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Prediction of a Subsequent Large Earthquake

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1. Introduction

Many large earthquakes come in pairs, separated by relatively small times and distances. Predicting the occurrence of a subsequent large earthquake 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 leading to 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.; a 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 found (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 us to predict correctly whether subsequent earthquakes would occur or not; the only mistake was a error failure-to-predict. The algorithm with all parameters fixed was then tested in different regions of the world, by application to 98 large earthquakes, 10 of which were followed by a subsequent large shock. 92 predictions were correct; among the six mistakes were four false alarms and two failures-to-predict.

Here we sum up the results of 25 advance predictions which have been made since 1989, including predictions for the 1991 Rachi earthquake (Georgia, Caucasus), and three 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. 21 were correct;

among the four mistakes were two false alarms and two failure-to-predicts. The statistical significance of advance predictions exceeds 99%.

2. Description of the Algorithm

2.1. Formulation of the problem

Consider a large earthquake with magnitude M and occurrence time t. The problem is to predict whether a subsequent large earthquake with magnitude $M_1 \geq (M - a)$ will occur before the time $(t + S)$ 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' 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).

The idea of prediction here is the same as in predicting a first large main shock (algorithms CN (Keilis-Borok and Rotwain, 1990), M8 (Keilis-Borok and Kossobokov, 1990)). According to these algorithms, a large earthquake is preceded by changes in the earthquake's flow: it becomes more intense and irregular in space and time. These changes are akin to the general symptoms of instability in many nonlinear systems. In our case the system is a set of earthquake-generating faults.

2.2.Hypothesis:

Similar symptoms in aftershocks of the first large shock—i.e., high activity and irregularity—precede the occurrence of a second large event in the vicinity of the first shock.

2.3.Similarity.

In order to make comparable the aftershock sequences of earthquakes of different magnitudes, the aftershocks were normalized by magnitude of the large main shock M and:

- a lower cutoff magnitude, $M - 3$, of aftershocks is analyzed;
- the area is a circle with radius $R = 0.03 \times 10^{0.5M}$ [km];
- the magnitude of shocks predicted is $M \geq M$ - 1; and
- the period of time is from 40 days to 1.5 years after the first shock.

The similarity of premonitory phenomena is presumed after normalization.

2.4. Design of the algorithm.

The prediction algorithm for the occurrence of a subsequent large earthquake was found by retrospective analysis of 21 large California earthquakes with $M \geq 6.4$ (Vorobieva and Levshina, 1994), as follows:

Prediction is made in two steps.

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

(ii) If this number is D or more, we determine eight characteristics of seismicity (listed below) which reflect premonitory phenomena, then a pattern recognition technique known as the Hamming distance is used (Gvishiani et al., 1980).

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 more characteristic is the number of earthquakes in the time interval (t - S', t - s') preceding the first large earthquake.

2.5. Functions representing the premonitory phenomena.

Large values of the following functions are premonitory:

1. ***N***, number of aftershocks with magnitude $M \geq M$ - m during [$t + s_1$, $t + s_2$];

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

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

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

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,*** 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.

Small values of the following functions are premonitory:

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

$$\boldsymbol{Vn} = \Sigma|\mathrm{n}_{i+1} - n_i|,$$

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

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; and

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 $1.5R$.

The values of parameters in the functions were chosen as shown in Table 1.

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

2.6.Reduction to pattern recognition.

In terms of pattern recognition, the problem is as follows. There are two types of large earthquakes: type *A,* which are those followed by a subsequent large shock; and type *B,* where there is a single large shock. Given a large earthquake, the *s*-days aftershocks, and the earthquakes preceding the main shock, determine whether the earthquake is type *A* or *B*.

To develop a decision rule we used "learning material" consisting of large earthquakes of types *A* and *B,* and their aftershock sequences, in California, using objects for recognition as follows.

The first step is discretization. Values of each function, excluding ***Vmed,*** were divided into two intervals, "large" and "small," so that the number of objects in each interval was equal. The values of function ***Vmed*** were divided into three intervals "large", "medium " and "small." The discretization thresholds are given in Table 1.

The second step is to determine the "typical" values. For each function, we count how often it was "large" (or "small") in A, and how often in B. If a function is "large" (or "small") for at least 2/3 of all A objects and less than 1/2 of B objects, this value is assumed to be typical of A, and similarly for B.

The last step is voting. For each aftershock sequence we count two numbers, n_A and n_B. n_A is the number of functions that are typical of *A*, while n_B is the same for *B*.

Decision rule: If n_A - $n_B \geq 3$, the earthquake is of type A (a subsequent large shock will occur); if n_A - $n_B < 3$ the earthquake is of type B (a subsequent large shock will not occur).

3. Performance

3.1 Retrospective test of the algorithm

The algorithm described here was developed on the data for California and then tested retrospectively with prefixed parameters in the following eight regions (Vorobieva and Levshina, 1994, Vorobieva and Panza, 1993) (the lowest value of *M* considered is given in parentheses): the Balkans (7.0), the Pamir and Tien-Shan (6.4), the Caucasus (6.4), Iberia and Maghrib (6.0), Italy (6.0), Baikal and Stanovoi Range (5.5), Turkmenia (5.5), and the Dead Sea Rift (5.0).

The results of retrospective testing are given in Table 2.

Two parameters have to be adjusted for each region: the boundary of the region and the cutoff magnitude of large earthquakes, M_0.

3.2. Choice of region.

The formal definition of the algorithm enables it to be applied to any large earthquake, if a representative catalog is available. In the Pacific subduction zones, however, the algorithm does not work. In the regions listed in Table 1 less than 15% of large earthquakes have a second large shock. For shallow earthquakes in subduction zones, this value is 30-40% if the same $R(M)$ and time intervals are used. The most important difference is that the occurrence of a subsequent large shock does not depend on the rate of events in the aftershock sequence of the first earthquake. For example, consider the Japanese earthquakes. There are 75 large, shallow earthquakes with magnitude $M \geq 7.0$. Of these, 29 have less than 10 aftershocks with magnitude $m \geq M$-3 within the circle $R(M)$ during the first 40 days, and 46 earthquakes had more than 10 aftershocks. The relative number of subsequent large shocks is the same for earthquakes with few aftershocks as for earthquakes with many aftershocks: 11 of 29 and 16 of 46, respectively (compare with Table 2). This fact demonstrates that an algorithm based on the rate of events in the aftershock sequence will not work in such regions.

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

3.3. 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. The tests were carried out with magnitudes M_0+0.2 and M_0-0.2, however, for all regions under study (Table 2). 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 2). Lower cutoff magnitudes lead to considerable increases in the number of errors. There are 18 errors (seven false alarms and eleven failures-to-predict) in a total of 171 earthquakes. The increase in number of failures-to-predict can be explained by the incomplete earthquake catalog, but there are three more false alarms, all in California (Table 2), which cannot be explained by the limited catalog. This fact shows that one must be careful when reducing M_0, even if the catalog is complete. This requires special investigation in each region.

3.4.The results of 1989-2001.10 monitoring.

All large earthquakes that occurred in the nine regions (Table 2) were monitored by the algorithm with prefixed parameters. (Levshina and Vorobieva 1992, Vorobieva, 1994) The results of the *advance predictions* are given in Table 3.

The prediction results with the prefixed parameters can be summarized as follows (Table 4):

3.5. Statistical significance and effectiveness of the algorithm.

The statistical significance and effectiveness of the algorithm is estimated by the method proposed by Molchan (1997). Using the results of this prediction-in-advance it is possible to 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 five cases, using seven alarms, is:

$$\varepsilon = [C_{18}^{2}C_{7}^{5} + C_{18}^{1}C_{7}^{6} + C_{18}^{0}C_{7}^{7}]/C_{25}^{7} \approx 0.7\%$$

where C_n^k are binomial coefficients.

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

ΔN	1	0	-1	-2
ε,%	0.56	0.70	0.86	1.07

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

The results of these predictions can be characterized by two quantities, n and τ. Here n is the relative number of the failures-to-predict, and τ is the relative alarm in the entire prediction space. The quantity $e=1-n-\tau$ is a characteristic of prediction effectiveness, because the case $e=0$ corresponds to the random guess strategy. We can estimate the effectiveness of an algorithm only approximately because the monitoring period is short and, consequently, the small number of N does not allow us to estimate n and τ reliably. In our case, n is 0.28 (2 failures-to-predict among 7 subsequent large earthquakes), and τ is 0.28 (7 alarms among 25 tested large earthquakes), so we have e=44%.

4. Case histories

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

4.1. 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 $m\geq3.3$ used for prediction are shown in Fig.2. This earthquake had a high rate of aftershocks (54 aftershocks with $m\geq3.3$), so it produced an alarm for an earthquake with $M\geq5.3$ within the distance $R(6.3)$=42 km, within 1.5 years of Joshua Tree. The voting of functions after Joshua Tree is shown in Table 5. 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 $m\geq4.6$ were used for prediction, as shown in Fig. 2. The aftershock sequence had few aftershocks (20 aftershocks with $m\geq4.6$), but they were strong and had a large total equivalent source area. It was predicted (Levshina and Vorobieva, 1992) that an earthquake with $M \geq 6.6$ would occur within the distance $R(7.6)=199$ km and within 1.5 years of the Landers earthquake; this alarm expired on 12 December, 1993. The voting of functions after Landers is shown in Table 5. The subsequent Northridge $M=6.8$ earthquake occurred within this distance, but 19 days after the expiration of the alarm, so that prediction was counted as a false alarm.

The Northridge earthquake of 17 January, 1994 was also tested for the occurrence of a subsequent earthquake with magnitude $M \geq 5.8$. Its aftershocks with magnitude $m \geq 3.8$ used for prediction are shown in Fig.2. In spite of many aftershocks (77 events with magnitude $m \geq 3.8$), the algorithm did not produce 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 such an earthquake did not occur. The voting of functions after Northridge is shown in Table 5.

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

The 3 August, 1993 earthquake in the Gulf of Aqaba occurred and had a magnitude of 5.8. The map of its aftershocks with magnitudes $m \geq 2.8$ used for prediction is shown in Fig.3. This earthquake had 171 aftershocks and produced an alarm. It was predicted that an earthquake with $M \geq 4.8$ would occur within a distance $R(5.8)=22$ km, within 1.5 years. The voting of functions after this earthquake is shown in Table 5. An earthquake with magnitude 4.9 occurred 92 days after the first one.

The largest earthquake in this region, with magnitude 7.3, occurred in the same place, two years later (on 22 November, 1995). The map of its aftershocks is shown in Fig.3. It had 14 aftershocks with magnitude $m \geq 4.3$, and did not produce an alarm. It was predicted that an earthquake with $M \geq 6.3$ would not occur within the distance $R(7.3)=135$ km, within 1.5 years, and there has been no such earthquake. The voting of functions after this earthquake is shown in Table 5.

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

4.3.Rachi, Caucasus, Georgia, FSU earthquakes of 1991.

The Rachi earthquake of 29 April, 1991 had a magnitude of M=7.1. The map of its aftershocks is shown in Fig.4. 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 15 June, 1991, magnitude 6.6 earthquake.

This later earthquake was also tested. The map of its aftershocks is shown in Fig.4. 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 has been 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 5 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.

5. Conclusions

The algorithm for predicting a subsequent large shock was successfully applied in different seismic regions of the world. 25 large earthquakes were tested for the last 12 years, producing only four errors: two false alarms and two failures-to-predict. The statistical significance of advance prediction is 99%. The algorithm can be used in other seismic regions, if the data are available. Of course, the algorithm must be tested first on the past data for each region.

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

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Figure captions

Fig 1. Formulation of the problem.

Fig 2. The Joshua Tree, Landers, and Northridge earthquakes and their aftershocks.

Fig 3. The Gulf of Aqaba earthquakes of 1993 and 1995 and their aftershocks.

Fig 4. The Rachi earthquakes of 1991 and their aftershocks.

Fig 5. The aftershock sequences of 1962-1992 Caucasian earthquakes in time.

Table 1. Values of parameters.

Function	Values of parameters				Threshold values	
	m	s_1, hrs	s_2, days	τ, days		
N	3	1	10	-	24	-
S	2	1	10	-	0.1	-
Vm	3	1	40	-	0.41	-
Vmed	3	1	40	-	0.7	2.6
Rz	3	10 days	40	10	0	-
Vn	3	1	40	-	0.98	-
Rmax	2	-	2	-	0.23	-
Nfor	1	5 years	3 mon.	-	2	-

Table 2. Retrospective test of the algorithm.

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

Table 3. The results of 1989 - 2001.10 monitoring.

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

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	Monitoring till 6/6/2002	
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

Table 4. The prediction summary with prefixed parameters.

Prediction: will a subsequent strong earthquake occur?		Number of predictions total/errors	
		in retrospect	in advance
Step (i)	NO	52/1	4/1
Step (ii)	NO	34/1	14/1
Step (ii)	YES	12/4	7/2
Total		98/6	25/4

Table 5. Voting of functions for Joshua Tree, Landers, Northridge, Gulf of Aqaba, and Rachi earthquakes.

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

Prediction of a subsequent strong earthquake: Formulation of the problem

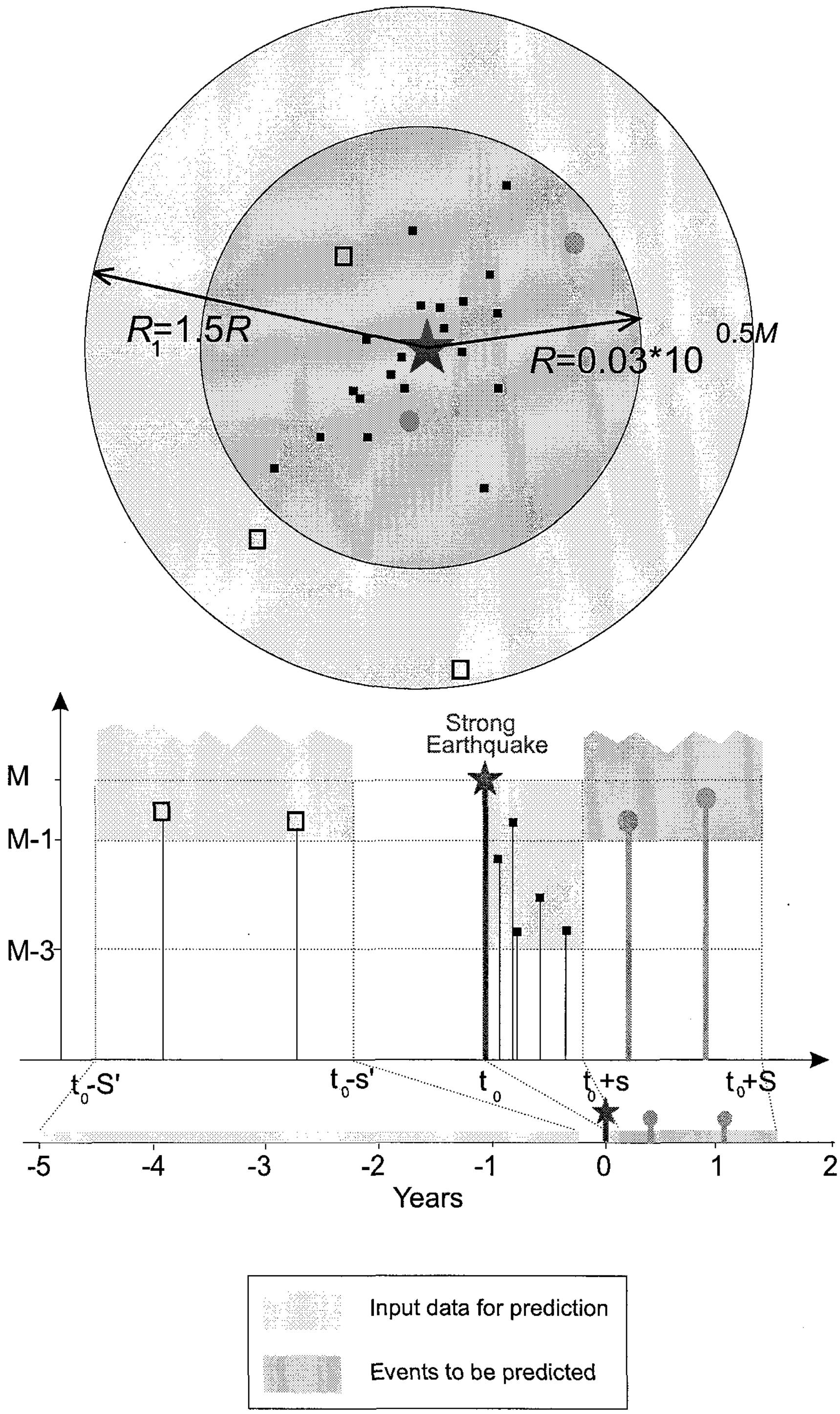
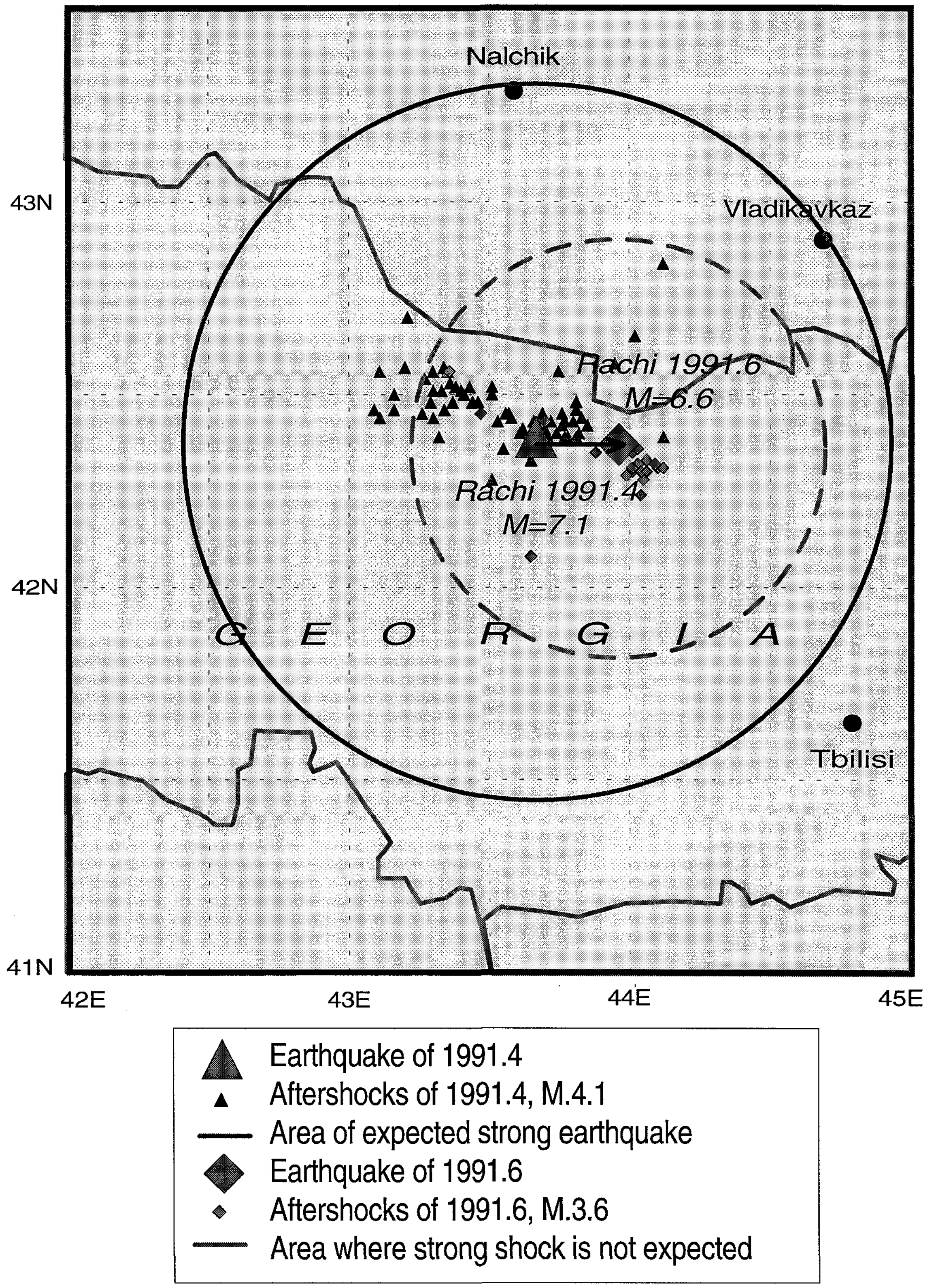
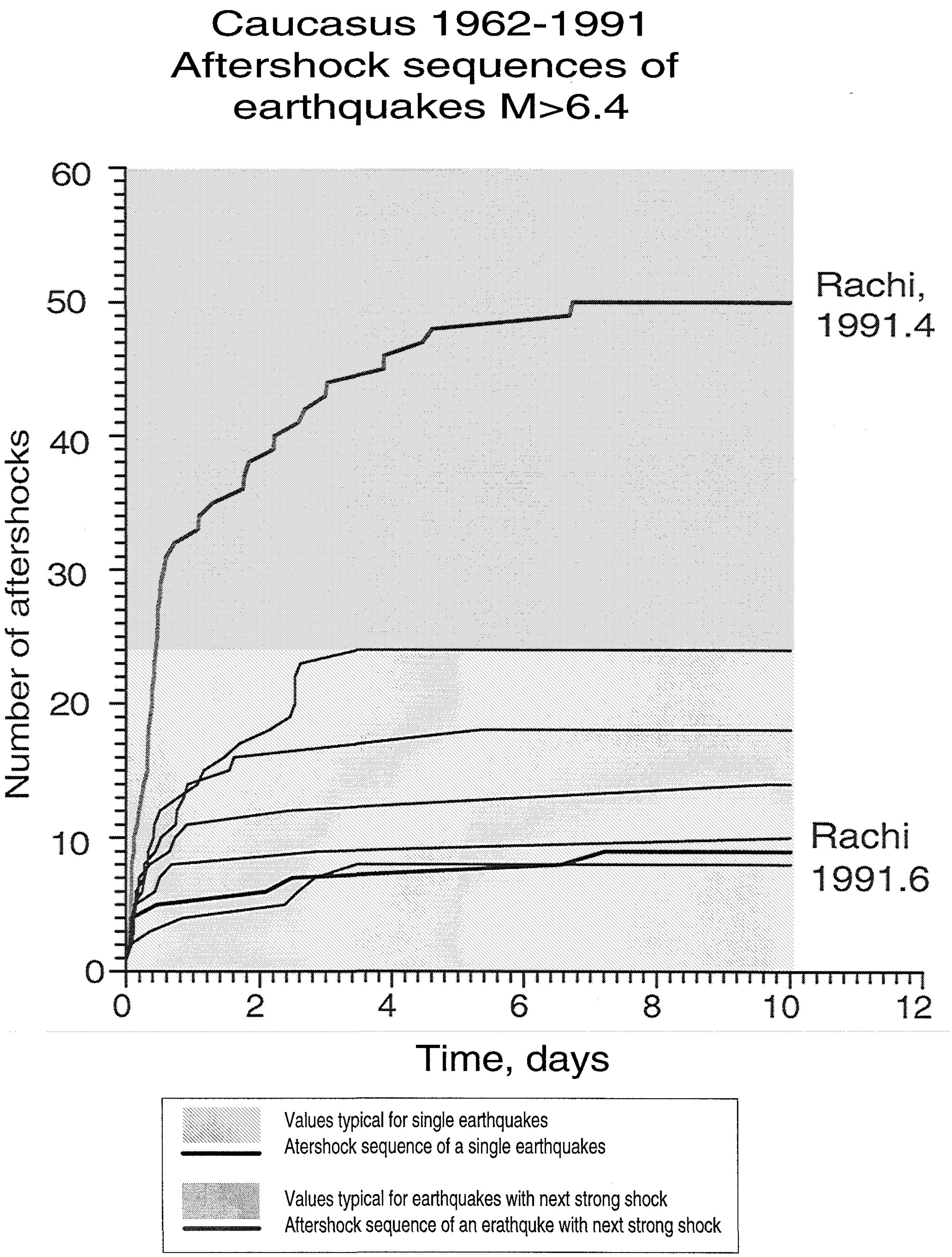


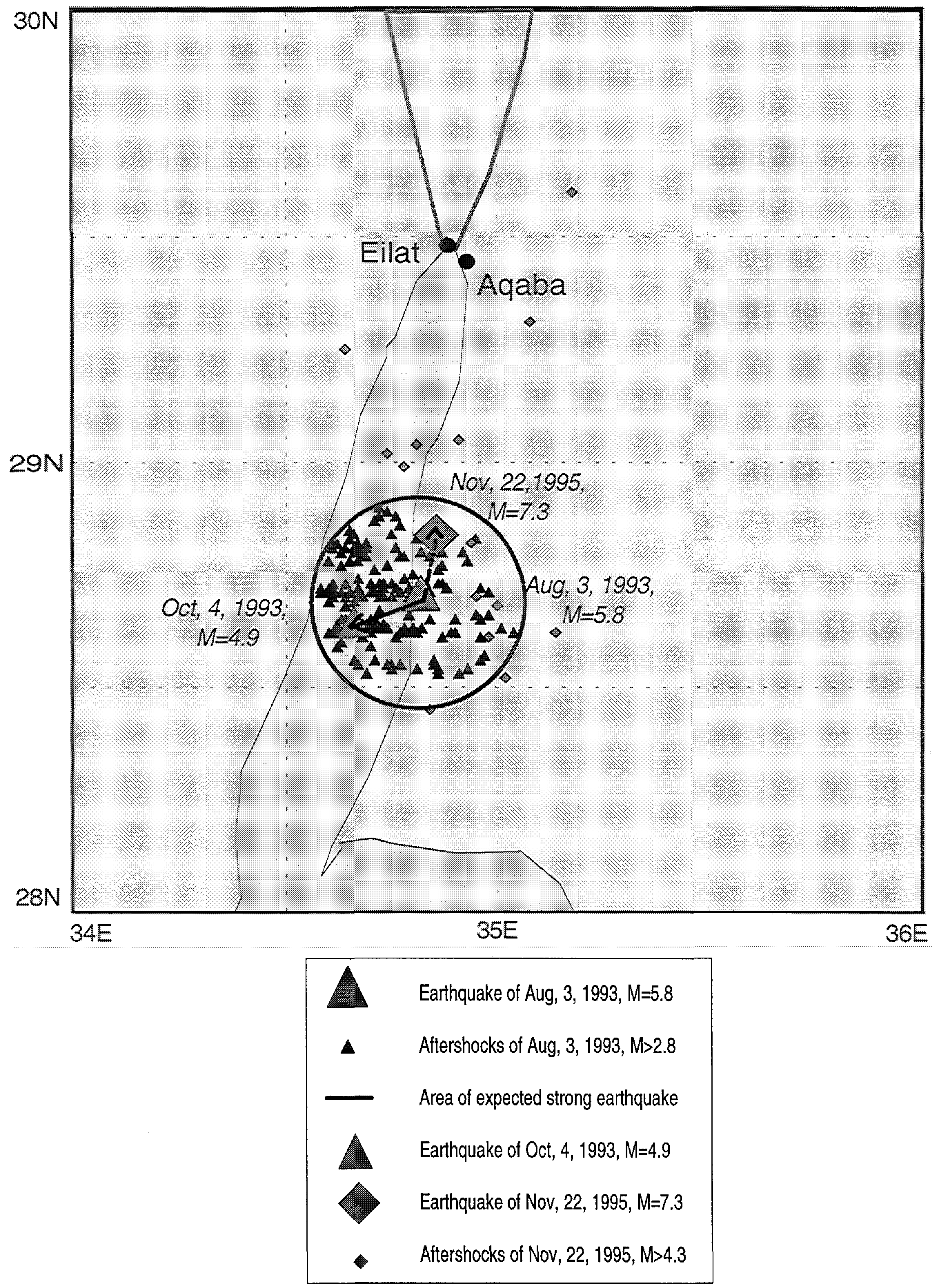
Figure 1

Rachi earthquakes 1991

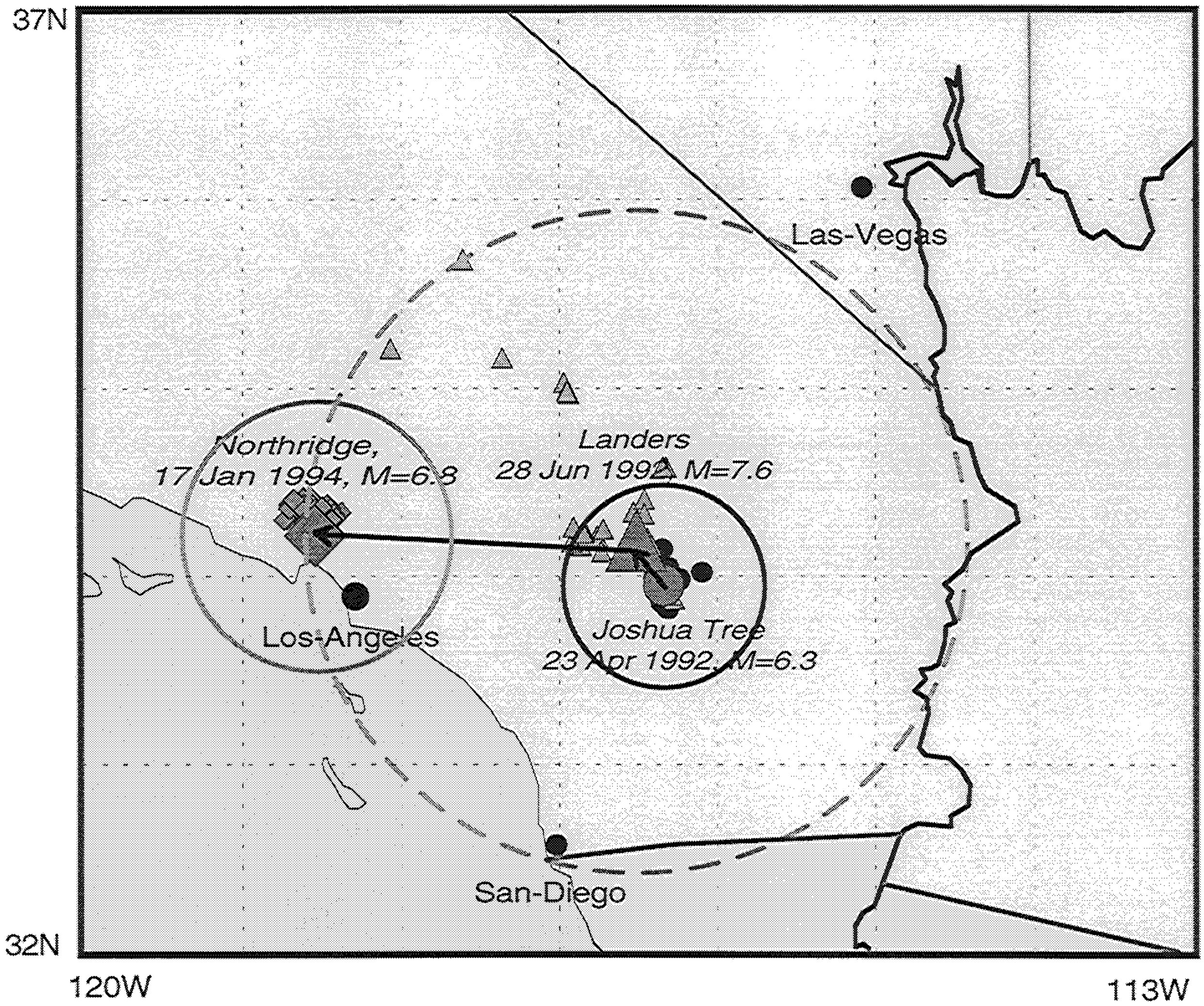



Caucasus 1962-1991
Aftershock sequences of
earthquakes M>6.4
Number of aftershocks
0
10
20
30
40
50
60
Rachi,
1991.4
Rachi
1991.6
0
2
4
6
8
10
12
Time, days
Values typical for single earthquakes
Atershock sequence of a single earthquakes
Values typical for earthquakes with next strong shock
Aftershock sequence of an erathquke with next strong shock

Gulf of Aqaba 1993 - 1995



Joshua Tree -- Landers -- Northridge



Joshua Tree earthquake
main shock
aftershocks M>6.3
area of expected large earthquake

Landers earthquake
main shock
aftershocks M>4.6
area of expected large earthquake

Northridge earthquake
main shock
aftershocks M>3.8
area where large shock is not expected