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**Prediction of a Subsequent Large Earthquake**

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increases; earthquakes occur in clusters (swarms); the number of aftershocks following the intermediate events becomes larger. Normalized description of the features mentioned above, taking into account the level of seismic activity, allows to find out the similarity of premonitory phenomena in the regions with different seismotectonic conditions. Both these facts are in the base of algorithms of intermediate term prediction of strong earthquakes, tested in the different seismoactive regions as well as in prediction in advance. (Vladimir I. Keilis-Borok, Alexandre A. Soloviev (Eds.), 2003)

Both, the hypothesis of instability symptom in non-linear system and similarity of premonitory phenomena were used for designing the algorithm for the prediction of subsequent large earthquakes. It can be formulated as follows:

*Hypothesis.* The process of preparation of subsequent large earthquake occurred soon and not far from previous large one, appears in symptoms of instability, which are like to the preparation of the first large earthquake. These symptoms may appear in the aftershock sequence of the first large earthquake and in the preceding seismicity in the vicinity of its epicenter. The premonitory phenomena are similar after normalization for the earthquake of different magnitude and in the different regions.

### 1.2. Formulation of the problem

Consider a large earthquake with magnitude  $M$  and occurrence time  $t$ . The problem is to predict whether a subsequent large earthquake with magnitude  $M_1 \geq (M - a(M))$  will occur before the time  $(t + S(M))$  within distance  $R(M)$  of the epicenter of the first large earthquake; this may be a large aftershock or a subsequent large main shock.

To solve this problem we analyze the aftershocks of the first earthquake in the magnitude range between  $M$  and  $M - m_a$  during the first  $s$  days following the first earthquake, and the earthquakes in the magnitude range between  $M$  and  $(M - m_f)$  that occurred during  $S'(M)$  years before it. The aftershocks are counted within the same distance  $R(M)$ ; the preceding earthquakes are counted within a larger distance  $CR(M)$  (Fig 1).

### 1.3. Formulation of the problem in the normalized form.

In accordance with the hypothesis of the similarity it is necessary to found the way of normalization for all the parameters of the problem in order to make comparable the aftershock sequences of earthquakes of different magnitudes. It allows to use the algorithm without additional adaptation in the different regions. To do this the following well known facts are used:

The linear size  $R_0$  of the aftershock zone is proportional to size of source of earthquake. In accordance with Tsuboi (1956)

$$R_0(M) = 0.02 \times 10^{0.5M} \text{ [km];}$$

So we consider the circle with the radius  $R \sim R_0$ , where aftershocks and subsequent large earthquake are concentrated. The area of this circle is proportional to the magnitude  $M$  of the large earthquake. If we take into account Gutenberg-Richter law

$$N(m) \sim 10^{-bm};$$

and the fact, that value of  $b$  is close to 1, then the number of aftershocks with the magnitude  $m \geq M - m_a$ , is approximately the same for the earthquakes with the different magnitudes during the same periods of time. So the following way of normalization was chosen:

- a lower cutoff magnitude,  $M - m_a$ , of aftershocks is analyzed,  $m_a$  is constant;
- the area is a circle with radius  $R = CR_0 = C0.02 \times 10^{0.5M}$  [km];
- the magnitude of shocks predicted is  $M \geq M - M_a$ ;  $M_a$  is constant
- the period of time does not depend on magnitude of the first large earthquake.

#### *1.4. Formulation of the problem in terms of pattern recognition.*

Usually the number of large earthquake in the region with good reported aftershock sequence is not large, in the best reported regions this number is not more than several tens. In such case the methods of pattern recognition are preferable comparing with statistical methods. Pattern recognition methods were successfully used for design of algorithms for intermediate-term prediction of strong earthquakes. Algorithm CN used “Cora”, algorithm M8 “Hamming”.

To solve the problem of prediction of subsequent large earthquake pattern recognition algorithm “Hamming” is used, as it is simpler then “Cora” Then simpler is algorithm, then more stable is the result of recognition. The problem is formulated as follows in the terms of pattern recognition.

Let us define two types of objects:

Type A – large earthquake, which is followed by subsequent large shock;

Type B – single large earthquake.

Each object for recognition is described by vector of values of functions, presenting premonitory phenomena. It is necessary to find decision rule separating the objects of different type.

To find decision rule the learning material is used, i.e. objects of type A (earthquakes with SLE) and B (single earthquakes).

#### *1.5 Function representing premonitory phenomena.*

The success of recognition depends firstly on the quality of object description, i.e. choice of functions representing premonitory phenomena. Of course, the choice is not unique; nevertheless there are some common criteria of function quality in the pattern recognition:

1. Than better function separates the object than more effective it is for recognition.
2. Functions must reflect the physical features of objects;
3. Functions must reflect different features of objects.
4. The number of function must be not large.
5. Functions must be as simple as possible, with few parameters.
6. Functions must be reliably determined in the most of objects.

In accordance with the hypothesis on the process of the preparation of subsequent large earthquake we choose the functions reflecting the activity of aftershock sequence and its irregularity in space and time. All the functions must be normalized to be independent on the magnitude of the large main shock. Functions reflecting irregularity in time and space must be also normalized to the activity of certain aftershock sequence. There are some additional requirements to the functions: they must be determined reliably on the sequences with few aftershock, it is the cause why we do not use functions which require statistical procedures, such as slope of Gutenberg-Richter graph, or parameters of Omori law.

Seven of the characteristics referring to the aftershock sequence reflect the number of aftershocks, the total area of their sources, the largest distance from the main shock, and the irregularity of this sequence. One characteristic is the number of earthquakes in the time interval  $(t - S', t - s')$  preceding the first large earthquake, and one more reflects how strong is the first large earthquake.

The following functions were chosen:

Functions reflecting activity of aftershock sequence. We propose that large values are premonitory:

1. **N**, number of aftershocks with magnitude  $M \geq M - m$  during  $[t + s_1, t + s_2]$ ;
2. **S**, total equivalent source area of aftershocks with magnitude  $M \geq M - m$  in  $[t + s_1, t + s_2]$ , normalized by the equivalent source area of the main shock

$$S = \sum 10^{m_i - M}$$

where  $m_i$  is the magnitude of the  $i$ -th aftershock;

Functions reflecting irregularity of aftershock sequence in time. We propose that large values are premonitory:

3. **Vm**, variation of magnitude from event to event for aftershocks with magnitude  $M \geq M - m$  in  $[t + s_1, t + s_2]$

$$Vm = \sum |m_{i+1} - m_i|,$$

where  $m_i$  is the magnitude of the  $i$ -th aftershock;

4. **Vmed**, variation of average magnitude from day to day for aftershocks with magnitude  $M \geq M - m$  in  $[t + s_1, t + s_2]$

$$Vmed = \sum |\mu_{i+1} - \mu_i|,$$

where  $\mu_i$  is the average magnitude of aftershocks for the  $i$ -th day; and

5. **Rz**, abnormal activation of aftershock sequence (deviation from the Omori law) for aftershocks with magnitude  $M \geq M - m$  in  $[t + s_1, t + s_2]$

$$Rz = \sum (n_{i+1} - n_i)$$

where  $n_i$  is the number of aftershocks in  $[t + i, t + i + \tau]$ ; negative differences being neglected.

Function reflecting how fast aftershock activity decreases. Small value is premonitory:

6. **Vn**, variation in the number of aftershocks from day to day for aftershocks with magnitude  $M \geq M - m$  in  $[t + s_1, t + s_2]$

$$Vn = \sum |n_{i+1} - n_i|,$$

where  $n_i$  is the number of aftershocks for the  $i$ -th day;

The premonitory effect of small values for this function seems to be in contradiction with basic hypothesis, because function is the variation of number of aftershocks. Nevertheless, correspondingly to Omori law, the number of aftershock decreases from day to day. It becomes clear that the main input in the value of this function give first several days. So the function **Vn** reflects mainly how fast the aftershock activity decreases. Larger is **Vn**, faster decreases aftershocks. Now it is clear that small values of **Vn** are premonitory.

Function reflecting the spatial distribution of aftershocks

7. **Rmax**, largest distance between the main shock and the aftershock with magnitude  $M \geq M - m$  in  $[t, t + s_2]$  divided by  $R$ ;

This function reflects the concentration of aftershocks near main shock. We propose that its small value is premonitory.

Function reflecting seismic activity preceding first large earthquake.

8. *Nfor*, local activity before the main shock, i.e., number of earthquakes with magnitude  $M \geq M - m$  during  $[t - s_1, t - s_2]$  before the first large earthquake within distance of  $1.5R$ .

It is hard to guess small or large values of this function are premonitory, because activation as well as seismic quiescence are typical for the period of preparation of large earthquake. It depends on the parameters of function, nevertheless, we hope to find parameters making the function *Nfor* informative.

Function reflecting the magnitude of the first large earthquake.

9.  $Dm = M - M_0$

It could be proposed that strongest earthquake are not followed by SLE, though it is in contradiction with the hypothesis of similarity. Nevertheless, we try to use this function as it is very simple and reflects the physical feature of object not reflected by other functions.

We hope these functions are informative and allow us to solve the problem of prediction of SLE. The values of parameters will be chosen analyzing the learning material.

### 1.6. Learning material.

California & Nevada seismoactive region was chosen as experimental one for design the algorithm for prediction of SLE. The map of epicenters of earthquakes with magnitude 5 and more and the boundaries of the region are shown in the map (figure 2).

The reasons of this choice are the following:

1. Region is high seismic, several tens of earthquakes with magnitude more than 6 occurred in the reported period
2. There are earthquakes followed by SLE as well as single earthquakes.
3. There is representative catalog of earthquakes from 1932 for this region (Table 1)
4. There are many large earthquakes with good reported aftershock series, which contain information on SLE preparation.
5. Region California & Nevada has been already used for design of algorithms for earthquake prediction, in particularly CN, "Burst of aftershock", which were successfully applied in many other regions of the world. This fact confirms that seismicity of this region has features, which are typical for many other regions.

We choose all the large earthquakes in California & Nevada with magnitude 6.4 and more occurred during 1942- 1988 as learning material. The reason for choice is following.

The period of time 1932-1942 is excluded as earthquakes with magnitude less than 4 are not presented for Northern California in this period. It is seen from the map in figure 3. The one more reason is that the accuracy of magnitude determination is 0.5 in this period. It is seen from the table 1, it contains the number of earthquakes of different magnitude depending on time.

To choose the threshold value  $M_0$  we consider the dependence of  $\Delta M$  on  $M$ , where  $M$  is the magnitude of first large earthquake and  $\Delta M$  is the difference of  $M$  and magnitude of the strongest subsequent shock. It is shown in the figure 4. For magnitudes less than 6.4 values of  $\Delta M$  are distributed from -1 to 3 without gaps, as for magnitudes more than 6.4 two groups of values are observed: less than 1 or more



than 1.6. It is the reason why we choose threshold  $M_0=6.4$ . It provides the good separation of the objects for learning into two groups: if  $\Delta M \leq 1$ , the object is of A type, if  $\Delta M > 1$  the object is of B type.

To choose the time and space limits, consider the distribution  $\Delta T$  and  $\Delta R$  for all subsequent large shocks. It is shown in the figure 5a,b.  $\Delta T$  is given in days, and  $\Delta R$  is given in the units of  $R_0(M)$  – size of aftershock zone estimated by Tsuboi (1956). In the period from 40 days to 1.5 year one group of subsequent strong shocks occurred within  $R_0(M)$  and another group in the distance about  $2R_0(M)$  and more. We choose  $1.5 R_0(M)$  as a threshold value.

So we have chosen the parameters in the formulation of problem. We will predict the subsequent large earthquakes which

Differ less than 1 in magnitude from the first earthquake;

Occur within period from 40 days to 1.5 year after first earthquake;

Within  $1.5 R_0(M)$  from the epicenter of first earthquake.

During the period 1942-1988 26 earthquakes with magnitude  $M \geq 6.4$  occurred in California & Nevada (table 2). 5 of them were excluded, as they are close in time forshocks and aftershocks of other earthquakes. Out of the rest 21 earthquakes 4 have less than 10 aftershocks (all were single). 17 earthquakes have 10 and more aftershocks, 11 are single, and 6 ones are followed by SLE. So we have 6 objects of A type and 15 of B type. The small number of objects A is typical for other regions also, it is specific feature of the problem. Objects for learning are shown in the map (figure 6). Note, that single earthquakes and earthquakes followed by SLE occur in the same places, so the place can not be used for recognition.

### *1.7 Two steps of recognition*

Let us compare the activity of aftershock sequences of types A and B. In the plot (figure 7) the number of aftershocks and their total source area are shown. It is seen that larger values are typical for objects of type A, in particularly all the objects with few aftershocks ( $<10$ ) are of type B (single). This fact confirms the hypothesis about the process of preparation of SLE. Nevertheless, these two characteristics do not separate the objects. It is necessary to consider the set of characteristics and apply the pattern recognition technique.

The recognition is made in two steps. In the first step we consider only one function – number of aftershocks

(i) If the number of the aftershocks is less than  $D=10$ , the next large earthquake is not expected within the time and distance ranges mentioned above, whatever the other characteristics may be.

(ii) If this number is  $D=10$ , or more, we determine the set of characteristics of seismicity reflecting premonitory phenomena, then a pattern recognition technique known as the Hamming distance is used (Gvishiani et al., 1980).

The two steps of recognition are reasonable as this allows to classify the part of objects in the simplest way, improves the ratio of objects of type A and B, allows to determine functions describing irregularity of aftershock sequence in space and time.

### *1.8 Choice of numerical parameters for function representing premonitory phenomena*

Let us consider the set of function representing premonitory phenomena to choose the values of numeric parameters. The values of parameters are chosen to

divide the objects of types A and B in the best way. We divide the values of function into two parts “small” and “large” using 50% quintile, i.e. the number of objects with small and large value of the function must be approximately equal. In the figure 8 the choice of threshold of discretization is illustrated for function  $N$ . A objects are shown by rhombi, B objects – by triangles. Threshold is marked by dashed line, the numbers of objects A and B is shown left and right of threshold. All 6 A objects have large value of  $N$ , nevertheless, 3 B objects also have large  $N$ , even large than for A objects. The informativeness of the function  $N$  is illustrated by histogram, it riches 72%, that is close to maximum, taking into account the difference in the number of objects A and B.

The histograms for 8 function are shown in the figure 9. The typical values for all of them are as expected in accordance with the hypothesis of process of preparation of SLE.

Numerical parameters chosen for 8 of 9 function are shown in Table 3 as well as values typical for A objects, thresholds for discretization and informativeness.

Function  $Dm = M - M_0$  is not informative for recognition. This is shown in the figure 10. The threshold value 0.4 provides the division of objects closest to 50%. 3 A objects and 7 B objects have small value of  $Dm$ , and 3 A objects and 4 B objects have large value. The informativeness of function  $Dm$  is just 13%. I.e. SLEs are not less typical for strongest earthquakes, even some opposite tendency is observed. It is the reason to exclude function  $Dm$  from further consideration. Nevertheless, this fact is important, as it confirms the hypothesis of similarity.

### 1.9 Decision rule and results of learning

In accordance with Hamming algorithm we count for each object two numbers,  $n_A$  and  $n_B$ . They are numbers of function with values typical for objects of A type and for objects of B type. Now we can formulate the decision rule.

*Decision rule:* Earthquake is of type A (a subsequent large earthquake is expected) if it has more than 10 aftershocks and  $n_A - n_B \geq 3$ , in all other cases the earthquake is of type B (a subsequent large earthquake will not occur).

The decision rule allows recognize right type for 20 out of 21 large earthquakes in California & Nevada. There is only one error failure-to-predict, it is an earthquake occurred in 1979 in Southern California. The results of learning are presented in table 4 and in figure 6.

In qualitative terms, the occurrence of a subsequent large earthquake is predicted if the number of aftershocks and their total source area is large, the aftershock sequence is highly irregular in time, aftershocks are concentrated near the epicenter of the main shock, and the activity preceding the first large earthquake is low.

Two large earthquakes and their aftershocks are shown in the figure 11. First one, earthquake occurred May 25, 1980, is most typical A object; all 8 function votes for SLE. Second one, earthquake occurred June 9, 1908, is most typical B object; seven function votes against SLE. The difference in activity is good seen. In the first case number of aftershocks and their magnitudes are larger, activity lasts all 40 days with the periods of activation, aftershocks are concentrated near the epicenter of main shock. In the second case activity decreases fast, after 6 days there are no aftershocks, cloud of aftershocks cover larger area.

## II Test of algorithm for prediction SLE

The algorithm for prediction of SLE formulated above is the result of fitting in the learning material. The number of parameters is quite large respective to number of object for learning. The algorithm needs to be tested. Three steps of testing were carried out.

The first one is the test of stability of obtained result to variation of parameters of algorithm and to errors in input data. This series of test was carried out on the learning material.

The second one is the test of algorithm on the independent data – large earthquakes in different seismoactive regions of the world.

The third one is the prediction in advance with all prefixed parameters of algorithm.

### 2.1 Estimation of an effectiveness of the algorithm.

To compare the effectiveness of difference algorithm for earthquake prediction the method proposed by Molchan (1997) is used. The results of predictions can be characterized by two quantities,  $n$  and  $\tau$ . Here  $n$  is the relative number of the failures-to-predict among  $A$  objects, and  $\tau$  is the relative volume of alarm in the entire prediction space. In the problem of prediction of SLE the relative volume of alarm is calculated by simplest way: It is the number of alarms divided by the whole number of objects. For algorithm described in previous section these values are

$$n_0 = 1 / 6 \approx 0.16$$

$$\tau_0 = 5 / 21 \approx 0.24$$

Let us consider a plot where X axis is  $\tau$  and Y axis is  $n$  (figure 12).  $n$  and  $\tau$  change from 0 to 1. Any prediction algorithm is presented by point with coordinates  $(n, \tau)$ . The points  $(0, 1)$  and  $(1, 0)$  correspond to trivial strategies.  $(1, 0)$  is the strategy of “optimist”, i.e. alarm is never announced, but all large earthquakes are failure-to-predicted.  $(0, 1)$  is strategy of “pessimist” i.e. alarm is announced forever and all strong earthquake are predicted. The points of diagonal correspond to strategy of random guessing with different probability of alarm announcement.

Nontrivial algorithms are presented by points, that are under diagonal. As far is the point  $(n, \tau)$  from diagonal as effective is prediction algorithm.

The quantity

$$e = 1 - n - \tau$$

is a characteristic of prediction effectiveness. This value is equal to 0 for trivial strategy, it is  $0 < e \leq 1$  for nontrivial prediction algorithm. The effectiveness of algorithm for prediction of SLE in the learning material

$$e_0 = 1 - 0.16 - 0.24 = 0.6$$

### 2.2. Stability tests:

#### A. Variation of numerical parameters

In this series of experiments we change numerical parameters of the algorithm. Only one parameter is changed by time. For each set of parameters the values  $n$  and  $\tau$  are determined. The algorithm is considered as stable, if points  $(n, \tau)$  are close to point  $(n_0, \tau_0)$  corresponding the basic algorithm.

The following experiments were carried out:

- I. Variations of parameters for determination of objects.
  1. Magnitude of the first large earthquake  $M_0$  from 6.2 to 6.6, step 0.1 (4 experiments)
  2. Radius of circle  $R$ ;  $R=R_0$  and  $R=2R_0$  (2 experiments)
  3. Period of time  $S$ ,  $S=1\text{year}$ ,  $S=2\text{years}$  (2 experiments)
  4. Difference of magnitude for SLE from 0.4 to 1.5, step 0.1 (11 experiments)

Total: 19 experiments

The results are presented in the figure 13a. The basic algorithm is marked by asterisk, The dashed line - effectiveness level of basic variant, dotted lines – minimum and maximum of effectiveness in experiments. They are 0.51 and 0.76 respectively. The result of recognition is far from random one for all the experiments.

- II. Variation of parameters of decision rule.
  1. Exclusion of functions, one by time (8 experiments);
  2. Variation of threshold to declare of alarm  $n_A - n_B$  from 0 to 5 (5 experiments);

Total: 13 experiments.

The results are presented in the figure 13b. Minimum and maximum of effectiveness are 0.52 and 0.71 respectively. The result of recognition is far from random one for all the experiments.

Algorithm shows good stability to the variation of the numerical parameters. In some cases result is even better than for basic algorithm. Nevertheless, it is not a reason to reject chosen set of parameters, as “overfitted” algorithm shows usually poor results on the independent data (i.e. other than learning material).

### *B. Stability to the quality of input data*

The input data for prediction of SLE is earthquake catalog. It is known that errors in magnitude determination reach several decimal, in epicenter determination – decimals of degree (tens of kilometers). The natural question appears: What is the influence of the errors in catalog to the result of prediction?

This problem becomes extremely essential in case of prediction in advance in real time. We have to use quick data, but the quality of this data is poor comparing with routine catalogs. Re-determination of magnitudes and epicenters can change situation considerably. Some object can disappear, another appear, the type of object can change, the territory for prediction can change, etc. The purpose of the experiments described in this section is to understand what changes of result can be expected with changing of input data taking into account the real values of errors in catalog.

To estimate the value of errors two version of NEIC catalog were compared QDE and PDE. The difference in magnitude and location of epicenter was determined for the same events. The standard deviation was calculated. It was 0.14 for magnitude  $0.06^\circ$  for coordinates of epicenter.

The quick data for the past are not available. To model the situation of the prediction in real time we carried artificial errors to the catalog with learning material used for design of algorithm. The artificial errors were normally distributed. The parameter is the maximum value of error, it is equal to standard deviation multiplied by three. The errors were carried to magnitudes and epicenters simultaneously.

Five series of experiment were carried out, 10 experiments in series. The summary of experiments is presented in the table 5 and in figure 14. The basic

algorithm is marked by asterisk. Dashed line marks its level of effectiveness. In the most of experiments effectiveness is higher than 0.35. The average effectiveness of prediction, obtained in the experiments, is better than 0.35 in all series. The result is far from random one even with maximal errors in the catalog. This fact shows the stability of algorithm to the errors in the data. The average effectiveness of prediction in the second series of experiment, when value of errors corresponds to the observed one for NEIC, is 0.4. This value shows the expected level of effectiveness in the prediction in advance

### *2.3. Test on the independent data*

The next step in the testing of the algorithm for prediction of SLE is its application to the independent data. All parameters of algorithm have been fixed. Actually, just two things were fitted: the set of regions, and magnitude  $M_0$  for choice of first large earthquakes to be tested. Following 8 regions were chosen for retrospective test of algorithm (Vorobieva and Levshina, 1994, Vorobieva and Panza, 1993) (the value of  $M_0$  is given in parentheses):

Balkans (7.0),  
Pamir and Tien-Shan (6.4),  
Caucasus (6.4),  
Iberia and Maghrib (6.0),  
Italy (6.0),  
Baikal and Stanovoi Range (5.5),  
Turkmenia (5.5),  
Dead Sea Rift (5.0).

The reason of this choice is explained later.

The total number of large earthquake in these regions is 98, 10 of them were followed by SLE, 88 were single. 52 large earthquakes had less than 10 aftershocks, only one of them was followed by SLE, 51 were single. 46 large earthquakes had 10 or more aftershocks, 9 of them were followed by SLE, 37 were single. 8 out of 10 SLE were recognized correctly, 2 were missed. Total number of declared alarms were 12; 8 were true and 4 false. The effectiveness of the prediction is:

$$e = 1 - (2/10 + 12/98) \approx 0.68$$

This value is even better than in the learning material. It is connected with few number of alarms.

The result of retrospective test is given in Table 6.

#### *Choice of region.*

The formal definition of the algorithm enables it to be applied to any large earthquake, if a representative catalog is available. The algorithm was tested in all the regions, where data were available. It showed good applicability everywhere, excluding the Circumpacific subduction zones. Here the algorithm does not work.

Seismicity of the Pacific subduction zones differ from one observed in the regions listed above. The number of shallow earthquakes followed by SLE is 30-40% here, while it is less than 15% in the other regions, if the same  $R(M)$  and time intervals are used. The most important difference is that the occurrence of a subsequent large shock does not depend on the rate of events in the aftershock sequence of the first earthquake. For example, consider the Japanese earthquakes. There are 75 large, shallow earthquakes with magnitude  $M \geq 7.0$ . Of these, 29 have less than 10 aftershocks with magnitude  $m \geq M-3$  within the circle  $R(M)$  during the first 40 days, and 46 earthquakes had more than 10 aftershocks. The relative number of subsequent

large shocks is the same for earthquakes with few aftershocks and for earthquakes with many aftershocks: 11 of 29 and 16 of 46, respectively. This fact demonstrates that an algorithm based on the rate of events in the aftershock sequence will not work in such regions.

So far, the algorithm works quite well in all regions where representative catalogs are available, other than the Pacific subduction zones.

#### *Choice of cutoff magnitude $M_0$ .*

The magnitude  $M_0$  was usually chosen in accordance with the lowest magnitude completely reported, because the algorithm requires aftershocks with magnitude  $m \geq M-3$  to test an earthquake with magnitude  $M$ . But there are exclusions. In particular, the quality of data for California and Italy allows to decrease  $M_0$ . However the tests were carried out for all 9 regions with magnitudes  $M_0+0.2$  and  $M_0-0.2$ . (Table 6). As expected, higher cutoff magnitudes did not worsen the results: there are two errors (one false alarm and one failure-to-predict) in a total of 67 earthquakes in nine regions (Table 6). Lower cutoff magnitudes lead to considerable increases in the number of objects (large earthquakes) and errors. There are 18 errors (seven false alarms and eleven failures-to-predict) in a total of 171 earthquakes.

Let us estimate the effectiveness of prediction for “small” earthquakes ( $M_0-0.2 \leq M < M_0$ ). Total number of these events is 52, 9 were followed by SLE, only 1 is predicted, 4 alarms were declared.

$$e = 1 - (8/9 + 4/52) \approx 0.03$$

This result shows quality of random prediction.

The increase in number of failures-to-predict can be explained by the incompleteness of earthquake catalog, but there are three more false alarms, all in California (Table 6), that cannot be explained by the limited catalog. This fact shows that one must be careful when reducing  $M_0$ , even if the catalog is complete. This requires special investigation in each region.

#### *The results of 1989-2003.10 monitoring.*

All large earthquakes that occurred in the nine regions (Table 6) were monitored by the algorithm with prefixed parameters. (Levshina and Vorobieva 1992, Vorobieva, 1999) The results of the *advance predictions* are given in Table 7.

26 large earthquake were tested, 7 were followed by SLE, 5 were successfully predicted. 7 alarms were declared. Up to now 22 predictions were correct, and there were 4 errors: 2 false alarms and 2 failures-to-predict. The effectiveness of the algorithm for prediction of SLE in advance

$$e = 1 - (2/7 + 7/26) \approx 0.45$$

It turns out even better than expected value 0.4

As predictions in advance were made with all prefixed parameters it is possible to estimate their statistical significance. Let us estimate the probability of getting such a result by chance. The probability of guessing five or more subsequent large earthquakes from a total of seven among twenty six cases, using seven alarms, is:

$$\varepsilon = [C_{19}^2 C_7^5 + C_{19}^1 C_7^6 + C_{19}^0 C_7^7] / C_{26}^7 \approx 0.56\% ,$$

where  $C_n^k$  are binomial coefficients.

It is possible that there are regions among those selected, to which the algorithm is not applicable. Accordingly we test how the level of statistical significance,  $\varepsilon$ , is changed when the number of aftershock sequences,  $N$ , is varied. We do not change the numbers of alarms and successes. The following table shows that  $\varepsilon$  is stable when  $N$  is varied:

$\Delta N$	1	0	-1	-2
$\varepsilon, \%$	0.43	0.56	0.70	0.86

So the result can be considered statistically significant at the 99% level.

### III Case histories

We wish to discuss several case histories of prediction for series of large earthquakes occurring in southern California. (Levshina and Vorobieva, 1992), Caucasus (Vorobieva, 1994), and the Dead Sea Rift zone.

#### 3.1. Joshua Tree – Landers – Northridge, southern California.

The Joshua Tree earthquake occurred 23 April, 1992, and had a magnitude of  $M=6.3$ . The map of its aftershocks with magnitude  $m \geq 3.3$  used for prediction are shown in Fig.15. This earthquake had a high rate of aftershocks (54 aftershocks with  $m \geq 3.3$ ), so it produced an alarm for an earthquake with  $M \geq 5.3$  within the distance  $R(6.3)=42$  km, within 1.5 years of Joshua Tree. The voting of functions after Joshua Tree is shown in Table 8. The subsequent Landers earthquake occurred within this distance,  $R(6.3)=42$ , 64 days after Joshua Tree.

The Landers earthquake of 28 June, 1992, with  $M=7.6$ , was then tested for the occurrence of a subsequent large shock. Its aftershocks with magnitude  $m \geq 4.6$  were used for prediction, as shown in Fig. 15. The aftershock sequence had few aftershocks (20 aftershocks with  $m \geq 4.6$ ), but they were strong and had a large total equivalent source area. It was predicted (Levshina and Vorobieva, 1992) that an earthquake with  $M \geq 6.6$  would occur within the distance  $R(7.6)=199$  km and within 1.5 years of the Landers earthquake; this alarm expired on 12 December, 1993. The voting of functions after Landers is shown in Table 8. The subsequent Northridge  $M=6.8$  earthquake occurred within this distance, but 19 days after the expiration of the alarm, so that prediction was counted as a false alarm.

The Northridge earthquake of 17 January, 1994 was also tested for the occurrence of a subsequent earthquake with magnitude  $M \geq 5.8$ . Its aftershocks with magnitude  $m \geq 3.8$  used for prediction are shown in Fig.15. In spite of many aftershocks (77 events with magnitude  $m \geq 3.8$ ), the algorithm did not identify an alarm. It predicted that an earthquake with  $M \geq 5.8$  would not occur within the distance  $R(6.8)=75$  km, within 1.5 years, and it was confirmed by observation. The voting of functions after Northridge is shown in Table 8.

#### 3.2.. Gulf of Aqaba earthquakes in 1993-1995, Dead Sea Rift.

The August 3, 1993 earthquake in the Gulf of Aqaba occurred and had a magnitude of 5.8. The map of its aftershocks with magnitudes  $m \geq 2.8$  used for prediction is shown in Fig.16. This earthquake had 171 aftershocks and produced an alarm. It was predicted that an earthquake with  $M \geq 4.8$  would occur within a distance

$R(5.8)=22$  km, within 1.5 years. The voting of functions after this earthquake is shown in Table 8. An earthquake with magnitude 4.9 occurred 92 days after the first one.

The largest earthquake in this region, with magnitude 7.3, occurred in the same place, two years later (on November 22, 1995). The map of its aftershocks is shown in Fig.16. It had 14 aftershocks with magnitude  $m \geq 4.3$ , and did not produce an alarm. It was predicted that an earthquake with  $M \geq 6.3$  would not occur within the distance  $R(7.3)=135$  km, within 1.5 years, and there has been no such earthquake. The voting of functions after this earthquake is shown in Table 8.

The 1993 earthquake, which produced an alarm, was probably a precursor of the 1995 earthquake, but the time between them was more than two years. Later in 1996, two earthquakes with magnitudes 5.0 and 5.4 occurred, but unfortunately the data to test these earthquakes still are not available.

### 3.3. *Rachi, Caucasus, Georgia, FSU earthquakes of 1991.*

The Rachi earthquake of April 29, 1991 had a magnitude of  $M=7.1$ . The map of its aftershocks is shown in Fig.17. This earthquake had a large aftershock sequence: 77 events with magnitude  $m \geq 4.1$ , with a large total equivalent source area. This earthquake produced an alarm. It was predicted that an earthquake with magnitude  $M \geq 6.1$  would occur within the distance  $R(7.1)=105$  km, within 1.5 years. This prediction was confirmed by the June 15, 1991, magnitude 6.6 earthquake.

This later earthquake was also tested. The map of its aftershocks is shown in Fig.17. It was predicted that an earthquake with magnitude  $M \geq 5.6$  would not occur within the distance  $R(6.6)=59$  km, within 1.5 years, and there was no such earthquake.

The case of the Rachi earthquake of April, 1991 is important, because all known large earthquakes since 1900 with magnitudes  $M \geq 6.4$  (12 events) in the Caucasus were single. The aftershock sequences of the seven Caucasian earthquakes in 1962-1992 are shown in Fig 18 as functions of time. The April, 1991 Rachi earthquake produced considerably more aftershocks than the others, while the subsequent large earthquake, in June, 1991, produced a normal amount of aftershocks.

## Conclusions

The algorithm for predicting a subsequent large shock was successfully applied in different seismic regions of the world. 26 large earthquakes were tested for the last 14 years, producing only four errors: two false alarms and two failures-to-predict. The statistical significance of advance prediction is 99%. The algorithm can be used in other seismic regions, if the data are available. Of course, the algorithm must be tested first on the past data for each region.

While applicable in rather diverse regions, the algorithm fails in subduction zones. Prediction of subsequent large earthquakes there is among the main unsolved problems in this line of research.



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## Figure captions

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Table 1. Distribution magnityde of earthquakes in Clifornia & Nevada 1900-1988, NEIC

[illegible]

Table 1. Continuation

M	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0
1931	.	.	.	.	.	2	.	1	.	.	.	1	.	1	1	.	.	.	.	.	.	.	.	.	.	.
1932	91	1	46	.	.	21	.	12	.	.	1	.	.	.	.	.	.	1	.	.	.	1	.	.	.	.
1933	51	13	23	47	28	59	28	32	10	8	10	2	2	1	.	1	1	.	.	.	.	.	.	.	.	.
1934	104	3	55	.	.	44	.	21	.	.	6	.	1	.	.	1	1	2	.	.	1	.	.	.	.	.
1935	174	.	91	.	.	54	.	15	1	.	6	.	.	.	1	1	.	.	.	.	.	.	.	.	.	.
1936	131	.	48	.	.	39	1	8	.	.	3	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.
1937	109	.	52	.	.	31	.	12	.	.	2	1	.	.	1	1	.	.	.	.	.	.	.	.	.	.
1938	85	.	64	.	.	33	.	14	.	.	4	.	2	1	.	.	.	.	.	.	.	.	.	.	.	.
1939	114	.	65	.	1	38	.	22	2	.	5	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.
1940	88	.	97	.	.	57	2	28	5	1	6	1	5	.	.	2	.	.	1	.	.	.	.	.	.	.
1941	99	.	65	.	1	47	.	14	.	1	4	2	4	.	2	3	.	1	1	.	.	.	.	.	.	.
1942	108	6	68	3	2	57	4	22	.	.	7	.	2	.	.	.	.	1	.	.	.	.	.	.	.	.
1943	92	4	60	9	4	34	4	11	1	1	.	1	3	.	.	.	.	.	.	.	.	.	.	.	.	.
1944	50	43	33	32	16	14	7	6	4	1	3	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1945	28	29	28	13	11	9	11	5	2	1	3	3	1	1	.	1	.	.	.	.	.	.	.	.	.	.
1946	73	54	62	60	20	25	11	6	6	4	4	4	2	1	.	.	1	.	.	.	.	.	.	.	.	.
1947	106	73	45	35	23	15	20	11	6	5	7	3	1	.	.	.	1	.	.	.	.	.	.	.	.	.
1948	83	54	43	28	19	16	7	10	8	4	1	1	.	.	.	1	.	1	.	.	.	.	.	.	.	.
1949	100	88	76	48	28	20	6	11	5	4	3	1	.	2	1	.	1	.	.	.	.	.	.	.	.	.
1950	83	67	77	37	39	29	15	10	13	4	.	.	3	1	.	.	.	.	.	.	.	.	.	.	.	.
1951	72	52	37	18	27	14	7	6	2	7	2	2	.	.	1	1	.	1	.	.	.	.	.	.	.	.
1952	62	55	46	35	53	74	53	45	24	11	7	3	3	4	2	3	.	1	.	.	.	.	.	1	.	.
1953	184	94	69	43	34	17	10	5	3	4	2	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.
1954	124	99	76	49	48	65	54	41	22	14	14	8	5	3	3	2	2	.	1	3	1	1	.	.	.	.
1955	93	58	43	44	44	35	34	17	13	4	3	4	5	.	.	.	.	.	.	.	.	.	.	.	.	.
1956	81	56	46	27	35	27	29	36	46	26	18	3	2	3	1	3	1	1	.	1	.	.	.	.	.	.
1957	70	65	40	39	26	12	12	6	9	1	2	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1958	65	47	46	27	22	21	13	11	9	2	1	.	1	.	1	.	.	.	.	.	.	.	.	.	.	.
1959	96	74	56	38	30	36	22	13	9	2	1	2	1	1	1	1	1	.	.	.	.	.	.	.	.	.
1960	65	38	48	28	27	23	5	7	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.

Table 1. Continuation

M	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0
1961	78	57	53	31	26	22	6	8	3	2	2	4	3	1												
1962	80	46	43	35	26	14	7	3	5	6	2	1	1	1												
1963	67	66	49	35	18	30	15	13	12	6	5	1	1	.	1	.	.	.	.	.	.	.	.	.	.	.
1964	64	46	42	20	17	13	9	27	9	4	5	3	3	1	.	.	1	.	.	.	.	.	.	.	.	.
1965	65	30	32	7	18	22	31	21	13	12	3	3	.	1	1	.	.	.	.	.	.	.	.	.	.	.
1966	61	48	32	18	16	27	31	20	17	4	3	1	1	.	.	.	1	1	.	.	.	.	.	.	.	.
1967	62	47	31	15	18	14	20	15	17	4	1	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.
1968	138	101	58	28	18	21	35	36	15	4	5	1	.	1	1	.	.	1	.	.	.	.	.	.	.	.
1969	127	68	47	23	13	27	25	22	20	27	18	14	3	5	4	1	.	.	.	.	.	.	.	.	.	.
1970	91	68	38	22	13	14	26	8	13	3	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.
1971	183	132	116	48	46	36	28	18	18	9	5	3	.	.	2	.	.	1	.	.	.	.	.	.	.	.
1972	101	63	46	32	14	20	7	7	8	4	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.
1973	57	34	20	25	13	9	13	8	7	8	1	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.
1974	39	20	33	17	9	17	9	12	5	4	2	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.
1975	67	39	32	18	19	24	24	10	12	9	8	5	1	2	1	.	.	.	.	.	.	.	.	.	.	.
1976	60	51	37	15	19	11	8	10	5	6	2	1	1	1	.	.	.	.	.	1	.	.	.	.	.	.
1977	88	50	43	26	17	15	7	4	5	5	4	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1978	125	99	64	37	25	18	12	17	8	4	2	2	1	1	1	.	.	.	.	.	.	.	.	.	.	.
1979	155	131	83	44	31	29	24	10	5	8	4	5	2	2	1	1	.	.	.	.	1	.	.	.	.	.
1980	327	262	198	121	86	49	25	18	19	16	9	4	2	4	3	1	1	2	1	.	.	1	.	.	.	.
1981	136	94	78	44	22	12	16	17	8	5	.	.	.	.	2	.	1	.	.	.	.	.	.	.	.	.
1982	129	92	55	33	34	18	16	14	3	3	3	2	3	1	.	.	.	.	.	.	.	.	.	.	.	.
1983	204	159	112	83	40	30	18	14	8	4	2	5	5	3	1	1	.	1	.	.	.	.	.	.	.	.
1984	143	116	68	53	46	28	22	10	8	4	2	1	2	1	.	.	2	.	.	.	.	.	.	.	.	.
1985	105	95	63	39	24	13	9	11	7	3	2	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.
1986	190	167	113	58	41	27	24	13	15	8	4	2	1	3	3	1	.	1	.	.	.	.	.	.	.	.
1987	174	121	69	38	23	20	15	7	6	3	.	1	1	1	.	2	.	1	1	.	.	.	.	.	.	.
1988	138	83	65	35	14	12	13	5	4	3	3	2	4	1	.	.	.	.	.	.	.	.	.	.	.	.

Table 2. Large earthquakes in California & Nevada  $M \geq 6.4$ , 1942 - 1988.

<i>First large earthquake</i>						<i>Largest subsequent earthquake</i>		
Date yyyy/mm/dd	Time	Epicenter	$M$	$R$ , km	$N$ <i>aft</i>	$\Delta M$	$r/R_0$	$\Delta T$ , days
Earthquakes followed by SLE, type A								
1954/7/6	11:13	39.42N; 118.53W	6.8	50	66	-0.4	0.61	163.00
1954/8/24	05:51	39.58N; 118.45W	6.8	50	36	-0.4	0.72	114.22
1968/4/9	02:28	33.18N; 116.12W	6.4	31	50	0.3	0.81	384.87
1979/0/15	23:16	32.63N; 115.33W	7.0	63	28	0.6	0.89	237.18
1980/5/25	19:44	37.56N; 118.82W	6.7	44	109	0.8	0.13	492.67
1983/5/2	23:42	36.21N; 120.31W	6.7	44	51	0.7	0.20	80.12
Single earthquakes, $N_{aft} \geq 10$ , type B								
1942/10/21	16:22	32.97N; 116.00W	6.5	35	30	2.0	0.56	240.00
1948/12/4	23:43	33.93N; 116.38W	6.5	35	21	2.4	0.12	404.23
1952/7/21	11:52	35.00N; 119.02W	7.7	141	39	1.8	0.00	540.49
1954/12/16	11:07	39.32N; 118.20W	7.2	79	28	1.7	0.19	340.39
1956/2/9	14:32	31.75N; 115.92W	6.8	50	103	1.8	0.23	90.89
1966/9/12	16:41	39.42N; 120.15W	6.4	31	27	1.9	0.58	88.80
1971/2/9	14:00	34.40N; 118.40W	6.5	35	154	1.6	0.24	44.37
1980/6/9	03:28	32.22N; 114.98W	6.4	31	19	2.9	1.18	484.62
1980/11/8	10:27	41.11N; 124.25W	7.2	79	13	1.9	1.16	455.07
1986/7/21	14:42	37.53N; 118.44W	6.5	35	99	2.3	0.34	58.72
1987/11/24	13:15	33.01N; 115.84W	6.7	44	20	2.0	0.41	64.57
Single earthquakes, $N_{aft} < 10$ , type B								
1951/1/24	07:17	32.98N; 115.73W	6.4	31	6	1.9	1.06	315.36
1954/11/25	11:16	40.27N; 125.63W	6.8	50	1	3.0	1.09	531.74
1954/12/21	19:56	40.78N; 123.87W	6.6	39	2	2.5	1.20	251.25
1976/11/26	11:19	41.28N; 125.70W	6.8	50	7	2.1	1.39	164.53
Excluded as close in time foreshocks and aftershocks								
1952/7/21	12:05	35.00N; 119.00W	6.4	31	115	0.5	0.06	540.48
1954/12/16	11:11	39.50N; 118.00W	7.1	70	34	1.6	0.16	340.38
1956/2/15	01:20	31.50N; 115.50W	6.4	31	48	1.4	0.00	192.61
1980/5/25	16:33	37.60N; 118.84W	6.5	35	224	0.6	0.12	492.81
1987/11/24	01:54	33.08N; 115.77W	6.5	35	44	1.8	0.58	65.04

Notes:  $M$  - magnitude;  $R = 1.5 R_0$ , km – radius of circle for aftershock selection;  $N_{aft}$  - number of aftershocks during 40 days;  $\Delta M$  – magnitude difference between first large earthquake and its largest subsequent earthquake;  $r / R_0$  - normalized distance between epicenters of first large earthquake and its largest subsequent earthquake;  $\Delta T$ , days – time between first large earthquake and its largest subsequent earthquake.

Table 3. Typical values, effectiveness and numerical parameters of 8 functions.

Function	Value Typical for A	Effecti- vennes %	$m$	Values of parameters			Threshold values	
				$s_1$ , hrs	$s_2$ , days	$\tau$ , days		
<i>N</i>	large	72	3	1	10	-	24	-
<i>S</i>	large	55	2	1	10	-	0.1	-
<i>Vm</i>	large	25	3	1	40	-	0.41	-
<i>Vmed</i>	large	30	3	1	40	-	0.7	2.6
<i>Rz</i>	large	25	3	10 days	40	10	0	-
<i>Vn</i>	small	63	3	1	40	-	0.98	-
<i>Rmax</i>	small	30	2	-	2	-	0.23	-
<i>Nfor</i>	small	63	1	5 years	3 mon.	-	2	-

Earthquake		Magnitude	Values of function and type of value								Voting	Result of recognition
#	date	$M$	$N$	$S$	$V_m$	$V_{med}$	$R_z$	$V_n$	$R_{max}$	$N_{for}$	$n_A - n_B$	Type
Earthquakes followed by SLE, type $A$												
1	1954/07/06	6.8	41 $A$	0.27 $A$	0.325 $B$	4.27 $A$	0.59 $A$	0.92 $A$	0.18 $A$	0 $A$	6	$A$
2	1954/08/24	6.8	24 $A$	0.17 $A$	0.372 $B$	2.60 $A$	0.13 $A$	0.88 $A$	0.13 $A$	0 $A$	6	$A$
3	1968/04/09	6.4	34 $A$	0.11 $A$	0.462 $A$	1.84	4.25 $A$	0.93 $A$	0.45 $B$	1 $A$	5	$A$
4	1979/10/15	7.0	25 $A$	0.27 $A$	0.744 $A$	0.54 $B$	0.00 $B$	0.92 $A$	0.59 $B$	0 $A$	2	$B$
5	1980/05/25	6.7	76 $A$	0.75 $A$	0.479 $A$	3.57 $A$	0.58 $A$	0.66 $A$	0.18 $A$	1 $A$	8	$A$
6	1983/05/02	6.7	35 $A$	0.08 $B$	0.495 $A$	2.00	0.00 $B$	0.98 $A$	0.10 $A$	0 $A$	3	$A$
Number of errors												1
Single earthquakes, $N_{aft} \geq 10$ , type $B$												
7	1942/10/21	6.5	17 $B$	0.20 $A$	0.404 $B$	1.37	0.22 $A$	1.23 $B$	0.73 $B$	4 $B$	-3	$B$
8	1948/12/04	6.5	12 $B$	0.01 $B$	0.412 $A$	0.20 $B$	2.00 $A$	1.25 $B$	0.12 $A$	4 $B$	-2	$B$
9	1952/07/21	7.7	22 $B$	0.08 $B$	0.458 $A$	3.00 $A$	1.67 $A$	1.32 $B$	0.27 $B$	0 $A$	0	$B$
10	1954/12/16	7.2	13 $B$	0.05 $B$	0.408 $B$	0.45 $B$	0.58 $A$	1.16 $B$	0.22 $A$	2 $B$	-4	$B$
11	1956/02/09	6.8	66 $A$	1.37 $A$	0.306 $B$	4.23 $A$	0.33 $A$	0.99 $B$	0.40 $B$	2 $B$	0	$B$
12	1966/09/12	6.4	15 $B$	0.05 $B$	0.595 $A$	1.10	0.00 $B$	1.20 $B$	0.00 $A$	0 $A$	-1	$B$
13	1971/02/09	6.5	65 $A$	0.08 $B$	0.346 $B$	1.55	0.00 $B$	0.84 $A$	0.42 $B$	0 $A$	-1	$B$
14	1980/06/09	6.4	15 $B$	0.02 $B$	0.327 $B$	0.15 $B$	0.00 $B$	0.93 $A$	0.58 $B$	4 $B$	-6	$B$
15	1980/11/08	7.2	10 $B$	0.01 $B$	0.430 $A$	0.10 $B$	0.00 $B$	1.30 $B$	0.95 $B$	2 $B$	-6	$B$
16	1986/07/21	6.5	73 $A$	0.60 $A$	0.482 $A$	2.44	0.00 $B$	0.70 $A$	0.28 $B$	4 $B$	1	$B$
17	1987/11/24	6.7	12 $B$	0.01 $B$	0.350 $B$	0.20 $B$	0.00 $B$	0.58 $A$	0.16 $A$	1 $A$	-2	$B$
Number of errors												0
Single earthquakes, $N_{aft} < 10$ , type $B$												
18	1951/01/24	6.4	6 $B$									$B$
19	1954/11/25	6.8	1 $B$									$B$
20	1954/12/21	6.6	2 $B$									$B$
21	1976/11/26	6.8	7 $B$									$B$
Number of errors												0



Table 5. Stability of Algorithm to errors in catalog.

series	Magnitude		Epicenter		Effectiveness	
	Max error	Standard deviation	Max error, deg	Standard deviation, deg	1- $n$ - $\tau$	Average 1- $n$ - $\tau$
1	0.2	0.066	0.1	0.033	0.34 $\pm$ 0.57	0.49
2	0.4	0.133	0.2	0.066	0.32 $\pm$ 0.47	0.40
3	0.6	0.2	0.3	0.1	0.06 $\pm$ 0.61	0.36
4	0.8	0.266	0.4	0.133	0.09 $\pm$ 0.56	0.36
5	1.0	0.333	0.5	0.166	0.07 $\pm$ 0.57	0.37

Table 6. Retrospective test of the algorithm.

Region	Mo	Total M≥Mo	With few aftershocks, Single #/Err	Tested by pattern recognition		
				Total #	Single #/Err	With the next shock #/Err
Learning						
California	6.4	21	4/0	17	11/0	6/1
Retrospective test						
Pamir & Tien-Shan	6.4	12	4/0	8	7/1	1/0
Caucasus	6.4	5	0/0	5	5/0	0/0
Baikal & Stanovoi r.	5.5	6	4/0	2	2/1	0/0
Iberia & Maghrib	6.0	13	11/0	2	1/0	1/0
Dead Sea rift	5.0	11	10/0	1	1/0	0/0
Turkmenia	5.5	12	7/1	5	4/0	1/1
Balkans	7.0	19	7/0	12	9/1	3/0
Italy	6.0	20	9/0	11	8/1	3/0
<b>Total retr. test</b>		<b>98</b>	<b>52/1</b>	<b>46</b>	<b>37/4</b>	<b>9/1</b>
<b>Total</b>		<b>119</b>	<b>56/1</b>	<b>63</b>	<b>48/4</b>	<b>15/2</b>
<b>Total test M<sub>0</sub>+0.2</b>		<b>67</b>	<b>31/0</b>	<b>36</b>	<b>26/1</b>	<b>10/1</b>
<b>Total test M<sub>0</sub>-0.2</b>		<b>171</b>	<b>90/6</b>	<b>81</b>	<b>62/7</b>	<b>19/5</b>

Table 7. The results of 1989 - 2003.10 monitoring.

<i>Origin Earthquake</i>		<i>Will a subsequent shock occur?</i>	<i>Note</i>	<i>Outcome of prediction</i>
<b><i>California</i></b>				
Loma-Prieta, 10/18/1989	7.1	NO	No shocks with $M \geq 6.1$	Confirmed
Mendocino 7/13/1991	6.9	NO	No shocks with $M \geq 5.9$	Confirmed
Mendocino 8/17/1991	7.1	NO	No shocks with $M \geq 6.1$	Confirmed, first step
Joshua Tree 4/23/1992	6.3	YES	Landers is predicted $M=7.6$	Confirmed
Landers 6/28/1992	7.6	YES	Northridge $M=6.8$ occurred 19 days after end of alarm	False alarm
Northridge 1/17/1994	6.8	NO	No shocks with $M \geq 5.8$	Confirmed
Mendocino 4/25/1992	7.1	NO	No shocks with $M \geq 6.1$	Confirmed
Mendocino 9/1/1994	7.1	NO	Earthquake with $M=6.8$ occurred	Failure, first step
Mendocino 2/19/1995	6.8	NO	No shocks with $M \geq 5.8$	Confirmed, first step
California-Nevada border 9/12/1994	6.3	YES	Earthquake with $M=5.5$ occurred	Confirmed
Hector Mine 10/16/1999	7.4	NO	No shocks with $M \geq 6.4$	Confirmed
<b><i>Caucasus</i></b>				
Iran 6/20/1990	7.7	NO	No shocks with $M \geq 6.7$	Confirmed
Rachi 7.1 4/29/1991		YES	Earthquake with $M=6.6$ occurred	Confirmed
Rachi 6/15/1991	6.6	NO	No shocks with $M \geq 5.6$	Confirmed
Erzincan 3/13/1992	6.8	YES	No shocks with $M \geq 5.8$	False alarm
<b><i>Pamir &amp; Tien-Shan</i></b>				
Kazakhstan 8/19/1992	7.5	NO	No shocks with $M \geq 6.5$	Confirmed
China 11/19/1996	7.1	NO	No shocks with $M \geq 6.1$	Confirmed

<i>Origin Earthquake</i>		<i>Will a subsequent shock occur?</i>	<i>Note</i>	<i>Outcome of prediction</i>
<b><i>Turkmenia</i></b>				
Iran 5/10/1997	7.5	NO	No shocks with M $\geq$ 6.5	Confirmed, first step
Turkmenia 6/12/2000	7.5	NO	No shocks with M $\geq$ 6.5	Confirmed.
<b><i>Iberia &amp; Maghrib</i></b>				
Morocco 5/26/1994	6.0	NO	No shocks with M $\geq$ 5.0	Confirmed
<b><i>Dead Sea Rift</i></b>				
Gulf of Aqaba 8/3/1993	5.8	YES	Earthquake with M=4.9 occurred	Confirmed
Gulf of Aqaba 11/22/1995	7.3	NO	No shocks with M $\geq$ 6.3	Confirmed
<b><i>Italy</i></b>				
Assisi 9/26/1997	6.4	YES	Earthquake with M=5.4 occurred	Confirmed
Friuli 4/12/1998	6.0	NO	No shocks with M $\geq$ 5.0	Confirmed
Molise 10/31/2002	5.9	YES	Monitoring till 1/5/2004	
<b><i>Balkan &amp; Asia Minor</i></b>				
Izmit Turkey 9/17/1999	7.8	NO	Earthquake with M=7.5 occurred	Failure
Turkey 11/12/1999	7.5	NO	No shocks with M $\geq$ 6.5	Confirmed

Table 8. Voting of functions for Joshua Tree, Landers, Northridge, Gulf of Aqaba, and Rachi earthquakes.

Earthquake	N	S	Vn	Vm	Vmed	Rz	Rmax	Nfor	Voting
Joshua-Tree	yes	no	yes	yes	yes	no	yes	yes	6:2 YES
Landers	no	yes	yes	yes	-	yes	yes	yes	6:1 YES
Northridge	yes	yes	yes	yes	yes	no	no	no	5:3 NO
1993 Aqaba	yes	yes	yes	yes	yes	yes	no	yes	7:1 YES
1995 Aqaba	no	no	yes	no	no	yes	no	yes	3:5 NO
Apr 1991 Rachi	yes	yes	yes	yes	yes	yes	no	yes	7:1 YES
Jun 1991 Rachi	no	no	no	yes	yes	no	yes	yes	4:4 NO

# Prediction of a subsequent strong earthquake: Formulation of the problem

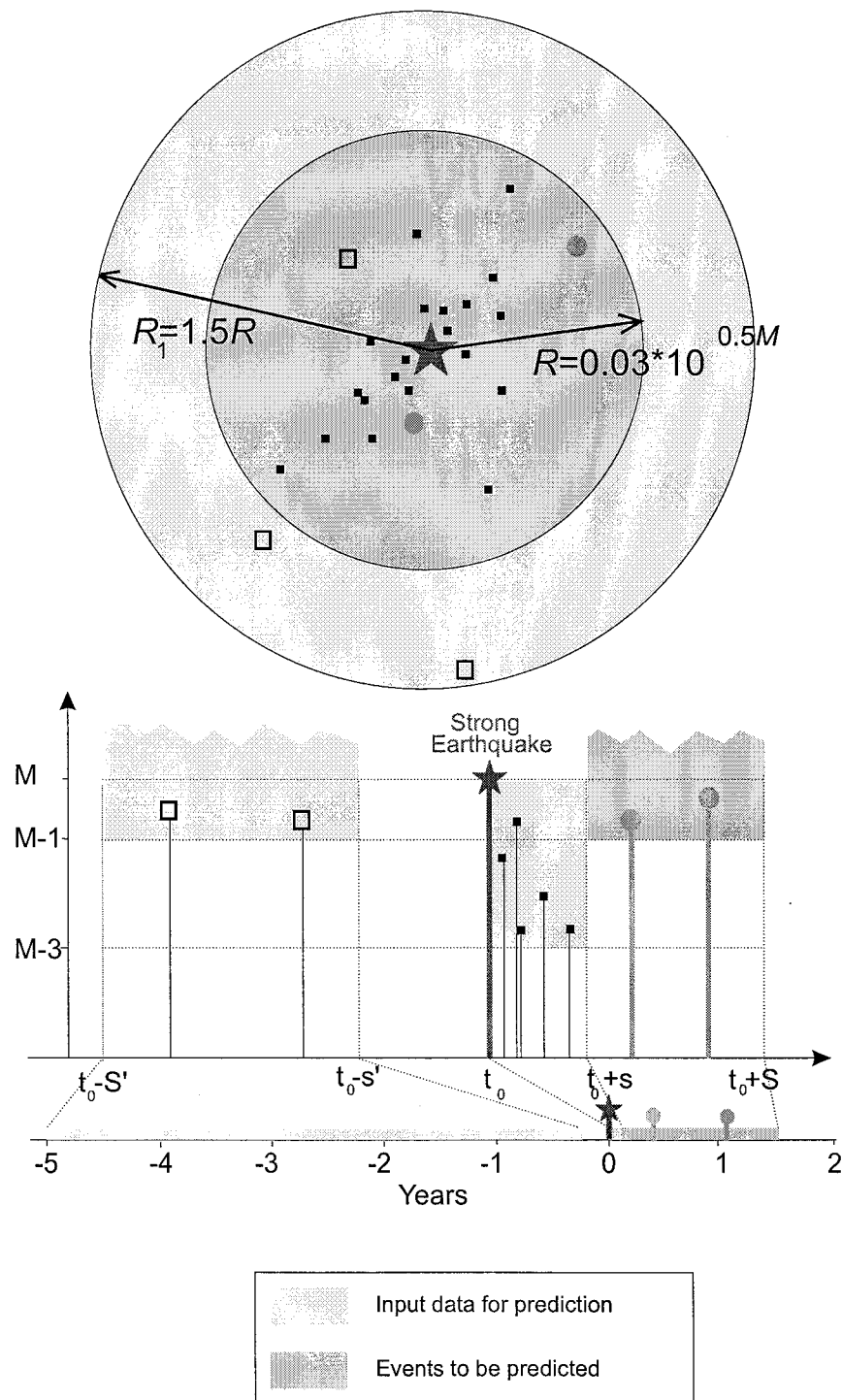


Figure 1

# California & Nevada: Sesmicity $M > 5$ , 1932-1988

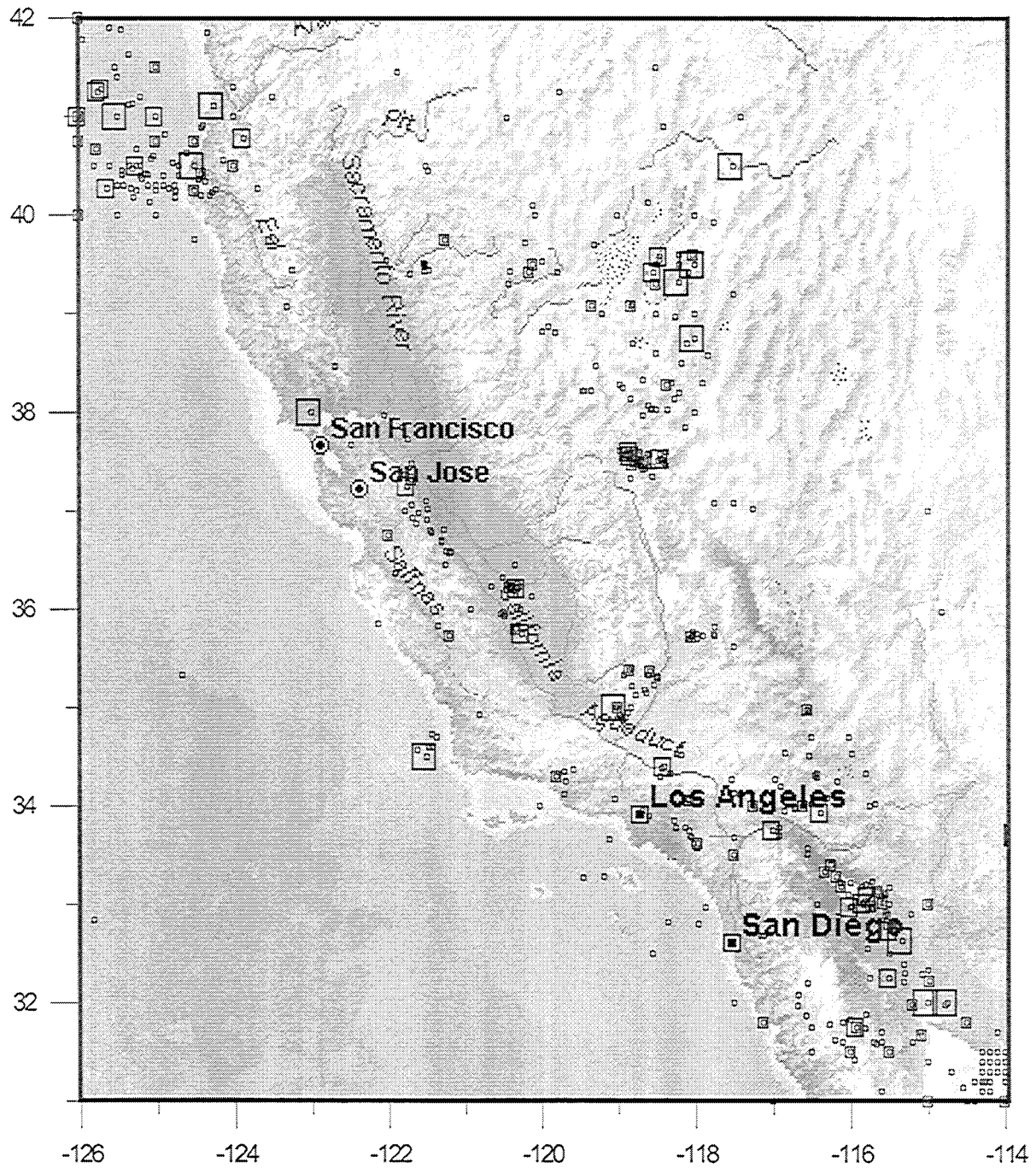


FIGURE 2

# California & Nevada: Sesmicity $3 < M < 4$ 1932-1942

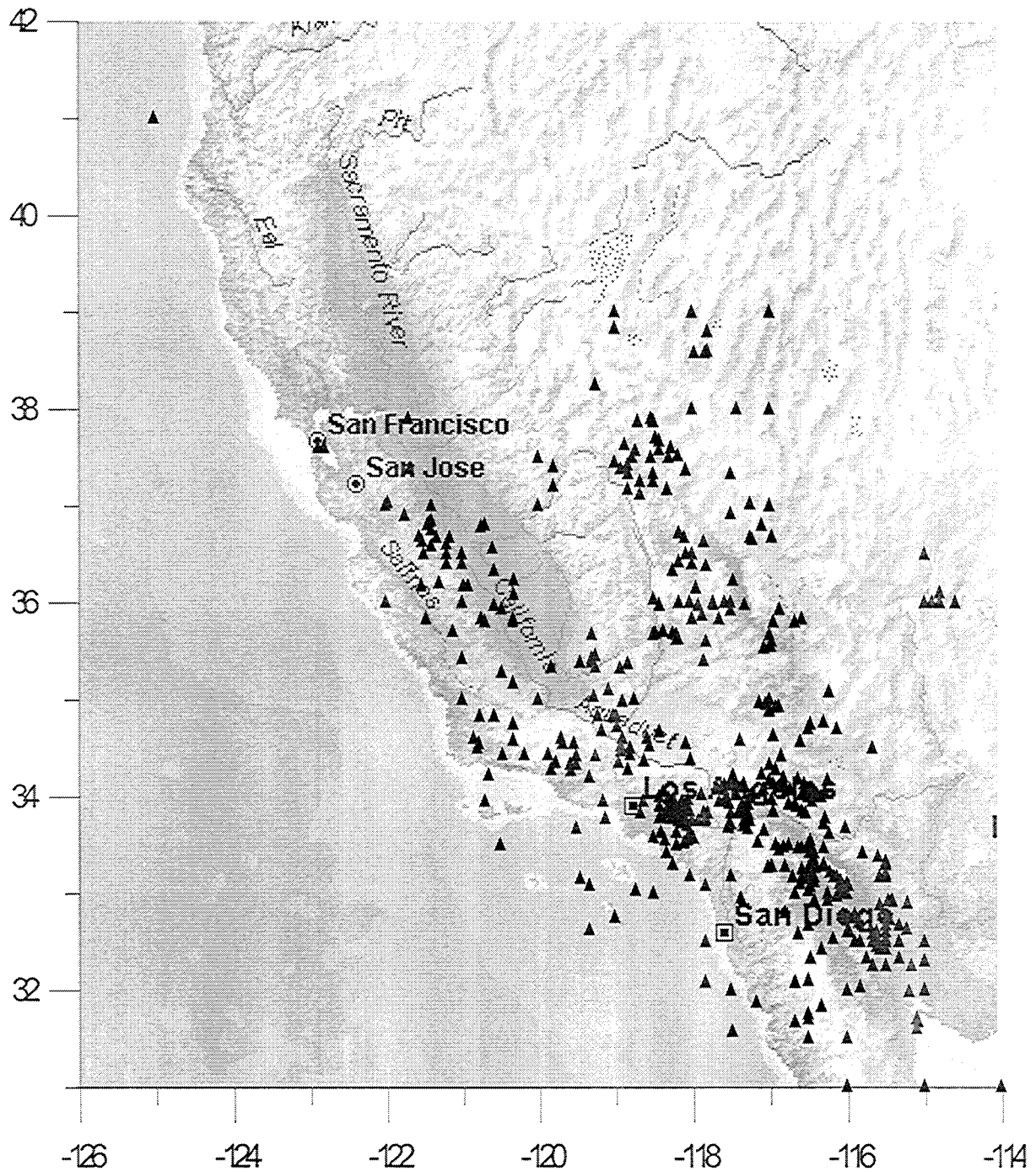


Figure 3

# Bath diagram for California & Nevada earthquakes

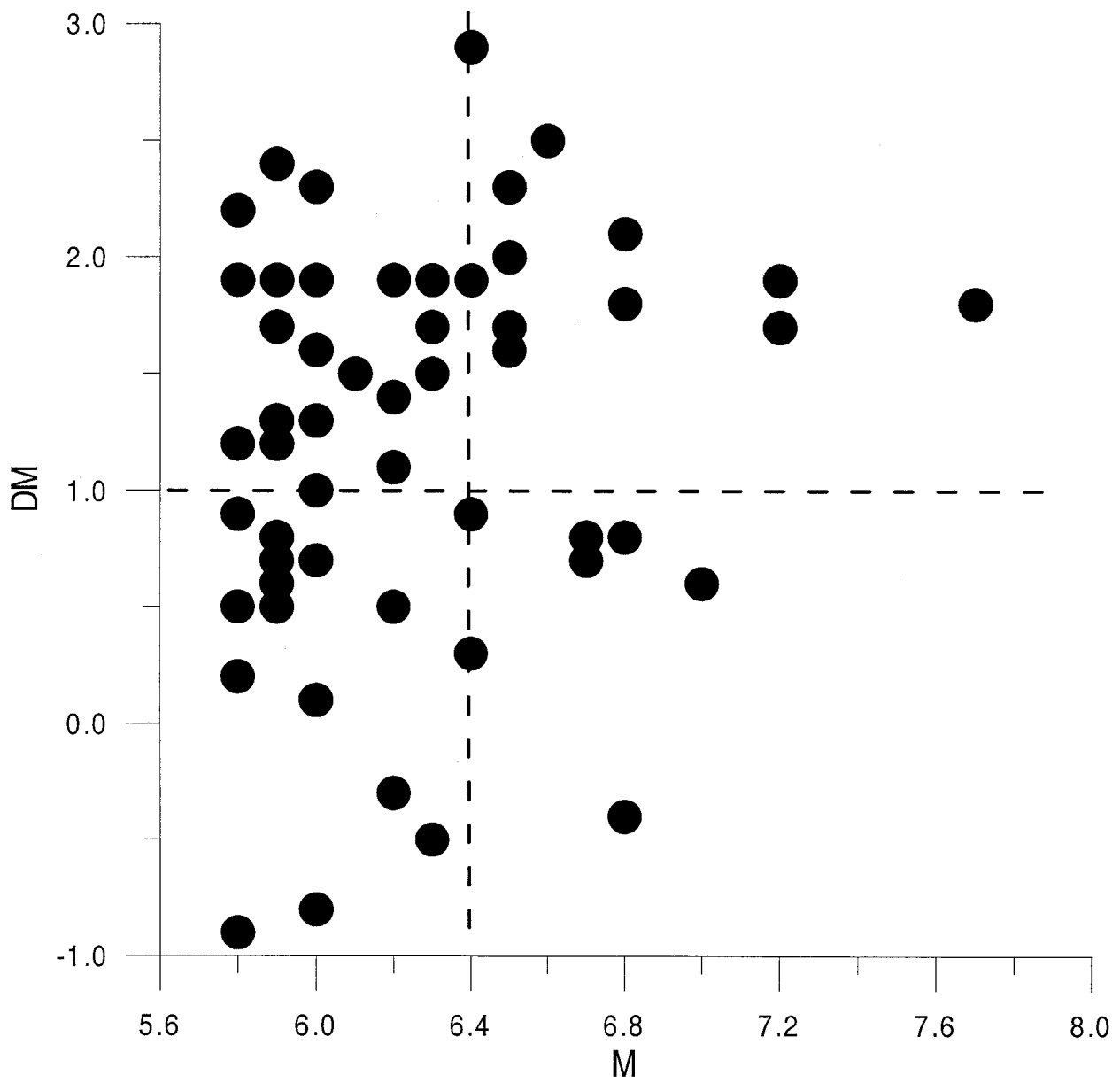


Figure 4

## Determining of time and spase parameters in formulation of the problem

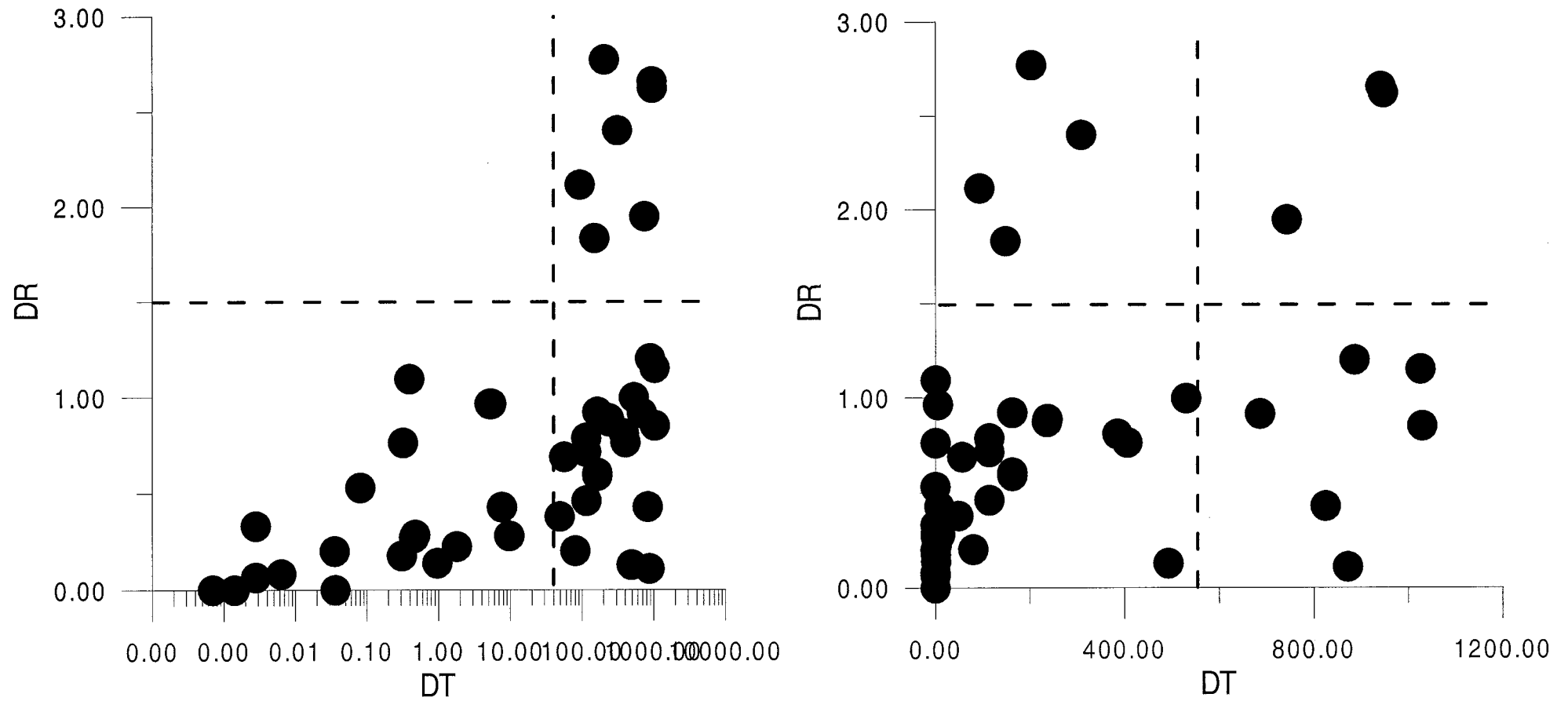


Figure 5



# California & Nevada: Objects for Learning

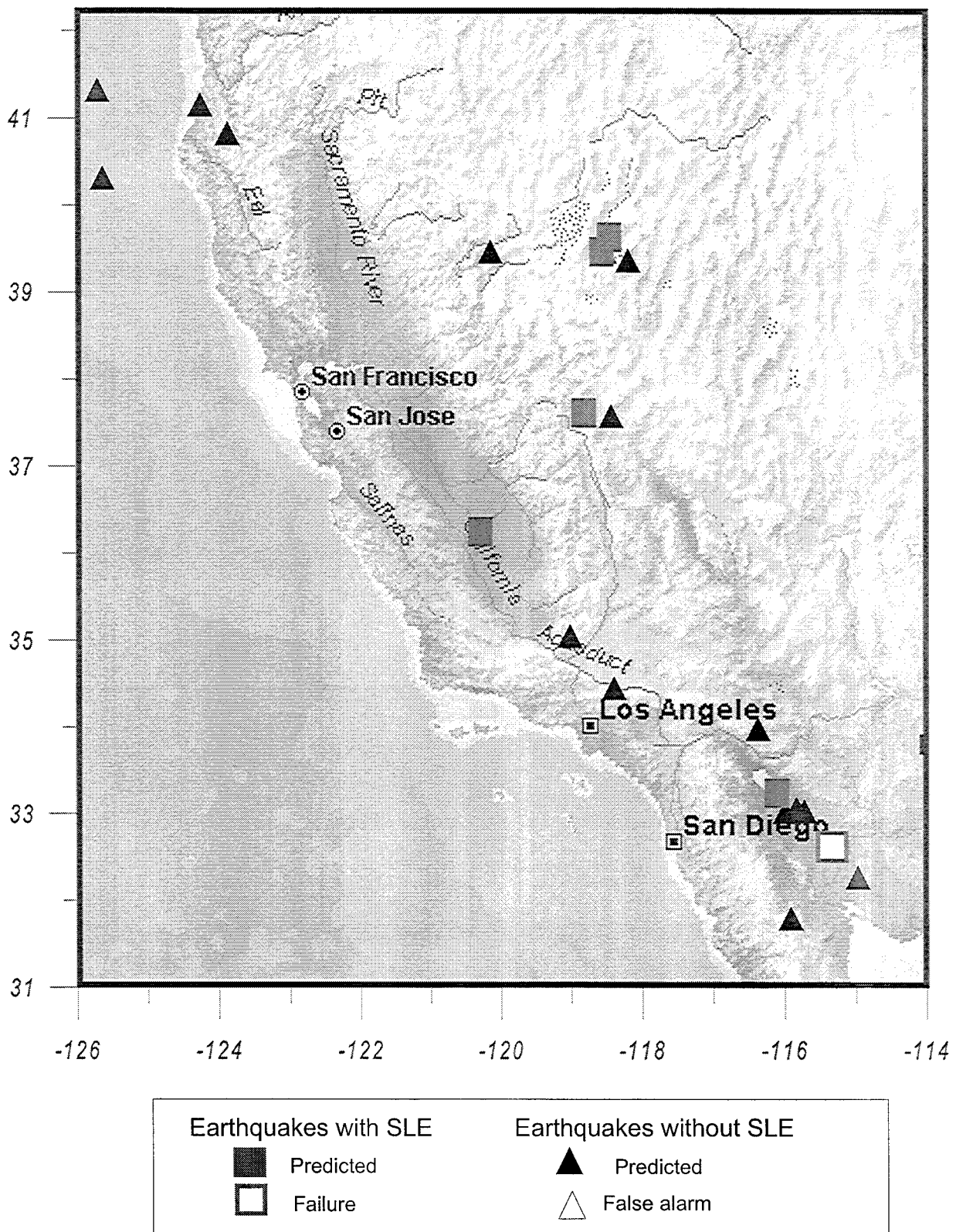


Figure 6

## Objects for learning: distribution of functions ***N*** and ***S***

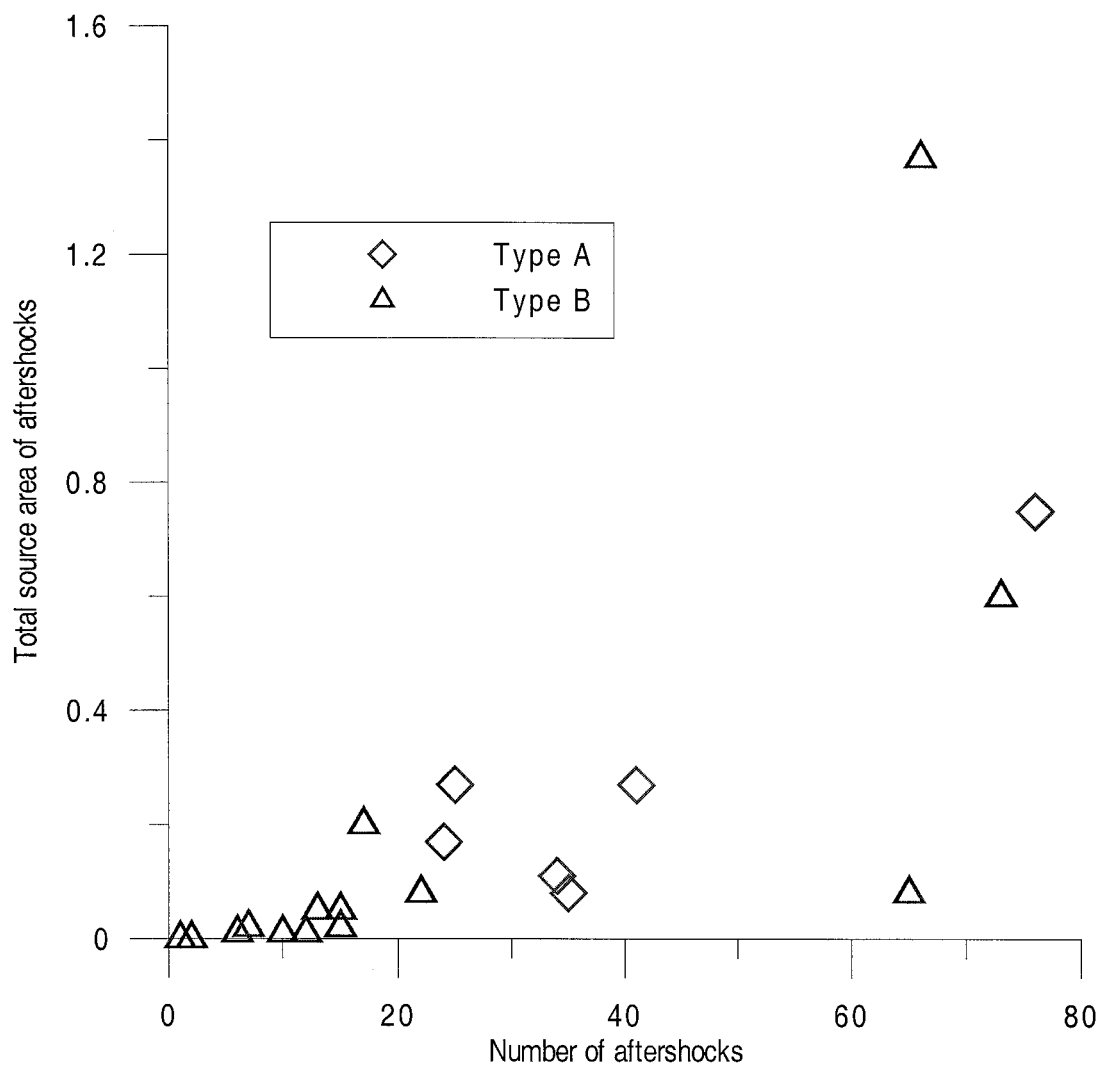


Figure 7

## Distribution of function $N$

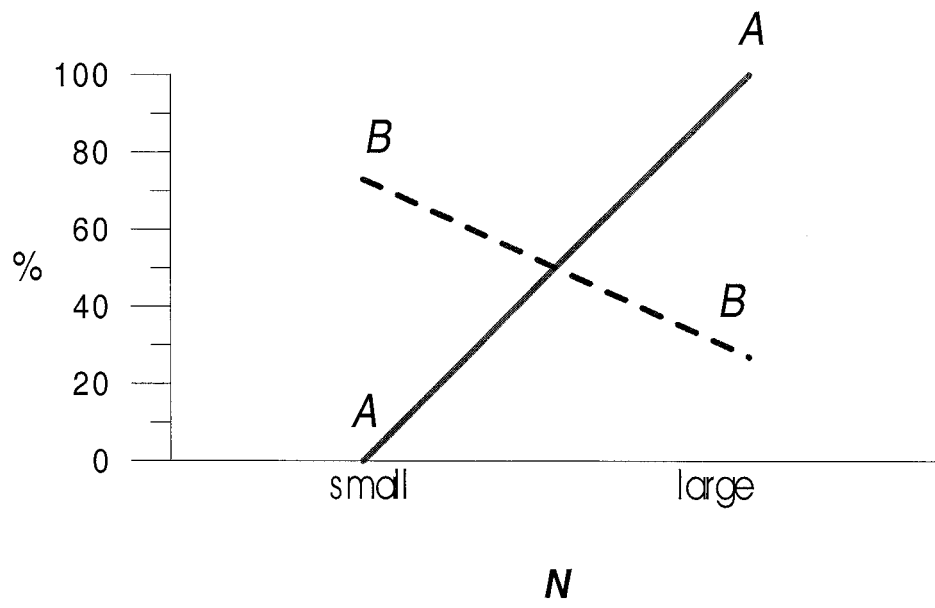
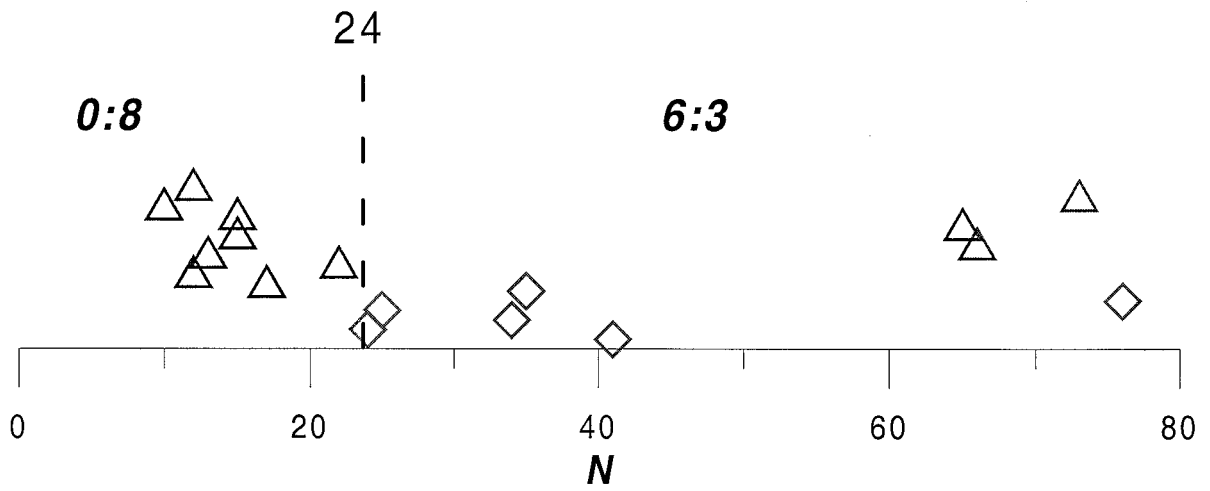


Figure 8

# Distributions for 8 functions

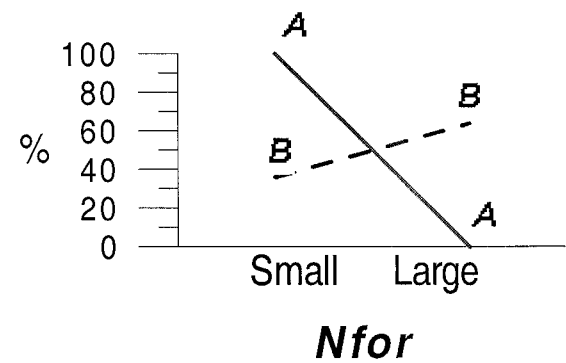
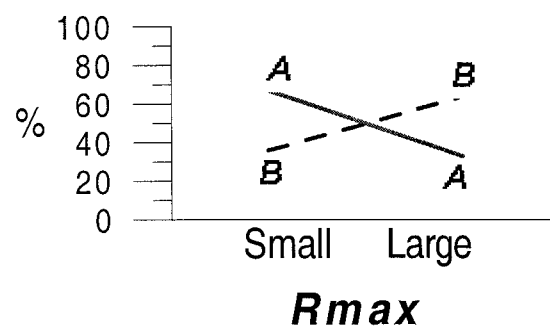
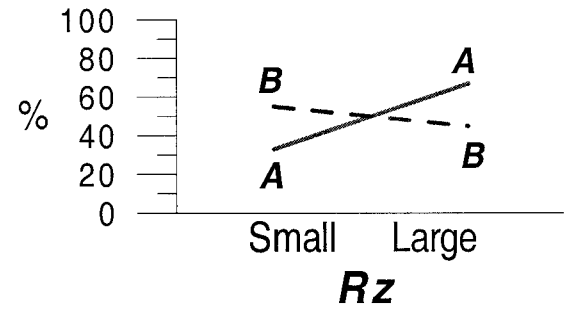
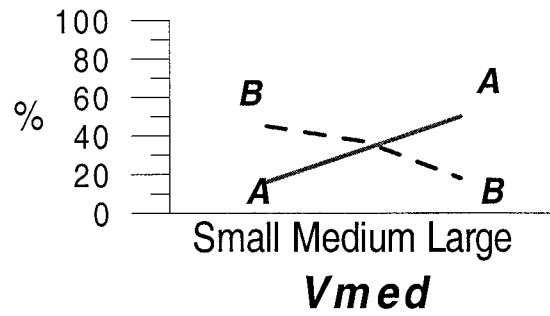
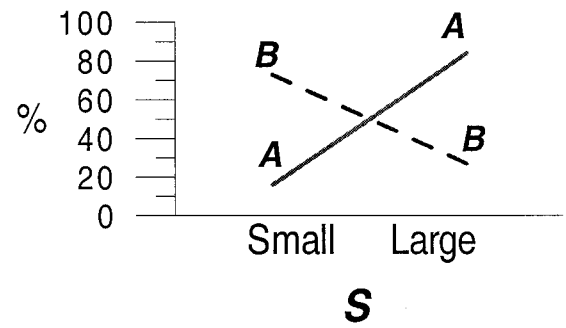
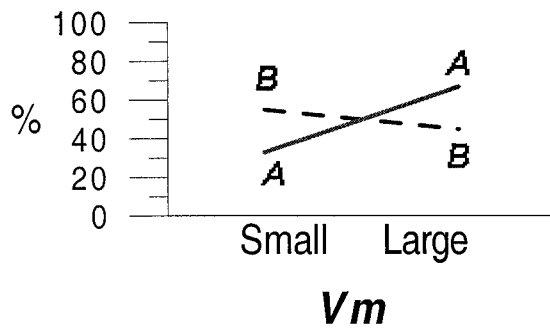
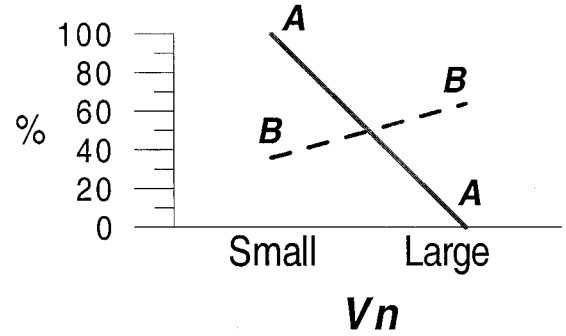
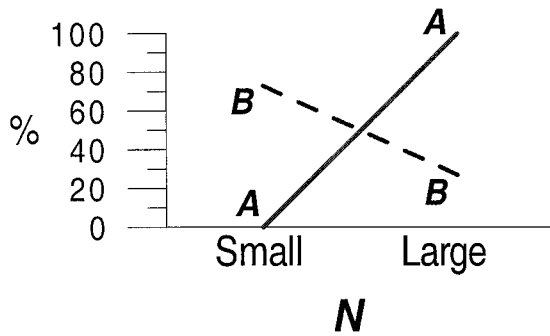


Figure 9

# Distribution of function *Dm*

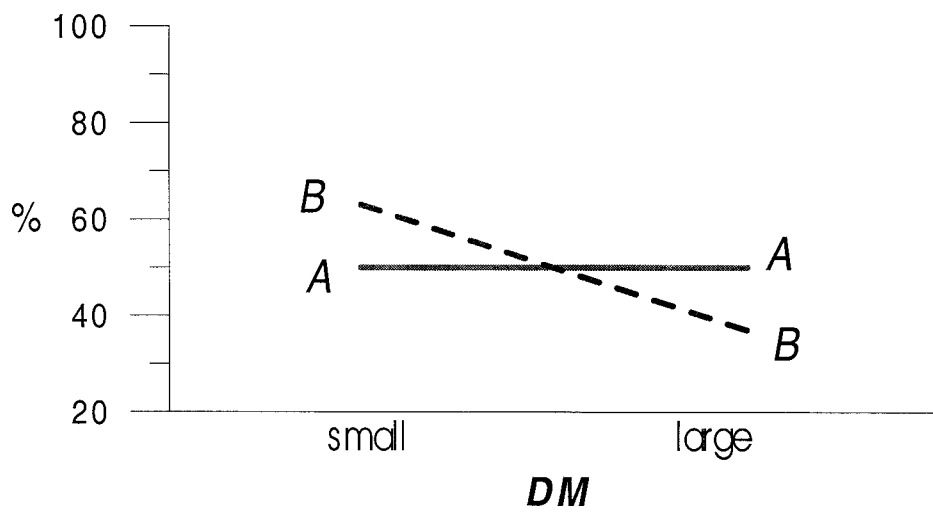
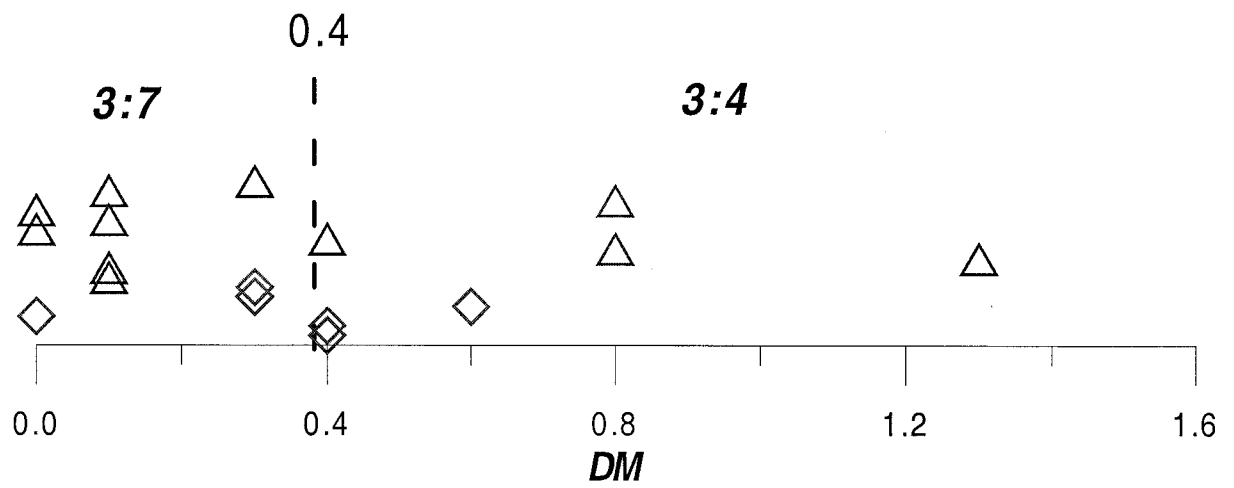
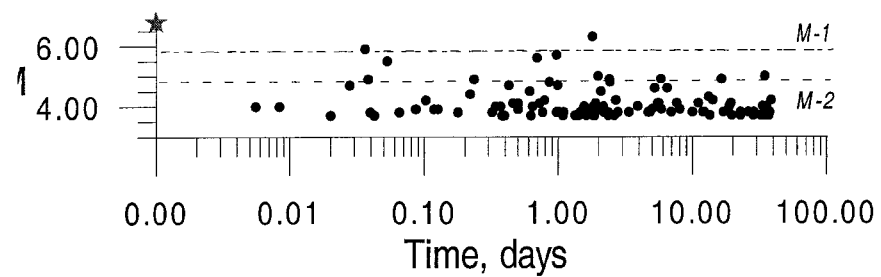


Figure 10

Object of A type, 25.05.1980



Object of B type, 09.06.1980

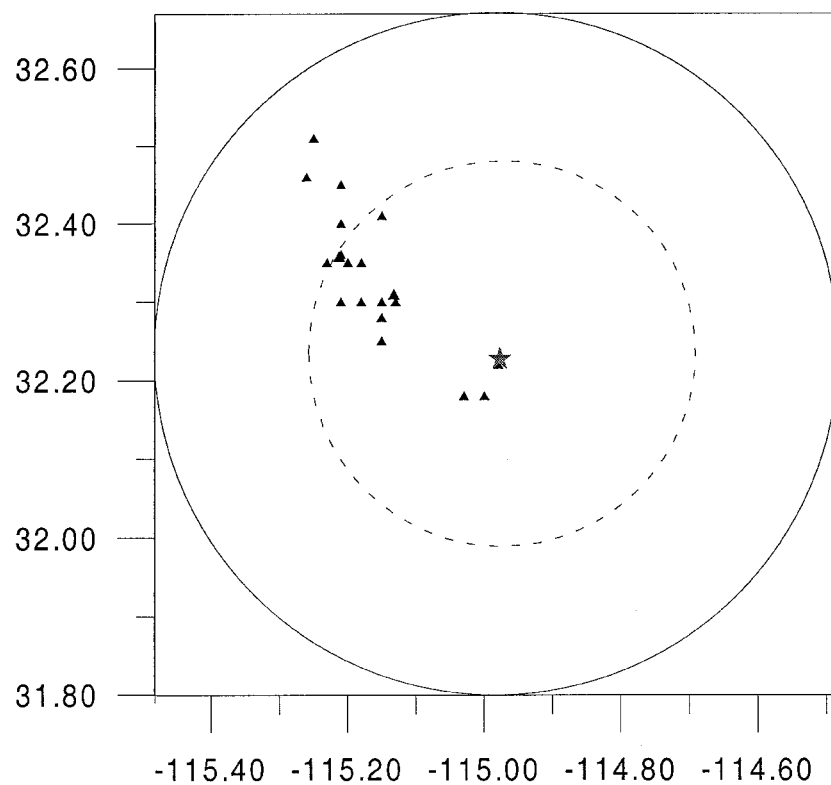
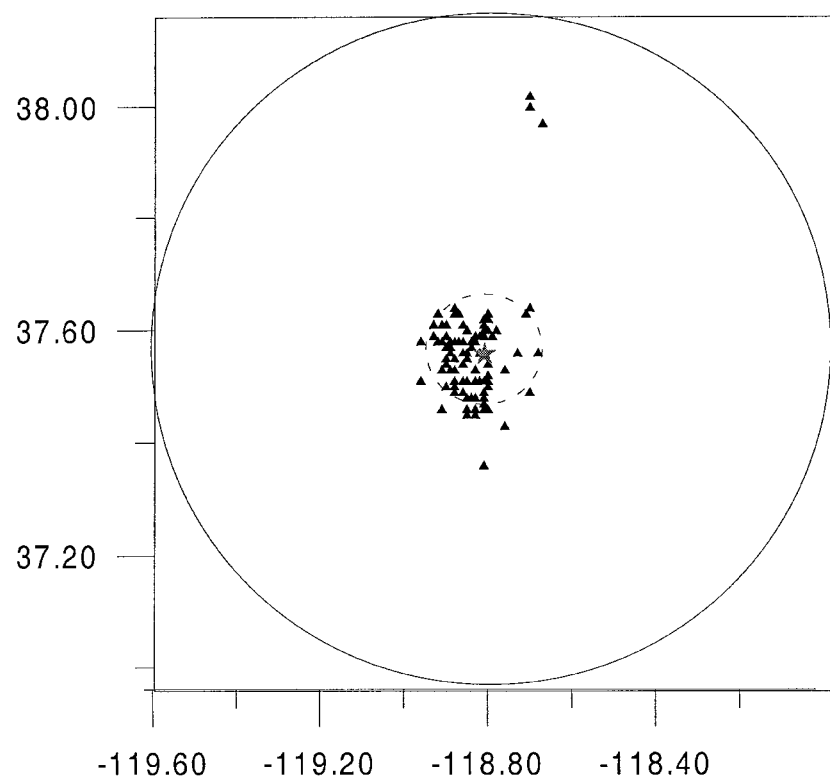
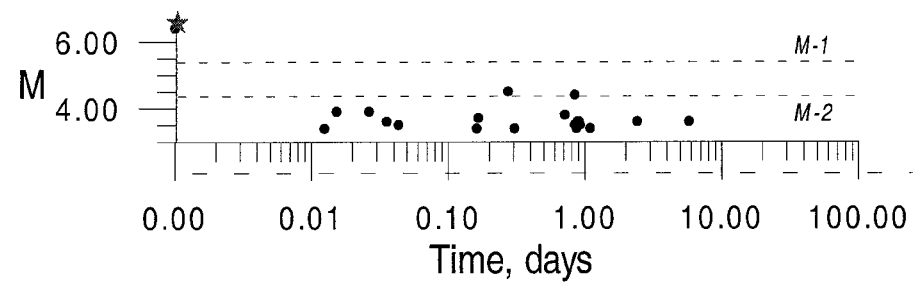


Figure 11

## $n - \tau$ diagram

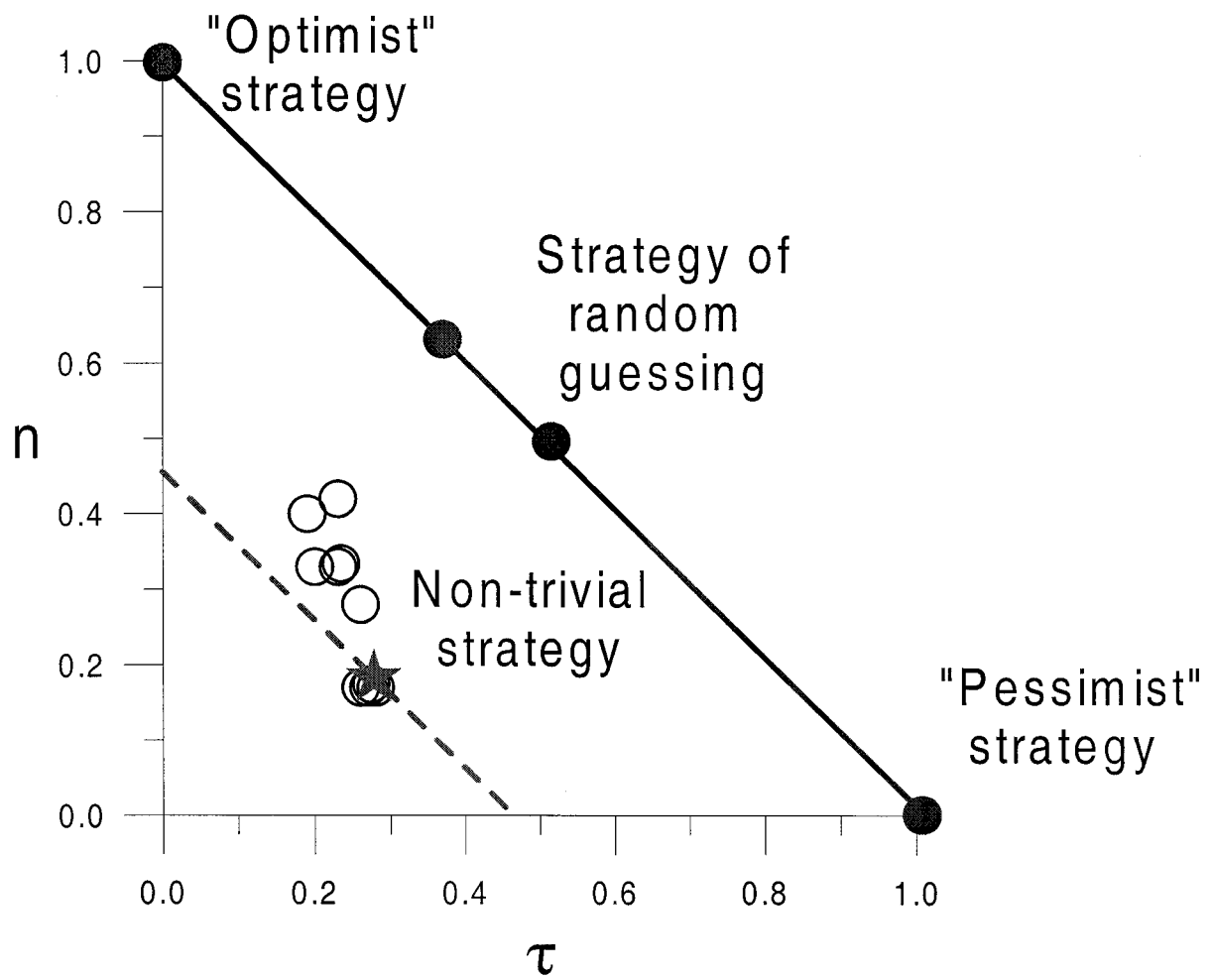
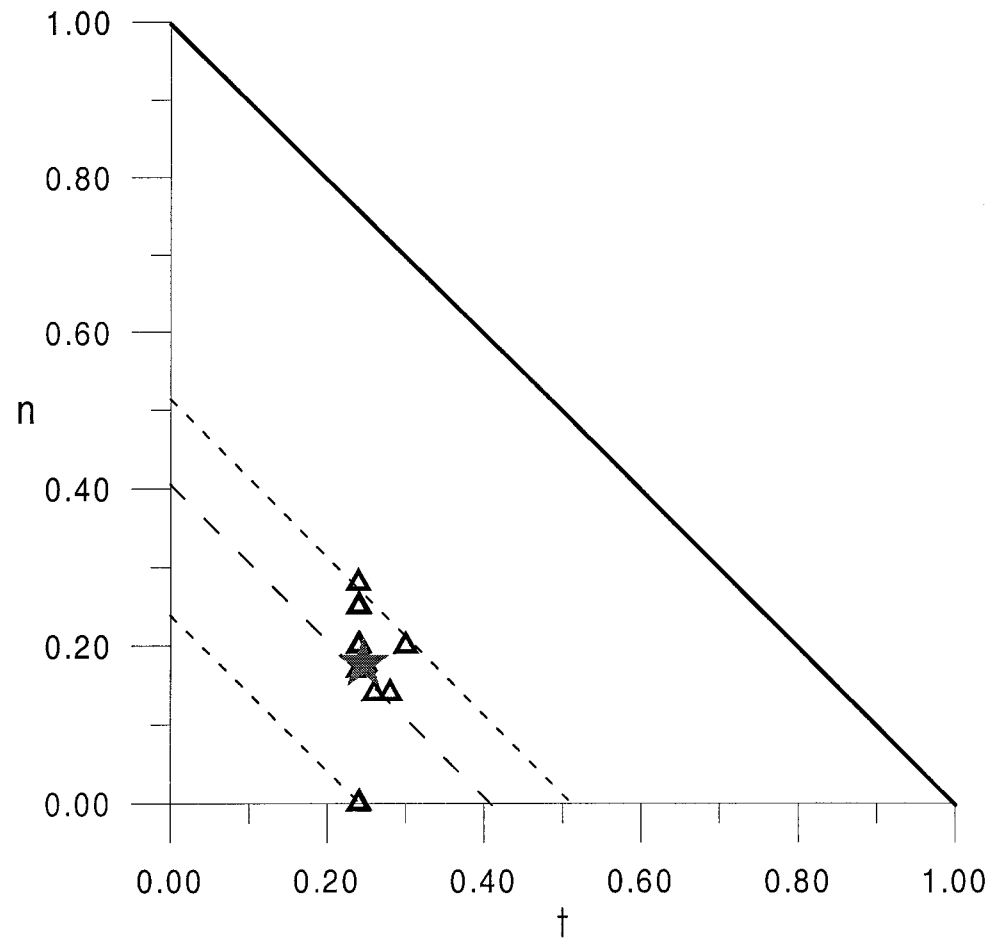


Figure 12

## Stability of the algorithm to variation of numerical parameters

a) parameters for object determination



b) parameters of decision rule

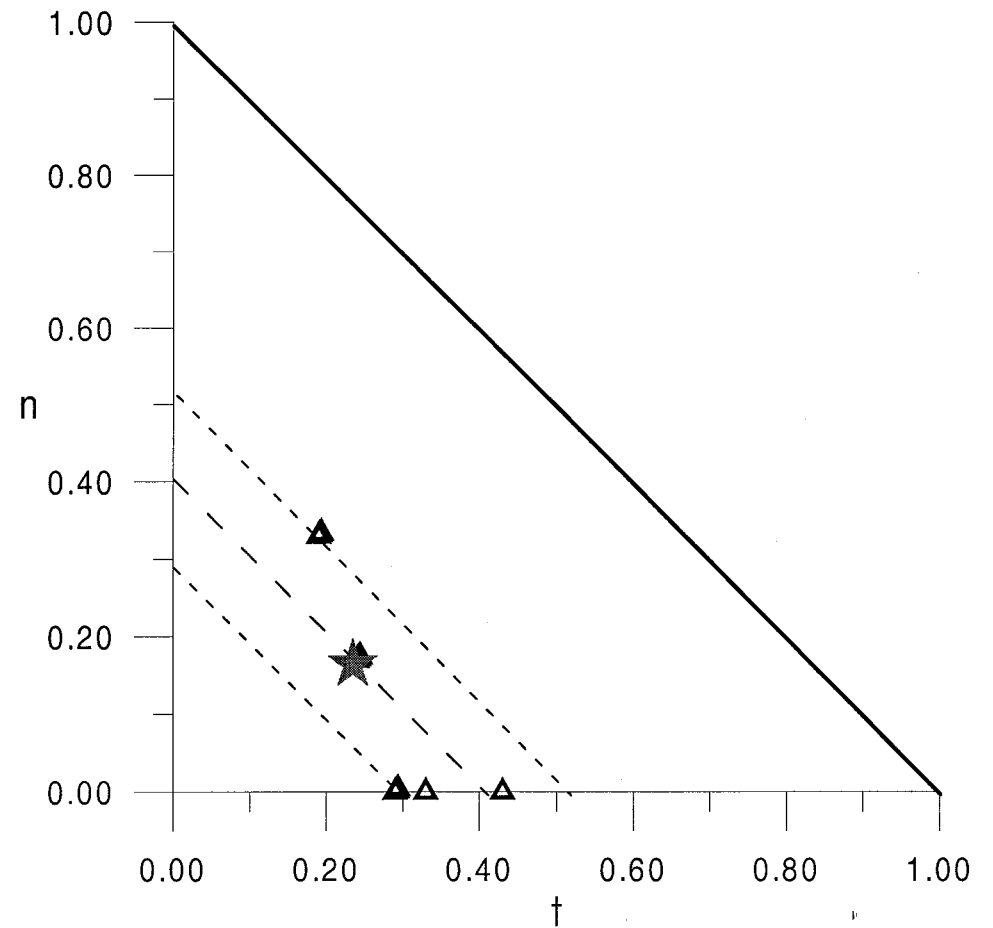


Figure 13



# Stability of the algorithm to errors in data

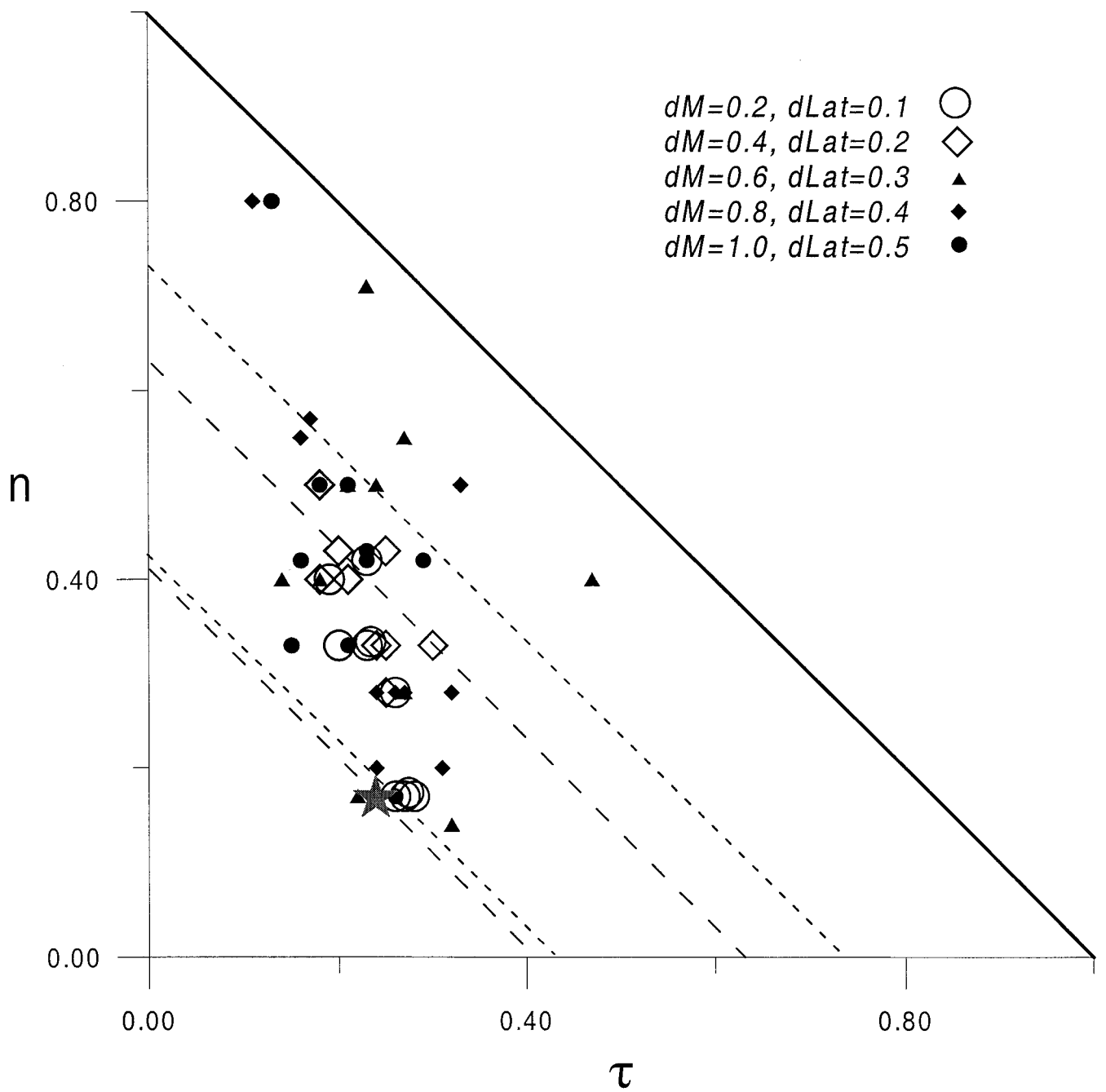


Figure 14

# Joshua Tree -- Landers -- Northridge

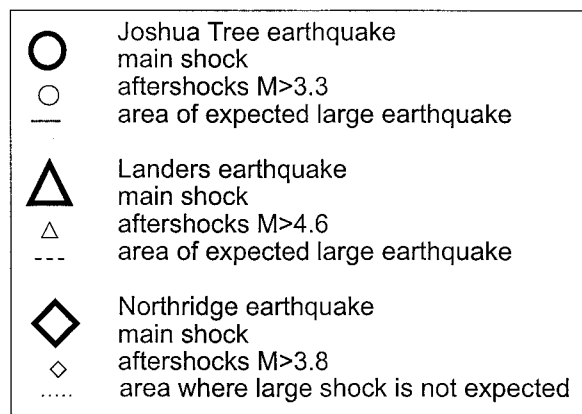
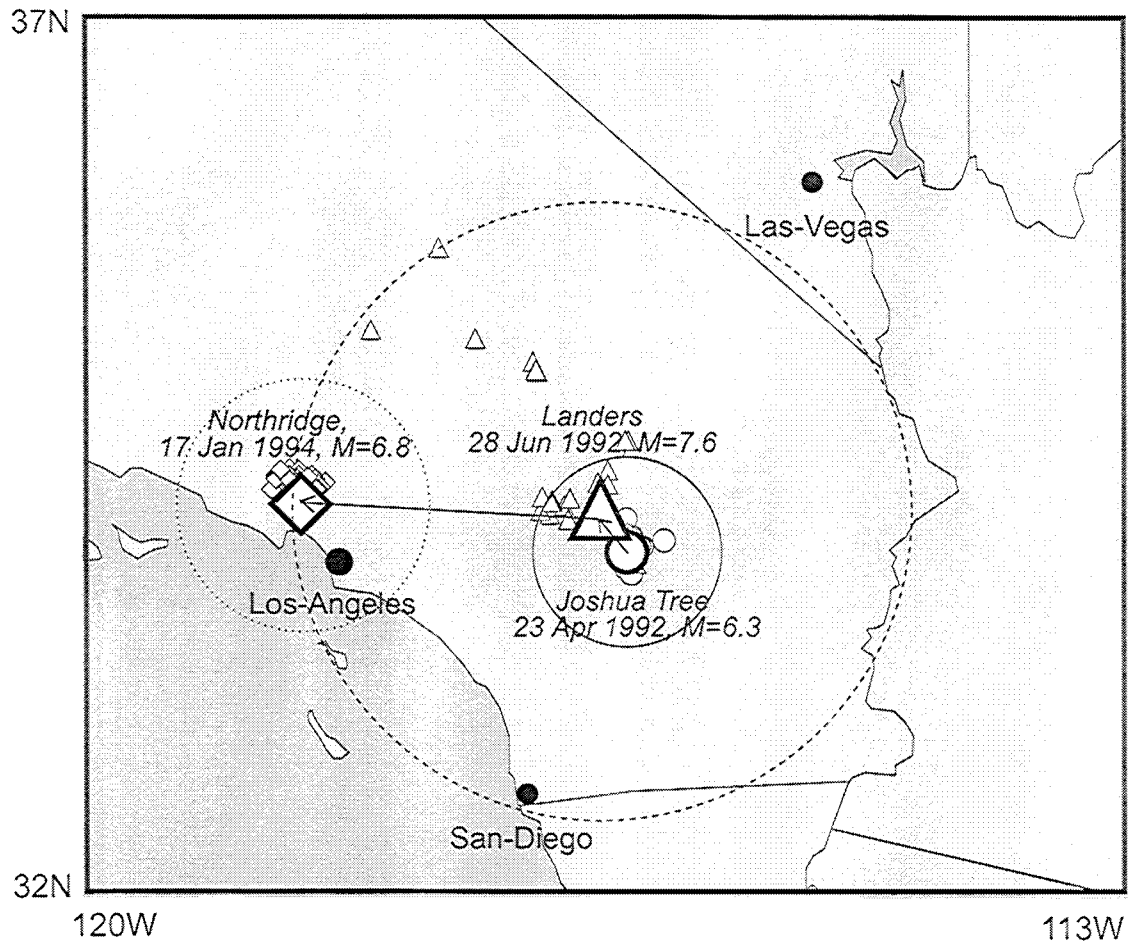


Figure 15

## Gulf of Aqaba 1993 - 1995

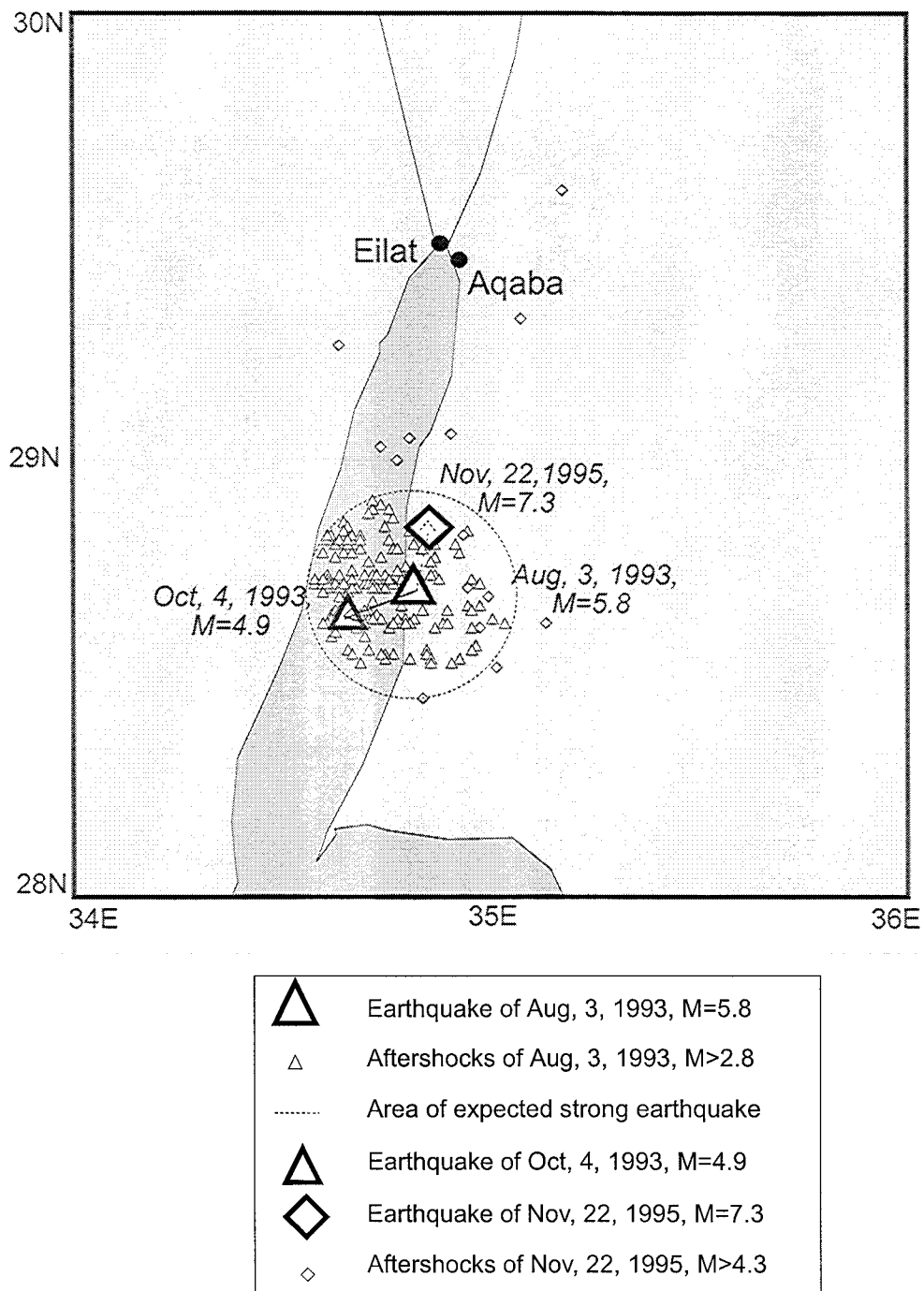


Figure 16

# Rachi earthquakes 1991

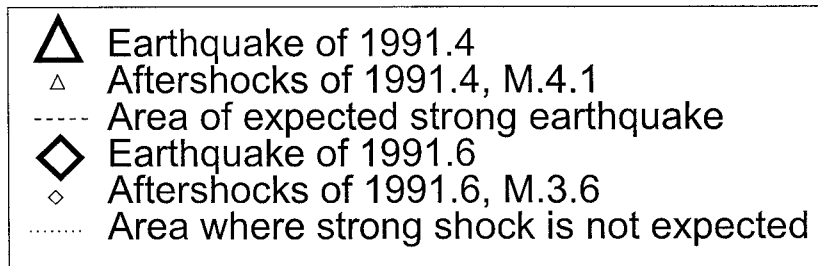
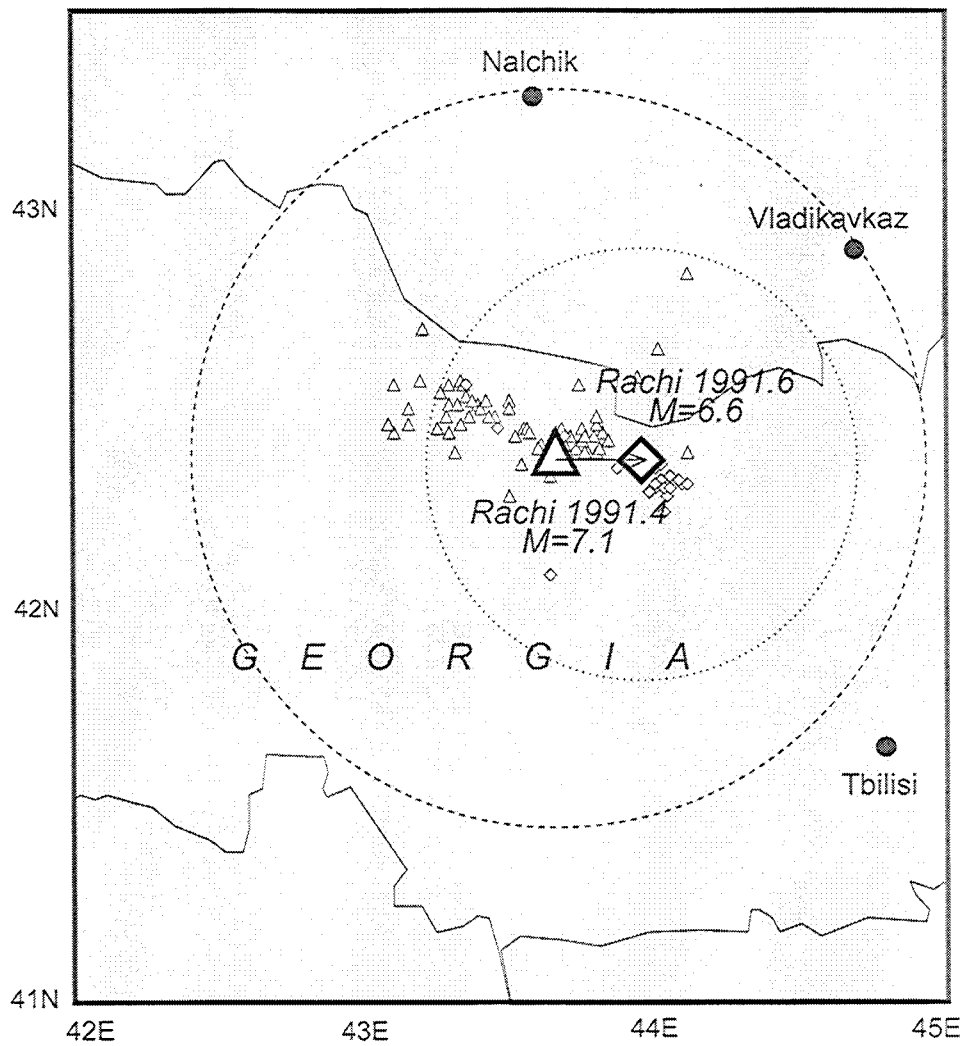


Figure 17

# Caucasus 1962-1991 Aftershock sequences of earthquakes $M > 6.4$

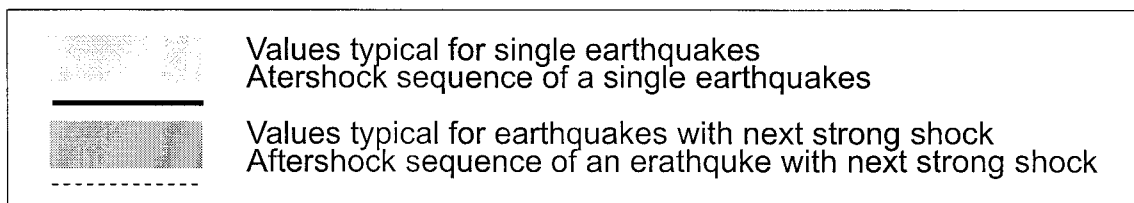
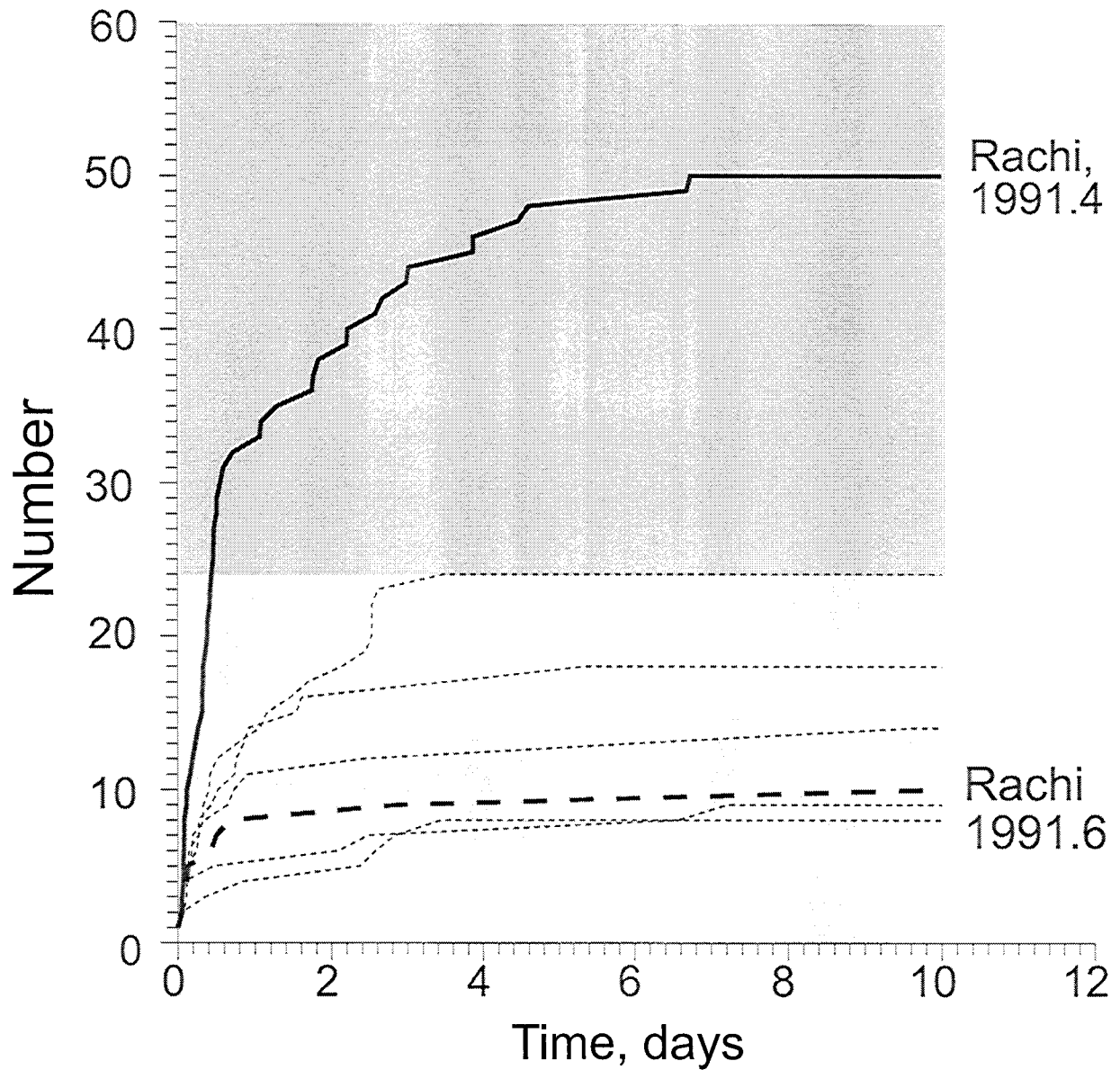


Figure 18