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QUANTIFICATION OF GREAT EARTHQUAKES

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The surface-wave magnitude, M_s, is widely used to represent the "size" of an earthquake. However, the wavelength of seismic waves used for the determination of M_s is about 50 km so that it is unclear whether M_s can adequately quantify great earthquakes whose fault dimension is much larger than the wavelength. Such great earthquakes, though they are relatively infrequent, contribute most to the total seismic energy budget. It is desirable to implement a parameter which represents better the overall "size" of such great earthquakes. The seismic moment, M_0, is one of the most reliable source parameters that represent the magnitude of the overall crustal deformations at the earthquake source, and is an adequate parameter for this purpose. For the period 1920—1976, the seismic moment M_0 has been determined either directly or indirectly (from the size of aftershock areas or the 100 sec magnitude) for 44 earthquakes out of 52 events whose M_s is larger than 8. By using the stress relaxation model of an earthquake, the seismic moment M_0 can be interpreted in terms of energy released by earthquakes. The strain energy drop W (difference in strain energy before and after an earthquake) is given by $W = [(\sigma_0 + \sigma_1)/2]\bar{D}S$ where σ_0 and σ_1 are the stresses on the fault plane before and after the earthquake, $\bar{D}$ is the average displacement on the fault and S is the area of the fault plane. When the stress drop $\Delta\sigma = \sigma_0 - \sigma_1$ is complete, $\Delta\sigma = \sigma_0$ and $W \equiv W_0 = \frac{1}{2}\Delta\sigma\bar{D}S = (\Delta\sigma/2\mu)\mu\bar{D}S = (\Delta\sigma/2\mu)M_0$ where μ is the rigidity. Since $\Delta\sigma$ is nearly constant at 20—60 bars for large earthquakes and $\mu = 3$ to $6 \cdot 10^5$ bars under crust—mantle conditions, $\Delta\sigma/\mu \sim 10^{-4}$ and $W_0 = M_0/(2 \cdot 10^4)$. This relation gives the strain energy drop from the seismic moment. When the stress drop is partial, $W = W_0 + \sigma_1\bar{D}S$. We let σ_f be the frictional stress during faulting, then $W = H + E$ where $H = \sigma_f DS$ is the frictional loss and E is the wave energy. Combining these equations:

$$E = [(\sigma_0 + \sigma_1)/2]\bar{D}S - \sigma_f\bar{D}S = (\Delta\sigma/2)\bar{D}S + \bar{D}S(\sigma_1 - \sigma_f) = W_0 + \bar{D}S(\sigma_1 - \sigma_f)$$

If the final stress is equal to the frictional stress (Orowan's condition), $E = W_0 = M_0/(2 \cdot 10^4)$. Thus we can estimate the seismic wave energy E by dividing the seismic moment M_0 by $2 \cdot 10^4$. Although the energy estimated here is subject to some uncertainty because of the complexity in earthquake faulting, it is a more reliable estimate of the total wave energy released in earthquakes than that calculated from M_s. A new magnitude scale M_w is defined

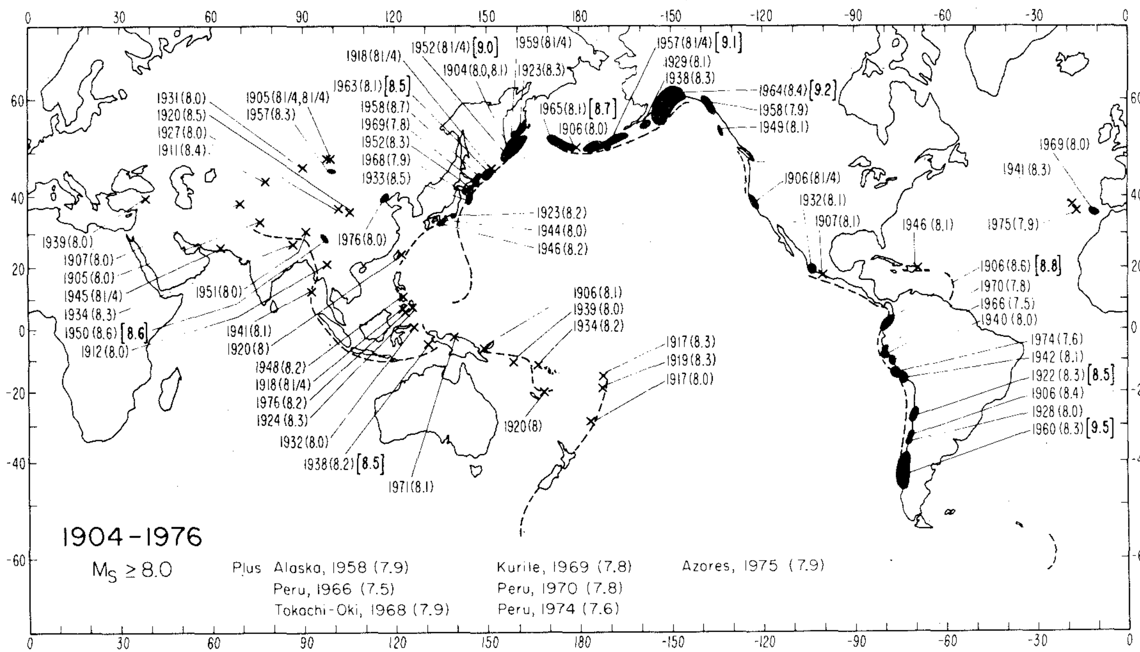

Fig. 1. Great earthquakes for the period from 1904 to 1976. The surface-wave magnitude M_s is given in the parentheses and M_w is given in the brackets for ten largest earthquakes. Major rupture zones are indicated by dark zones. (H. Kanamori, Nature, 221 (411), 1978).

TABLE I

Comparison of M_s and M_w

Event	Year	M_s	M_0 (dyne-cm)	M_w
Chile	1960	8.3	$2 \cdot 10^{30}$	9.5
Alaska	1964	8.4	$8.2 \cdot 10^{29}$	9.2
Aleutians	1957	8.25	$5.9 \cdot 10^{29}$	9.1
Kamchatka	1952	8.25	$3.5 \cdot 10^{29}$	9.0
Ecuador	1906	8.6	$2.0 \cdot 10^{29}$	8.8
Aleutians	1965	7.75	$1.25 \cdot 10^{29}$	8.7
Assam	1950	8.6	10^{29}	8.6
Kurile Is.	1963	8.1	$6.7 \cdot 10^{28}$	8.5
Chile	1922	8.3	$6.9 \cdot 10^{28}$	8.5
Banda Sea	1938	8.2	$7.0 \cdot 10^{28}$	8.5
Sanriku	1933	8.5	$4.3 \cdot 10^{28}$	8.4
Niigata	1964	7.4	$3 \cdot 10^{27}$	7.6
Guatemala	1976	7.5	$2.6 \cdot 10^{27}$	7.6
San Fernando	1971	6.6	10^{26}	6.6
Borrego Mt.	1968	6.7	10^{26}	6.6
Oroville	1975	5.6	10^{25}	5.9

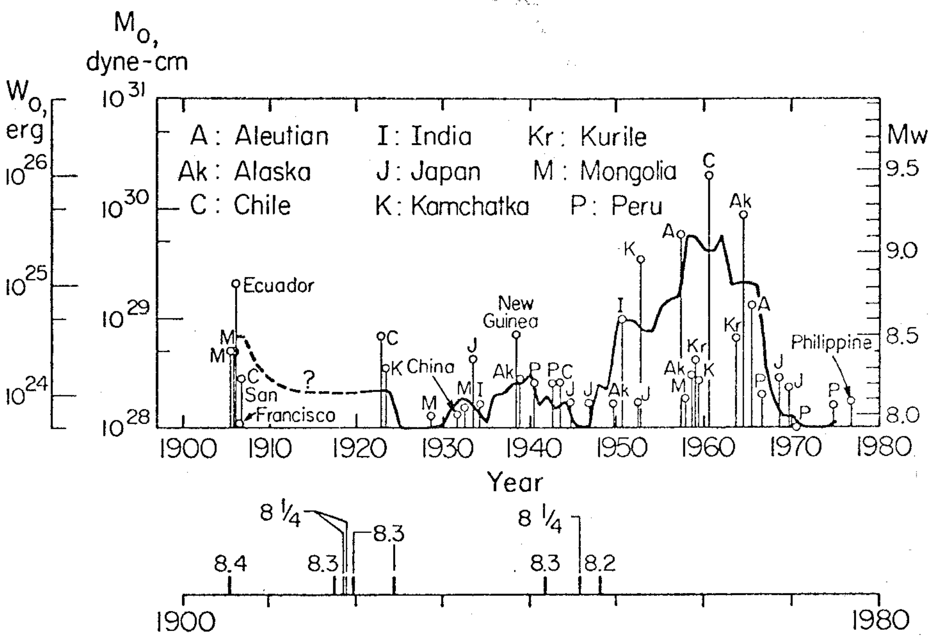

Fig. 2. The minimum strain energy drop W_0 (equal to the seismic-wave energy if Orowan's condition is met) in great earthquakes as a function of year. The solid curve shows unlagged 5-year running average (unit ergs/year) taken at the center of the interval. The ordinate is given in three scales, the seismic moment M_0, W_0 and M_w. Large earthquakes for which M_0 has not been determined are plotted at the bottom with the surface-wave magnitude M_s. (H. Kanamori, J. Geophys. Res., 82 (2981), 1977.)

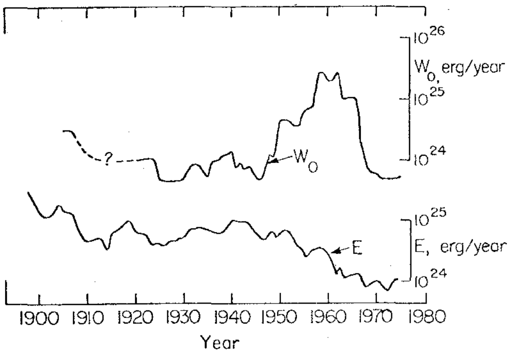

Fig. 3. Comparison between W_0 (5-year running average) and the energy E estimated from M_s.

in terms of W_0 through the Gutenberg-Richter relation $\log W_0 = 1.5M_w + 11.8$. M_w can be expressed in terms of M_0 by $M_w = (1/1.5)\log M_0 - 10.73$. This magnitude scale, M_w represents the total wave energy released by an earthquake. Table I compares M_s and M_w for various earthquakes. The values of M_w differ significantly from M_s for great earthquakes, but M_w and M_s agree very well for smaller earthquakes indicating that the Gutenberg-Richter relation is adequate for these smaller events. M_w is, therefore, a natural extension of M_s toward great earthquakes. The difference is significant for about ten earthquakes shown in Fig. 1. These ten earthquakes account for about 90% of the energy release of all earthquakes during the period 1920—1976. The seismic energy release estimated by the present method is shown in Fig. 2. As shown in Fig. 3, the new energy release curve is completely different from that previously estimated from M_s. During the 15-year period from 1950 to 1965, the annual average of W_0 is more than one order of magnitude larger than that during the periods from 1920 to 1950 and 1965 to 1976. The new energy release curve is more relevant to the study of global problems such as the Chandler wobble, plate motion and heat flow.

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DISCUSSION OF KANAMORI'S PRESENTATION

K. Mogi

Have you any idea about the recent greatest earthquakes which occurred in the higher latitude regions?

H. Kanamori

I do not have an explanation.

S.J. Duda

Your curves referring to the Chandler wobble and to the seismic energy release show a phase difference. (The curves were shown concurrently only during the oral presentation. Remark by editor) Is the difference conclusive as to what is the cause and what the effect?

H. Kanamori

It looks like the change in the Chandler wobble precedes that of the earthquake energy release. However, the details are still unknown. For more details please refer to H. Kanamori, J. Geophys. Res., 82 (2981), 1977.

N.V. Kondorskaya

How many stations did you use for each case; were these the same stations or did they differ?

H. Kanamori

The number of stations varies from event to event. For example, a very large number of stations is used for the 1964 Alaska, and the 1963 Kurile Islands earthquake. However, a relatively small number of records is used for the 1952 Kamchatka and the 1960 Chile earthquake. In some cases the size of the aftershock area is used. The stations used are different for different events.

R.D. Adams

Is the method applicable to deep earthquakes?

H. Kanamori

Yes. Long-period body waves give the seismic moment from which W_0 and M_w can be obtained.

M. Wyss

You said: "The method to estimate the new magnitude is applicable for deep earthquakes." In my opinion it is not directly applicable because you have to assume a constant stress drop with a value appropriate for shallow shocks. Deep earthquakes may have a larger stress drop on the average.

H. Kanamori

In practice, the value of the stress drop must be known. Since the stress drops for deep focus earthquakes are still somewhat uncertain, the estimate of W_0 is correspondingly uncertain.

A. Dziewonski

How reliable are the estimates of seismic moments of earthquakes that occurred prior to 1952; that is before the adequate long period instrumentation has been developed. The probability of random grouping of three of sixteen largest events in that period of time is 1/600 (I am referring to the figure of a paper by O'Connell and Dziewonski in Nature, 22 July 1976).

H. Kanamori

The accuracy of the moment determination is considerably lower for earthquakes prior to 1952. However, old instruments are still good enough to distinguish great earthquakes such as the 1960 Chilean earthquake from moderate-to-large earthquakes. Very long-period mantle waves are clearly registered by these great earthquakes, while no such waves are found for moderate-to-large earthquakes. I am almost certain that there was no great earthquake such as the 1960 Chilean earthquake during the period 1920 to 1952. For the time prior to 1920, I have not finished the analysis.