{JMA}	Magnitude scale used by the Japan Meteorological Agency
M_M	Moment magnitude by Brune and Engen (1969)
M_w	Kanamori (1977)
M_E	Purcaru and Berckhemer (1978)
M_t	Tsunami magnitude regressed against M_w, Abe (1979)
M_C	Coda (or duration magnitude), e.g., Bisztricsány (1959), Tsumura (1967), Real and Teng (1973)
M_I	Magnitude determined from intensity data and macro-seismic data, e.g., Nuttli and Zollweg (1974), Nuttli et al., (1979), Utsu (1979).
M_K	Kawasumi (1951)

Since these three scales were established, a large number of other scales have been introduced for different regions, magnitude ranges and instruments (see Båth, 1981). Although these scales are intercalibrated, because of the difference in the type of seismic waves and wave period, complete calibration cannot be made. Different scales may represent fundamentally different properties of the source. Since seismic waves at a given period may represent, if not very accurately, the source spectrum at that period, the difference in the period is more fundamental than that in the wave type. In this sense, it is probably reasonable to group the magnitude scales according to the period as shown in Table I. If inter-scale regressions are made for the scales in each group, more meaningful calibrations can be expected.

Since the installation of the World-Wide Standardized Seismograph Network (WWSSN), the body-wave magnitude has been determined routinely mainly from the WWSSN short-period vertical component seismograms at a period about 1 sec. Instead of the maximum amplitude, a maximum amplitude during the first few seconds of the P-wave arrival is used for the determination of this magnitude, here denoted by m_b. Despite the substantial difference in the period and the way the maximum amplitude is measured, the same formula as that used for m_B is used. In other words, the m_b scale was not regressed against the existing scale. For this reason, the m_b values deviate very substantially from those of any existing scales as shown by a dotted curve in Fig. 1. Since the m_b scale was developed mainly for the purpose of discrimination of nuclear explosions, use of this scale for seismological purposes requires some caution. Since m_b is determined by the maximum amplitude from the very beginning of the P-wave group, it represents the "size" of an earthquake at the beginning rather than the overall "size". Also, it is determined from P waves alone, and is more strongly affected by the source mechanism. In general, direct P waves from a strike-slip event are nearly an order of magnitude smaller than those from a dip-slip event. If the magnitude is determined from not only direct P waves but also PP, S and other phases as is done for m_B, the effect of the mechanism would be substantially reduced. For these reasons, the usefulness of the m_b scale for general seismological purposes is somewhat limited, although it can be useful for special problems. This is particularly true for very large events where the first few seconds represent only a very small fraction of the total rupture time of the event.

MOMENT MAGNITUDE

Another class of the magnitude scale is the one based on the seismic moment (Brune and Engen, 1969; Kanamori, 1977; Purcaru and Berckhemer, 1978; Hanks and Kanamori, 1979). Although the seismic moment represents the size of an earthquake only at a period much longer than the source process time ($\sim$ source dimension/shear velocity), it can be determined very accurately from the seismograms. Furthermore, it can be related to some physical parameters of the fault such as the amount of slip. For these reasons, it is a desirable parameter to be used for quantification of earthquakes. However, since the magnitude scale has been used for a very long time, it is desirable to convert the seismic moment into some kind of magnitude. There are many possible methods to do this. One obvious way is to assume a certain parameterized functional relation between the seismic moment and the magnitude, and, by using a data set of events for which both the seismic moment and the magnitude are known, determine the parameters which fit the observed magnitude-seismic moment relation best.

An alternative method is to use the energy radiated by seismic waves. After many revisions, Gutenberg and Richter (1956) obtained a relation between the radiated energy E (in ergs) and the surface-wave magnitude M_s given by:

$$\log E = 1.5M_s + 11.8 \tag{1}$$

Although this is an empirical relation established by using various simplified assumptions, it has been calibrated by using various types of seismic waves and is considered to be a good gross relation.

Since the seismic moment represents a long-period end of the source spectrum, it is not necessarily related to the radiated energy which corresponds to the integral of the square of the source velocity spectrum over the entire frequency band. Therefore, unless the shape of the entire spectrum is uniquely determined by the long-period end, we would not expect a one-to-one relation between the seismic moment and the radiated energy. Several studies have indicated (e.g., Aki, 1967; Kanamori and Anderson, 1975) that there are some scaling relations with which the spectral shape can be approximately determined from the long-period end of the spectrum. Kanamori (1977) used this concept and a very simple source model proposed by Orowan (1960), and obtained a relation between the radiated energy E and the seismic moment M_0:

$$E = (\Delta\sigma/2\mu)M_0 \tag{2}$$

where $\Delta\sigma$ is the average stress drop in the earthquake, and μ is the rigidity of the medium near the fault. Since $(\Delta\sigma/\mu)$ is approximately 10^{-4}, E can be estimated from the seismic moment M_0 by dividing it by $2 \cdot 10^4$. Equation 2 is derived for a very simple fault model and its validity for very complex faulting has not been proved rigorously. Rudnicki and Freund (1981) show that, if the fault rupture velocity is near the Rayleigh-wave velocity and the time rate of change of fault surface traction is small, (2) gives a good approximation of the radiated energy.

Most large earthquakes are known to be very complex and it is not clear whether the assumptions made above are all valid or not. With these uncertainties in mind, Kanamori (1977) combined (1) with (2) to define a magnitude scale M_w [$M_w = (\log M_0 - 16.1)/1.5$]. Since M_w is derived from the seismic moment, it is often called the moment magnitude. It is to be noted that the determination of M_w from the seismic moment is not by empirical regression, as in other magnitude scales, but is based on a physical source model, though it is admittedly very simplified.

The relation between M_w and M_s is shown by a solid curve in Fig. 1. For $M_s \leqslant 8$, M_w is approximately equal to M_s. Since, as mentioned above, M_w is not regressed against M_s, this agreement indicates that both Gutenberg-Richter relation (1) and the moment-energy relation (2) are correct, although it is still possible that both (1) and (2) are incorrect and $M_s \simeq M_w$ is fortuitous. Despite its imperfect theoretical basis, the M_w scale provides a useful magnitude scale which quantifies earthquakes on the basis of the radiated energy.

It should be pointed out, however, that the scaling relations used are valid only in a gross sense, and it is known that there are anomalous earthquakes which significantly deviate from the gross average trend (e.g., slow earthquakes, anomalously high-stress drop earthquakes, etc.).

Recently, Vassiliou and Kanamori (1982) estimated the amount of radiated energy in earthquakes by using the far-field source-time functions which had been determined by various investigators through detailed modelling studies. Since these source-time functions are good at periods as short as 1 sec, these energy estimates are good approximations in the period range longer than 1 sec. Vassiliou and Kanamori used several near-source strong motion records to estimate the amount of energy contained in the period range shorter than 1 sec. They conclude that the total amount of energy contained in this short-period range is relatively small so that the energy estimated from the far-field time functions is a good approximation of the

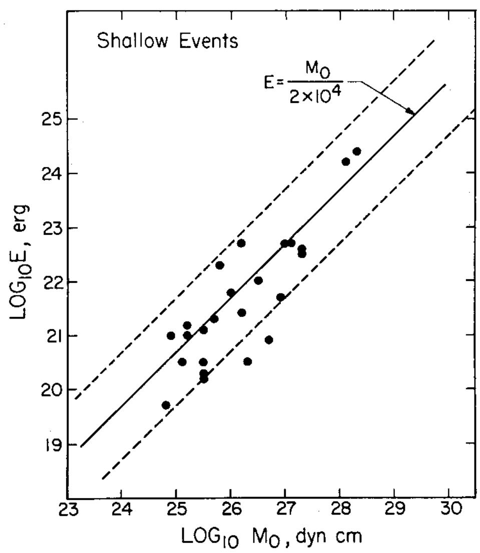

Fig. 2. Relation between seismic moment and energy for shallow events (Vassiliou and Kanamori, 1982). The solid line indicates the relation $E = M_0/(2 \cdot 10^4)$ suggested by elastostatic consideration (Kanamori, 1977).

total energy radiated in earthquakes. Figures 2 and 3 compare the energy, E, thus estimated with the seismic moment M_0. The solid lines in these figures indicate the relation $E = M_0/(2 \cdot 10^4)$ which is derived from elastostatic considerations for

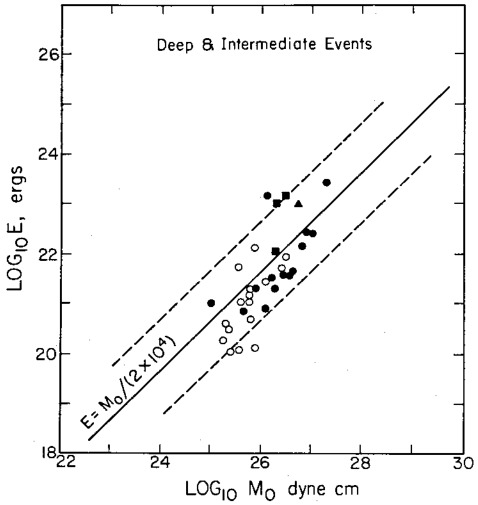

Fig. 3. Relation between seismic moment and energy for intermediate and deep earthquakes (Vassiliou and Kanamori, 1982). Different symbols indicate the data from different sources.

shallow earthquakes (Kanamori, 1977). Figure 2 demonstrates that this relation is a good approximation for shallow events. The result that the same relation fits the data for deep and intermediate events equally well is somewhat surprising because the elastostatic argument applies to only shallow events. Although the significance of this agreement is presently unknown (see Vassiliou and Kanamori, 1982), if we accept these relations they suggest a possibility of using the seismic moment for quantification of deep and intermediate earthquakes (see the following section on magnitude of deep and intermediate-depth earthquakes).

Hanks and Kanamori (1979) noted that the relation between M_L and M_0 obtained by Thatcher and Hanks (1973) for earthquakes in southern California is very similar to that between M_w and M_0 for large earthquakes. This means that if the seismic moment M_0 for relatively small events is converted into a magnitude through $M = (\log M_0)/1.5 - 10.7$ (the same relation between M_w and M_0), this magnitude should agree with M_L.

Purcaru and Berckhemer (1978) propose a magnitude scale M_E on the basis of (2) in which the value of the stress drop for the individual event is used. However, unlike the seismic moment, the stress drop is a very crudely defined seismic parameter, and it is not clear whether the variation in the stress drop for different events is significant or not. If the values of the stress drop determined by the conventional method are used, the difference between M_E and M_w is insignificant, the average difference being only 0.1 (Båth, 1981).

RELATIONS BETWEEN DIFFERENT MAGNITUDES SCALES

In order to illustrate the relations between the magnitude scales discussed above, M_L, M_S, m_B and m_b are shown as a function of M_w in Figs. 4a and 4b. These figures are graphically constructed from Fig. 1. The ranges for the various magnitude scales represent not only the observational errors but also the intrinsic variations. As discussed above, a magnitude scale represents a gross property of earthquakes and, because of the intrinsic variations in the source properties such as the stress drop, complexity, fault geometry and size, and depth, considerable variations in the inter-magnitude relations are expected. Heaton et al. (1982) emphasize the importance of these variations for engineering applications of the magnitude scales.

In addition to the magnitude scales used in Fig. 4, a large number of other scales are currently in use. Detailed discussions on the relations between different scales are found in Geller and Kanamori (1977), Abe and Kanamori (1979, 1980), Miyamura (1978), Chung and Bernreuter (1981), Abe (1981) and Båth (1981).

MAGNITUDE OF DEEP AND INTERMEDIATE-DEPTH EARTHQUAKES

For deep and intermediate-depth earthquakes (hereafter called collectively "deep earthquakes"), the m_B scale introduced by Gutenberg (1945c) is most frequently used (see Abe and Kanamori, 1979). However, for many events which occurred since 1960, only m_b is given. Furthermore, since M_s is more frequently used than m_B for large shallow earthquakes, it is not very obvious how to compare the size of old and

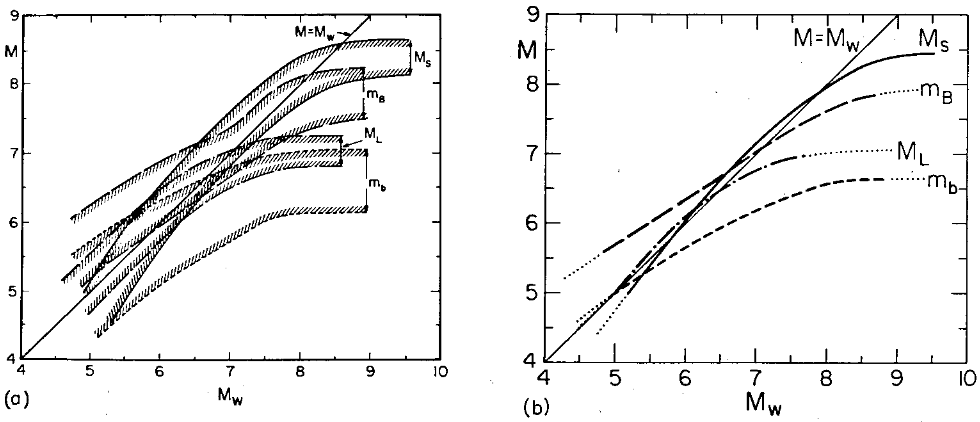

Fig. 4. a. Relations between various magnitude scales obtained from Figure 1. b. Relations between various magnitude scales. The curves indicate the mid-point of the ranges shown in Fig. 4a.

recent deep earthquakes and of deep and shallow earthquakes. One possible solution is to use the seismic moment for quantification of deep earthquakes too.

As shown by Fig. 3, the energy–moment relation used for shallow earthquakes appears to apply to deep earthquakes. Substituting this relation into the Gutenberg-Richter relation between m_B and E, $\log E = 2.4m_B + 5.8$ (Gutenberg and Richter, 1956), we have:

$$\log M_0 = 2.4m_B + 10.1 \qquad (3)$$

Figure 5 shows this relation between M_0 and m_B together with the data for relatively large deep earthquakes compiled by Abe (written commun., 1980). The relation given by (3) explains the data very well. This is equivalent to saying that the energy estimate made by Vassiliou and Kanamori (1982) is in good agreement with that of Gutenberg and Richter (1956).

In any case, since (3) can explain the data very well, we may use (3) to define a moment magnitude m_w [$m_w = (\log M_0 - 10.1)/2.4$] for deep earthquakes from the seismic moment M_0, in much the same way as M_w is defined from M_0. Furthermore, in order to compare the magnitude of deep earthquakes with that for shallow events, m_w can be converted to M_w by using the standard relation between m_B and M_s. This is actually equivalent to computing M_w for deep earthquakes from the seismic moment M_0 by using the same relation [$M_w = (\log M_0 - 16.1)/1.5$] as that for shallow earthquakes. Table II lists the values of m_w and M_w computed from the seismic moments. The values of m_w agree very well with those of m_B.

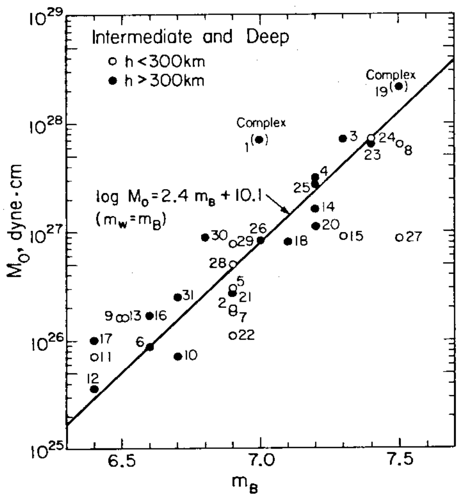

Fig. 5. Relation between the seismic moment M_0 and the body-wave magnitude m_B for intermediate and deep earthquakes (Abe, personal communication, 1980). The numbers attached to each data point refer to the event number used by Abe. The solid curve is the relation obtained by combining the magnitude-energy relation $\log E = 2.4m_B + 5.8$ (Gutenberg and Richter, 1956) and the energy-moment relation $E = M_0/(2 \cdot 10^4)$ (Vassiliou and Kanamori, 1982).

TABLE II

Magnitude of several large intermediate and deep earthquakes

Event	Date	Depth (km)	m_b (1)	m_B (2)	m_w (3)	M_w (4)
Colombia	July 31, 1970	653	7.1	7.5	7.6	8.1
Peru	Aug. 15, 1963	543		7.3	7.4	7.8
S. Bolivia	Nov. 29, 1957	170		7.4	7.4	7.8
N. Korea	Sept. 29, 1973	567	6.5	7.4	7.4	7.8
S. Sandwich	May 26, 1964	114	5.9	7.5	7.4	7.8
Spain	Mar. 29, 1954	640		7.0	7.4	7.8

Note:
(1) From EDR.
(2) Abe and Kanamori (1979).
(3) Computed from the seismic moment by $m_w = (\log M_0 - 10.1)/2.4$
(4) Computed from the seismic moment by $M_w = (\log M_0 - 16.1)/1.5$

In principle, the above procedure uses the energy estimated from the seismic moment as the basis of quantification; the size of earthquakes, both shallow and deep, is measured by the amount of seismic-wave energy expressed by the magnitude scale. As mentioned earlier, the process involved in earthquakes is very complex so that we obviously need more than one parameter for detailed description of seismic events. The magnitude scale based upon the seismic moment should be regarded as a gross parameter, and a large variation in the source characteristic should be always recognized. This variation is partly reflected in the scatter of the moment–energy relation shown in Figs. 4a and 4b.

In view of the recent progress in the methodology of routine seismic moment determination (e.g., Dziewonski et al., 1981; Kanamori and Given, 1981), the moment magnitude provides a useful and simple scale for earthquake quantification for both shallow and deep focus earthquakes. In the conventional magnitude determination, we have to treat shallow and deep events differently, which often causes some inconvenience in practice.

DISCUSSION AND CONCLUSIONS

Despite the various shortcomings, magnitude scales will continue to be used in seismology as one of the fundamental parameters for earthquake quantification. As discussed earlier, in order to accommodate various situations (different instrumentation, depth, level of seismicity, etc.), different magnitude scales would inevitably have to be used for different regions.

Recent studies have demonstrated that, although a gross scaling relation can be established (e.g., Aki, 1967; Kanamori and Anderson, 1975; Geller, 1976), significant variations in the source spectral characteristics exist between different earthquakes. In view of this variation, it is desirable to distinguish the magnitude scales determined at different periods. The difference in the instrument type or in the wave type used is probably less important than the difference in the period. Once the magnitude scales are grouped according to the period of the seismic waves used for their determination, then they can be regressed, in each group, against each other to establish a magnitude scale at that period.

A mixed use of different magnitude scales, particularly those determined at different periods, often causes confusion and should be avoided as much as possible. If we are to use several scales for quantification purposes, the following scales may be used:

(1) *Surface-wave magnitude* M_s. Although this scale suffers from the saturation at $M_s \geqslant 8$, it can be determined very easily, and is a useful scale for most events larger than $M_s = 5$. The relations between different surface-wave magnitudes which are frequently used in several global catalogs are summarized by Abe (1981).

(2) *Body-wave magnitude* m_B. The body-wave magnitude which is determined from the maximum amplitude of various body-wave phases, here denoted by m_B, is useful to represent the source spectrum at a period range from 1 to 10 sec. Many recent studies on the amplitude attenuation curves and their regional variations (for summary, see Båth, 1981) will hopefully make inter-region comparisons of m_B more meaningful than in the past.

(3) *Body-wave magnitude* m_b. This scale, which is determined from the first few seconds of short-period P waves, represents the size of an earthquake at its beginning. Because of this, for earthquakes with a large fault dimension and complex rupture mechanism, the usefulness of this scale is limited. However, for relatively small events (e.g., $m_b \leqslant 5.5$), this scale approximately represents the source spectrum at the period of 1 sec and is useful for quantification of earthquakes at short periods.

(4) *Moment magnitude.* As is discussed earlier, the moment magnitude represents the source spectrum at the period where the moment determination is made (longer than 100 sec for very large events) more directly than the conventional scales. If the energy–moment relation obtained by Vassiliou and Kanamori (1982) is correct, the moment magnitude can be determined from the seismic moment by using the same formula [$M_w = (\log M_0 - 16.1)/1.5$] for both shallow and deep earthquakes. Since the determination of the seismic moment is becoming a relatively routine practice, the moment magnitude is a very useful parameter for earthquake quantification.

(5) *Local and regional scales.* The examples of the scales which belong to this group are the local magnitude M_L, the JMA (Japan Meteorological Agency) magnitude M_{JMA}, L_g magnitude m_{bLg}, the coda (duration) magnitude M_C and the intensity magnitude M_I. Since the types of the data used in these scales are very different from region to region, it is often difficult to relate one scale to another. In order to compare the nature of earthquakes from region to region (e.g., western U.S. vs.

eastern U.S.), it is important to establish relationships between different regional scales. Herrmann and Nuttli (1982) made a detailed study on the relation between m_{bLg} (mainly used in the central and eastern United States) and M_L (mainly used in the western United States) and concluded that m_{bLg} and M_L are essentially equivalent between $M_L = 3$ and 5. This type of study for other scales is highly desirable.

Since the magnitude scales determined at different periods represent different parts of the seismic source spectrum, use of several different scales (e.g., M_s, m_B, M_L, M_w) in earthquake catalogs would substantially increase the usefulness of the catalogs for various research purposes. However, since the physical process associated with earthquakes is far more complex than can be adequately described by a few parameters, use of these parameters for detailed studies should be made very carefully. The main purpose of earthquake catalogs is to provide the users with simple parameters for first-cut interpretation of the data. When some significant features are found as a result of the analysis of the catalog data, it is desirable to go back to the original seismograms for further analyses before final conclusions are made.

ACKNOWLEDGMENTS

I thank Tom Heaton and Mario Vassiliou for useful discussions at the various stages of this study. Katsuyuki Abe kindly allowed me to use some of his unpublished data on intermediate and deep earthquakes. This research was partially supported by the Earth Sciences Section of the National Science Foundation, grant EAR-811-6023. Contribution Number 3781, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

REFERENCES

Abe, K., 1979. Size of great earthquakes of 1837–1974 inferred from tsunami data. J. Geophys. Res., 84: 1561–1568.

Abe, K., 1981. Magnitudes of large shallow earthquakes from 1904 to 1980. Phys. Earth Planet. Inter., 27: 72–92.

Abe, K. and Kanamori, H., 1979. Temporal variation of the activity of intermediate and deep focus earthquakes. J. Geophys. Res., 84: 3589–3595.

Abe, K. and Kanamori, H., 1980. Magnitudes of great shallow earthquakes from 1953 to 1977. Tectonophysics, 62: 191–203.

Aki, K., 1967. Scaling law of seismic spectrum. J. Geophys. Res., 72: 1217–1231.

Båth, M., 1981. Earthquake magnitude—recent research and current trends. Earth-Sci. Rev., 17: 315–398.

Bisztricsány, E., 1959. On a new method of determining earthquake magnitudes. Publ. BCIS, Trav. Sci., Fasc., A20: 9–15.

Brune, J.N. and Engen, G.R., 1969. Excitation of mantle Love waves and definition of mantle wave magnitude. Bull. Seismol. Soc. Am., 59: 923–933.

Chung, D.H. and Bernreuter, D.L., 1981. Regional relationships among earthquake magnitude scales. Rev. Geophys. Space Phys., 19: 649–663.

Duda, S.J., 1965. Secular seismic energy release in the circum-Pacific belt. Tectonophysics, 2: 409–452.

Dziewonski, A.M., Chou, T.-A. and Woodhouse, J.H., 1981. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J. Geophys. Res., 86: 2825–2852.

Geller, R.J., 1976. Scaling relations for earthquake source parameters and magnitudes. Bull. Seismol. Soc. Am., 66: 1501–1523.

Geller, R.J. and Kanamori, H., 1977. Magnitudes of great shallow earthquakes from 1904 to 1952. Bull. Seismol. Soc. Am., 67: 587–598.

Gutenberg, B., 1945a. Amplitudes of surface waves and magnitudes of shallow earthquakes. Bull. Seismol. Soc. Am., 35: 3–12.

Gutenberg, B., 1945b. Amplitudes of P, PP and S and magnitudes of shallow earthquakes. Bull. Seismol. Soc. Am., 35: 57–69.

Gutenberg, B., 1945c. Magnitude determination for deep-focus earthquakes. Bull. Seismol. Soc. Am., 35: 117–130.

Gutenberg, B., 1956. The energy of earthquakes. Q.J. Geol. Soc. London, 112: 1–14.

Gutenberg, B. and Richter, C.F., 1954. Seismicity of the Earth and Associated Phenomena. Princeton University Press, Princeton, N.J., 2nd Ed., 310 pp.

Gutenberg, B. and Richter, C.F., 1956. Magnitude and energy of earthquakes. Ann. Geofis. (Rome), 9: 1–15.

Hanks, T.C. and Kanamori, H., 1979. A moment magnitude scale. J. Geophys. Res., 84: 2348–2350.

Heaton, T.H., Tajima, F. and Wildenstein-Mori, A., 1982. Estimating ground motions using recorded accelerograms. Preprint.

Herrmann, R.B. and Nuttli, O.T., 1982. Magnitude: the relation of M_L to m_{bLg}. Bull. Seismol. Soc. Am., 72: 389–397.

Kanamori, H., 1977. The energy release in great earthquakes. J. Geophys. Res., 82: 2981–2987.

Kanamori, H. and Anderson, D.L., 1975. Theoretical basis of some empirical relations in seismology. Bull. Seismol. Soc. Am., 65: 1073–1095.

Kanamori, H. and Given, J.W., 1981. Use of long-period surface waves for rapid determination of earthquake-source parameters. Phys. Earth Planet. Inter, 27: 8–31.

Kanamori, H. and Jennings, P.C., 1978. Determination of local magnitude, M_L, from strong-motion accelerograms. Bull. Seismol. Soc. Am., 68: 471–485.

Kawasumi, H., 1951. Measures of earthquake danger and expectancy of maximum intensity throughout Japan as inferred from the seismic activity in historical times. Bull. Earthquake Res. Inst. Tokyo Univ., 29: 469–482.

Miyamura, S., 1978. Magnitude of earthquakes (I). Lecture Notes, Int. Inst. Seismol. Earthquake Eng., Tokyo, No. 11, 83 pp.

Noguchi, S. and Abe, K., 1977. Earthquake source mechanism and $M_s - m_b$ relation. Zisin II, 30: 487–507 (in Jap., with Engl. abstr.).

Nuttli, O.W., 1973. Seismic wave attenuation and magnitude relations for eastern North America. J. Geophys. Res., 78: 876–885.

Nuttli, O.W. and Zollweg, J.E., 1974. The relation between felt area and magnitude for central United States earthquakes. Bull. Seismol. Soc. Am., 64: 73–85.

Nuttli, O.W., Bollinger, G.A. and Griffith, D.W., 1979. On the relation between Modified Mercalli in tensity and body-wave magnitude. Bull. Seismol. Soc. Am., 69: 893–909.

Orowan, E., 1960. Mechanism of seismic faulting. Geol. Soc. Am. Mem., 79: 323–345.

Purcaru, G. and Berckhemer, H., 1978. A magnitude scale for very large earthquakes. Tectonophysics, 49: 189–198.

Real, C.R. and Teng, T.-L., 1973. Local Richter magnitude and total signal duration in southern California. Bull. Seismol. Soc. Am., 63: 1809–1827.

Richter, C.F., 1935. An instrumental earthquake magnitude scale, Bull. Seismol. Soc. Am., 25: 1–32.
Richter, C.F., 1958. Elementary Seismology. Freeman, San Fransicso, Calif., 768 pp.
Rudnicki, J.W. and Freund, L.B., 1981. On energy radiation from seismic sources. Bull. Seismol. Soc. Am., 71: 583–595.
Singh, S.K. and Havskov, J., 1980. On moment-magnitude scale. Bull. Seismol. Soc. Am., 70: 379–383.
Thatcher, W. and Hanks, T.C. 1973. Source parameters of southern California earthquakes. J. Geophys. Res., 78: 8547–8575.
Tsumura, K., 1967. Determination of earthquake magnitude from total duration of oscillation. Bull. Earthquake Res. Inst., Tokyo Univ., 45: 7–18.
Utsu, T., 1979. Seismicity of Japan from 1885 through 1925. Bull. Earthquake Res. Inst. Tokyo Univ., 54, 253–308.
Vaněk, J., Zátopek, A., Kárnik, V., Kondorskaya, N.V., Riznichenko, Y.V., Savarensky, E.F., Solov'ev, S.L. and Shebalin, N.V., 1962. Standardization of magnitude scales. Bull. Acad. Sci. USSR, Geophys. Ser., 1962: 108–111 (Engl. transl.).
Vassiliou, M.S. and Kanamori, H., 1982. The energy release in earthquakes. Bull. Seismol. Soc. Am., 72: 371–387.

Editor's Note

The paper was presented upon the special invitation of the convenor of the Workshop on Quantification of Earthquakes, held as part of the London, Ontario (Canada), General Assembly of IAPEI.