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Rise of Seismicity Correlation range Before Large Events Displayed by Earthquake Chains

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Long-range correlation of seismicity prior to large earthquakes

- V. Keilis-Borok, L. Malinovskaya, 1964, JGR
- D. Bowman, G. Ouillon, G. Sammis, A. Sornette, D. Sornette, 1998, JGR

Rise of earthquakes correlation range

1) models of seismicity

A. Gabrielov, V. Keilis-Borok, I. Zaliapin, W. Newman, 2000, Phys. Rev.

2) real seismicity

- P. Shebalin, I. Zaliapin, V. Keilis-Borok, 2000, PEPI
- G. Zöller, S. Hainzl, J. Kurths, 2001, JGR
- I. Zaliapin, V. Keilis-Borok, G. Axen, 2002, JGR

Premonitory seismicity patterns

- ROC (weeks or months - P. Shebalin et al., 2000, PEPI)
- Accord (years - I. Zaliapin, V. Keilis-Borok, G. Axen, 2002, JGR)
- ROC+Accord (months - V. Keilis-Borok, P. Shebalin, I. Zaliapin, 2002, PNAS)
- "Chain" (months) - combines ROC and Accord

Prediction algorithm

RTP (Reverse trasing of precursors) - pattern recognition of Chains using intermediate-term premonitory patterns (V. Keilis-Borok, P. Shebalin, A. Gabrielov, D. Turcotte, 2004, PEPI; P. Shebalin et al., 2004, EPS)

Possible mechanisms of long-range correlations

- Long-range correlation is a general feature of complex systems in a near-critical state.

- Microrotation of tectonic plates (Press, Allen, 1995) and crustal blocks; microfluctuations of mantle currents - redistribution of normal and shear stress through a large part of the fault network.

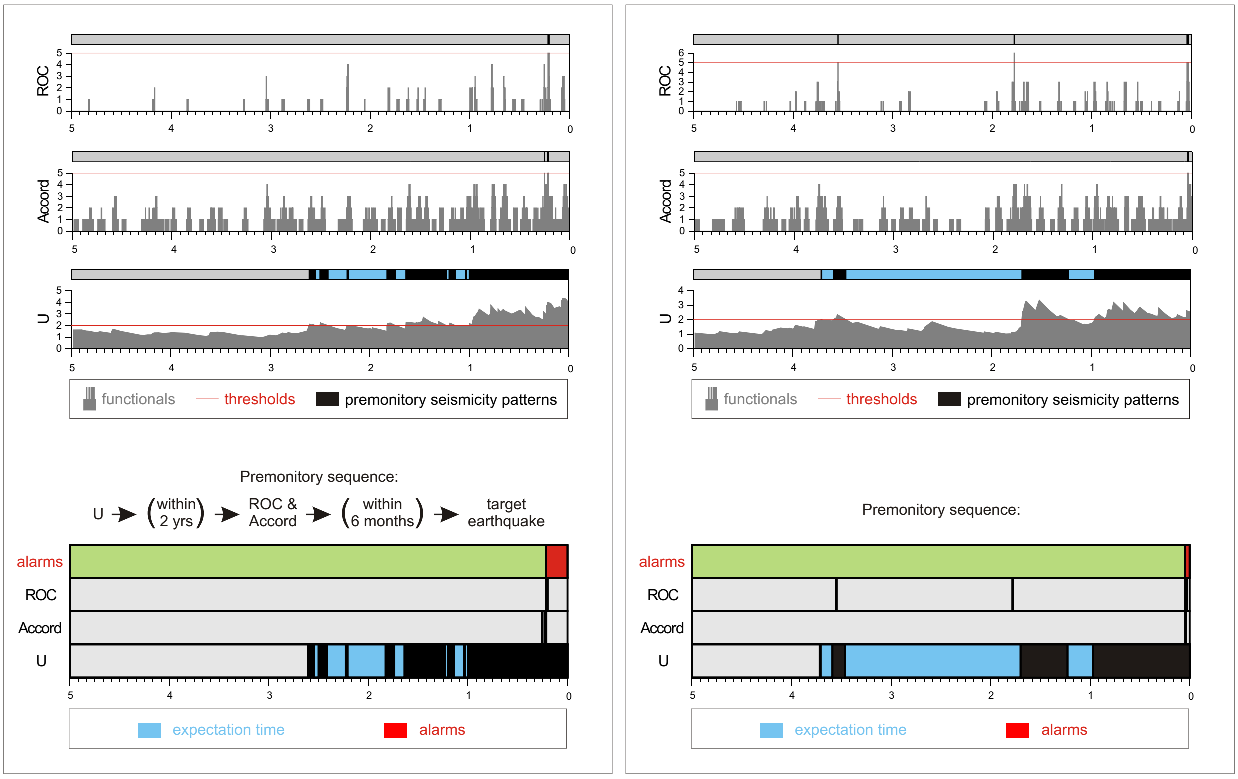
- Migration of pore fluids in a fault system: lubrication, stress corrosion, destabilization waves, redistribution of hydrostatic pressure between the solid and fluid components of the fault zone.

- Hydrodynamic waves in the upper mantle (Pollitz, Burgmann, Romanovitcz, 1998)

- Activity of creep fractures in the ductile part of the lithosphere, increasing the stress in the brittle part (Aki, 1996)

- Inelasticity and inhomogeneity of the lithosphere (Barenblatt, 1993)

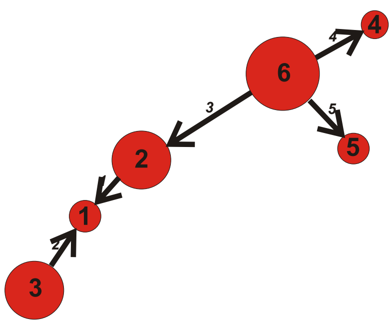
Landers, 1992 Loma Prieta, 1989



V. Keilis-Borok, P. Shebalin, I. Zaliapin, 2002, PNAS

Pattern “Chain”

Chain is a sequence of earthquakes that follow each other closely in time and space, quickly extending over large distances



Pattern ***Chain*** depicts the rise of **earthquakes correlation range**. Accordingly, only large chains are considered (at least k_0 elements and length >= l_0).

Pattern ***Chain*** combines previously found patterns ***ROC*** and ***Accord***

The chain is formed by union of all pairs of “neighbors” with

M>=M_{min}

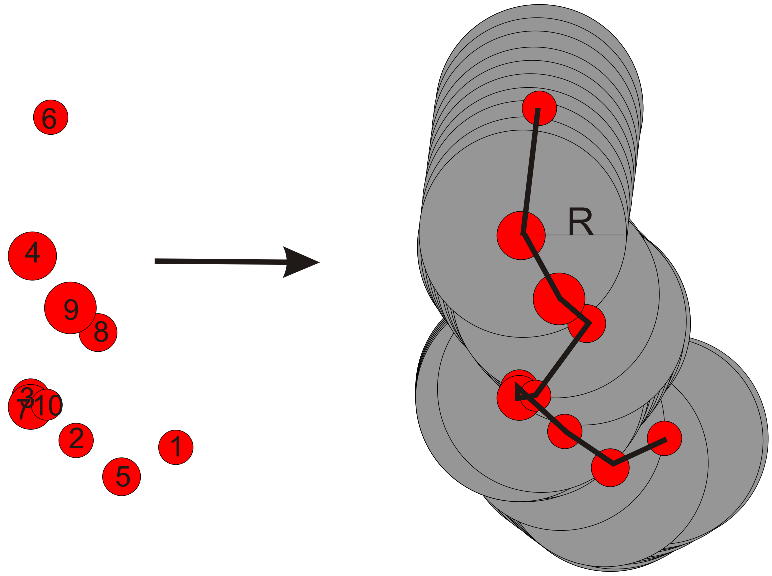
$\Delta r_{ij} \leq r_0 10^{c\cdot\{\min(M_i,M_j)-2.5\}}$ and

$\Delta t_{ij} \leq \tau_0$

List of parameters:

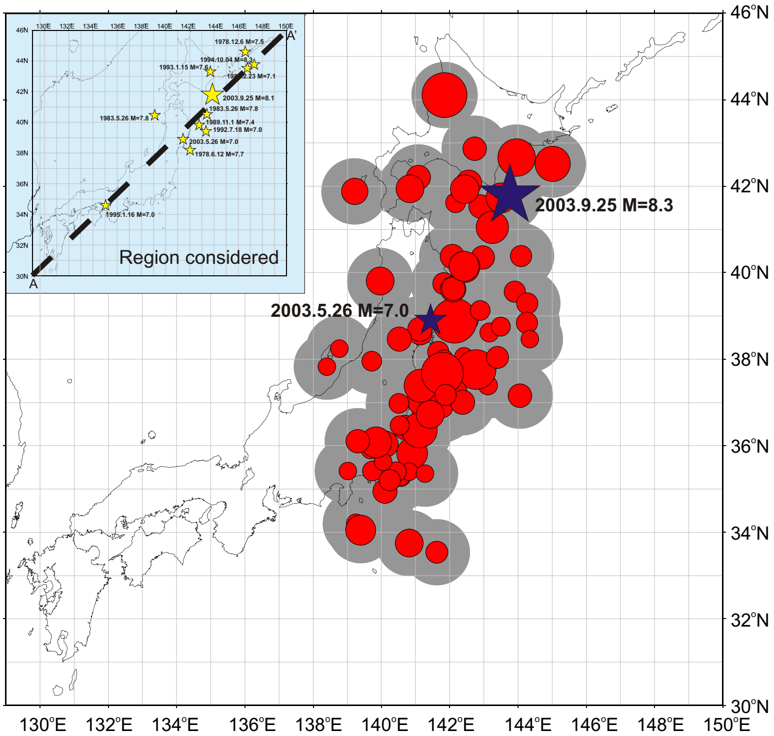
M_{min}, τ_0, r_0, c, k_0, l_0.

R-vicinity of the chain



Time order is not taken into account

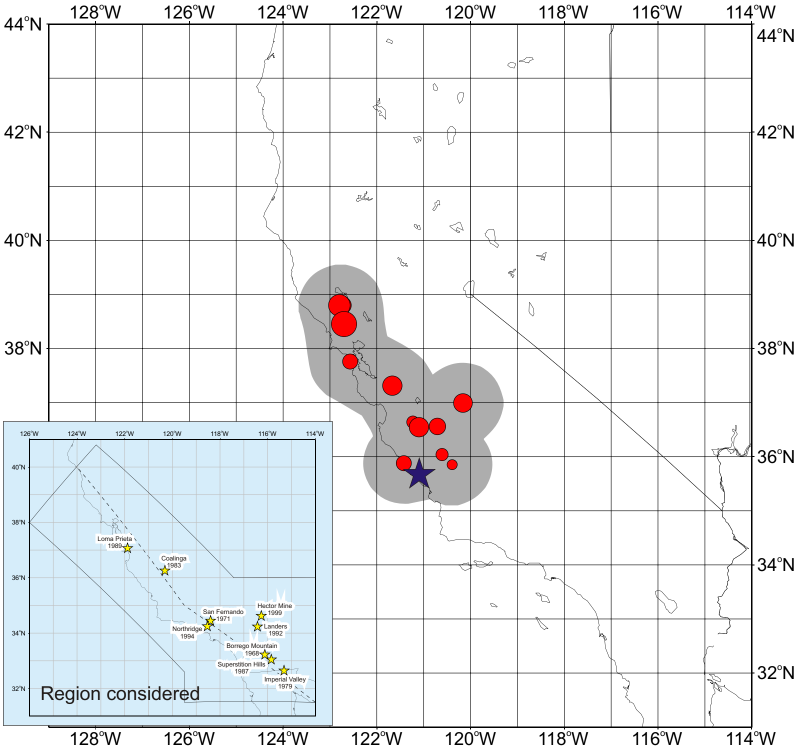
Advance prediction of Tokachi-oki earthquake, Japan, Sept. 25, 2003, M = 8.3



Dots show earthquakes, forming precursory chain. Stars - target earthquakes.

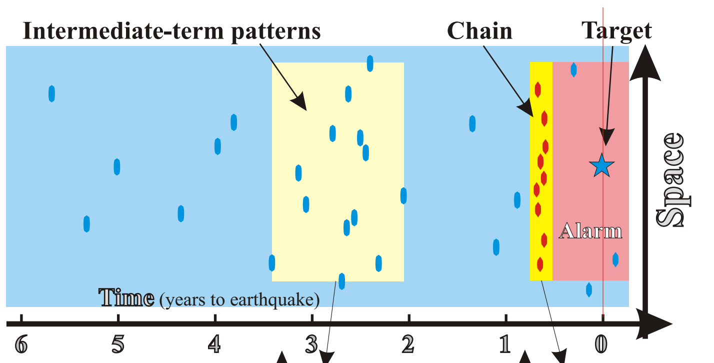
Case history, 2003
March 27: *Precursory chain* of earthquakes was formed. It indicates that an earthquake with magnitude 7 or more will occur in gray area within 9 months.
May 26: *Earthquake with magnitude 7.0* occurred in gray area; precursor was not reported in advance.
July 2: *Precursor reported* at IUGG (Sapporo, Japan).
Sept. 25: *Tokachi-oki earthquake* in gray area.

Advance short-term prediction of San Simeon earthquake in central California, M=6.5

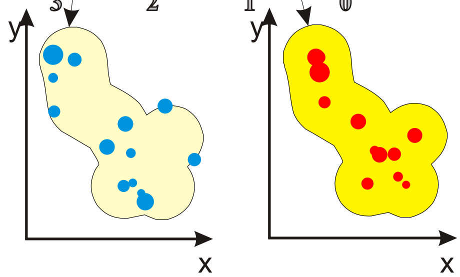


Case history, 2003
May 5: *Precursory chain* of earthquakes was formed. It indicates that an earthquake with magnitude 6.4 or more will occur in gray area within 9 months.
June 21: *Prediction was distributed* among relevant scientists and administrators.
Dec. 22: *San Simeon earthquake* (star).

RTP - pattern recognition using intermediate-term (years) premonitory seismicity patterns in the vicinities of the ***Chains*** (available case histories are used for learning)

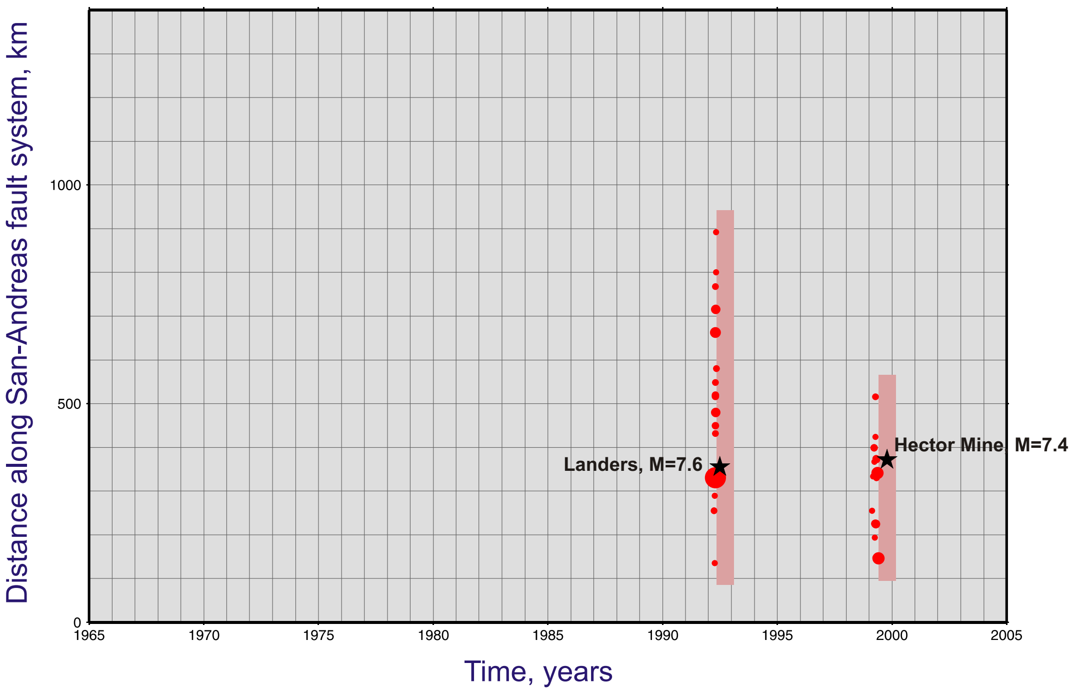


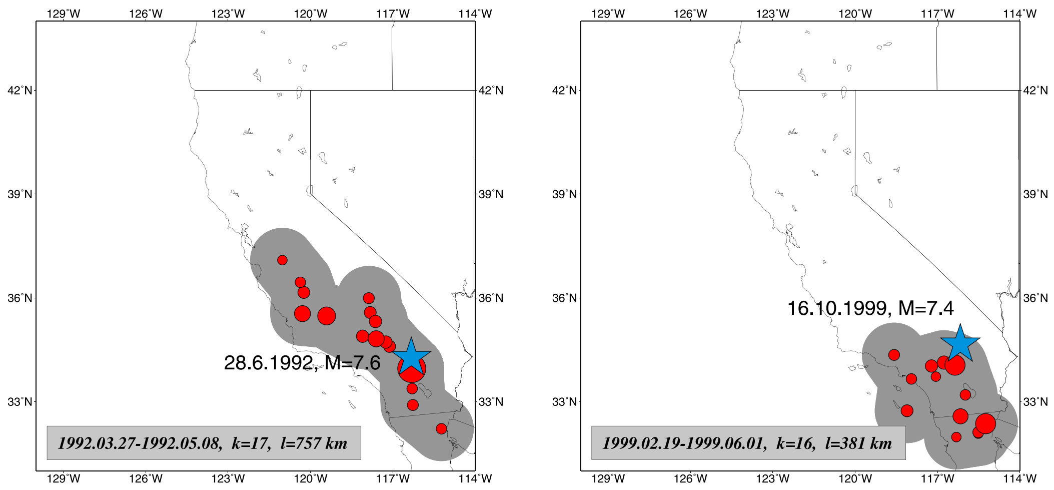
Hypothesis: shorter-term pattern



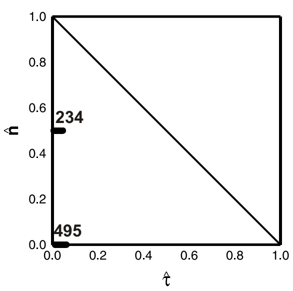
Question: are the chains in fact precursors, or they just give the way to specify the area of analysis of intermediate-term patterns?

Only two chains are detected in California in 1965-2003 with: the catalog of main shocks in the box: 30°-45°N,130°-110°W M_{min}=3.4, τ=20 days, r_0=60 km, c=0.35, k_0=15, l_0=175 km, no RTP

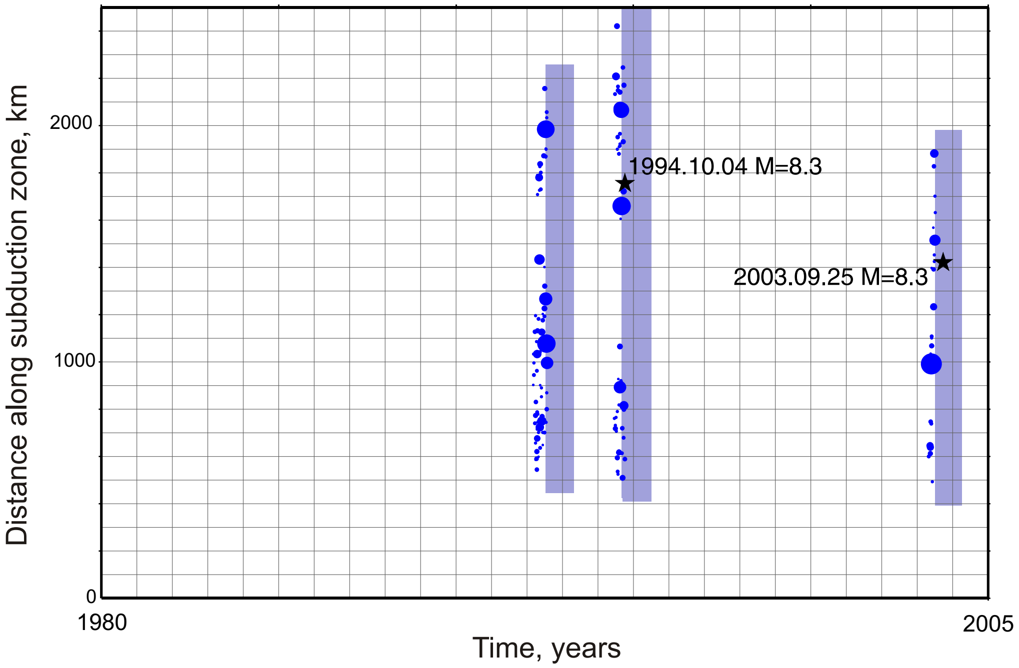


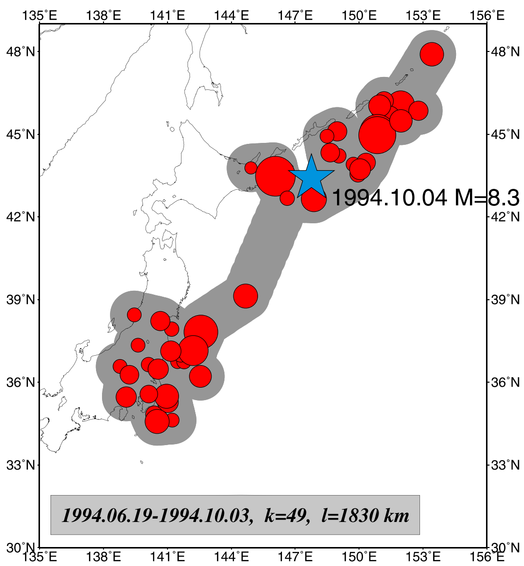


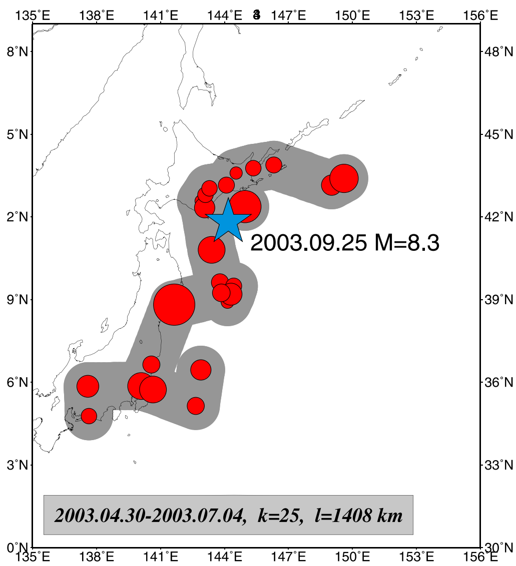
Error diagram
(parameters varied within 10%)



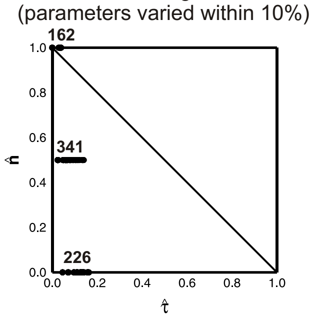
Japan-S.Kurils, 1980-2004, M ≥ 8.0







Error diagram
(parameters varied within 10%)



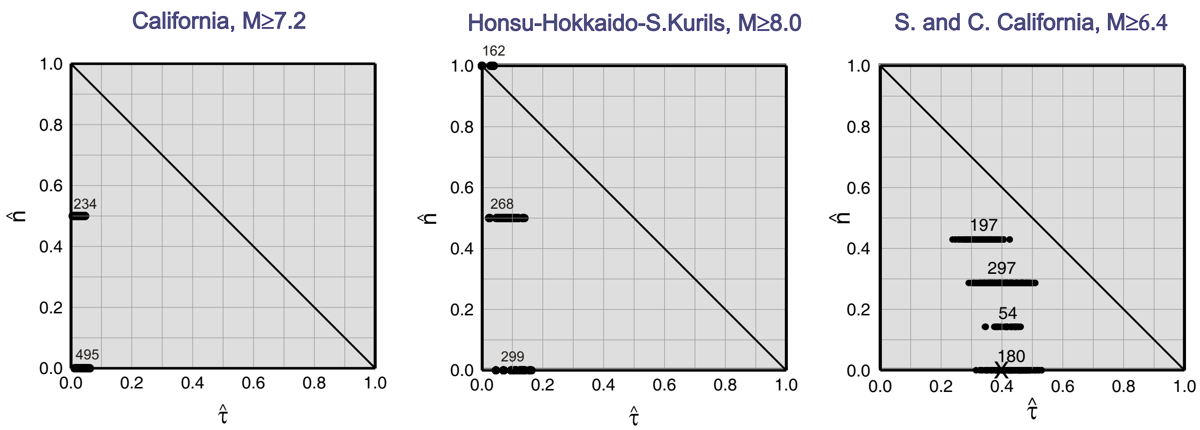
Parameters of the chains for target earthquakes with $M \geq M_0$.

Region	M_0	M_{min}	τ, days	r_0, km	c	k_0	l_0, km
1. Southern California	6.4	2.9	20	50	0.35	6	175
2. Central California	6.4	2.9	30	50	0.35	10	250
3. Eastern California	6.2	2.9	30	50	0.35	8	175
4. Northern California	6.4	2.9	25	50	0.35	6	175
5. Honshu-Hokkaido-S.Kurils	7.2	3.5	20	50	0.33	25	800
6. Eastern Mediterranean	6.5	3.0	40	50	0.35	8	175
7. Po valley, Alps, N.Dinarides, Central Apennines	5.5	2.9	45	50	0.35	6	165

	Number of chains	*Number of earth-quakes/no chain*	*p*
Central and Southern California, $M_{ANSS} \geq 6.4$	**70**	**10 / 0**	**0.35**
Mendocino, California-Nevada, $M_{ANSS} \geq 6.2$	**68**	**11 / 1**	**0.44**
Honsu-Hokkaido-S.Kurils, $M_w \geq 7.2$	**28**	**9 / 1**	**0.39**
Israel, Cyprus, $M_w \geq 6.0$	**8**	**2 / 0**	**0.12**
Apennines, Northern Dinarides, $M \geq 5.5$	**84**	**15 / 2**	**0.52**
California, $M \geq 7.2$	**2**	**2 / 0**	**0.01**
Honsu-Hokkaido-S.Kurils, $M_w \geq 8.0$	**3**	**2 / 0**	**0.01**
Worldwide, $M_w \geq 8.3$	**24**	**7 / 0**	**0.19**
Kurils-Kamchatka, $M_w \geq 7.2$	**36**	**11 / 0**	**0.35**
Aleutians-Alaska, $M_W \geq 7.2$	**25**	**6 / 1**	**0.25**
NE Pacific (Canada to Gulf of California), $M_w \geq 7.2$	**20**	**4 / 0**	**0.16**
Vrancea, $M_w \geq 5.2$	**5**	**5 / 0**	**0.04**

p - probability that a large earthquake is randomly preceded by a chain, estimated using 1000 simulations of random earthquake catalogue

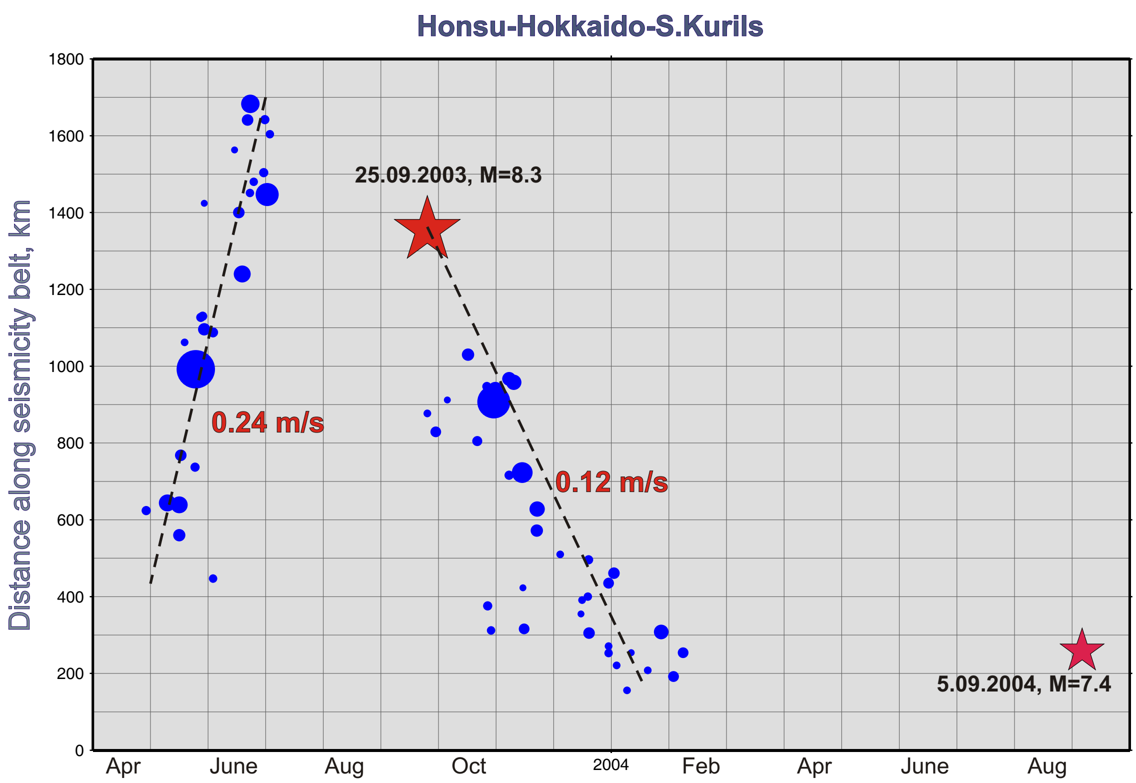
Stability tests (Molchan's error diagrams)



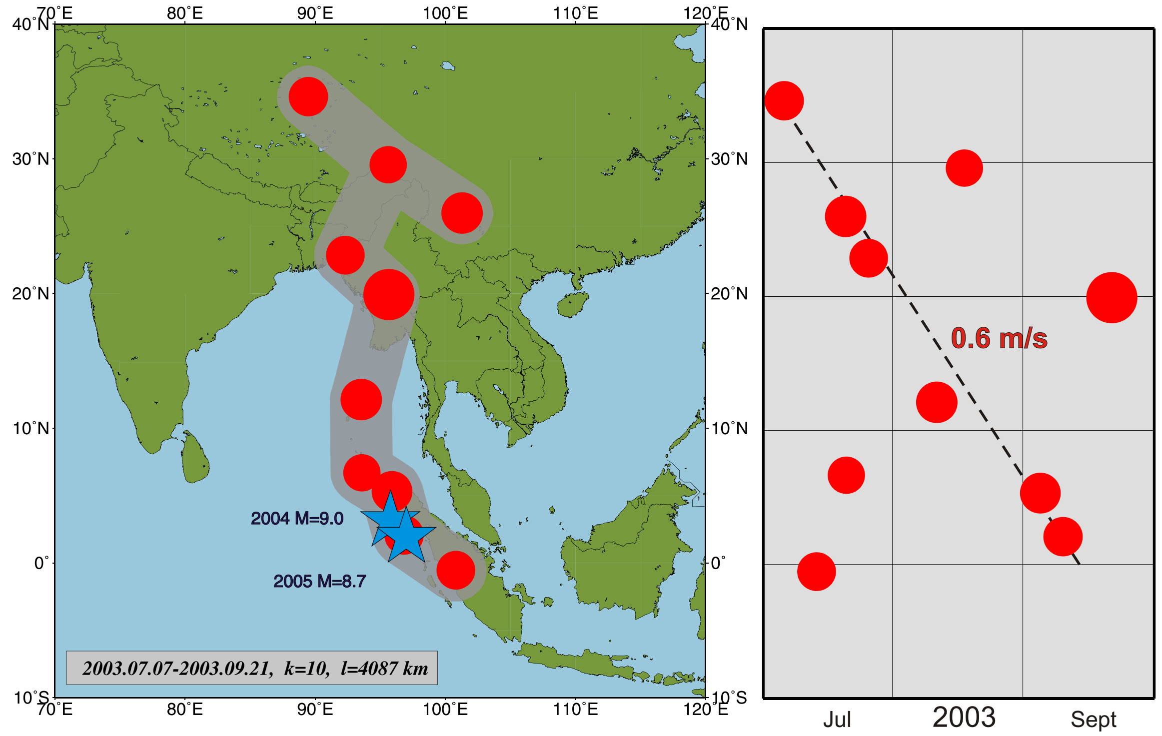
All 6 parameters of the chains were varied independently in a range of 10%, in total 3^6=729 variants. τ estimated as time-space volume of alarms weighted by seismicity

^

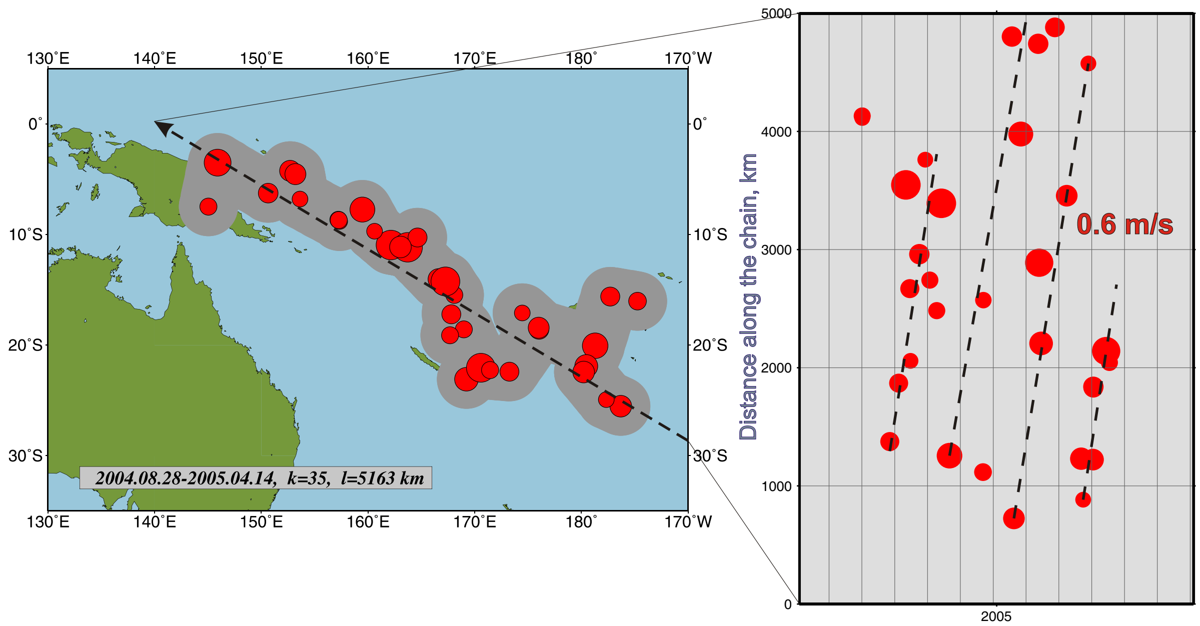
Chains or trees?



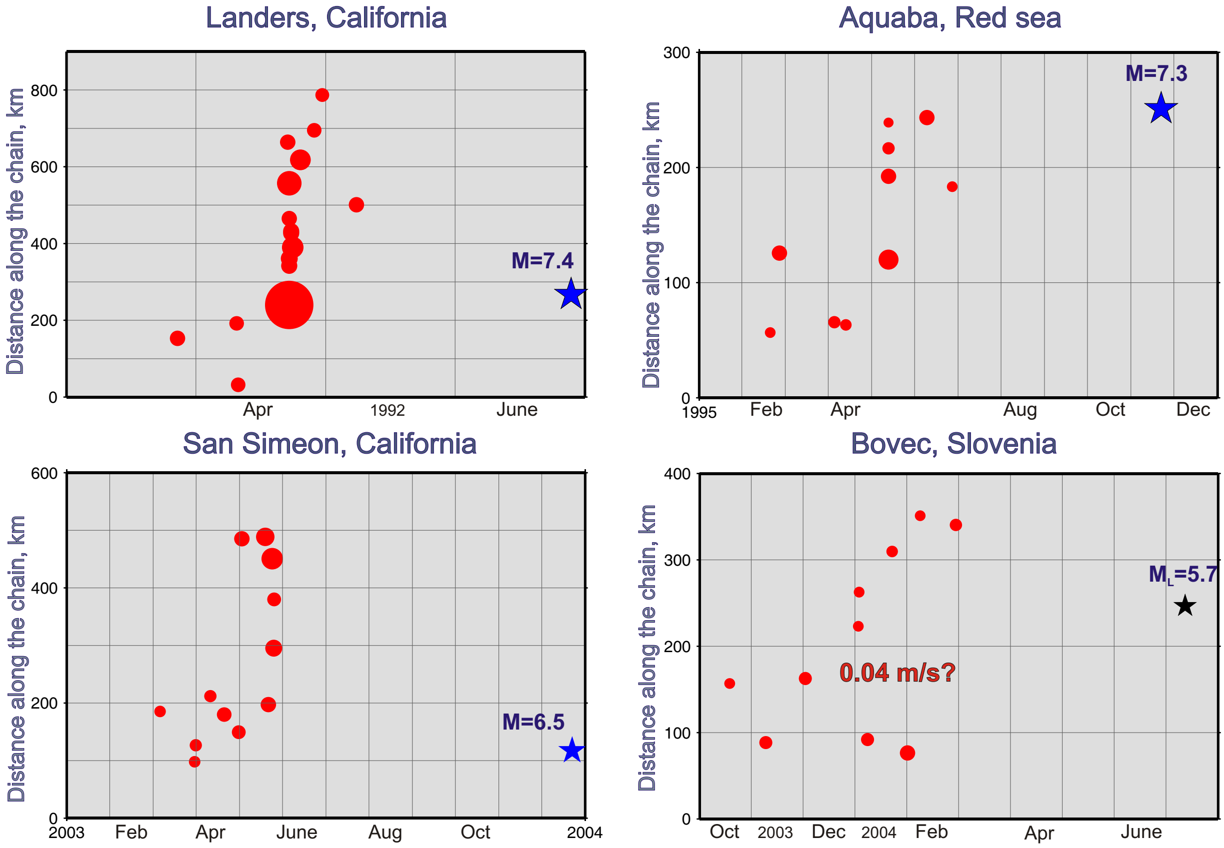
Chain prior to Sumatra earthquake of 26 Dec. 2004, M=9.0



Current chain in Melanesia



Other examples



Correlation length and magnitude in the chain

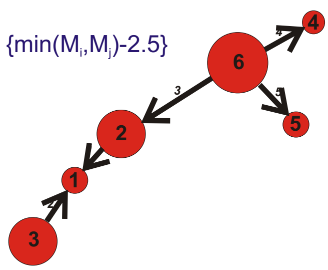
$M \geq M_{min}$

$\Delta r_{ij} \leq r_0 10^{c\,\{\min(M_i,M_j)-2.5\}}$

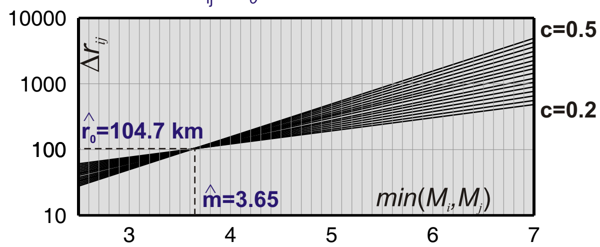
$\Delta t_{ij} \leq \tau_0$

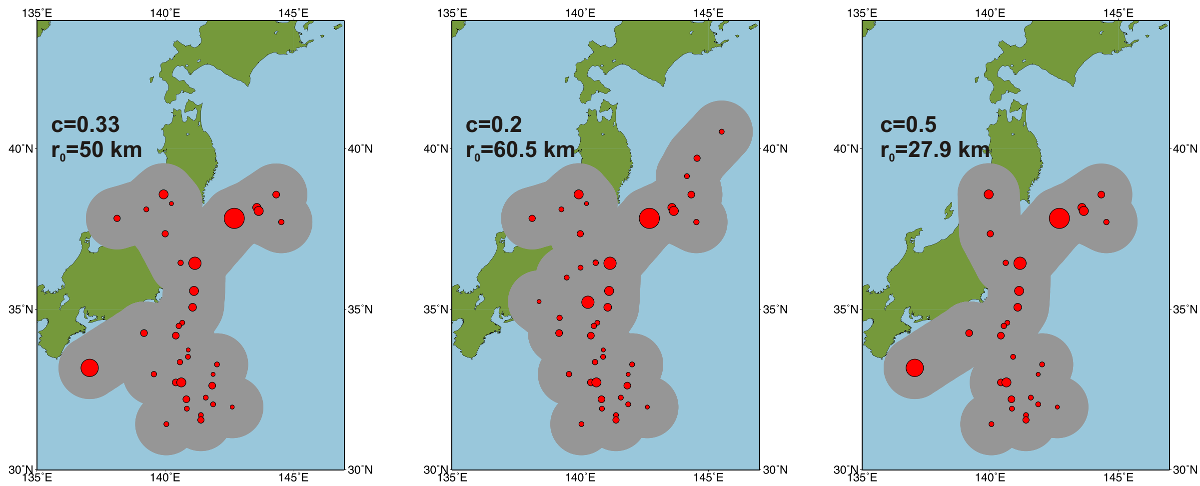
$k \geq k_0$

$l \geq l_0$

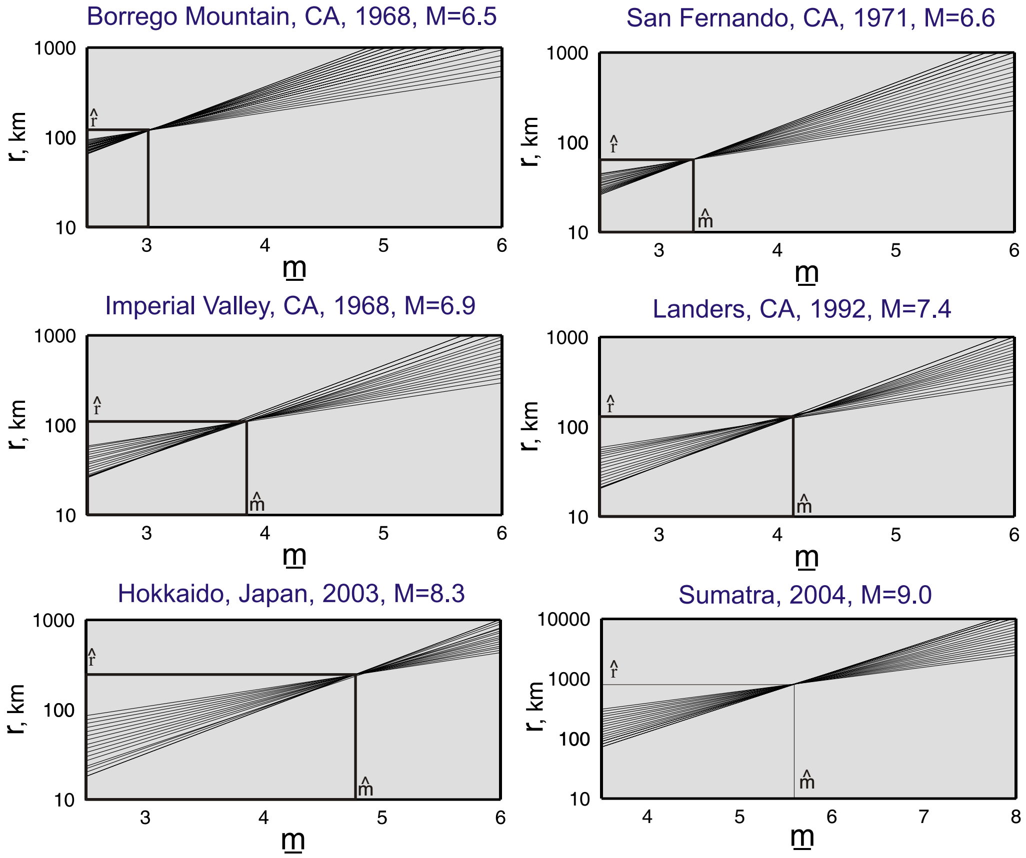


$\Delta r_{ij} \leq \hat{r}_0 10^{c\,\{\min(M_i,M_j)-\hat{m}\}}$

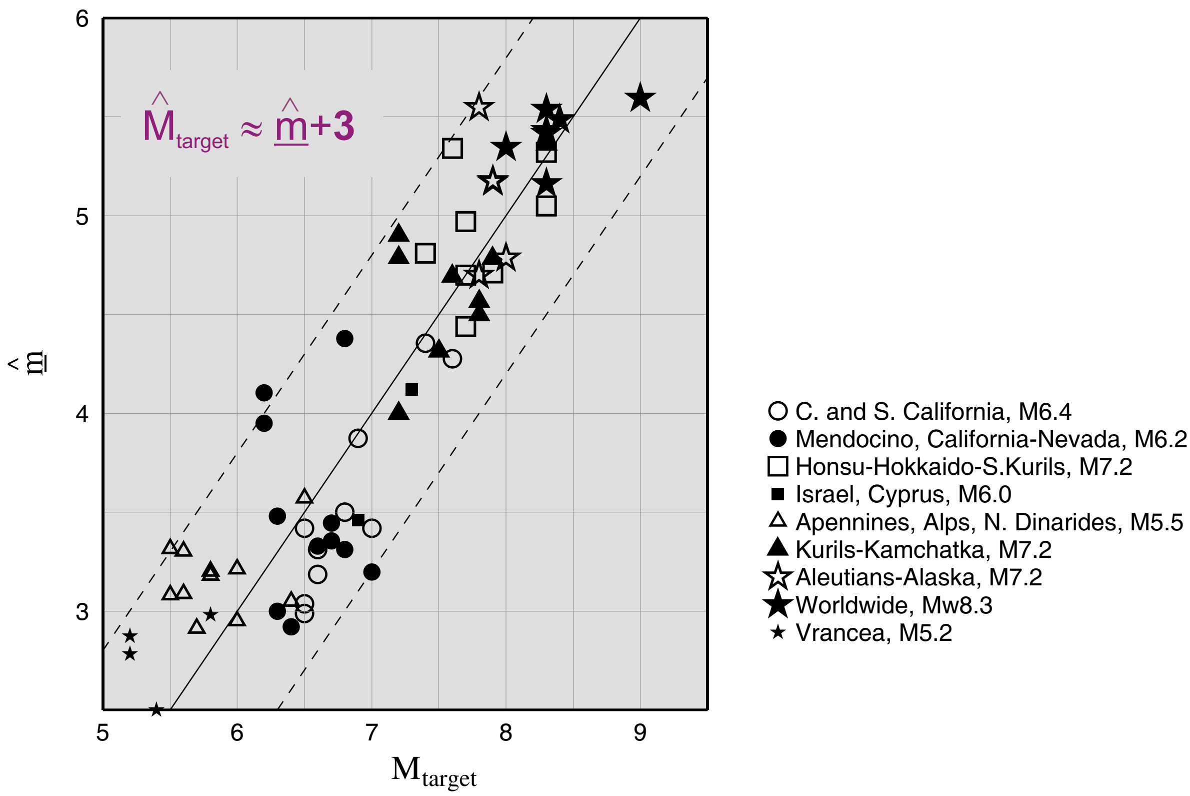




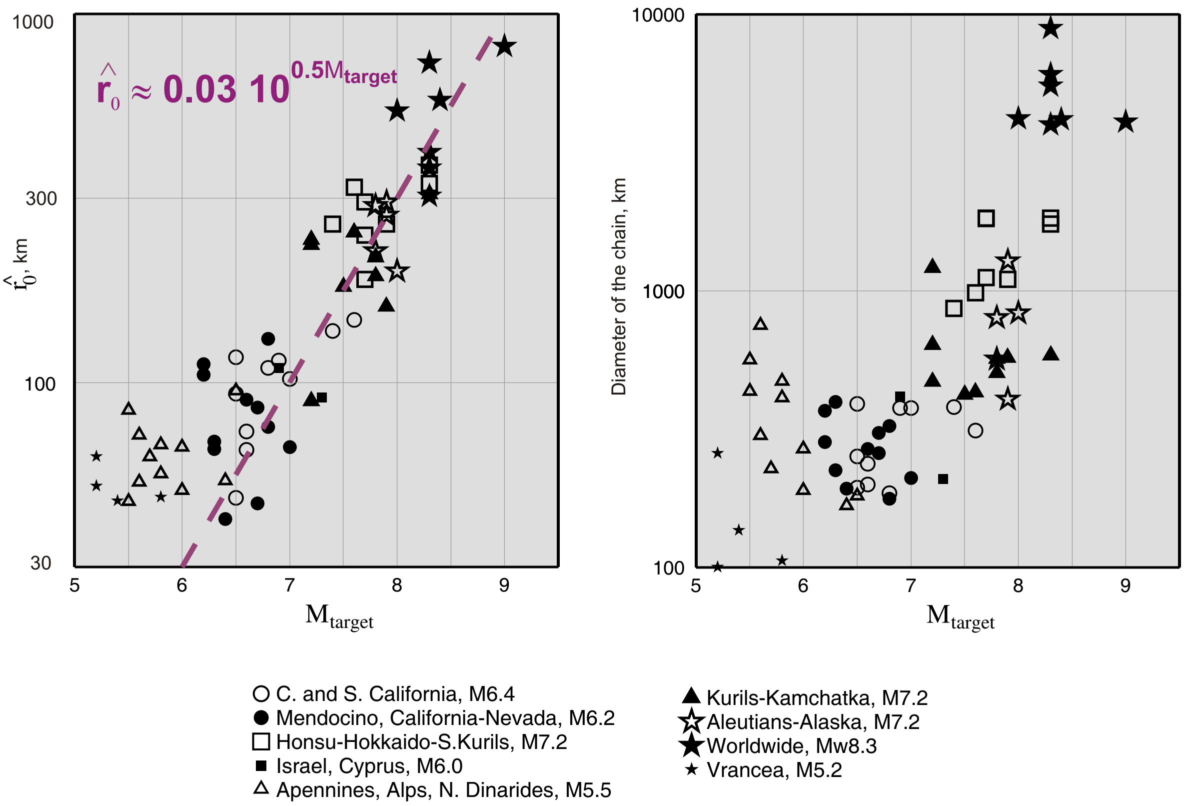
Examples



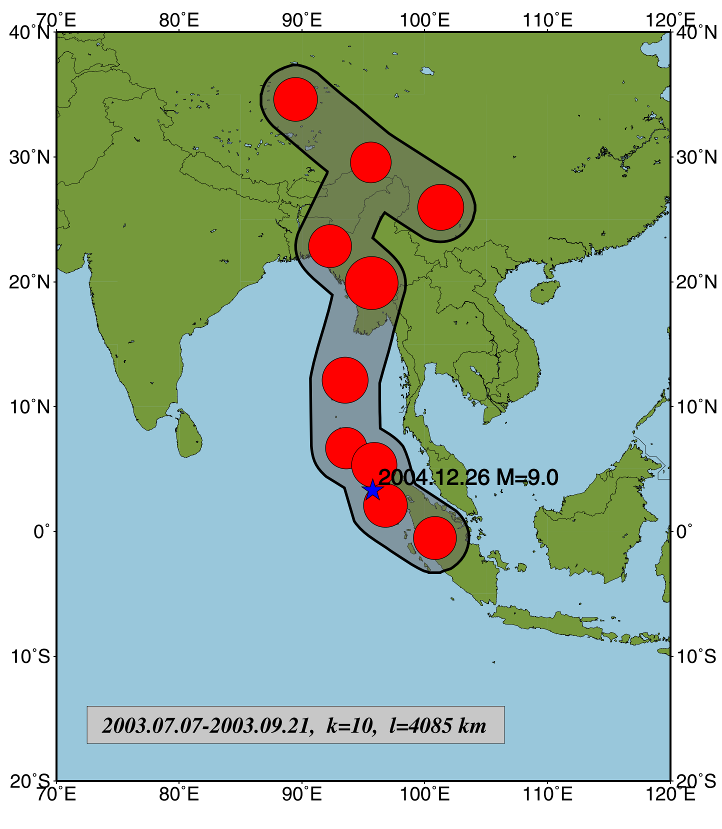
Scaling of magnitudes

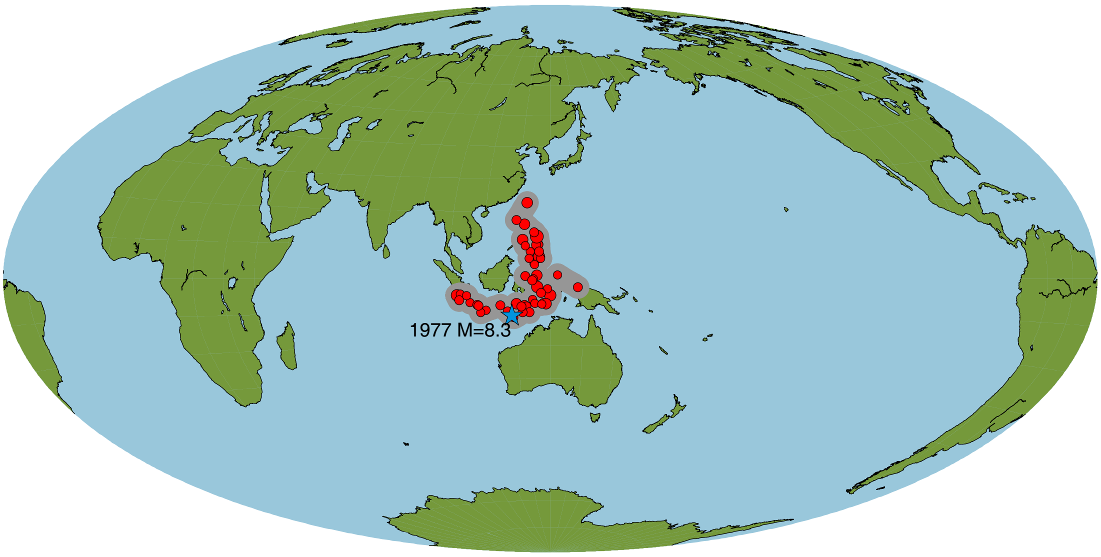


Scaling of distances

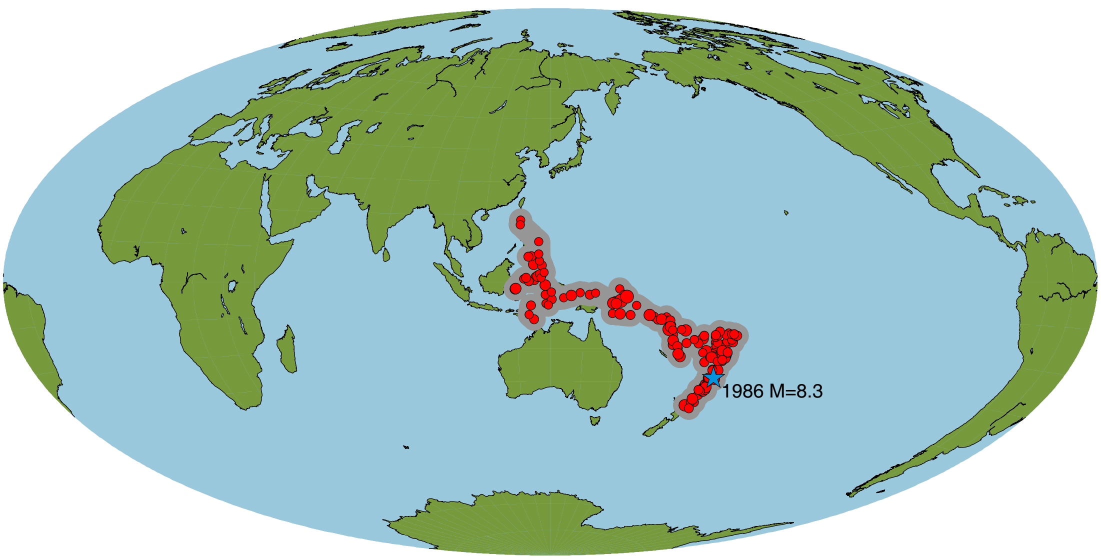


Chain 15 months before Sumatra earthquake of 26 Dec. 2004, M=9.0

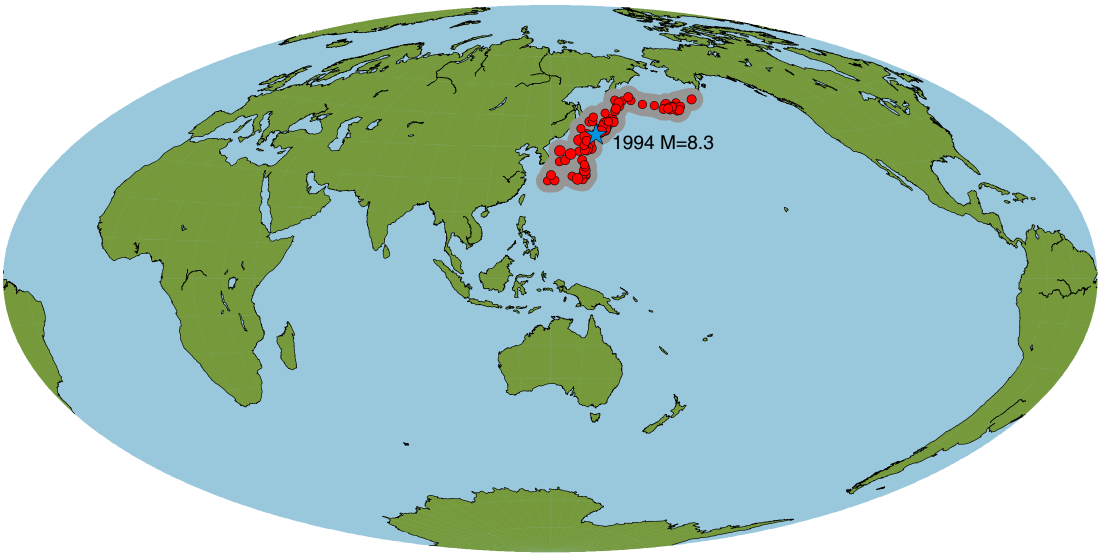




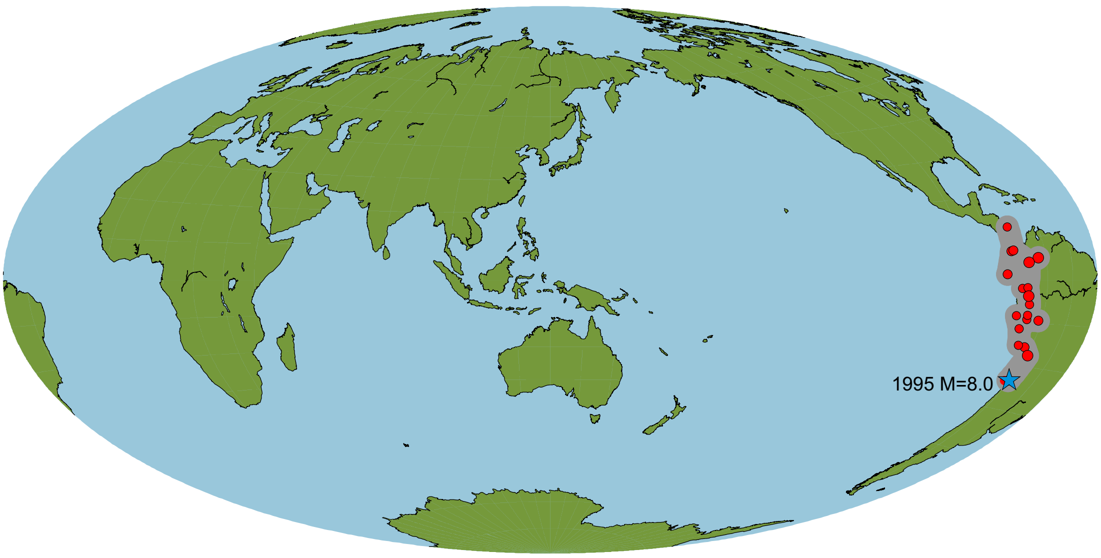
1975.01.14-1976.03.28, k=56, l=4003 km



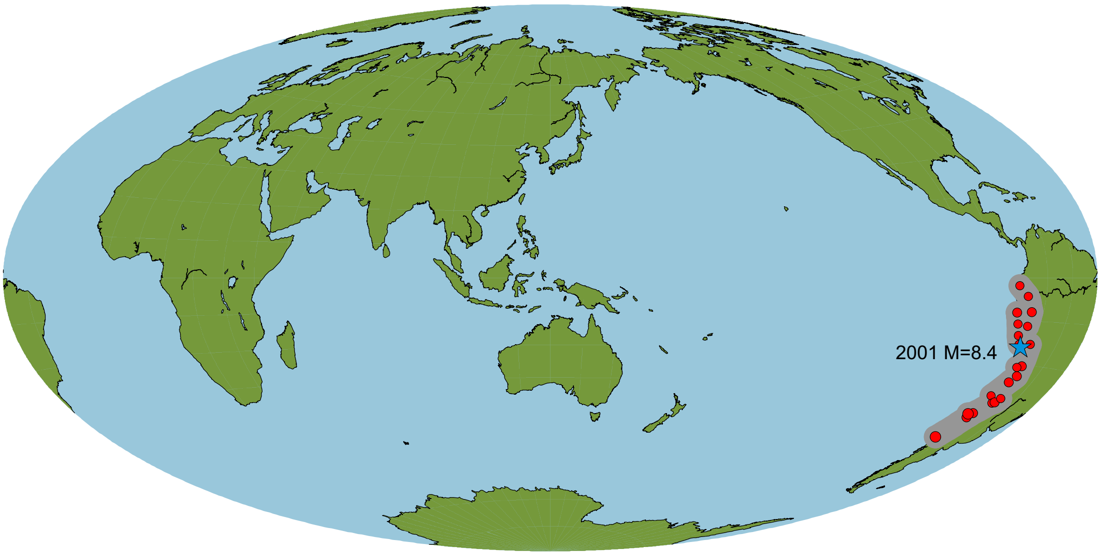
1984.06.25-1986.09.15, k=158, l=8928 km



1991.04.24-1993.03.25, k=85, l=6062 km

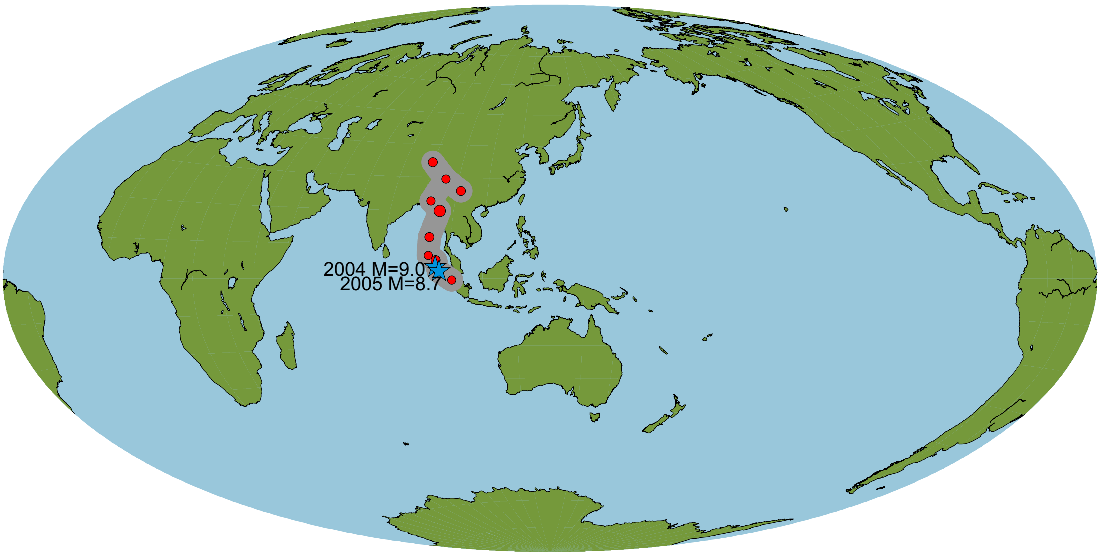


1994.10.16-1995.06.21, k=19, l=4193 km



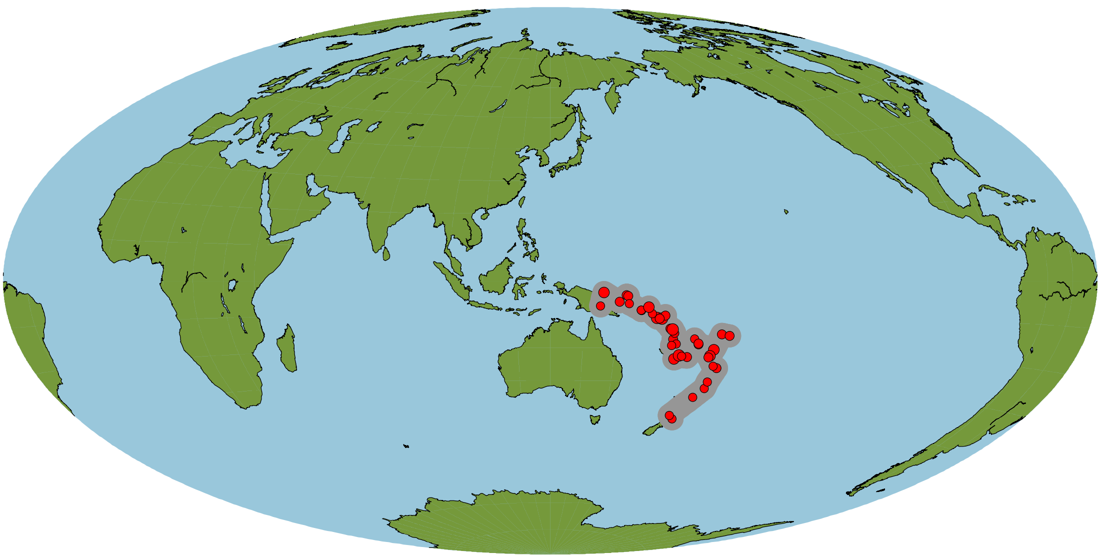
2000.09.20-2001.06.19, k=21, l=4168 km

2001.08.13-2002.07.28, k=23, l=5514 km



2003.07.07-2003.09.21, k=10, l=4087 km

Next possible candidate, M8.3+



2004.08.28-2005.04.14, k=40, l=5163 km

7 earthquake with $M_w \geq 8.3$ have occurred since 1976. All of them were preceded by such chains. In total 24 such chains were found for same period, 8 of them precede earthquakes with $M \geq 8.0$.

Probability that a large earthquake is randomly preceded by a chain is estimated as 0.19 (500 simulations of random earthquake catalogue)

RISE OF SEISMICITY CORRELATION RANGE BEFORE LARGE EVENTS DISPLAYED BY EARTHQUAKE CHAINS.

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Abstract
"Earthquake chains" are extending over large distances clusters of epicenters of moderate earthquakes, formed by statistically rare pairs of epicenters that are close in space and time ("neighbors"). Earthquake chains are supposed to be precursors of large earthquakes with lead time few months. Here we ground this hypothesis by massive tests with random earthquake catalog. Also, we study some properties of the chains and their stability to the variation of parameters. We found two invariant parameters of the chains; they characterize the spatial and energetic scales of earthquake correlation. Good covariance of those parameters with the magnitude of target earthquakes gives the possibility to estimate in advance the magnitudes in earthquake prediction. Earthquake chains are known as the first stage of the earthquake prediction algorithm Reverse Tracing of Precursors (RTP) now prospectively tested. The discussion of the complete RTP algorithm is outside the scope of this paper, however presented here results are important to ground the RTP approach.

Keywords: earthquake chains, earthquake correlation range, precursors, Reverse tracing of precursors.

1. Introduction

Earthquakes are correlated over the distances far exceeding their source dimension. This general phenomenon, hardly explained in the framework of elastic models, has various manifestations with different physical mechanisms: simultaneous change of seismicity in large areas (Mogi, 1985; Press, Allen, 1995), migration of seismisity along seismic belts (Richter, 1958; Mogi, 1968), global interdependence in the occurrence of major earthquakes (Romanowicz, 1993) and others. The phenomenon met a big interest of seismological community after the Landers earthquake in California in 1992 with magnitude M=7.6, that has caused an obvious seismicity activation in the whole San Andreas fault system over distances more than 1000 km. The evidence of long-range correlations was established also in many studies of spatio-temporal changes of seismic activity prior to large earthquakes (Willis, 1924; Imamura, 1937; Gutenberg and Richter, 1954; Keilis-Borok and Malinovskaya, 1964; Prosorov, 1975; Shaw et al., 1997; Keilis-Borok, 2003; Jaume and Sykes, 1999).

The area where premonitory patterns can be observed was first estimated by V. Keilis-Borok and L. Malinovskaya (1964). They found the linear size of that area as approximately 10 times larger than the linear size of the target earthquake fault. During last years, large interest was given to the studies of accelerating moment release prior to large earthquakes (Varnes, 1989; Bufe and Varnes, 1993; Bowman et al., 1998; Jaume and Sykes, 1999). The size of the area where the phenomenon is observed is also scaled with the size of the target earthquake (coefficient about 5). Many other premonitory seismicity patterns are observed in approximately same range of distances (see the summary in Keilis-Borok, 2003, Table 1.2). Recently, F. Press and K. Allen (1993) extended possible range of correlations to about 100 linear sizes of earthquakes.

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Physical mechanisms underlying the phenomenon of long-range correlations of earthquakes can be divided into two groups (Keilis-Borok, 2003). The first group attributes long-range correlations to large-scale processes controlling stress and strength in the system of faults: microrotation of tectonic plates (Press and Allen, 1995) and crustal blocks (Soloviev and Ismail-Zadeh, 2003) causing redistribution of normal and shear stress and, consequently redistribution of strength through a large part of the fault network; migration of pore fluids (Barenblatt et al., 1983) affects strength field through lubrication, stress corrosion, destabilization waves, and redistribution of hydrostatic pressure; hydrodynamic waves in the upper mantle (Pollitz et al., 1998) that propagate through thousands of kilometers during decades and may trigger strong earthquakes connecting seismicity across the globe; creep deformation in the ductile part of the lithosphere (Aki, 1996) increases the stress in its brittle part; inelasticity and inhomogeneity of the lithosphere (Barenblatt, 1993) may cause redistribution of stress after a fracture to much greater distances than in a homogeneous elastic media. In the second group of explanations the lithosphere is considered as a complex system; long-range correlation is a general feature of such systems in a near-critical state. The concepts of "self-organized criticality", "critical point behavior", "finite-time singularity" (Sadovskiy, 1989; Knopoff, 1993; Bak, 1996; Turcotte, 1997; Sornette, 2000; Rundle et al., 2000) form this group. The different physical mechanisms of both groups are not mutually exclusive.

The concepts of the lithosphere as a complex system suggest that earthquake correlation ranges are not only large but also increase with time prior to large earthquakes. This was confirmed first in modeled seismicity by Pepke et al. (1994), Gabrielov et al. (2000), Zaliapin et al. (2003) and then in real seismicity (Shebalin et al., 2000; Zöller et al., 2001; Zöller and Hainzl, 2001; Zaliapin et al., 2002; Keilis-Borok et al., 2002).

2. Earthquake chains

Earthquake chains reflect the premonitory increase of the earthquakes correlation range. Qualitatively speaking, the chains are the dense, long, and rapidly formed sequences of small and medium sized earthquakes; this is a special form of spatio-temporal clusters of epicenters.

The idea to use earthquake chains came as a generalization of premonitory seismicity patterns ROC (ongoing increase of earthquake correlation range, expressed via the pair-wise correlation function) and ACCORD (simultaneous activation of several major parts of the regional fault network) introduced by Gabrielov et al. (2000), Shebalin et al. (2000), Zaliapin et al. (2002), Keilis-Borok et al. (2002). Patterns ROC and ACCORD represent complimentary approaches to detecting the earthquake correlation; it was observed that they usually appear close in time.

In application to real seismicity patterns ROC and ACCORD were found in a retrospective analysis; the choice of the space could be optimized. Keilis-Borok et al. (2002) used a regionalization based on a fault map, but the degree of arbitrariness to choose subdivision boundaries was obviously high. Novikova et al. (2002) introduced a simplified regionalization; they used parallelogram areas and studied stability of patterns ROC and ACCORD to the variation of their sizes, location and orientation. They have shown that retrospective results depend significantly on the choice of those parameters. Thus, the correct choice of the space of analysis for actual predictions using patterns ROC and ACCORD is a difficult problem. A similar problem arises in application of other long-range premonitory seismicity patterns, for example, Accelerating Moment Release (Bowman et al., 1998), algorithm M8 (Kossobokov et al., 1999; see also comments by V. Kossobokov concerning the 26 December, 2004, Mw9.0 Indian Ocean earthquake at web page www.mitp.ru). Earthquake chains give a solution of this problem: they not only reflect the increase of earthquakes correlation range and generalize patterns ROC and ACCORD, but also give the location, the size and the shape of the area where the phenomenon is observed. The author previously used earthquake chains in a modification of the prediction algorithm Seismic Reversal (Shebalin and Keilis-Borok, 1999; Kossobokov and Shebalin, 2003).

2.1. Definition of earthquake chains

We consider a catalog of main shocks with magnitude $M \geq M_{min}$, aftershocks removed using coarse window method (Gardner and Knopoff, 1974). Let us call two earthquakes "neighbors" if their epicenters are closer than r and their times are closer than τ_0. A chain is a sequence of earthquakes where each earthquake has at least one neighbor belonging to that sequence and, therefore, no neighbors outside the sequence. The average density of epicenters decreases with increasing magnitudes. Accordingly, r is normalized as $r = r_0 10^{c(\underline{m}-2.5)}$, where $\underline{m}$ is the smallest magnitude in the pair. There is no scaling for parameter τ_0. We consider only the chains with two sufficiently large characteristics: number of earthquakes $k \geq k_0$, maximal distance between epicenters $l \geq l_0$. The total number of parameters is six: M_{min}, r_0, c, τ_0, k_0, and l_0. The R-vicinity of a chain is outlined by the smoothed envelope of the circles of a radius R drawn around each epicenter in the chain.

2.2. Earthquake chains and Reverse Tracing of precursors

Earthquake chains are used as the first step of the earthquake prediction algorithm Reverse Tracing of Precursors, RTP (Keilis-Borok et al., 2004; Shebalin et al., 2004, 2005). This algorithm is designed to predict large earthquakes few months in advance. The algorithm RTP needs the second step because up to 90% of the chains are not followed so closely by strong earthquakes and in prediction they would cause false alarms. To eliminate false alarms, each chain is considered as a candidate, and at the second step of the algorithm the intermediate-term precursors preceding the chains are determined in the space indicated by the chains. Pattern recognition is used to separate precursory chains from false alarms. Precursors are analyzed in the order, opposite to their occurrence: first, shorter-term precursors, earthquake chains that appear months prior to large earthquake, and second, intermediate-term precursors having lead time years. Hence the name of the algorithm.

The idea of RTP is based on the hypothesis that intermediate-term precursors and shorter-term precursors, earthquake chains, reflect different stages of the same process and, accordingly, they occur in approximately the same space. The advantage of the RTP approach is obvious if this hypothesis is true: the earthquake chain automatically depicts the location, the size and the shape of the area, where intermediate-term precursors are hoped to have the most contrast manifestation than in an alternative approach, for example scanning the territory by circles. In section 5 we shall show that the size of precursory chains correlate with the magnitude of large earthquakes they precede; this gives an important confirmation of the hypothesis.

The algorithm RTP is now tested by documented predictions made in advance in several seismically active regions (Shebalin et al., 2005) and its performance is yet to be validated. Current results of the test can be found at http://www.igpp.ucla.edu/prediction/rtp/

In the present paper we study two important questions concerning the first step of the RTP algorithm: 1) (section 4) are earthquake chains short-term (time scale months) precursors, or they just give a unique formalized rule to choose an area of the analysis of intermediate-term precursors? 2) (section 5) do precursory chains have scaling properties, with the magnitudes of large earthquakes they precede?

3. Area of the study, data used and parameters of the chains

We consider the same regions (Fig. 1) as in the test of documented predictions made in advance using the RTP method (Shebalin et al., 2005). Parameters of the chains as well as magnitudes of target large earthquakes (Table 1) are also the same as in the RTP test. In addition, we consider chains with modified parameters aimed to be precursors of only largest earthquakes in California (M≥7.4) and Honsu-Hokkaido-Southern Kurils (M≥8.0). Next, we consider three new regions not yet included in the RTP test: Kurils-Kamchatka, Aleutians-Alaska and NE Pacific (Canada to Gulf of California), with magnitudes of target earthquakes $M_W \geq 7.2$ in all three regions.

After the catastrophic earthquake near Sumatra, Indonesia, 26 December 2004, M=9.0 we have naturally tried to find a precursory chain preceding the earthquake. Such a chain was found in a large area surrounding the epicenter. After that it was found that the chains with same parameters precede all 7 earthquake with $M_W \geq 8.3$ in 1976-2005. The total worldwide number of such chains in 1976-2005 is only 24. We add those chains in the analysis in sections 4 and 5.

The last considered region, Vrancea, Rumania (target earthquakes with $M_W \geq 5.2$) is very specific. The large earthquakes in the region occur at the depths more than 100 km, and the seismicity is clustered to almost vertical plane crossing the Earth surface in SW-NE direction. Accordingly, here we consider chains in this plane, and not at the Earth surface as in other regions.

The catalogs used in each of regions are indicated in the Table 1. The catalogue ANSS is the composite catalogue produced by Advanced National Seismic System (ANSS) and hosted by the Northern California Data Center (NCEDC), it is available at the web site http://quake.geo.berkeley.edu/cnss/catalog-search.html. The PDE catalogue is the NEIC/USGS catalogue. We used data in EHDR format: PDE monthly (ftp://hazards.cr.usgs.gov/pde/) updated by PDE weekly and then QED (ftp://hazards.cr.usgs.gov/weekly/). JMA catalogue is the Japan Meteorological Agency earthquake catalogue received through the Japan Meteorological Business Support Center. GII is the earthquake catalog of Geophysical Institute of Israel, Holon, it covers large part of eastern Mediterranean. NIEP catalogue is produced by National Institute for Earth Physics, Bucharest, Romania.

The values of parameters of the chains for each of 14 cases are listed in the Table 1. Two parameters are common, with few exceptions, for all the cases: r_0=50 km, $c = 0.35$. Other parameters are common for all chains within a region, but differ between regions. In Honsu-Hokkaido-S. Kurils the value $c = 0.33$ is slightly different from the standard value. Initially, we used in that region the standard value $c = 0.35$. But in the middle 2003 JMA has decided to completely change magnitudes in their catalog, and this gave the change of the b-value of the magnitude-frequency relation. Accordingly, the previously obtained chains also have changed. The simplest way to correct the situation was just to change slightly the value c.

4. Are earthquake chains precursors of large earthquakes?

The first promising results of the test of the RTP method do not prove that earthquake chains themselves are precursors of large earthquakes with lead time months. Any of the following cases also could give non-random RTP results: (a) earthquake chains are completely random, they just give a unique way to specify the area of a complex shape for the analysis of intermediate-term precursors; (b) the chains are not shorter-term precursors, but they indicate correctly the space where intermediate-term precursors have a bright manifestation; (c) the chains are shorter-term precursors, but the space they indicate is not necessarily connected with the epicenter of the future large earthquake nor with the area of manifestation of intermediate-term precursors. What is the contribution of the chains in the aggregate RTP result? The results of the next three subsections corroborate that the chains are really precursors of large earthquakes, with lead time months.

4.1 Earthquake chains preceding largest earthquakes

First, let us try to change the parameters of the chains in order to "predict" only largest earthquakes and simultaneously to decrease the total number of chains. We have tried to do this in California and Honsu-Hokkaido-S. Kurils regions (items 8 and 9 in the table 1), and this happened to by possible. In California we have increased the magnitude cut-off M_{min}, spatial parameters r_0 and l_0, and the minimal number of epicenters in the chain k_0 (compare items 1 to 4 and item 8 in the Table 1). As the result, only two chains are detected, both precede two largest earthquakes with M≥7.4 (Fig. 2). In Honsu-Hokkaido-S. Kurils we have just increased the magnitude cut-off M_{min} and the value l_0 (compare items 5 and 9 in the Table 1). Three chains are found, two of them precede both largest earthquakes in the region, M≥8 (Fig. 3). Below we shall show that both results are significantly non-random and stable to variation of parameters.

4.2 Tests with randomized earthquake catalogues

First columns of the Table 2 give statistics of the chains for all 14 considered cases specified in the Table 1. In all regions all or almost all target earthquakes were preceded within T months by chains, and their epicenters lie in the R-vicinity of those chains (R and T are given in the Table 2). Except two cases described above and the case of Vrancea, the number of chains is significantly larger than the number of target earthquakes; the ratio varies from 3.27 to 7.86. The number of non-precursory chains is large, but the chains occupy only the part of considered regions, so that the time-space of hypothetic alarms (R-vicinity of chains in space, and period T months in time) takes less than a half of the whole considered time-space in all cases. What is the probability to obtain similar results by chance? For the estimate of this probability, α, in each of 14 cases we generated 1000 times a random catalog, then we used the realizations of this catalog to detect chains, and then we calculated how many target earthquakes occurred in time-space of hypothetic alarms given by those chains; the corresponding average rate p is shown in the Table 2. Finally, we used the binomial model to calculate α from p (see the last column of the Table 2). Binomial model gives rough estimate, because it does not take into account that some large earthquakes are preceded more often by random chains than others due to heterogeneity of the seismicity. For relatively large estimates $\alpha > 0.02$ (cases 2, 3 and 4) we verified them directly, increasing the number of realizations of the random catalog to 5000, and calculating the number of realizations giving 3 "successes" out of 3, 7 "successes" out of 8 and 8 "successes" out of 9 (see Table 2; corresponding estimation α is given in brackets). The direct estimates well agree with those obtained from the binomial model.

To generate random catalog we used the following procedure: origin times are taken from the real catalog of main shocks, and the epicenters coordinates together with magnitudes are taken from a randomly chosen records (with nonrepeated samples) of the same catalog. This method ensures conservation of spatio-magnitude structure of seismicity, temporal clustering, but significantly (not completely) destroys spatio-temporal links. Using different randomization method, for example generating Poisson distribution times, we would obtain smaller estimates p and α.

4.3 Tests of stability of the chains to variation of their parameters

The results obtained here are retrospective. Choosing parameters of the chains, we tried to avoid their over-optimization (data fitting); the round-off-like values give evidence. Still, some chance remains, but in that case results should be sensitive to variation of parameters. We tested stability by independent variation of the values of parameters within at least 10% (0.2 magnitude units for the parameter M_{min}). Each of the six parameters was presented by 3 values: standard one, smaller value, and larger value, $729=3^6$ variants in total. For each of the variants we detected the chains and compared them in time-space with target earthquakes.

A convenient way to present results is given by Molchan's (2003) error diagrams. We calculate two interdependent measures: fraction of target earthquakes that occurred outside time-space of hypothetic alarms (R-vicinity of a chain during T months), n; and the time-space τ covered by all alarms together, normalized by the whole space-time considered. The space is measured not in km^2 but in long-term average of seismicity. We used the average number of main shocks with $M \geq 4$. The line (0,1; 1,0) in the (n, τ) diagram corresponds to a random result, an ideal prediction is the point (0,0).

Each of 729 variants of the stability test gives one point in (n, τ) diagram. For all 14 cases all or most of points lie far from the line of a random result, several examples are shown in Fig. 4. Good stability of the results confirms that the parameters were not over-optimized and, accordingly, gives one more argument in favour of the chains as real short-term precursors of large earthquakes.

We have studied also how large are admissible ranges of the variation of the parameters. For each of the parameters we found that if simultaneously to the change of the parameter to correct correspondingly the value of only one more parameter (for example, the change of the magnitude cut-off M_{min} needs correction of the value k_0), then the range of the changes, giving approximately same number of the chains, their location, size and shape, is very large: 0.5 to 2 units of magnitude for the parameter M_{min}, 30% to 150% of relative changes for other parameters.

5. Scaling of the precursory chains with the magnitude of large earthquakes

Studying admissible limits of parameter values, we found an interesting property of earthquake chains. If to vary the value c in the limits from 0.2 to 0.5, and each time to find an appropriate value r_0, leaving other parameters unchanged, the chain remains the same or only slightly different (as in an example in Fig. 5). Usually values r_0 in some range are appropriate, we take the minimum. The graphs of the function $r = r_0 10^{c(\underline{m}-2.5)}$ (see the definition of the chains in section 2.1) drown for the obtained pairs (c, r_0), as a rule intersect at one point $(\hat{m}, \hat{r}_0)$; those values vary from chain to chain (see examples in Fig. 6). This rule makes values $\hat{m}$ and $\hat{r}_0$ convenient parameters of the energetic scale and range of earthquake's correlation in the chains respectively. The statistics of both $\hat{m}$ and $\hat{r}_0$ for considered cases are given in Fig. 7. Both demonstrate a good covariance with magnitudes of target earthquakes, this covariance is better than that between linear sizes of chains and target magnitudes (Fig. 7c).

6. Discussion and conclusions

Results of this paper confirm that earthquake chains are a real precursory phenomenon preceding large earthquakes months in advance. Statistical significance of non-randomness of the result is high.

Earthquake chains depict an increased range of correlation of earthquakes of medium magnitudes. Accordingly, they give one more evidence of the premonitory increase of the correlation range.

The chosen definition of earthquake chains ensures high stability to the variation of their parameters, the admissible limits of the variation are large.

The found invariant parameters of the chains, $\hat{m}$ and $\hat{r}_0$, characterize energetic and spatial scales of the correlation. Parameter $\hat{r}_0$ can be used as the definition of the range of correlation in earthquake chains. Parameter $\hat{m}$ could be used in the prediction algorithm RTP based on earthquake chains to estimate magnitudes of predicted earthquakes, on the basis of the regression $M_{target} \approx \hat{m} + 3 \pm 0.6$.

The definition of the earthquake chains does not imply that their shape is chain-like, and probably the term "tree" would be more appropriate. But actually real chains most often have significantly gaunt shape, few examples are shown in Fig. 8. This explains why we prefer the term "chains". It is interesting that chains obtained from a randomized catalog usually are less organized. This fact is one more confirmation of the phenomenon of the premonitory increase of earthquake correlation range.

In time-space earthquake chains have various structures. Some of them demonstrate a well-organized, directional, wave-like arrangement. For example, the chain prior to Tokachi Oki earthquake near Hokkaido, 26 September 2003, M=8.3 clearly grown from South to North (Fig. 9a). The earthquake has occurred in the northern part of the chain three months later. After the quake, a new chain started to grow from North to South, and 7 months later two earthquakes, M=7.2 and M=7.4 have occurred in South. The velocities of the chains propagation are 0.24 m/s and 0.12 m/s accordingly. The propagation of the chain preceding Sumatra earthquake of 26 December 2004, M=9.0, is less evident (Fig. 9b), but its velocity is higher (0.6 m/s). The examples of the chains prior to Landers earthquake, California, 28 June 1992, M=7.6 is an almost immediate sequence of long-range "aftershocks" of the Joshua Tree earthquake, 23 April 1992, M=6.1, propagating over distances of 600 km (Fig. 9c). The chains prior to San Simeon earthquake in central California, 22 December 2003, M=6.5 also demonstrates very fast propagation over large distances (300 km), but the sequenced was not initiated by a larger quake (Fig. 9d). Such a diversity is an evidence of a complex physical nature of the phenomenon. We listed some possible physical mechanisms of long-range correlation of seismicity, but yet a physical interpretation of the premonitory earthquake chains remains open.

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Table 1. Parameters of the chains aimed to be precursors of target earthquakes with $M \geq M_{target}$

Region	M_{target}	*Catalog used*	*Period from*	M_{min}	τ_0, *days*	r_0, *km*	*c*	k_0	l_0, *km*
1. Regions of the test of the RTP algorithm									
1. Southern California	6.4	ANSS	1965	2.9	20	50	0.35	6	175
2. Central California	6.2	ANSS	1980	2.9	30	50	0.35	10	250
3. Eastern California	6.2	ANSS	1965	2.9	30	50	0.35	8	175
4. Northern California	6.4	ANSS	1975	2.9	25	50	0.35	6	175
5. Honshu-Hokkaido-S. Kurils	7.2	JMA	1980	3.5	20	50	0.33	25	800
6. Eastern Mediterranean	6.5	GII	1983	3.0	40	50	0.35	8	175
7. Po valley, Alps, Northern Dinarides, Central Apennines	5.5	PDE	1970	2.9	45	50	0.35	6	165
2. Other regions or target earthquakes									
8. California	7.4	ANSS	1965	3.4	20	60	0.35	15	350
9. Honshu-Hokkaido-S. Kurils	8.0	JMA	1980	3.8	20	50	0.33	25	1800
10. Kurils-Kamchatka	7.2	ANSS	1975	4.0	12	50	0.35	6	400
11. Aleutians-Alaska,	7.2	ANSS	1985	3.5	16	50	0.35	10	400
12. NE Pacific	7.2	ANSS	1980	4.0	34	50	0.35	7	250
13. Worldwide	8.2	ANSS	1976	5.5	60	30	0.5	10	4000
14. Vrancea	5.2	NIEP	1994	2.5	30	50	0.35	25	90

Table 2. Results of the tests with randomized catalog

	Number of chains	*Number of target earthquakes: preceded by a chain / total*	*T, months*	*R, km*	*p*	α
1) Southern California, $M_{ANSS} \geq 6.4$	55	7 / 7	9	75	0.35	0.0006
2) Central California, $M_{ANSS} \geq 6.2$	11	3 / 3	9	75	0.29	0.024 (0.027)
3) Eastern California-Nevada, $M_{ANSS} \geq 6.2$	22	3 / 3	9	75	0.36	0.047 (0.049)
4) Northern California, $M_{ANSS} \geq 6.4$	47	7 /8	9	75	0.47	0.024 (0.029)
5) Honsu-Hokkaido-S.Kurils, $M_w \geq 7.2$	28	8 / 9	9	100	0.39	0.003
6) Eastern Meditteranean, $M_w \geq 6.0$	8	2 / 2	9	75	0.12	0.014
7) Apennines, Alps, Northern Dinarides, $M \geq 5.5$	84	13 / 15	9	75	0.52	0.0067
8) California, $M \geq 7.4$	2	2 / 2	9	75	0.02	0.0004
9) Honsu-Hokkaido-S.Kurils, $M_w \geq 8.0$	3	2 / 2	9	100	0.01	0.0001
10) Kurils-Kamchatka, $M_w \geq 7.2$	36	11 /11	12	150	0.35	0.00001
11) Aleutians-Alaska, $M_w \geq 7.2$	25	5 / 6	12	150	0.25	0.0046
12) NE Pacific, $M_w \geq 7.2$	20	4 / 4	12	150	0.16	0.0007
13) Worldwide, $M_w \geq 8.3$	24	7 / 7	18	200	0.19	0.00001
14) Vrancea, $M_w \geq 5.2$	5	5 / 5	2	50	0.04	10^{-7}

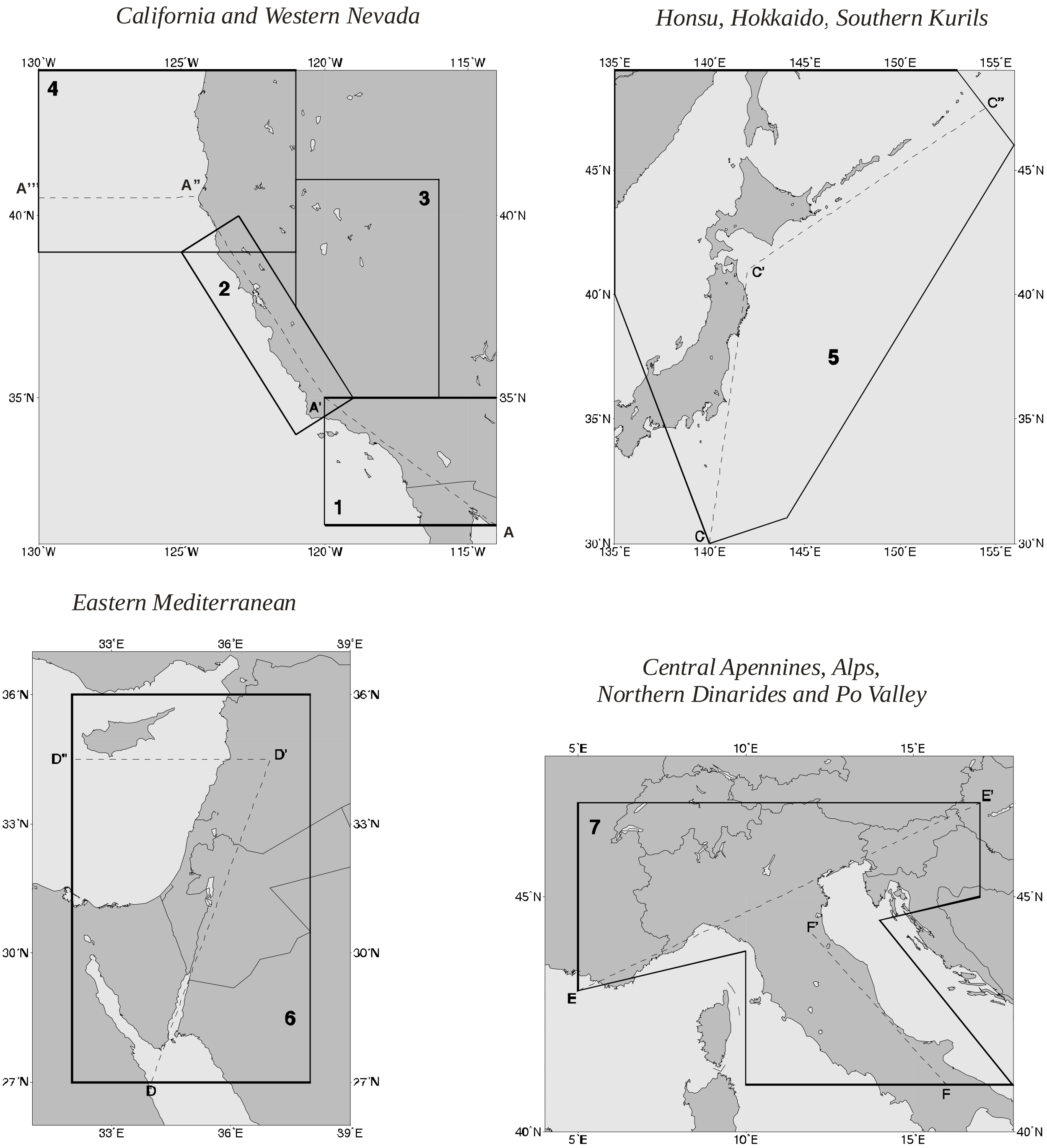


Figure 1. Regions of the analysis of earthquake chains (items 1 to 7 in the Table 1; same numbers in the frames in the figure). Regions are the same as those where the algorithm RTP is being tested by predictions documented in advance. Dashed lines indicate lines of projections for next figures.

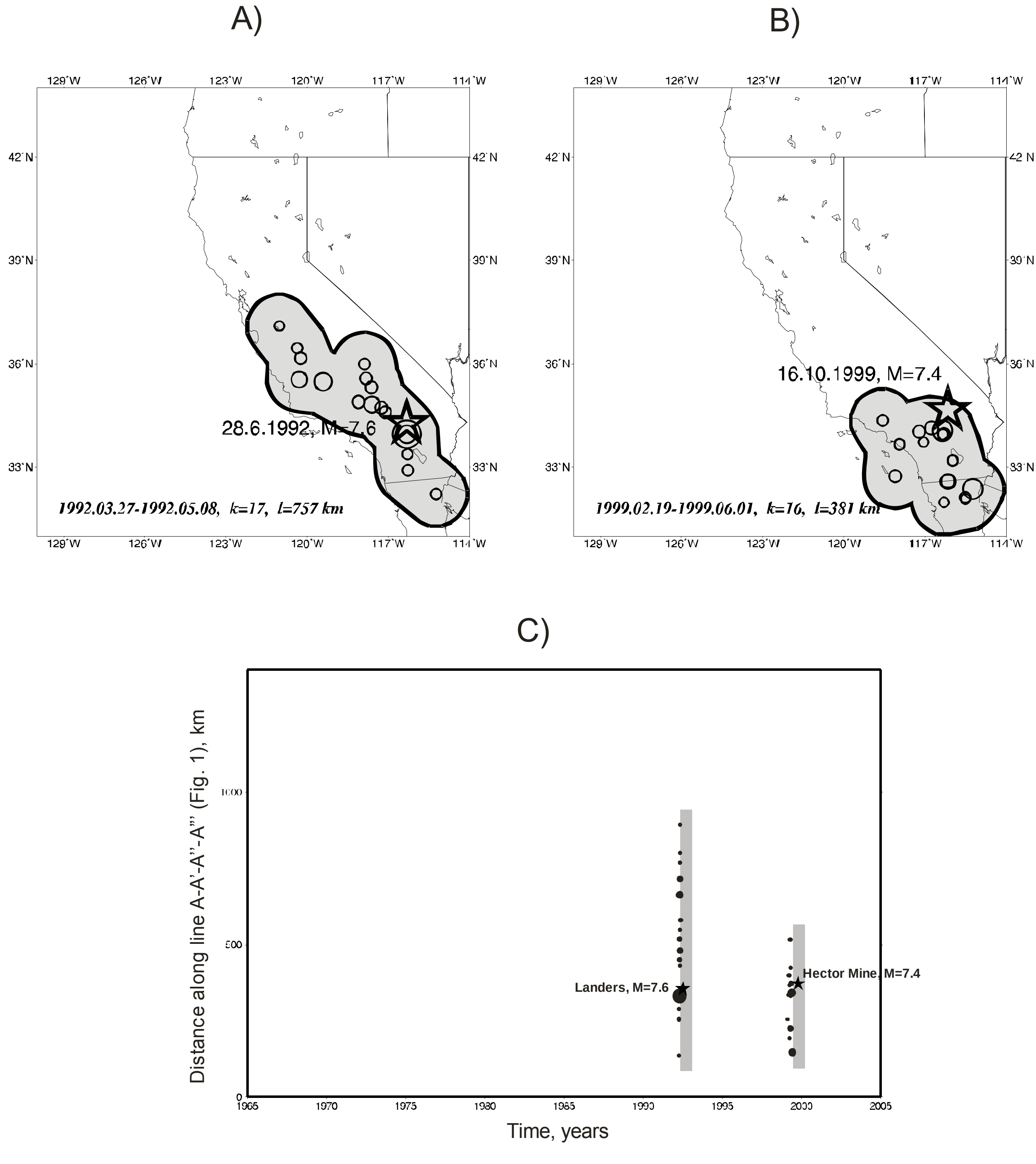
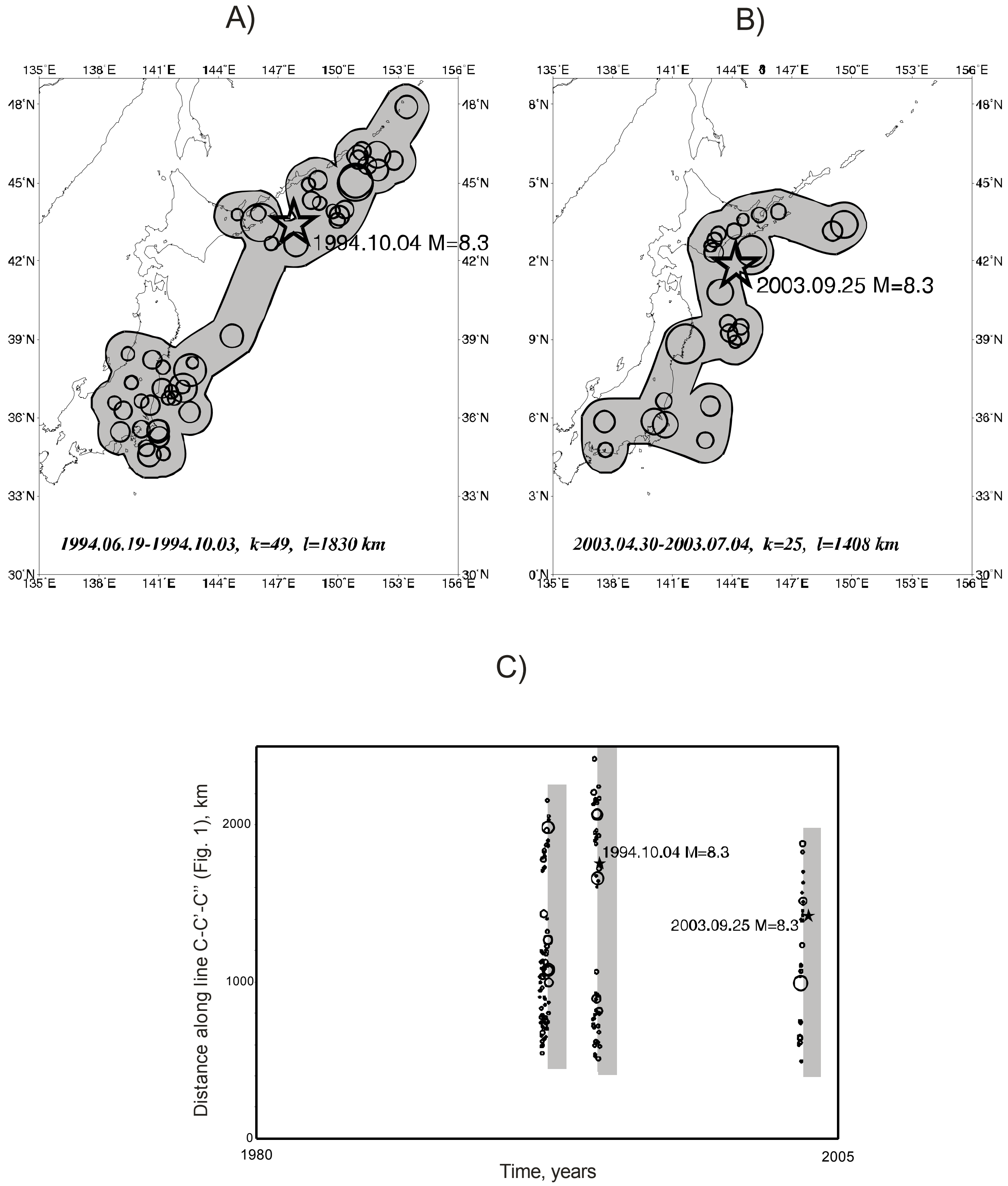


Figure 2. Earthquake chains before largest earthquakes (M≥7.4) in California, 1965-2005 (case 8 in the Table 1). A) and B) maps of the chains and their 75km-vicinities, C) time-space diagram of the chains. Circles indicate epicentres forming the chains (larger sizes correspond to larger magnitudes), stars target large earthquakes, shadowed area 75km-vicinities of the chains. Dates of the beginning and of the end, number of epicentres, and linear size of the chains are indicated in their maps. Shadowed strip in time-space diagram corresponds to 9-months interval.



Figures 3. Earthquake chains before largest earthquakes (M≥8) in Honsu-Hokkaido-S. Kurils, 1980-2005 (case 9 in the Table 1). Other notations as in Fig. 2.

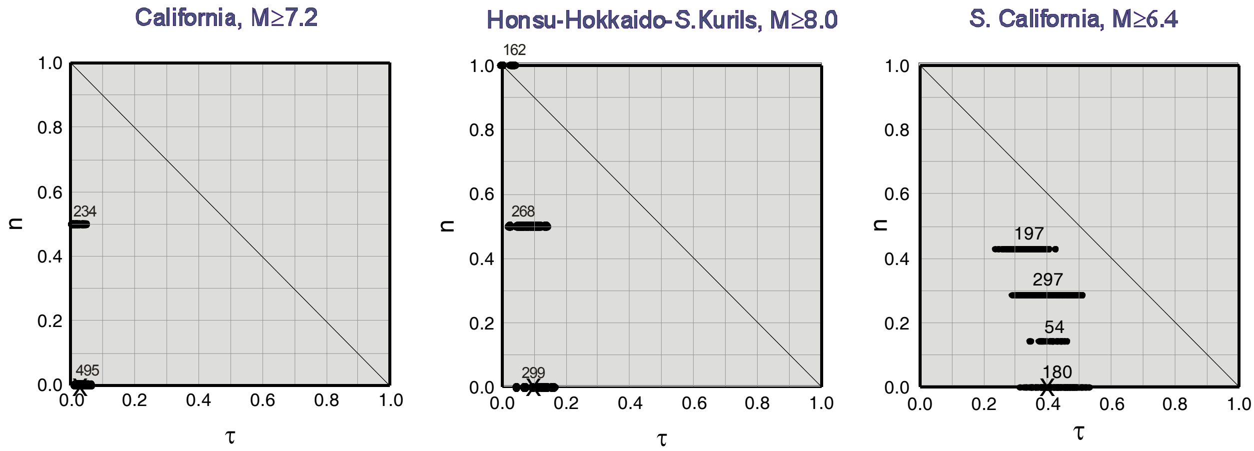


Figure 4. Examples of the error diagrams for stability tests (for the cases 8, 9 and 1 in the Table 1). See explanations in the text.

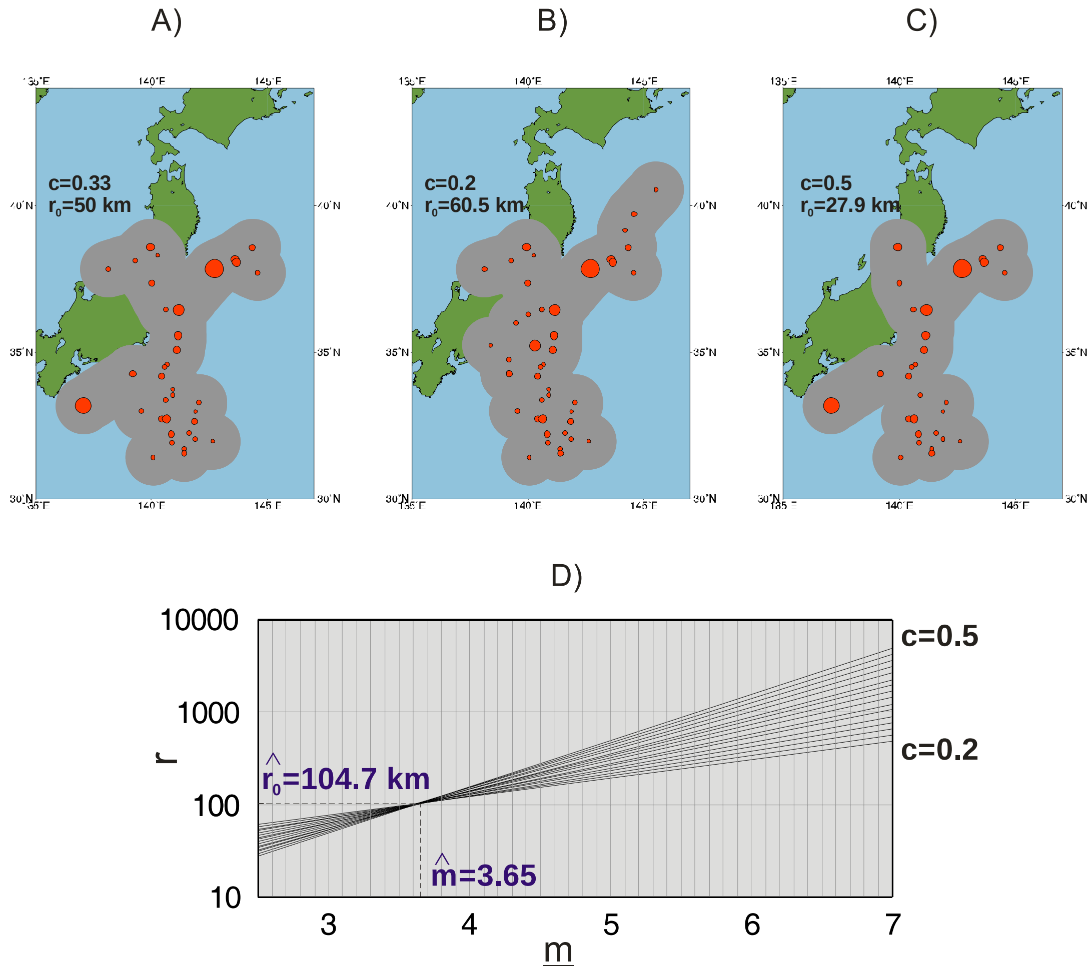


Figure 5. Variants of the chain preceding two earthquakes with M=7.2 and M=7.4 South of Honsu, Japan, 5 September 2004. A) the chain with standard values of parameters, B) with c=0.2 (r_0=60.5 km), C) with c=0.5 (r_0=60.5 km), D) the graphs of dependences $r = r_0\ 10^{c(m-2.5)}$ for the whole range of c from 0.2 to 0.5 with appropriate value of r_0 (see the text).

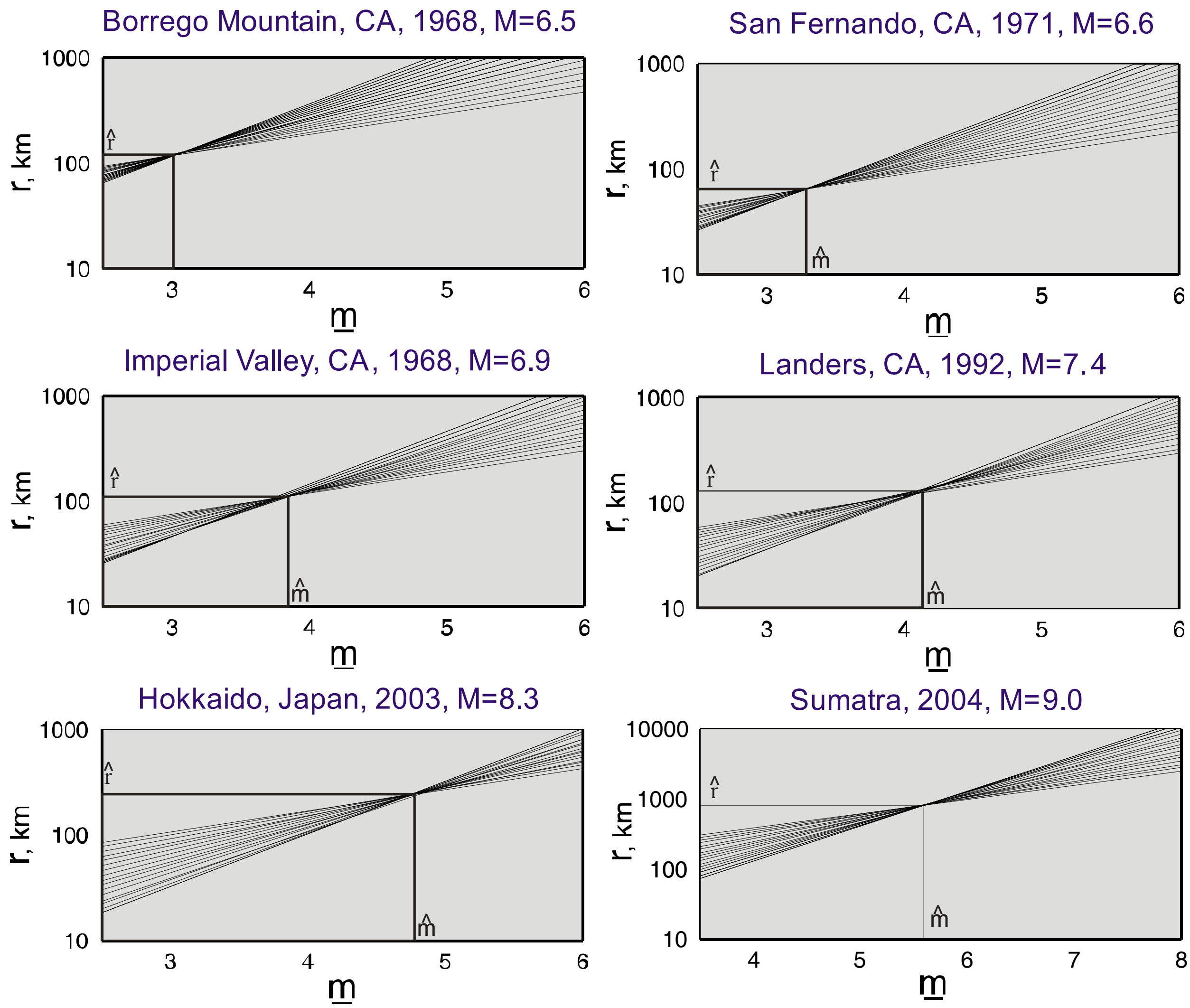


Figure 6. Examples of the graphs of dependences r = r$_0$ $10^{c(\underline{m}-2.5)}$ for the whole range of c from 0.2 to 0.5 with appropriate value of r_0 (see the text). Six precursory chains preceding large earthquakes.

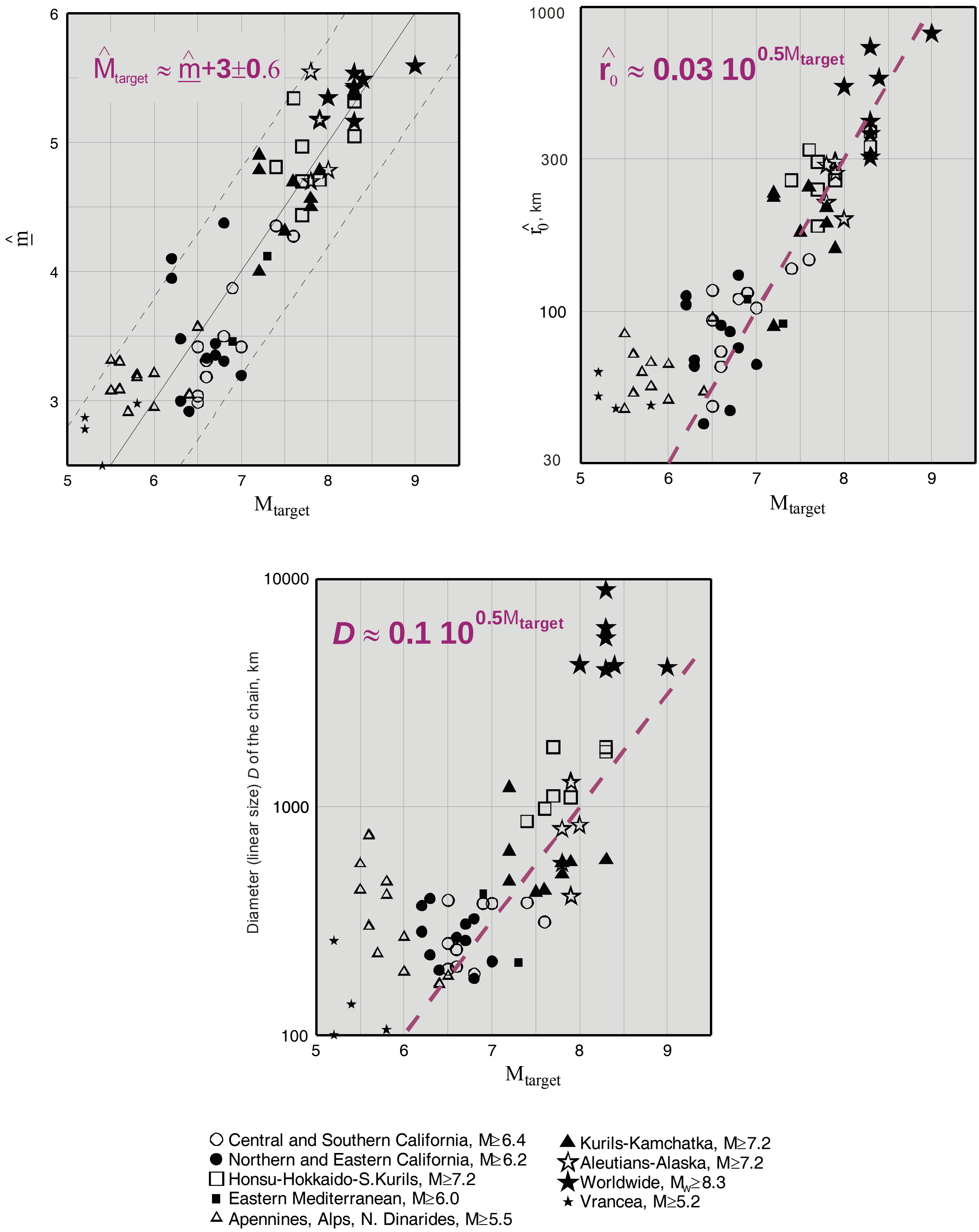


Figure 7. Covariance of parameters $\hat{m}$, $\hat{r}_0$ and D (linear size) of the chains with the magnitudes of target earthquakes. Different symbols represent values for different cases (see Table 1).

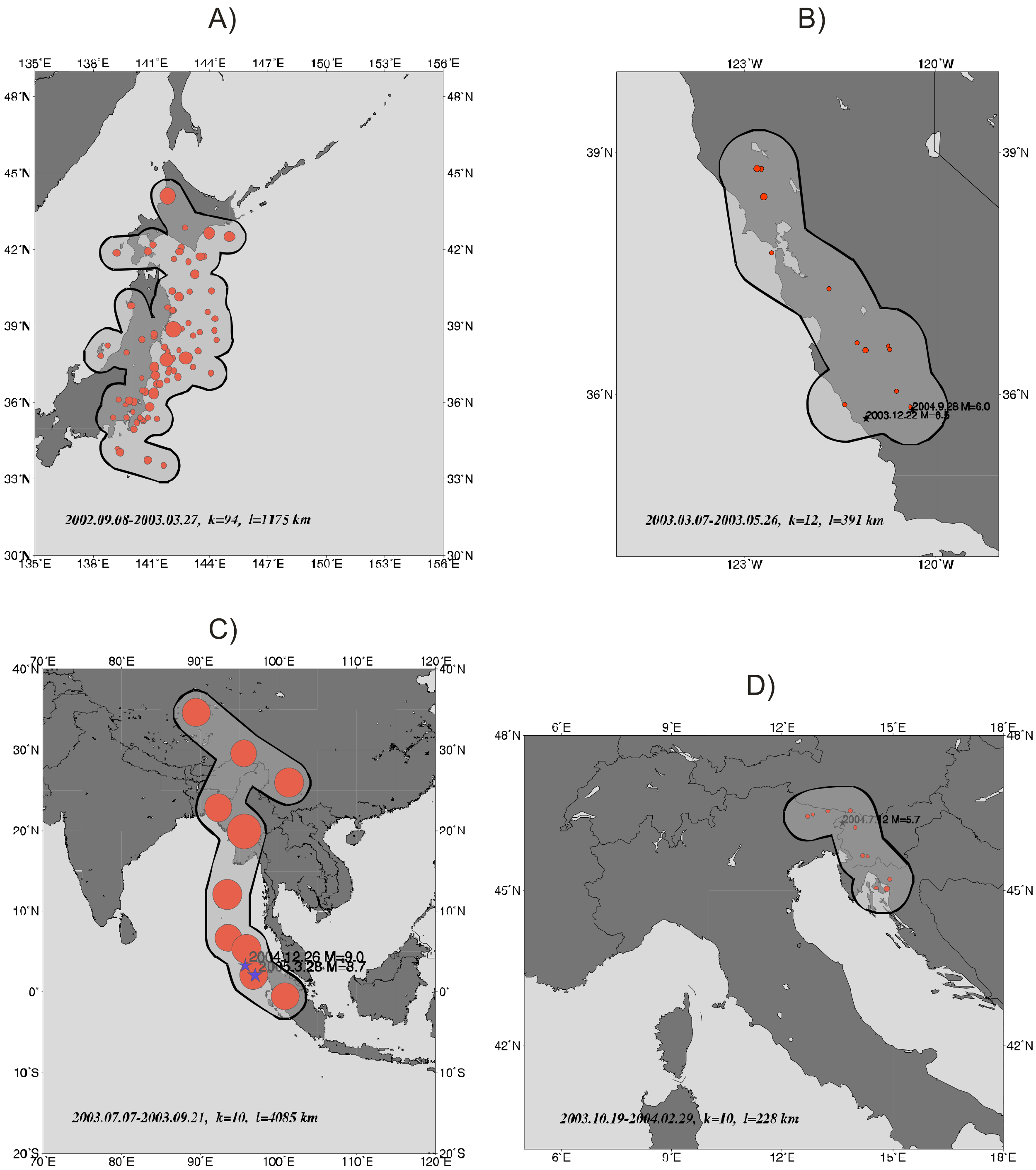


Figure 8. Examples of precursory chains. See notations in Fig. 2.

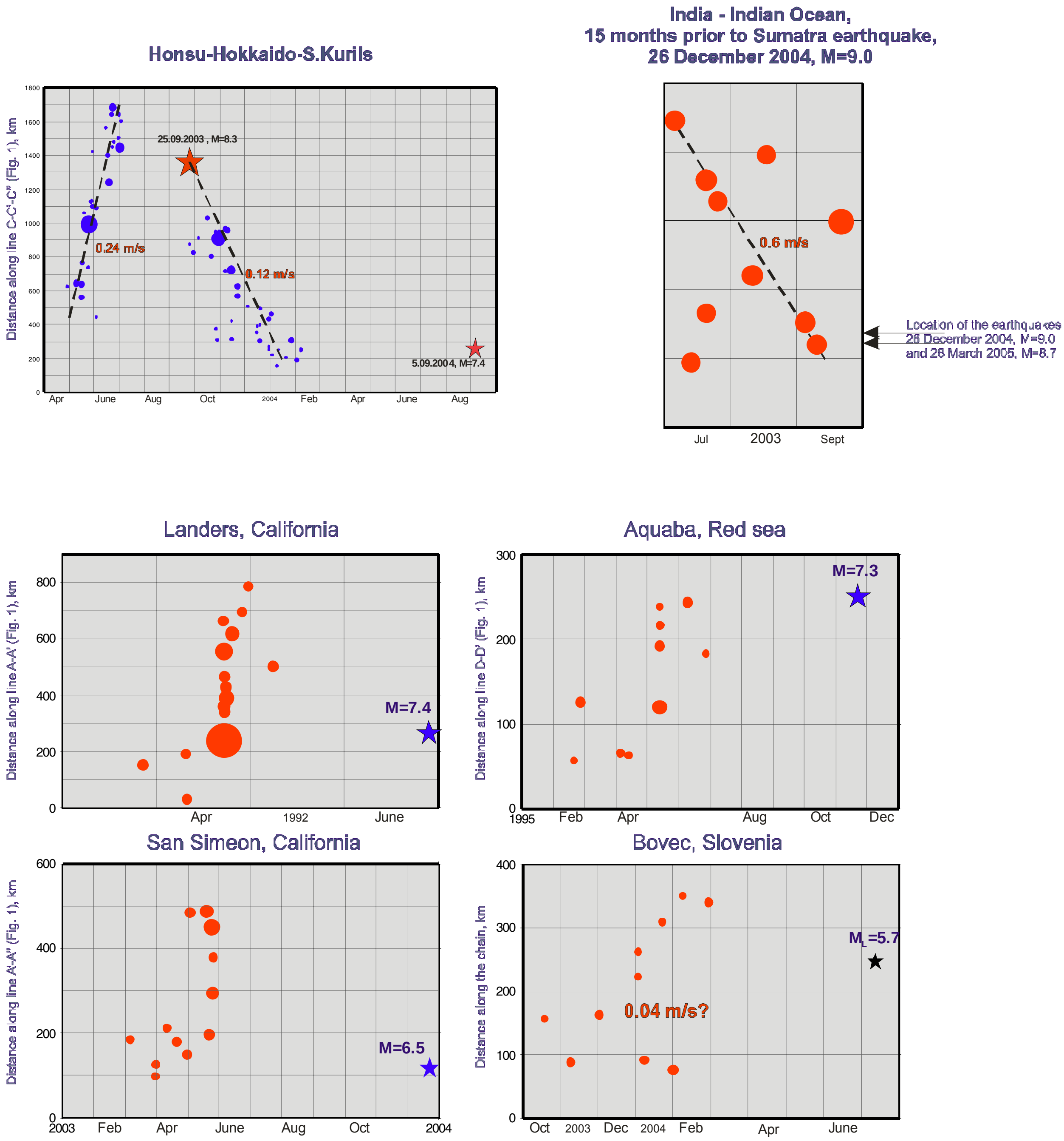


Figure 9. Examples of time-space diagrams of precursory chains. See comments in the text.