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ABSTRACT

This paper reports on a study of the historic temporal variations in earthquake occurrence and seismic energy release on a regional basis throughout the world. The regionalization scheme employed divides the world into large areas based either on seismic and tectonic considerations (Flinn-Engdahl Scheme) or geographic (longitude and latitude) criteria. The data set is the worldwide earthquake catalog of the National Geophysical Solar-Terrestrial Data Center. The analysis reveals: 1.) that an apparent relationship exists between the maximum energy released in a limited time within a seismic region and the average or background energy per year averaged over a long time period; 2.) that in terms of average or peak energy release, the most seismic regions of the world during the 50 - 81 year period ending in 1977 were the Japanese, Andean South American, and the Alaska-Aleutian Arc regions; 3.) that the year-to-year fluctuations in regional seismic energy release are greater, by orders of magnitude, than the corresponding variations in the world-wide seismic energy release; and 4.) that the "b" values of seismic regions range from 0.7 to 1.4 when earthquake magnitude is in the range 6.0 to 7.5.

REGIONAL ANALYSIS OF EARTHQUAKE OCCURRENCE AND SEISMIC ENERGY RELEASE

INTRODUCTION

Although much is known about the temporal and spatial patterns of earthquake occurrence, new insights continue to emerge from the reexamination of cataloged data. For example, recent investigations have shed light on the temporal variations in the number and seismic energy associated with intermediate and deep focus earthquakes (Abe and Kanamari, 1979), and the magnitude-space-time interactions of shallow focus earthquakes (Kagan and Knopoff, 1978). Studies of variations and similarities in regional seismicity have been reported by Bloom and Erdmann (1980) and Everden (1970) among others. The present analysis examines the characteristics of earthquake occurrence and seismic energy release on a regional basis using the seismic regionalization scheme of Flinn and Engdahl (1965) (herein called F–E) as well as 5°, 10°, and 15° longitude-latitude blocks. The results reveal: 1.) that an apparent relationship exists between the maximum seismic energy released in a limited time within a region and the average background energy released in that region over a much longer time; 2.) that in terms of average or peak energy release in a region, the most seismically active regions of the world during the last 50–81 years are the Japanese, Andean South America, and Alaska-Aleutian Arc regions; 3.) that the year-to-year fluctuations in regional seismic energy release in the fifty F–E regions are several orders of magnitude, even in the most seismically active regions, whereas the world-wide fluctuation is only about one order of magnitude; and 4.) that the regional b values, that is the (absolute value of the) slope of the logarithm of the number of earthquakes occurring with magnitude greater than or equal to M_S versus M_S, range from 0.7 to 1.4, for all regions with reliable data when M_0 is the magnitude range 6.0–7.5. The catalog we have used for the analysis is the National Geophysical and Solar-Terrestrial Data Center (NGSDC) Earthquake Data File (Meyers and von Hake, 1976) from 1638–1977.

METHODS AND RESULTS

The adoption of a seismic regionalization scheme is necessarily a compromise of often competing objectives. Our basic desire is to examine seismic history in a region that is sufficiently well defined by geology, tectonics, or seismicity to be regarded as a logical unit. It is necessary to avoid choosing small units such as geologic provinces which are, in many cases, clearly delineated, but which divide the world into too fine a net with insufficient levels of seismic activity within many grid divisions. Conversely, there is the danger of choosing regions so large that they can no longer be regarded as reasonable units. One regionalization scheme which has been widely adopted in the past and which has proved useful in the present study is that of Flinn and Engdahl (1965) and Flinn, Engdahl, and Hill (1974) based on the pioneering work of Gutenberg and Richter (1954). This scheme divides the world into fifty seismic regions as shown in Figure 1, and further subdivides these fifty into a total of 729 geographical regions. The geographical region number is a part of the record of each event in the NGSDC catalog; therefore, this scheme is particularly easy to use. We use the coarse subdivision into seismic regions to avoid data sparsity in the finer geographical net.

For each event which has an associated earthquake magnitude we calculate an energy using the usual relationship between surface wave magnitude and energy, namely

$$\log E = 12.24 + 1.44\, M_S \tag{1}$$

In general if a catalog has a value for M_S derived either from the world-wide seismic network or alternative source, that value is used in the energy calculation. If no value of M_S is available, an equivalent M_S is derived from the reported body wave magnitude, m_b, or if that is not available from a reported local magnitude, M_L. The relationships we have used for deriving equivalent surface wave magnitudes are

$$M_S = -3.81 + 1.71\, m_b \tag{2}$$

and

$$M_S = -1.29 + 1.22\, M_L \tag{3}$$

Equations 2 and 3 are derived from an analysis of the NGSDC data using a reduced major axis formulation which treats two sets of variables on a symmetric basis without regarding either as the dependent or independent variable. The associated linear correlation coefficients are 0.74 and 0.83 respectively. The derived relations agree with those deduced elsewhere; for example, Bath (1966) quotes Gutenberg and Richter (1956) equations

$$M_S = -3.97 + 1.59\, m_b$$

and

$$M_S = -1.27 + 1.27\, M_L - 0.016\, M_L^2$$

We are well aware of the difficulties associated with the use of equations 1 – 3, particularly with regard to high magnitude events (see, for example Kanamori, 1977). Nevertheless our calculation of seismic energies offers several advantages over alternative schemes for analyzing seismicity. In particular the use of energy is to be preferred over counting with equal weight all events over a certain magnitude. Since seismic energy varies by almost a factor of 1000 for a magnitude change of 2, it is inappropriate, for example, to weigh equally events of magnitudes 6.5 and 8.5. Furthermore, since energies can be added, the combined energies of foreshocks, main shock, and aftershocks can be determined, as can the energy release associated with swarms and large events occurring close in time (e.g. seven events occurred in three days in the Kurile Islands with magnitudes 6.6 to 7.6 in March 1978).

Figure 1 shows the fraction of the worldwide seismic energy attributable to each region averaged over the fifty year period 1928–1977. The highest average energy is associated with region 19 (Japan, Kuriles, Kamchatka) and amounts to 7 x 10^{23} ergs/year. This is followed by region 8 (Andean South America) at 5 x 10^{23} ergs/year and region 1 (Alaska-Aleutian Arc) at over 3 x 10^{23} ergs/year. Contributing less than 0.0005 of the cataloged worldwide energy are regions 35 (Eastern South America), 36 (Northwestern Europe), 38 (Australia), 44 (Gulapagos Area), 49 (Northern Asia), and 50 (Antarctica). Figure 2 shows similar results for the world-wide seismic energy based on 15 degree blocks. The high average seismicity of the circum-Pacific and Hymalian belts show clearly as do the low seismicity of plate interiors. Other tectonic features, such as the mid-ocean ridge system are not well evidenced by their recorded average seismic energy release.

The other parameters we have derived for the seismic regions are the maximum energy in any one year (1897–1977), E_m, and the b value of the frequency-magnitude relationship

$$\log N = a - bM_s \tag{4}$$

where N is the number of events with magnitude greater than or equal to M_s. As is well known, the value of b increases with M_s. For the present analysis we have chosen M_s in the region 6–7.5. For magnitudes much below 6, the data in the NGSDC catalog is incomplete in several regions particularly in the earlier years of our 50 year data analysis. Similarly several regions have few if any events with $M_s > 7.5$ since 1928; furthermore the validity of equation 4 is most suspect at higher magnitudes. Table I summarizes calculated seismic parameters for the seismic regions. The maximum energy released in any year 1928–1977 was the greatest for region 8 (Andean South America), 1.6×10^{25} ergs in 1906, followed closely by region 22 (Philippines) in 1897, region 19 (Japan, Kuriles, Kamchatka) in 1933, and region 1 (Alaska-Aleutian Arc) in 1938 all with energies greater than 1×10^{25} ergs. The b values for all regions with reliable data are in the range $1.4 \geq b \geq .7$. The regions with the most number of events with magnitudes greater than or equal to 6.0 were, in order, region 19 (Japan, Kuriles, Kamchatka) with 579 events, region 8 (Andean South America) with 467 events, region 12 (Kermadec-Tonga-Samoa Area) with 417 events and region 1 (Alaska-Aleutian Arc) with 413 events. The regions with the most number of events with magnitudes greater than or equal to 7.5 were region 8 (Andean South America) with 25 events and regions 19 (Japan, Kuriles, Kamchatka) and 15 (Bismark and Solomon Islands) with 19 events. On the basis of the preceding observations regarding average energy, maximum energy, and number of large events it seems reasonable to consider Japan, Kamchatka, Kuriles, region 19, and Andean South America, region 8, as the most seismically active regions. They are followed by the Alaska-Aleutian Arc area, region 1. For the world as a whole the average energy per year was 3.9×10^{24} ergs during the period 1928–1977 and 4.8×10^{24} ergs between 1898 and 1977. For the former period the b value for events with $6.0 \leq M_S \leq 7.5$ was

1.0, the number of events with $M_s \geq 6.0$ was 6022, the number with $M_s \geq 7.5$ was 219. For the latter period the maximum energy was 2.5×10^{25} ergs in 1906.

A curious result is obtained when the maximum energy, E_m, and average energy, or more correctly background energy, E_b, in the various regions are considered. In Figure 3 the logarithm of E_m chosen over the period 1897–1977 is plotted against the logarithm of background energy, E_b, chosen over the period 1928–1977. The longer period is used for choosing the maximum energy because the NGSDC catalog is more complete for older large events than moderate ones. The value of E_b equals the fifty year average if the year of maximum energy, E_m, did not occur during the period 1928–1977; otherwise E_b is a 49 year average excluding the year of the maximum. The apparent relationship between log E_m and log E_b has correlation coefficient 0.88. The reduced major axis line passed through the data has slope slightly greater than unity. (The reduced major axis results from a symmetric treatment of the variables on each coordinate axis; the usual least squares regression line minimizes the variance along one axis, in this case E_m. The slope for the usual regression is almost unity.) These results are stable with respect to changes in the average period for E_m (nominally one year), E_b (nominally 49 or 50 years), and to minor changes in the magnitude-energy relationship. They are consistent with the notion that the more seismically active regions have longer faults that permit both more numerous moderate events and occasional larger events than can occur in regions with smaller faults. This almost intuitive notion must be tempered somewhat by the awareness that the seismic regions differ in areal extent, tectonic features, and other ways; nevertheless, the tendency for increasing log E_m with increasing log E_b appears real. Curiously the worldwide data point for E_m and E_b falls well below the curve derived for the individual regions. Another contrast between the regional and worldwide occurrences of seismic energy release can be found in the year-to-year fluctuations in energy. On a worldwide basis the energy is relatively constant, varying only by one order of magnitude over the last fifty years. By contrast the energy release in the individual regions generally fluctuates by several orders of magnitude even in the most seismically active regions. Figure 4 shows the yearly variations in energy release for the very active Japan region, for the less active California-Nevada region, and for the world.

CONCLUSIONS

The use of earthquake energies as deduced from cataloged magnitude data is convenient for quantitatively comparing the seismicity of different regions. While one must be cautious about uncertainties in magnitude determinations and energy-magnitude relations for individual events, general trends over time appear reliable. Of course it must be recognized that the present study is limited by the short time span of reliable records. Even though the regions chosen are sufficiently large to allow for numerous moderate to large earthquakes during the studied time interval, the fact that some earthquake cycles may be hundreds of years or longer may mean that longer term features have not been detected.

Table 1
Regional Earthquake Occurrences and Seismic Energy Release Parameters*

Region Number	$N_{6.0}$	$N_{7.5}$	b	E_m 10^{24} ergs	Yr	E 10^{23} ergs	Region Number	$N_{6.0}$	$N_{7.5}$	b	E_m 10^{24} ergs	Yr	E 10^{23} ergs
1	413	9	1.2	5.9	1938	33.5	26	98	6	0.8	5.9	1950	19.5
2	39	3	0.8	4.2	1899	3.2	27	33	3	0.7	4.2	1920	1.5
3	76	1	1.1	1.6	1906	2.9	28	50	4	0.8	0.8	1905	5.4
4	45	0	-	0.3	1902	0.5	29	62	2	0.9	1.6	1945	4.8
5	201	12	0.8	3.7	1902	11.6	30	116	3	1.0	1.6	1903	3.6
6	126	3	1.1	2.0	1904	2.7	31	30	-	-	0.03	1935	0.3
7	73	4	0.9	2.6	1900	4.6	32	45	3	1.2	2.2	1941	8.0
8	467	25	0.9	16.0	1906	50.0	33	119	4	1.0	1.6	1942	7.1
9	28	2	0.9	0.5	1949	1.5	34	25	1	0.9	0.4	1932	1.2
10	126	4	1.0	1.6	1929	6.3	35	1	-	-	0.009	1955	-
11	86	5	0.9	1.7	1924	5.0	36	1	-	-	0.002	1911	-
12	417	12	1.1	10.1	1917	13.0	37	72	1	1.4	0.2	1967	0.9
13	155	3	1.3	1.6	1919	3.6	38	9	-	-	0.3	1906	-
14	357	10	1.0	4.9	1910	16.1	39	21	-	-	0.06	1947	0.3
15	387	19	0.9	2.2	1906	17.1	40	23	-	-	0.06	1975	0.3
16	194	5	1.0	0.9	1971	6.9	41	85	5	0.9	0.4	1950	1.6
17	33	0	-	0.8	1911	0.5	42	28	-	-	0.07	1958	0.4
18	159	1	1.3	5.9	1914	3.2	43	108	-	-	0.05	1954	0.9
19	573	19	1.0	11.5	1933	69.6	44	25	-	-	0.009	1945	0.1
20	81	4	0.9	5.9	1911	9.8	45	38	-	-	0.03	1945	0.3
21	90	5	0.8	1.6	1910	3.2	46	73	2	1.1	5.9	1941	13.1
22	195	8	0.8	12.1	1897	11.9	47	22	1	0.8	0.1	1935	0.5
23	191	11	0.9	4.2	1939	18.6	48	73	5	0.8	0.8	1907	2.5
24	294	10	1.0	4.3	1938	19.8	49	1	-	-	0.01	1928	-
25	53	4	0.7	4.1	1912	2.6	50	0	-	-	7×10^{-6}	1950	-
							World	6022	219	1.0	25.4	1906	3.9×10^2

*$N_{6.0}$ = Number of events with equivalent $M_S \geq 6.0$; period 1928-1977.

$N_{7.5}$ = Number of events with equivalent $M_b \geq 7.5$; period 1928-1977.

b = Seismic event frequency parameter from equation $\log N = a - b M_s$ when N is cumulative number of events with magnitude greater than or equal to M_S. b is derived from a reduced major axis curve fitting analysis.

E_m = Maximum seismic energy release in any one year in period 1897-1977.

Yr = Year associated with E_m.

E = Average energy release during fifty year period 1928-1977.

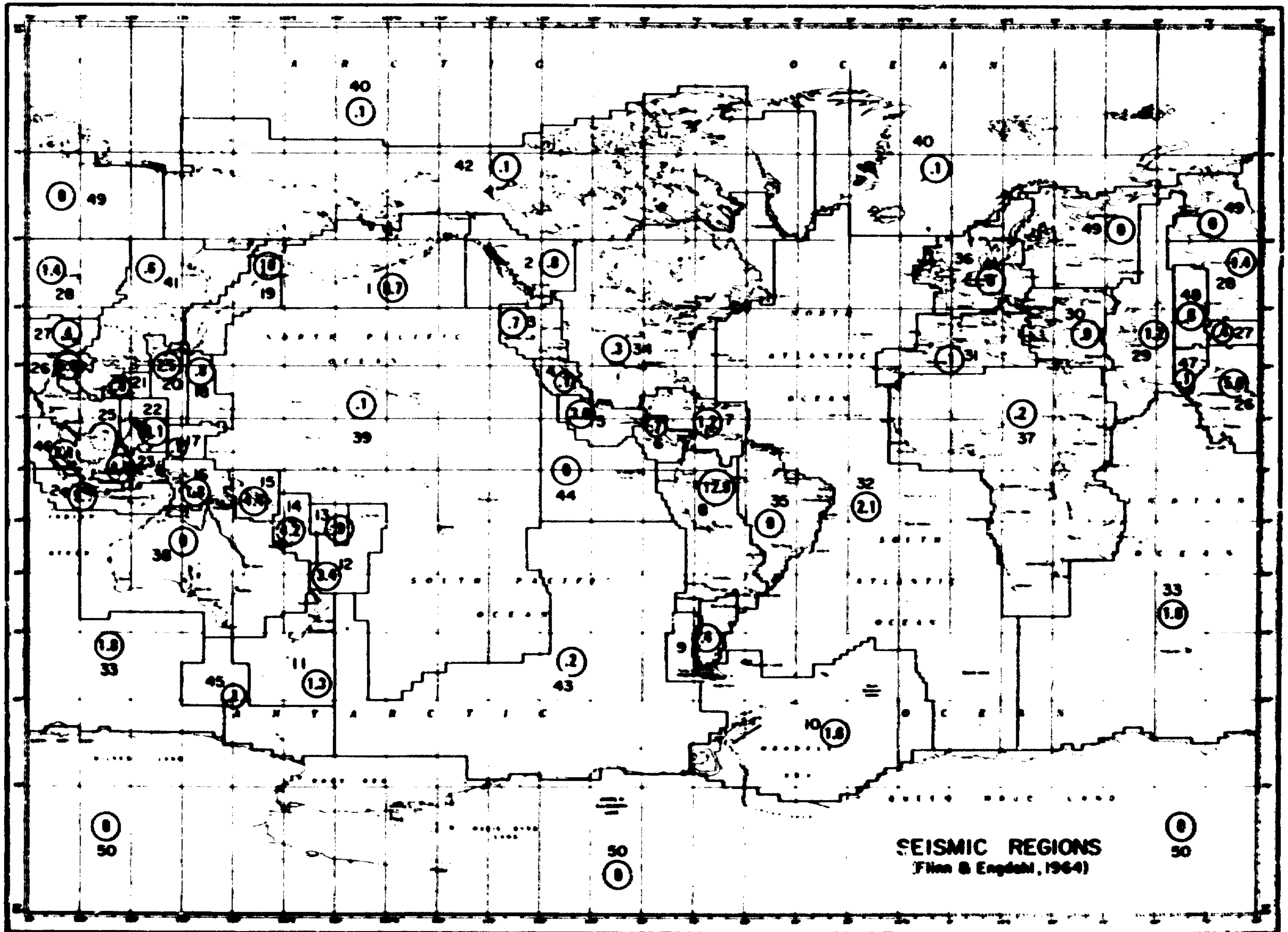
FIGURE CAPTIONS

Figure 1. Seismic regions and energy release; uncircled numbers = region number, circled numbers = percentage of worldwide seismic energy release associated with that region, 1928–1977.

Figure 2. Fraction of worldwide seismic energy release, f, associated with 15° longitude-latitude blocks, 1928–1977. Cross hatches, $f \geq 0.1$, left-dipping lines, $0.1 > f \geq 0.01$, stipples, $0.01 > f \geq 0.001$, otherwise, $0.001 > f$.

Figure 3. Regional maximum energy versus background energy. E_m is the maximum energy released in any one year in period 1898–1977, E_b is average energy released/year during period 1928–1977, excluding year associated with E_m if it occurred during averaging period. Numbers designate the seismic region.

Figure 4. Yearly seismic energy release; upper trace = worldwide, middle trace = region 19, Japan, Kuriles, Kamchatka, lower trace = region 3, California, Nevada.



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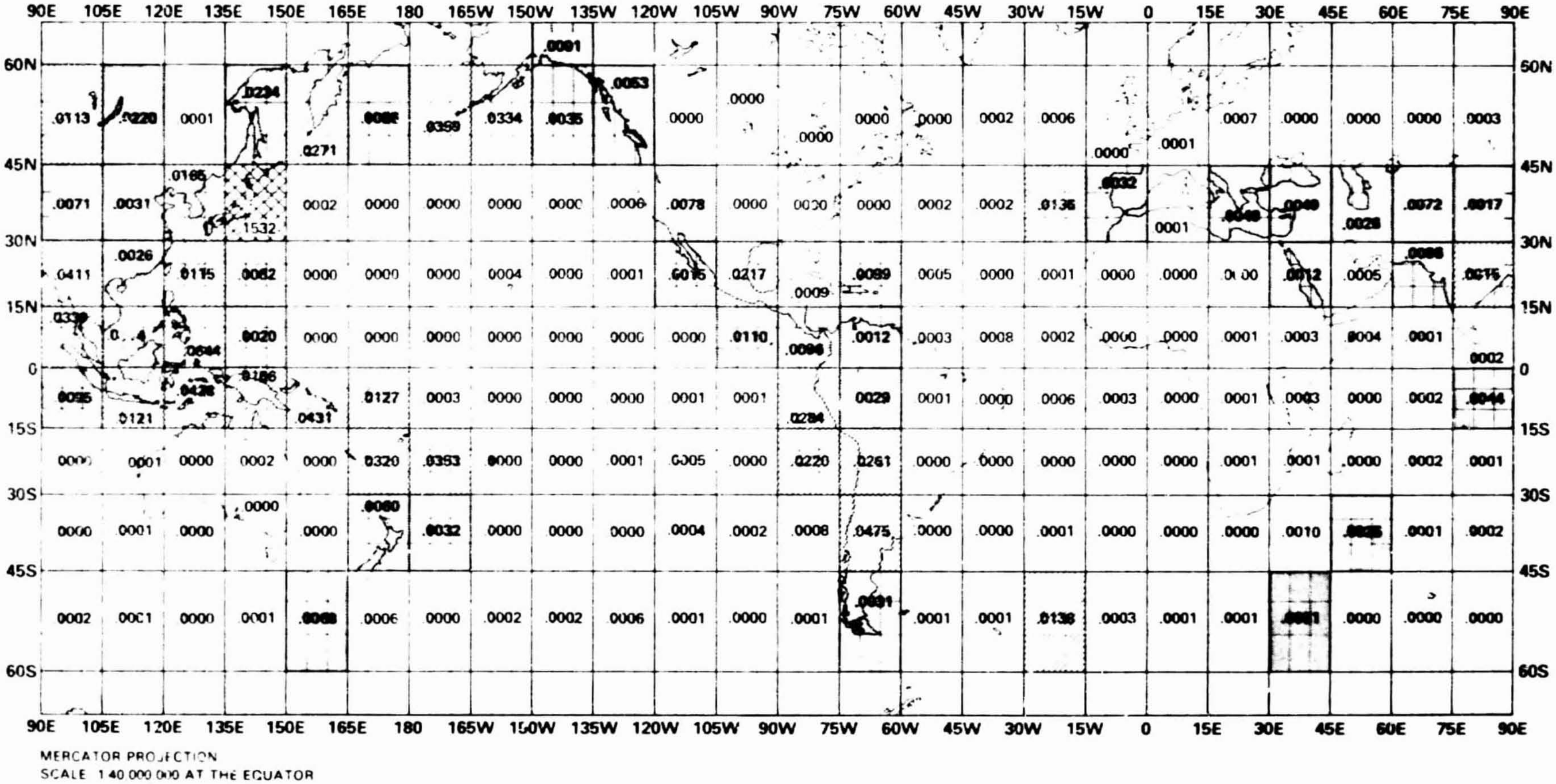

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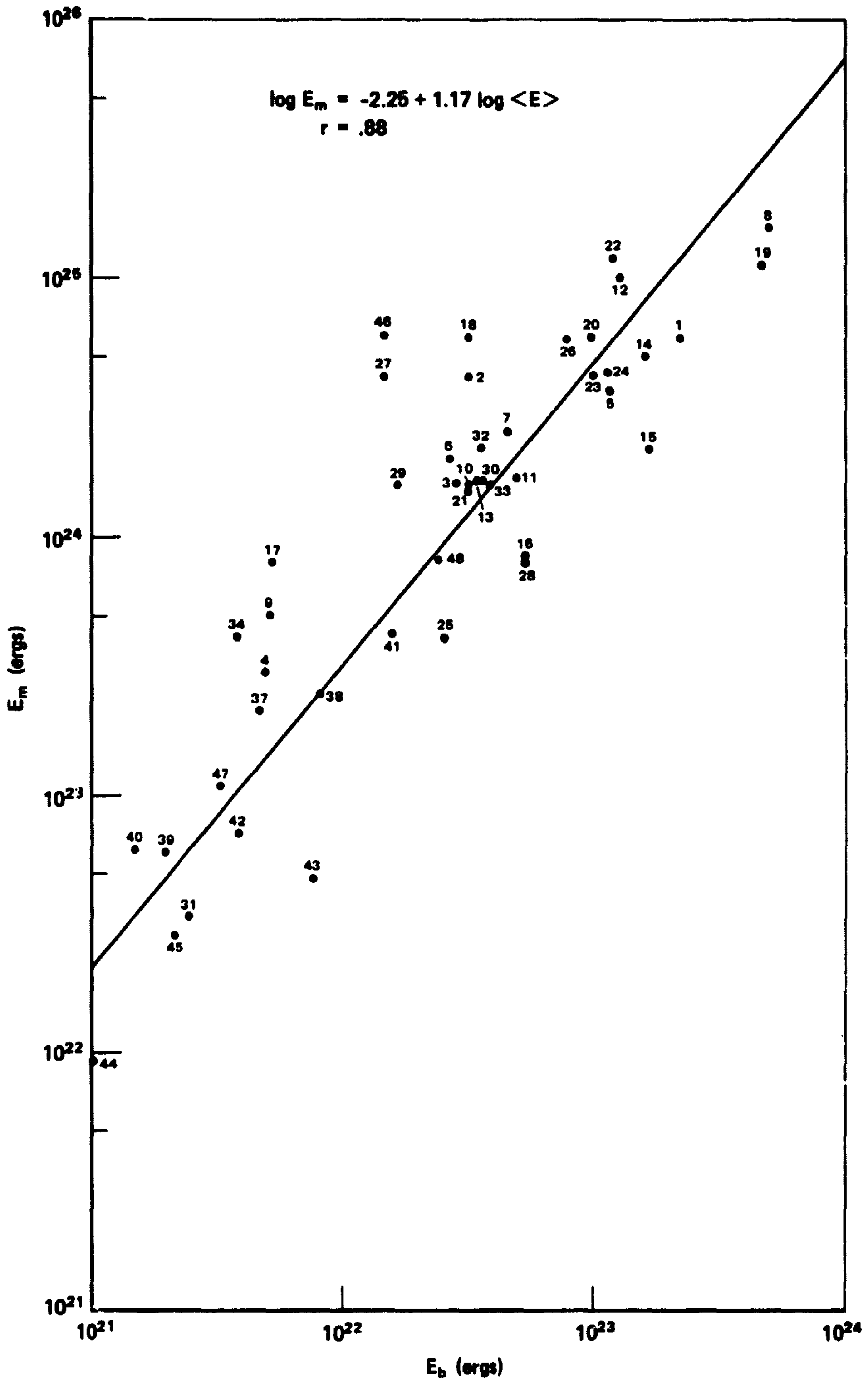

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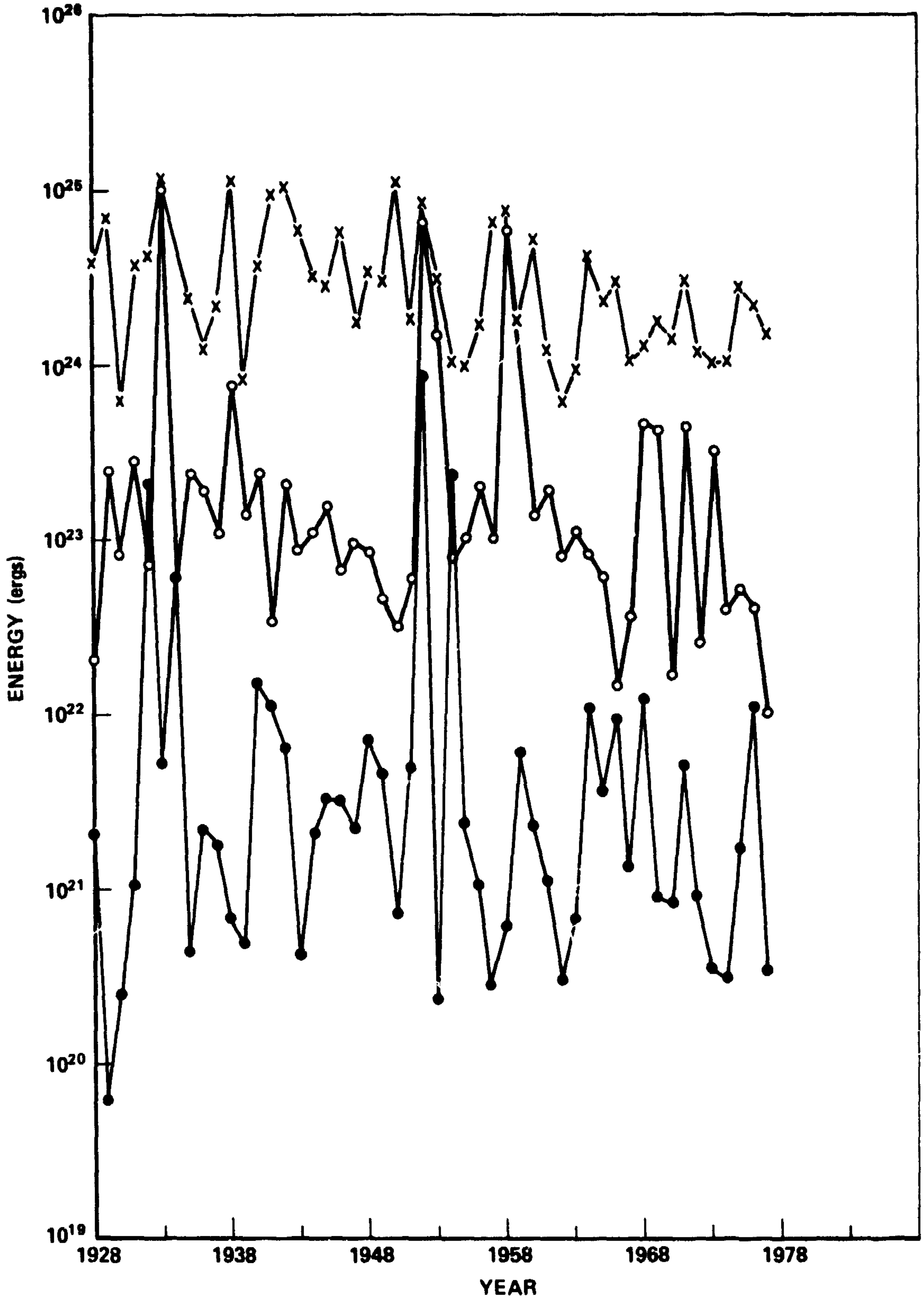

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