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Seismic Energy Release Preceding Earthquakes In Three Areas In Japan

by

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SEISMIC ENERGY RELEASE PRECEDING EARTHQUAKES IN THREE AREAS IN JAPAN

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A year ago, at the Annual Meeting of the Society in Santa Barbara, I described a method for analyzing the accelerating release of seismic energy during a foreshock sequence. The method leads to an estimate of the time of the main shock and sometimes to an idea of its magnitude.

Today, I will apply the method to seismic sequences in three areas along the Pacific Coast of south-central Japan. But, before doing so, I will briefly outline the procedure that is followed.

Some earthquakes are preceded by seismic events that, in retrospect, can be regarded as forerunners of the main shock. In general, these increase irregularly in magnitude and commonly also in the number of events per unit time as the time of main shock approaches.

FIGURE 1

The hypothesis to be tested is that, overall, the rate of release of seismic energy during a precursory sequence follows a definite course as expressed by this simple differential equation. The rate of change of the accumulated sums of the square roots of the energies of the precursory events is, at any time, t, inversely proportional to a power of the time remaining until the main shock, that is, to a power of t_f minus t.

The process culminates with a theoretical infinite rate of release of energy at the time t_f. If the observed course of energy release of a seismic sequence follows an equation of the type shown, then t_f may represent the possible time of a main shock. Details of the method to determine the best fit of observations to equation (1), or to its integral (shown below), have been described elsewhere and are available, together with discussion of possible basis for the method in physical theory.

FIGURE 2

In brief, the method consists of suitably transforming equation (1) or its integral, to obtain linear expressions generally by taking logarithms. Observed values of the sums of square roots of energies at a series of times are inserted into one of the linear expressions, together with an estimated value for the unknown time of failure, t_f. Using repeated linear regressions with different estimates of t_f, the value of t_f is identified that yields the maximum value of the coefficient of determination.

HYPOTHESIS

$$\frac{d(\Sigma\sqrt{E})}{dt} = \frac{c}{(t_f - t)^n} \quad (1)$$

$\Sigma\sqrt{E}$ = SUM OF SQUARE ROOTS OF ENERGIES OF PRECURSORY SEISMIC EVENTS

t = TIME OF OBSERVATION

t_f = POSSIBLE TIME OF MAIN SHOCK

c AND n ARE CONSTANTS

$$\Sigma\sqrt{E} + \underbrace{\left[\frac{c}{n-1}(t_f - t_1)^{1-n} - (\sqrt{E})_1\right]}_{\Delta} = \frac{c}{n-1}(t_f - t)^{1-n}$$

FIG. 1

LINEAR RELATIONS

$n=1$

$$\mathrm{LOG}\,\frac{d(\Sigma\sqrt{E})}{dt} \ \mathrm{VS}\ \mathrm{LOG}\,(t_f-t)\ \mathrm{OR}\ \Sigma\sqrt{E} \qquad (2)$$

$$\Sigma\sqrt{E}\ \mathrm{VS}\ \mathrm{LOG}(t_f-t) \qquad (3)$$

$$\frac{dt}{d(\Sigma\sqrt{E})}=\frac{1}{\mathrm{RATE}}\ \mathrm{VS}\ t \qquad (4)$$

$n\neq 1$

$$\mathrm{LOG}(\sqrt{E}+\Delta)\ \mathrm{VS}\ \mathrm{LOG}\,(t_f-t) \qquad (5)$$

$$\mathrm{LOG}\,\frac{d(\Sigma\sqrt{E})}{dt}\ \mathrm{VS}\ \mathrm{LOG}\,(t_f-t) \qquad (6)$$

FIG. 2

I have applied the procedure to many seismic sequences using the times, magnitudes, and space and time boundaries as reported by individual authors in the literature. The results are tested by seeing how closely an analysis could have predicted the time of main shock, and how long in advance the prediction could have been made. These two quantities are plotted on the next figure, at logarithmic scales.

FIGURE 3

To date, 74 back-analysis predictions have been calculated using published data on 38 sequences in 30 localities in a variety of geologic settings. In some instances, several predictions were made, as they would be in a real situation while information accumulates. Some predictions used equation (1), some used its integral. One measure of potential usefulness of the method is to look at the ratio formed if the error of the prediction is divided by the time remaining after the last data used for analysis and until the main shock. The four diagonal lines in the figure indicate positions at which this relative error ratio is 1, 1/2, 1/10, and 1/100. Open circles indicate predictions that were too early, filled circles those that were after the actual event. The median relative error is about -0.2, that is, about one-fifth of the time remaining and on the safe side, which is too soon.

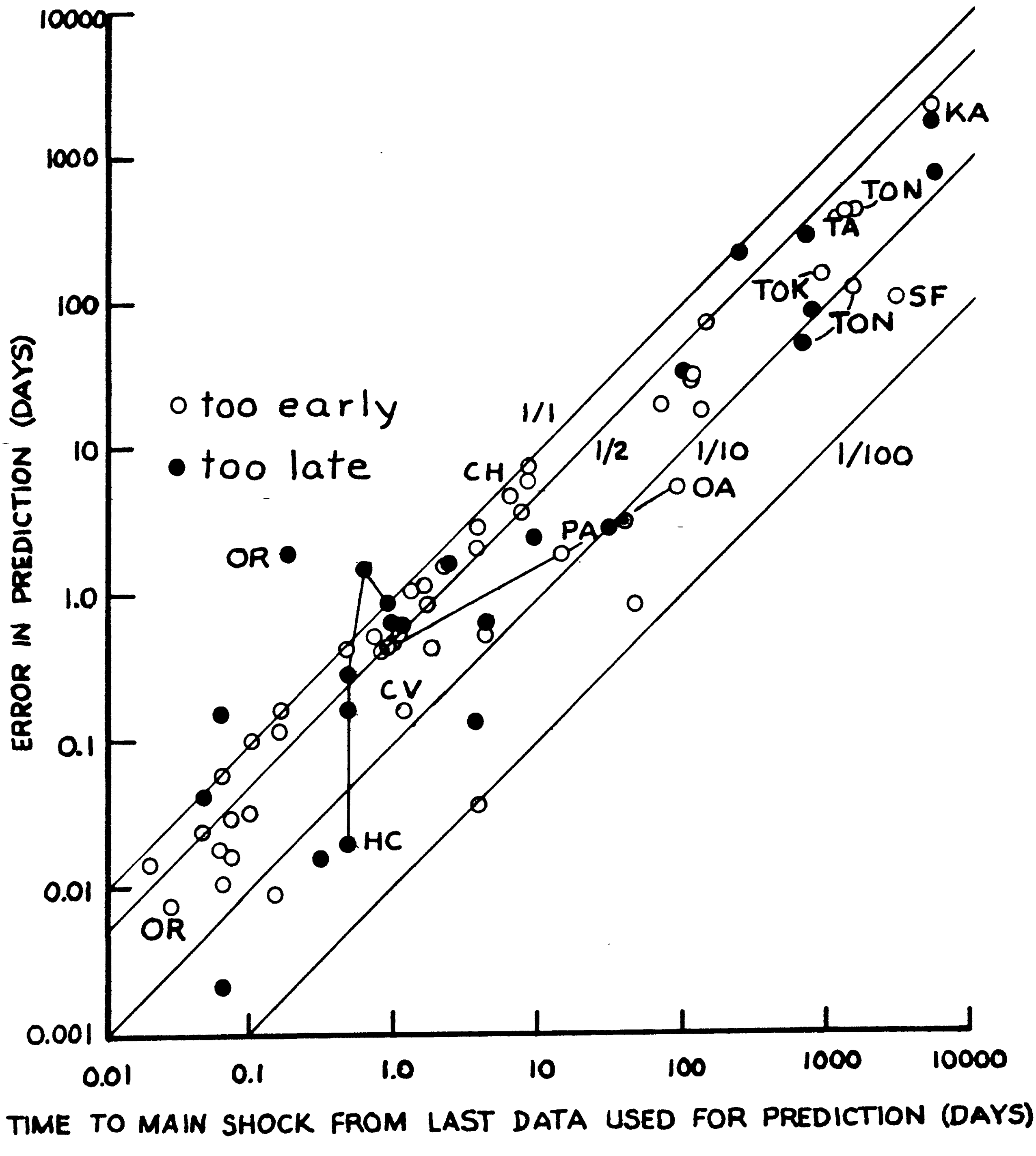
For example, these five connected dots (labeled HC) represent five successive predictions of the magnitude 7.3 Haicheng, China, earthquake of February 4, 1975, using more and more data on foreshocks as they occurred. The last analysis using data up to about 10 hours before the main shock just before quiescence began, predicts the main shock with an error of 16 minutes, too late.

The work reported last year used foreshock data over periods no longer than one year. Recent study has involved precursory sequences over many years or decades. For instance, this point here (labeled SF) is derived from records of northern coastal California published by Ellsworth and others (1981). The best analysis required using information beginning in the late 1850s and ending in 1898. This indicated a culminating event in 1906, 8 years in advance of the San Francisco earthquake with an error of 106 days, too soon.

The back analyses in areas of Japan that I now wish to discuss are these: TON represents the Tonankai earthquake of December, 1944, these lower two are the main shock and this upper one a foreshock; KA represents the Kanto or Tokyo earthquake of 1923; and TOK an event in 1983 in the Tokai area.

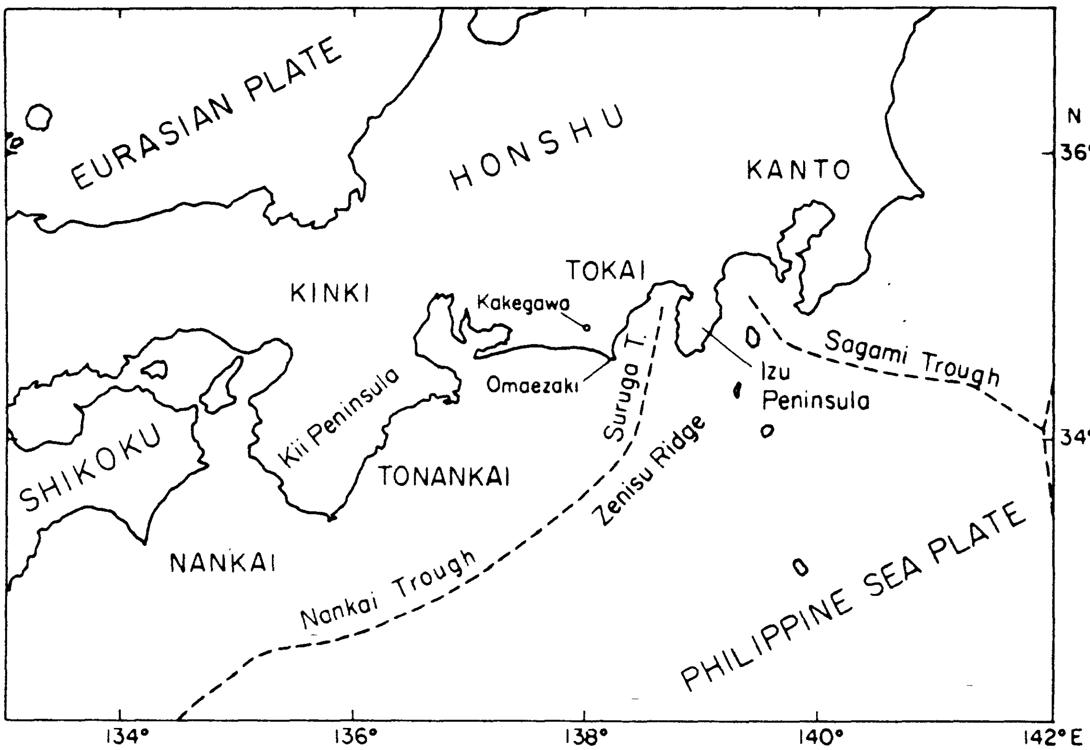
FIGURE 4

Those three areas on the south coast of Honshu are identified in this figure taken from Professor Mogi's paper (1987a) on the expected major earthquake in the Tokai region.



10000
1000
100
10
1.0
0.1
0.01
0.001
ERROR IN PREDICTION (DAYS)
0.01
0.1
1.0
10
100
1000
10000
TIME TO MAIN SHOCK FROM LAST DATA USED FOR PREDICTION (DAYS)
o too early
• too late
1/1
1/2
1/10
1/100
KA
TON
TA
TOK
TON
SF
CH
OA
PA
OR
CV
HC
OR

FIG. 3



Geographical map of the Tokai region and the surrounding area.

FIG. 4

The first area to be discussed is Tonankai.

FIGURE 5

This is Professor Mogi's record of magnitude versus time for events in three intervals of depth from 1925 through 1944 (Mogi, 1987b). The main shock, magnitude 7.9, occurred in December 1944.

FIGURE 6

This shows a plot of accumulated square roots of energy versus time derived from the information on the previous figure.

Note the generally accelerating aspect of the plot until a period of more or less steady, but slower, rate beginning about 1941. The portion of the graph within dashed lines will be enlarged on the next figure.

FIGURE 7

Analyses using rates or energies themselves on both upper and lower bounds were explored. The best analysis used the three rates shown here as defined by the slope of lines between points on the upper envelope of the saw-toothed plot of energy versus time.

FIGURE 8

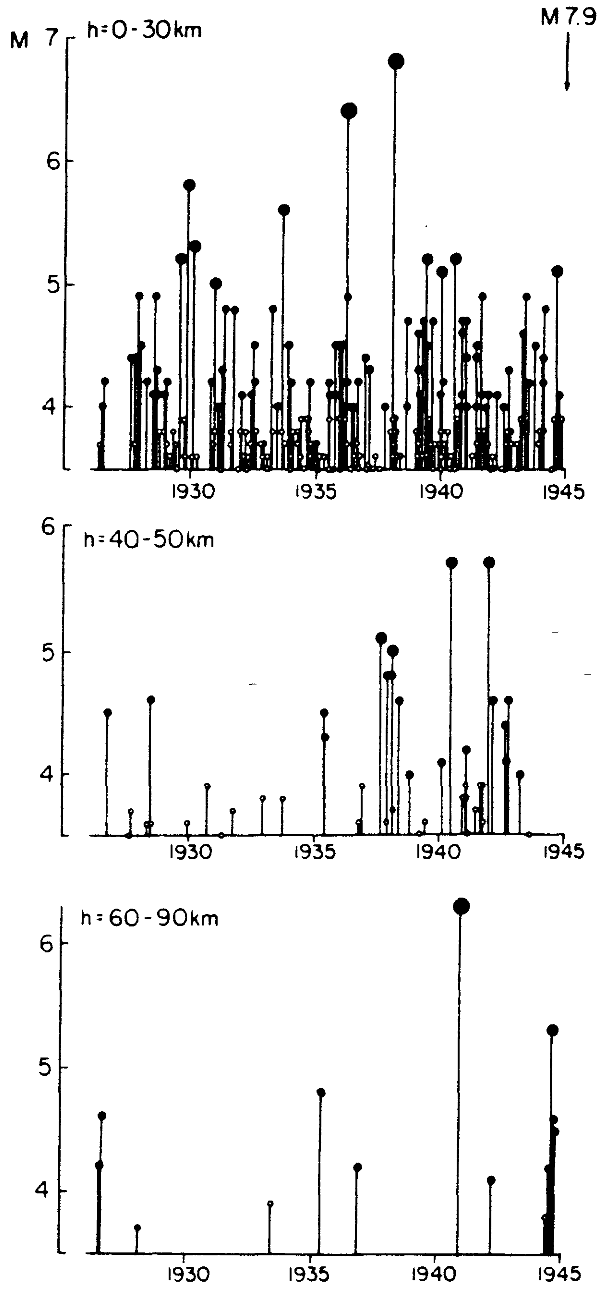
This shows prediction of the December 7, 1944, M 7.9 earthquake based on that part of the energy-time plot within the dashed rectangle. The analysis used data up until 4.13 years before the expected event. Beyond this time, the rate decreased and no further predictions could be made. The error was 123 days too soon.

FIGURE 9

This figure shows information from a paper by Suyehiro and Sekiya (1972) on the great Kanto earthquake of 1923. In the upper left is a plot of log energy, summed for each year, of earthquakes within the area A surrounding the epicentral area B. From this energy information, I have plotted, below, the accumulated square roots of energy for the years 1887 through 1923. It is apparent that radiated energy accelerated during the period 1894 through 1910. The integral of equation (1), using the upper envelope, yielded a prediction of 1917; the lower envelope yielded 1927. The predictions straddle the actual main shock date of 1923. Although the predictions were not very accurate, it is encouraging that they could be made at all, considering that the information used was simply yearly totals of energy. Another point is that 10 years of decelerating activity--until 1920--did not remove the hazard indicated by the previous period of accelerating activity.

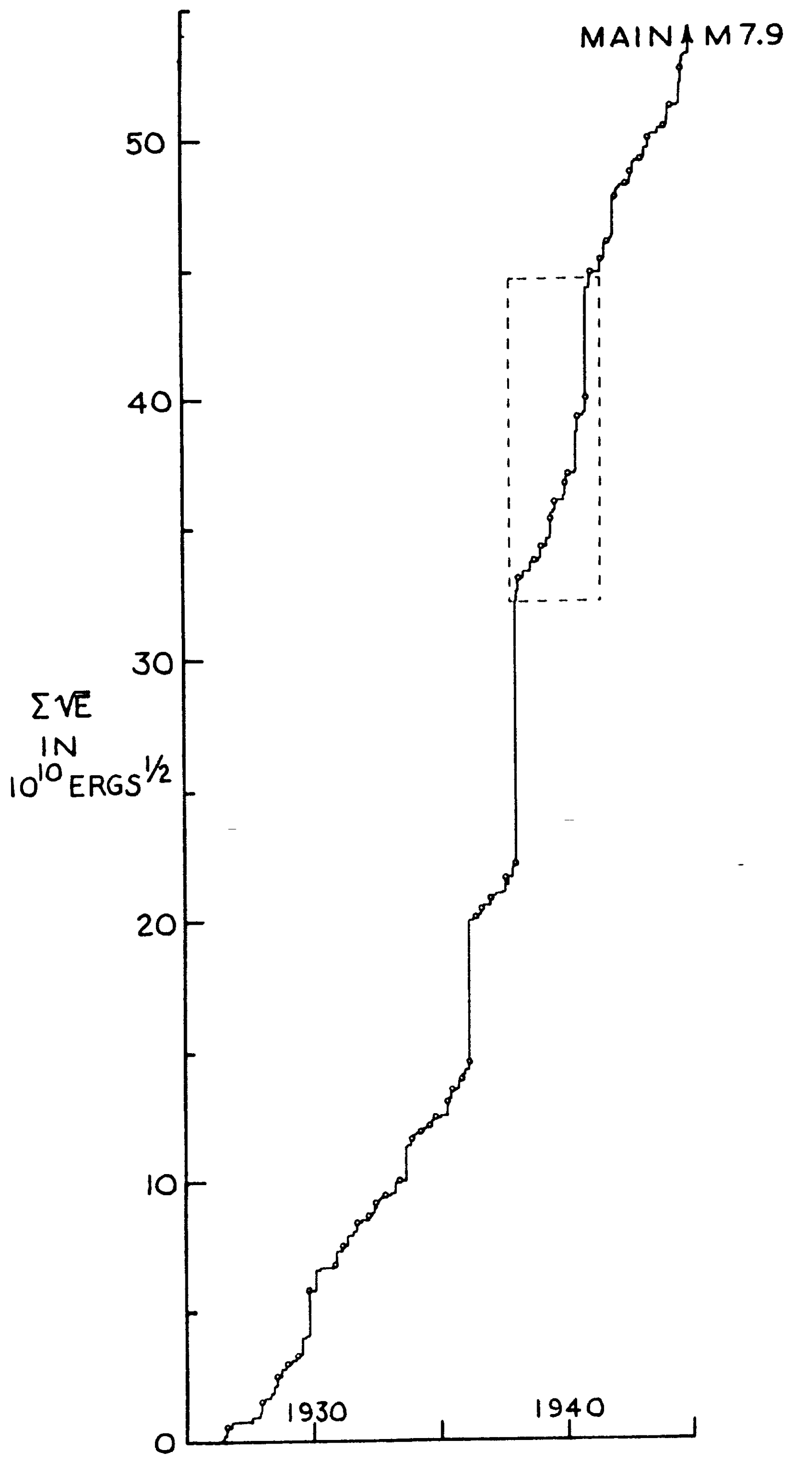
FIGURE 10

The third area to be discussed is a portion of the Tokai area lying southwest of Tokyo, which has been described by Professor Mogi (1987a). This figure shows the area to which the data apply. It includes much of Surugu Bay and extends inland into Shizuoka Prefecture. Magnitudes and times are shown



Precursory seismic activity before the 1944 Tonankai (Japan) earthquake

FIG. 5



TONANKAI

FIG. 6

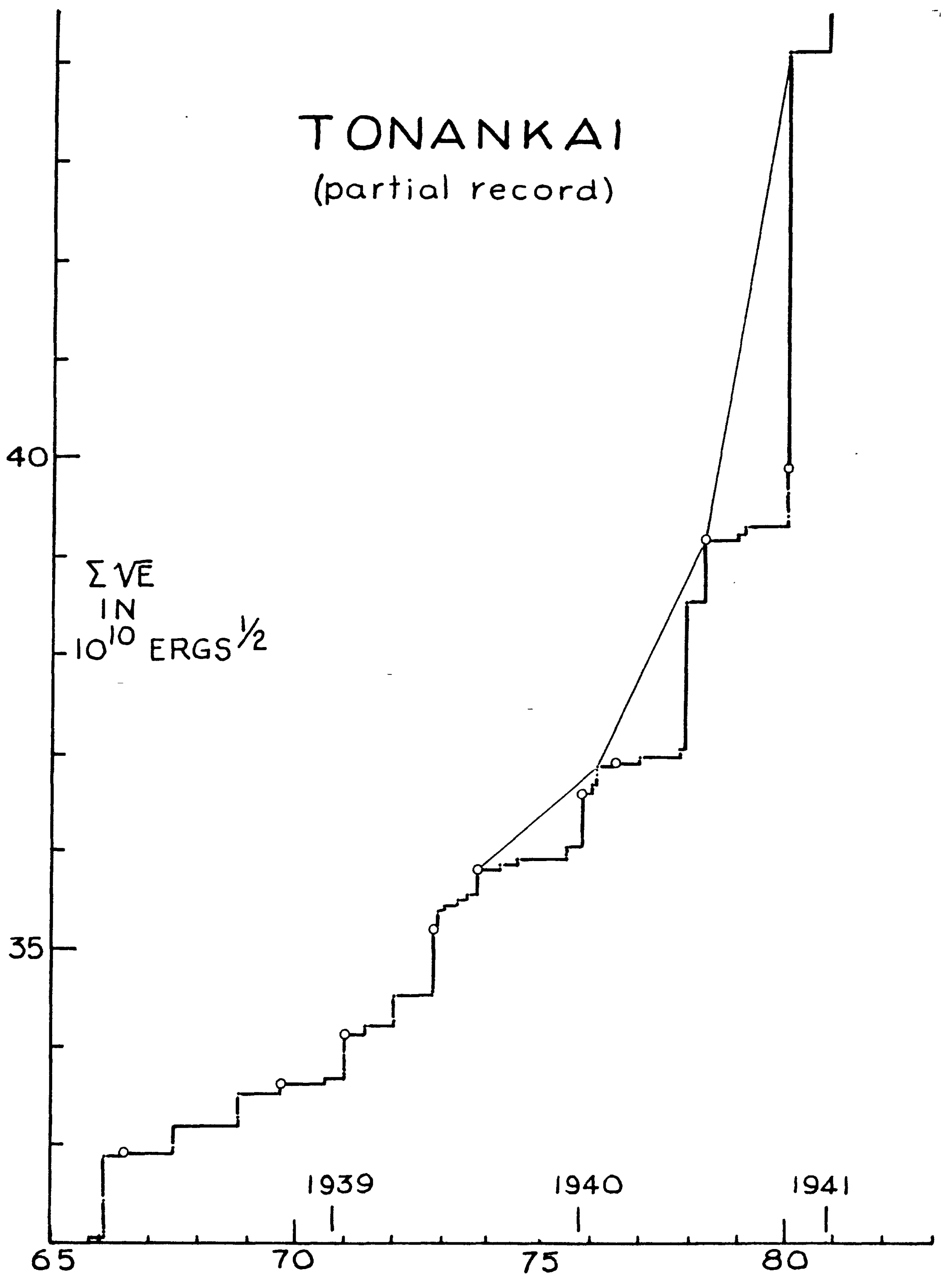
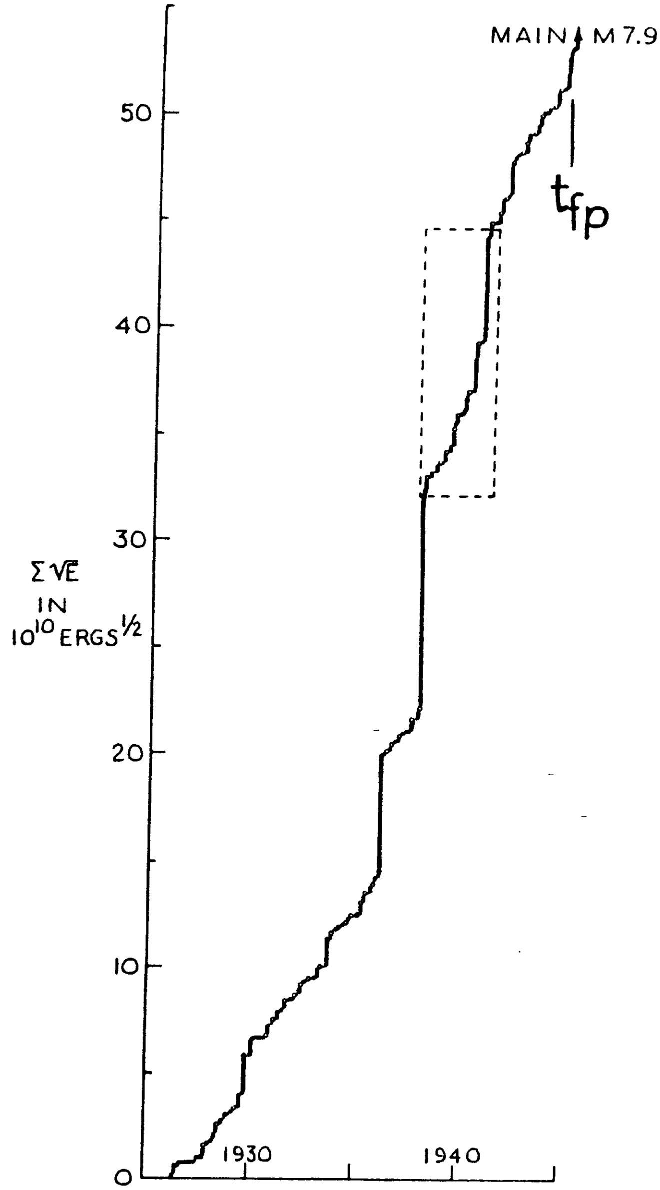

TONANKAI
(partial record)
40
35
Σ √E
IN
10^10 ERGS^1/2
1939
1940
1941
65
70
75
80

FIG. 7



TONANKAI

FIG. 8

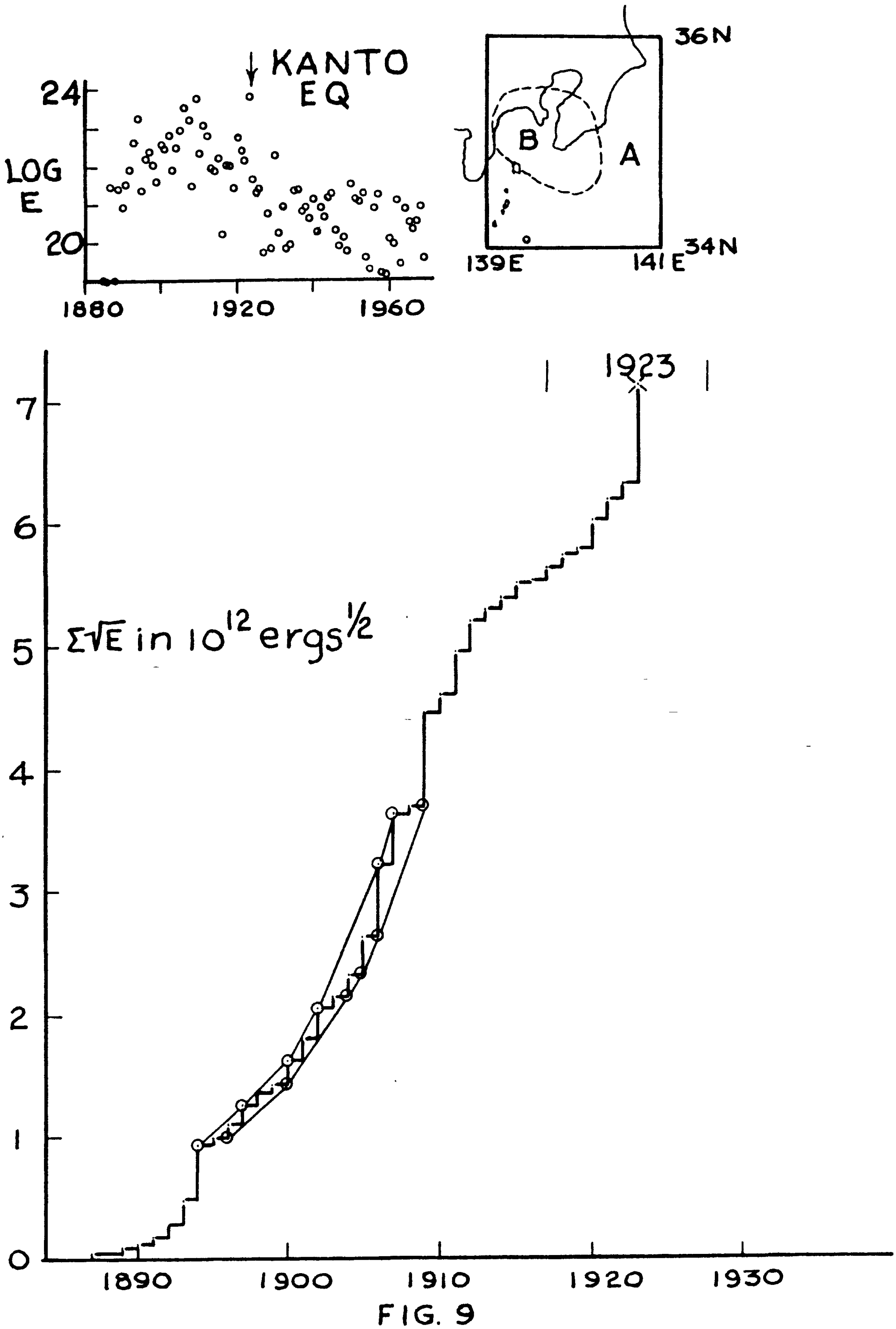
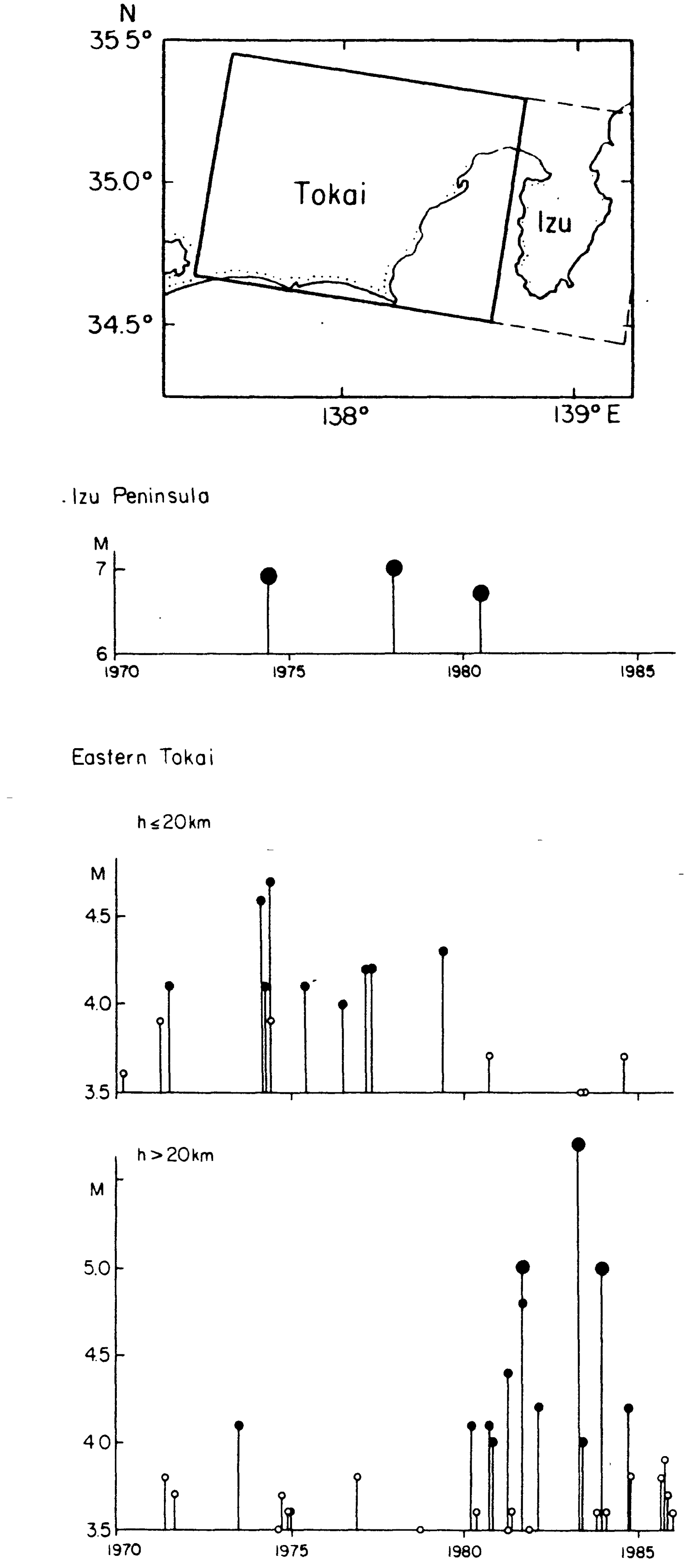

KANTO EQ
LOG E
24
20
1880
1920
1960
36N
34N
139E
141E
B
A
1923
Σ√E in 10^12 ergs^1/2
0
1
2
3
4
5
6
7
1890
1900
1910
1920
1930

FIG. 9



N
35.5°
35.0°
34.5°
Tokai
Izu
138°
139° E
. Izu Peninsula
M
7
6
1970
1975
1980
1985
Eastern Tokai
h ≤ 20km
M
4.5
4.0
3.5
h > 20km
M
5.0
4.5
4.0
3.5
1970
1975
1980
1985

FIG. 10

for events with magnitude equal to, or greater than, 3.5 for the years 1970 through 1985. Many studies relating to seismic hazard and disaster prevention are being carried out in this region.

FIGURE 11

Professor Mogi's data of the previous figure on magnitudes and times of events for the Tokai area, at all depths, and from 1970 through 1985, were used to plot the sum of square roots of energy for the same period. I've added some less definite data derived from other sources through October 1987.

Note that the general aspect of the energy plot is quite similar to that previously shown for the Tonankai area farther southwest. Periods having many small events are punctuated by times of much more rapid energy release or large individual events.

Using three upper bound rates, shown here by the light lines, two predictions could be made of the largest event in the figure, of magnitude 5.7 in 1983. One prediction made 908 days in advance has an error of 154 days, too soon. Another prediction, using the three rates shown, covered a longer span of time and could be made 601 days in advance with an error of 132 days, too soon.

The Tokai energy graph, as you can see, accelerates until about the end of 1985, when Professor Mogi's data ends. The shape of the whole curve to that time is currently under study with the view toward making predictions for the long-expected Tokai event.

Before going on with discussion of the Tokai data, I want to make some further statements:

1. The method I have described has not been tested by making a prediction of a future event that was subsequently confirmed.

2. The area considered, as chosen by Professor Mogi, may need to be compared with, or augmented by, other adjacent areas such as the Izu Peninsula, of which the activity was described yesterday by Dr. Yoshida.

3. Good data since 1985 need to be built into the analysis.

4. I speak as an individual, with permission, but with neither official support nor denial by the U.S. Geological Survey.

FIGURE 12

This figure shows three spans of time for which the rates of energy release can be calculated as defined by points on the lower bound of the graph of cumulated energy versus time. It yields a prediction of February 1990 for a major event.

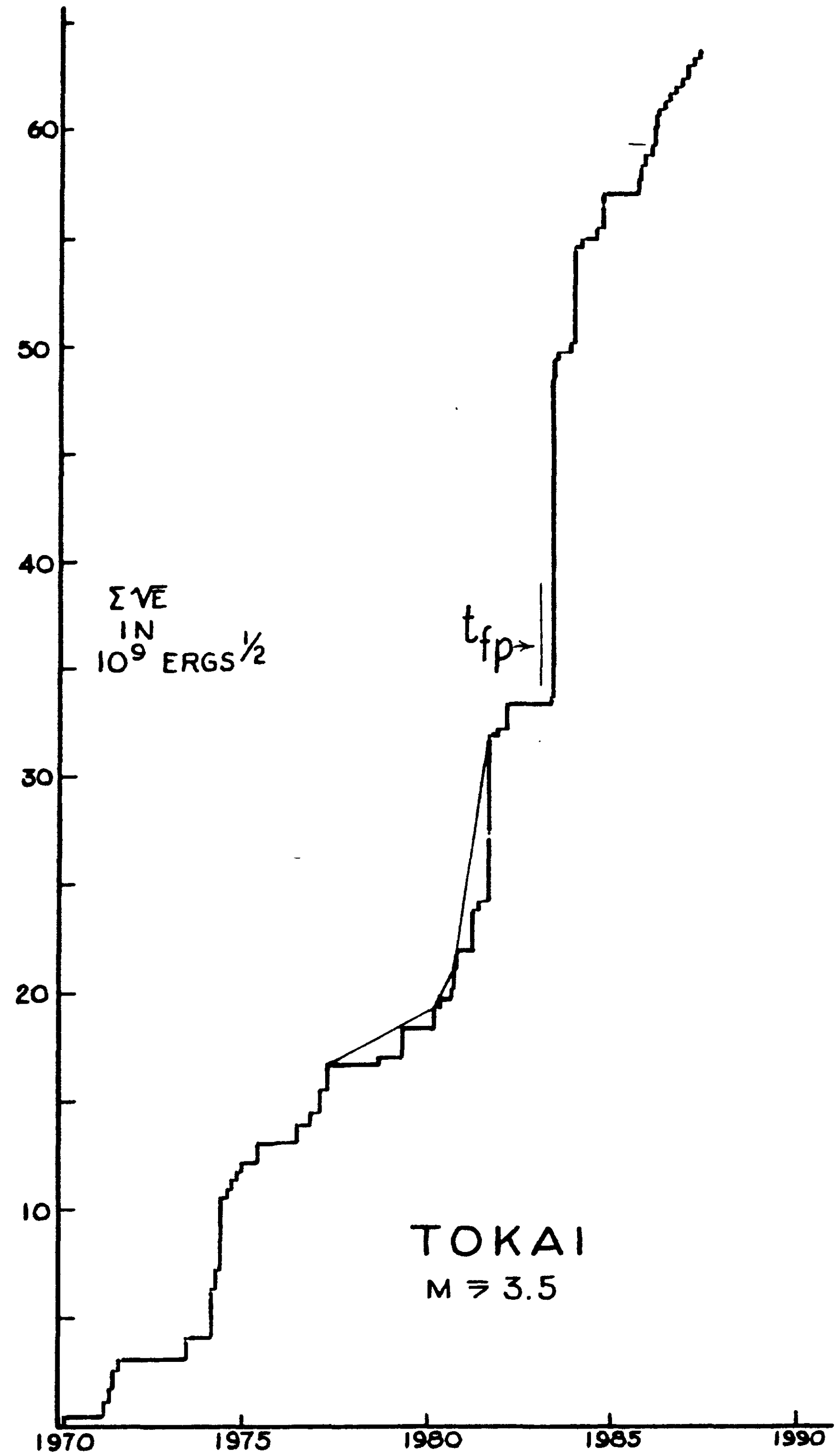

60
50
40
30
20
10
ΣVE
IN
10⁹ ERGS ½
t_{fp}
TOKAI
M ⩾ 3.5
1970
1975
1980
1985
1990

FIG. 11

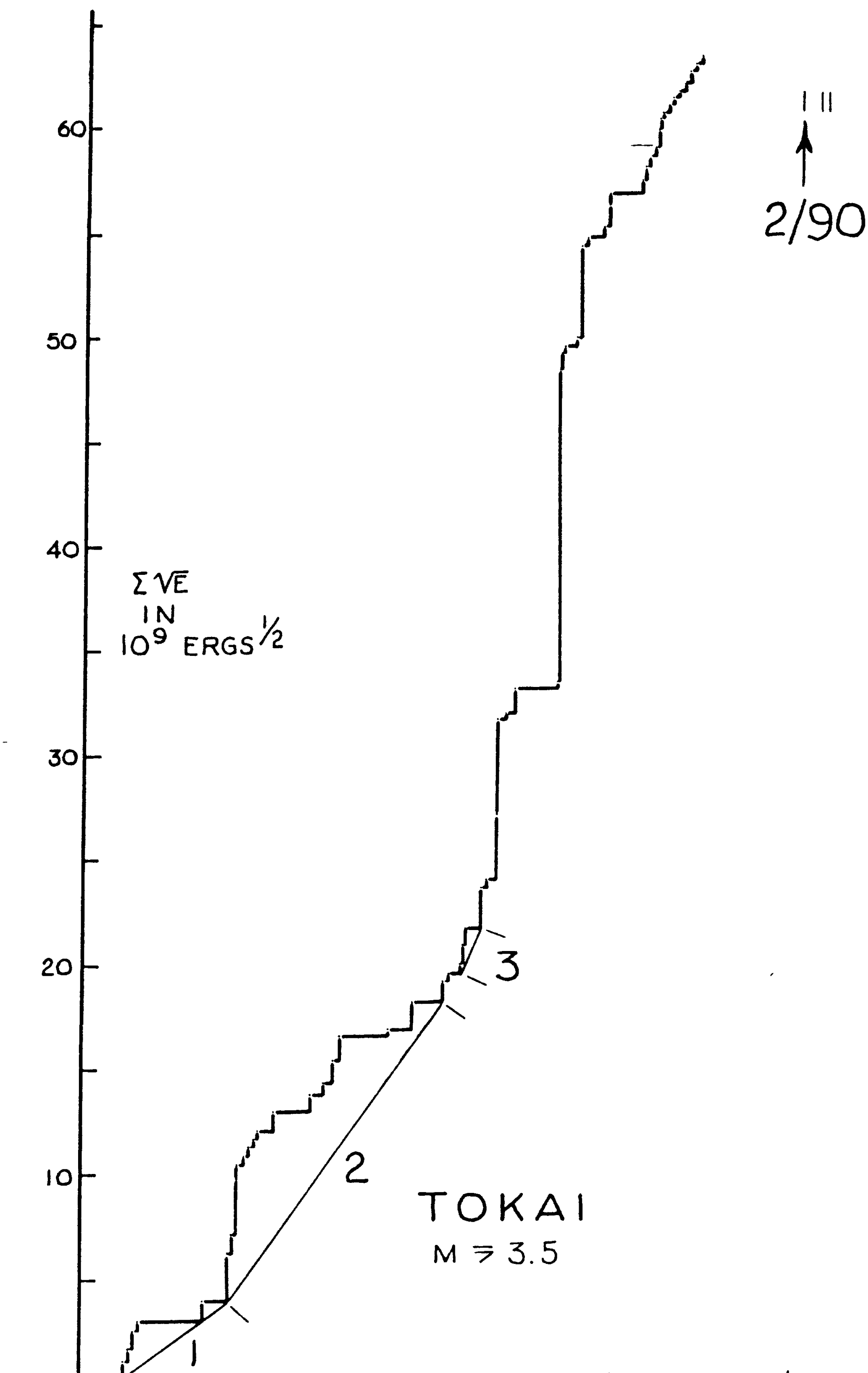

60
50
40
30
20
10
ΣVE
IN
10^9 ERGS ½
1970
1975
1980
1985
1990
1
2
3
TOKAI
M ⩾ 3.5
2/90

FIG. 12

FIGURE 13

Adding more data and a fourth rate yields a prediction of December 1990.

FIGURE 14

Adding another couple of years of data and a fifth rate yields a prediction of September 1990. This may be the last prediction that can be made, or it may not be, depending on the behavior of the curve since 1985, which is uncertain. However, the fifth rate, as shown, is closely confirmed by the rate of the upper envelope of the energy release curve during that time interval. Any lesser slope, when used with the previous four rates, leads either to no solution or to one unreasonably far in the future.

The stability of the prediction as data are added lends credibility to the solution. However, as I employ non-standard statistical methods, I cannot give you any firmly grounded error bars on the prediction.

In conclusion, the method is still experimental and in the developing stage. But I believe it is applicable not only to foreshocks in a limited sense but also to precursory activity over fairly long spans of time and space. By using it, I hope others can generate information helpful in saving lives and property.

Thank you.

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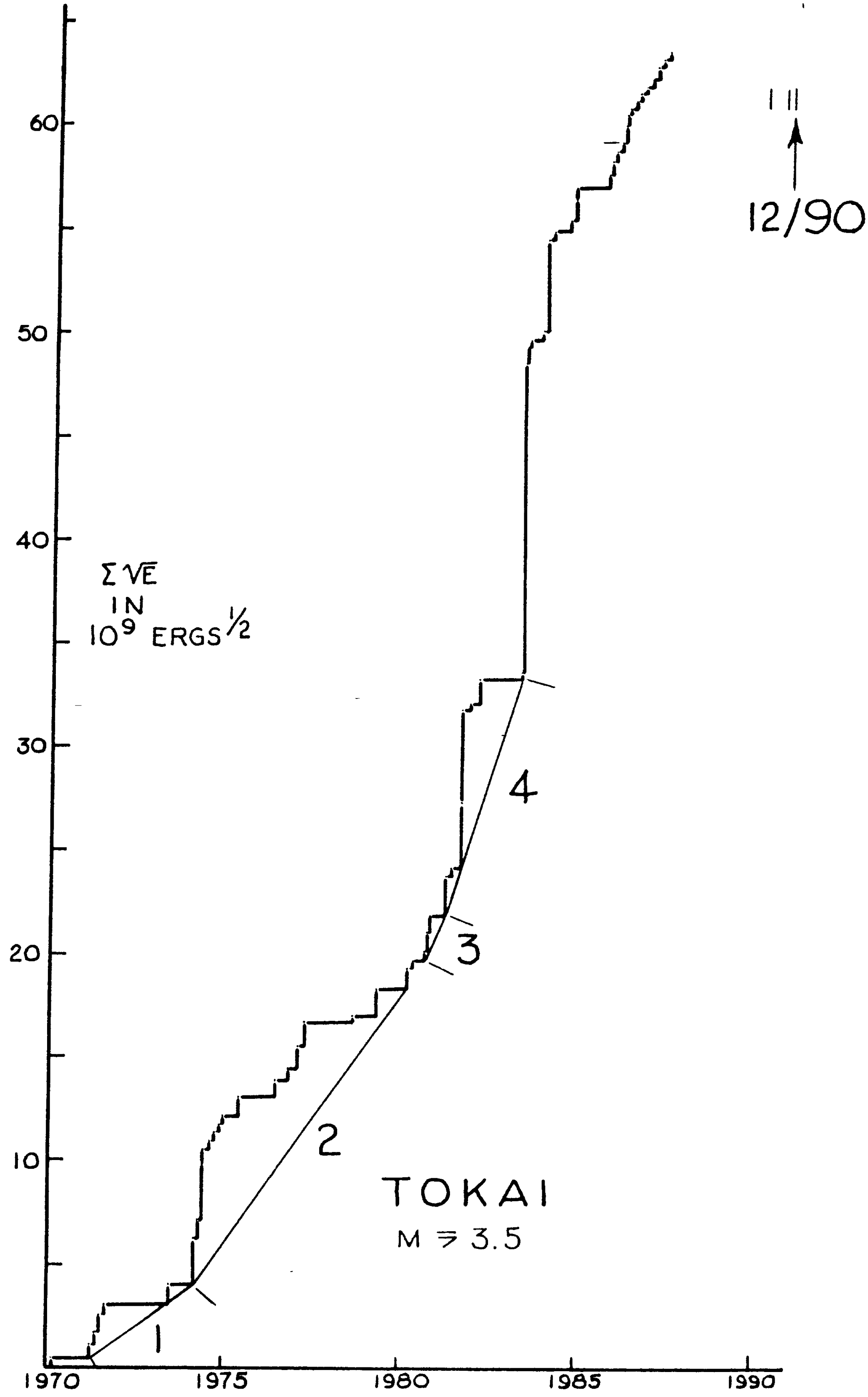
60
50
40
30
20
10
ΣVE
IN
10^9 ERGS^1/2
1970
1975
1980
1985
1990
1
2
3
4
TOKAI
M ⩾ 3.5
12/90

FIG. 13

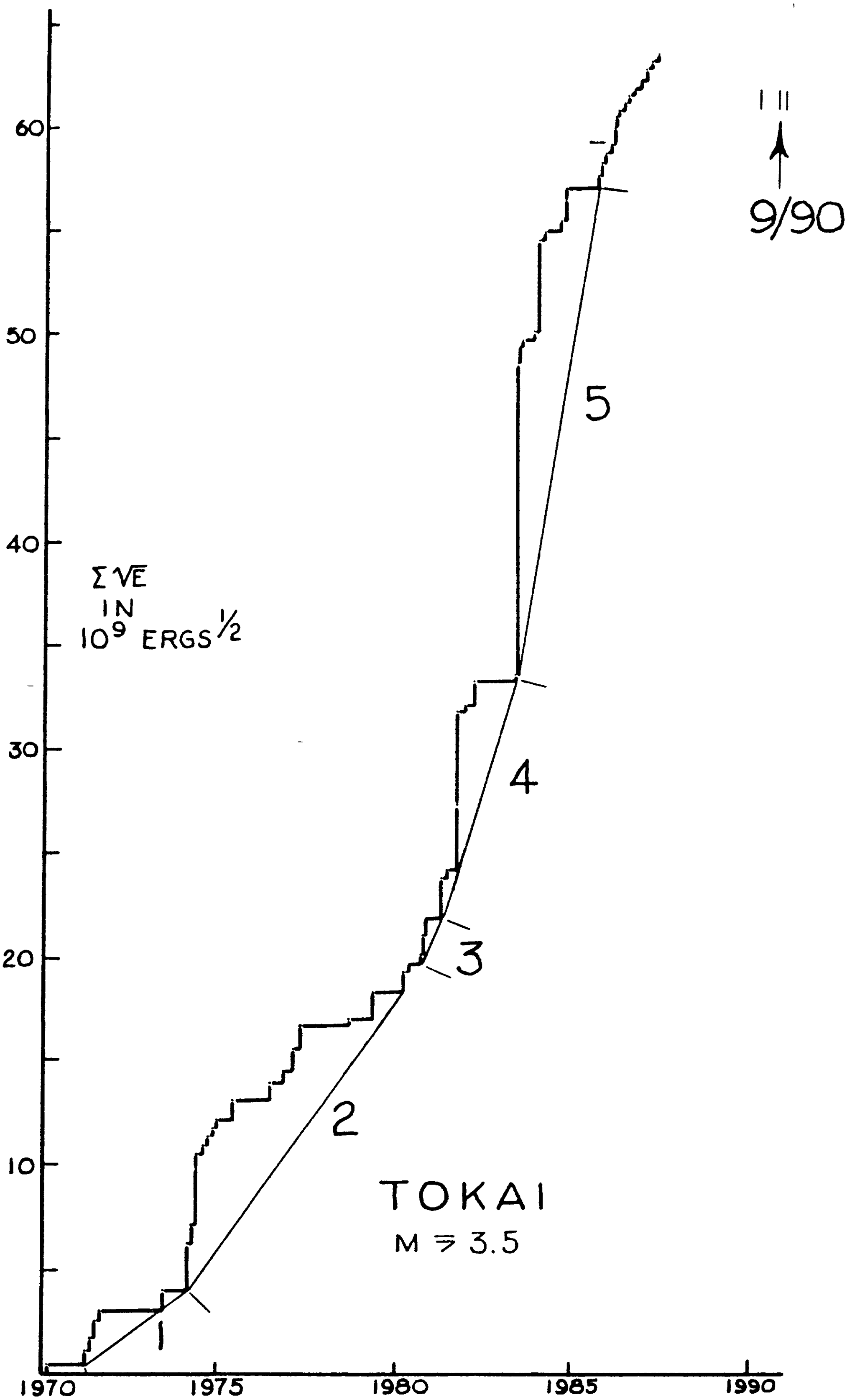
60
50
40
30
20
10
Σ √E
IN
10⁹ ERGS ½
1970
1975
1980
1985
1990
1
2
3
4
5
TOKAI
M ⩾ 3.5
9/90

FIG. 14