1. Introduction

The activity of intermediate and deep focus earthquakes provides clues to the mechanical properties and the stress distribution within the downgoing lithosphere. Gutenberg [1956, 1957] discovered the variation of seismic energy release as a function of depth by using the magnitude of intermediate and deep focus earthquakes. Hanks [1967] used body waves to explain the stress changes in the downgoing slab. The detailed physical mechanism provides important constraints on various models of plate subduction.

From this point of view, the size (or magnitude) of intermediate and deep focus earthquakes is one of the most important parameters. The magnitude of intermediate and deep focus earthquakes was first determined by Gutenberg [1954] by using seismic body waves. Since then a large number of determinations have been made by various investigations, seismic observations, and have been published in various catalogs [Gutenberg and Richter, 1954; Richter, 1958; Duda, 1965; Roshch, 1969; Earthquake Data Reports (EDR) of the U.S. Coast and Geodetic Survey and U.S. Geological Survey; Bulletin of International Seismological Center (ISC)].

Unfortunately, as will be discussed later, the magnitude used in these catalogs varies significantly from one catalog to another so that it is not possible to discuss the spatial and temporal variation of seismicity of intermediate and deep focus earthquakes.

The purpose of this paper is to provide a uniform magnitude catalog of large intermediate and deep focus earthquakes and to discuss the temporal and depth variations of these earthquakes. Following Gutenberg and Richter [1954], here 'intermediate' is used for the depth range from 20 to 300 km, and 'deep' for depths larger than 300 km.

Since the magnitude of an earthquake is defined from observed records without due consideration to the source model of the earthquake, its physical significance in terms of the earthquake source size is somewhat vague. This is particularly so for very large shallow earthquakes in which the source size is much larger than the wavelength of seismic waves used for magnitude determination, and consequently the scale saturates. On the other hand, for intermediate and deep focus earthquakes, the source size is probably very small, so that the magnitude determined at 20 to 30 sec period either broad-band or long-period records would probably represent the overall size of the earthquake reasonably well.

2. Magnitude Scales Used in Various Catalogs

We first review the scales used in various catalogs (see Table 1 for a summary). For the period 1904 to 1952, the catalog of Gutenberg and Richter [1954] is the most complete. However, the magnitude M is used in this catalog (denoted by M in this paper) is not observed. We investigated the original notes of Gutenberg and Richter and found that

\[ M_a = \log \left( \frac{A}{T} \right) + Q_{sa} + c \]

where A and T are the amplitude and the period of seismic body waves such as P, PP, and S and defined in Gutenberg [1954a]. The Q function used above, Q_{sa} is significantly different from that used in Richter [1956] and described in Richter [1958]. It is described in Gutenberg [1945a]. In the above expression, c is the station correction, and c is the correction applied to large earthquakes [Gutenberg, 1945a, 1956]. This correction changed as a function of time. The magnitudes listed in Tables XIV-3 and XIV-4 of
TABLE 1. Magnitudes of Deep Earthquakes

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| Richter [1958] were calculated from the body wave magnitude m by |
|---------------|-------------------|
| Mw = m - 2.5 + 0.63 |

where m is determined by

m = log (T) + Qv + t + r

(3)

Here the Q function is the revised one given in Gutenberg and Richter [1954] and reproduced in Richter [1958, pp. 688-689]. Equation (2) was applied to the earthquakes with m > 7.5. For these large events, Mw is significantly larger than m (e.g., for m = 7.5, Mw = 7.8). Dade [1965] catalog employs different scales for different periods and magnitude ranges as shown in Table 1. The magnitude for intermediate and deep focus earthquakes in Richter [1960] is essentially the same as that in Dade for large earthquakes.

For the period from 1904 to 1974, the data for the individual stations listed in the unpublished notations of Gutenberg and Richter [1954] were carefully examined and Mw values calculated. For 1953 to 1958, Gutenberg's unpublished data of amplitudes and periods were used. For the period from 1959 to 1974, we used amplitude and the period data reported in the seismological bulletins of various stations. Approximately 20 stations were used. Since 1975, most stations reported the amplitude data, from either long-period or broad-band records, in their station bulletins so that no reliable independent determination could be made. Two examples of such m determinations are illustrated in Tables A-1 and A-2 in Appendix A (on microscopes).

3. RESULT

The m scale adopted here is the same as that originally defined by Gutenberg (see 31), and the revised Q function described in Gutenberg and Richter [1956] and Richter [1958] is used. For the station corrections, we used the values listed by Gutenberg [1958] when available; if it is not listed, x is assumed to be zero. Since we used a large number of data

The appendix is available with the entire article on microscopes. Order from American Geophysical Union, 1909 K Street, N.W., Washington, D.C. 20006. Document #J93/001. $1.00. Payment must accompany order.

from the Bulletin of the International Seismological Center (ISC) have published the body-wave magnitudes m determined from short-period, usually about 1 sec, body waves. These values are different from the m values determined in this paper as shown by Figure 2, where the m values are taken from Bulletin of the International Seismological Center for the period from 1964 to 1974 and the data for m < 7.0 are added from our unpublished files. In all cases, m is significantly (approximately 0.8 unit) larger than m. Thus m is determined for recent large events (e.g., Colombian earthquakes of July 31, 1970, m = 6.5, m = 7.5) cannot be compared directly with m used for older events. In the present study, m was determined for all the events with m > 7.0 to enable direct comparison. It is well known that very large shallow earthquakes are often complex multicycle events. This is also true for intermediate and deep focus earthquakes. Examples are the Brazil earthquake of November 9, 1963 [Fukao, 1972], and Spanish earthquake of March 19, 1954 [Chang and Kanamori, 1976]. For these events, m may not adequately represent the entire source process. Nevertheless, since m is determined at 10 to
TABLE 1. Magnitudes of Deep Earthquakes

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Here the Q function is the revised one given in Gutenberg and Richter [1954] and reproduced in Richter [1958].

4. RESULT

The Ms scale adopted here is the same as that originally defined by Gutenberg (see 3), and the revised Q function described in Gutenberg and Richter [1954] and Richter [1958] is used. For the station corrections, we used the values listed by Gutenberg [1948] when available; if it is not listed, a is assumed to be zero. Since we used a large number of data.

3. DESCRIPT

The Ms scale adopted here is the same as that originally defined by Gutenberg (see 3), and the revised Q function described in Gutenberg and Richter [1954] and Richter [1958] is used. For the station corrections, we used the values listed by Gutenberg [1948] when available; if it is not listed, a is assumed to be zero. Since we used a large number of data.

The Ms scale adopted here is the same as that originally defined by Gutenberg (see 3), and the revised Q function described in Gutenberg and Richter [1954] and Richter [1958] is used. For the station corrections, we used the values listed by Gutenberg [1948] when available; if it is not listed, a is assumed to be zero. Since we used a large number of data.
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The dotted curve shows an unlagged 5-year running average. Three peaks are notable, around 1910, 1940, and 1950. The sudden decrease in N prior to 1910 may be partly due to detection and location capability. The data prior to 1922 may be somewhat incomplete (Gutenberg, 1956), but the existence of the 1910 peak is probably real. The number of events above the recent years is consistently smaller than the average, 4.7/5. It is interesting to compare this curve with that for shallow earthquakes. Figure 4 shows the comparison. The curve for shallow earthquakes shows the number of events with M ≥ 7 taken from Kanamori [1977a]. The correlation is quite remarkable; the correlation coefficient is 0.7 for the period from 1910 to 1972.

Another comparison can be made in terms of the amount of energy released in earthquakes. According to Gutenberg and Richter [1954, 1956] the seismic wave energy released in earthquakes can be written as

\[ E = 5.8 + 2.4 m \] (4)

(E in ergs). Figure 5 shows E as a function of time together with an unlagged 5-year average (solid curve). Although the major feature of this curve is similar to that of the annual number N (Figure 3), the peak around 1910 is more pronounced. This peak is marked by a large intermediate-depth earthquake, June 16, 1910 (New Hebrides, M = 7.9), June 15, 1911 (Ryukyu Island, m = 8.1), and November 24, 1914 (Mariana Islands, M = 7.9). This energy release curve is compared with that for shallow earthquakes which is taken from Kanamori [1977a, Figure 4]. The energy release for the period prior to 1920 is uncertain in Kanamori's [1977a] paper, but recent studies by Kanamori and Ahf [1978] and Ahf [1979] indicate that there is probably no peak of energy release in shallow earthquakes around the turn of the century. Thus the energy release curve for shallow earthquakes seems to be uncorrelated with that for intermediate and deep focus earthquakes. It is interesting to note that the peak of shallow earthquake activity is dominated by great earthquakes in Chile, Alaska, the Aleutians and Kamchatka (see Kanamori, 1977a) where major thrust earthquakes occur very frequently, whereas the three intermediate earthquakes that contribute to the peak of the intermediate-deep focus earthquake activity occurred in subduction zones where no great (large Mw, see Kanamori [1977a]) earthquakes occur (see Figure 4 of Kanamori [1978]). It thus appears that the major energy release in shallow and shallow-intermediate-deep earthquakes occurs in a complementary manner. If this is the case, the lack of correlation between them may not be surprising. In this context, it is interesting to compare these energy release curves with the amplitude of the Chandler wobble (Figure 4).

The Chandler wobble amplitude shows a maximum, one around 1910 and the other around 1950. Kanamori [1977a] showed that the peak around 1950 seems to be correlated with the peak of the energy release for shallow earthquakes. However, the peak around 1910 remained unexplained. It is noteworthy that the 1910 peak correlates very well with the peak of the intermediate-deep focus earthquakes. Since the sum of the energy release for shallow and intermediate-deep earthquakes represents the total global energy release, it is reasonable that a global wobble should correlate with the sum rather than the individual energy release curve. However, it has been demonstrated [e.g., Kanamori, 1977a] that the amount of energy release in earthquakes expressed by \( W_E \) or \( E \) in Figure 4 is much too small to affect the Chandler wobble significantly. Thus even if the above correlation is significant, the physical mechanisms relating these two processes is unknown. One possibility is that earthquakes involve large aseismic deformation (Kanamori, 1975b) so that the energy release curve represents only a part of the total energy budget. This interpretation is tentative and further studies are obviously necessary.

Depth Variation

Figure 6 shows the variation of the number of events N and the energy release E as a function of depth. Except for the depth of 35 km (shallow earthquakes), each data point represents the total for the depth interval of 50 km centered at the depth given by the solid circle and for the time interval of 71 years from 1904 to 1974. These are calculated from all the
TABLE 2. (Continued)

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<td>88</td>
<td>2S87W</td>
<td>7.3</td>
<td>6</td>
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<td>Nov 24, 1971</td>
<td>19:33</td>
<td>99</td>
<td>52S179W</td>
<td>7.4</td>
<td>6</td>
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<td>Feb 14, 1972</td>
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<td>1646E</td>
<td>7.3</td>
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<tr>
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<td>16:41</td>
<td>136</td>
<td>39N124E</td>
<td>7.4</td>
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<td>Aug 28, 1972</td>
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<td>18S6W</td>
<td>7.3</td>
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<tr>
<td>Sept 29, 1972</td>
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<td>367</td>
<td>41N91E</td>
<td>7.4</td>
<td>6</td>
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</tbody>
</table>

The dotted curve shows an unlagged 5-year running average. Three peaks are notable, around 1910, 1940, and 1950. The existence of these peaks is due to the detection and location capability. The data prior to 1922 may be somewhat incomplete (Kikuchi, 1956), but the existence of the 1910 peak is probably real. The number of events for the recent years is considerably smaller than the average for the period 1877-1910.

4. DISCUSSION

The number of intermediate and deep focus earthquakes with $m_0 \geq 7.0$ as a function of year. The dotted curve is unlagged 5-year running average taken at the center of the interval.

Another comparison can be made in terms of the amount of energy released in earthquakes. According to Gutenberg and Richter [1953; 1956] the seismic wave energy released in earthquakes can be written as

$$\log E = 5.8 + 2.4 m_0$$

The Chandler wobble amplitude shows two maxima, one around 1910 and the other around 1950. Kanaomori [1973a] showed that the peak around 1950 seems to be correlated with the peak of the energy release for shallow earthquakes. However, the peak around 1910 remained unexplained. It is noteworthy that the 1910 peak correlates very well with the peak of the intermediate-deep-focus earthquakes. Since the sum of the energy release for shallow and intermediate-deep-focus earthquakes represents the total global energy release, it is reasonable that a global wobble signal should exist. This correlates better with the sum rather than the individual energy release curve. However, it has been demonstrated [e.g., Kanaomori, 1973a] that the amount of energy release in earthquakes expressed by $W_e$ or $E$ in Figure 4 is much too small to affect the Chandler wobble significantly. Thus even if the above correlation is significant in the physical mechanism relating these two processes is unknown. One possibility is that earthquakes involve large aseismic deformation [Kanaomori, 1973b] so that the energy release curve represents only a part of the total energy budget. This interpretation is tentative and further studies are obviously necessary.

Depth Variation

Figure 6 shows the variation of the number of events $N$ and the energy release $E$ as a function of depth. Except for the depth of 35 km (shallow earthquakes), each data point represents the total for the depth interval of 30 km centered at the depth given by the solid circle and for the time interval of 71 years from 1904 to 1974. These are calculated from all the events.
Fig. 6. The variation of intermediate and deep focus earthquakes as a function of depth. The solid curve shows the energy and the dotted curve the number of events with $m_0 > 7$. The scale at the top refers to $E$, and that at the bottom refers to the number of events. Each point represents the value for a depth range of 50 km centered at the depth of each data point and for the time period of 75 years from 1904 to 1974.

TABLE 3. Largest Earthquakes for Given Depths, 1904-1974

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth, km</th>
<th>$m_0$</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 22, 1960</td>
<td>Normal</td>
<td>7.9</td>
<td>Chile ($M_s = 9.5$)</td>
</tr>
<tr>
<td>March 26, 1968</td>
<td>N</td>
<td>7.9</td>
<td>Alaska ($M_s = 9.2$)</td>
</tr>
<tr>
<td>March 9, 1957</td>
<td>N</td>
<td>7.7</td>
<td>Alaska ($M_s = 9.1$)</td>
</tr>
<tr>
<td>Nov 4, 1952</td>
<td>N</td>
<td>7.9</td>
<td>Kamchatka ($M_s = 9.0$)</td>
</tr>
<tr>
<td>Nov 6, 1958</td>
<td>N</td>
<td>8.2</td>
<td>Kurile Is.</td>
</tr>
<tr>
<td>100</td>
<td>1960</td>
<td>100</td>
<td>New Hebrides</td>
</tr>
<tr>
<td>Nov 24, 1914</td>
<td>N</td>
<td>7.7</td>
<td>Mariana Is.</td>
</tr>
<tr>
<td>150</td>
<td>1915</td>
<td>151</td>
<td>Ryukyu Is.</td>
</tr>
<tr>
<td>200</td>
<td>1920</td>
<td>200</td>
<td>New Guinea</td>
</tr>
<tr>
<td>250</td>
<td>1921</td>
<td>251</td>
<td>Hinde Kash</td>
</tr>
<tr>
<td>750</td>
<td>1937</td>
<td>750</td>
<td>New Hebrides</td>
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<td>1966</td>
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<td>Japan</td>
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<tr>
<td>450</td>
<td>1976</td>
<td>450</td>
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<td>500</td>
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<td>Japan</td>
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<td>550</td>
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<td>650</td>
<td>Peru</td>
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<tr>
<td>700</td>
<td>1984</td>
<td>700</td>
<td>Colombia</td>
</tr>
<tr>
<td>750</td>
<td>1984</td>
<td>750</td>
<td>Philippine Is.</td>
</tr>
<tr>
<td>800</td>
<td>1984</td>
<td>800</td>
<td>Okinawa</td>
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Acknowledgments. We thank Gordon Stewart for reviewing the manuscript. This research was supported by the Earth Sciences Section of the National Science Foundation, grant EAR-77-1640. Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California contribution 352.

References


In order to obtain a uniform magnitude catalog for intermediate and deep focus earthquakes, we adhered to Gutenberg's [1945] original definition of body-wave magnitude, $m_b$, determined from body waves recorded on a broad-band or long-period seismogram. The $Q$ function defined by Gutenberg and Richter [1956] was used. The average period of the waves is 5 to 20 sec for large earthquakes. These periods are long enough to make $m_b$ represent the overall size of intermediate and deep focus earthquakes. The determination of $m_b$ was made for all the events larger than $m_b \geq 7$ for the period from 1904 to 1974. Various inhomogeneities in the existing catalogs have been thus removed in the catalog obtained in this study (Table 2, Appendix B).

The temporal variation of the number of intermediate and deep earthquakes with $m_b \geq 7$ is remarkably similar to that of shallow earthquakes with $M_s \geq 7$. The temporal variation of the energy release in intermediate and deep earthquakes shows a maximum around 1910. The sum of the energy release curve of intermediate-deep and shallow earthquakes shows a good correlation with the amplitude of the Chandler wobble. The energy release becomes a maximum at depths of 350 and 600 km.

Acknowledgments. We thank Gordon Stewart for reviewing the manuscript. This research was supported by the Earth Sciences Section of the National Science Foundation, grant EAR-77-1646 (Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California contribution 3212).

**REFERENCES**