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Prediction of the subsequent large Earthquake
I. Algorithm
II. Results of monitoring

Inessa Vorobieva
Russian Academy of Sciences
International Inst. of Earthquake Prediction Theory and Matematical Geophysics
Warshavskoye Sh. 79. Kor2
117556 Moscow
Russia

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

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I.A.Vorobieva

International Institute of Earthquake Prediction Theory and Mathematical Geophysics
Russian Academy of Sciences
Moscow 113556
Russian Federation

Introduction

Many large earthquakes come in pairs, separated by relatively small times and distances. Predicting the occurrence of a subsequent large earthquake (SLE) is important, both from a scientific and a practical point of view. The study of phenomena preceding the occurrence of a subsequent large earthquake may help in understanding the process of preparation of it. At the same time such prediction is practically important in populated areas. The first earthquake may destabilize buildings, lifelines, and other constructions, mountain slopes, etc.; subsequent large earthquakes may destroy them. The problem of predicting a subsequent earthquake is considered in several papers of Bath, (1965), Vere-Jones (1969), Prozorov, (1978), Reasenberg and Jones (1989), Matsu'ura (1986), Haberman and Creamer (1990).

The prediction algorithm considered here is described in full detail in (Vorobieva and Levshina, 1994, Vorobieva and Panza, 1993, Vorobieva, 1999). We use for prediction the local seismic activity preceding a large earthquake and the aftershock sequence following it. Let M be a magnitude of a large earthquake. The problem is to predict whether a subsequent earthquake, with magnitude $M_1 \geq (M - a)$, will occur soon near the epicenter of the first earthquake; it may be either an aftershock or another main shock.

The algorithm was designed (Vorobieva and Levshina, 1994) by analyzing 21 large earthquakes in the California-Nevada region, six of which were followed by subsequent large earthquakes. In 20 out of 21 cases the algorithm allowed to predict correctly whether subsequent earthquakes would occur or not; the only one mistake was failure-to-predict. The algorithm with all parameters fixed was then tested in different regions of the world, by application to 96 large earthquakes, 11 of which were followed by a subsequent large shock. 90 predictions were correct; among the six mistakes there were four false alarms and two failures-to-predict.

29 advance predictions have been made since 1989, including predictions for the 1991 Rachi earthquake (Georgia, Caucasus), and Californian earthquakes: Loma-Prieta, 1989; Joshua Tree, 1992; 1992 Landers, and Northridge, 1994. Formally, the Landers, 1992 earthquake also fits the prediction, but too wide an interval was indicated for its magnitude. 24 were correct; among the four mistakes were three false alarms and two failure-to-predicts. The statistical significance of advance predictions exceeds 99%.

I. Design of the Algorithm for prediction of SLE

1.1. Hypothesis on the process of preparation of the subsequent large earthquake.

The main hypothesis used for design of algorithms predicting large earthquakes is that some changes occur in the intermediate and small seismicity in the period of preparation of the large event. These changes are akin to the symptoms of instability, which are typical for many non-linear systems before critical transition. The behavior of system becomes more active and irregular, the response to small perturbation increases; it lasts longer in time and in larger distances.

In the case of earthquake prediction this non-linear system is the network of seismogenic faults of the region. It was found that the flow of small earthquake becomes more intensive and irregular in space and time before large shock. These phenomena appear in the activation: the number and magnitudes of small events increases; earthquakes occur in clusters (swarms); the number of aftershocks following the intermediate evens becomes larger. Normalized description of the features mentioned above, taking into account the level of seismic activity, allows 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. Formalization 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 $M_1 \geq (M - m_a(M))$ 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 using 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)

$$R_0(M) = 0.02\times10^{0.5M} \text{ [km]};$$

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 low

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

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 $R = CR_0 = C0.02\times10^{0.5M}$ [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 classes of objects:

Class *A* is large earthquake, which is followed by subsequent large shock;

Class *B* is 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 class.

To find decision rule the learning material is used, i.e. objects of class *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 aftershocks, 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 low.

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 firs 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

$$\boldsymbol{S}=\Sigma 10^{mi-M}$$

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 $[t + s_1 , t + s_2]$

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

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 $[t + s_1 , t + s_2]$

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

where μ_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 $[t + s_1 , t + s_2]$

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

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

Function reflecting rate of aftershock activity decreasing. 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 $[t + s_1 , t + s_2]$

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

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 low, 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 quaesence is typical for the period of preparation of large earthquake. It depends oh the parameters of function, nevertheless, we hope to found 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, thought 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 ΔM on M, where M is the magnitude of first large earthquake and ΔM 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 ΔM 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 objets for learning into two groups: if $\Delta M \leq 1$, the object is of *A* class, if $\Delta M > 1$ the object is of *B* class.

To choose the time and space limits, consider the distribution ΔT and ΔR for all subsequent large shocks. It is shown in the figure 5a,b. ΔT is given in days, and ΔR 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 foreshocks 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* class and 15 of *B* class. 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 classes *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 class *A*, in particularly all the objects with few aftershocks (<10) are of class 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 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 classify the part of objects in the simplest way, improves the ratio of objects of class *A* and *B*, and 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 classes *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 quality 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 functions 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 functions are shown in Table 3 as well as values typical for *A* objects, thresholds for discretization and quality.

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* class and for objects of *B* class. Now we can formulate the decision rule.

Decision rule: Earthquake is of class *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 class *B* (a subsequent large earthquake will not occur).

The decision rule allows recognize right class for 20 out of 21 large earthquakes in California & Nevada. There is only one error failure-to-predict, it is an earthquake occurred in1979 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, 1980, is most typical *B* object; seven functions 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, and 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 quality of the algorithm.

To compare the quality 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 τ. Here n is the relative number of the failures-to-predict among A objects, and τ 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 τ and Y axis is n (figure 12). n and τ change from 0 to 1. Any prediction algorithm is presented by point with coordinates (τ, n). The points (0, 1) and (1, 0) correspond to trivial strategies. (0,1) is the strategy of “optimist”, i.e. alarm is never announced, but all large earthquakes are failure-to-predicted. (1, 0) 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 (τ, n) from diagonal as better is prediction algorithm.

The quantity

$q=1-n-\tau$

is a characteristic of prediction quality. This value is equal to 0 for trivial strategy, it is $0 < e \leq 1$ for nontrivial prediction algorithm. This value for 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 τ

are determined. The algorithm is considered as stable, if points (n, τ) are close to point (n_0, τ_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=1year, S=2years (2experiments)
4. Difference of magnitude for SLE from 0.4 to 1.5, step 0.1 (11experiments)

Total: 19 experiments

The results are presented in the figure 13a. The basic algorithm is marked by asterisk, the dashed line - quality level of basic variant, dotted lines – minimum and maximum of quality 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 quality 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 objects can disappear, another appear, the class 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 are expected with changing of input data taking into account the observed 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^o 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 errors, 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 variant is marked by asterisk. Dashed line marks its quality level.

The average quality 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 quality 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 quality 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),
Lake Baikal region (5.5),
Turkmenia (5.5),
Dead Sea Rift (5.0).
Antilles (6.0)

The reason of this choice is explained later.

The total number of large earthquake in these regions is 96, 11 of them were followed by SLE, 85 were single. 48 large earthquakes had less than 10 aftershocks, only one of them was followed by SLE, 47 were single. 48 large earthquakes had 10 or more aftershocks, 10 of them were followed by SLE, and 38 were single. 9 out of 11 SLE were recognized correctly, 2 were missed. Total number of declared alarms was 12; 8 were true and 4 false. The effectiveness of the prediction is calculated using the relative number of errors in classes *A* and *B*:

e=1 – (2/11 + 4/85) ≈ 0.77

The result of retrospective test is given in Table 6. It demonstrates similarity of the process of preparation of SLE in wide magnitude range from 5 to 8, and in different seismotectonic conditions: subduction zones (Antilles; Hellenic arc), Transforms (San-Andreas in California, Anatolian fault in Asia Minor), rifts (Dead Sea, Baikal), thrust zones (Caucasus, Central Asia)

Choice of region.

The formal definition of the algorithm enables it to be applied to any 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 zones of the highest seismic activity. Here the algorithm does not work.

Seismicity in these 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. Formal application of the algorithm demonstrates here quality of random guessing. This fact sows the limitations of similarity. The definition of the subsequent large earthquake needs to be changed (i.e. magnitude, time and space parameters) taking into account high level of regional seismic activity.

So far, the algorithm works quite well in all regions of intermediate-high seismic activity where representative catalogs are available.

2.4. 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 particularly, the quality of data for California and Italy allows to decrease M_0 However the tests were carried out for 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 quality of prediction for "small" earthquakes (M_0-0.2 ≤ M < M_0). Total number of these events is 52, 9 were followed by SLE, only 1 is predicted, 4 alarms were declared.

q=1 – (8/9 + 4/52) ≈ 0.03

This result shows quality of random guessing.

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 other limitation of selfsimilarity that is observed for regionally large earthquakes: it is not extended to intermediate events.

2.5. The results of 1989-2005.10 monitoring.

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

29 large earthquake were tested, 8 were followed by SLE, and 6 were successfully predicted. 9 alarms were declared. Up to now 24 predictions were correct, and there were 5 errors: 3 false alarms and 2 failures-to-predict. The effectiveness of the algorithm for prediction of SLE in advance

e=1 – (2/8 + 3/21) ≈ 0.6

It turns out even better than expected value 0.55

As predictions in advance were made with all prefixed parameters it is possible to estimate its 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:

$$\varepsilon = [C_{21}^{3}C_{8}^{6} + C_{21}^{2}C_{8}^{7} + C_{21}^{1}C_{8}^{8}]/C_{29}^{9} \approx 0.39\%,$$

where C_n^k are binomial coefficients.
So the result can be considered statistically significant at the 99% level.

2.6 Analysis of the errors of monitoring

False alarms. Two false alarms occur in California: after Landers earthquake, June, 28, 1992 *M*=7.6, and after San-Simeon, December 22, 2003 *Ms*=6.4. But both of them were confirmed informal. Northridge occurred January 17, 1994, *M*=6.8 within alarm area in 20 days after alarm expiration, Parkfield occurred September 28, 2004, *M*=6.0 within alarm time in 17 km out of alarm area. These cases are described in more detail below. The third false alarm occurred after Erzincan earthquake, Caucasus, March 13, 1992, *M*=6.9. It can be explained by the quality of input data. The data of Ankara agency were used, as representativity of NEIC quick data was not enough. Further analysis show that magnitudes of aftershocks were systematically increased by 0.2-0.3. This generated false alarm. All three cases are counted as errors estimating statistical significance and effectiveness of the prediction in advance.

Failures-to-predict. There were two failures: after Izmit, Asia Minor, August 17, 1999, *M*=7.8; and after Mendocino January 9, 1994, *M*=7.1. Both of them had low active aftershock sequence; values of functions are typical for single earthquakes. Failures can not be explained by data quality or other reasons, they are "unforced errors". Probably, Izmit earthquake is "too large and does not fit similarity limitations.

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 Antilles.

*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*≥3.3 used for prediction are shown in Fig.15. This earthquake had a high rate of aftershocks (54 aftershocks with *m*≥3.3), so it produced an alarm for an earthquake with *M*≥5.3 within the distance *R*(6.3)=42 km, within 1.5 years of Joshua Tree. 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*≥4.6 were used for prediction, as shown in Fig. 15. The aftershock sequence had few aftershocks (20 aftershocks with *m*≥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*≥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 28 December, 1993. The subsequent Northridge *M*=6.8 earthquake occurred within this distance, but 20 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*≥5.8. Its aftershocks with magnitude *m*≥3.8 used for prediction are shown in Fig.15. In spite of many aftershocks (77 events with magnitude *m*≥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.

3.2. San-Simeon, California, 2003 The San-Simeon earthquake occurred December 22, 2003, and had magnitude $Ms=6.4$. The map of aftershocks used for prediction is shown in Fig. 16. This earthquake had 74 aftershocks with magnitude $m \geq 3.4$. It produced an alarm for an earthquake with $M \geq 5.4$ within the distance $R(6.4)=48$ km, within 1.5 years San-Simeon. Formally this alarm is false, because the subsequent Parkfield earthquake, $M=6.0$, occurred within alarm time on September 28 2004, but in 17 km out of alarm area (Fig 16). There were no other earthquakes that fit to the prediction.

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.

The similar situation is in Dead sea rift and Lake Baikal regions: in the retrospective stage of analysis all large earthquake were single, while events with SLE occur during period of monitoring.

3.4.Antilles earthquakes of 2004.

It is most recent successful prediction of SLE. The large shallow earthquake occurred in Antilles November 21, 2004, $M=6.3$. The map of aftershocks with magnitude $m \geq 3.3$ used for prediction is shown in Fig. 19. It was predicted that SLE of magnitude $M \geq 5.3$ is expected till May 21, 2006, within the distance $R(6.3)=42$.km. It was confirmed February 14, 2005 when SLE of magnitude 5.9 occurred within alarm area. Antilles are typical subduction zone, with dip seismicity. It differs from Circumpacific subduction zones (where algorithm is not applicable) by rate of seismic activity. This fact confirms the hypothesis about selfsimilarity of the preparation of SLE in the different seismotectonic conditions in the regions with intermediate high rate of seismic activity.

Conclusions

The algorithm for predicting a subsequent large shock was successfully applied in different seismic regions of the world. 29 large earthquakes were tested for the last 16 years, producing only five errors: three false alarms (two of them were confirmed informally) 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.

The results of the algorithm's test confirm the hypothesis about the preparation of SLE as critical transition in non-liner system. The hypothesis about similarity of the premonitory phenomena in wide range of magnitudes and seismotectonic conditions is confirmed as well as limitations: similarity is observed in the regions of intermediate-high rate of seismic activity and for regionally large events.

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Figure captions

Fig. 1. Formulation of the problem.
Fig. 2. Seismicity of California &Nevada, $M \geq 5$, NEIC
Fig. 3. Small earthquakes in California & Nevada 1932-1942, NEIC
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Fig. 15. Joshua Tree, Landers**,** and Northridge earthquakes and their aftershocks.
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Fig. 17. Rachi earthquakes and their aftershocks.
Fig. 18. The aftershock sequences of 1962-1992 Caucasian earthquakes in time.
Fig. 19 Antilles earthquake and its aftershocks

Table 1. Distribution of earthquakes by magnitude in California & Nevada 1900-1988, NEIC

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
1900	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1901	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1902	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1903	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1904	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1905	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1906	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.
1907	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1908	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1909	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.
1910	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.
1911	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.
1912	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1913	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1914	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1915	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	.	.	1	.	.	.	1	.
1916	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.
1917	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1918	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	.	.	.
1919	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1920	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1921	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1922	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	1	.	.	.	.
1923	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	.	1	.	.	.	.
1924	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1925	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	.	.	.
1926	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	.
1927	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	1	.	.	.	.	.	1	.	.	.	.
1928	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1929	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1930	.	.	.	.	.	.	.	1	.	.	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.

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.

First large earthquake						***Largest subsequent earthquake***		
Date yyyy/mm/dd	**Time**	**Epicenter**	***M***	***R***, km	***N aft***	***ΔM***	***r/R₀***	***ΔT***, days
		Earthquakes followed by SLE, class *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, ***Naft*** ≥10, class 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, ***Naft***<10, class 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; ***Naft-*** number of aftershocks during 40 days; ***ΔM*** – 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; ***ΔT***, 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 %	Values of parameters				Threshold values	
			m	s_1, hrs	s_2, days	τ, days		
N	large	72	3	1	10	-	24	-
S	large	55	2	1	10	-	0.1	-
Vm	large	25	3	1	40	-	0.41	-
Vmed	large	30	3	1	40	-	0.7	2.6
Rz	large	25	3	10 days	40	10	0	-
Vn	small	63	3	1	40	-	0.98	-
Rmax	small	30	2	-	2	-	0.23	-
Nfor	small	63	1	5 years	3 mon.	-	2	-

Table 4. Result of learning

Earthquake		Magnitude	Values of function and class of value								Voting	Result of recognition
#	date	*M*	***N***	***S***	***Vm***	***Vmed***	***Rz***	***Vn***	***Rmax***	***Nfor***	n_A-n_B	Class
					Earthquakes followed by SLE, class *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, *Naft* ≥ 10, class *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, *Naft* < 10, class *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		Quality	
	Max error	Standard deviation	Max error, deg.	Standard deviation, deg.	1-n-τ	Average 1-n-τ
1	0.2	0.066	0.1	0.033	0.34÷0.57	0.49
2	*0.4*	*0.133*	*0.2*	*0.066*	*0.32÷0.47*	*0.40*
3	0.6	0.2	0.3	0.1	0.06÷0.61	0.36
4	0.8	0.266	0.4	0.133	0.09÷0.56	0.36
5	1.0	0.333	0.5	0.166	0.07÷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
Lake Baikal region.	5.5	6	4/0	2	2/1	0/0
Iberia & Maghrib	6.0	7	5/0	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
Antilles	6.0	4	2/0	2	1/0	1/0
Total retr. test		**96**	**48/1**	**48**	**38/4**	**10/1**
Total		**117**	**52/1**	**65**	**49/4**	**16/2**
Total test M_0+0.2*		**67**	**31/0**	**36**	**26/1**	**10/1**
Total test M_0-0.2*		**171**	**90/6**	**81**	**62/7**	**19/5**

* - Result for nine regions (Without Antilles)

Table 7. The results of 1989 - 2005.10 monitoring.

Origin Earthquake		*Will a subsequent shock occur*?	*Note*	*Outcome of prediction*
California				
Loma-Prieta, 10/18/1989	7.1	NO	No shocks with M≥6.1	Confirmed
Mendocino 7/13/1991	6.9	NO	No shocks with M≥5.9	Confirmed
Mendocino 8/17/1991	7.1	NO	No shocks with M≥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≥5.8	Confirmed
Mendocino 4/25/1992	7.1	NO	No shocks with M≥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≥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≥6.4	Confirmed
San-Simeon 12/22/2003	6.4	YES	Parkfield M=6.0 in occurred 17km out of alarm area	False flarm
Caucasus				
Iran 6/20/1990	7.7	NO	No shocks with M≥6.7	Confirmed
Rachi 4/29/1991	7.1	YES	Earthquake with M=6.6 occurred	Confirmed
Rachi 6/15/1991	6.6	NO	No shocks with M≥5.6	Confirmed
Erzincan 3/13/1992	6.8	YES	No shocks with M≥5.8	False alarm
Pamir & Tien-Shan				
Kazakhstan 8/19/1992	7.5	NO	No shocks with M≥6.5	Confirmed
China 11/19/1996	7.1	NO	No shocks with M≥6.1	Confirmed

Origin Earthquake		***Will a subsequent shock occur?***	***Note***	***Outcome of prediction***
Turkmenia				
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.
Iberia & Maghrib				
Morocco 5/26/1994	6.0	NO	No shocks with $M \geq 5.0$	Confirmed
Dead Sea Rift				
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
Italy				
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
Balkan & Asia Minor				
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
Antilles				
12/21/2004	6.3	YES	Earthquake with $M=5.9$ occurred	Confirmed

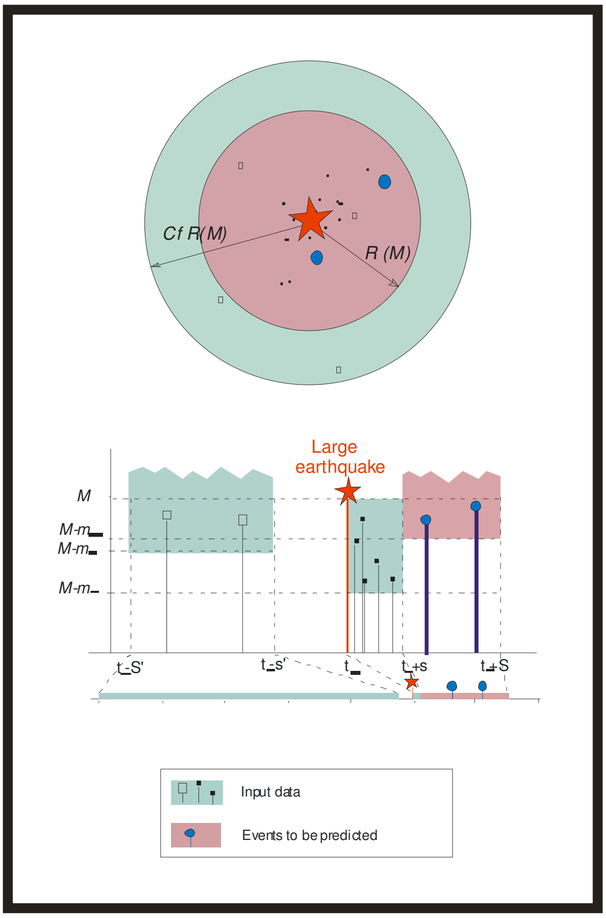

Cf R(M)
R (M)
Large
earthquake
M
Input data
Events to be predicted

Figure 1.

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

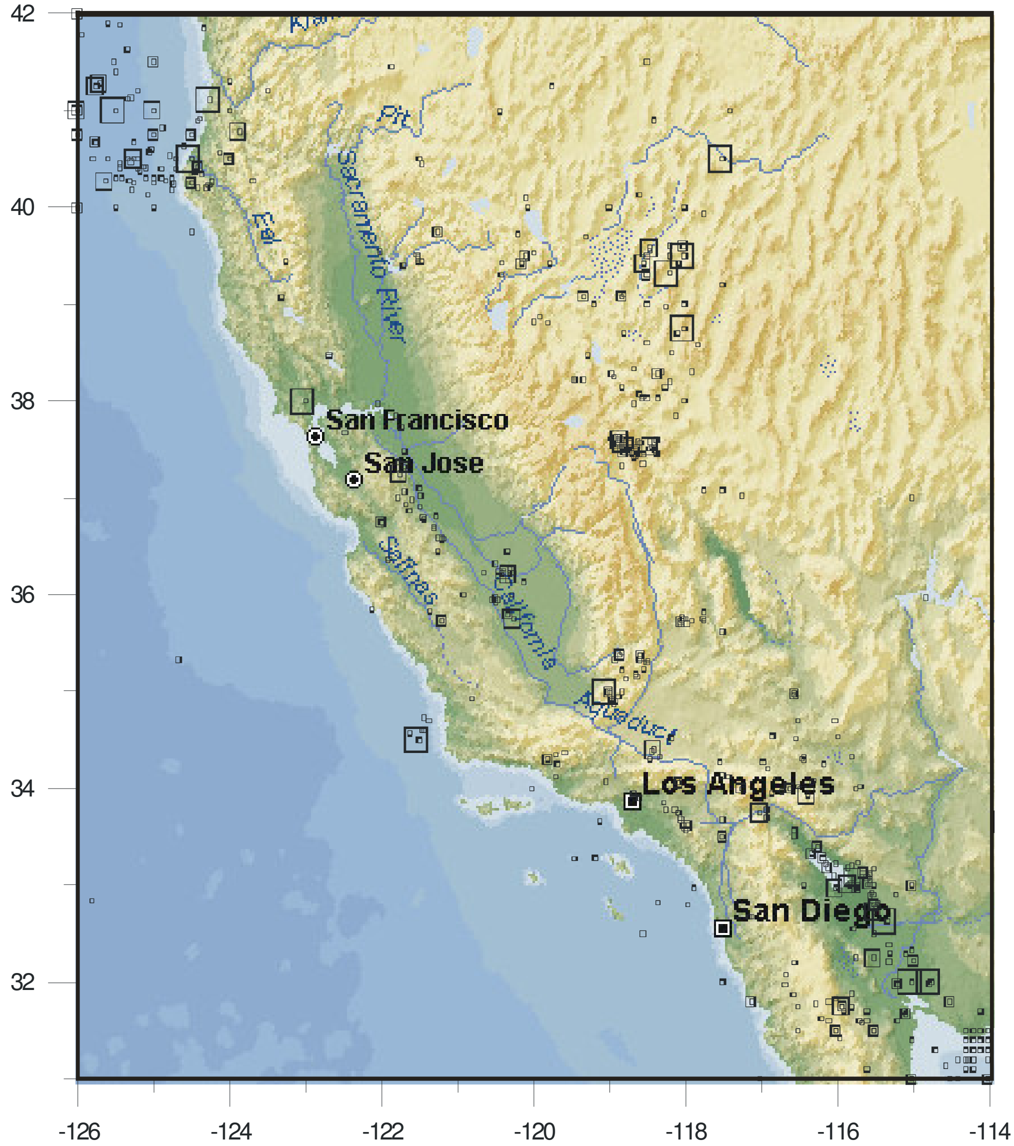


Figure 2.

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

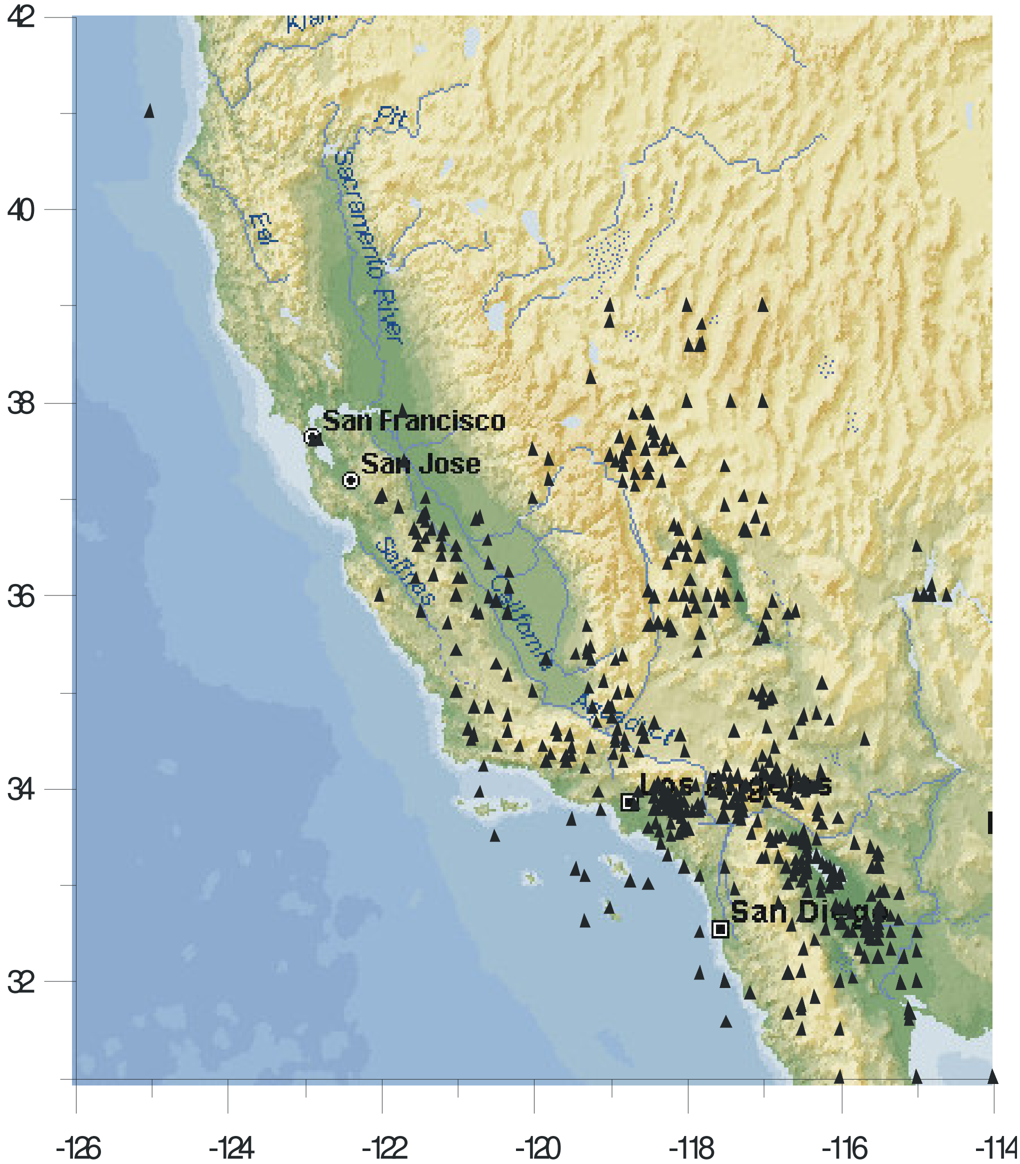


Figure 3

Bath diagram for California & Nevada earthquakes

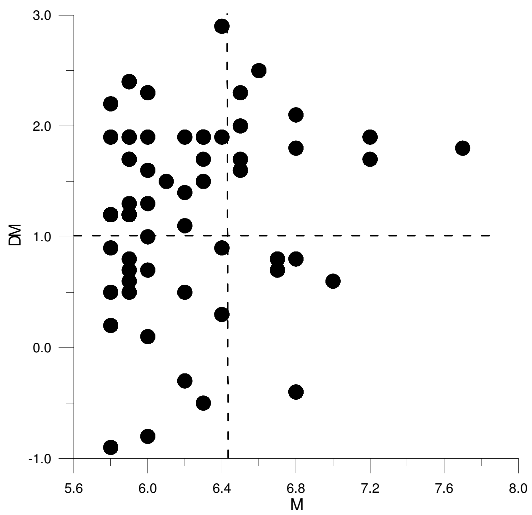


Figure 4.

Determining of time and spase parameters in formulation of the problem

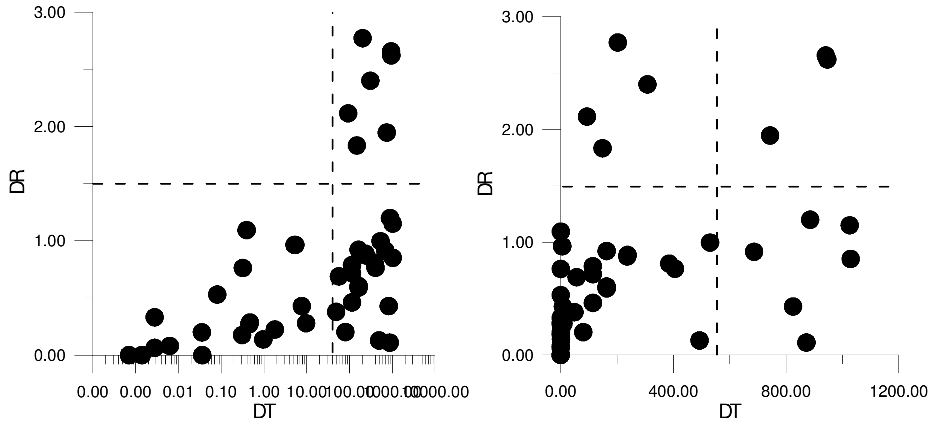


Figure 5

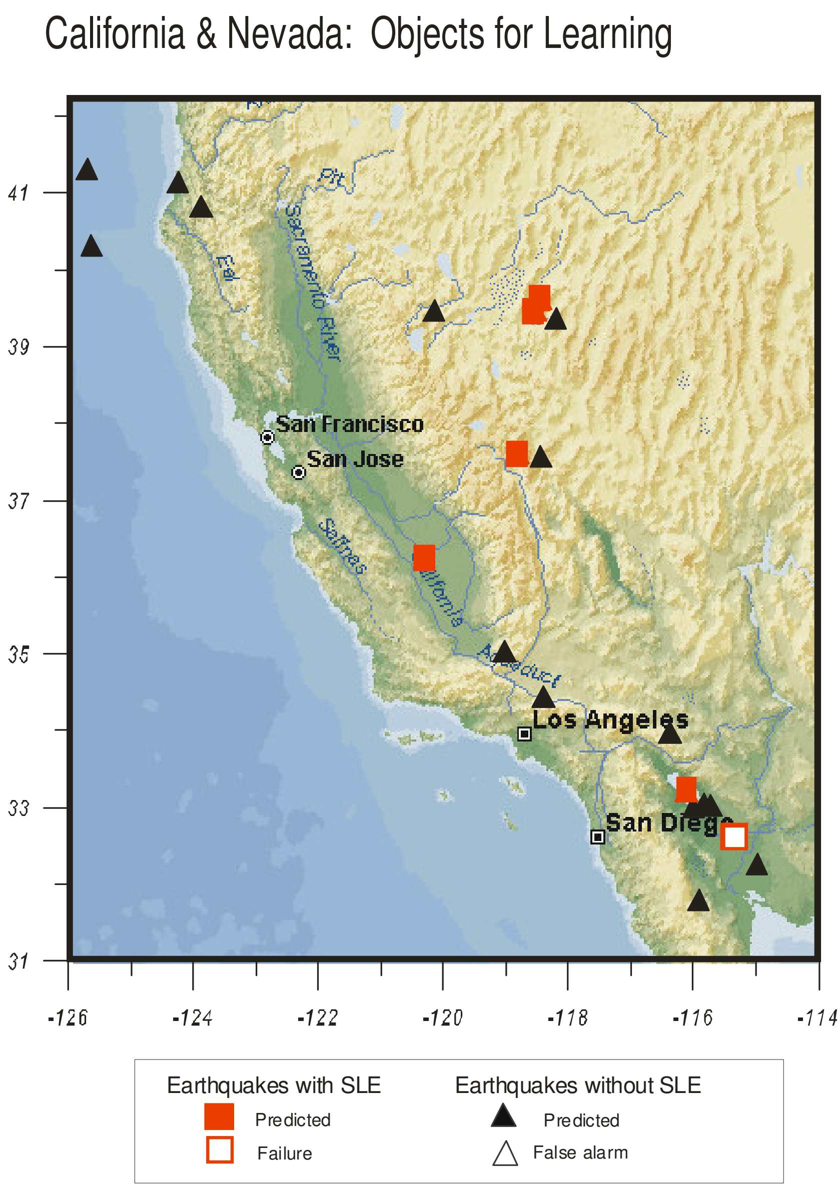

California & Nevada: Objects for Learning
41
39
37
35
33
31
-126
-124
-122
-120
-118
-116
-114
San Francisco
San Jose
Los Angeles
San Diego
Sacramento River
Pit
Eel
Salinas
Aqueduct
Earthquakes with SLE
Predicted
Failure
Earthquakes without SLE
Predicted
False alarm

Figure 6.

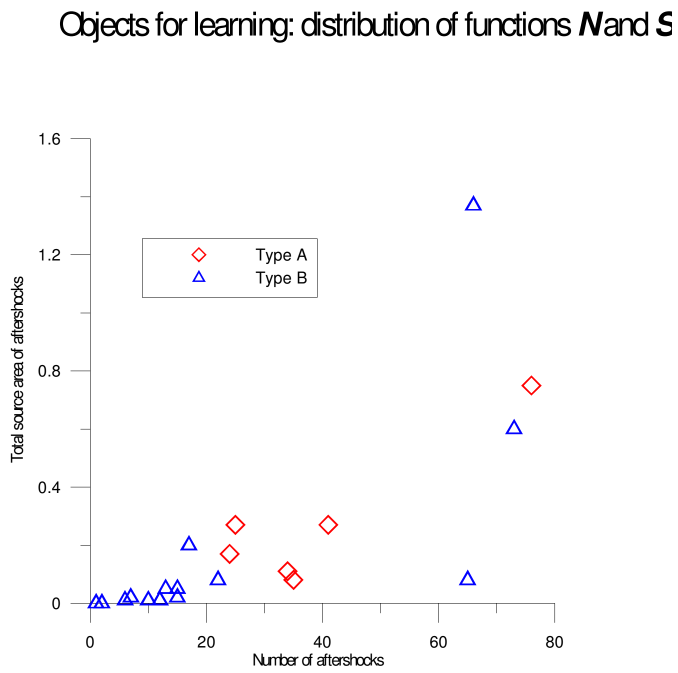


Figure 7

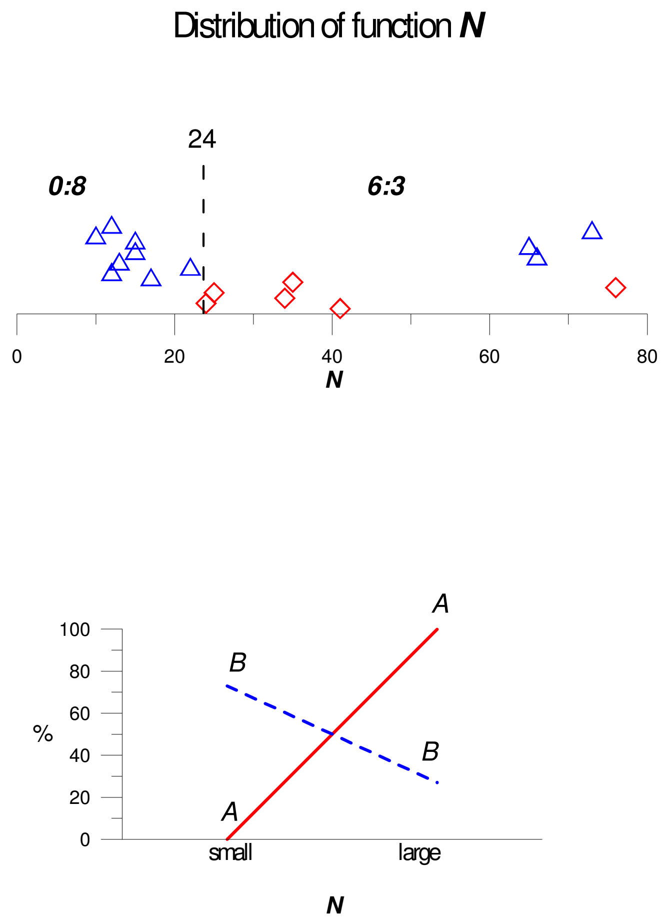


Figure 8.

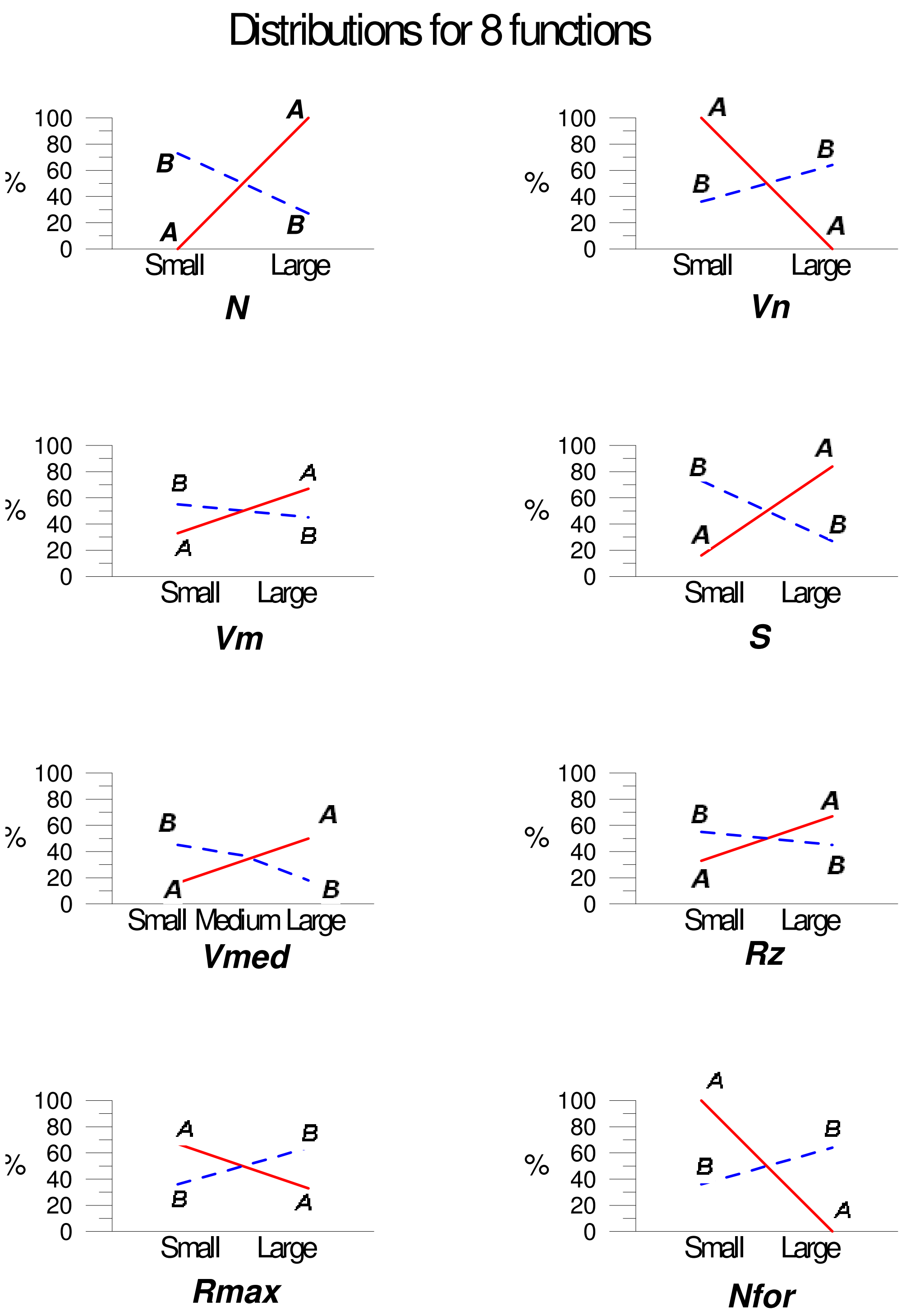
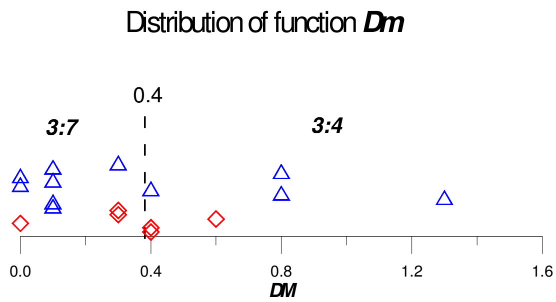

Distributions for 8 functions
100
80
60
40
20
0
%
A
B
Small
Large
Medium
N
Vn
Vm
S
Vmed
Rz
Rmax
Nfor

Figure 9.



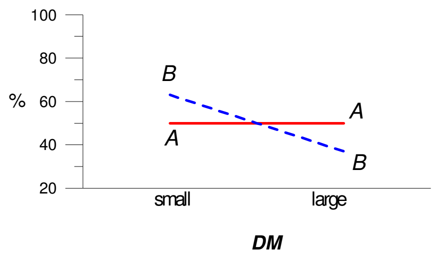


Figure10

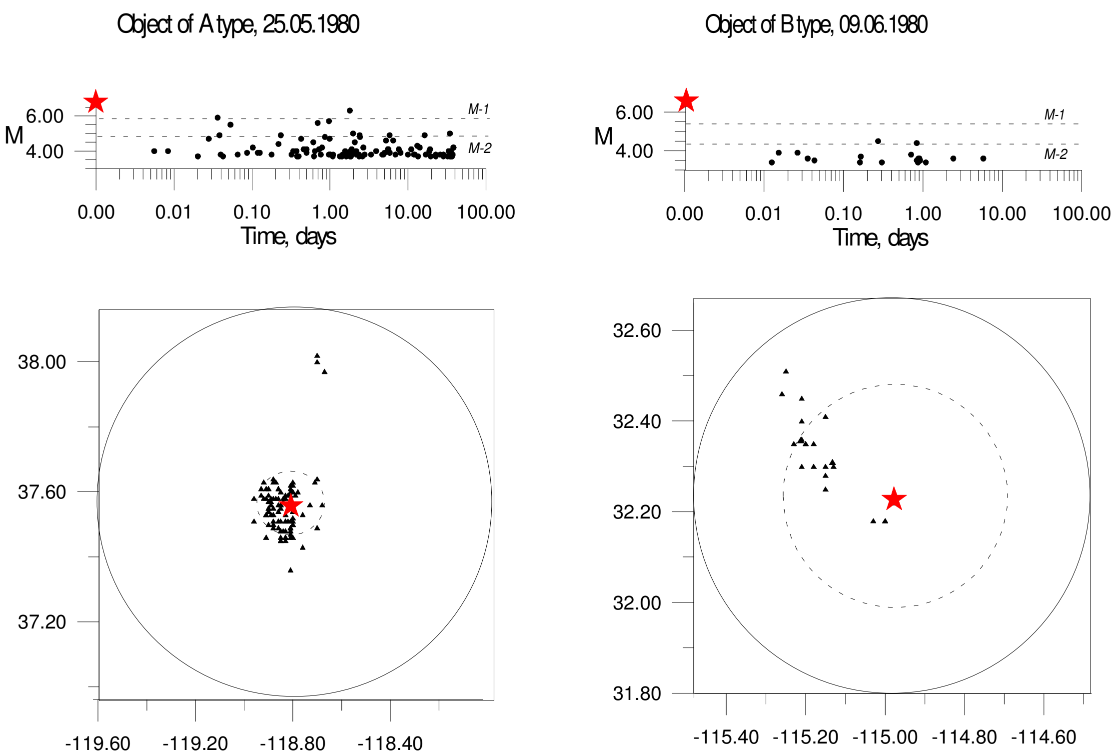


Figure 11

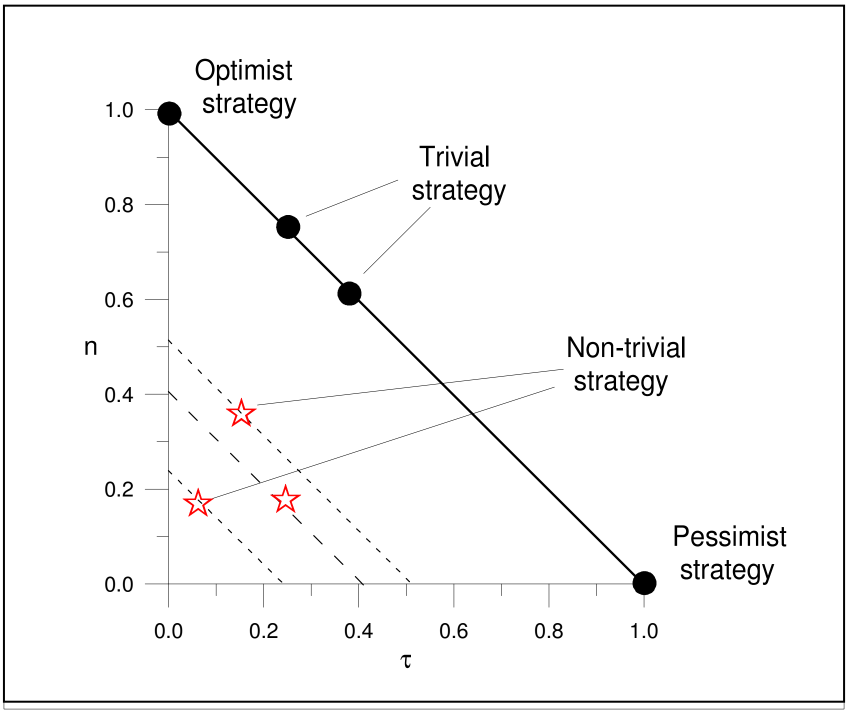


Figure 12

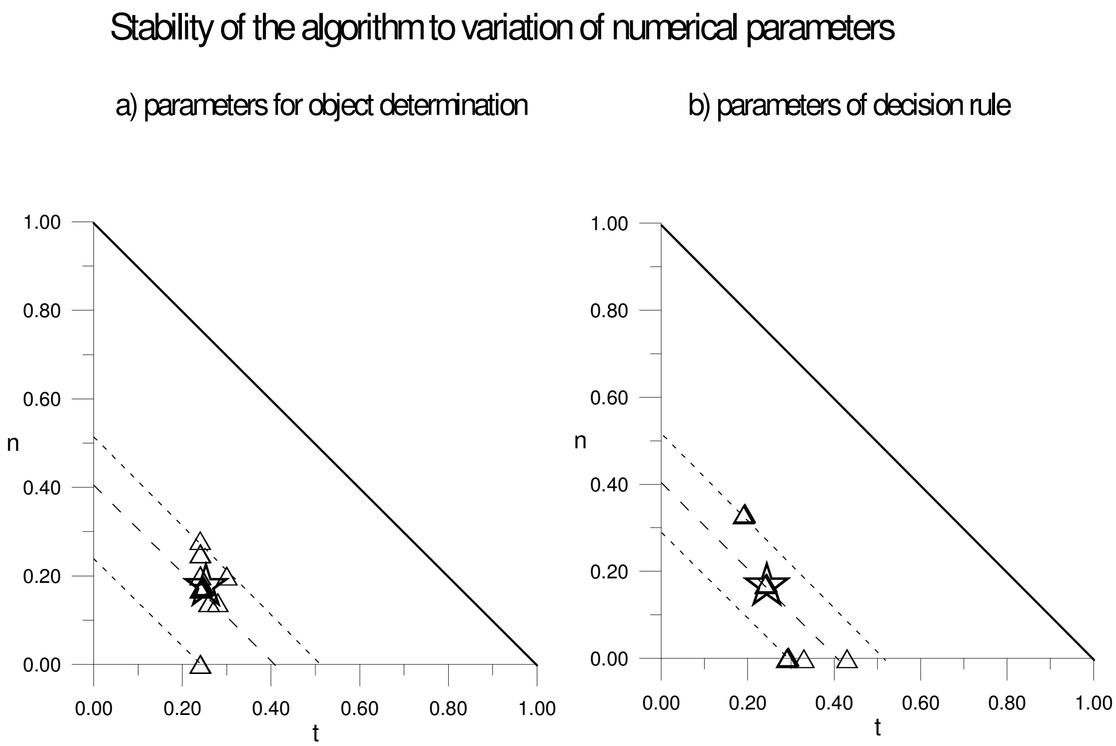


Figure 13

Stability of the algorithm to errors in data

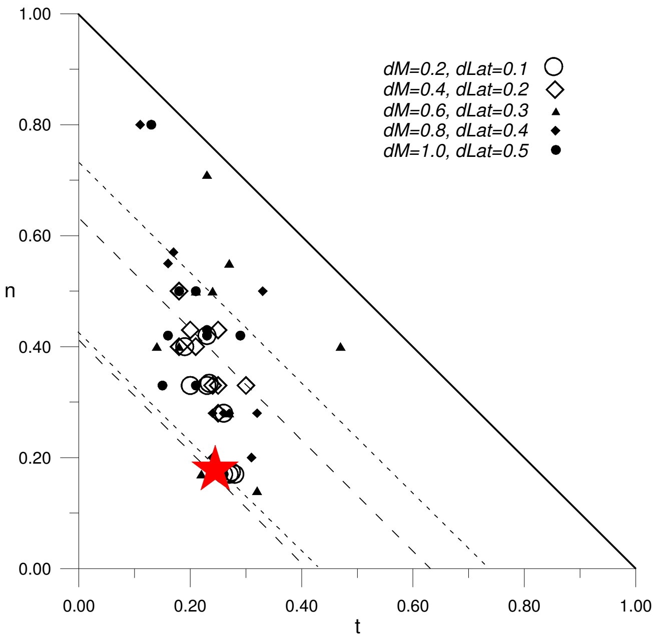


Figure 14

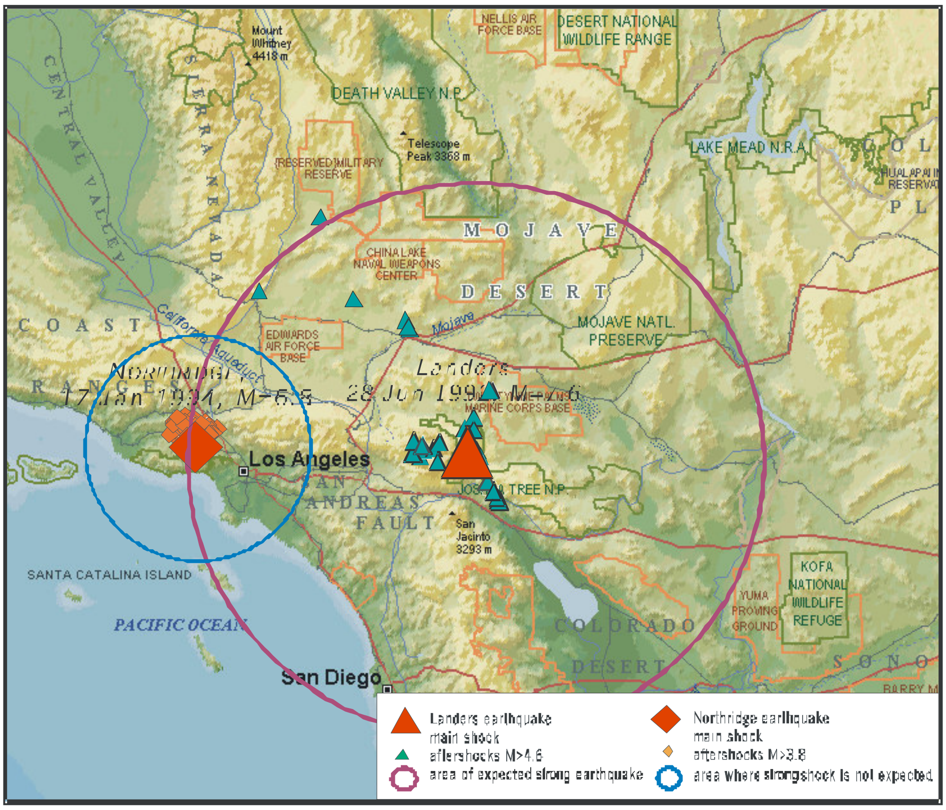


Figure 15

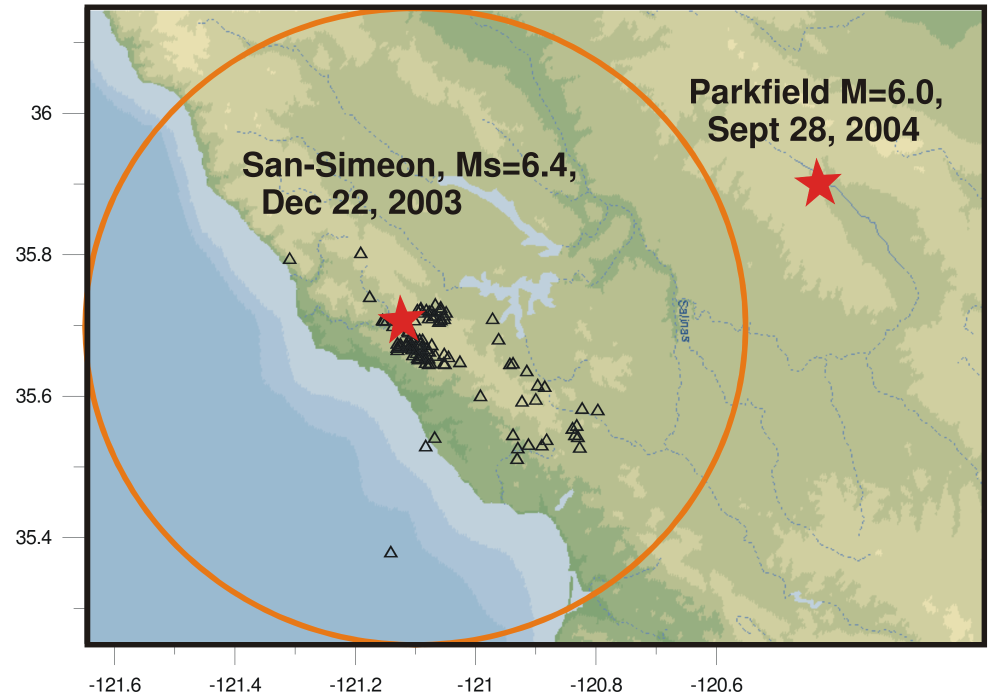


Figure 16

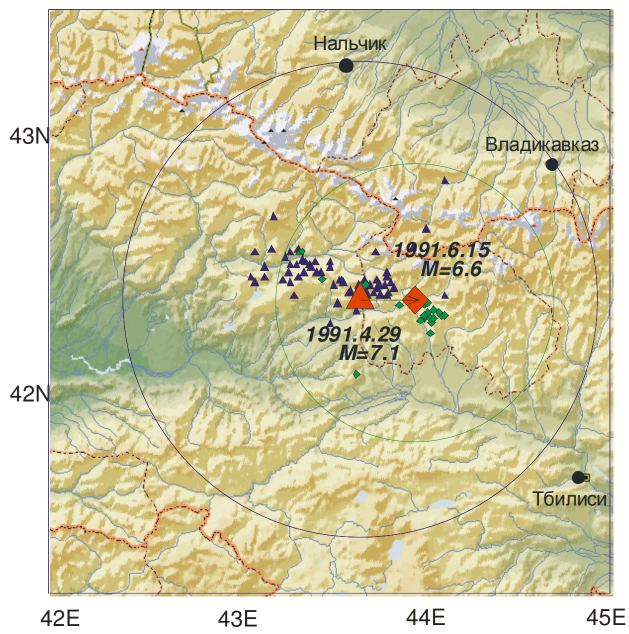


Figure 17

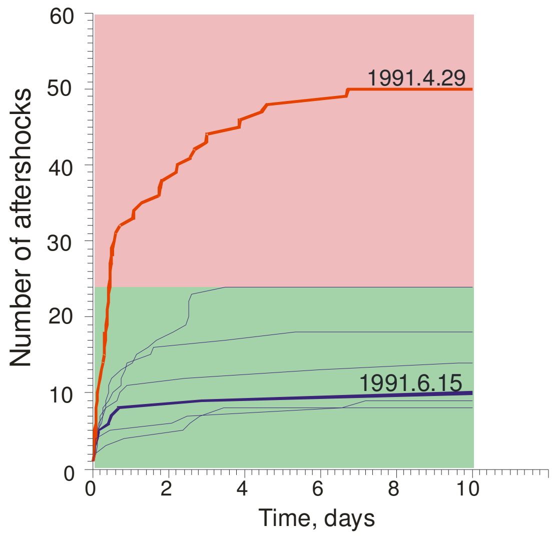


Figure 18

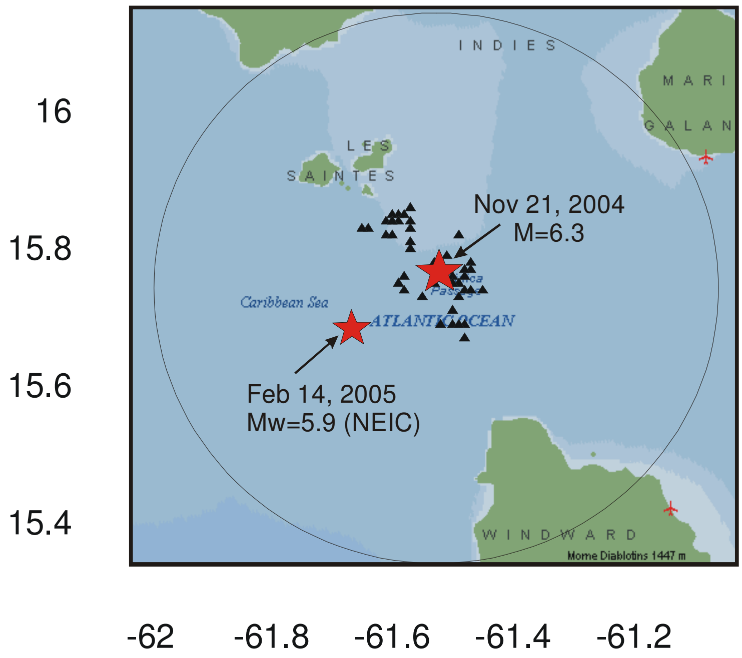

16
15.8
15.6
15.4
-62
-61.8
-61.6
-61.4
-61.2
INDIES
MARI
GALAN
LES
SAINTES
Nov 21, 2004
M=6.3
Caribbean Sea
ATLANTIC OCEAN
Feb 14, 2005
Mw=5.9 (NEIC)
WINDWARD
Morne Diablotins 1447 m

Figure 19.