Algorithm for prediction of subsequent strong earthquake

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Importance of prediction of SSE

- Many strong earthquakes come in pairs, separated by relatively small times and distances. The first earthquake may destabilize buildings, lifelines, and other constructions, mountain slopes, etc.; that might increase vulnarability to subsequent strong earthquake.
- Precursors to subsequent strong earthquake shed light to the process of stress release in the source area.

Prediction of subsequent strong earthquake as a critical phenomenon

- SSE as a critical phenomenon in the complex non-linear system of seismogenic faults
- Idea of selfsimilarity in the earthquake prediction: applicability and limitations
- Pattern recognition approach

Idea of prediction of SSE

We look in the aftershock sequence for the same “universal” symptoms of critical transition that have been found in the main shocks sequences preceding a first strong earthquake

Universal symptoms

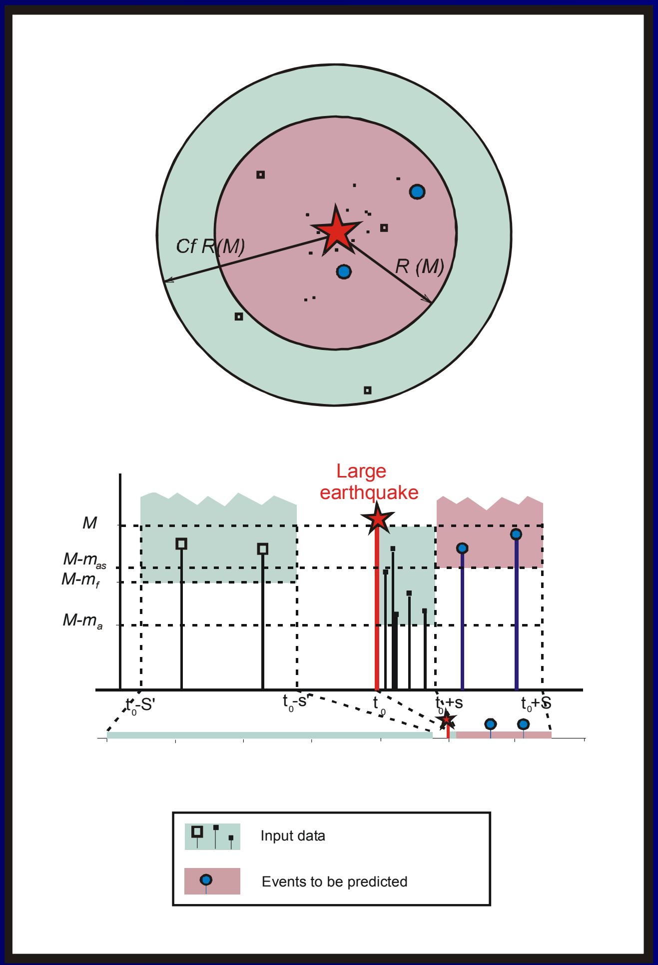
1. Raise of the system grows;
2. Behavior of system becomes more irregular;
3. Response to small perturbation increases, it lasts longer in time and in larger distances.

Subsequent strong earthquake preparation

1. Aftershock activity is high;
2. Aftershocks are clustering in space and time;
3. Aftershock activity decay is low.

Formalization of the problem

Let a strong earthquake occurs with magnitude $M \geq M_0$.



Given:

- The beginning of its aftershock sequence during 40 days;
- Seismisity before strong earthquake during 5 years.

To determine:

Will the next strong earthquake occur soon in the vicinity of the first one.

- **magnitude $M_1 \geq M$ -1;**
- **time period from 40 days to 1.5 year;**
- **distance $R \leq 0.03 \bullet 10^{0.5M}$ (30 km for M=6.0, 300 km for M=8.0)**

Algorithm for prediction of SSE was designed analyzing strong earthquakes in California and Nevada 1942 - 1988

First strong earthquakes: $M \geq 6.4$

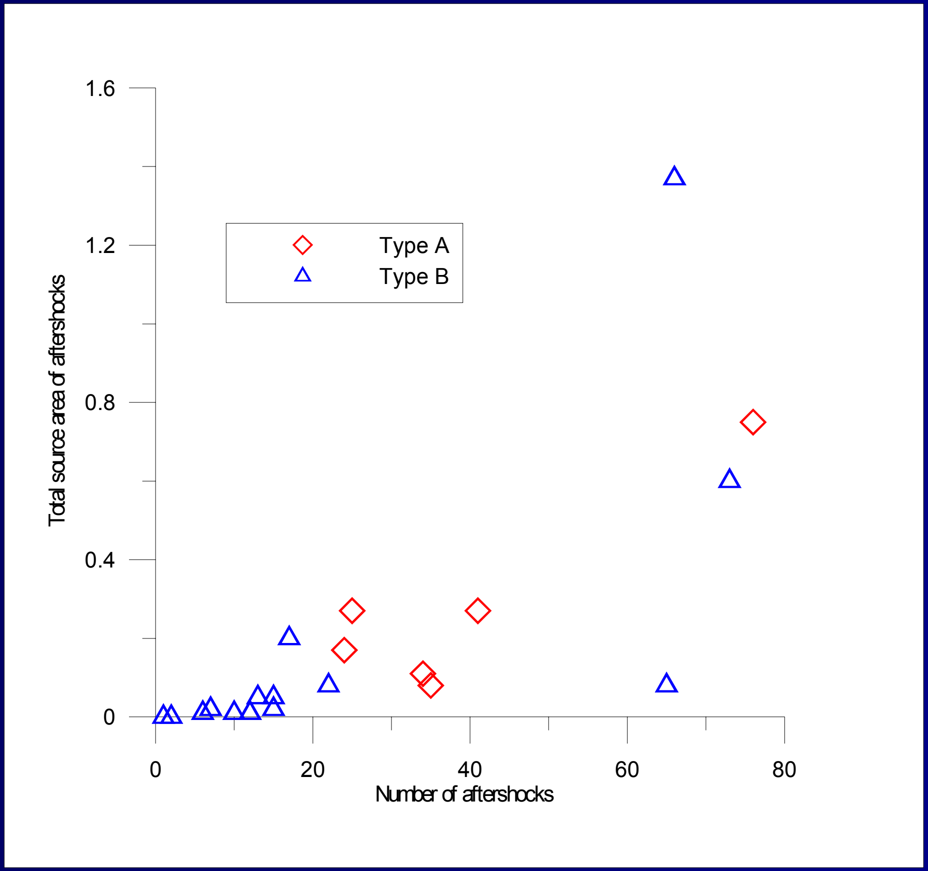
Subsequent strong earthquake after event with magnitude M

- **magnitude $M_1 \geq M$ -1;**
- **time period from 40 days to 1.5 year;**
- **distance $R \leq 0.03 \bullet 10^{0.5M}$ (30 km for M=6.0)**

Objects for learning:

- **6 earthquakes with SSE (class *A*)**
- **15 single earthquakes (class *B*)**

Aftershock activity after strong earthquakes in California 1942-1988: with SSE (class *A*) and single (class *B*)



Aftershocks activity is higher after earthquakes with SSE

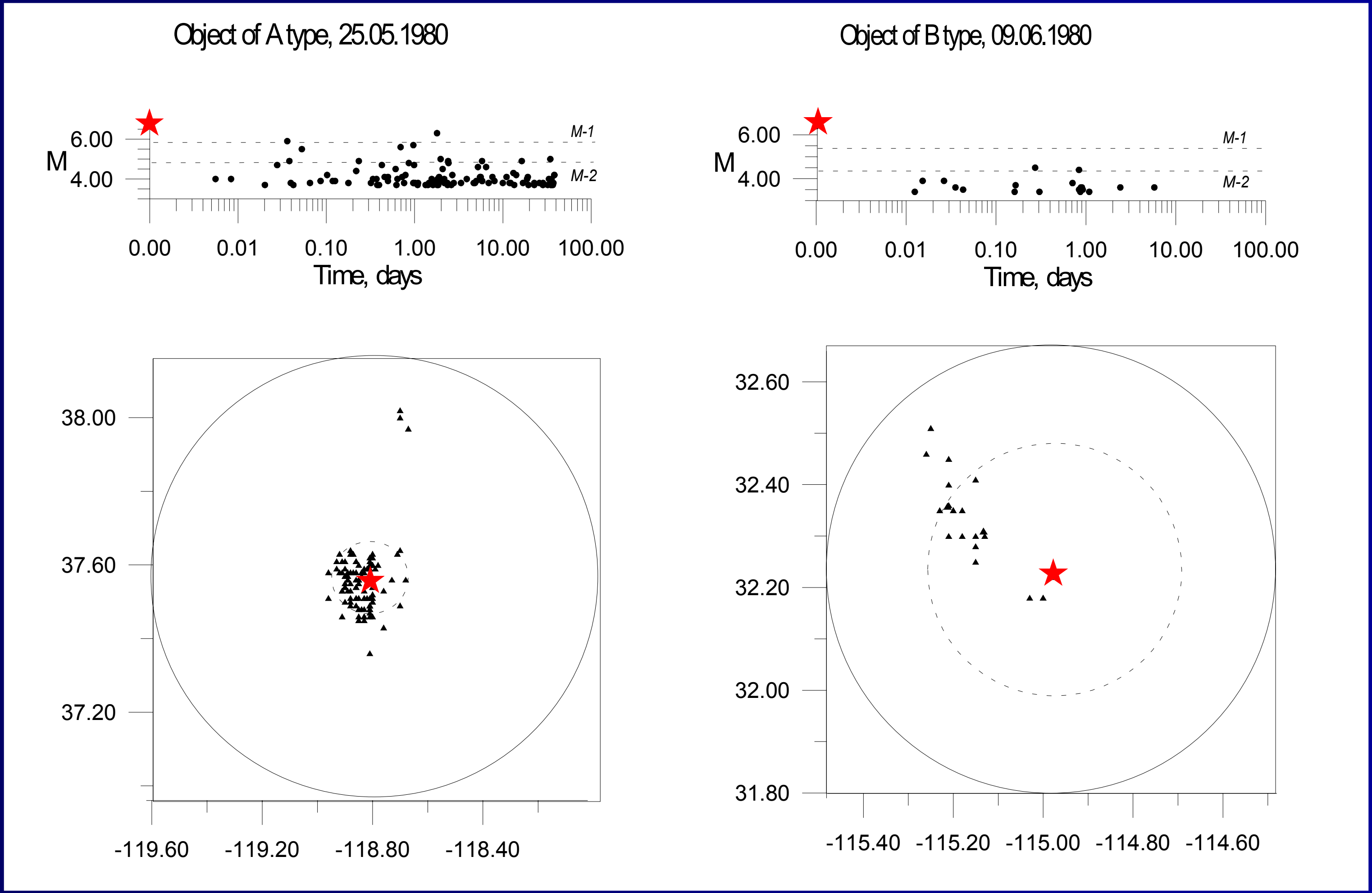
Analysis of strong earthquake in California shows that SSE is expected if :

- Aftershock activity is high
  - large number of aftershocks
  - high magnitudes of aftershocks
- Aftershocks are irregular in time
- Aftershocks activity decay is low
- Aftershocks are concentrated near main shock
- Before the first strong earthquake seismic activity is low

Results for California

20 earthquakes out of 21 are recognized correctly; there is one failure to predict.

Look of typical earthquakes with SSE (*A*) and single (*B*)



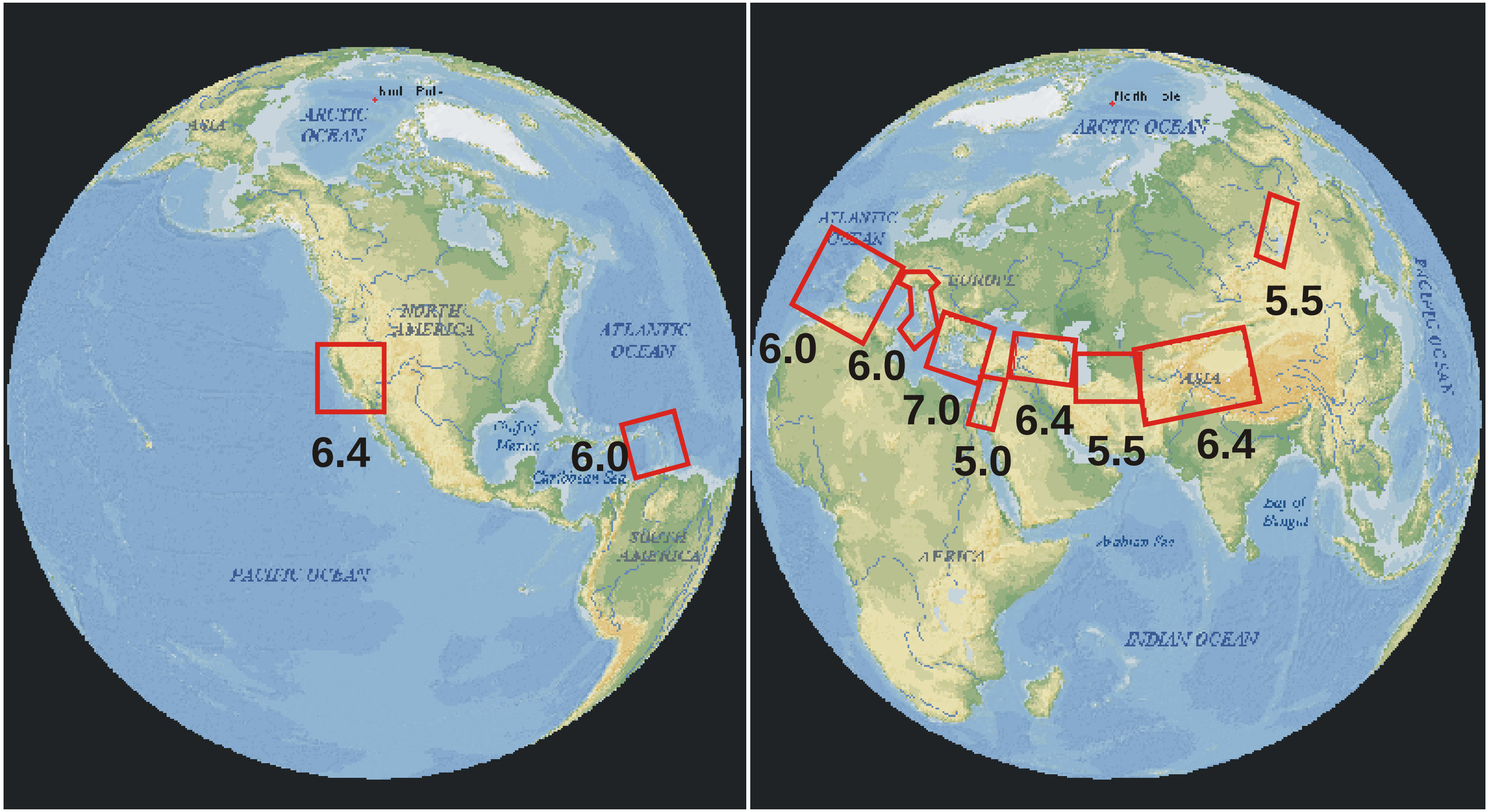
Test on independent data – strong EQ in other seismoactive regions

- ***Free parameters:***
  - Set of regions
  - Threshold value M_0 for determination of the first strong earthquake

  All other parameters are fixed

- ***Criteria of choice of the regions and M_0 – availability of the representative earthquake catalog.***

Ten regions for monitoring of subsequent large earthquakes



Result of the retrospective test in 10 regions of the world

Region	M_0	EQ number # /errors	EQ with SLE # / failures	Single EQ # / false alarms
		Learning		
California	6.4	21/1	6/1	15/0
		Independent data		
Central Asia	6.4	12/1	1/0	11/1
Caucasus	6.4	5/0	0/0	5/0
Turkmenia	5.5	12/2	2/2	10/0
Lake Baikal region	5.5	6/1	0/0	6/1
Balkans and Asia Minor	7.0	19/1	3/0	16/1
Dead sea rift	5.0	11/0	0/0	11/0
Italy	6.0	20/1	3/0	17/1
Iberia and Maghrib	6.0	7/0	1/0	6/0
Antilles	6.0	4/0	1/0	3/0
Total		***117/7***	***17/3***	***100/4***

Selfsimilarity

- Results of test of the algorithm on the independent data demonstrate similarity of the process of SSE preparation
  - Magnitudes of EQ under consideration vary from 5.0 to 8.0
  - Different seismotectonic :
    - Subduction zones (Antilles, Hellenic arc)
    - Thrust zones (Central Asia, Caucasus)
    - Transforms (California, Anatolian fault)
    - Rift zones (Dead sea, Baikal)

Prediction SSE in advance in 10 regions of the world

- Experiment started in 1989 in the 9 regions and in 2004 in the 10th region (Antilles).
- All parameters of the algorithm were fixed as they were chosen in the retrospective test.
- All strong earthquake are tested *if input data are available*

Results of monitoring of SSE in 10 regions 1989-2006

Region	EQ number # /errors	EQ with SLE # / failures	Single EQ # / false alarms
California	12/3	3/1	9/2
Central Asia	3/0	0/0	3/0
Caucasus	4/1	1/0	3/1
Turkmenia	2/0	0/0	2/0
Lake Baikal region	0/0	0/0	0/0
Balkans and Asia Minor	2/1	1/1	1/0
Dead sea rift	2/0	1/0	1/0
Italy	2/0	1/0	1/0
Iberia and Maghrib	1/0	0/0	1/0
Antilles	1/0	1/0	0/0
Total	***29/5***	***8/2***	***21/3***

Results of advance prediction of SSE 1989-2005

- *29 strong earthquake were tested,*

  8 of them were followed by SSE; 6 were predicted; 2 were missed

  21 strong earthquake were single;

  18 were recognized correctly; three alarms were false.

  Total: *5 errors out of 29 predictions*
- 9 alarms were declared, 6 were confirmed, 3 were false;

  2 out of 3 false alarms were confirmed informal.
- *Effectiveness of prediction in advance*

  $$e = 1 - (3/21 + 2/8) \approx 0.6$$
- *Statistical significance exceeds 99%*

Analysis of the errors in advance prediction

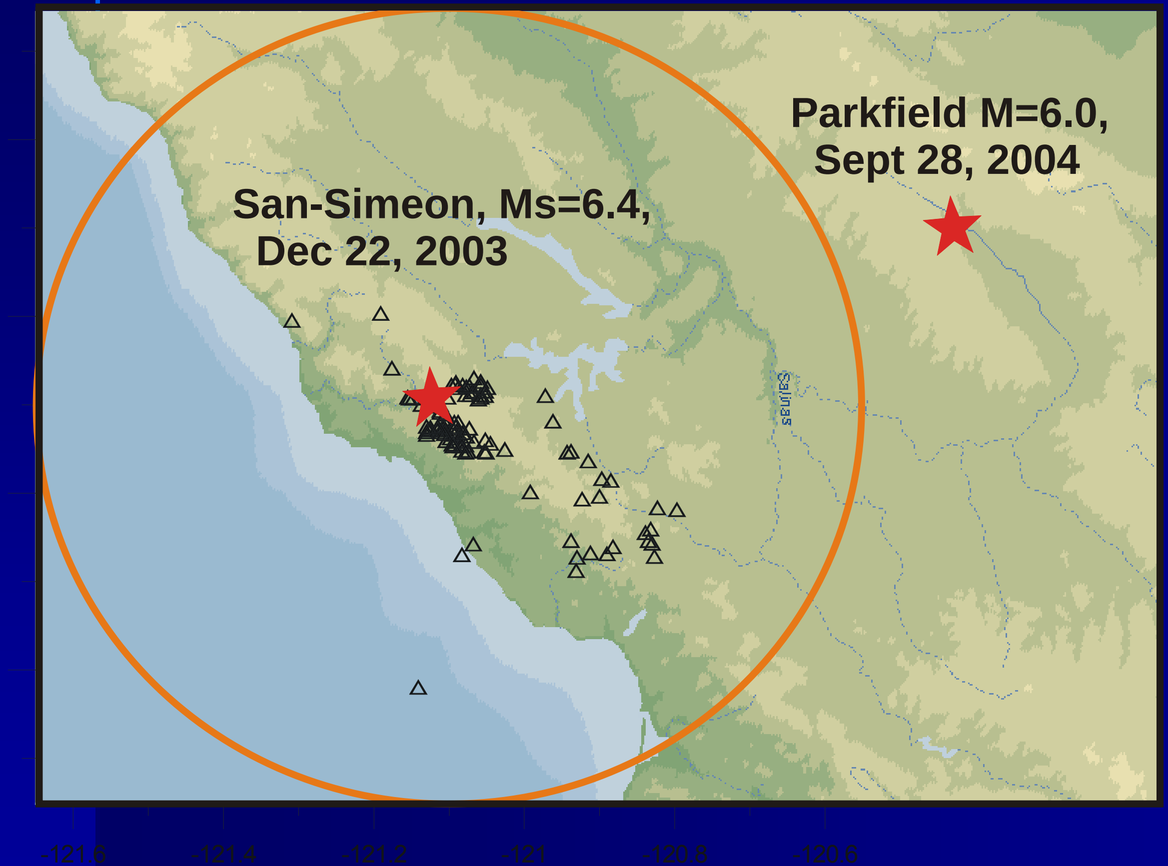
False alarms

- Alarm after Landers EQ, Southern California, M=7.6, 1992 was confirmed informal: Northridge EQ, *M*=6.8, occurred in the alarm area in 20 days after alarm expiration
- Alarm after San-Simeon EQ, Southern California, Ms=6.4, 2003 was confirmed informal: Parkfield EQ, *M*=6.0, occurred in the alarm time in 17 km out of area of alarm
- Alarm after Erzincan EQ, Caucasus1992, M=6.8, can be explained by data quality

Failures to predict

- Failures to predict after Izmit EQ, Asia Minor M=7.8, 1999, and after Mendocino EQ, California, M=7.1 1994 are “unforced errors”

Southern California 2003-2004 San-Simeon – Parkfield: informal confirmation of alarm



__Prediction__

SSE is expected with magnitude *M≥5.4 during 18 months within 48km of San-Simeon*

__Outcome__

Parkfield, *M*=6.0 occur in 17km out of alarm area

Southern California 1992-1994

Landers - Northridge

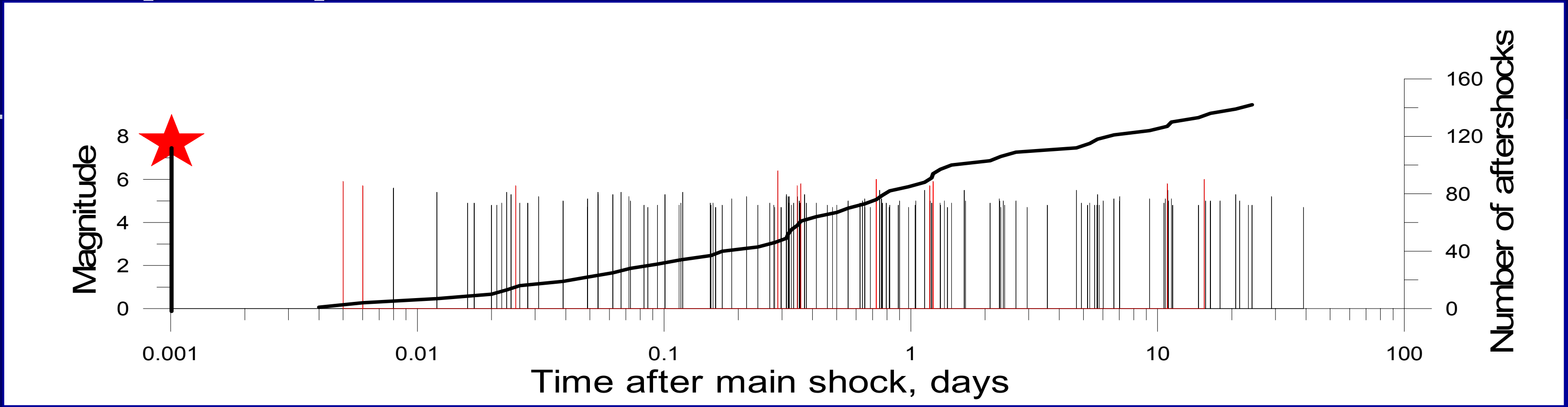
Landers, June 28, 1992, M=7.6:
Prediction: SLE is expected with *M* >= 6.7 during 18 months and within 198 km of Landers.

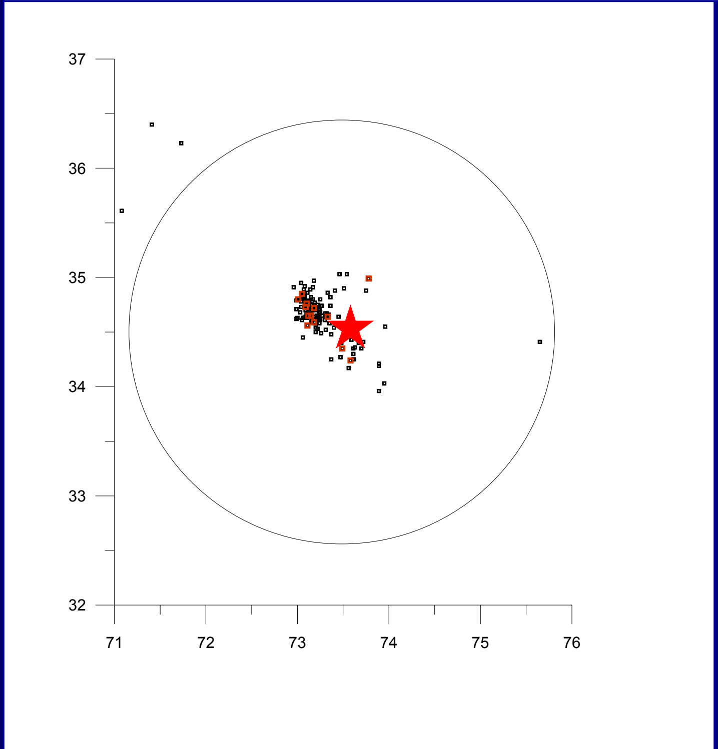
Outcome of prediction:
Northridge earthquake, M=6.8 occurred 19 days after expiration of alarm

Northridge, January 17, 1994, M=6.8:
Prediction: SLE is not expected with *M* >= 5.8 during 18 months and within 75 km of Northridge

Outcome of prediction:
no earthquake occurred

Pakistan earthquake October 8 2005 looks like an event with subsequent strong





- High aftershocks activity

  many aftershocks
  strong aftershocks (red)
- Irregularity of aftershocks in time
- Decay of aftershocks is low
- Cloud of aftershocks is concentrated near main shock.

Prediction of SSE after Pakistan earthquake October 8, 2005

A subsequent strong earthquake is expected

- with magnitude M≥6.7
- till April 8, 2007
- within 212 km of the October 8 epicenter

Input data:
NEIC (QED), CSEM (quick data)

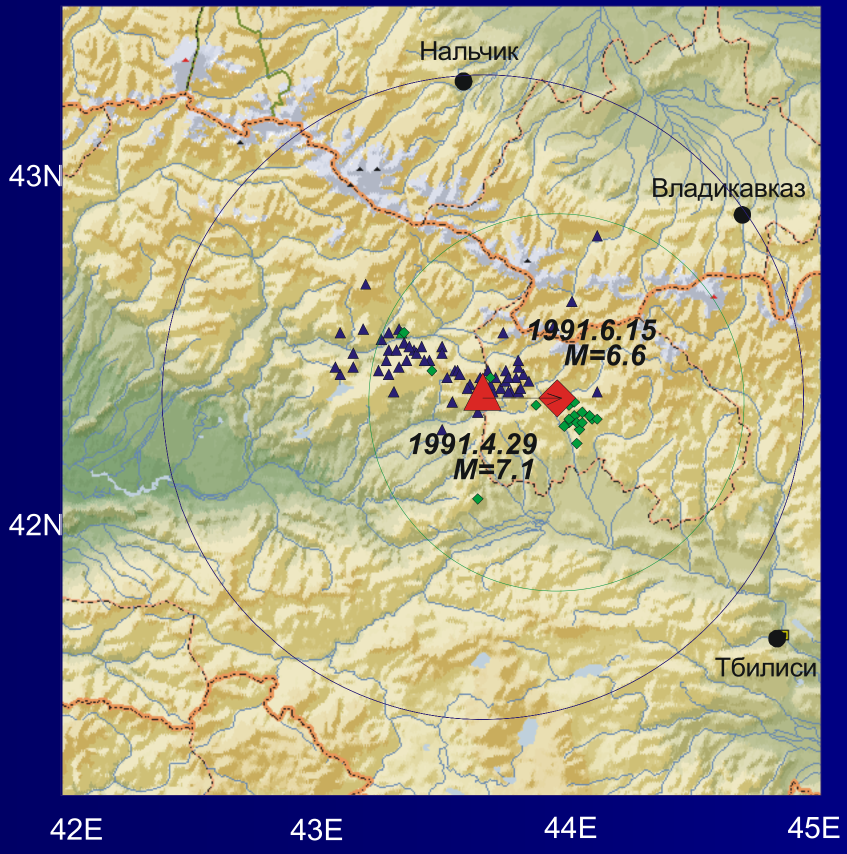
Prediction is available in
www.mitp.ru

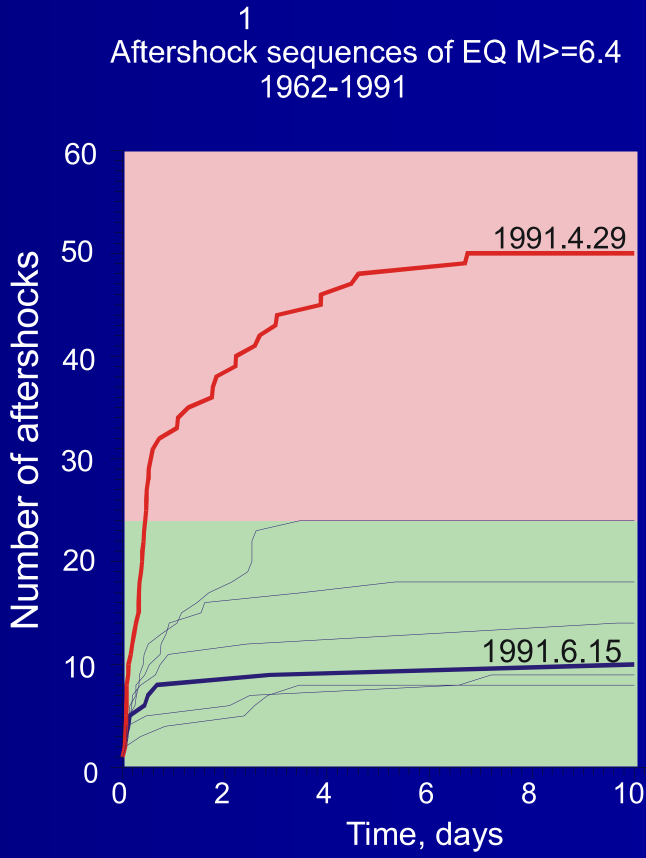
Large circle is alarm area
Small circles are nodes prone for M≥6.5

Retrospective analysis of the strong earthquakes in the vicinity of 8 October epicenter

- All strong earthquake were single
- There no representative data for the analysis of past earthquakes
- There is three regions where SSE occurred during the period of monitoring (after 1989), while before such events were unknown
  - Caucasus
  - Lake Baikal region
  - Dead sea rift

Rachi, Caucasus 1991, *M*=7.1, *M*=6.6





Distribution of time and space interval between first and subsequent strong earthquake