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EARTHQUAKE FREQUENCY DISTRIBUTION AND THE MECHANICS OF FAULTING

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Abstract. The level of intraplate seismicity in Japan generally shows a positive correlation with the density of Quaternary faulting. In southwest Japan, where intraplate seismicity is concentrated on land, rates of seismic moment release ($\dot{M}_0$) are similar when calculated from either the 400-year historical record of seismicity or geologically determined slip rates of Quaternary faults. A data set of 18 earthquakes with seismic moments (M_0) ranging from ~0.01 to 3×10^{27} dyn cm shows a relationship between rupture length ℓ and M_0 ($\log M_0 = 23.5 + 1.94 \cdot \log \ell$). When seismic moment on each Quaternary fault is assumed to occur in discrete events every $T = M_0/\dot{M}_0^g$ years (where M_0 is estimated for a rupture extended over the entire fault length, and $\dot{M}_0^g$ is proportional to the slip rate of each Quaternary fault), the moment frequency distribution of earthquakes ($\log N = A - B \cdot \log M_0$) predicted from the geologic record is virtually identical to that seen with the 400-year record of seismicity. In contrast, if it is assumed that earthquakes on each fault occur according to the Gutenberg-Richter relation, we obtain poor agreement with the observed seismicity. Thus, while regional seismicity satisfies the relation $\log N = A - B \cdot \log M_0$ (or equivalently, $\log N = a - b \cdot \log M$, where M is magnitude), it appears that seismicity on individual faults does not. This further implies that the primary factor that leads to the magnitude frequency distribution in regional seismicity studies is the relative distribution of the slip rates and lengths of preexisting faults.

Introduction

The issue addressed in this paper is whether or not seismicity on a fault obeys the Gutenberg-Richter relation

$$\log N = a - b \cdot M \qquad (1)$$

where N is the number of earthquakes with magnitude greater than or equal to M and a and b are empirical constants. It is well known that the frequency distribution of earthquakes in a broad region that includes many faults generally satisfies (1) [Ishimoto and Iida, 1939; Gutenberg and Richter, 1944], and that the b value in this relation is often used to characterize the seismicity of a region. In addition to being true for a regional data set, many investigators have assumed that seismicity particular to a single fault or fault segment may also be described with (1) [e.g., Andrews, 1980; Hanks, 1979; Nur, 1978; von Seggern, 1980]. This assumption implies that during the repeat time of one maximum magnitude (M^{max}) earthquake on a fault, some fault slip is also accommodated by the occurrence of smaller earthquakes that obey (1) up to the limiting value M^{max}. This concept is schematically illustrated in Figure 1a as a plot of the expected number of events versus magnitude on a fault during the repeat time of one M^{max} event. The relative number of lesser events ($M < M^{max}$) during the repeat time of M^{max} is then determined by the b value of the fault. The consequences of this model, if correct, are far reaching with respect to our understanding of the fault rupture process as well as our interpretation of seismic hazard. A number of studies, for example, have attempted to relate the b value to physical properties of the fault rupture surface, such as the state of stress and the degree of heterogeneity [e.g., Andrews, 1980; Hanks, 1979; Nur, 1978; von Seggern, 1980]. With respect to seismic hazard, this model predicts that a number of smaller, though potentially damaging earthquakes will occur on a fault during the repeat time of the maximum expected event on that same fault. Let us subsequently refer to this hypothesis of fault behavior as the b value model.

The southern segment of the San Andreas fault that ruptured during the 1857 ($M_w = 7.8$) Ft. Tejon earthquake provides an appropriate example to compare predictions of the b value model with empirical data. Information from trenching across the San Andreas suggests that the average repeat time of similar sized events on the same fault segment is about 150 years [Sieh, 1978a]. The number and, hence, recurrence time of smaller events expected on the fault during the 150-year repeat time is simply computed with (1) once a value of b is assumed. Taking b to equal 1.0 ± 0.5, a range of values considerably greater than has been reported in southern California [e.g., Gutenberg and Richter, 1944; Allen et al., 1965; Utsu, 1971], the computation indicates that the recurrence interval of events of magnitude less than 7.8 and greater than 5.0 should average between about 2 days and 5 years. In the nearly 50 years since 1934, when instrumental coverage became complete for events of M > 5.0 in this region [Allen et al., 1965], we should have then expected between about 10 and 9000 events of M > 5.0 to have occurred on that section of fault. None, however, have been reported [Allen et al., 1965; Hileman et al., 1973]. A similar inconsistency can be observed along the northern segment of the San Andreas that broke in 1906 [e.g., see Ellsworth et al., 1981]. The discrepancy between the observed and predicted number of events might

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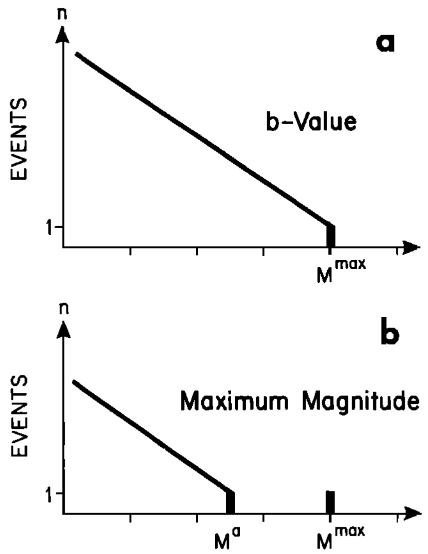

Fig. 1. Expected number of events versus magnitude on a fault during the repeat time of one M^{max} event, predicted by the (a) b value and (b) maximum magnitude models of fault behavior.

be attributed to temporal variations of seismicity on the fault. Records of seismicity are too short to either prove or disprove such an explanation, although such an explanation would largely obviate the usual interpretation that (1) describes a size distribution that is stationary in time. The simple exercise and result presented here is, however, sufficient to suggest the b value model may not be applicable to an individual fault or fault segment and that we consider an alternative. Another model of fault behavior that simply accounts for the absence of moderate and small earthquakes along the 1857 fault rupture segment was, in fact, proposed by Allen [1968].

Allen [1968] made the critical observation that the mode of strain release along the San Andreas fault zone strongly differs along strike. Those portions of the San Andreas that exhibit a complex fault trace, as evidenced by branching, splaying, and en echelon breaks, show abundant small and moderate earthquakes, fault creep, and the absence of great earthquakes. In contrast, the two segments of the San Andreas where slip is generally confined to a single, though bent, fault trace have ruptured during great earthquakes in 1857 and 1906, respectively. Further, these same two segments are now essentially devoid of seismicity down as far as the microearthquake level. Allen [1968] attributed the variation in seismic character along strike to the varying geologic and tectonic setting along the fault length and further suggested that the variation is a permanent feature of the fault. Scholz [1977] interpreted observations of the New Zealand transform fault system in a like manner. Allen [1968] thus suggested that the absence of small shocks along the 1857 and 1906 rupture segments is typical of the past and future behavior of these portions of the fault between the infrequent occurrence of great earthquakes, with the notable exception of foreshocks and aftershocks. Such an idea is also consistent with the other segments of fault except that the maximum expected event is smaller. The observations and interpretation of Allen [1968] thus imply a fault model whereby faults, or fault segments, generate earthquakes of a characteristic size that is a function of fault length and tectonic setting, and that these characteristic events together with their foreshocks and aftershocks account for all the seismic slip on the fault. Analyses of earthquake frequency statistics [Utsu, 1971; Singh et al., 1981; Bäth, 1981; Lahr and Stephens, 1982] and site specific geologic investigations [Sieh, 1978a, b; Schwartz et al., 1981] reported for other regions have more recently lent further credence to this concept of fault behavior. The concept is illustrated in Figure 1b as the expected frequency distribution of earthquakes on a fault during the repeat time of one characteristic event. The magnitude of the characteristic event is M^{max}, the maximum expected earthquake on a fault. The largest aftershock (M^a) is usually one to two magnitude units less than M^{max}, and in accord with observation the sequence of aftershocks is assumed to obey the Gutenberg-Richter relation [Utsu, 1971]. The total slip registered by aftershocks is generally less than 5% of that occurring in the mainshock M^{max} [Scholz, 1972]. Foreshocks are not illustrated but by definition are smaller than the mainshock and, like aftershocks, spaced closely in time to the occurrence of the mainshock. For convenience, the mode of fault behavior described in Figure 1b will be referred to as the maximum magnitude model.

There thus coexist two schools of thought concerning the seismic behavior of faults, for which the main features of each are portrayed in Figure 1. Determining which model best describes fault behavior is of both practical and scientific importance. The b value model implies a relatively stationary process, whereby seismic events of all sizes occur continually on a fault during the interval between the maximum expected events. On the other hand, the maximum magnitude model specifies that the time between maximum expected events is essentially quiescent but for the possible occurrence of foreshocks and aftershocks. The decision of which model to use is then of critical importance for seismic hazard studies. Similarly, estimates of the repeat time of maximum expected events on a fault will be dependent on which fault model is assumed. As an example, consider two faults with identical slip rates and the same maximum expected earthquake M^{max} but each respectively described by one of the two fault models. The estimated repeat time of a M^{max} event will be longer for the fault described with the b value model for the simple reason that slip is also being accommodated by smaller earthquakes. We shall later return to discuss this idea in more quantitative terms. Finally, an explanation of why regional seismicity satisfies the Gutenberg-Richter relation is linked to our understanding of which model is most accurate. For example, if faults behave according to the maximum magnitude model and the maximum expected earthquake on a fault is a function of fault length, then a plausible explanation of the frequency distribution of earthquakes in a region might be that it simply reflects the distribution of fault lengths in the area. Alternatively,

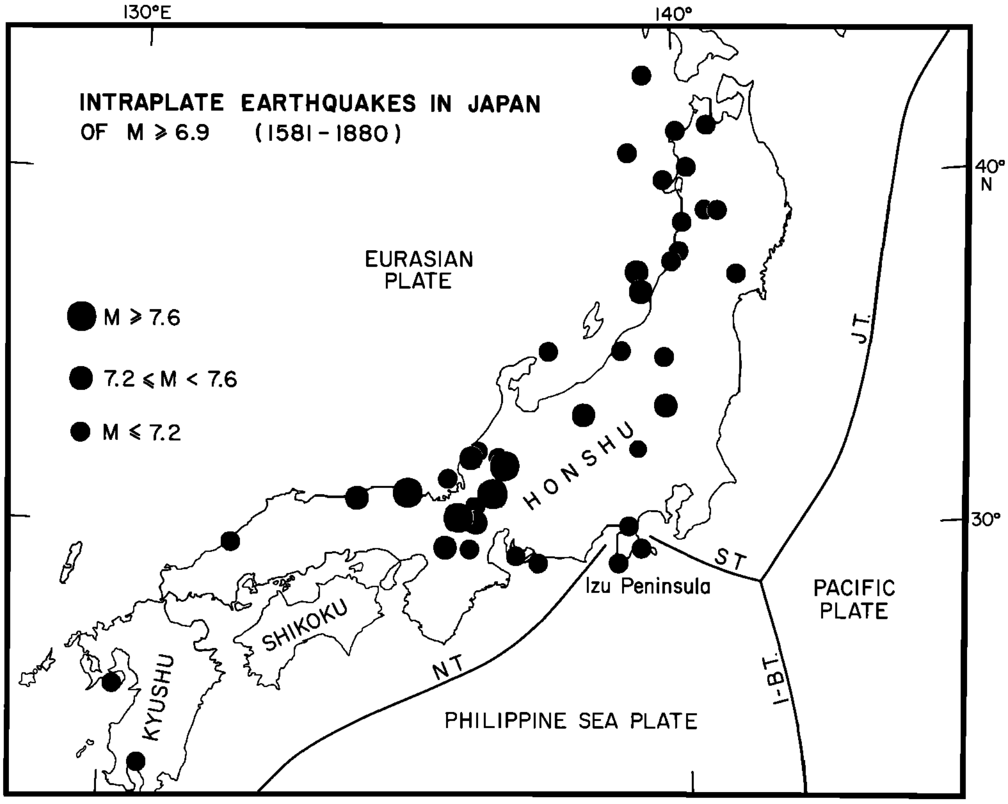

Fig. 2. Intraplate earthquakes in Japan (excluding Hokkaido) of M > 6.9 during the period 1581-1980 (data from Wesnousky et al. [1982]). The Nankai Trough (N.T.), Japan Trench (J.T.), Sagami Trough(S.T.), and Izu-Bonin Trench (I.-B.T.) are shown schematically.

if the b value model is the correct one, the regional earthquake frequency distribution is the cumulative effect of the frequency distribution of earthquakes on each fault. The purpose of this paper, then, is to use seismicity and Quaternary fault data as a basis for determining which style of faulting best describes the true behavior of faults. The region of southwest Japan is chosen as the area of study because it is for this region that presently exists the most extensive data set concerning seismicity and Quaternary faulting.

The seismic moment M_0, a more fundamental measure of earthquake strength than is magnitude M, will be used for the ensuing analysis. M_0, like M, can be measured directly with instrumental data. M_0, however, has the added advantage that it may be related to physical parameters that describe the earthquake source. For shearing on a fault, M_0 is equal to μuA, where μ is the rigidity, u the average slip on the fault, and A the fault area [e.g., Aki and Richards, 1980]. The regional rate of seismic moment release $\dot{M}_0$ resulting from earthquakes on a network of faults is then a fundamental measure of seismic activity. Similarly, an estimate of the average rate of seismic moment release from a set of active faults may be determined if geologic estimates of the average slip rate of each fault are known. Wesnousky et al. [1982] determined $\dot{M}_0$ in intraplate Japan, an area where seismicity is shallow and occurs on an extensive set of mapped Quaternary faults. It was observed in that study that $\dot{M}_0$ estimated from the geologically determined slip rates of Quaternary faults is similar to $\dot{M}_0$ determined from the available 400-year record of earthquakes in regions where seismicity is concentrated on land. Aseismic creep has not been observed on any active faults in Japan except for relatively minor amounts of fault slip immediately after great earthquakes [Matsuda, 1977]. The results of Wesnousky et al. [1982] are thus consistent with the hypothesis that seismicity in intraplate Japan has been steady through the late Quaternary. An analogous interpretation is that the geologic record of fault offsets in Japan contains an essentially complete record of seismicity during the late Quaternary.

The problem in resolving which style of faulting best represents the actual behavior of faults is, of course, the fact that the length of instrumental and historical records of seismicity are, as a general rule, much shorter than the average repeat time of large earthquakes on any particular fault. Hence, as for the 1857 rupture segment of the San Andreas, the data base describing seismicity on a certain fault is generally insufficient to decide conclusively in which manner a certain fault behaves. In this study, we approach the problem differently by considering the extensive data set available which describes the average slip rates of Quaternary faults [Research Group for Active Faults of Japan, 1980a, b] and historical

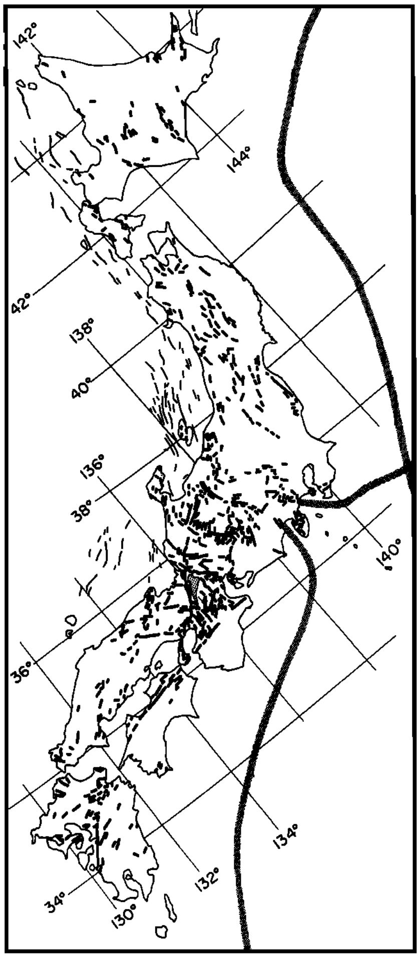

Fig. 3. Distribution of active intraplate faults in Japan. Faults mapped by marine seismic reflection surveys are denoted by thinner lines. Adjacent plate boundaries are represented as thick stippled lines. (Data are adapted directly from Research Group for Active Faults of Japan [1980a, b]).

seismicity [Usami, 1975; Utsu, 1979] in Japan. Geologic data describing the lengths and slip rates of faults may be utilized to estimate the repeat time of earthquakes on faults when certain assumptions are made concerning the mechanics of faulting. In this study, it is initially assumed that the occurrence of earthquakes on a fault is described by either of two fault models, constructed to predict seismicity on a fault according to each of the two respective styles of seismicity previously described (Figure 1). Each of the idealized fault models in conjunction with data describing the slip rates and lengths of Quaternary faults in southwest Japan is then employed to compute the moment frequency distribution of earthquakes expected in southwest Japan during a 400-year period. Comparison of the number of earthquakes predicted with each fault model and the geologic data to the seismicity observed during the last 400 years provides a test to decide which model most accurately depicts the gross characteristics of fault behavior.

Seismicity and Faulting in Intraplate Japan

A detailed description of seismicity and faulting, and a quantitative estimate of the amount of deformation that takes place as slip on intraplate faults in Japan, is presented by Wesnousky et al. [1982]. The data set and results described in that paper provide the foundation on which we address the question of which style of faulting most accurately portrays fault behavior. Only the salient features and results pertinent to this analysis are repeated here.

An epicentral plot of large ($M > 6.9$) shallow earthquakes that have occurred in intraplate Japan during the last 400 years is shown in Figure 2. The level of intraplate seismicity generally shows a positive correlation with the density of Quaternary faulting (Figure 3). The orientation and displacement of Quaternary faults closely mimic movement observed in recent earthquakes, as evidenced by recent focal mechanism data (Figure 4). Similarly, large intraplate earthquakes in Japan commonly produce surface ruptures along preexisting, mappable Quaternary faults [Matsuda, 1977]. The sense of surface displacement produced by these earthquakes is consistent with, though smaller than, the total geologic offset registered across the faults on which they occur. The data thus support the idea that the total displacement documented on the Quaternary faults is the cumulative result of the repeated occurrence of earthquakes through the Quaternary.

Wesnousky et al. [1982] used the extensive data set describing historical seismicity [Usami, 1975; Utsu, 1979] and Quaternary faulting [Research Group for Quaternary Faults of Japan, 1980a, b] to decide whether or not the rate of seismicity or, in effect, the rate of slip on active faults has been steady through the Quaternary period. Seismic moments of large historical earthquakes were either gathered from the literature or estimated from seismic intensity data. The data set enabled computation of the average seismic moment release rate $\dot{M}_0$ during the last 400 years. The results indicated that $\dot{M}_0$ was relatively steady when averaged over periods as small as 200-300 years. In conjunction with this result, data describing the lengths and geologically determined slip rates of Quaternary faults were also used to assess the average moment release rate of each Quaternary fault in Japan. The data set used in that study is located in Research Group for Active Faults of Japan [1980a, b] (hereinafter referred to as the 'active faults book'). Specific values of slip rate for faults are given in the active faults book only when the ages of displaced features have been precisely determined. In general, the precise age of displaced geologic markers is not known but can be constrained within certain limits. In such cases, the active faults book provides estimates of the 'degree' of slip rate for each fault: degree 'A,' 1-10 mm/yr; degree 'B,' 0.1-1 mm/yr; degree 'C,' 0.01-0.1 mm/yr. Wesnousky et al. [1982] found, within the bounds placed by the geologically assessed slip rates, that the cumulative moment release rate resulting from slip on mapped Quaternary faults is in accord with estimates of $\dot{M}_0$ determined with the

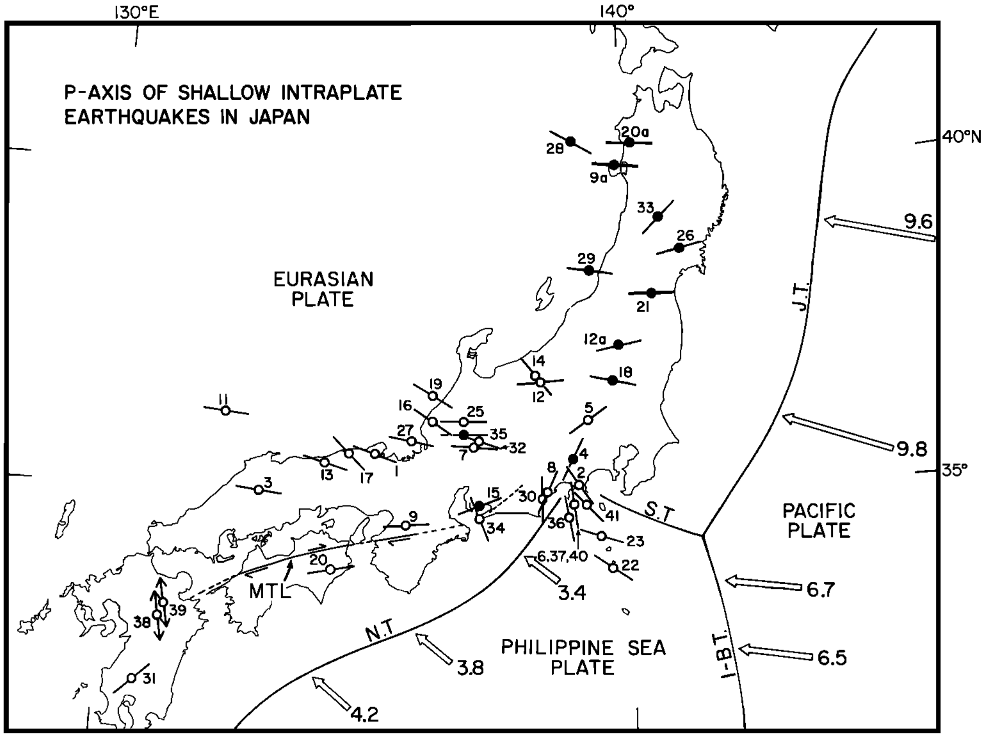

Fig. 4. P axes of intraplate earthquakes with magnitude of about 6.0 and greater. Epicenters of strike slip and reverse-type faults are denoted by open and solid circles, respectively. The horizontal projection of P axes is shown by lines through epicenter symbols. Numbers next to earthquake symbols correspond to list of earthquake data for each event in Table 1 of Wesnousky et al. [1982]. Schematic plate boundaries are given and labeled as in Figure 2. Relative plate velocities (cm/yr) calculated from Seno [1977] are shown by large hollow arrows. The median tectonic line (MTL) has right-lateral offset (half-sided arrows) and is shown as a solid and dashed line where it has and has not, respectively, been active during the Quaternary.

400-year record of historical seismicity. This result supports the hypothesis that the rate of seismicity has been steady during the late Quaternary and relatively free from secular variation when averaged over periods of time greater than a few hundred years.

Idealized Earthquake Recurrence Models

The Gutenberg-Richter relation (equation 1) may also be expressed as a function of seismic moment. The relationship between seismic moment M_0 and magnitude M is of the general form $\log M_0 = c + d \cdot M$ [e.g., Wyss and Brune, 1968; Thatcher and Hanks, 1973]. Substituting M_0 for M in (1), the magnitude frequency relation of Gutenberg and Richter [1944] (equation 1) becomes the moment frequency relation

$$N(M_0) = \eta M_0^{-B} \qquad (2)$$

where $\eta = \exp [2.3 (a + bc/d)]$ and $B = b/d$ [Wyss, 1973]. The frequency distribution of earthquakes then is readily characterized by either the value of b or B, depending on whether M or M_0, respectively, is being used as the measure of earthquake strength. In this section, the maximum magnitude and b (or B) value models of fault behavior (Figure 1) are recast in terms of seismic moment, so that seismicity on a geologic fault may be predicted as a function of the fault length and slip rate.

The B Value Model

The first style of faulting considered, for convenience termed the 'B value' model, stems from the observation that the size of earthquakes in a region is generally described by (2). The assumption is made here that seismicity particular to a certain fault is also described by (2). This implies that during the repeat time (T^{max}) of the maximum expected seismic moment (M_0^{max}) on a fault, some fault slip will also occur during earthquakes with smaller seismic moments. The number of smaller earthquakes expected to occur during the repeat time of M_0^{max} is determined by B. To approximate the total seismic moment release ($\sum M_0$) resulting from all earthquakes during the repeat time T^{max} of one M_0^{max} event, we define the moment probability density function as the derivative of (2) with respect to seismic moment,

$$\frac{dN(M_0)}{dM_0} = -\eta_{max} \cdot B \cdot M_0^{-(B+1)} \qquad (3)$$

where η_{max} is determined from (2) for the case

$N(M_0^{max}) \equiv 1$. $\sum M_0$ is thus approximated

$$\sum M_0 = \int_{M_0^{min}}^{M_0^{max}} M_0 \cdot \frac{dN(M_0)}{dM_0} \cdot dM_0$$
$$= \frac{\eta_{max} \cdot B}{1-B} \left[M_0^{1-B} \right]_{M_0^{min}}^{M_0^{max}} \tag{4}$$

where M_0^{min} is the seismic moment of the smallest earthquake considered. Though (4) is incorrect for $B = 1$, empirical data generally indicate that $b \approx 1$ [Utsu, 1971], $\log M_0 \; .^{\cdot}. \; 1.5\, M$ [e.g., Thatcher and Hanks, 1973; Purcaru and Berckhemer, 1978] and, as a result, $B \approx 2/3$. Noting that earthquakes of the largest seismic moment, though less frequent in occurrence, are responsible for most of the seismic moment release [Brune, 1968], and taking M_0^{min} as the minimum sized earthquake that contributes significantly to the total moment release, an estimate of T^{max} on a fault may be written

$$T^{max} = \frac{\sum M_0}{\dot{M}_0^{g}} \tag{5}$$

where $\dot{M}_0^{g}$ is the geologically assessed rate of seismic moment release on the fault. The repeat time of smaller events (T^{sm}) on the same fault with seismic moment $M_0^{sm} \pm \Delta M_0$ may be computed as

$$T^{sm} = T^{max} \Big/ \int_{M_0^{sm}-\Delta M_0}^{M_0^{sm}+\Delta M_0} \frac{dN(M_0)}{dM_0} \cdot dM_0 \tag{6}$$

The Maximum Moment Model

The second of the two fault models will be referred to as the maximum moment model. The model assumes that the repeat time of earthquakes on a fault is equal to the seismic moment of the maximum expected earthquake on a fault (M_0^{max}) divided by the geologically determined rate of moment release ($\dot{M}_0^{g}$) on the fault:

$$T = M_0^{max} / \dot{M}_0^{g} \tag{7}$$

The maximum moment model thus states that seismic moment on a fault is periodically released in earthquakes of only one size, M_0^{max}. Another assumption, addressed later in the text, is that M_0^{max} is proportional to the length of the preexisting fault. Hence a direct consequence of this fault model, if correct, is that the frequency distribution of earthquakes for an area is simply a function of the regional distribution of fault lengths and slip rates. Finally, it should be noted that the maximum moment model is, in fact, equivalent to the B value model for the case $B = 0$.

To depict further the dissimilarity between the two fault models, let us use each fault model to predict seismicity on a fault for which M_0^{max} and $\dot{M}_0^{g}$ are defined to equal $10^{27.75}$ dyn cm and $10^{25.75}$ dyn cm/yr, respectively. These parameters are approximate to those estimated for the segment of San Andreas fault that ruptured in 1857 [e.g., Sykes and Quittmeyer, 1981]. Seismicity for this hypothetical fault predicted with the B value model, assuming that B is 0.67 (or equivalently, $b = 1$, assuming $\log M_0 = 1.5\,M + 16.1$ [Hanks and Kanamori, 1979]), a value representative of southern California seismicity [e.g., Allen et al., 1965], is shown in Figure 5 as the cumulative number of events with seismic moment $\geq M_0$. For reference, seismic moment is also expressed in approximately equivalent units of magnitude in Figure 5. The B value model (equation 5) indicates that the fault should produce one M_0^{max} event every $T^{max} = 200$ years. The B value model (equation 6) further indicates that earthquakes with $M_0 < M_0^{max}$ will also occur on the fault with repeat times much less than 200 years. The number of smaller events in this case is computed with (6), taking ΔM_0 as $10^{0.25}$ dyn cm. The maximum moment model in turn predicts no events of $M_0 < M_0^{max}$. Further, T^{max} predicted by the maximum moment model is only 100 years, one half that predicted by the B value model, even though M_0^{max} and $\dot{M}_0^{g}$ are assumed identical for both cases.

Comparison of the Fault Models

The moment frequency distribution of earthquakes expected from the distribution of active faults in Japan, assuming either the B value or maximum moment fault model may be calculated once M_0^{max}, M_0^{min}, and $\dot{M}_0^{g}$ for each fault are established. Prior investigations have shown that slip u and, hence, seismic moment release during large earthquakes are proportional to ℓ, the rupture length [Matsuda et al., 1980; Scholz, 1982]. The source parameters of virtually all large intraplate earthquakes in Japan that occurred during the last 100 years have been determined with detailed study of instrumental, geodetic, and geologic data. This data set is tabulated by Wesnousky et al. [1982] and, accordingly, shows a systematic relationship between seismic moment and rupture length (Figure 6). Large intraplate earthquakes in Japan commonly produce surface ruptures that extend over the entire length of a preexisting, mappable fault [Matsuda, 1977]. These observations are the basis for assuming that M_0^{max} for each Quaternary fault in Japan is proportional to the mapped fault length. Many faults described separately in the active faults book form linear trends and show the same sense of offset. The intervals between such linearly trending faults are often small with respect to the lengths of the faults. A reasonable assumption, consistent with observation [e.g., Matsuda, 1972, 1974; Matsuda et al., 1980], is that these linear trends of faults may rupture simultaneously during a single earthquake. The active faults book data set amended in this manner is presented in Appendix II of Wesnousky [1982]. The relation in Figure 6, the assumption that rupture may extend over the entire fault length, and the amended active faults book data set are thus used to estimate M_0^{max} for each Quaternary fault. M_0^{min} is taken to equal zero. Finally, $\dot{M}_0^{g}$ is determined for each fault in the amended data

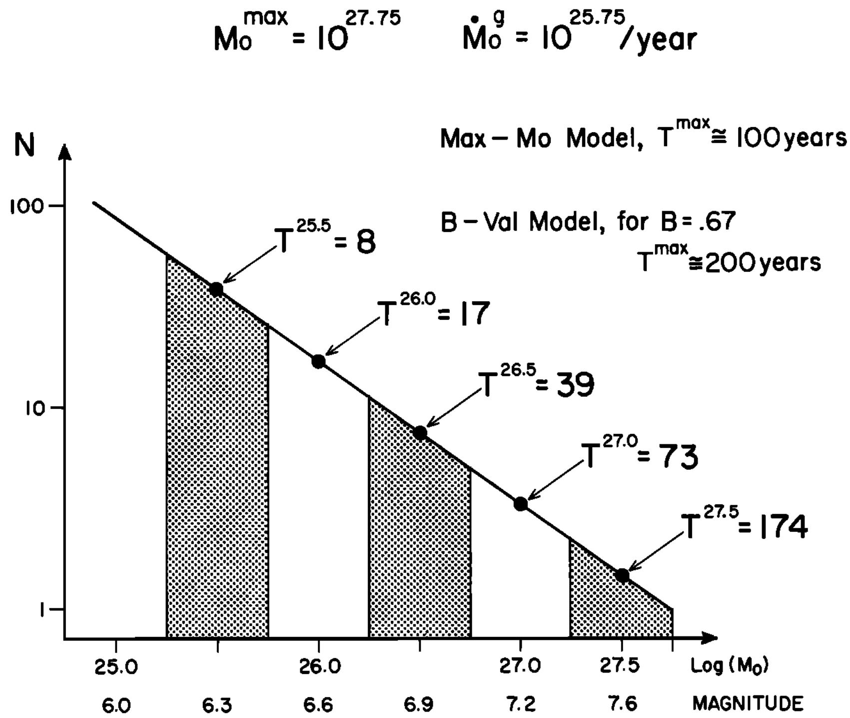

Fig. 5. Seismicity on a fault described by maximum moment and B value models of fault behavior.

set with the methodology explicitly outlined by Wesnousky et al. [1982].

We consider only southwest Japan, the area encompassing Shikoku and central and western Honshu (Figure 2). It is for this region that seismicity and, hence, faulting are concentrated on land. The Quaternary fault data and each fault model are used to compute the expected moment frequency distribution of earthquakes for southwest Japan during a 400-year period. Wesnousky et al. [1982] compared $\dot{M}_0^g$ determined with the Quaternary fault data to $\dot{M}_0$ assessed from the 400-year record of seismicity. The historical record of earthquakes presented by Wesnousky et al. [1982] is composed of events with 26.0 < log M_0 < 27.3. Hence to compare the seismicity predicted with each fault model to the observed seismicity, the rates of slip (of those faults categorized with degree 'A,' 'B,' or 'C' slip rates) are adjusted to produce $\dot{M}_0$, resulting from earthquakes with 26.0 < log M_0 < 27.3, equal to that computed from the 400-year historical record. The moment frequency distribution predicted for southwest Japan with each fault model is compared to the empirical 400-year record of seismicity in plots of the cumulative number of earthquakes versus log M_0 in Figure 7.

The 400-year record of seismicity for southwest Japan is displayed in Figure 7 as open symbols. Data for events of log M_0 > 26 (open circles) are from the 400-year record of seismicity presented by Wesnousky [1982] and Wesnousky et al. [1982]. Data for events of log M_0 < 26.0 (open triangles) are obtained from recent catalogues that describe the last 100 years of seismicity [Utsu, 1979; Japan Meteorological Agency, 1958, 1966, 1968 and supplementary volumes], multiplied by 4. Magnitudes of events listed in these recent catalogues are converted to M_0 with the relation log M_0 = 1.5 M + 16.1. This relation is representative of a large suite of earthquakes [Thatcher and Hanks, 1973; Purcaru and Berckhemer, 1978; Hanks and Kanamori, 1979] and is in general accord with the data set of Japanese intraplate earthquakes [Wesnousky, 1982]. The solid circles in Figure 7 represent the seismicity predicted with the maximum moment model. The shaded region in Figure 7 indicates the moment frequency distribution predicted with the B value model when B, for each fault, is assigned a value of 0.67 ± 0.13. This range of values corresponds to magnitude b values of 1.0 ± 0.2 if log M_0 is taken to equal 1.5 M + 16.1. The curve predicted by the maximum moment model mimics best the observed seismicity. In contrast, the slope of the curves determined with the B value technique are steeper, predicting fewer large events and more smaller events than

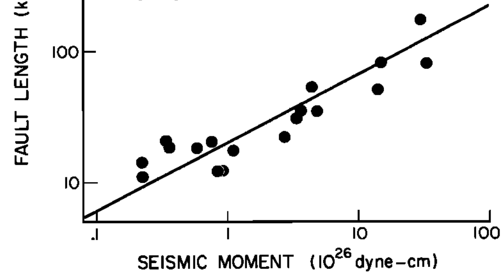

Fig. 6. Fault rupture length ℓ versus seismic moment M_0 for large intraplate earthquakes in Japan.

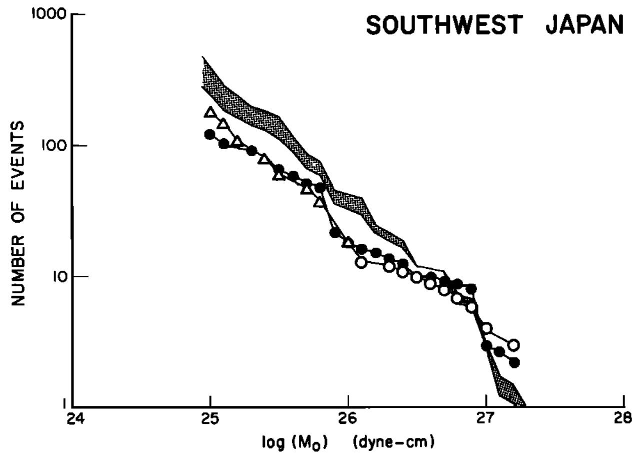

Fig. 7. Plot of the number of events per 400 years in southwest Japan with seismic moment greater than or equal to M_0. Open symbols are the observed seismicity. Solid circles and shaded regions represent seismicity predicted from the Quaternary fault data by the maximum moment and B value models, respectively. See text for further explanation.

have been observed. These observations imply that the mechanical behavior of faults lies closest to the extreme described by the maximum moment model.

Discussion

It has long been observed that seismicity of a region is generally described by the Gutenberg-Richter relation [e.g., Ishimoto and Iida, 1939; Gutenberg and Richter, 1944]. It is sometimes assumed that seismicity particular to a fault satisfies the same relation [e.g., Nur, 1978; Andrews, 1980; Hanks, 1979; von Seggern, 1980]. The results of this analysis do not support this assumption. Rather, this study argues that the mechanics of faulting lie closer to the extreme described by the maximum moment model than to the B value model. Consequently, the data support the hypothesis that the frequency distribution of earthquakes is, at least in intraplate Japan, primarily a function of the regional distribution of fault lengths and slip rates. These simple results are of fundamental importance to our understanding of fault mechanics, provide insight into the Gutenberg-Richter relation, and are of consequence to any analysis of seismic hazard.

The implications regarding the mechanics of faulting and interpretation of the Gutenberg-Richter relation warrant further discussion in light of the observation that large earthquakes are generally accompanied by the occurrence of foreshocks and aftershocks. The period of time during which these events occur brackets the mainshock and is typically short with respect to the repeat time of the mainshock. Further, the seismic moment contribution of the foreshock and aftershock sequences is ordinarily small compared to the seismic moment of the mainshock [Scholz, 1972]. The occurrence of such sequences is thus considered a second-order effect with respect to the mechanics of faulting described by the maximum moment model.

The assumption that faults behave according to the B value model has been the basis of several efforts to relate the degree of heterogeneity and associated stresses on a fault to the number-size distribution of earthquakes. More specifically, it has been argued that seismicity on a fault obeys a self-similar power law distribution (i.e., the Gutenberg-Richter relation) that reflects the spectral composition of ambient shear stresses existing on a fault [e.g., Hanks, 1979; von Seggern, 1980; Andrews, 1980]. It is of interest to examine this assumption and its consequences in light of the major result of this paper, that the mechanical behavior of faulting is more accurately described by the maximum moment model than by the B value model. The maximum moment model implies that the description of stresses on a fault as a power law distribution may be applicable for aftershock sequences but is not continuous up to the 'fault length' wavelength. If, however, one considers the stresses responsible for faulting on a global scale, the stress distribution might be appropriately described by a self-similar power law distribution (T. Hanks, personal communication), as evidenced by the observation that regional seismicity generally satisfies equation (1). Returning our interest to a single fault, the maximum moment model implies that following the aftershock sequence, the shear stress composition on a fault is nearly monochromatic, which, in turn, implies that the existing state of stress on a fault is quite regular and not so chaotic as implied by a power law distribution (i.e., the B value model). Finally, it has also been suggested that major fault ruptures tend to roughen or increase the high-frequency components of stress on a fault and that smaller earthquakes during the interval between major ruptures act to smooth out or increase the spectral composition of shear stress on a fault surface [e.g., Andrews, 1980]. The maximum moment model implies that this smoothing, if real, is not a steady state process that continues throughout the interval between mainshocks but rather is primarily limited in time to the aftershock sequence.

With respect to seismic hazard, this analysis indicates that separate approaches should be taken to evaluate seismic hazard, depending on whether concern is with seismicity associated with a particular fault or from a network of many faults. When evaluating seismic hazard due to a single fault, it is not appropriate to assume that seismicity on the fault obeys the Gutenberg-Richter relation, and hence, very few or no moderate sized earthquakes should be anticipated on a fault during the repeat time of a maximum expected earthquake on that same fault. In contrast, if a statistical approach is taken to predict seismicity in a region that results from many faults, then it is correct to assume that the earthquake frequency distribution will satisfy the Gutenberg-Richter relation.

The discussion thus far has centered on results obtained from data describing seismicity and Quaternary faulting in intraplate Japan. The maximum moment model assumes that earthquakes rupture the entire length of a preexisting fault. The assumption is reasonable for intraplate Japan but conflicts with observations along major plate boundary faults, such as the San Andreas. Earthquakes along such features commonly do not rupture the entire length of the boundary. We would thus suggest, as was implied in Allen's [1968] work, that major plate boundaries may, in general, be considered as many connected fault segments, each of which behaves according to the maximum moment model. Hence, for example, if seismicity were monitored over the entire length of the San Andreas, it would probably satisfy the Gutenberg-Richter relation simply because there exist many fault segments of varying size.

Conclusions

Two concepts of fault mechanics have been compared using empirical data describing seismicity and Quaternary faulting in Japan. The comparison supports a hypothesis whereby seismic slip on preexisting faults takes place cyclically during earthquakes of characteristic size. The size and repeat time of the characteristic event are a function of the fault length and slip rate, respectively. The results also suggest that the earthquake frequency distribution particular to a single fault does not satisfy the Gutenberg-Richter relation. A consequence is that the primary factor responsible for the earthquake frequency distribution in regional seismicity studies is the relative distribution of fault lengths and slip rates.

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