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WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

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# PREMONITORY ACTIVATION OF SEISMIC FLOW: ALGORITHM M8

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# Premonitory activation of seismic flow :

# Algorithm M8

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Problem:

to define Time of Increased Probability (TIP) for the strongest earthquakes worlwide

Data:

World's Hypocenters Data File (USGS-NOAA)

Method:

Complex analysis of well-known seismological precursos

Hope:

Evidence of self-similarity for California and Nevada (algorithm CN) in Allen et al,1984

Common description of earthquake prone areas for magnitude above 8.2 in Gurvitch & Kossobokov,1984

**Preliminary results were obtained in 1984.**

Additional improvement:

- test in other regions for smaller magnitudes
- scaling
- models
- monitoring of TIP

most are still required

Formal statement of the problem:

Objects {U} are the vicinities of places where earthquakes with $M \geq 8$ may occur:
- 132 known epicenters, 1885-1982
- 11 point where $M \geq 8$ are possible according to pattern recognition of earthquake prone areas but yet unknown

An object is a rectangle on latitude-longitude plane

$F_U(t)$ is a vector function of time

Find a rule for diagnosis of TIP

A rule is acceptable if
- TIPs cover less than 7.5 % of total space-time
- more than 2/3 of $M \geq 8$ are within TIPS

Time considered : 1964-1982

Catalog of main shocks:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| M | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 |
| R(M) | 40 | 40 | 50 | 50 | 50 | 100 | 100 | 150 | 200 km |
| T(M) | 23 | 46 | 91 | 183 | 183 | 365 | 730 | 913 | 1096 days |

Functions $F_u(t)$:

1.Seismic activity- $N(t \mid m, s)$ is the number of main shocks with $M \geq m$ in (t-s,t)

2.Increment of seismic activity-
$K(t \mid m, s) = N(t \mid m, s) - N(t-s \mid m, s)$

3.Variation of seismic activity-
$V(t \mid m, s, u) = \sum \mid N(t_{i+1} \mid m, s) - N(t_i \mid m, s) \mid$

4.Deviation from long term tren of activity-
$L(t \mid m, s, t_0) =$
$N(t \mid m, t-t_0) - N(t-s \mid m, t-s-t_0)\cdot(t-t_0)\cdot(t-s-t_0)^{-1}$

5.Concentration criterion (Zhurkov) -
$Z(t \mid m, M', s, a, \beta) =$
$\sum 10^{\beta(Mi-a)} / [N(t \mid m, s) - N(t \mid M', s)]^{2/3}$

6.Clustering (B precursor) :

$b(t \mid m, M', s, M_a, e)$

maximal number of aftershocks with $M \geq M_a$ in the first e days after a main shock within intervals (t-s,t) and (m,M')

Functions which differ by values of some parameters in their definition are considered to form a group

Constant average yearly rate of occurence of main shocks with $M \geq m$:

10 events per year - $N_1$, $L_1$, $Z_1$,
20 events per year - $N_2$, $L_2$, $Z_2$

For these functions s = 6 years.

$M' = M_0 - .5$ for Z, and $m = M_0 - 2$, $M' = M_0 - .2$ for b

To diagnose a TIP at time t we require that over the preceeding 3 years -

- each group $\{N_1,N_2\}$, $\{L_1,L_2\}$, $\{Z_1,Z_2\}$, $\{b\}$ contains functions with extremely large values,

- at least 6 out of 7 functions $\{N_1,N_2,L_1,L_2,Z_1,Z_2,b\}$ have extremely large values

Extremely large are the values exceeding 90 % quantile

$F_u(t)$ is computed for discrete times $\{t_i\}$ with half-a-year step.

$(t_i, t_i+\tau)$ is a TIP if the condition above occurs at $t_{i-1}$ and $t_i$

Original data analysis

M ≥ 8 worldwide

Six acceptable rules which correspond to variations of the main one were obtained

5 out of 7 in 5 % of total space-time

few false alarms

BADLY DATA FITTED

TEST ON INDEPENDENT DATA

Transformations of space and time :

$l(M_0) = \exp(M_0 - 5.6) + 1°$ of Earth meridian, corresponding to $M_0 = 8$ and $l = 12°$
( lg R = .43M suggested by Dobrovolsky et al.,1979)

Time scale does not depend on magnitude.

$$\lg T = \lg N = A + B \cdot M + C \cdot \lg l$$

Main shocks of Pamir and Tien Shan
$\lg N = -3.88 - 0.72M + 1.39 \lg l$ and $\lg l = 0.54M - 2$
$\lg N = -6.66 + 0.03M$
(Kossobokov & Mazhkenov, in press)

16 regions

Magnitude $M_0$ ranging from 8 to 4.9

No changes in parameters for 13 regions -

20 out of 22 (90%)
TIPs cover less than 20% of space-time
(TEs about 10%)

In Himalaya, Vrancea, and Vancouver Is.
10 and 20 were changed for 1 and 3
due to incompleteness of low magnitudes
In these regions:
all 8 strong earthquakes are within TIPs
which occupy only 12.5% (TEs 5.5%)

Statistical significance is not estimated since there was some freedom in choice of $M_0$
However, the results constitute an argument in favour of-

self-similarity, and
further test of algorithm M8 in forward monitoring of TIPS

# Premonitory activation of an earthquake flow:
# Algorithm M8.

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## Abstract

The 32 out of 36 strongest earthquakes which have recently occured in different regions of the world are preceded by specific activation of the earthquake flow in the lower magnitude range. This activation is depicted by the algoritm M8 designed in [1] for diagnosis of the Times of Increased Probability (TIPs) of strong earthquakes. A TIP refers to a time period of 5 years and an area which linear size is several times larger than that of incipient earthquke source. All together the TIPs diagnosed in this study occupy less than 20%, and the Times of Expectation (TEs) - about 10 % of the total space-time domain considered. These results constitute an argument in favour of at least partial selfsimilarity of the earthquake flow in deverse seismotectonic environment and magnitude ranges. It also implies possibility of intermediate-term prediction of the strongest earthquakes in the regions. Such prediction may be used for precautionary measures.



## Algorithm M8

This paper suggests a methodology for experimental anticipation of future strong earthquakes in several seismic regions of the USSR and other countries.

More specifically an algorithm of evaluation of Times of Increased Probability for strong earthquakes in a region is presented here. Next section describes the results of its application on independent data from different regions.

The general outline of the algorithm M8 is the following: The earthquake flow is considered within a certain area, and we are looking for the TIPs associated with earthquakes of magnitudes equal or above a certain threshold $M_0$, unless they are aftershocks of some stronger earthquake. The size of an area depends on the magnitude $M_0$ of "the strong earthquakes" for which we diagnose TIPs. Several integral traits of an earthquake flow are estimated as functions of a sliding time window. If most of them become extremely large within a certain narrow time interval a TIP is diagnosed for $\tau$ years.

<u>The area.</u> The seismic territory under consideration is scanned by overlaping areas. Their diameter depends on $M_0$ as $L = \exp(M_0 - 5.6) + 1°$ in degrees of the Earth meridian. (In the studies described bellow an area was either a circle or a rectangle formed by meridians and parallels.)

<u>The functions.</u> The functions are determined and TIPs are diagnosed in each area independently. For the convenience

let us repeate definitions of the functions which are used in the algorithm M8 [1]. (A wider set of functions depicting earthquake flow one can find in [2].)

The functions are defined on a sequence of main shocks. To separate aftershocks we have used rough but generally accepted time and space windows [2, 3]. Each mainshock is defined by the vector of 6 components { $t_i$, $\varphi_i$, $\lambda_i$, $h_i$, $M_i$, $B_i(e)$ } where i is the sequence number of the main shock, t is the origin time, $\varphi$ is the latitude, $\lambda$ is the longitude, h is the depth, M is the magnitude and B(e) is the number of aftershocks that occured in the first e days after the main shock.

The intensity of an earthquake flow (i.e. current level of seismic activity is depicted by the number of main shocks that occured in time interval (t-s, t) and had magnitude greater than a lower limit $\underline{M}$; we refer to this number as $N(t|\underline{M}, s)$.

The deviation of seismic activity from a long linear trend is characterized by the function

$L(t|\underline{M}, s, t_0) = N(t|\underline{M}, t-t_0) - N(t-s|\underline{M}, t-s-t_0)\cdot(t-t_0)/(t-s-t_0)$

where $t_0$ is the begining of the catalog.

The concentration of mainshocks in space can be measured in the following way. Let $S(t|\underline{M}, M, s, \alpha, \beta) = \sum 10^{\beta\cdot(M_i-\alpha)}$ be a weighted sum of the mainshocks within (t-s, t) time and ($\underline{M}$, M) magnitude intervals. For $\beta = b/3$ it is proportional to the total length of fractures. Here b is the coefficient in the magnitude energy relation $\log E = a + bM$. (The parameter $\alpha$ just normalizes the function.) The average length of a fracture is proportional to S/N, and the average distance between



them is proportional to $N^{1/3}$ in case of the uniform distribution. Their ratio is characterizing concentration, and can be roughly estimated by the function

$Z(t|\underline{M}, M, s, \alpha, \beta) =$

$$S(t|\underline{M}, M, s, \alpha, \beta)/(N(t|\underline{M}, s) - N(t|M, s))^{2/3}.$$

The clustering of earthquakes is depicted by the maximal count of aftershocks (which is one of the parameters of a mainshock) in the last year for the mainshocks from ($\underline{M}$, M) magnitude range $B(t|\underline{M}, M, 1\ \text{year}) = \max\ \{ B_i(e) \}$. It is refered as B below.

The intensity of an earthquake flow in the regions considered is obviously different. Thus we have to introduce normalization of a flow adjusting the magnitude threshold $\underline{M}$ so that the average yearly rate of occurence of mainshocks in an area is constant. For one set of functions designated as $N_1$, $L_1$, and $Z_1$ the constant is 10 per year, and it is 20 per year for another set $N_2$, $L_2$, and $Z_2$. For all these six functions the duration of a time interval s = 6 years. The upper magnitude threshold M is adjusted to $M_0$. For functions Z we have used $M = M_0 - 0.5$ ; for B the thresholds were $\underline{M} = M_0 - 2$ and $M = M_0 - 0.2$.

<u>The diagnosis of a TIP.</u> Now the earthquake flow at a time t is represented by a vector of the 7 functions evaluated from the preceding time. The problem is to deduce whether t starts the Time of Increased Probability for a strong earthquake. As a result of the data analysis of the global earthquake flow presented in the catalog [4], the duration of a TIP was chosen to be 5 years, and the following rule was

formulated in [1]:

To declare a TIP at time t we require that over the preceeding 3 years (including t) -

- each group $\{N_1, N_2\}$, $\{L_1, L_2\}$, $\{Z_1, Z_2\}$, and $\{B\}$ contains functions that have extremely large values,

- at least six of the functions $N_1$, $N_2$, $L_1$, $L_2$, $Z_1$, $Z_2$, and B have extremely large values.

Here "extremely large" are values in the upper Q % quantile (Q = 10 for all functions but B, and Q = 25 for B).

The vector is computed at discrete times $\{ T_j \}$ with half-a-year step. The interval $(T_j, T_j + \tau)$ is diagnosed as a TIP if the condition above occurs at $T_{j-1}$ and $T_j$.

This rule reflects an idea of some specific activation of seismicity long before a strong earthquake. The activation is exposed by extremly high level of seismic activity, deviation from liner trend, concentration, and clustering. Each characteristic is depicted by a group of rough estimates which are the values of functions for normalized the normalized magnitude thresholds. Another kind of normalization is envolved by the quantile presentation of those values. The rule integrate the extrema of of characteristics in time. The results which were obtained on the original and independent data improve the algorithm.

**Original data analysis: M ≥ 8 worldwide**

The algorithm M8 as defind above was designed first for



the strongest earthquakes of the world. 132 epicenters of all earthquakes with M ≥ 8 in 1885 - 1982, according to [4], were taken as the centers of rectangles. The size of a rectangle was chosen to be 12° of the Earth meridian. Added were 2 epicenters of the strongest Californian earthquakes in 19th century and 9 points near which the earthquakes with M ≥ 8 are possible, though yet unknown according to [5]. For 14 rectangles the algorithm could not be applied due to incompleteness of the catalog available for the study [1]. The algorithm including numerical parameters was data-fitted in such a way which gives the best success-to-failure score. The results are presented in the first line of Table 1. They show that TIPs are diagnosed before 5 out of 7 strong earthquakes. All together the TIPs occupy 5 % while expectation time covers 3 % of the total space-time domain considered. Among them are 9 "false alarms" - TIPs not confirmed by subsequent strong earthquakes. The false alarms are even clustered in 5 groups [1]. One of the false alarms and both missed earthquakes are very close in space and time: the TIP was diagnosed for 1969 through 1973 in the rectangle with coordinates 10° S and 165° E; it was followed by the earthquakes of 28 December 1973 with M = 7.8 (14° 30'S, 166° 36'), 21 April 1977 with M = 8.1 (10° S, 160° 42'), and 17 July 1980 with M = 8.0 (12° 30', 165° 54'); there were no earthquakes with M ≥ 7.8 in the region in 1957-1973.

Such a success-to-failure score is acceptable. However it was reached by a retrospective data-fitting. That is why an independent test of the algorithm M8 was neccessary.

## General rules of application

Transformations of space and time scales.

As it was already mentioned, the algorithm M8 was originally designed for application in areas with different earthquake flow. So most of the parameters in definition of the functions which are used in diagnostics should not be cnanged at all. However we have to fulfil space-time transformations in transfer of the diagnostics from one region to another.

For space we accept the common assumption that the diameters of the source and its area of preparation are proportional to each other. Accordingly, we assumed for the diameter of an area

$$l(M_0) = \exp(M_0 - c) + 2\varepsilon ,$$

taking a possible error in an epicenter $\varepsilon = 0.5°$ and calculating c from the data-fitted $l(8) = 12°$. (This formula is in a good agreement with relation $\lg R = 0.43M$ suggested in [6] for the maximal distance between an earthquake and its precursor.)

The time scale so far is taken the same for all regions and magnitude ranges. This assumption seems to be more questionable: the time units are expected to be smaller for lower magnitudes. However, some evidences (though still inconclusive) indicate that such decreasing may be rather slow. Following [7], let us consider the reocccurence Gutenberg-Richter law in the form

$$-\lg T(M,L) = \lg N(M,L) = A + B \cdot M + C \cdot \lg L$$

where T(M,L) and N(M,L) are the reoccurence time and the number of



mainshocks with a magnitude M in an area with a linear size L, and A, B, C are numerical coefficients. For the Pamirs and Tien Shan we obtained: $B = 0.72$ and $C = 1.39$. In the same region, according to [8] a linear size of a sourse follows $\lg L(M) = 0.54M - 2$ Km. This implies -

$$\lg T(M,L) = \lg N(M,L(M)) = A + 0.72M + 1.39 \cdot (0.54M - 2)$$
$$= A_1 + 0.03M$$

and shows that T(M,L(M)) and N(M,L(M)) practically do not depend on M in the region.

Thus time scale and numerical parameters meassured in the units of time were not changed in our study.

The choice of $M_0$. The only remaining uncertainty in application of the algorihm M8 is due to some freedom in a choice of the magnitude of strong earthquakes. Usually we were badly limited in variations of $M_0$ in a region. Of course we have to "predict" some earthquakes to prove that the algorithm M8 is suitable for the region. On the other hand we were limited by condition that the catalog should be complete for the magnitudes $M \geq \min\{M_0 - 2, M(20)\}$ (here M(20) corresponds to the magnitude threshoold adjusted in a region so that the average rate of occureuce of the main shocks with $M \geq M(20)$ is 20 per year). For the most of the regions and catalogs considered in the test of the algorithm M8 it led to selection of $M_0$ with variations less than 0.5.

## Test on independent data

Algorithm M8 was tested in the regions where the earthquake catalogs available are sufficiently complete. Recently we have managed to apply the algorithm M8 in the regions and for magnitudes $M_0$ mentioned in Table 1.

Let us describe the obtained results of the test on independent data in more details:

The territories where algorithm M8 was applied are listed in Table 1. They can be devided into three groups. The first corresponds to $M_0 = 8$ worldwide where the algorithm M8 was originally designed. The second group is formed by the regions where the only $M_0$ have been chosen and no other parameters of the algorithm was changed (regions 2-14). In the last group (regions 15-17) the catalogs of the regions have no data about main shocks with the occurrance rate of 20 per year in an area of diagnostics. Therefore the magnitude thresholds M(10) and M(20) were changed to M(1) and M(3), respectively. In region 17 the authors [9] have made readjustment of some other parameters of the algorithm.

The results of the test are summarized in two lines at the bottom of Table 1. Most of the strong earthquakes (90%) occured within the TIPs diagnosed by the algorithm M8. All together the TIPs cover less than 20%, and the Times of Expectation - about 10 % of a total space-time considered in a region. The strong earthquakes and the TIPs diagnosed are presented in Figures 1-12. In the left part of the figures the spacial distributions of the epicenters of the strong earthquakes and centers of the areas of



diagnostics are shown. In the right part the heavy lines and arrows under the time scale indicate TEs and origin times of strong earthquakes, respectively. Each light line points to the center the area where the TIP occurred.

The last two colomns present the total number of TIPs in a region and the number of those TIPs which were "successful". Ssuch are the majority of the TIPs. Most of them (about 75%) were confirmed and terminated during the first 3 years.

## Conclusions

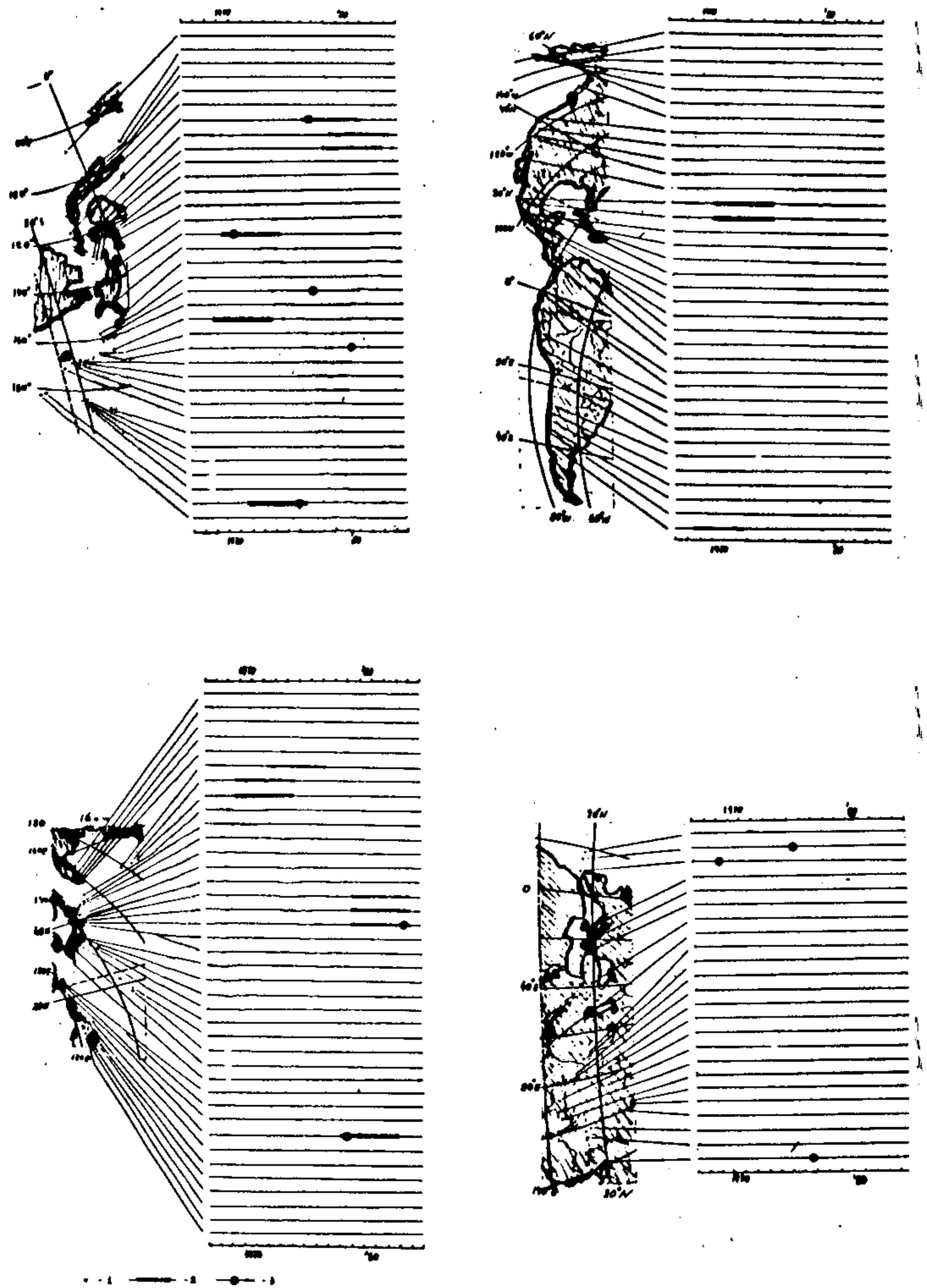
The nature of the regions considered is quite different from the view point of geodynamics: there are typical subduction zones (as the Kurils), ridges (as Baikal), transform faults (as San Andreas), and their junctions. There are: the Vrancea region (in the Carpathians) with the intermidiate depth earthquakes and the region of the Koyna reservoir with induced seismicity. The magnitude of a strong earthquake in a region $M_0$ varies from 8 to 4.9. It implies that the algorithm is reflecting rather universal features of the approach of a strong earthquake.

The results of the test on independent data give an arguement for reliability of the algorithm M8. We do not estimate the statistical significance, since there was some freedom in the choice of $M_0$. However, the results seem to justify the further test by the forward monitoring of TIPs.

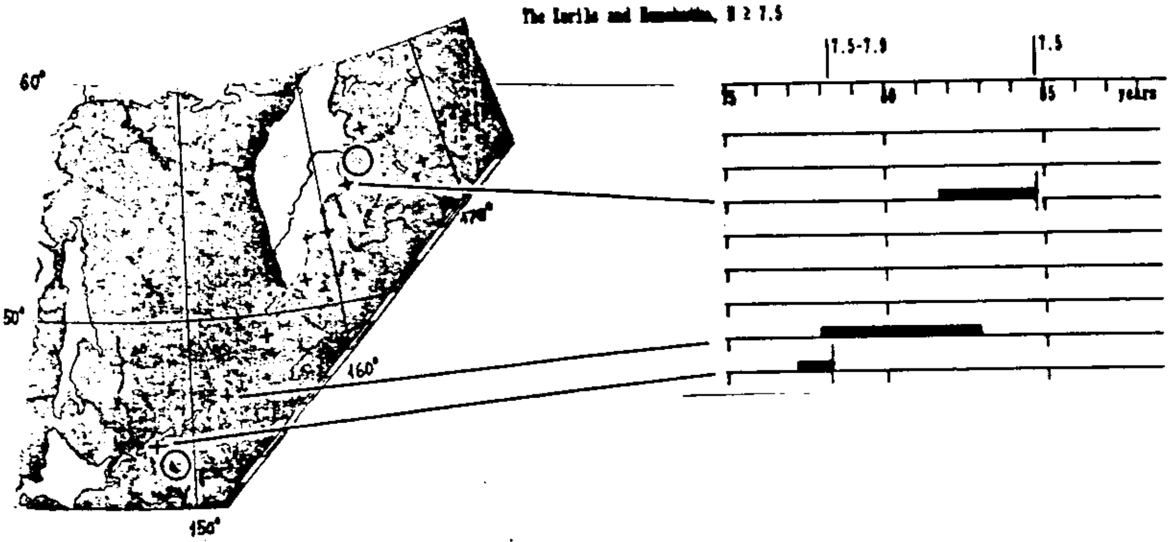
Table 1. The summary of the TIPs diagnosed by the algorithm M8

| Region | Mo | Time considered in diagnostics | Strong earthquakes: all | Strong earthquakes: within TIPs | Space-time volume (in mln.sq.km·year): of TIPs | of TS | total | Number of TIPs: all | S |
|---|---|---|---|---|---|---|---|---|---|
| 1. The world | 8.0 | 1967-1982 | 7 | 5 | 124.2 (5%) | 76.4 ( 3%) | 2588.8 | 16 | 7 |
| 2. Central America | 8.0 | 1977-1986 | 1 | 1 | 12.0 (16%) | 12.0 (16%) | 73.6 | 2 | 1 |
| 3. The Kurils and Kamchatka | 7.5 | 1975-1987 | 2 | 2 | 4.7 (17%) | 1.8 (7%) | 26.9 | 3 | 2 |
| 4. Southern America | 7.5 | 1975-1986 | 3 | 3 | 18.0 (18%) | 13.0 (13%) | 102.0 | 8 | 3 |
| 5. Western United States | 7.5 | 1975-1987 | - | - | 2.2 (5%) | 2.2 (5%) | 45.5 | 1 | 0 |
| 6. Southern California | 7.5 | 1947-1987 | 1 | 1 | 3.2 (12%) | 0.3 (1%) | 27.2 | 1 | 1 |
| 7. Western United States | 7.0 | 1975-1987 | 2 | 2 | 4.7 (24%) | 1.9 (10%) | 19.3 | 2 | 2 |
| 8. Baikal and Stanovoy range | 6.7 | 1975-1986 | - | - | 0 (0%) | 0 (0%) | 11.6 | - | - |
| 9. The Caucasus | 6.5 | 1975-1986 | 2 | 1 | 1.1 (12%) | 0.6 ( 7%) | 9.1 | 1 | 1 |
| 10. East of Central Asia | 6.5 | 1975-1987 | 5 | 4 | 3.2 (24%) | 1.5 (11%) | 13.2 | 6 | 5 |
| 11. North Eastern Tien Shan | 6.5 | 1963-1987 | 4 | 4 | 4.0 (27%) | 2.2 (15%) | 14.7 | 5 | 5 |
| 12. Western Turkmenia | 6.5 | 1979-1986 | - | - | 0 (0%) | 0 (0%) | 2.9 | - | - |
| 13. Apennines | 6.5 | 1970-1986 | 1 | 1 | 0.7 (10%) | 0.1 (1%) | 7.5 | 1 | 1 |
| 14. The Koyna reservoir | 4.9 | 1975-1986 | 1 | 1 | 0.1 (42%) | 0.1 (30%) | 0.3 | 1 | 1 |
| 15. The Himalayas with surroundings | 7.0 | 1970-1987 | 2 | 2 | 3.1 (8%) | 0.7 (2%) | 38.0 | 4 | 3 |
| 16. Vrancea | 6.5 | 1975-1986 | 2 | 2 | 1.0 (56%) | 0.5 (28%) | 1.8 | 2 | 2 |
| 17. Vancouver Island | 6.0 | 1957-1985 | 4 | 4 | 2.3 (20%) | 1.6 (14%) | 11.3 | 7 | 5 |
| Regions No.1-17 together | | | 36 | 32 (89%) | 18% | 10% | | 50 | 30 |
| Regions No.2-14 together | | | 21 | 19 (91%) | 18% | 10% | | 30 | 22 |

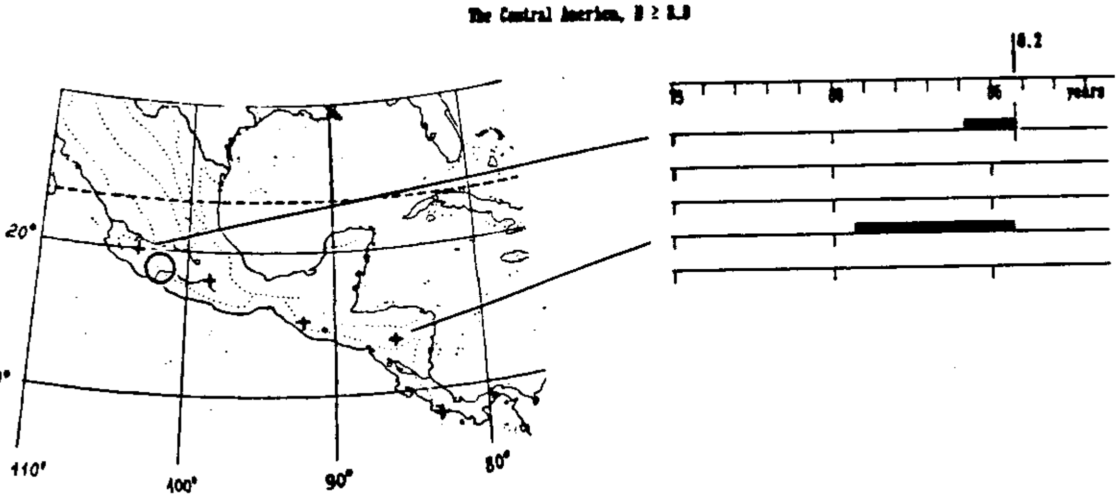
Note: The March 24th 1978 earthquake with M = 7 in North-Eastern Tien-Shan is presented both in lines 10 and 11.

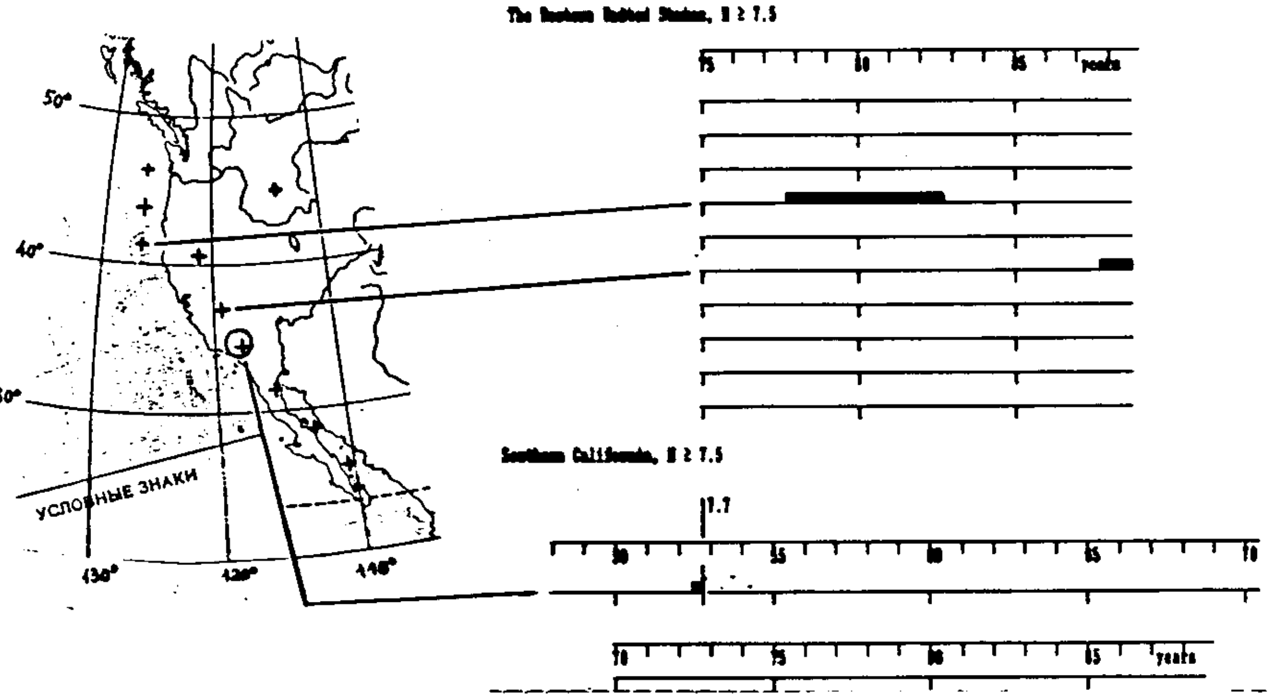


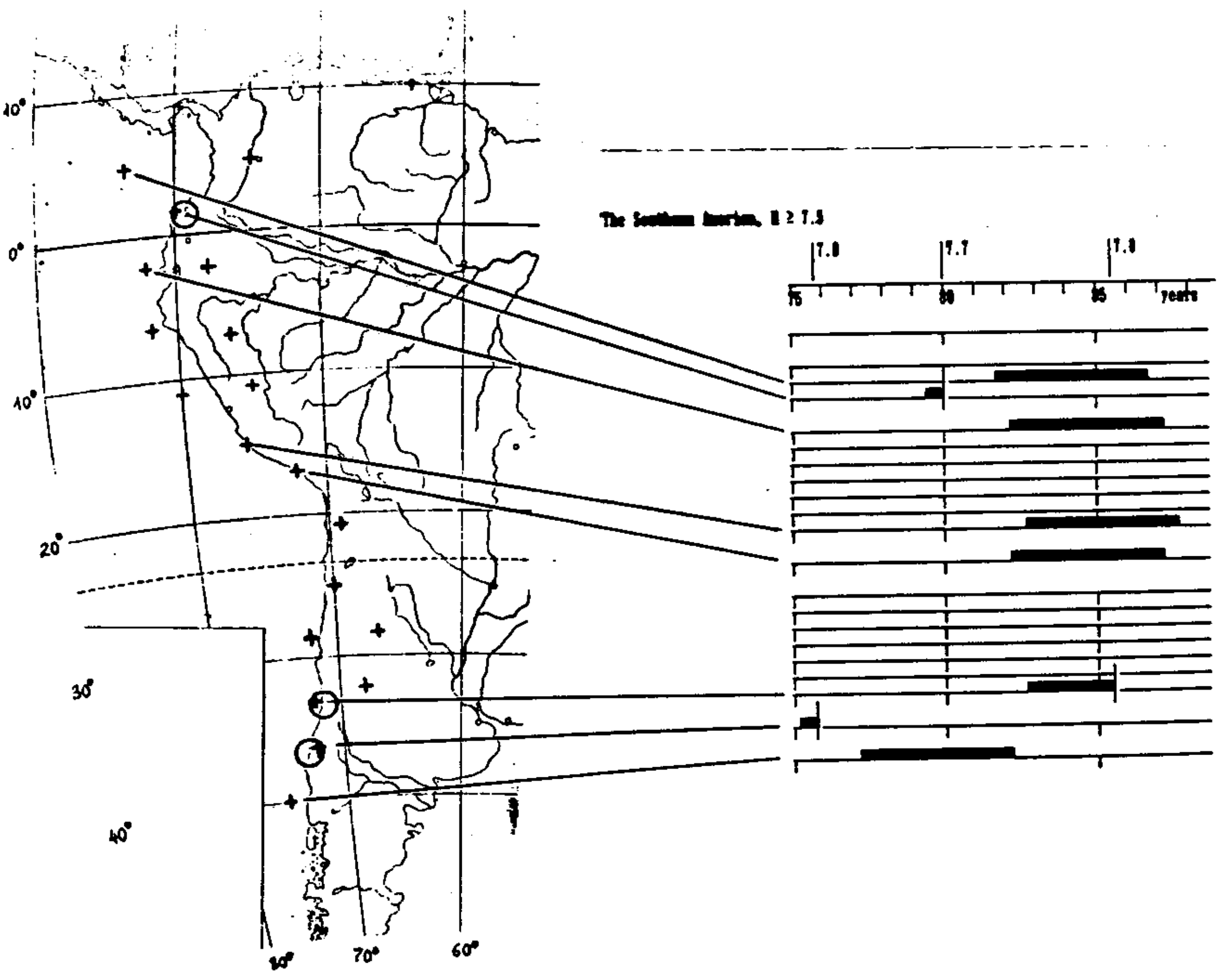
The Kurils and Kamchatka, M ≥ 7.5



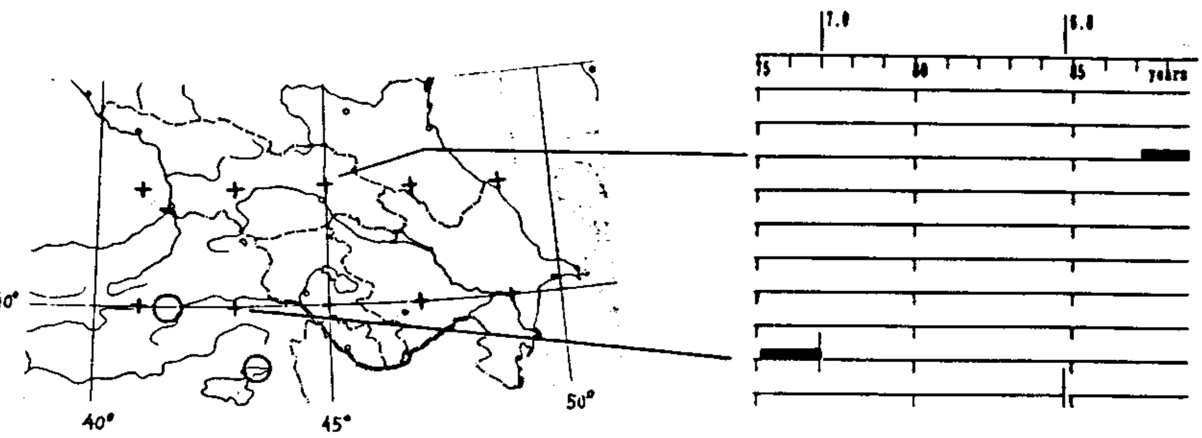

The Central America, M ≥ 8.0



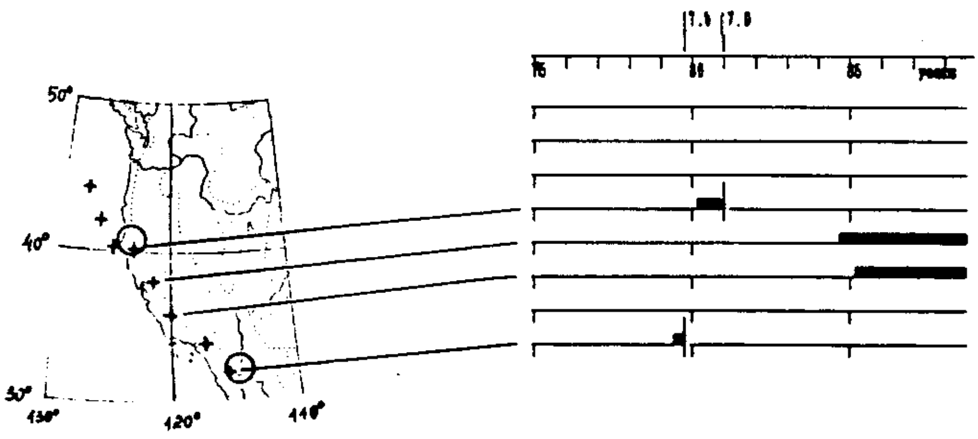

The Western United States, M ≥ 7.5
75
80
85
years
Southern California, M ≥ 7.5
7.7
50
55
60
65
70
70
75
80
85
years
50°
40°
30°
130°
120°
110°
УСЛОВНЫЕ ЗНАКИ


The Southern America, M ≥ 7.5
7.0
7.7
7.8
75
80
85
years
10°
0°
10°
20°
30°
40°
80°
70°
60°

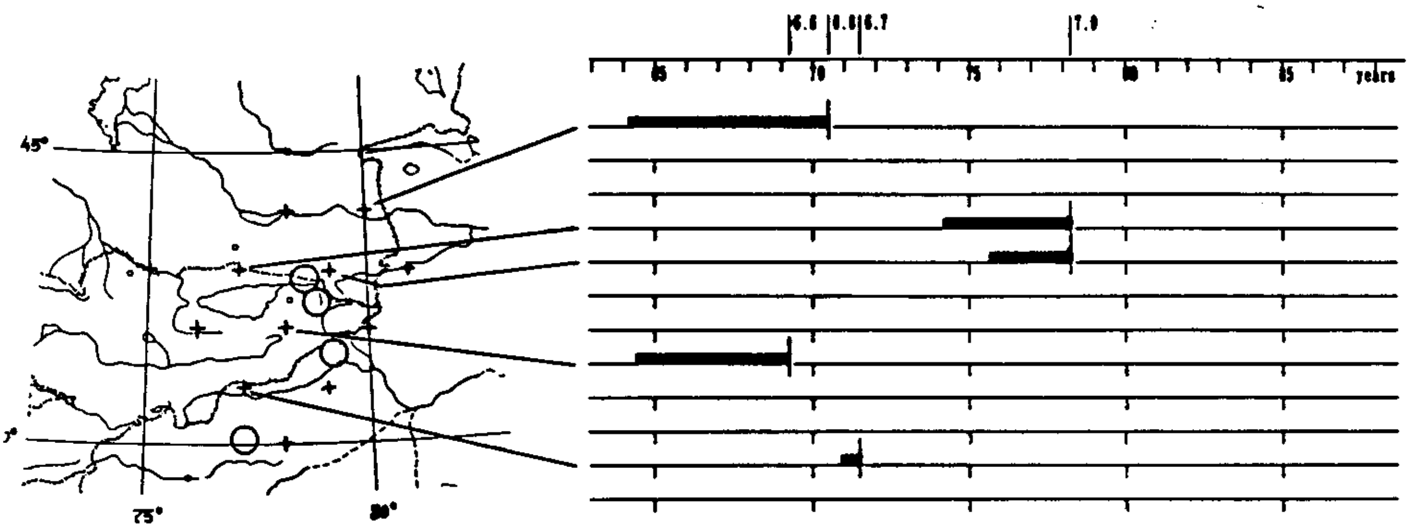
The Caucasus, M ≥ 6.5



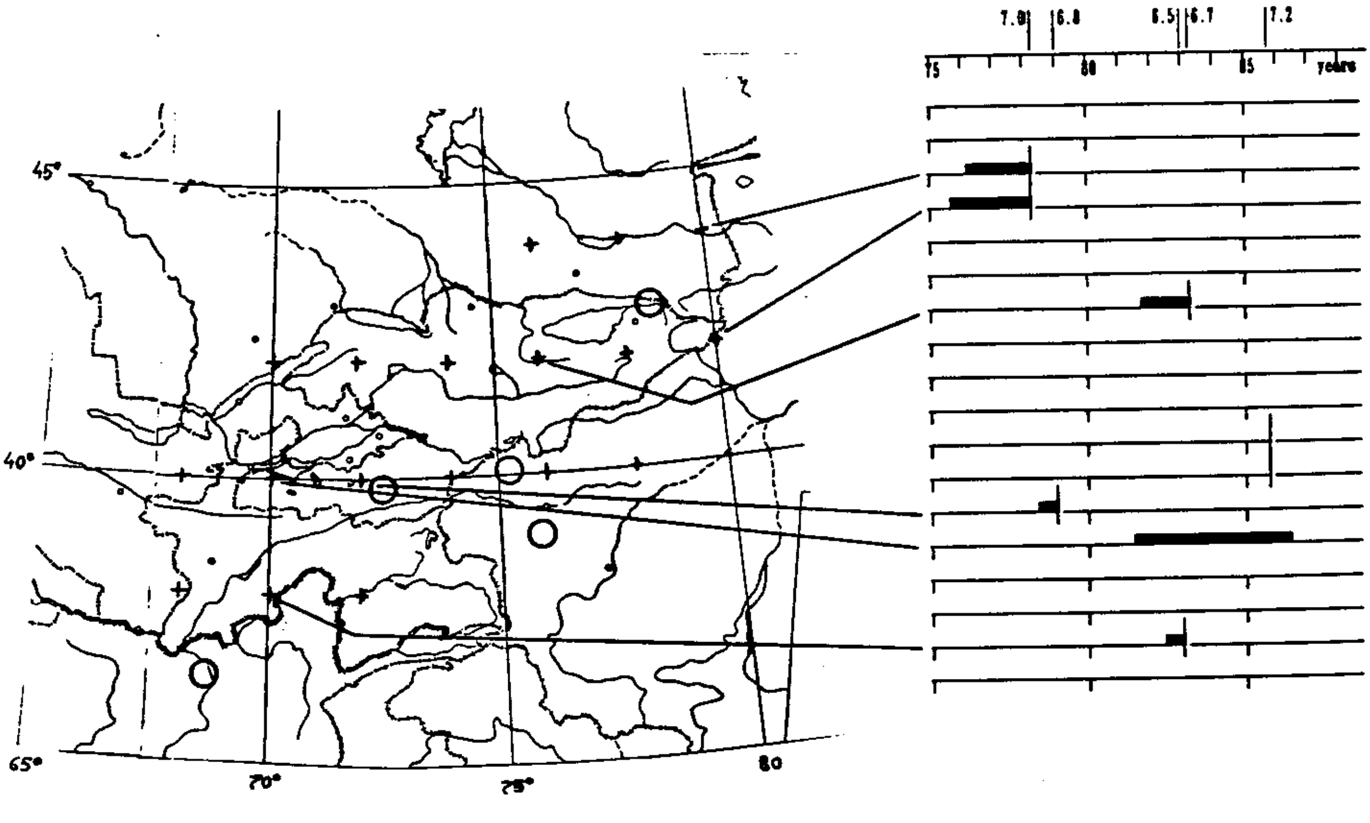

The Western United States, M ≥ 7.0

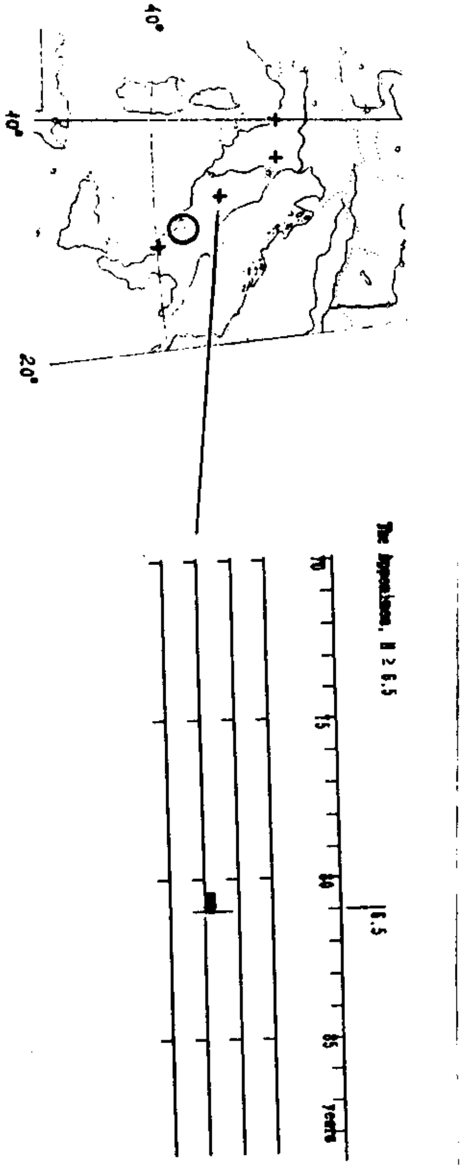


The North-Eastern Tien Shan, M ≥ 6.5




The Eastern Central Asia, M ≥ 6.5

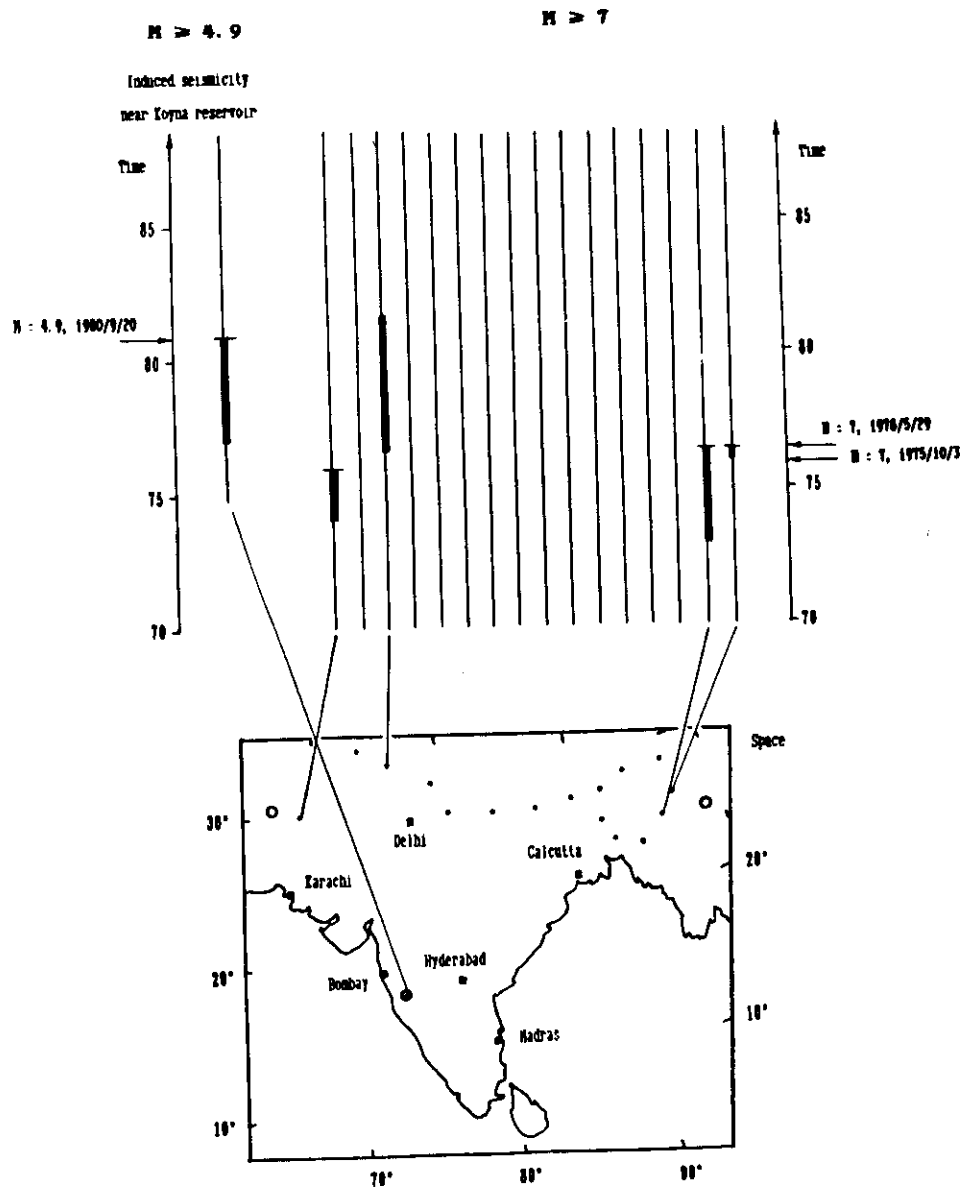




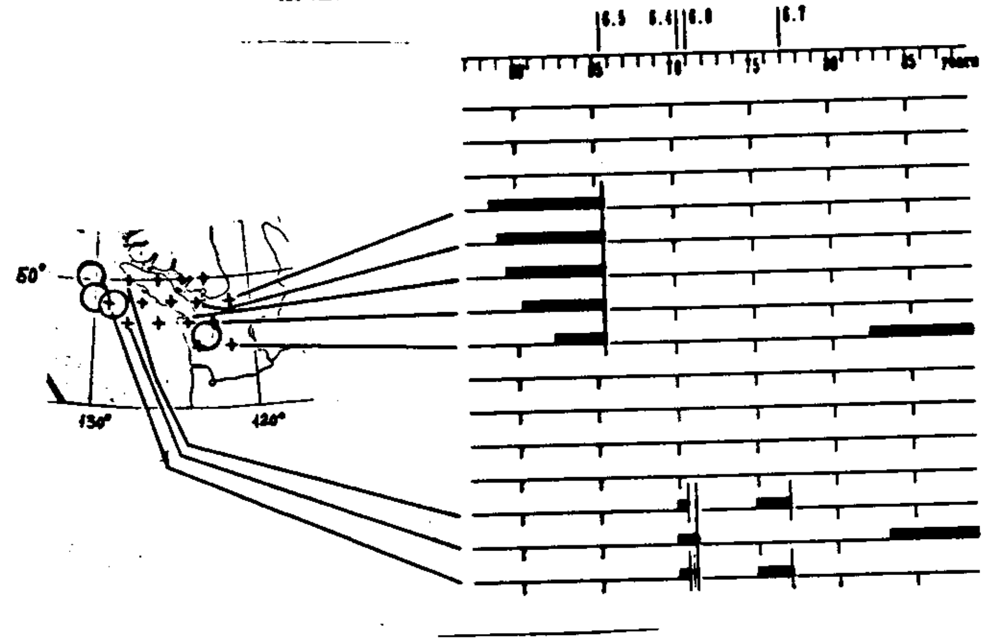
## The diagnosis of Times of Increased Probability (TIPs) of a strong earthquake in India and adjacent areas

Below are the centers of space windows for diagnosis (points) and epicenters of strong earthquakes (circles).

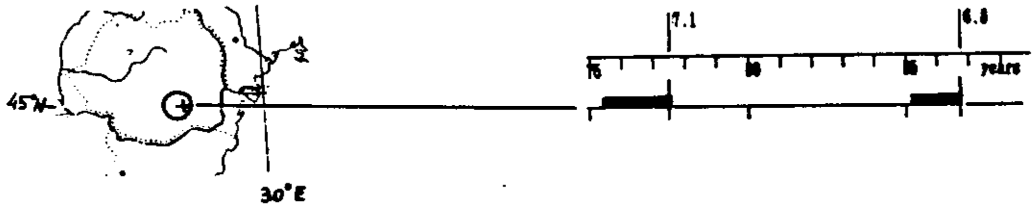
On top the TIP's diagnostics are presented: arrows marc the dates of strong earthquakes, heavy lines correspond to TIPs.



The Vancouver Island, M ≥ 6.0




The Vrancea region, M ≥ 6.5



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