Algorithm for prediction of subsequent strong earthquake

I.A.Vorobieva

International institute of earthquake prediction theory and mathematical geophysics

Moscow, Russia

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

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.; subsequent strong earthquakes may destroy them.
- The study of phenomena preceding the occurrence of a subsequent strong earthquake may help in understanding the seismic process in the source area of strong event.

Prediction of SSE as a particular task in the general problem of earthquake prediction

- Formulation of the hypothesis of the preparation of subsequent strong earthquake
- Formalization of the problem
- Choice of the method of solution
- Design of algorithm
- Test of algorithm
  - **Stability test**
  - **Retrospective test on independent data**
  - **Forward prediction**

Idea of prediction

strong earthquakes are predictable. They are preceded by instability phenomena that are typical for non-linear systems before critical transition

Non-liner system	*strong earthquake preparation*
1. Activity of the system grows;	1. Seismic activity grows;
2. Behavior of system becomes more irregular;	2. Earthquake are clustering in space and time;
3. Response to small perturbation increases, it lasts longer in time and in larger distances.	3. Long range interaction of seismicity in space and time

The processes of preparation of the first strong and subsequent strong earthquake show similar symptoms of instability:
Activity is high and
irregular in space and time

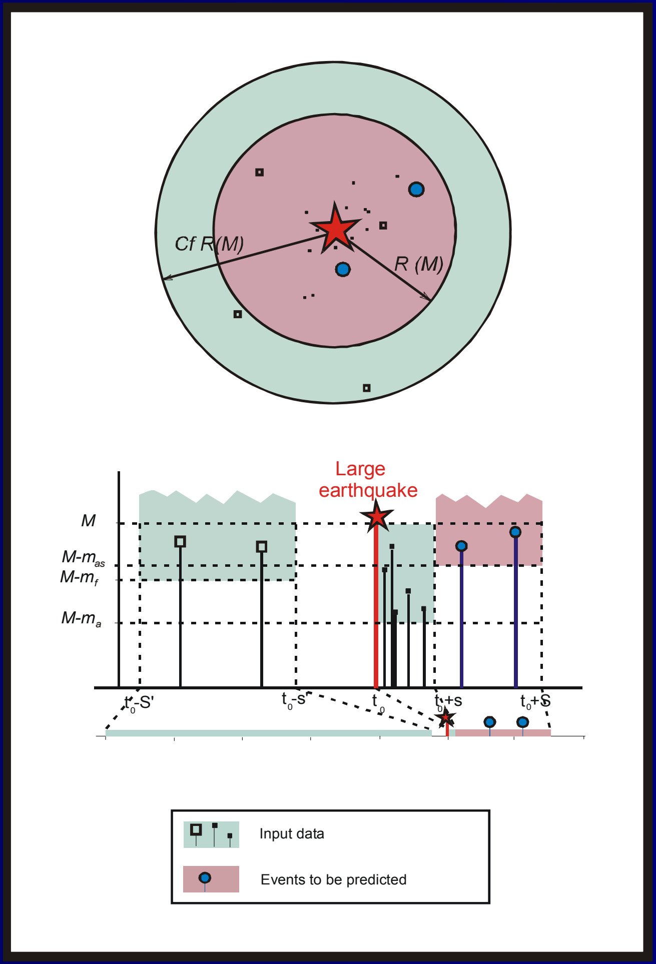
Preparation of subsequent strong earthquake

- We call ‘subsequent’ a strong earthquake, that occurred soon after and not far from a previous strong one
- ***Hypothesis.*** Preparation of first and subsequent strong earthquakes are similar processes reflected in the main shock sequence and aftershock sequence respectively:

  Activity is high and irregular in space and time

- ***Scaling***. Premonitory phenomena in different sesmotectonic conditions and magnitude range are quantitatively the same after normalization to the first earthquake magnitude

Formalization of the problem



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

Given:

- The beginning of its aftershock sequence;
- Seismisity before strong earthquake.

To determine:

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

Normalization

According to G-R law number of earthquakes per units of time, area and magnitude

$$N \sim 10^{-bM}; b \approx 1$$

We consider the circle around epicenter of the first earthquake. Its radius is proportional to the linear size of the source,

$$R \sim 10^{0.5M} \; (R^2 \sim 10^{M})$$

Number of earthquakes in that circle per unit of time

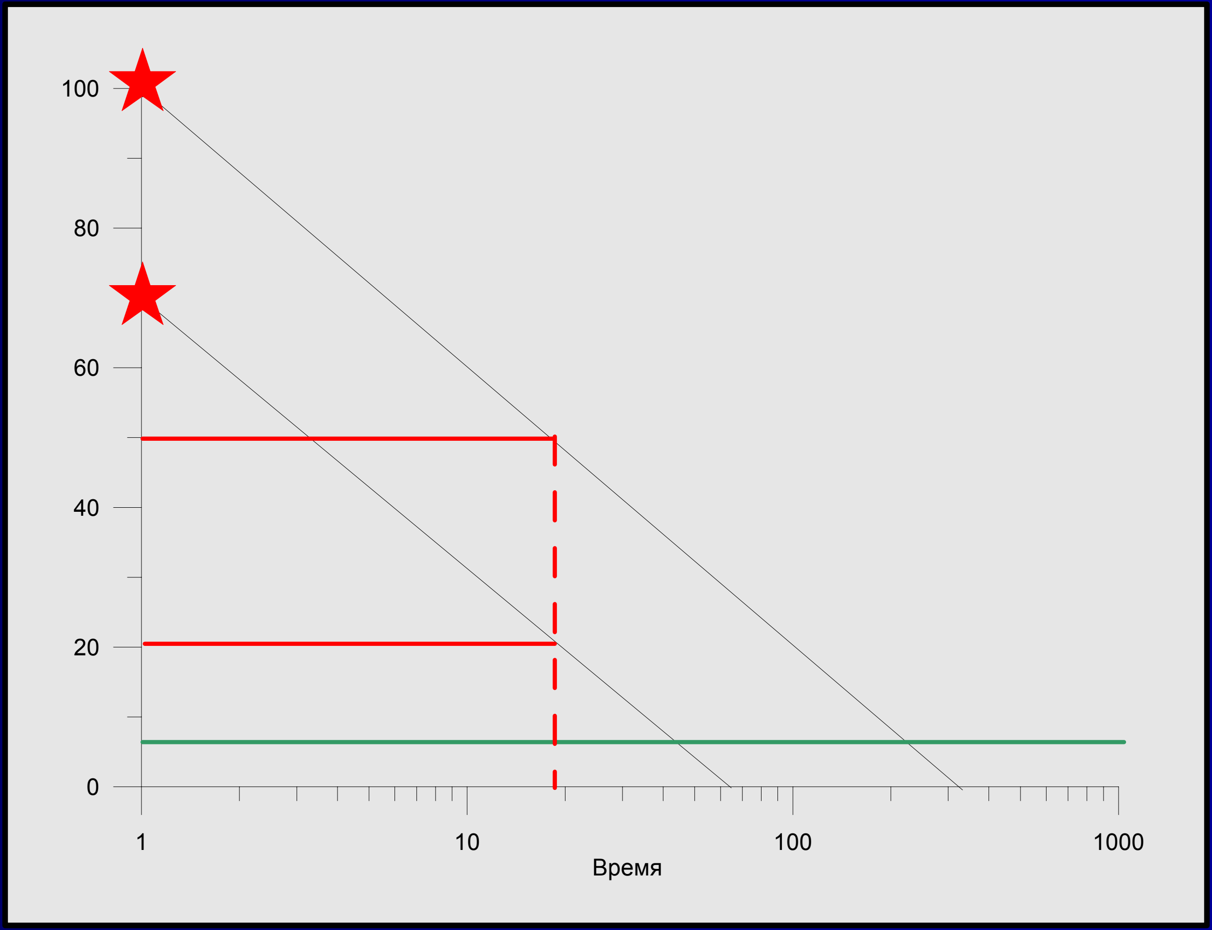
$\sim R^2 N$: it is independent on M!

In other words

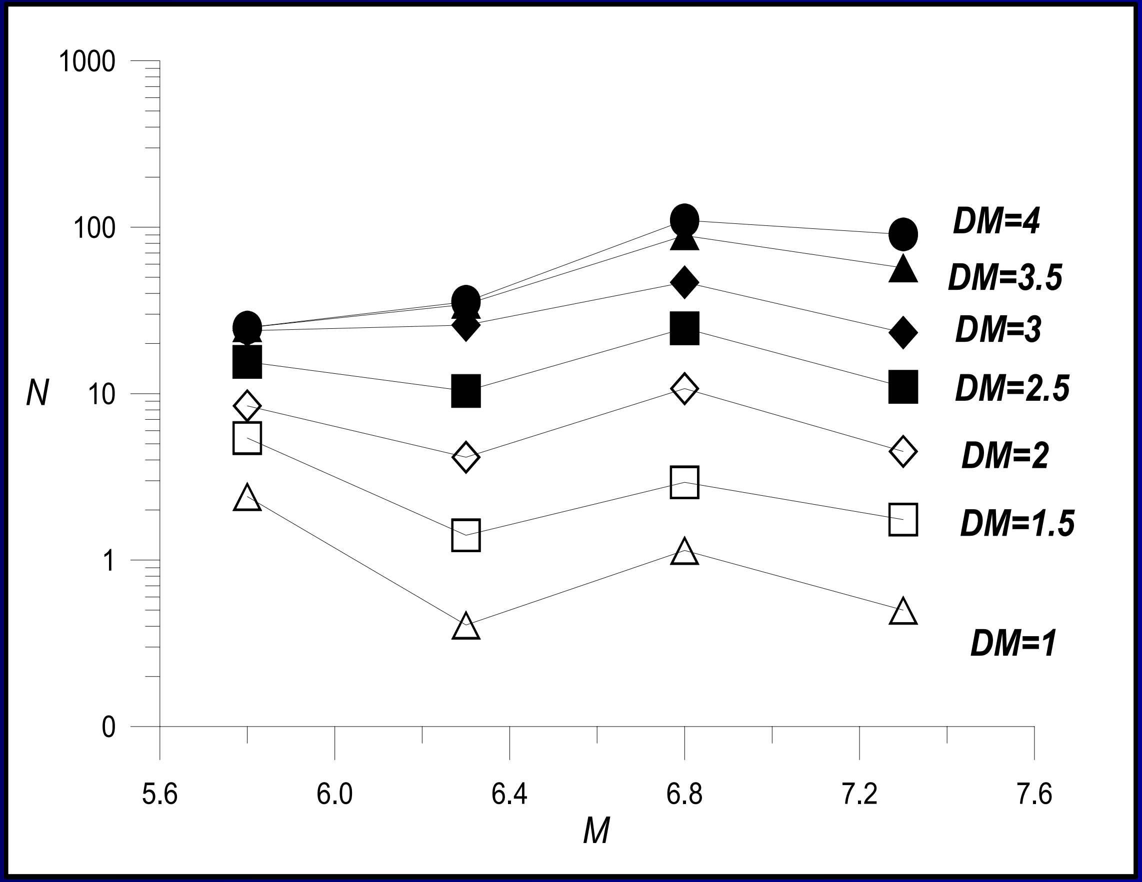
- All magnitude parameters are normalized by the magnitude *M* of the first strong earthquake; they differ from *M* by a constant.
- Diameter of the area considered is proportional to the liner size of the source.

- *Then the time parameters do not depend on M!*

Duration of the aftershock activity

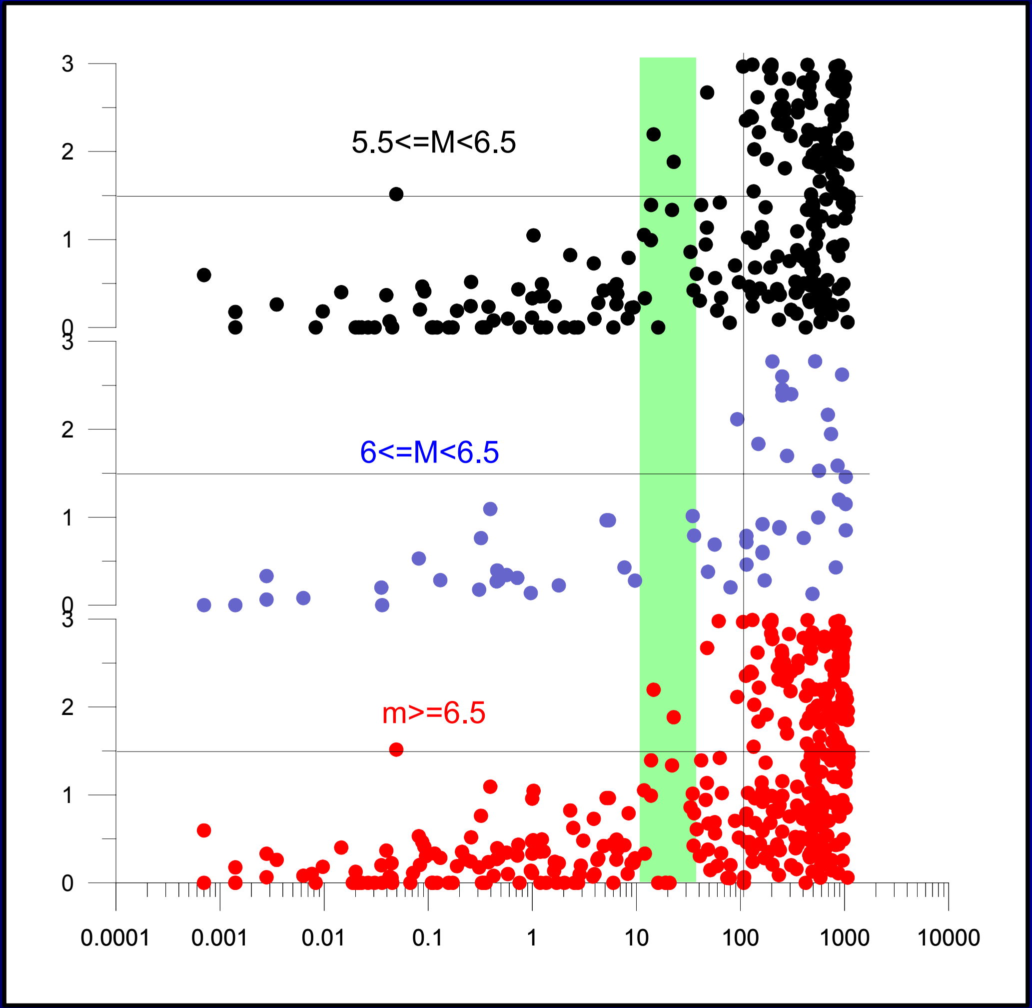


Number of aftershocks in the relative magnitude window for EQ of different magnitude



Distribution of distance between SE and SSE in space and time

It is practically independent on magnitude



Precursors of SSE

№	Function	Description	Expected value
1	***N***	Number of aftershocks	*Large*
2	***S***	Total source area of aftershocks	*Large*
3	***Vm***	Variation of magnitude of aftershocks	*Large*
4	***Vmed***	Variation of average magnitude of aftershocks	*Large*
5	***Rz***	Abnormal growth of aftershocks number in time	*Large*
6	***Vn***	Rate of decreasing of aftershock activity	*Small*
7	***Rmax***	Clustering of aftershocks in space	*Small*
8	***Nfor***	Seismic activity before first large earthquake	*?*

Formulation of the problem in terms of pattern recognition

Strong earthquake is object for recognition

Each object is described by several statistics of the aftershocks; one more statistics describes activity before this earthquake.

Given: examples of the objects of two classes (‘learning material’):

- class *A* – earthquakes followed by SSE;
- class *B* – single earthquakes.

To determine: the type, *A* or *B* of the earthquake considered.

Pattern recognition provides the decision rule for classification of the objects

Development of the algorithm for prediction of SSE

Data – seismicity in California and Nevada 1942-1988

First strong earthquakes: $M \geq 6.4$

Subsequent strong earthquake after event with magnitude M

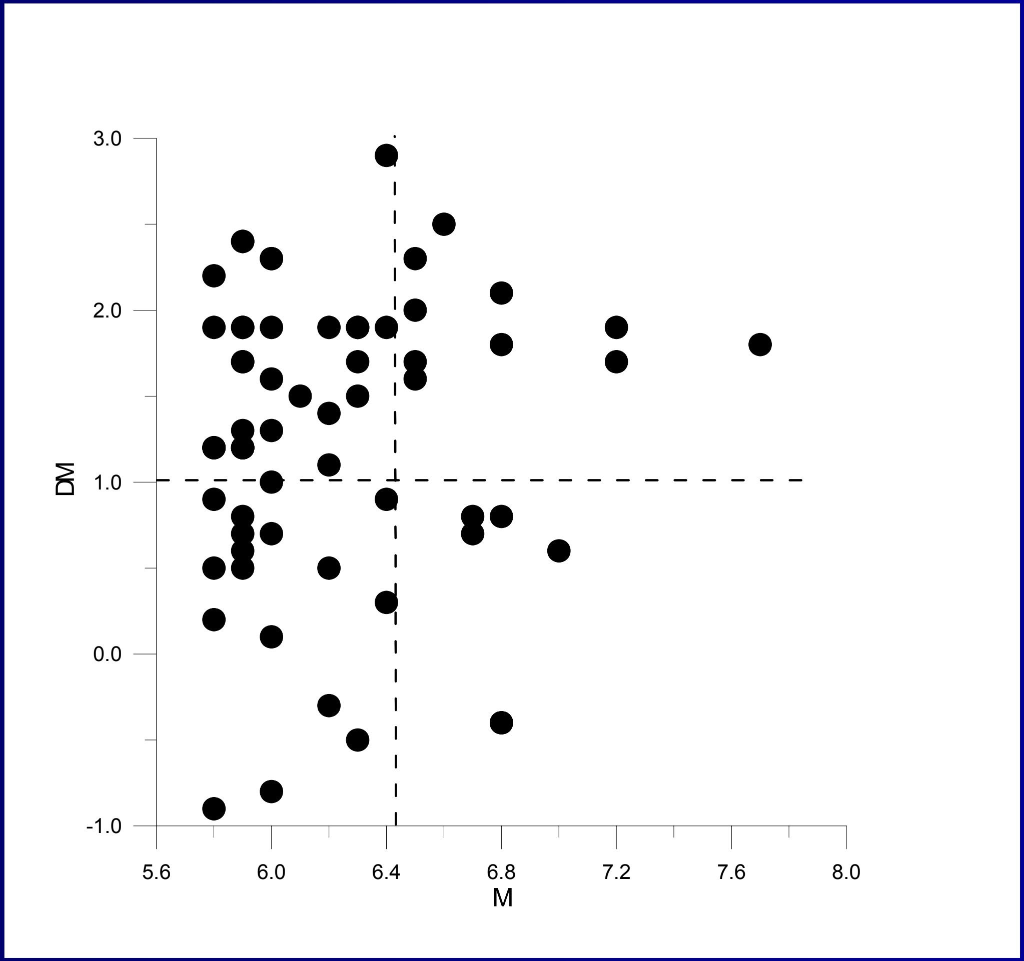
- **magnitude $M_1 \geq M - 1$;**
- **time period from 40 days to 1.5 year;**
- **distance $R \leq 0.03 \bullet 10^{0.5M}$ (30 km for M=6.0)**

Objects for learning:

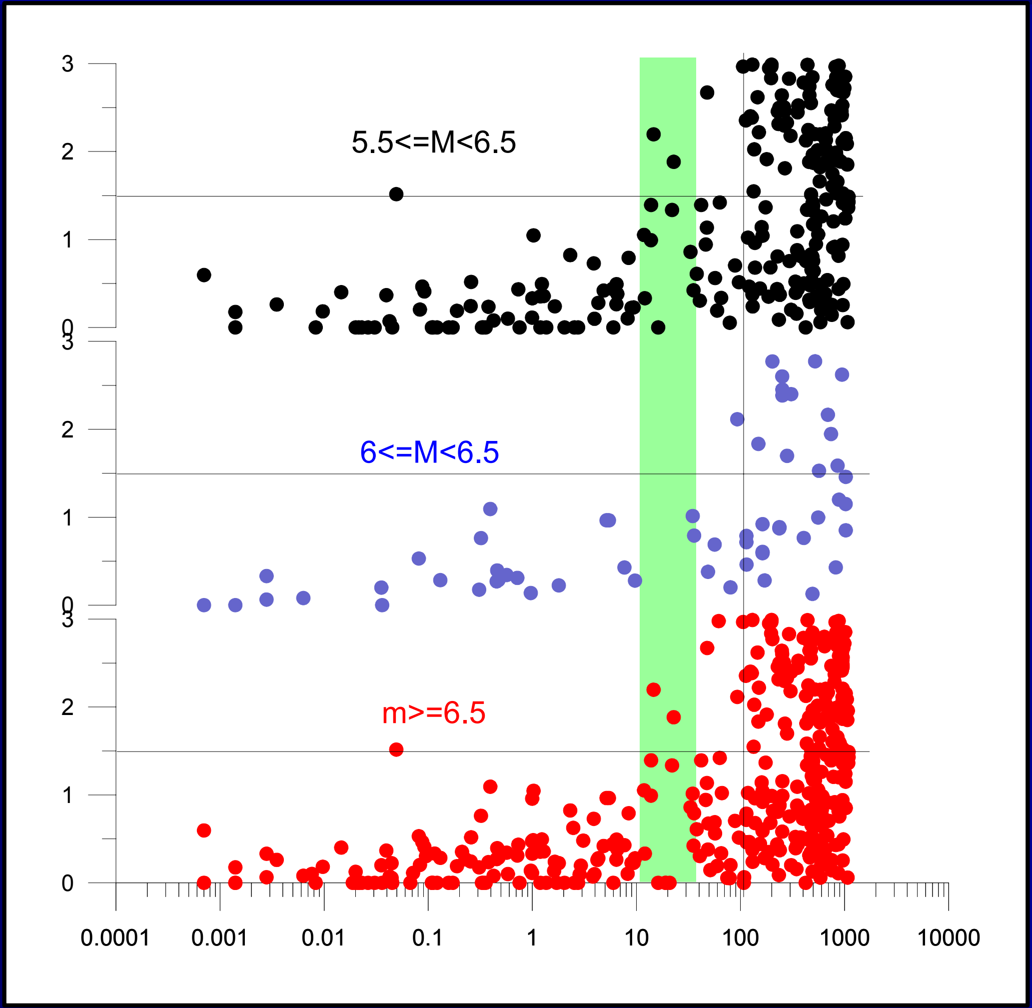
- **6 earthquakes with SSE (class *A*)**
- **15 single earthquakes (class *B*)**

'Bath diagram' for Californian earthquakes 1942 - 1988

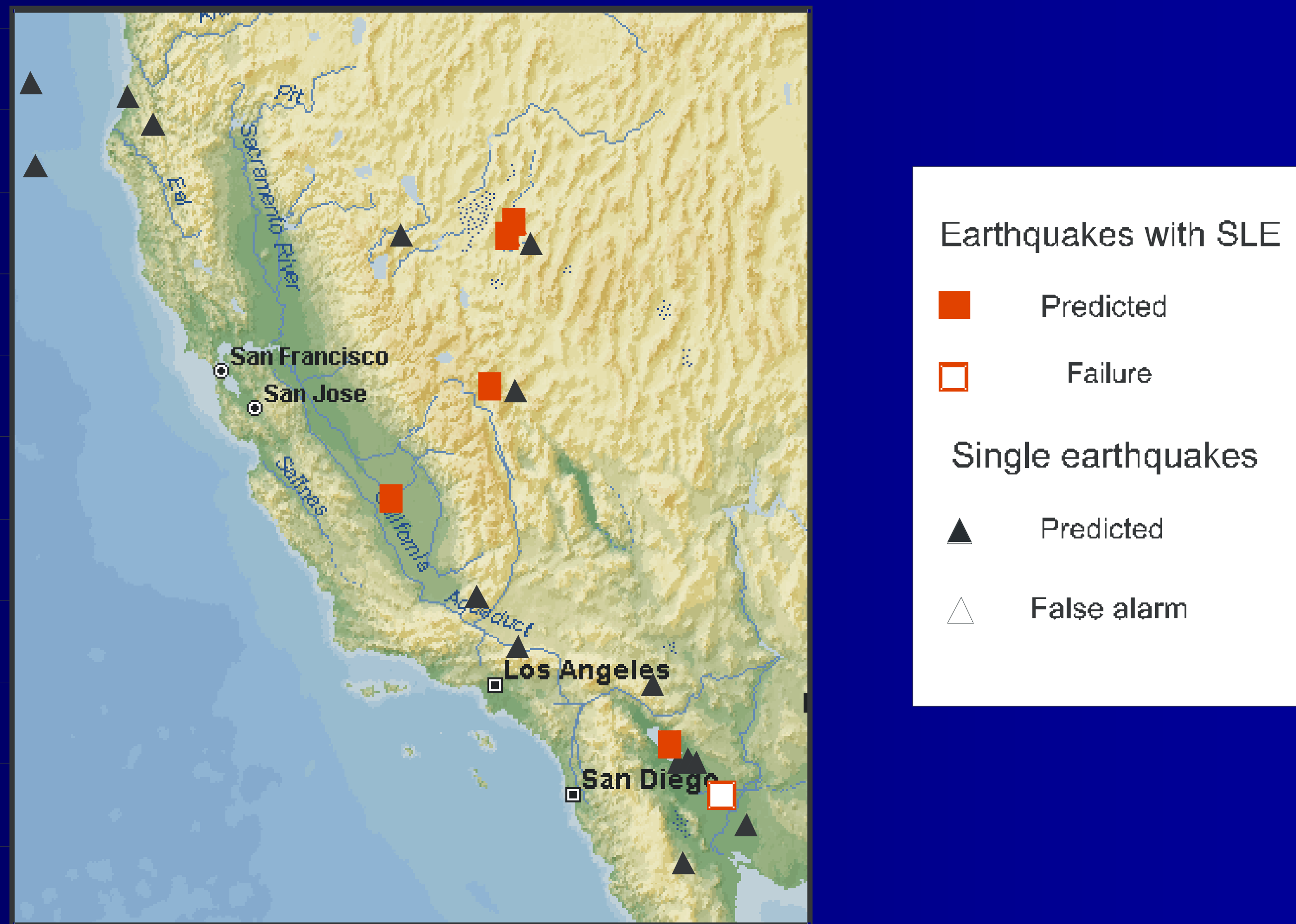
Bath diagram for California & Nevada earthquakes



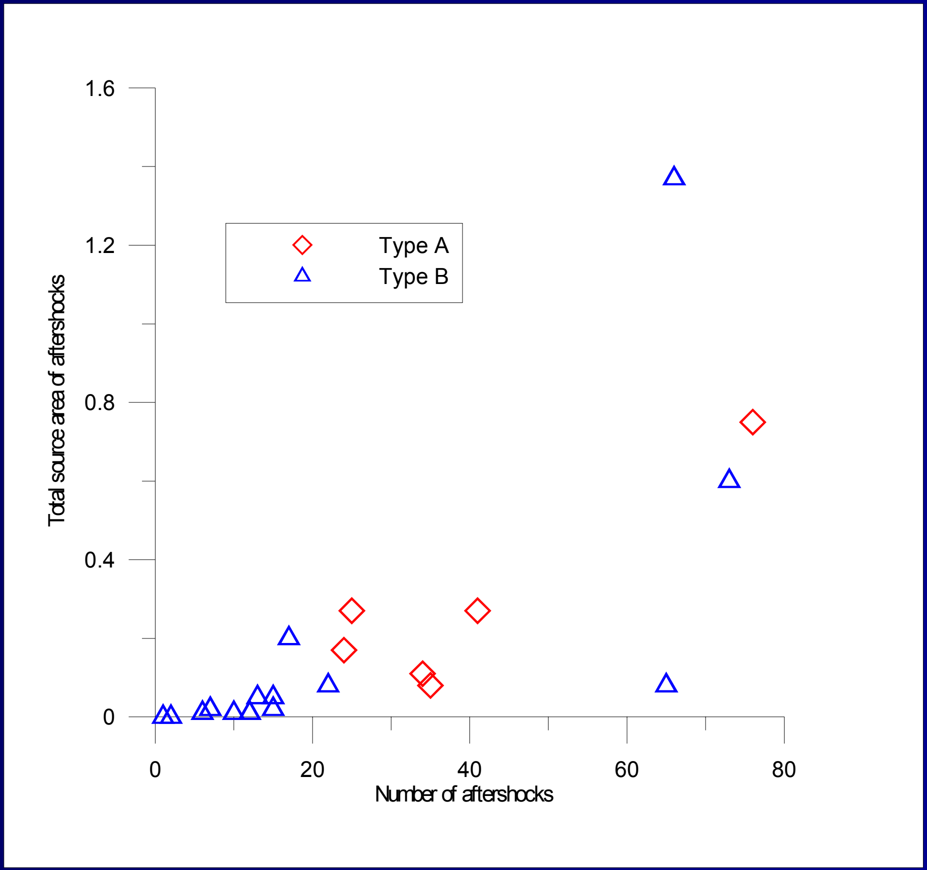
Distribution of distance between LE and SSE in space and time (why 40 days?)



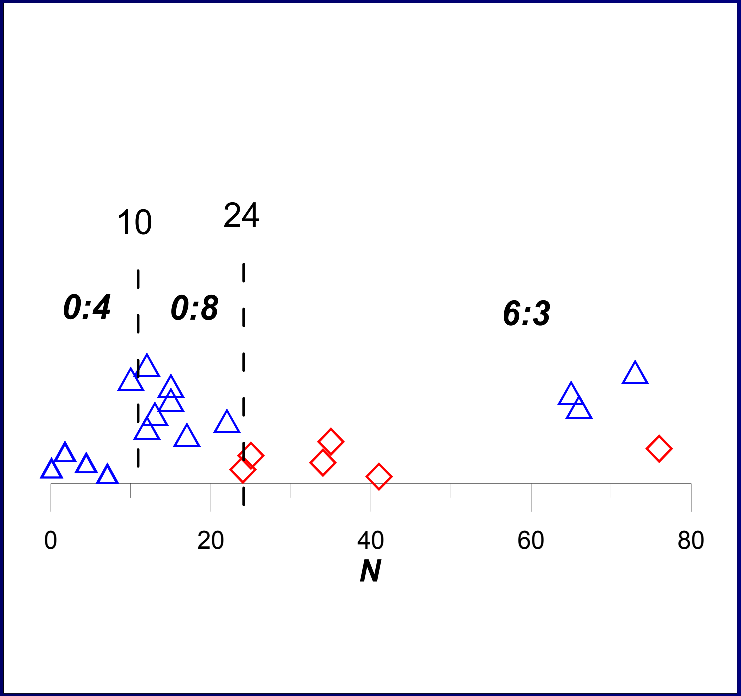
Objects for learning: California 1942 - 1988

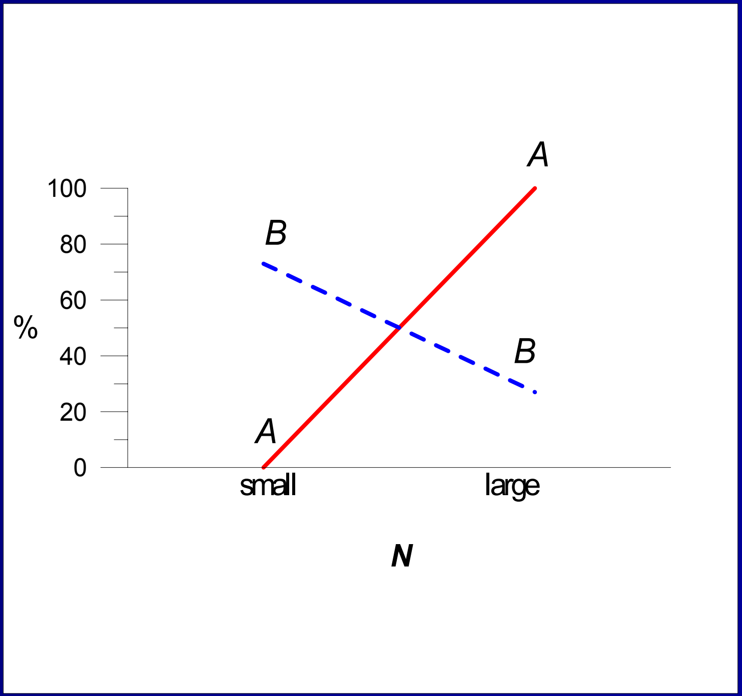


Aftershock activity after earthquakes: with SSE (type *A*) and single (class *B*)



Distribution of number of aftershocks for objects *A* and *B*





Results for California

Two steps of recognition

I. Earthquakes with few aftershocks (<10) are single (class *B*)

II. Earthquakes with many aftershocks (≥ 10) are classified by "Hamming" algorithm (voting)

- n_A **– the number of functions that have values of *A* type**
- n_B **- the number of functions that have values of *B* type**

Decision rule: if the strong earthquake has many aftershocks (≥ 10) and $n_B \leq 2$, subsequent strong earthquake is expected

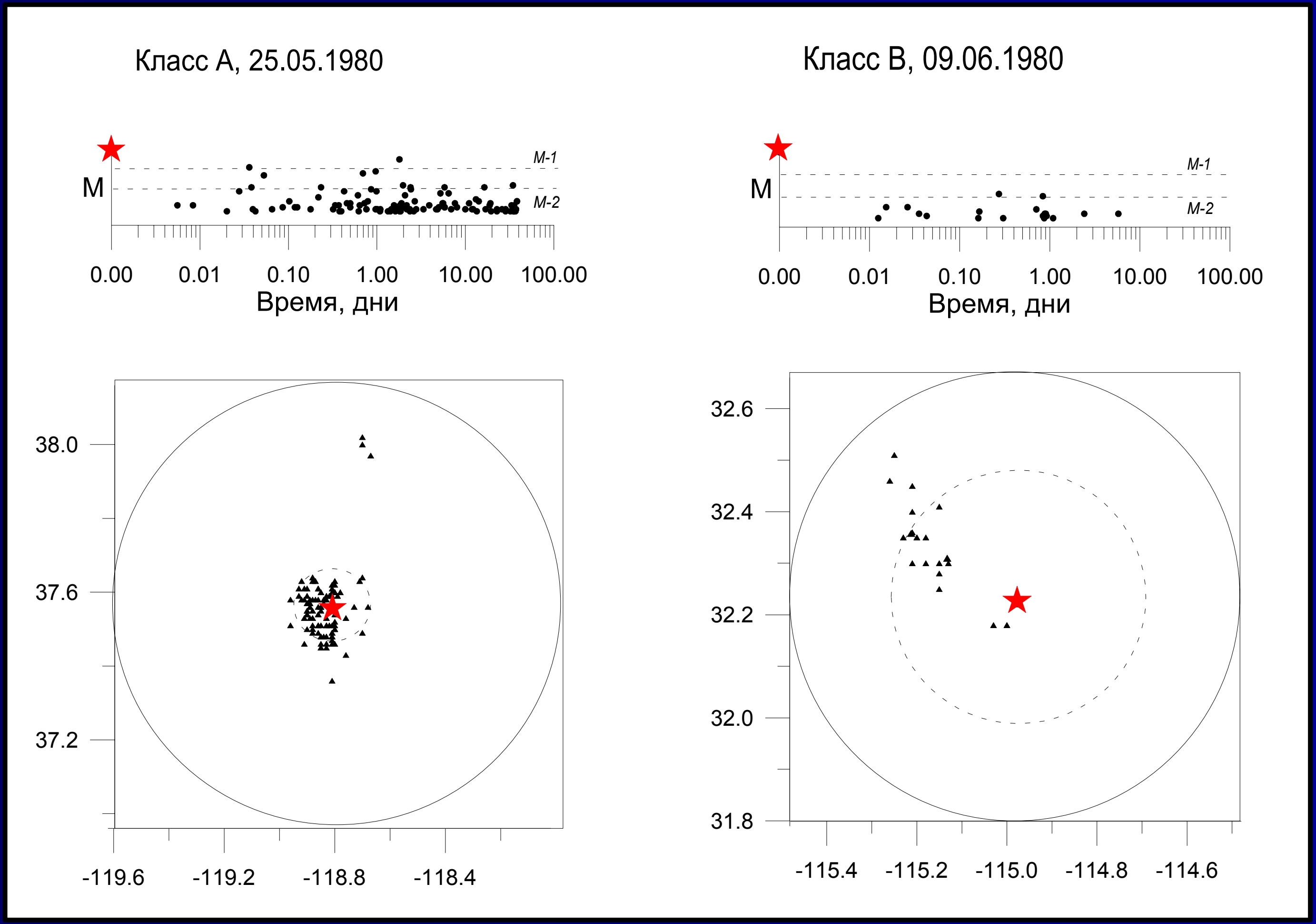
Results of learning

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

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

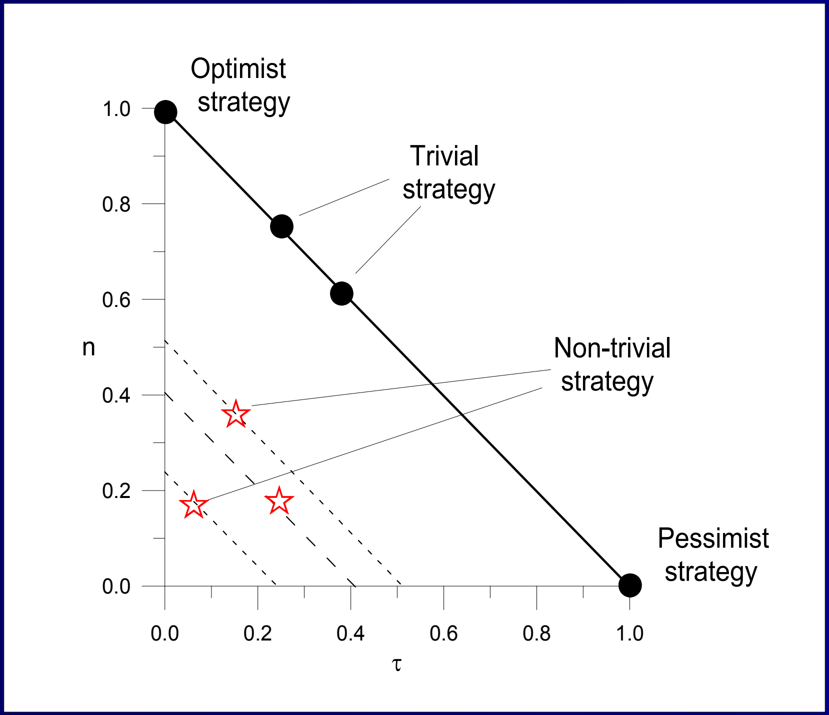
Typical earthquakes *A* and *B*



Stability tests

- The algorithm has a lot of free parameters while number of objects for learning is few. The obtained result can be consequence of data fitting
- Tests on learning material:
  - Variation of free parameters
  - Quality of input data (earthquake catalog)

Error diagram - tool to study stability

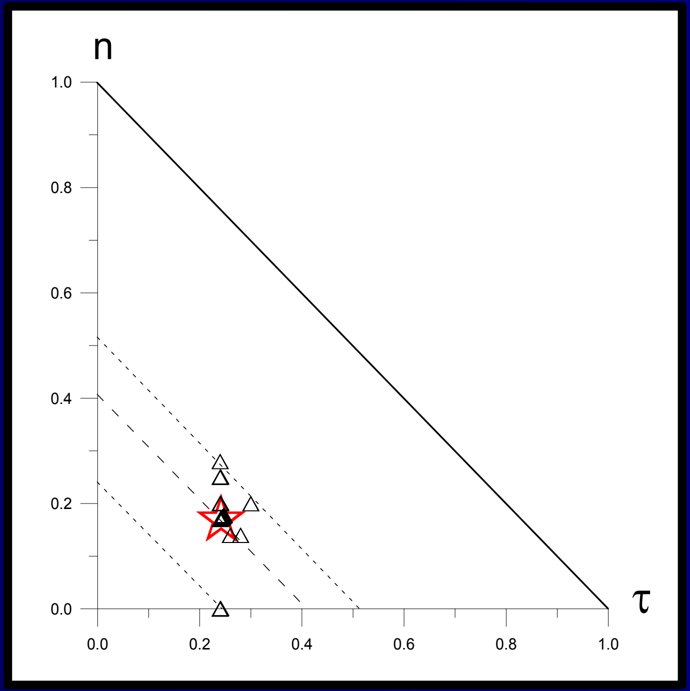


- *n*=failures/total EQ
- *τ*=alarm space/total space of prediction

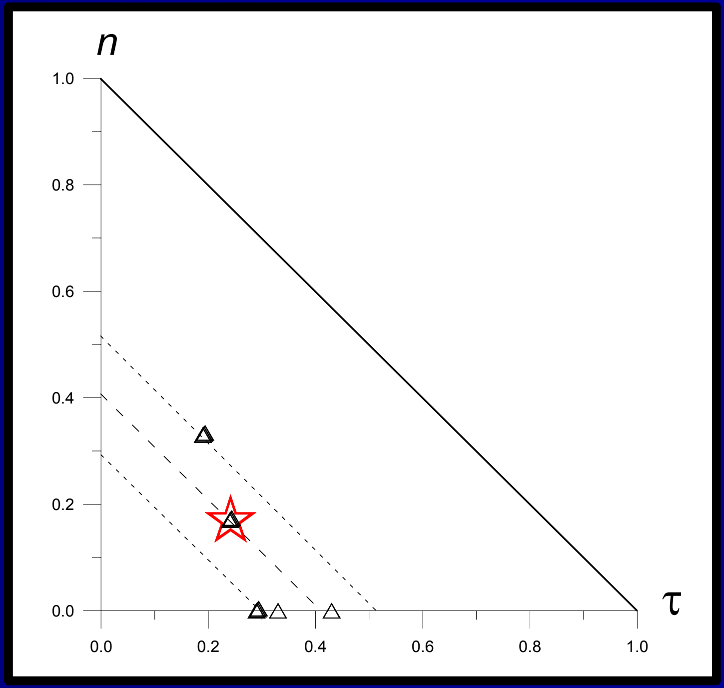
- <u>In case of SSE prediction</u>
- Total EQ is number of SSE (*A* class EQ)
- Space of prediction is total number of EQ (*A* and *B* classes)

Variation of free parameters of algorithm

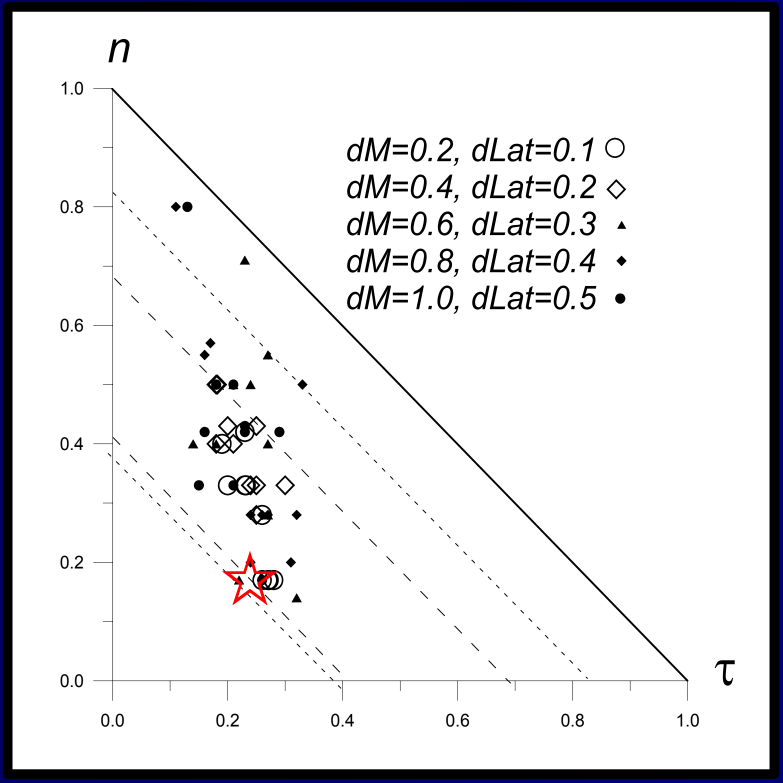
parameters for object definition



parameters of decision rule



Stability to the catalog quality



- The algorithm is stable to the data quality. It is applicable to quick data in real time prediction.
- Expected effectiveness of prediction using quick data

  e = 1-(0.37+0.08)=0.55

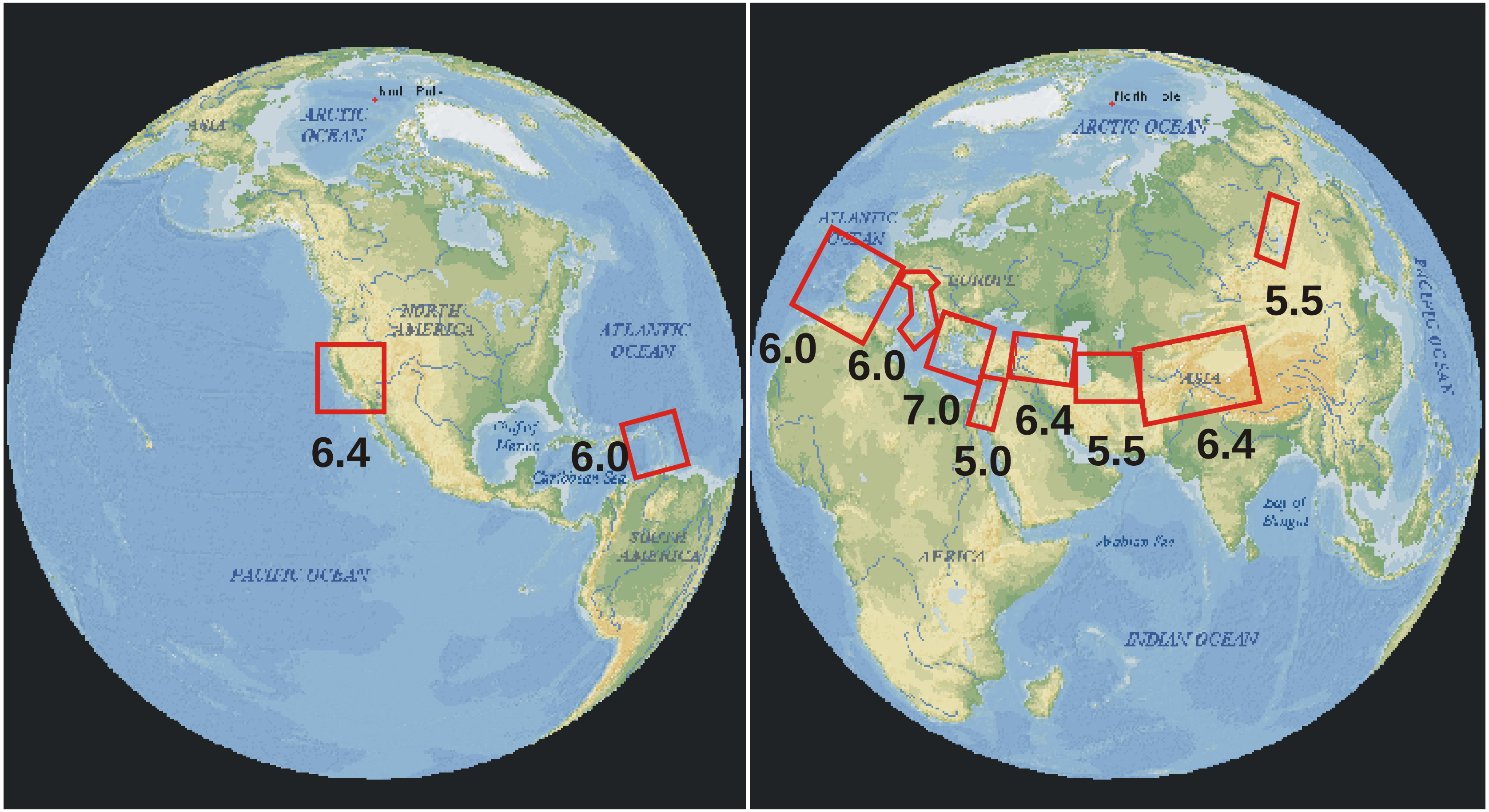
Test on independent data – application of algorithm in other regions

- ***Free choices:***
  - Regions
  - Threshold 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.***
- ***Exept subd***

Ten regions for monitoring of subsequent large earthquakes



Result of the test on the independent data - 9 regions of the world

Region	M_0	EQ number # /errors	EQ with SLE # / failures	Single EQ # / false alarms
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		***96/6***	***11/2***	***85/4***

Effectiveness prediction in 10 region

$e = 1 - (4/85 + 2/11) \approx 0.77$

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)

Limitations of similarity

- The algorithm does not work in zones of the highest seismic activity. Worldwide retrospective analysis of EQ with M≥7.5 shows almost random result of prediction.
- Analysis of smaller EQ in 10 regions also shows random result of prediction

- *Similarity is observed in the regions with intermediate-high level of seismic activity and for regionally strong EQ*

Results of prediction 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 1989-2005

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*

- *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

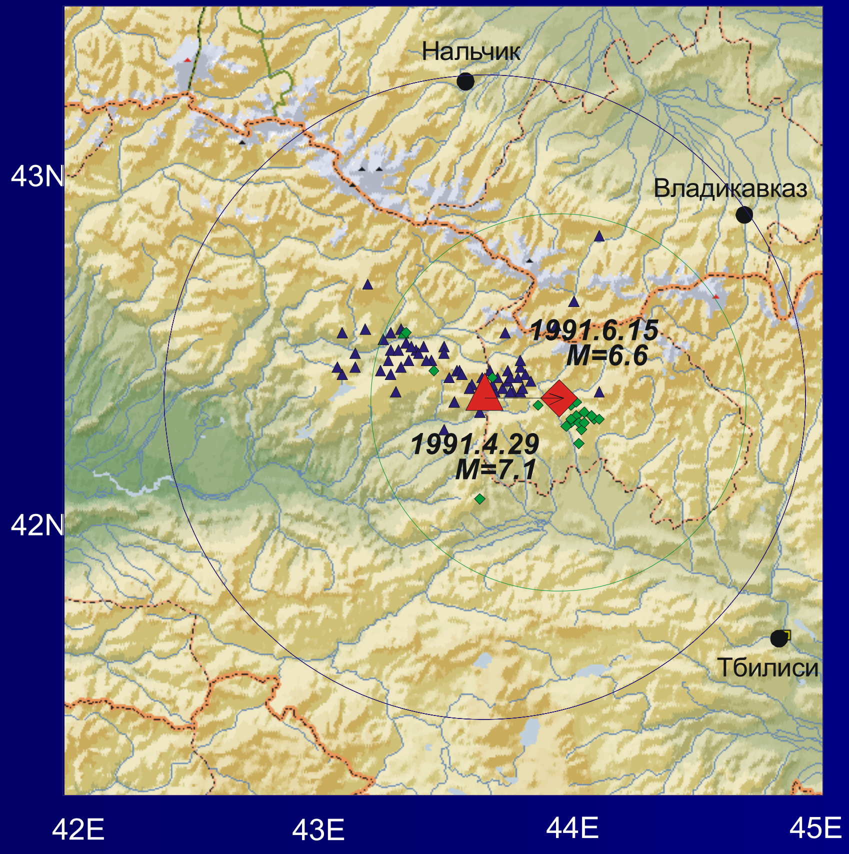
False alarms

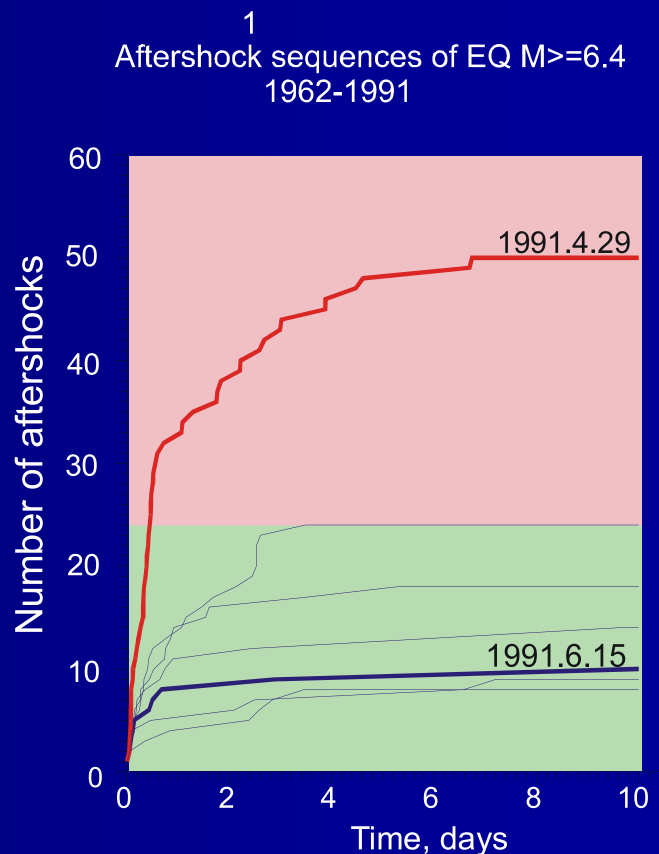
- Alarm after Landers EQ, Southern California, M=7.6, 1992 was confirmed informal: Northridge EQ, *M*=6.8, occurred in the alarm area in 20 days after alarm expiration
- Alarm after San-Simeon EQ, Southern California, Ms=6.4, 2003 was confirmed informal: Parkfield EQ, *M*=6.0, occurred in the alarm time 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”

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





Southern California 1992-1994

Landers - Northridge

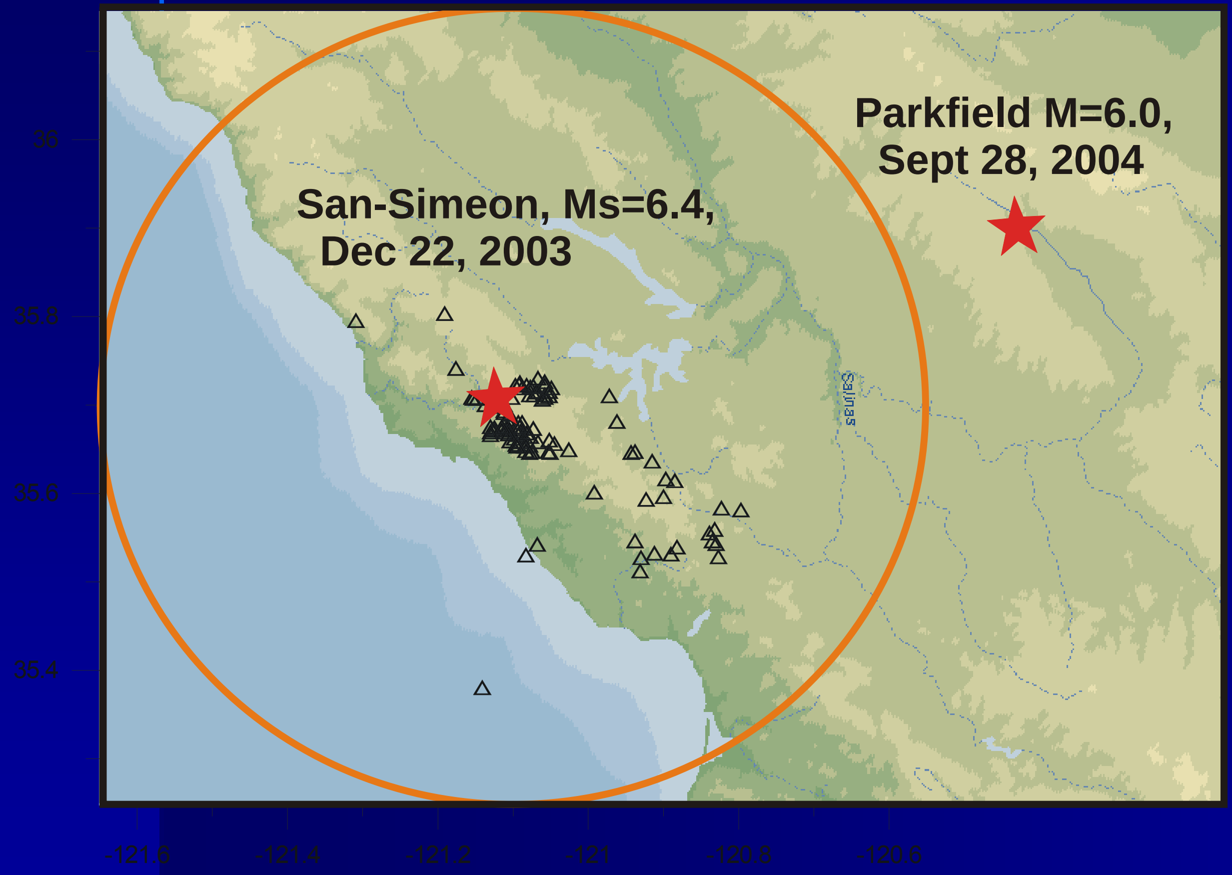
Landers, June 28, 1992, M=7.6:
Prediction: SLE is expected
with *M* >= 6.7 during 18 months
and within 198 km of Landers.

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

Southern California 2003-2004



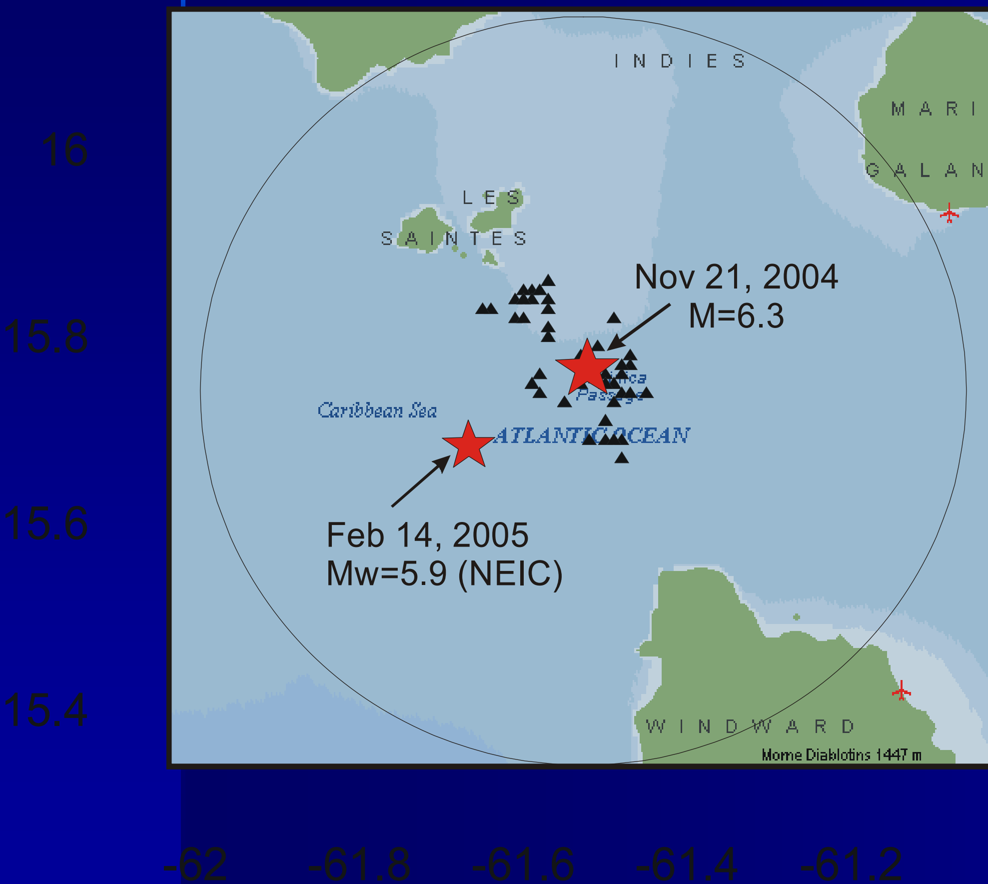
Prediction

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

Antilles 2004



Prediction

SSE is expected till May 21 2006 with magnitude M≥5.3 within 43 km of the epicenter of the first strong earthquake.

Outcome of prediction:

the alarm is confirmed.

The earthquake with magnitude Mw=5.9 (NEIC) occurred

February 14 2005 in the alarm area.

Conclusions

- Preparation of the SSE appears in symptoms of instability, which are like to the preparation of the first strong earthquake. These symptoms appear in the aftershock sequence of the first strong earthquake and in the preceding seismicity in the vicinity of its epicenter.
- Preparation of SSE is similar in the different seismotectonic conditions and for different magnitudes, but has limitations: it appears for earthquake in the magnitude interval 6.0 – 7.5 in case this earthquakes are strong in the region under consideration.