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Long-Term Premonitory Seismicity Patterns in Tibet and the Himalayas

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An attempt is made to identify seismicity patterns precursory to great earthquakes in most of Tibet as well as the central and eastern Himalayas. The region has considerable tectonic homogeneity and encompasses parts of China, India, Nepal, Bhutan, Bangladesh, and Burma. Two seismicity patterns previously described were used: (1) pattern Σ is a peak in the sum of earthquake energies raised to the power of about 2/3, taken over a sliding time window and within a magnitude range less than that of events we are trying to predict; and (2) pattern S (swarms) consists of the spatial clustering of earthquakes during a time interval when the seismicity is above average. Within the test region, distinct peaks in pattern Σ have occurred twice during the 78-year-long test period: in 1948–49, prior to the great 1950 Assam-Tibet earthquake ($M = 8.6$), and in 1976. Peaks in pattern S have occurred three times; in 1932–1933, prior to the great 1934 Bihar-Nepal earthquake ($M = 8.3$), in 1946, and in 1978. The 1934 and 1950 earthquakes were the only events in the region that exceeded $M = 8.0$ during the test period. On the basis of experience here and elsewhere, the current peaks in both Σ and S suggest the likelihood of an $M = 8.0$ event within 6 years or an $M = 8.5$ event within 14 years. Such a prognostication should be viewed more as an experimental long-term enhancement of the probability that a large earthquake will occur than as an actual prediction, in view of the exceedingly large area encompassed and the very lengthy time window. Furthermore, the chances of a randomly occurring event as large as $M = 8.0$ in the region are perhaps 21% within the next 6 years, and the present state of the art is such that we can place only limited confidence in such forecasts. The primary impact of the study, in our opinion, should be to stimulate the search for medium- and short-term precursors in the region and to search for similar long-term precursors elsewhere.

INTRODUCTION

The purpose of this study is to investigate long-term seismicity patterns in a region of frequent great earthquakes with the hope of identifying precursory phenomena. The area chosen for study (Figure 1) is basically that of the central and eastern Himalayas, including the great syntaxial bend at the eastern end of the mountain chain arc, together with most of Tibet to the north. It encompasses parts of China, India, Nepal, Bhutan, Bangladesh, and Burma. Many disastrous historic earthquakes have occurred in the region [*Richter*, 1958], and its high seismicity is associated with the continental collision between the Indian and the Eurasian plates [*Molnar and Tapponnier*, 1975]. Seismotectonic boundaries within the region are diffuse and necessarily somewhat arbitrary owing to the fact that the region north of the Himalayan frontal fault cannot be divided readily into a series of rigid sub-blocks or miniplates, but instead shows many aspects of continuous deformation extending far to the north into China [*Tapponnier and Molnar*, 1977]. Throughout the region the stress distributions are related to the impingement of the Indian plate, with its very sharp northeast corner, against the Eurasian plate; thus the study region includes both areas of dominant thrust faulting within the Himalayas, as well as the area of dominant strike slip faulting east and northeast of the syntaxial bend in Burma and southern China. It should be noted that the study region is very large indeed, encompassing an area equivalent to that of the entire conterminous United States west of the Rocky Mountain crest, or that of the combined areas of the Ukraine, Georgia, Turkmenia, Uzbek, Tadzhik, and Kirghiz republics. That there should be mechanical interconnection over this entire area associated with the 'preparation' for individual great earthquakes is perhaps surprising, but this is one of the conclusions of our study.

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DEFINITIONS

We tested three premonitory patterns, Σ, S, and B [*Caputo et al.*, 1979; *Keilis-Borok and Malinovskaya*, 1964; *Keilis-Borok and Rotvain*, 1979; *Keilis-Borok et al.*, 1979. Their definitions are given in the work of *Keilis-Borok et al.* [1979] and will be summarized here only briefly. We seek precursors of events with magnitudes $M \geq M_0$; events of these magnitudes are called strong earthquakes.

Pattern Σ (sigma). This pattern was introduced by *Keilis-Borok and Malinovskaya* [1964] and is represented by a peak of the function

$$\Sigma(t) = \sum_i G(M_i)$$

Here M_i, $i = 1, 2 \cdots$, are the magnitudes of consecutive earthquakes. The summation is taken over all earthquakes in the

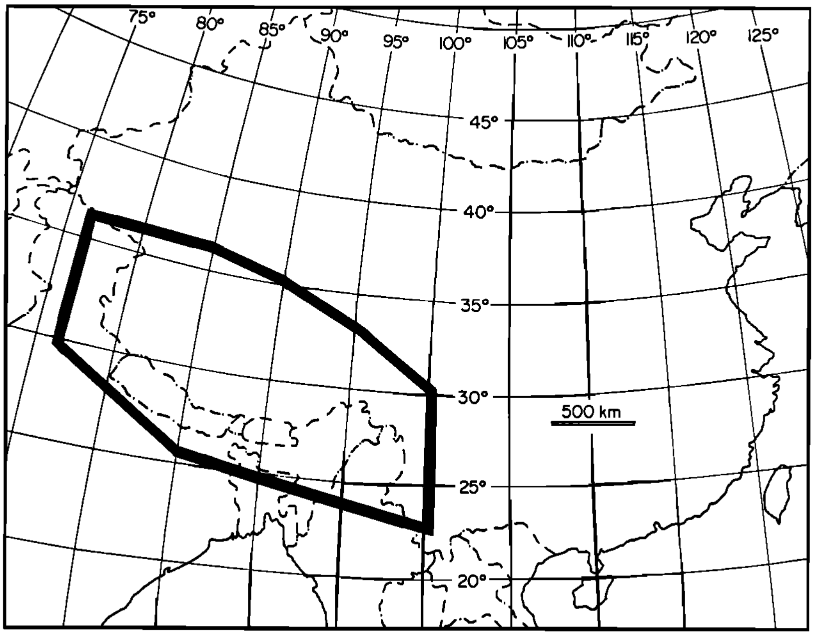

Fig. 1. Map showing area of study (heavy line).

region within the sliding time window of width s:

$$t - s \leq t_i \leq t$$

within the magnitude range

$$M_0 - d_2 \leq M_i \leq M_0 - d_1$$

and within the depth interval,

$$h_2 \leq h_i \leq h_1$$

The time of the ith earthquake is t_i, and h_i is its focal depth. Aftershocks of earthquakes with $M \geq M_0$ are eliminated from the summation in order to test the potential that earthquakes of intermediate magnitudes have for triggering larger events.

The function $G(M)$ is assumed to be

$$G = 10^{d(m-f)}$$

Pattern Σ is diagnosed when

$$\Sigma(t) \geq cG(M_0)$$

Pattern S ('swarms'). This pattern was introduced by *Caputo et al.* [1979] and consists of a clustering of earthquakes during a time interval when the seismicity is above average. The formal definition is as follows. We count earthquakes in the sliding time interval from $t - s$ to t and in the magnitude range $M_i \geq M_1$. $N(t)$ is the total number of such earthquakes in the whole region, $n(t)$ is obtained from $N(t)$ by the elimination of aftershocks of strong earthquakes. We determine $r(t)$, which is the maximum number of epicenters for which $n(t)$ has been calculated and which can be surrounded by a small rectangular area of size $\Delta\phi$ in latitude and $\Delta\lambda$ in longitude. Pattern S is diagnosed when

$$N(t) > c_1 \qquad n(t) > c_2\overline{N}(t) \qquad r(t) \geq c_3 n(t)$$

$\overline{N}(t)$ is the average value of $N(t)$ in the interval from the beginning of the catalog to t or in the sliding window extending from $t - c_4$ to t.

Pattern B ('burst of aftershocks'). This pattern was introduced by *Keilis-Borok et al.* [1979] and is represented by an earthquake with an abnormally large number of aftershocks at the beginning of its aftershock sequence. Aftershocks are identified as the earthquakes within a distance $R(M)$ from the main shock and time interval $T(M)$ after the main shock, M being its magnitude. The number b_i of aftershocks during the first e days after the ith main shock is estimated. Pattern B is diagnosed when b_i is abnormally large, $b_i \geq \overline{b}$.

The threshold $\overline{b}$ was determined as follows. Let $b(t)$ be the maximum value of b_i during the sliding time interval $t - s \geq t_i \geq t$. Then by analogy with $\overline{N}(t)$ the function $\overline{b}(t)$ is the running average value of $b(t)$ in the interval extending from t_0 to t; if this average is less than some constant, we replace it by this constant. Alternatively, a constant threshold may be used.

All three patterns are probably similar projections of a general pattern, which is the abnormal clustering of earthquakes in the time-space-energy domain. This general pattern was called 'burst of seismicity' by *Keilis-Borok et al.* [1979].

DATA ANALYSIS

We listed the earthquakes of the region under consideration from the revised catalog of earthquakes of China and adjacent regions [*Lee et al.*, 1976, 1978]. The catalog of historical earthquakes is, not unexpectedly, far less complete than the instrumental catalog which begins around 1900 (Table 1). We therefore confine our attention to the instrumental catalog. A list of all earthquakes in this region with $M \geq 7.0$ is given in Table 2.

Pattern Σ. Parametric values were assigned a priori, on the basis of previous studies, as follows: $s = 5$ years, $d = 0.91$, $f = 4.5$. Note that the choice of f plays no role in the determination of pattern Σ. No limits were imposed on focal depths, since the catalog shows unknown or normal depths for almost all earthquakes. The magnitudes and rates of occurrence of the largest earthquakes in the region (Table 2) indicate a choice of M_0 of between 8.0 and 8.5. We selected $M_0 = 8.0$ and $M_0 - d_1 = 7.8$ [*Keilis-Borok and Malinovskaya*, 1964]; the lower limit, $M_0 - d_2 = 6.0$ is dictated by the lack of reliability of the catalog below the cutoff. All earthquakes within a distance of 100 km from the epicenter of each of the three strong earthquakes with $M \geq 8.0$ and within one year after it were la-

TABLE 1. Statistics of Earthquakes in Tibet and the Himalayas, after *Lee et al.* [1976, 1978]

Date	Magnitude				
	<6.0	6.0–6.4	6.5–6.9	7.0–7.4	≥7.5
1450–1899	10	1	2	0	0
1900–1919	0	3	3	2	0
1920–1939	0	14	6	1	1
1940–1959	0	30	9	0	4
1960–1976	0	12	6	4	0

beled as aftershocks of these earthquakes and hence were eliminated from Σ. The thresholds for the definition of aftershocks are the same as in some of the previous studies. Generally, not all aftershocks will be identified by these thresholds after strong or main shocks. However, for this catalog an increase in the thresholds will not alter our conclusions and indeed will only make our results look better; Σ will be smaller except in the intervals preceding strong earthquakes.

The function $\Sigma(t)$ is shown in Figure 2, and the significant peak in the function Σ before the 1950 Assam-Tibet earthquake is evident. *Keilis-Borok and Malinovskaya* [1964] took the threshold value $c = 0.5$; if we take this value, we identify pattern Σ and declare a long-term alarm when $\Sigma(T) \geq 765$. This a priori threshold has thus far given no false alarms. On the other hand, we failed to detect pattern Σ prior to the 1934 earthquake, $M = 8.3$, which took place on the border of the region. We cannot establish pattern Σ prior to the 1951 earthquake with $M = 8.0$, since it occurs within too short a time after the Assam-Tibet earthquake.

Pattern S. We assumed $M_0 = 8$, $s = 5$, as before; the choice $M_1 = 6$ was dictated by the catalog; $c_2 = 1$, $c_3 = 0.5$, as in previous studies [*Caputo et al.*, 1979; *Keilis-Borok and Rotvain*, 1979]; $\Delta\phi = 0.4°$, $\Delta\lambda = 0.8°$. The results are inconclusive (Figures 3 and 4). Except for a brief interval around 1918, we do not consider the period before 1930, when $\bar{N} < 5$ and is too small. After 1930, pattern S with both $n > \bar{N}$ and $r \geq 0.5n$ occurs twice, prior to both the 1934 and the 1950 earthquakes; the latter occurred contemporaneously with pattern Σ. The locations of the swarms are shown by stars in Figures 4*a*, and 4*b*. We believe the values of N are too small to use pattern S as an independent precursor, although it can be summoned as supporting evidence. Five earthquakes in 1976 near the southeast corner of our region are not diagnosed as pattern S because $n/\bar{N}$ is too small in the corresponding time window, 1972–1976. If the time window were chosen to be 3 years, pattern S would have been diagnosed (see last point on Figure 3) and would have been a result in correspondence with our observation of pattern Σ for this period.

Pattern B. Pattern B cannot be studied in this region because the catalog at our disposal has almost no aftershocks for most earthquakes.

Figures 2 and 3 imply the existence of premonitory patterns Σ and S in this region; the strongest earthquake, with $M = 8.6$ in 1950, is preceded by both patterns; the earthquake of $M = 8.3$ in 1934 is preceded by pattern S. Neither of the patterns has generated false alarms.

We discuss the danger of self-deception. Two decisions related to pattern Σ were not made in previous papers. One is the choice $M_0 = 8.0$. Nothing in the catalog dictates that we make this choice. If we had chosen $M_0 = 8.5$, we would take $M_0 - d_1 = 8.3$ [*Keilis-Borok and Malinovskaya*, 1964]. This would lead to the following changes. The $M = 8.3$ earthquake of 1934 is no longer a strong earthquake and hence would be included in Σ. This would generate a major maximum in Σ about 16 years prior to the 1950 Assam-Tibet earthquake. This maximum was described by *Keilis-Borok and Malinovskaya* [1964] on the basis of the Gutenberg-Richter catalog. The time interval of 16 years is consistent with a rough correlation between the magnitude of the forthcoming earthquake and its delay after the rise of Σ. We cannot reject the notion that the occurrence of pattern Σ in 1948 is not the first but the second in a sequence of precursors. Another consequence of the increase of M_0 and $M_0 - d_1$ would be that the earthquake of 1951 with $M = 8.0$ with its two aftershocks, $M = 6.2$ and 7.5, would also be included in Σ, and this would give a false alarm in 1951, immediately after the Assam-Tibet earthquake. The results are reasonably stable to the variation of the other numerical parameters.

In the investigation of pattern S we arbitrarily chose $M = 6$ and $s = 5$ years. These values are essentially predetermined by the catalog; any increase of M_1 or decrease of s would reduce N, which is already too small. We also assumed $\Delta\phi = 0.4°$, $\Delta\lambda = 0.7°$. The results remain the same if we increase these values, since the swarms, small as they are, are well concentrated in space. Hence pattern S is weak but reasonably stable.

More important was the decision by which the boundaries of the region were selected. These boundaries are generally nonunique, and for this part of the world the uncertainty is larger than usual, as was indicated in the introduction. We have been concerned that a change in the boundaries might lead to a significant change in the results. However, the test described below shows that our results are relatively stable to variations in the boundaries.

POSSIBLE TECTONIC IMPLICATIONS

There is so far no unique answer to the following question: What zones of active structure should be analyzed together in the study of the occurrence of strong earthquakes? Let us assume that pattern Σ, described in the previous section, is significant and discuss its possible meaning.

TABLE 2. Earthquakes with $M \geq 7$

Year	Date	M
1905	April 4	8.0*
1908	Aug. 20	7.0
1915	Dec. 3	7.0
1934	Jan. 15	8.3
1934	Dec. 15	7.1
1947	July 29	7.7
1950	Aug. 15	8.6
1951	Nov. 18	8.0
1952	Aug. 17	7.5
1973	July 14	7.0
1975	Jan. 19	7.1
1976	May 29	7.0
1976	May 29	7.1

*Located slightly outside of test area.

TABLE 3. Comparison of Catalogs, 1973–1976

Year	Date	*Lee et al.* [1978]	*Academia Sinica* [1976]
1973	July 14	7.0	7.3
	July 14	6.0	6.0
	Sept. 8	6.0	6.0
1975	Jan. 19	7.1	6.9
	March 18	6.3	6.0
	May 5	6.5	6.4
1976	May 29	7.0	7.5
	May 29	7.1	7.6
	May 29	not listed	6.0
	May 31	6.3	6.6
	June 1	not listed	6.1
	June 9	6.0	6.1
	July 4	not listed	6.0
	July 21	6.4	6.8

Nine earthquakes occurred during the period 1943–1947 that contributed to the marked peak of Σ in 1948. The positions of their epicenters are shown in Figure 4*a*. Sixty-four percent of the contribution to the peak was made by a single earthquake of magnitude 7.7 in 1948. The eight remaining events might be considered as normal random background except that seven of them occurred in the western part of the region, where the long-term seismicity is much lower than in the east; during the entire 1900–1976 period the numbers of events west and east of longitude 90° are 31 and 65, respectively (excepting aftershocks). The probability of getting 7 out of 8 of the 1944–1948 events west of 90° by a random binomial model is 0.002, which is small. Therefore we propose that there is a mechanical connection between these events, and, taken together with the larger magnitude 7.7 shock to the east, they represent systematic 'unlocking' of the plate boundary in this area preparatory to the great earthquake of 1950, which was centered still farther southeast. We recognize that the faulting associated with the 1950 earthquake did not extend over the entire 1500-km-long zone encompassed by the premonitory shocks, but we do suggest that the 'mechanical preparation' for this great earthquake was taking place over a very wide area in the years before the earthquake, with redistribution of stresses pointing toward the subsequent more localized epicentral area. This could be an a posteriori qualitative explanation of the premonitory pattern in Σ in 1948.

Let us now see whether this premonitory pattern could have been identified if the boundaries of the test region had been drawn on the basis of other seismotectonic considerations. Differences between solely tectonically and solely seismologically based regionalizations should be kept in mind. The purpose of the first is to outline areas with common features of historic tectonic development and makeup. The purpose of the second is to outline zones with interdependent stress-strength fields, which may form transition zones between tectonic provinces defined in the usual sense. That is, such seismic zones may show very diverse tectonic features and earthquake mechanisms, since earthquake-producing stresses do not necessarily terminate at tectonic boundaries. With this in mind, we repeat our analysis for four additional variations of the test area boundaries. These are shown in Figure 5.

Area A (Figure 5) simply represents a minor expansion in the boundaries of the original test area. Area B encompasses a somewhat larger area to the southeast, thereby including a considerably increased number of shocks from the very active southern Yunnan seismic area. The eastern boundary of the original test area at 100°E longitude was particularly arbitrary, so this additional test is significant. Area C includes an even greater number of shocks to the east, including those of northern Yunnan and southern Szechwan. Area D is an area more limited than that of the original test area, encompassing a large 'cloud' of epicenters but drawn without any tectonic basis; region D excludes territory lying to the west of longitude 90°.

Patterns Σ for each of these regions are compared in Figure 6. We indicate on this figure only those values of Σ which are greater than 750. The diagnosis of pattern Σ is evidently stable to the thresholds c and M_0. In all four cases a major maximum of $\Sigma \geq 1200$ precedes the 1950 earthquake. As might have been expected, with the expansion of the region some secondary maxima also increase. The maxima in the 1970's will be discussed separately.

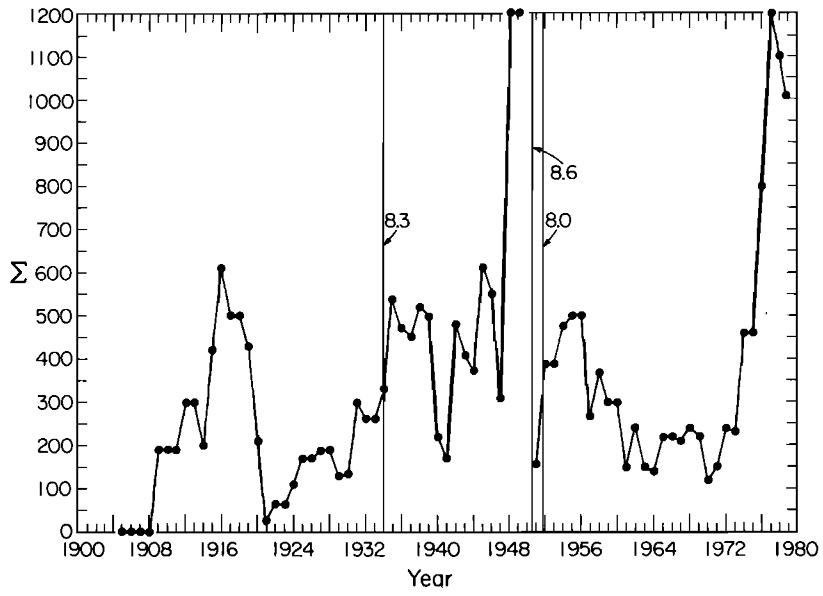

Fig. 2. Pattern Σ (solid circles) and strong earthquakes for the area of study (vertical lines, with magnitudes).

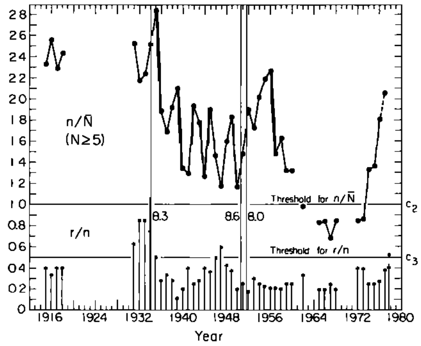

Fig. 3. Pattern S and the strongest earthquakes (vertical lines). Top curve shows $n(t)/\overline{N}(t)$ when $N \geq 5$, and bottom diagram shows $r(t)/n(t)$.

Pattern S before the 1934 (M = 8.3) earthquake persists through all the variations; pattern Σ appears 6 years and more before this same earthquake in variations A and C. Pattern Σ appears as a false alarm around 1940 in variations C and D. Patterns Σ and S both appear through all variations before the 1950 (M = 8.6) earthquake, with the exception that pattern S disappears in variations C and D. In region C it disappears because the swarms that produced pattern S in the other cases do not pass the increased threshold $\overline{N}$; in region D it disappears because the swarm is now outside the region. Finally, the occurrence of pattern Σ in the late 1970's vanishes in variation D and is replaced by pattern S. We note that variation D inflicts the greatest change on the original assignment to the region, since D describes only the eastern half of the entire region. The process of excluding earthquakes from the region west of longitude 90° from our count creates a strong instability in the appearance or disappearance of the two patterns.

A further expansion of the region may include other strong earthquakes, but we see no compelling reason to consider them here. If all of the boundaries of the region are extended by 500 km, for example, thereby more than doubling the test area, only two additional earthquakes with $M \geq 8$ are included. One of these, the 1905 Kangra (India) earthquake, occurred too close to the start of the instrumental catalog period to search for precursors; the other is a 1912 event of M = 8.0 in central Burma, an area for which our catalog is markedly deficient. The great 1897 Assam (India) earthquake with M = 8.7 occurred within the original test area, but catalogs for that time are too inadequate to search for precursors.

THE RECENT PATTERN Σ

We discuss the fact that $\Sigma(t)$ reached the same height, 1200, in 1976 as before the 1950 Assam-Tibet earthquake. This implies that another earthquake of $M \geq 8$ may occur within several years in the study region. We consider the similarity of this recent pattern to the pattern which preceded the earthquake of 1950 with M = 8.6. Thirteen earthquakes are listed in the catalog for the period 1972–1976 and generate the peak of $\Sigma(t)$ at the end of 1976. The locations of their epicenters and contributions to Σ are shown in Figure 4*b*. The major difference in the patterns of 1948 (Figure 4*a*) and 1976 is the following: the peak in 1948 was formed mainly by one earthquake, M = 7.7, which contributed 64% of Σ and was located relatively close to the earthquake of 1950 (see Figure 4*a*). The more recent peak is formed by several relatively weaker earthquakes, two with M = 7.1, three with M = 7.0, three with M = 6.5, and so on. The epicenters of these earthquakes are distributed over two regions, each contributing about one half of Σ. This difference may be important. However, we know of no reasons to withdraw the forecast of an enhanced probability of occurrence due to such a difference; indeed, the experience of *Keilis-Borok and Malinovskaya* [1964] suggests just the opposite, namely, that pattern Σ preceding a strong earthquake can be formed by several earthquakes, as well as by a single

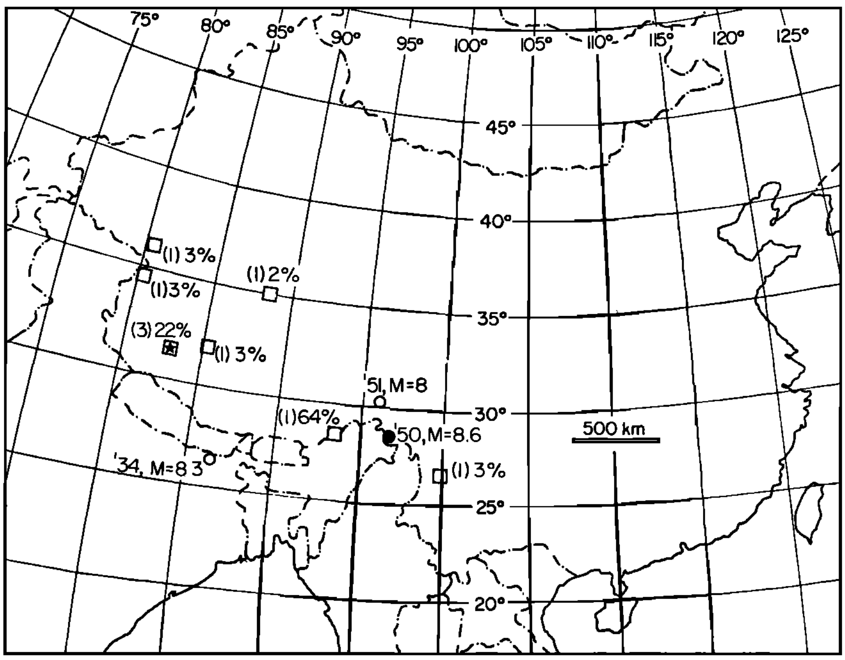

Fig. 4*a*. Epicenter of the 1950 Assam-Tibet earthquake (solid circle) and locations of the earthquakes which formed patterns Σ and S in 1943–1947 (squares). Parentheses indicate numbers of events at given locations, and percentages indicate individual contributions to Σ. The star indicates the location of the swarm which gave rise to pattern S. The 1934 and 1951 epicenters are indicated by open circles.

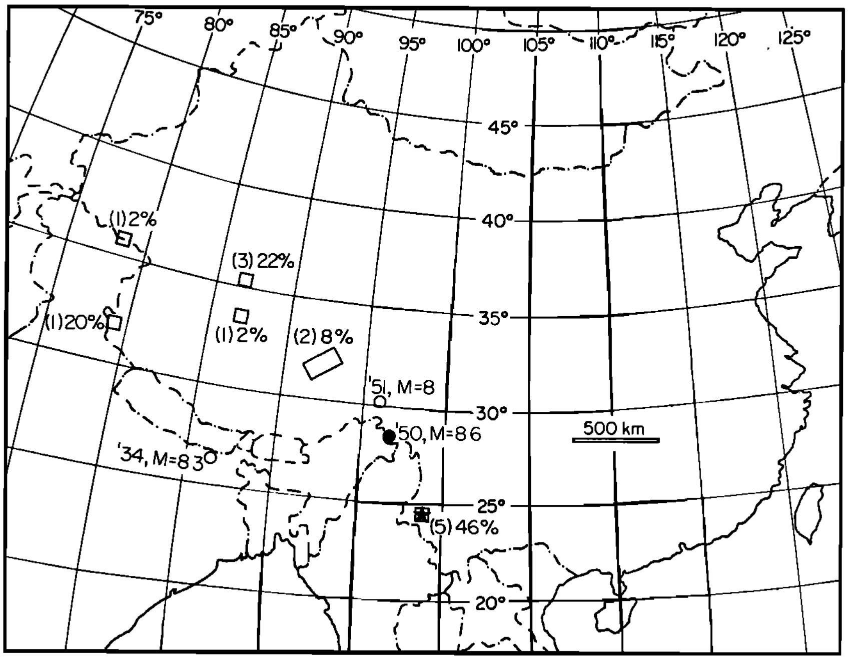

Fig. 4*b*. Pattern Σ in 1977. Symbols are the same as in Figure 4*a* except that squares indicate earthquakes in 1973–1976 contributing to peak of Σ.

one with larger magnitude. One might simply replace pattern Σ by the occurrence of a single earthquake with sufficiently large magnitude or, equivalently, by a peak of energy release. However, this would greatly increase the number of errors (both false alarms and failures to predict), since the correlation between strong and slightly smaller earthquakes, although positive, is too weak to be of value as a precursory criterion.

We discuss the corrections to the earthquake catalog introduced in *Academia Sinica* [1976]. For the region under consideration the only significant changes took place for the earthquakes of 1973–1976. These are summarized in Table 3. The corrections will lead to the following changes in our analysis: the peak of Σ(*t*) in 1976 will increase to 2100; evidently the peak in 1948 will remain the same. In other words, pattern Σ in 1977 will become more pronounced. At the same time, 75% of the peak of Σ in 1976 will be contributed by the cluster of earthquakes at the southeast corner of the region, so that the above mentioned difference between pattern Σ in 1948 and 1976 will not be as great. Three additional earth-

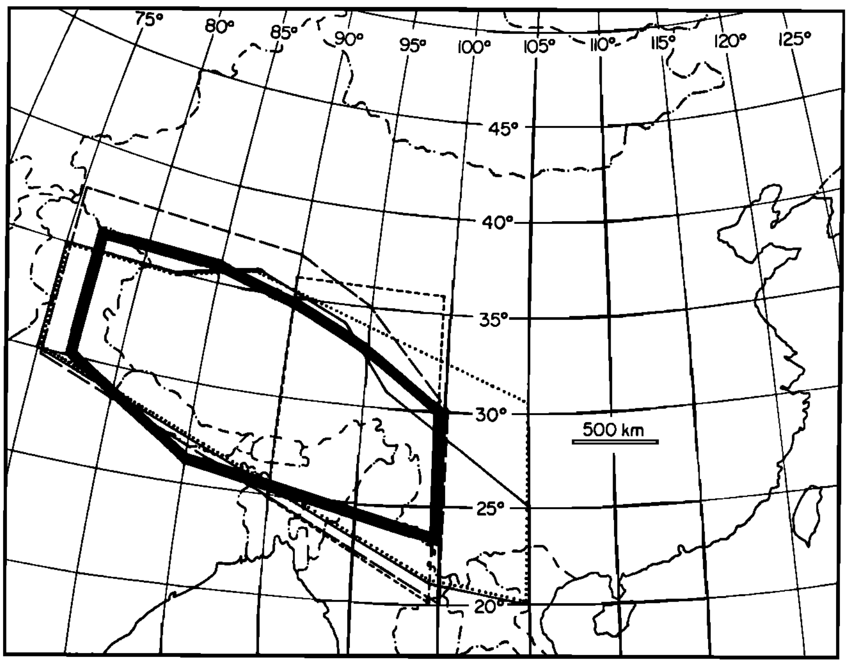

Fig. 5. Variations in the boundaries of the region. Original test area I is indicated by the heavy solid line. The long-dashed line indicates test area A; the thin solid line test area B; the dotted line test area C; and the short-dashed line test area D.

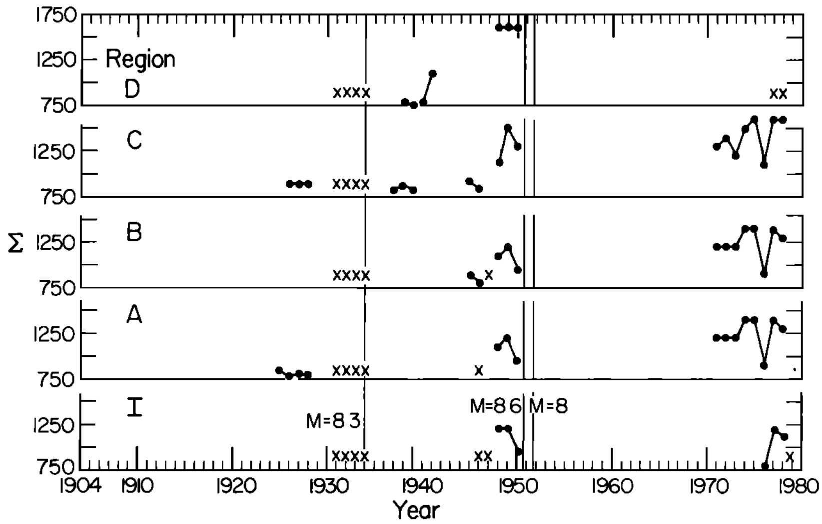

Fig. 6. Stability of patterns Σ and S to variations in the boundaries of the region. Solid circles represent values of Σ greater than 750; crosses indicate the identification of pattern S. Regions are as defined in Figure 5.

quakes in 1976 (May 29, June 1, July 4) will amplify the swarm of 1976 by producing an increase in both n and r by 3, so that both thresholds will be passed and pattern S diagnosed. Comparison of the catalog which we used with the NOAA catalog shows no differences which influence our conclusions. The only exception is the earthquake of 1934, M = 8.3, which we have taken into consideration.

If we consider the peak of Σ in 1976 to be a precursor to a strong earthquake with $M \geq 8$, the following questions arise: when is it expected, what is the probability of its occurrence, and where within the region may its epicenter be located? These questions have no exact answers, since our experience is too limited. Moreover, to narrow the place and time of a predicted earthquake, one should also study medium and short-term precursors. According to *Keilis-Borok and Malinovskaya* [1964] the time interval between the appearance of pattern Σ and the following strong earthquake is 8–16 years for magnitudes of strong earthquakes 8–8.6, respectively. Later experience with other patterns [*Caputo et al.,* 1979; *Keilis-Borok et al.,* 1979] suggests shorter intervals, so that it seems reasonable to expect an earthquake of magnitude about 8 in the study region some time before 1985 or of about 8.6 before 1993.

We estimate how informative this statement is by comparison with a Poissonian model of earthquake occurrence. We base our calculation on the assertion that three strong earthquakes have occurred in this century in or very close to the study region. These are 1905 (M = 8.0), 1934 (M = 8.3), and 1950 (M = 8.6). For our purposes we take the 1951 event (M = 8.0) as an aftershock of the stronger 1950 event, even though they occurred about 6° apart; in our analysis we are unable to forecast the second of two events occurring within such a short time span. Based on a model of occurrence in which 3 events with $M \geq 8$ occur randomly in 78 years, during the next 6 years, at least one earthquake with $M \geq 8$ will occur with a probability of about 21%; similarly, based on a random rate of occurrence of one event per 78 years, during the next 14 years, at least one earthquake with $M \geq 8.5$ will occur with a probability of 17%. We have arbitrarily chosen to start our calculation with the year 1900, thereby including the 1905 event but deleting the 1897 event from our list; this has represented to us a reasonable compromise between the extremes including both the 1897 and 1905 events or deleting them both according to choice of date of start of the catalog. The inclusion of events near the turn of the century, which was a period of unusually high world-wide seismicity, overestimates the probability of occurrence for the near future. In any case the expectation based on patterns Σ and S is statistically significant when compared with that of randomly occurring events. A defect of this calculation is that we have estimated the probability of occurrence of an event with $M \geq 8.5$ in the next 14 years from a Poisson rate of one earthquake with this magnitude per 78 years. The rate may be significantly different; if it is lower than 1/78, then our Poissonian comparison probability is reduced. Comparison models other than the Poissonian random model can be introduced at the reader's discretion; these may raise or lower the comparison probabilities compared with those given above, but such models are too numerous for us to anticipate on an individual basis.

It is difficult to estimate the probability of a false alarm. If was below 20% in the previous studies of the occurrence of pattern Σ before strong earthquakes, but our experience is much too limited to accept this figure for any consequential purpose. More accurate estimates will require that we study other medium-term patterns. Other patterns are also necessary for attempts to specify the places of future epicenters within the very large region.

CONCLUSIONS

Within the area of this study, which encompasses the central and eastern Himalayas, the seismicity pattern Σ has occurred only once during the 1900–1975 period, in 1948. This was followed in 1950 by the largest earthquake during the period, the Assam-Tibet event of M = 8.6. The seismicity pattern S also preceded the 1950 earthquake but was only marginally diagnostic; it also occurred once before, in 1933, prior to the only other earthquake with magnitude exceeding 8.0 during the test period, the 1934 Bihar-Nepal event of M = 8.3. Both premonitory patterns were generated by earthquakes that were widely distributed throughout the region, particularly near the northern and eastern borders, and were by no means limited to the specific areas of the major events and their aftershocks. A large contribution to the peak in Σ that preceded the 1950 event was in fact from earthquakes centered more than 1,000 km to the west, although the largest single contribution came from a somewhat closer earthquake with $M = 7.7$. A possible qualitative explanation is that patterns Σ and S indicate that the plate boundary between the Indian and the Eurasian plates is becoming progressively unlocked; redistributions of stresses trigger the more localized large events.

A clear pattern Σ and a marginally diagnostic pattern S reappear for the Himalaya-Tibet region in 1976. In view of past experience regarding premonitory patterns in this region and others [*Keilis-Borok and Malinovskaya,* 1964] this pattern suggests the approach of an earthquake of at least $M = 8$ somewhere in the region and suggests that it should occur within the next 14 years if it is as large as $M = 8.5$. Such a prognostication should be regarded more as an experimental long-term forecast of an enhanced probability of occurrence than as an actual prediction, in view of the exceedingly large area encompassed (including parts of six countries) and the very lengthy time window. In our opinion it calls mainly for a vigorous scientific effort to identify medium- and short-term precursors in the region. Furthermore, we emphasize the following points. (1) Earthquakes of very large magnitude are relatively frequent in this region anyway, having occurred recently in 1897, 1905, 1934, and 1950. We estimate that the probability of a randomly occurring event of $M = 8.5$ during any given 14-year period is about 17%. (2) A clear possibility obviously exists that the allegedly precursory pattern is instead a false alarm, and the state of the art is such that we can at present have only limited confidence in such prognostications. On the basis of using this particular technique in other parts of the world, we estimate that the probability is perhaps 80% that the forecast of an enhanced probability of occurrence is in fact valid, although this estimate must to some degree be tempered by the fact that clear precursory patterns in Σ preceded only one of the two largest earthquakes in this particular region during the test period.

In summary, the primary impact of this study should, in our opinion, be to stimulate the search for medium- and short-term precursors in the Himalaya-Tibet area and to stimulate the search and evaluation elsewhere in the world for long-term precursors similar to those suggested in this paper.

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