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Prediction of subsequent large earthquake

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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 seismic process. 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 error 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.

30 advance predictions have been made since 1989, including 1991 Rachi earthquake (Georgia, Caucasus), and Californian earthquakes: Loma-Prieta, 1989; Joshua Tree, 1992; 1992 Landers, and Northridge, 1994. 24 were correct; among the six errors there were four 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.

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 increase; 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. 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. (Keilis-Borok and. 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. Aftershocks are counted within the same distance $R(M)$; 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 with different magnitudes. It allows using the algorithm without additional adaptation in the different regions.

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 located. The area of the circle is proportional to the 10^M , where M is magnitude of main shock. 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 period of time. The following 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 they are not more than several tens, and the methods of pattern recognition are preferable comparing with statistical methods. 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 is described by vector that components present 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. Learning material.

California & Nevada seismoactive region was chosen as experimental one for designing the algorithm for prediction of SLE. 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 1942 for this region
4. There are many large earthquakes with good reported aftershock series, which contain information on SLE preparation.

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.

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 2. 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 objects 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.

Consider the distribution ΔT and ΔR for all subsequent large shocks to determine time and space limits,. It is shown in the figure 3a,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.

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 distance 1.5 $R_0(M)$ from the epicenter of first earthquake. 26 earthquakes with magnitude $M \geq 6.4$ occurred in California & Nevada from 1942 to 1988 (table 1). 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 also typical for other regions; it is specific feature of the problem.

1.6 Function representing premonitory phenomena.

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.

The following functions were chosen:

Functions reflecting activity of aftershock sequence. We expect 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 expect 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 expect 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 1.5*R*.

It is hard to guess small or large values of this function are premonitory, because activation as well as seismic quiescence 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.

The values of parameters will be chosen analyzing the learning material.

1.7 Two steps of recognition

Let us compare the activity of aftershock sequences of classes *A* and *B*. In the plot (figure 4) 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 are not enough to 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).

1.8 Choice of numerical parameters for function representing premonitory phenomena

The values of numerical 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 5 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* are 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 6. The typical values for all of them are as expected in accordance with the hypothesis of process of preparation of SLE. Numerical parameters of functions are shown in Table 2 as well as values typical for *A* objects, thresholds for discretization and quality.

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 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 3.

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 4. 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 clearly seen. In the first case number of aftershocks and their magnitudes are larger, activity lasts all 40 days, it is inhomogeneous in time, and aftershocks are concentrated near the epicenter of main shock. In the second case activity decays 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.

Firstly we test the algorithm on the independent data – large earthquakes in different seismoactive regions of the world, and then by prediction in advance with all prefixed parameters.

2.1. Test on the independent data

All numerical 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. The algorithm was tested in all the regions, where data was available. It showed good applicability everywhere, excluding zones of the highest seismic activity, i.e. Pacific and Indian oceans subduction zones. Here the algorithm does not work.

Following 8 regions were chosen for retrospective test of algorithm; the value of M_0 is given in parentheses (Vorobieva and Levshina, 1994, Vorobieva and Panza, 1993):

Balkans (7.0),
Pamir and Tien-Shan (6.4),
Caucasus (6.4),
Iberia and Maghreb (6.0),
Italy (6.0),
Lake Baikal region (5.5),
Turkmenia (5.5),
Dead Sea Rift (5.0).
Antilles (6.0)

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 result of retrospective test is given in Table 4. 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)

*2.2. The results of 1989-2005.10 monitoring***.**

All large earthquakes that occurred in the ten regions 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 5.

30 large earthquakes were tested, 8 were followed by SLE, and 6 were successfully predicted. 10 alarms were declared. Up to now 24 predictions were correct, and there were 6 errors: 4 false alarms and 2 failures-to-predict.

As prediction in advance is made with all prefixed parameters it is possible to estimate its statistical significance. Let us calculate the probability of getting such a result by chance. The probability of guessing 6 or more subsequent large earthquakes from a total of 8 among 30 cases, using 10 alarms, is:

$$\varepsilon = [C_{22}^{4} C_{8}^{6} + C_{22}^{3} C_{8}^{7} + C_{22}^{2} C_{8}^{8}] / C_{29}^{9} < 0.5\%,$$

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

2.3 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 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 overestimated by 0.2-0.3. This generated false alarm. False alarm after Pakistan earthquake, October 8, 2005, M=7.6 is “unforced error” All four cases are counted as errors while estimating statistical significance 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 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 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≥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≥3.4. It produced an alarm for an earthquake with M≥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≥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≥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. 30 large earthquakes were tested for the last 18 years, producing only 6 errors: 4 false alarms (2 of them were confirmed informally) and 2 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 retrospective 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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Table 1. 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/R_0	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, $N_{aft} \geq 10$, 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 2. Typical values, effectiveness and numerical parameters of 8 functions.

Function	Value	Informati vennes	Values of parameters				Threshold values	
	Typical for A	%	*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 3. 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 4. 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**

Table 7. The results of 1989 - 2007.10 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 alarm
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
Central Asia				
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
Pakistan 10/08/2005	7.6	YES	No shocks with M≥6.6	False alarm

Origin Earthquake		*Will a subsequent shock occur*?	*Note*	*Outcome of prediction*
Turkmenia				
Iran 5/10/1997	7.5	NO	No shocks with M≥6.5	Confirmed, first step
Turkmenia 6/12/2000	7.5	NO	No shocks with M≥6.5	Confirmed.
Iberia & Maghrib				
Morocco 5/26/1994	6.0	NO	No shocks with M≥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≥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≥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≥6.5	Confirmed
Antilles				
12/21/2004	6.3	YES	Earthquake with M=5.9 occurred	Confirmed

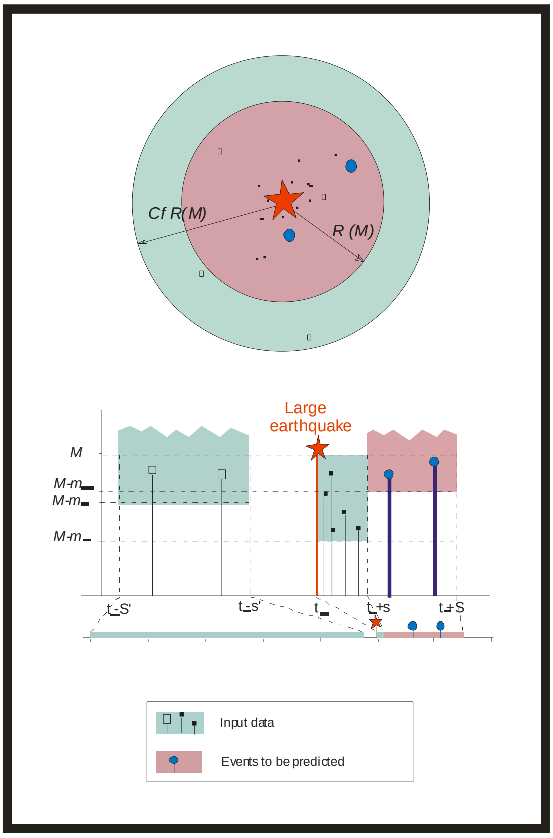

Figure 1. Formulation of the problem.

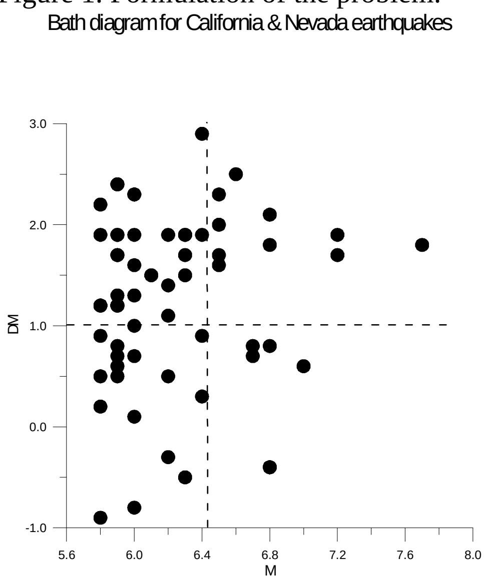

Figure 2. Both diagram for California &Nevada $M \geq 5.8$, 1942-1988

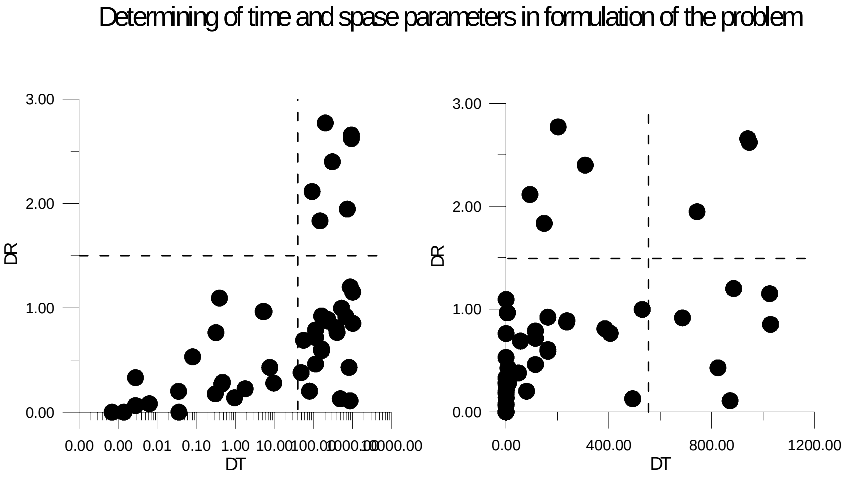

Figure 3 Distribution of SLE in time and distance

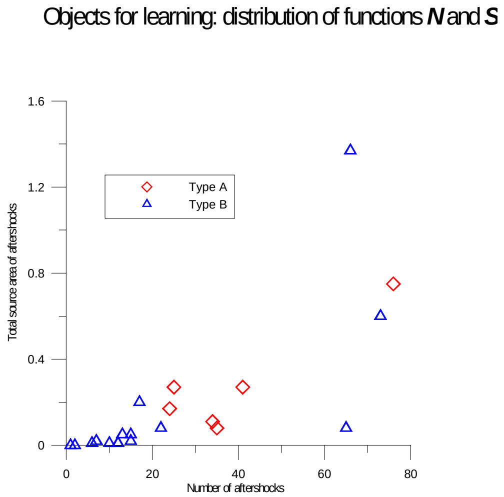

Figure 4 Distribution of function ***N*** and S: objects for learning

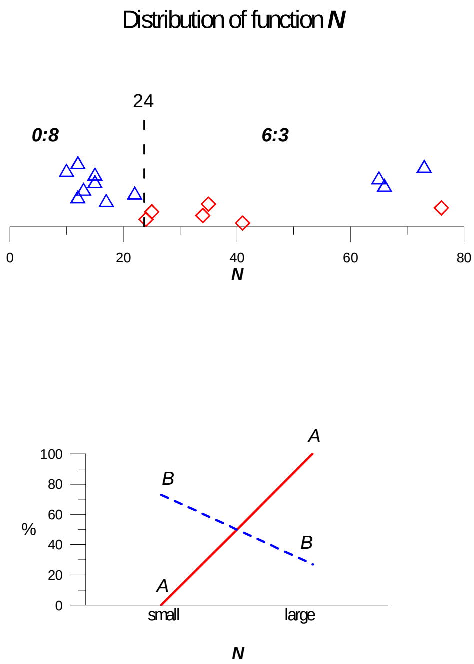

Figure 5 Distribution and histogram for function ***N***.

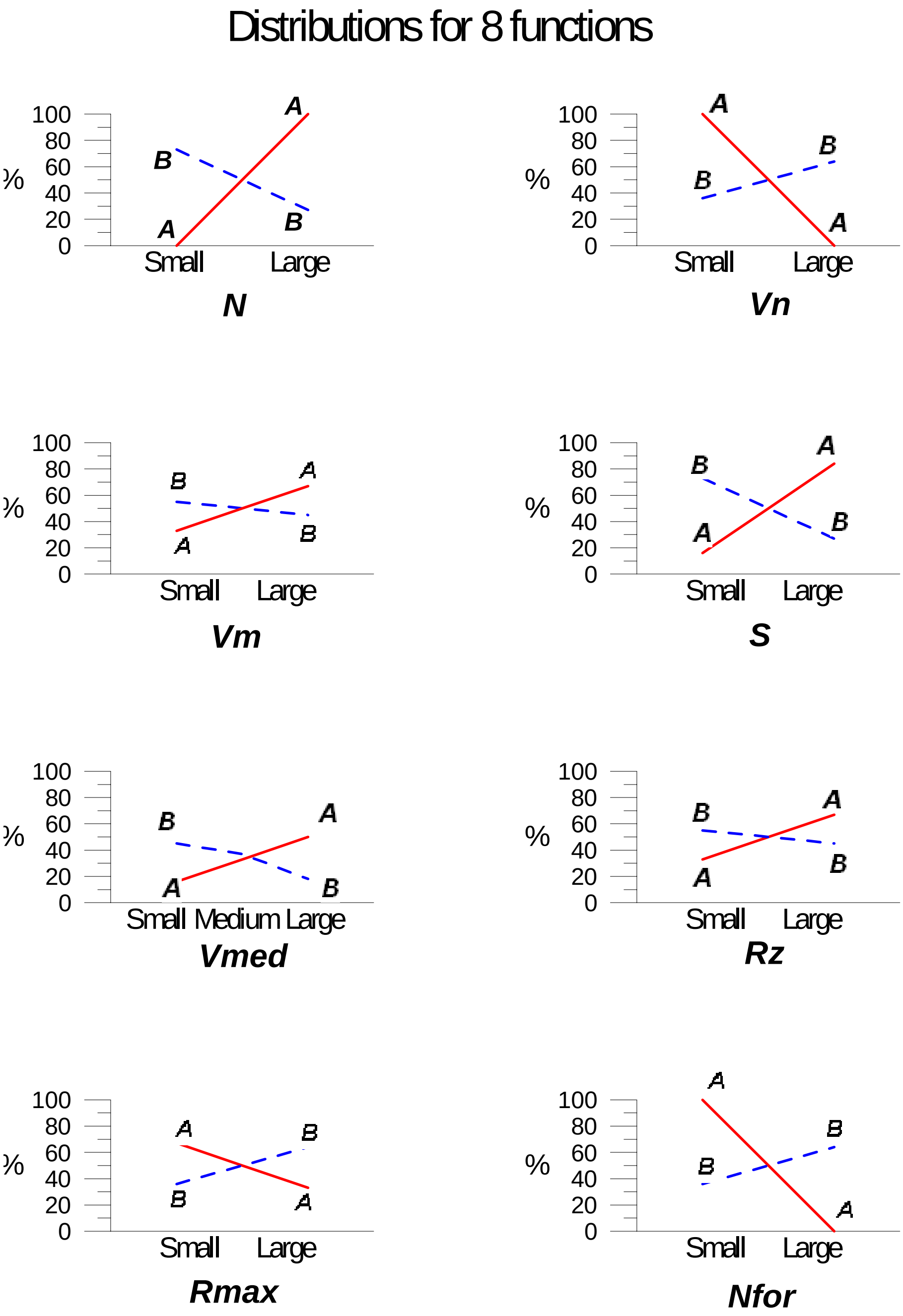

Figure 6. Histograms for 8 functions

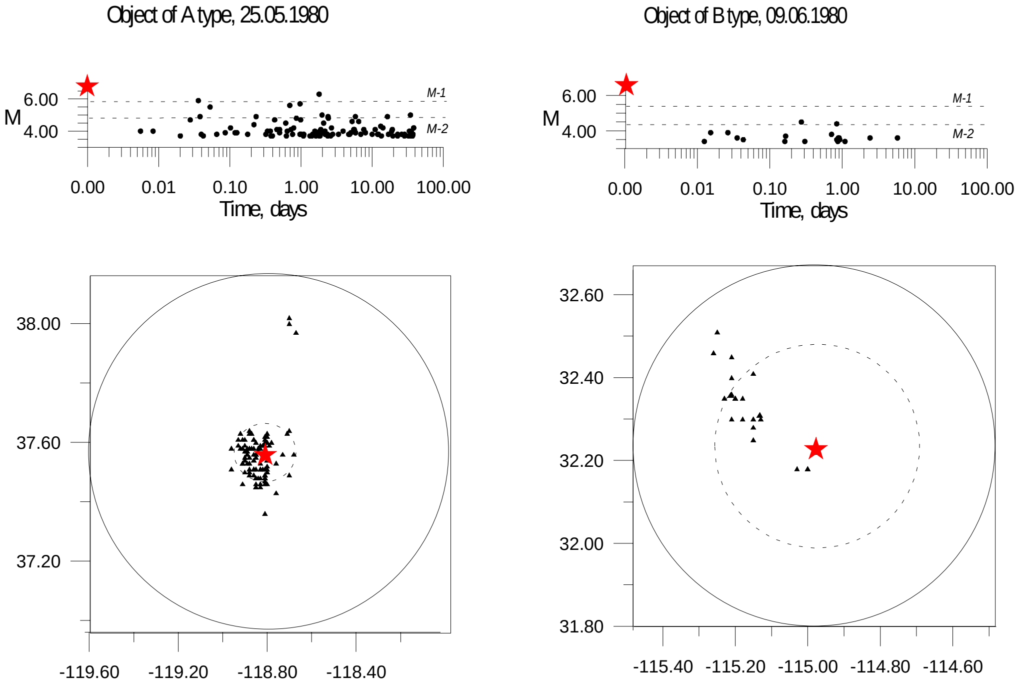

Figure 7 Typical objects *A* and *B.*

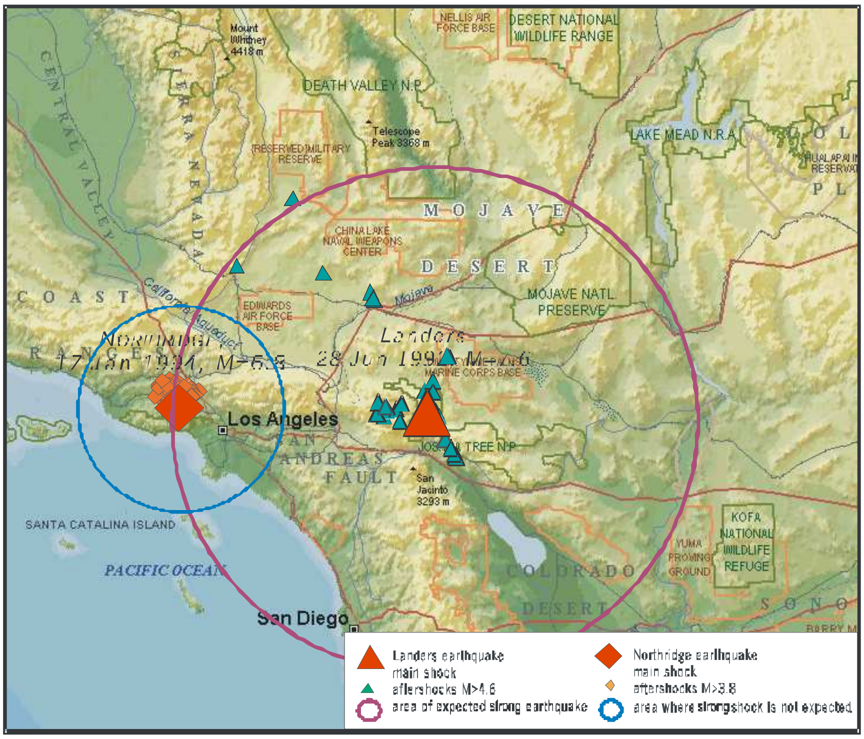

Figure 8 Joshua Tree, Landers**,** and Northridge earthquakes and their aftershocks.

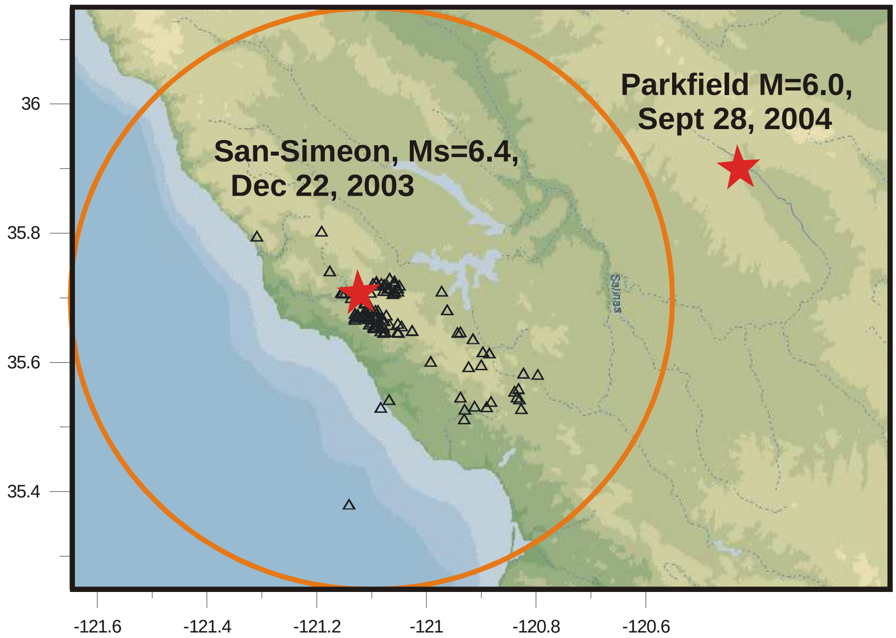

Figure 9 San-Simeon earthquake and its aftershocks.

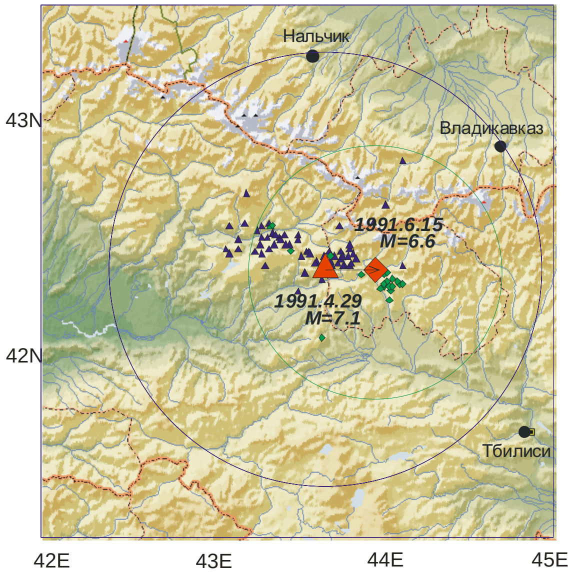

Figure 10 Rachi earthquakes and their aftershocks

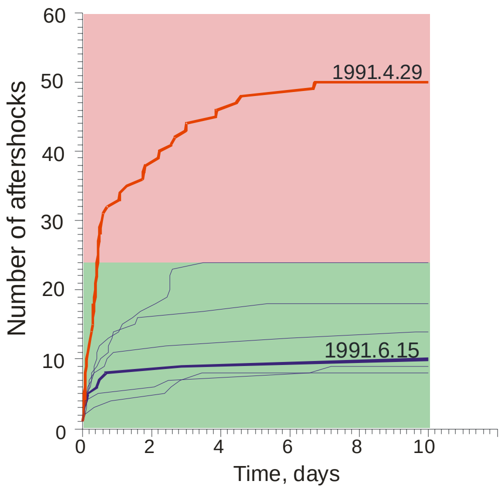

Figure 11. The aftershock sequences of 1962-1992 Caucasian earthquakes in time

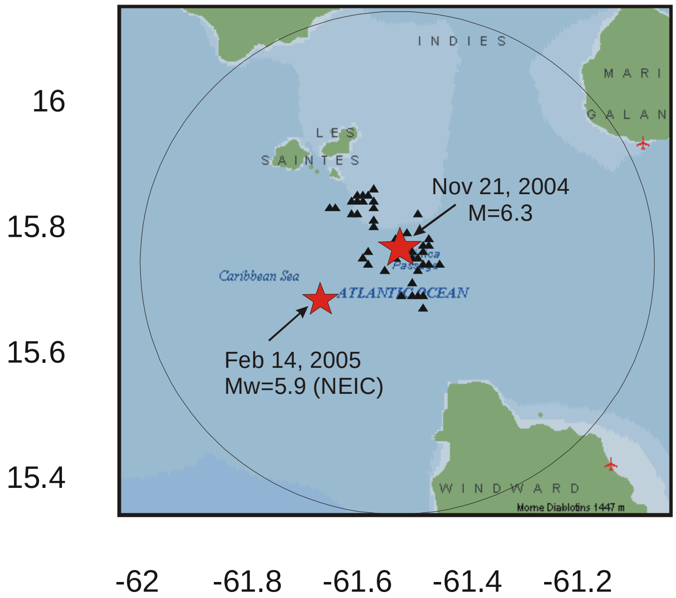

Figure 12. Antilles earthquake and its aftershocks