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Reverse Tracing of Precursors
Part I

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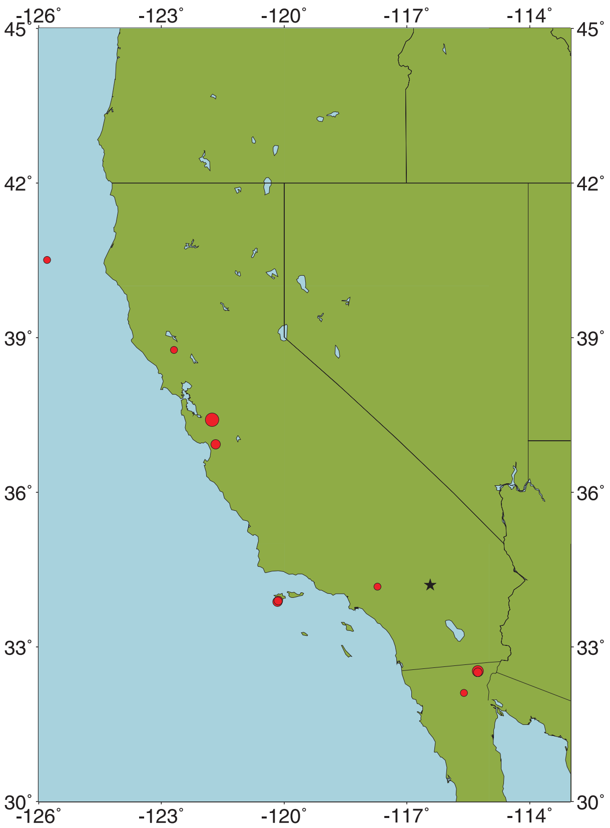
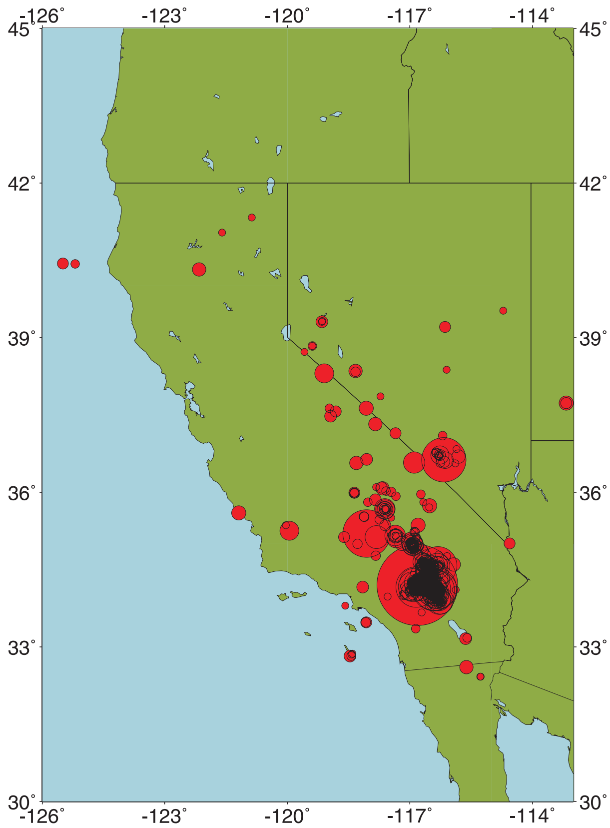
28.6.1990-28.7.1990



28.6.1992-28.7.1992



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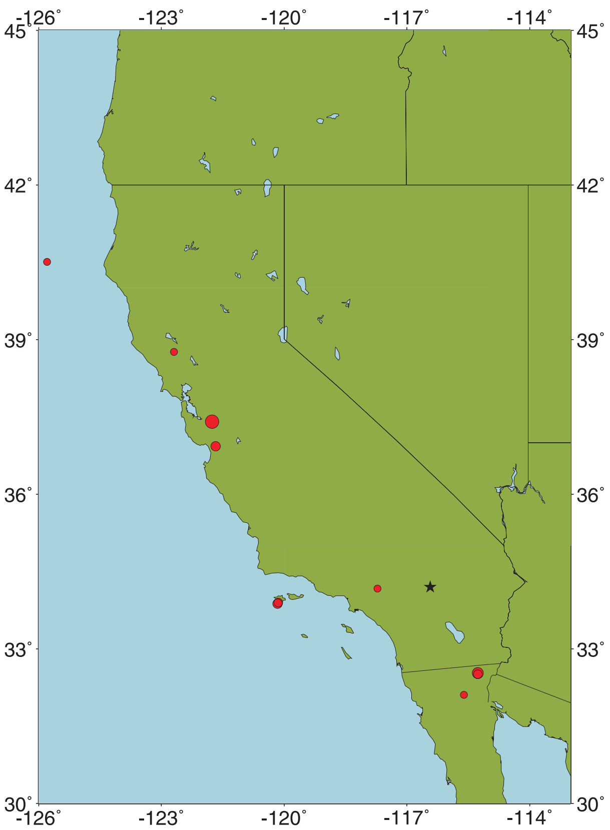
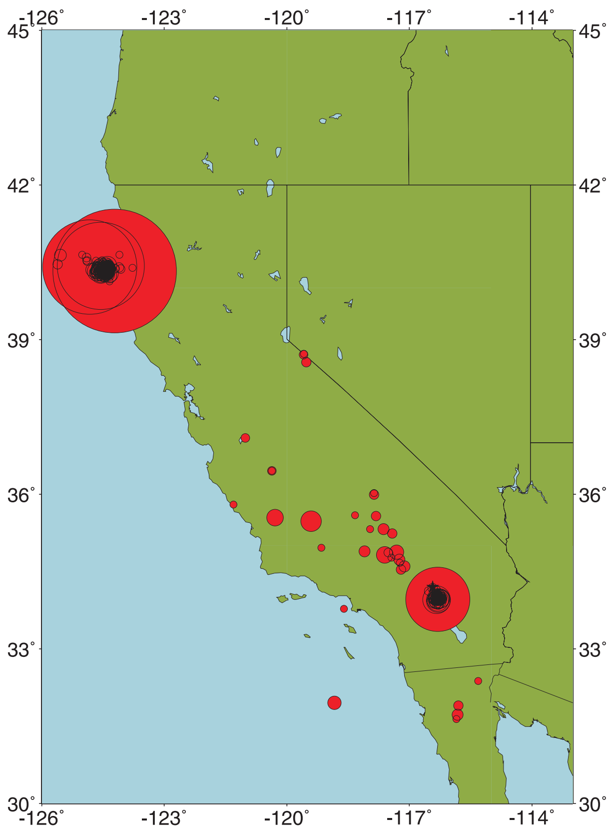


23.4.1992-23.5.1992



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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)

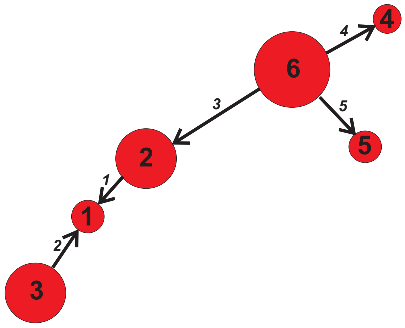
* * *

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; P. Shebalin et al., 2006, Tectonophysics)

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

$M >= M_{min}$

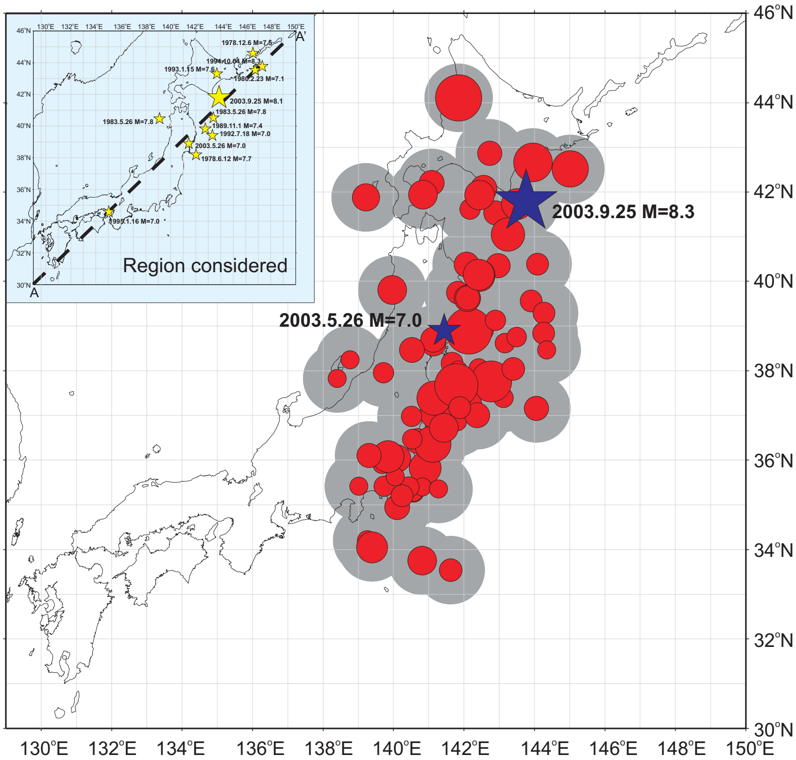
$Dr_{ij} <= r_0 10^{c \cdot \{\min(M_i, M_j) - 2.5\}}$ and

$Dt_{ij} <= t_0$

List of parameters:

$M_{min},\ t_0,\ r_0,\ c,\ k_0,\ l_0$.

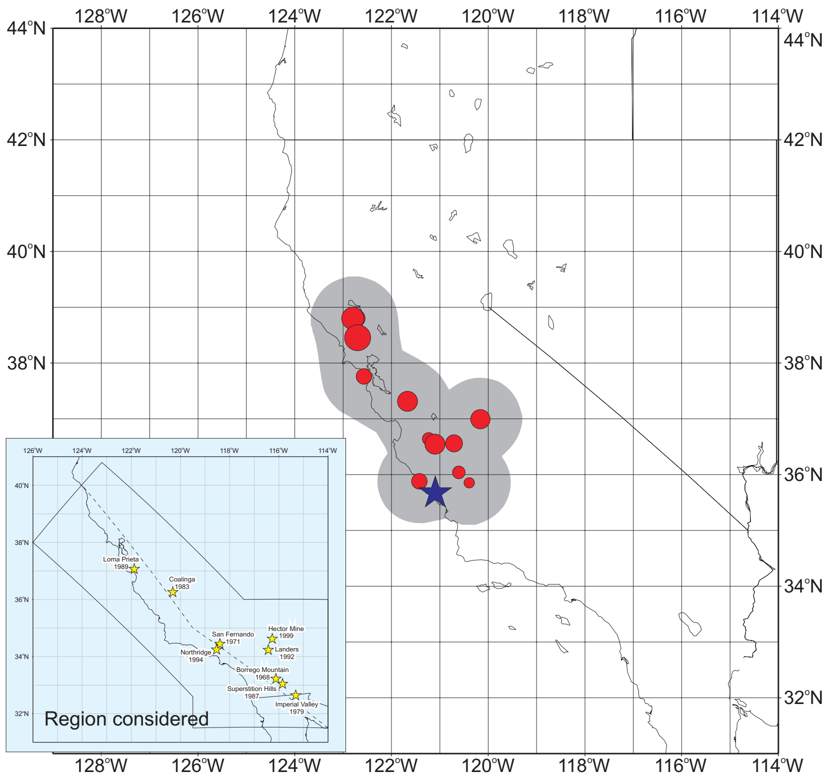
Advance prediction of Tokachi-oki earthquake, Japan, Sept. 25, 2003, M = 8.3



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

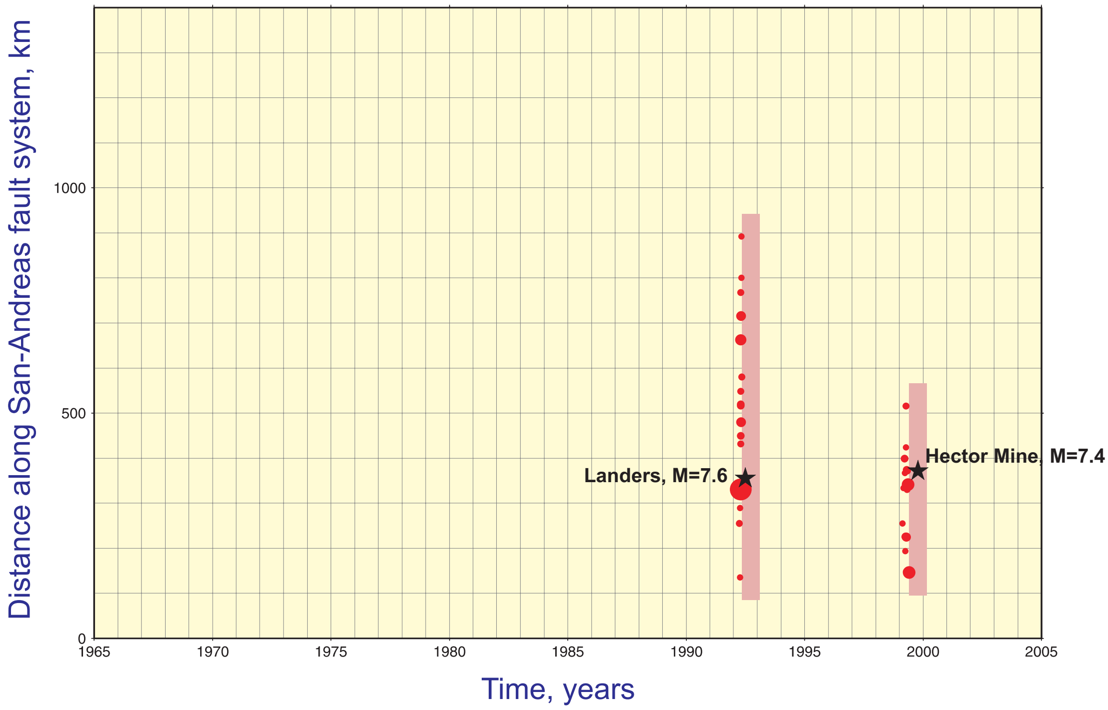
Case history, 2003
March 27: *Precursory chain* of earthquakes was formed. It indicates that an earthquake with magnitude 7 or more will occur in gray area within 9 months.
May 26: *Earthquake with magnitude 7.0* occurred in gray area; precursor was not reported in advance.
July 2: *Precursor reported*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

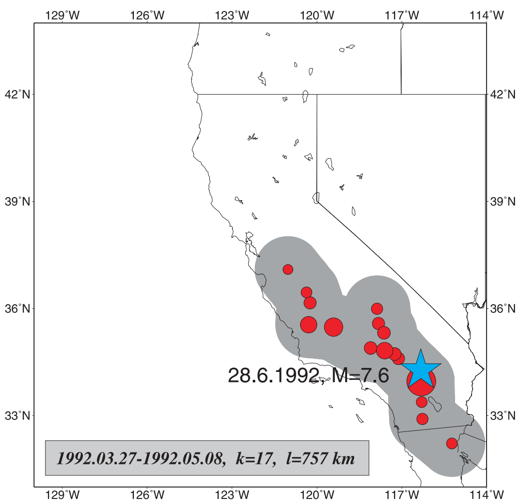
Advance short-term prediction of San Simeon earthquake in central California, M=6.5

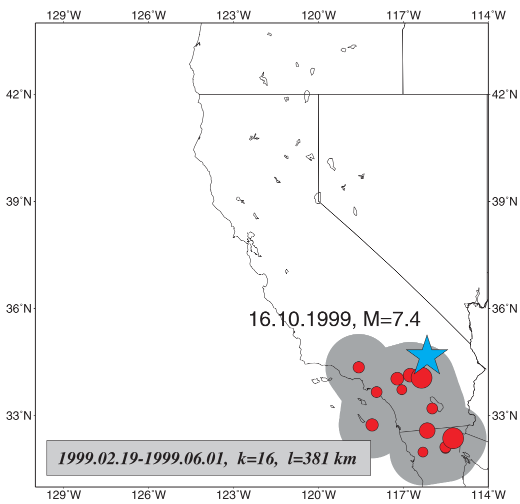


Case history, 2003
May 5: *Precursory chain* of earthquakes was formed. It indicates that an earthquake with magnitude 6.4 or more will occur in gray area within 9 months.
June 21: *Prediction was distributed* among relevant scientists and administrators.
Dec. 22: *San Simeon earthquake* (star).

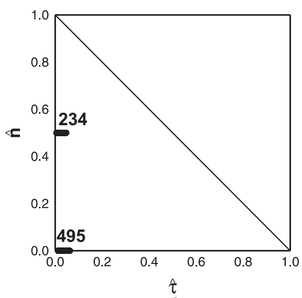
Only two chains are detected in California in 1965-2003 with: the catalog of main shocks in the box: 30°-45°N,130°-110°W M_{min}=3.4, τ=20 days, r_0=60 km, c=0.35, k_0=15, l_0=175 km, no RTP



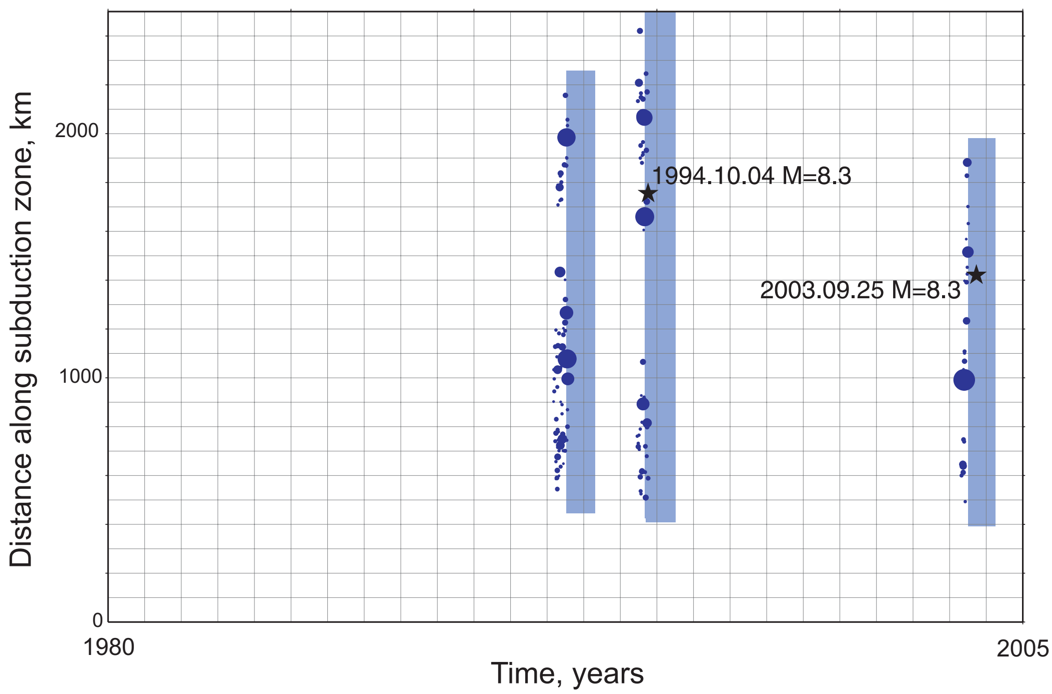




Error diagram
(parameters varied within 10%)



Japan-S.Kurils, 1980-2004, M ≤ 8.0



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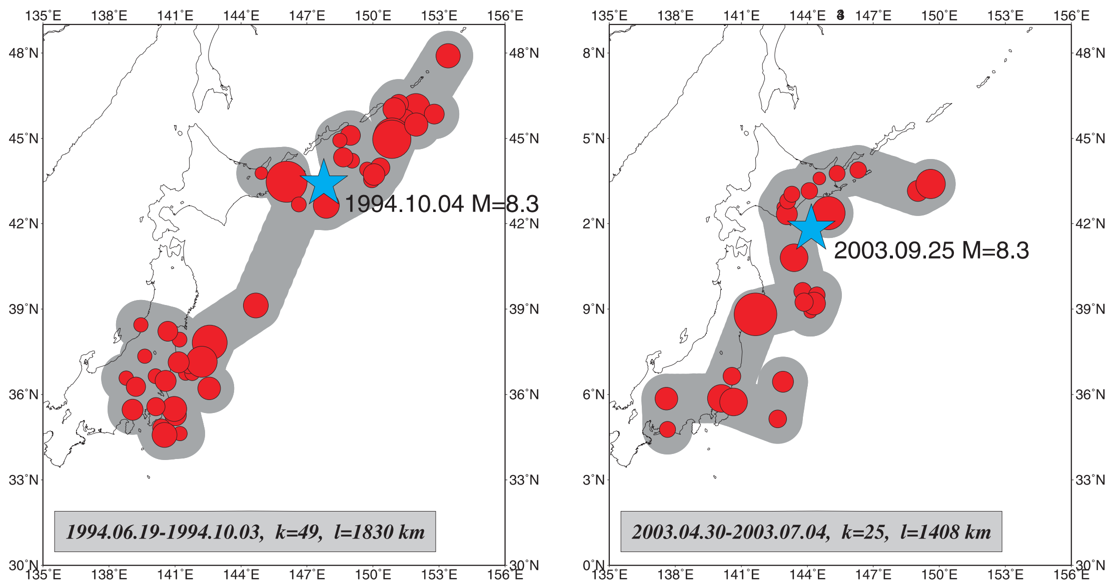
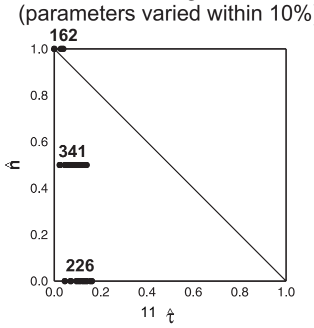


Error diagram
(parameters varied within 10%)



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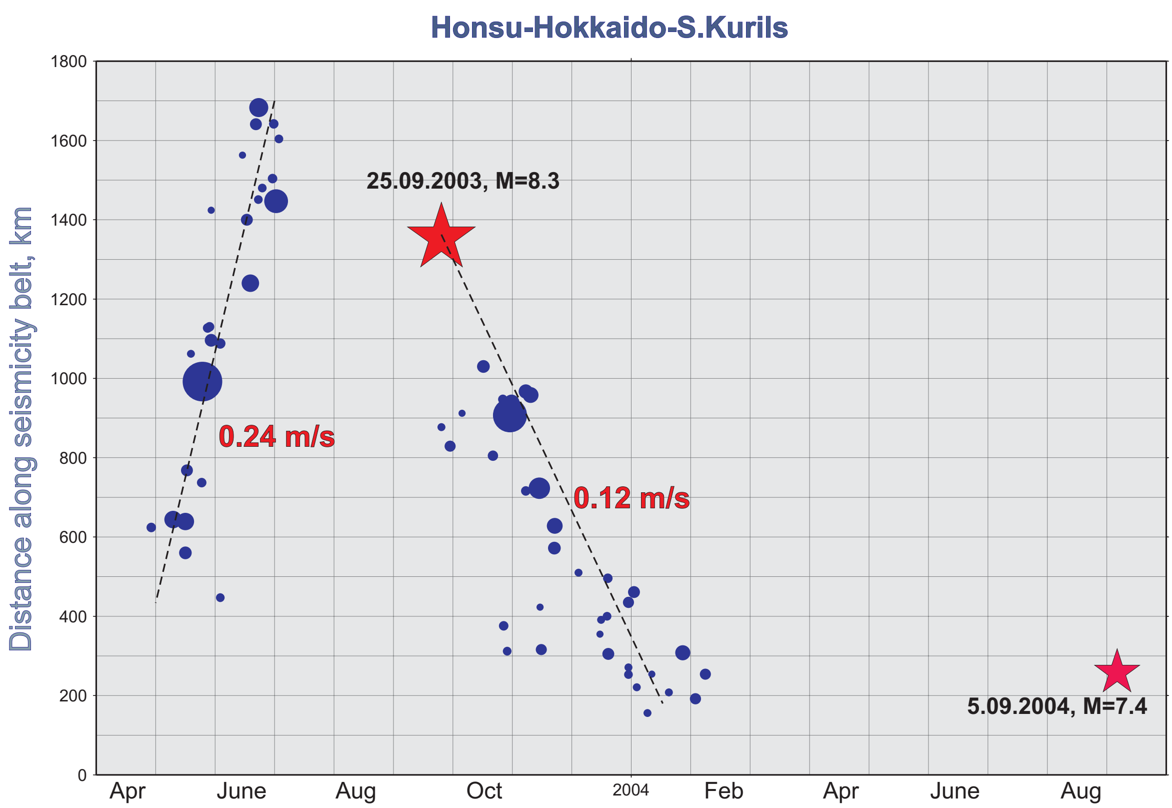
Rise of earthquake's correlation range (radius of correlation)

or

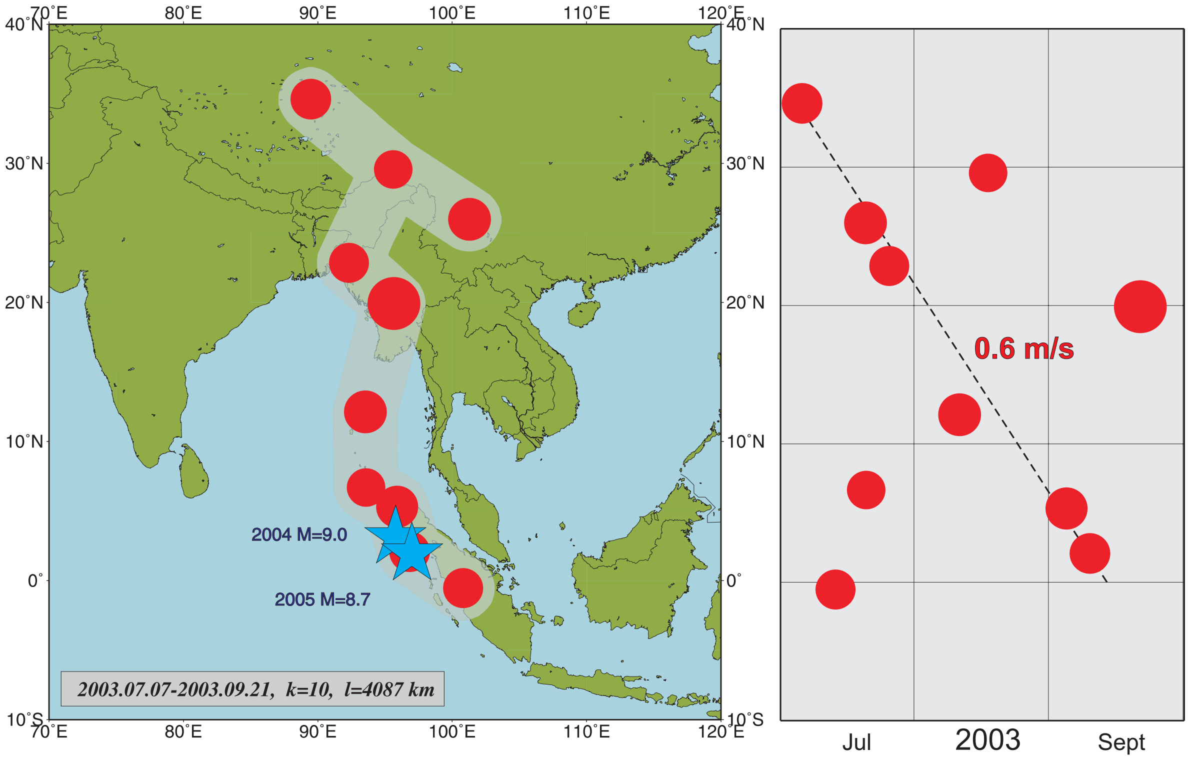
Long-range short-term activation?

What is the time-space structure of chains?

Chains or trees?

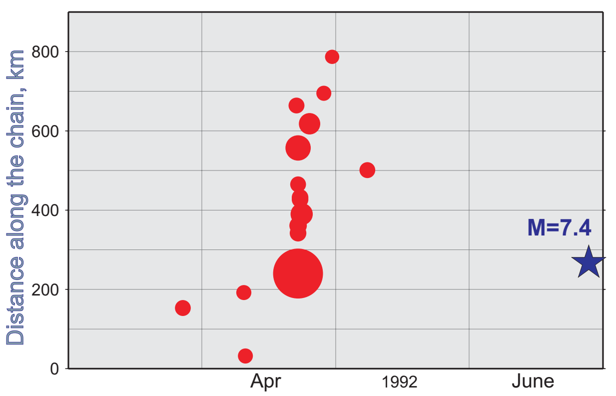


Chain prior to Sumatra earthquake of 26 Dec. 2004, M=9.0

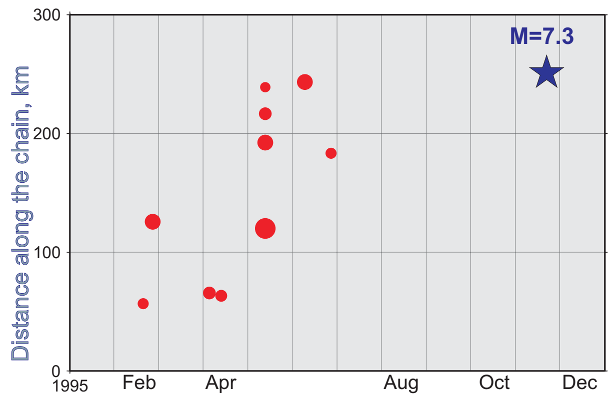


Other examples

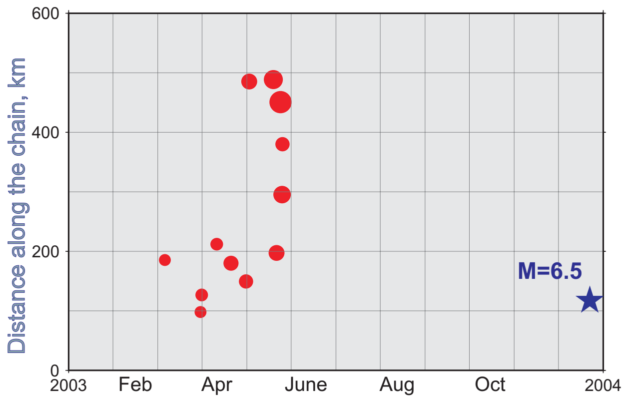
Landers, California



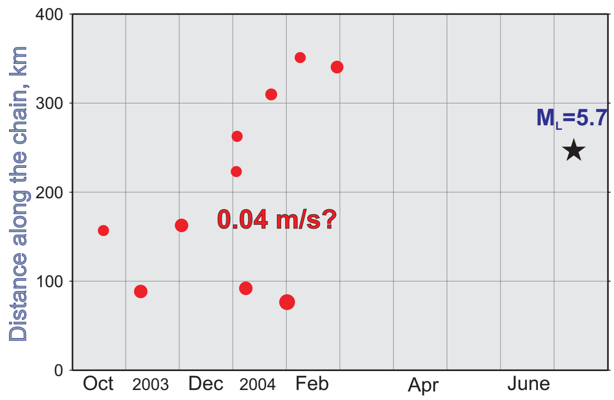
Aquaba, Red sea



San Simeon, California



Bovec, Slovenia



Correlation length and magnitude in the chain

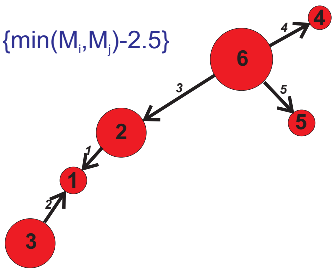
$M \leq M_{min}$

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

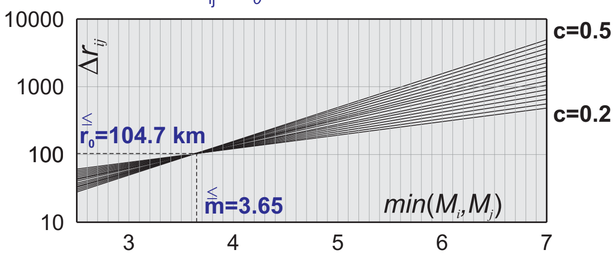
$\Delta t_{ij} \leq \tau_0$

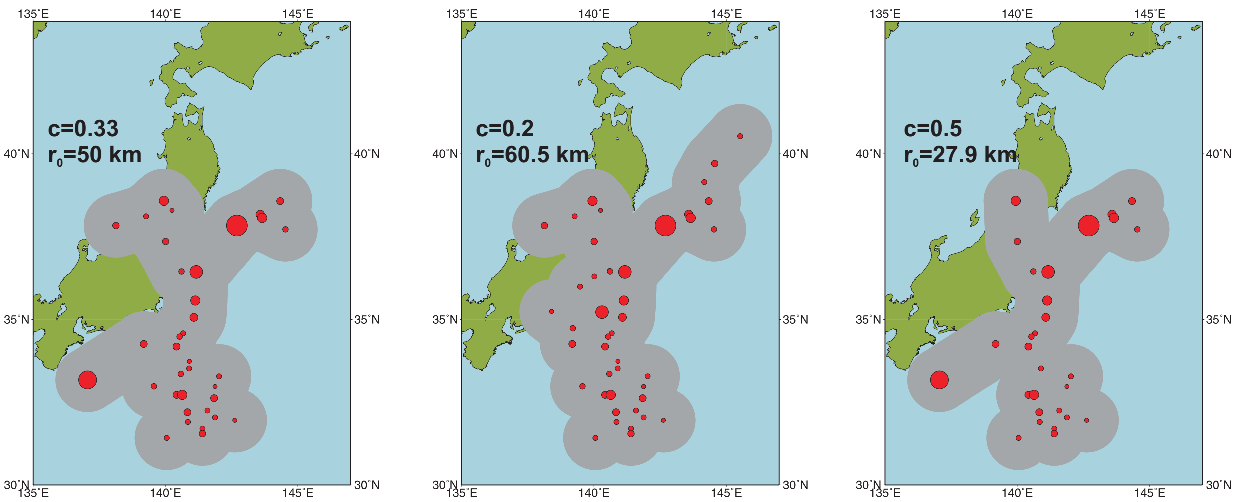
$k \leq k_0$

$l \leq l_0$



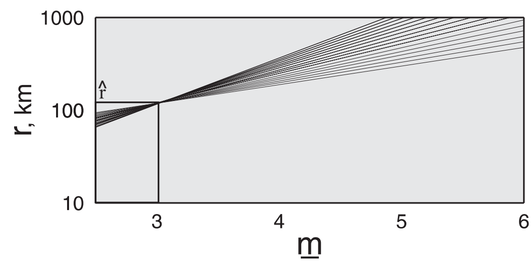
$\Delta r_{ij} \leq \overset{\leq}{r}_0 10^{c\{\min(M_i,M_j)-\overset{\leq}{m}\}}$



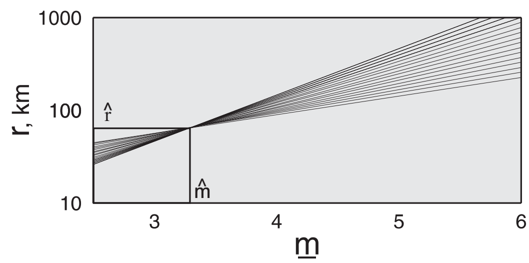


Examples

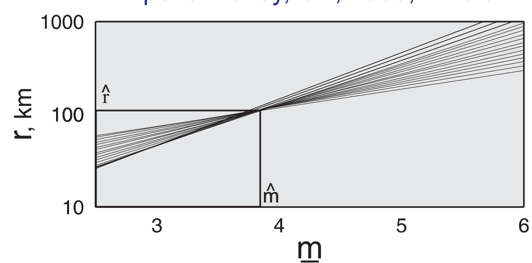
Borrego Mountain, CA, 1968, M=6.5



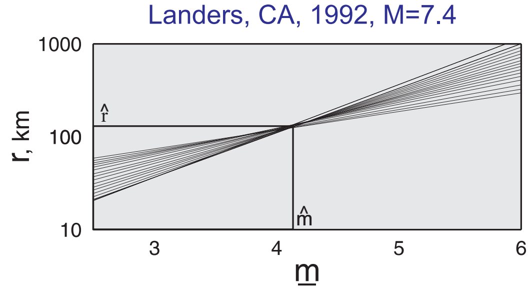
San Fernando, CA, 1971, M=6.6



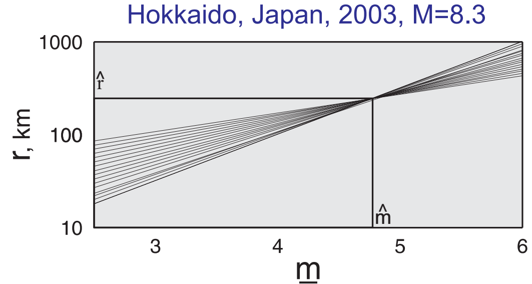
Imperial Valley, CA, 1968, M=6.9



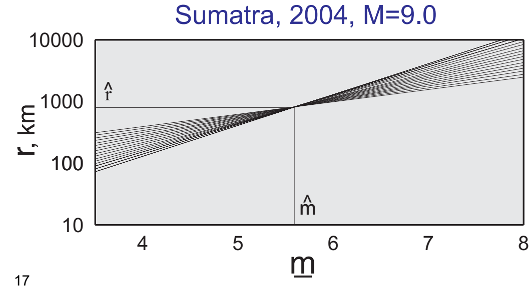
Landers, CA, 1992, M=7.4



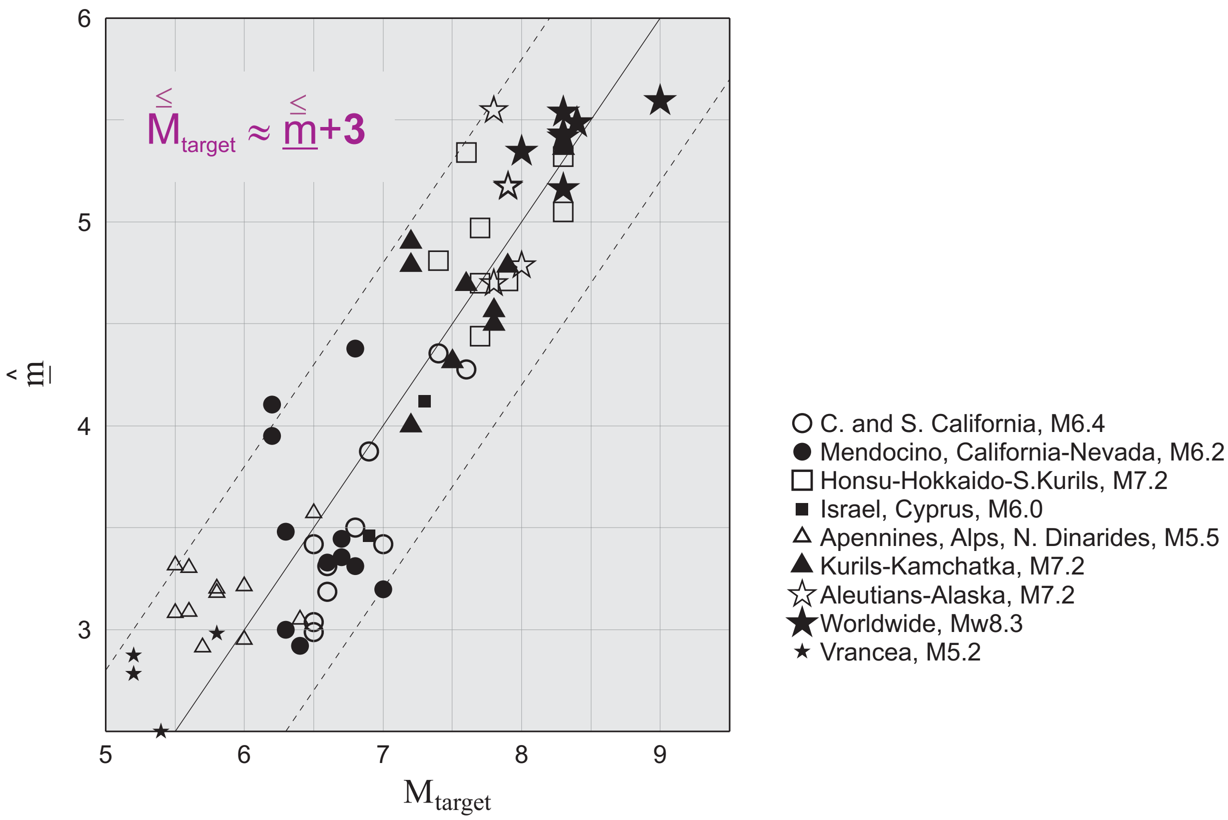
Hokkaido, Japan, 2003, M=8.3



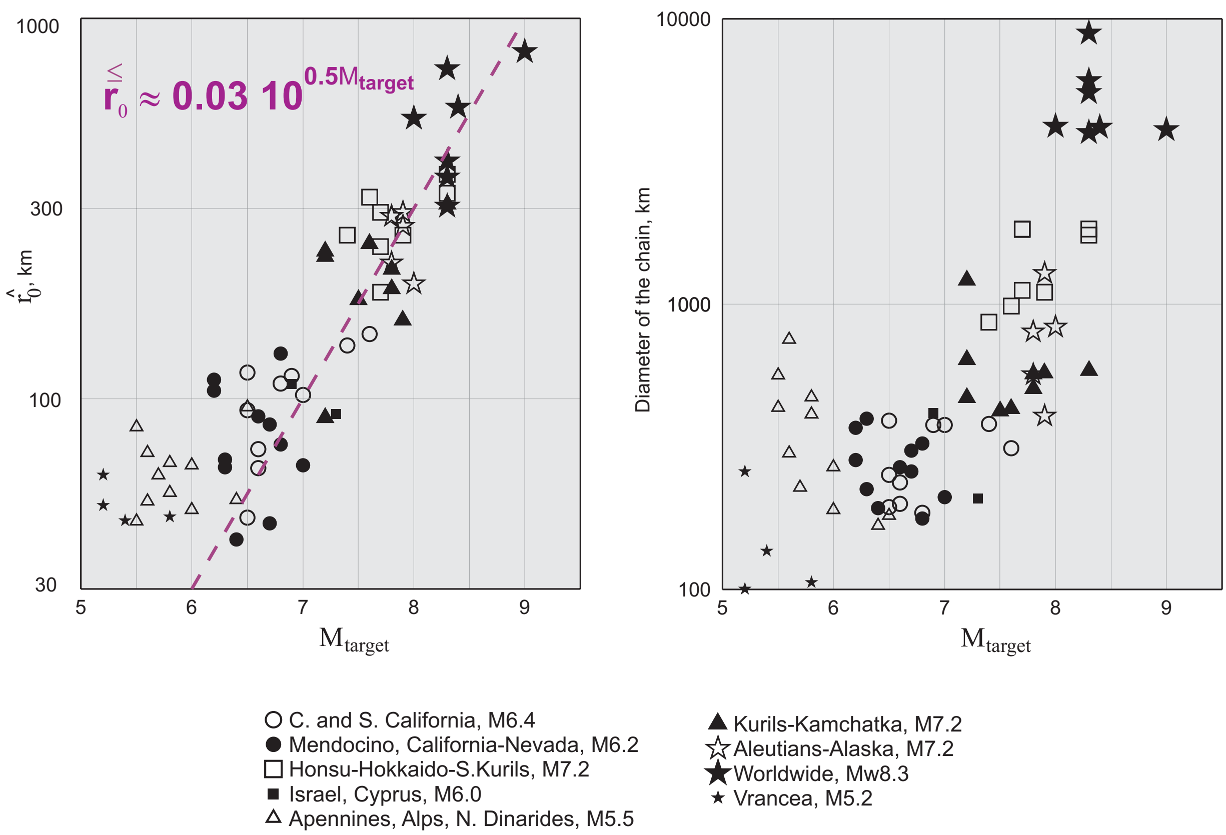
Sumatra, 2004, M=9.0



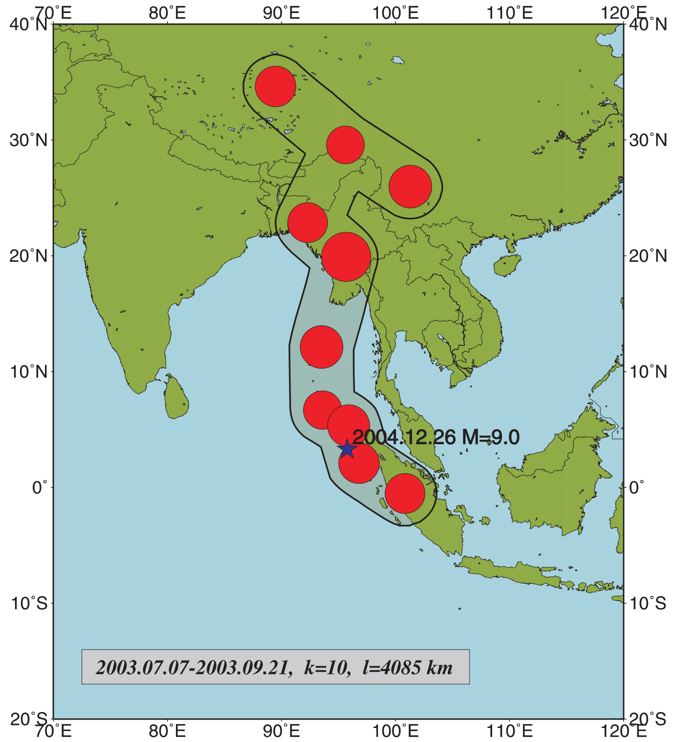
Scaling of magnitudes



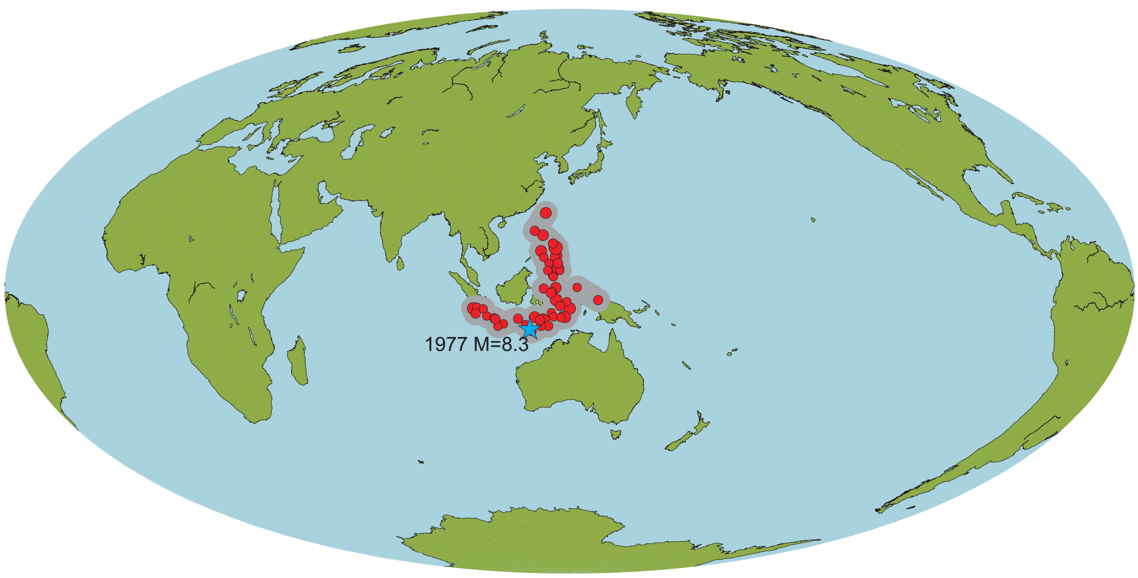
Scaling of distances



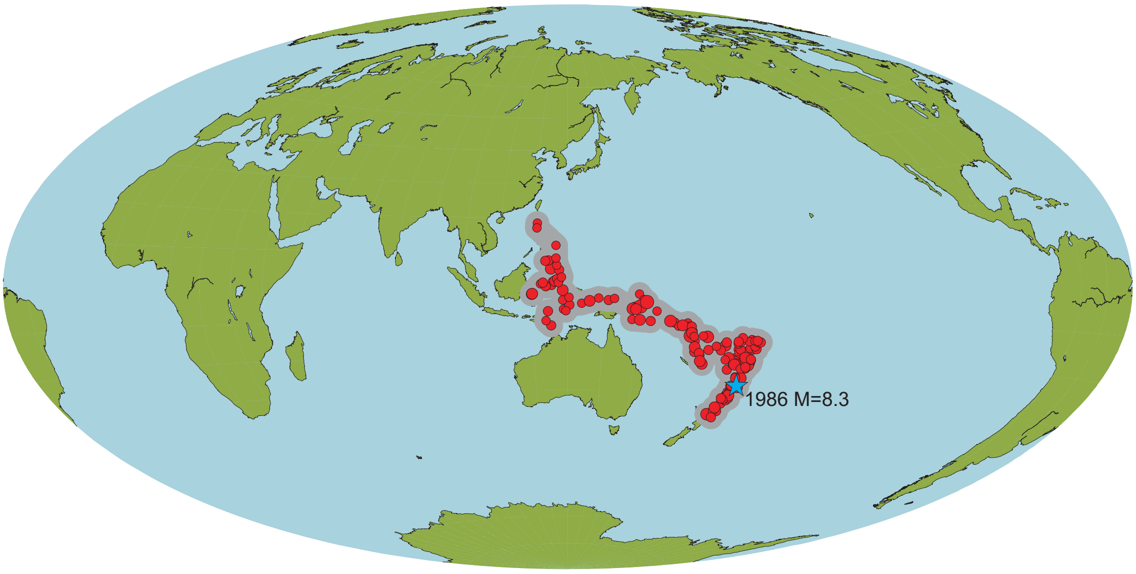
Chain 15 months before Sumatra earthquake of 26 Dec. 2004, M=9.0



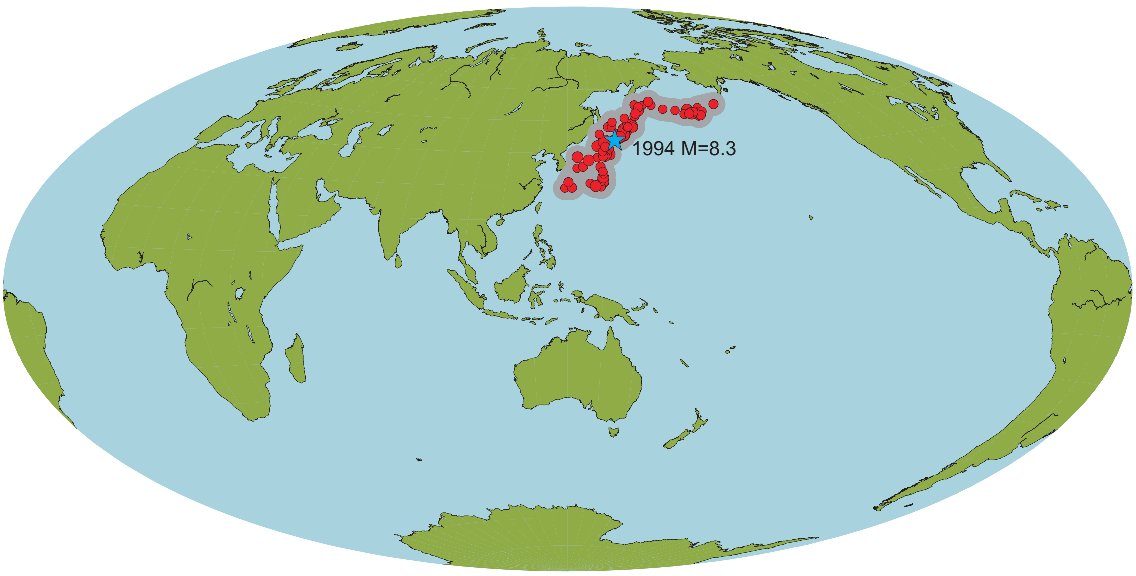
10 earthquake with $M_w \leq 8.3$ have occurred since 1976. 9 of them were preceded by such chains; the focus depth of one exceptional earthquake is 637 km.
In total 26 such chains were found for same period.



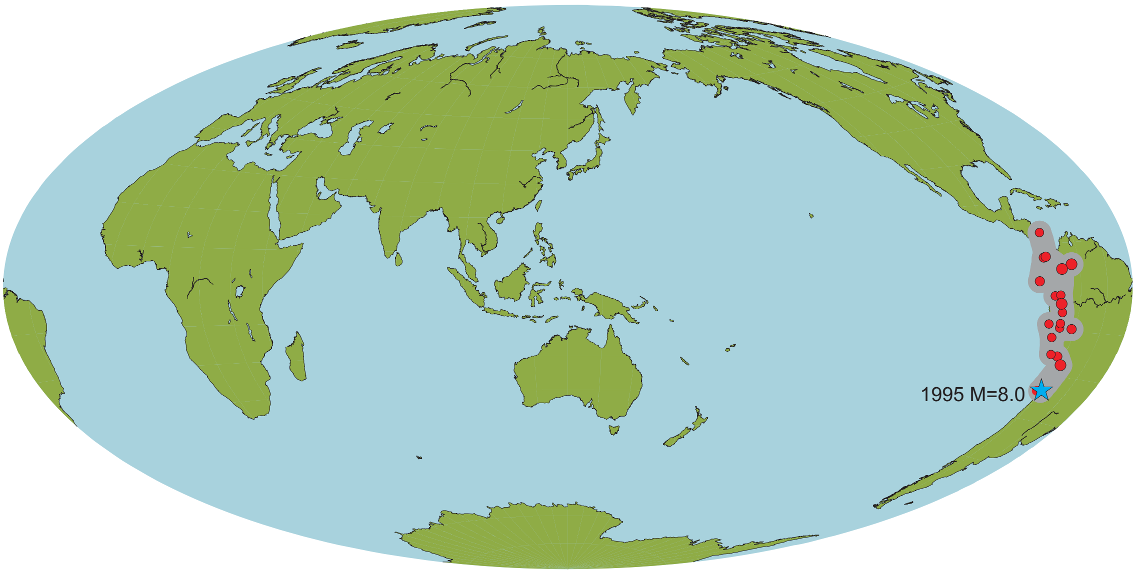
1975.01.14-1976.03.28, k=56, l=4003 km



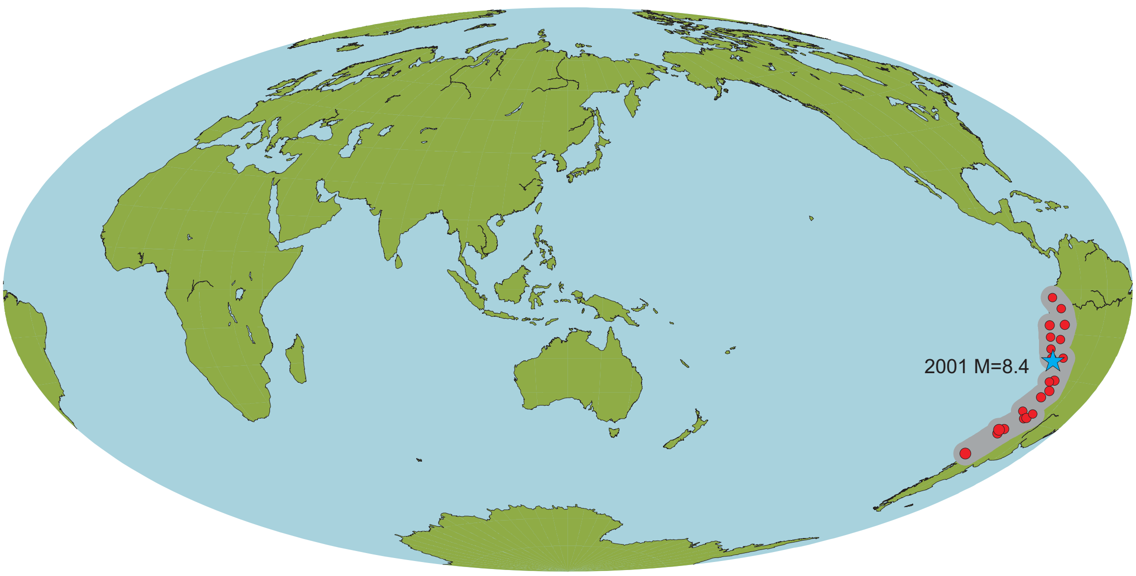
1984.06.25-1986.09.15, k=158, l=8928 km



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

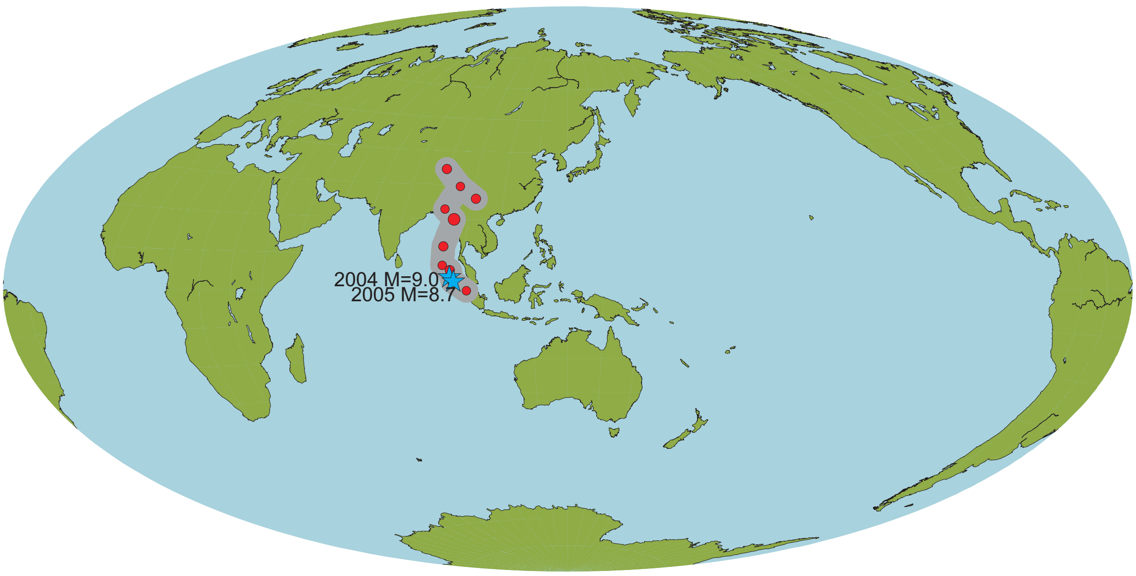


1994.10.16-1995.06.21, k=19, l=4193 km



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

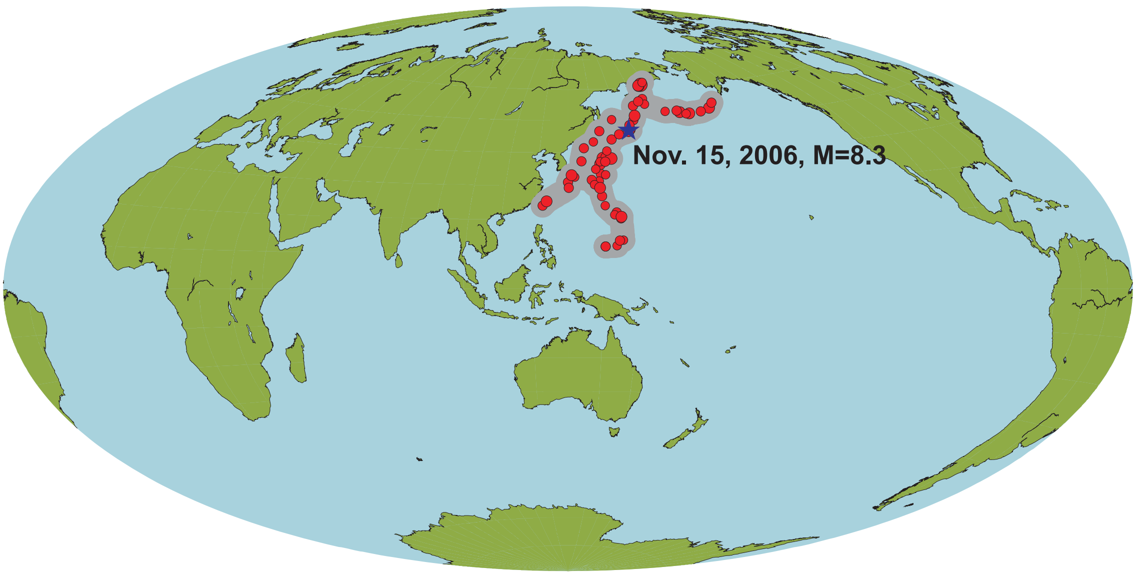
2001.08.13-2002.07.28, k=23, l=5514 km

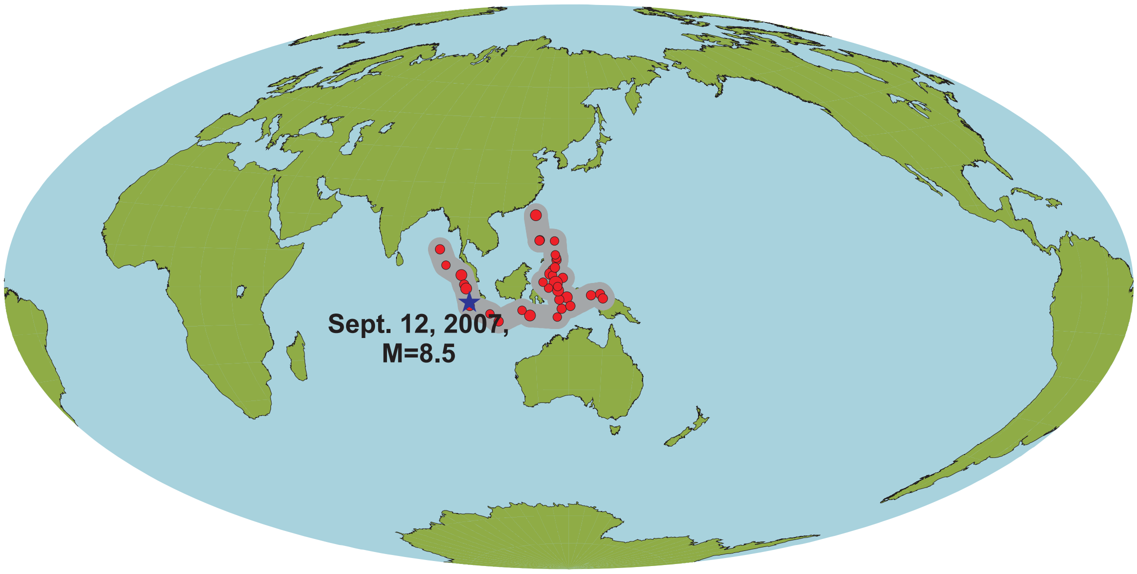


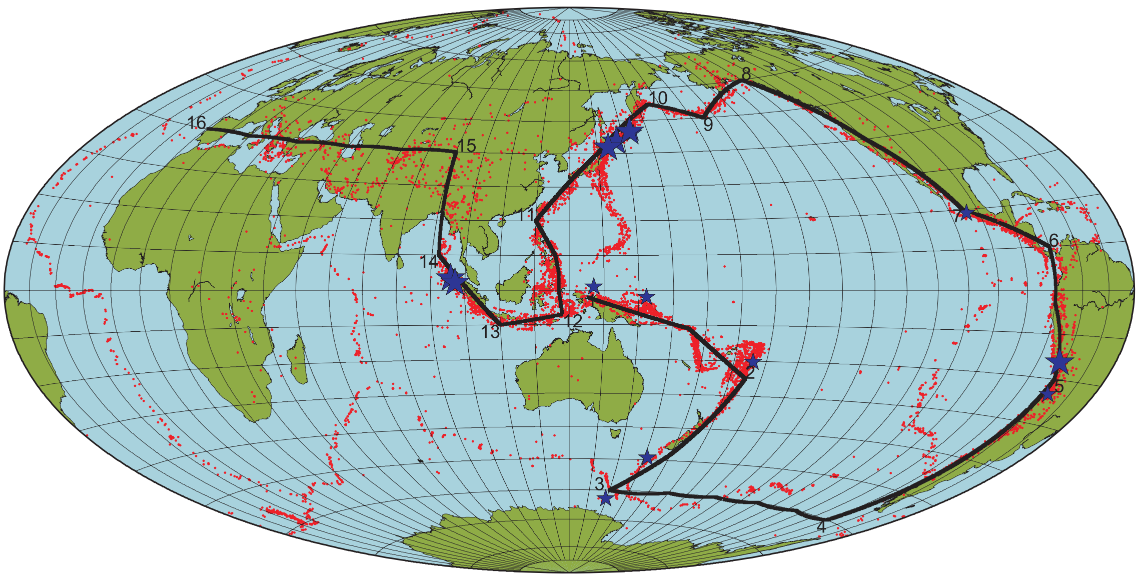
2003.07.07-2003.09.21, k=10, l=4087 km

Next possible candidate, M8.3+

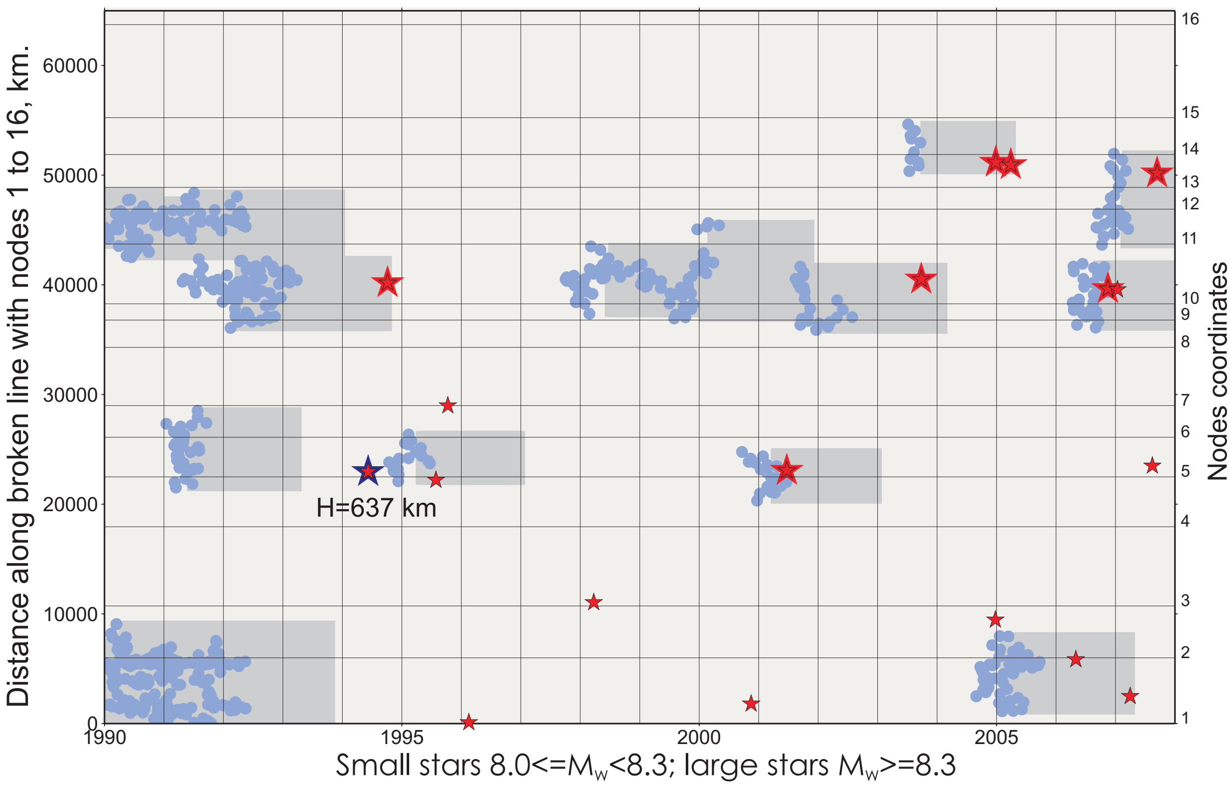
Shebalin et al., Talk at EGU meeting, Vienna, EGU06-A-04511, April 2006.
Slide shown at my lecture in Moscow University on November 1, 2006







Definition of 1-D space: projection to the broken line with nodes 1 to 16.



Probability that a large earthquake is preceded by a chain within 18 months just by chance is estimated as 0.19 (500 simulations of random earthquake catalogue) or 0.21 (measured by epicenters of M_w>=7); probability that all 9 out of 9 earthquakes are preceded by chains by chance is 0.19^9= 3 10^{-7} or 0.21^9= 8 10^{-7} correspondingly

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Increased correlation range of seismicity before large events manifested by earthquake chains

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Abstract

"Earthquake chains" are clusters of moderate-size earthquakes which extend over large distances and are formed by statistically rare pairs of events that are close in space and time ("neighbors"). Earthquake chains are supposed to be precursors of large earthquakes with lead times of a few months. Here we substantiate this hypothesis by mass testing it using a random earthquake catalog. Also, we study stability under variation of parameters and some properties of the chains. We found two invariant parameters: they characterize the spatial and energy scales of earthquake correlation. Both parameters of the chains show good correlation with the magnitudes of the earthquakes they precede. Earthquake chains are known as the first stage of the earthquake prediction algorithm reverse tracing of precursors (RTP) now tested in forward prediction. A discussion of the complete RTP algorithm is outside the scope of this paper, but the results presented here are important to substantiate the RTP approach.

Keywords: Earthquake chains; Earthquake correlation range; Precursors; Reverse tracing of precursors

1. Introduction

Earthquakes are correlated over distances far exceeding their source dimension. This general phenomenon, which can hardly be understood in the framework of elastic models, is observed as various occurrences that proceed according to different physical mechanisms: simultaneous change of seismicity rate in large areas (Mogi, 1985; Press and Allen, 1995), migration of seismicity along seismic belts (Richter, 1958; Mogi, 1968), global interdependence in the occurrence of major earthquakes (Romanowicz, 1993) and some others. The phenomenon aroused a strong interest in the seismological community after the Landers, California earthquake of 1992, magnitude 7.6, generating an obvious seismicity increase in the whole San Andreas fault system over distances more than 1000 km (Hill et al., 1993). The evidence for long-range correlation was established also in many studies of spatio-temporal changes in seismicity prior to large earthquakes (Willis, 1924; Imamura, 1937; Gutenberg and Richter, 1954; Keilis-Borok and Malinovskaya, 1964; Prozorov and Schreider, 1990; Shaw et al., 1997; Jaume and Sykes, 1999; Keilis-Borok, 2003).

The area where premonitory patterns can be observed was first estimated by Keilis-Borok and Malinovskaya (1964). They found the linear size of that area to be

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approximately 10 times that of the target earthquake fault length. In recent years, the interest focused on 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 by the size of the target earthquake at a ratio of about 5. Many other premonitory seismicity patterns were observed in about the same range of distance (see the summary in Keilis-Borok, 2003, Table 1.2). Recently, Press and Allen (1995) extended possible range of correlations to about 100 linear earthquake size.

Many physical mechanisms were invoked to account for the phenomenon of long-range correlation of earthquakes; they are not mutually exclusive and may act separately or in combination (Keilis-Borok, 2003). One group attributes long-range correlations to large-scale processes controlling stress and strength in fault systems: microrotation of tectonic plates (Press and Allen, 1995) and crustal blocks (Soloviev and Ismail-Zadeh, 2003) causing redistribution of normal and shear stress, hence a redistribution of strength through a large part of the fault network; migration of pore fluids (Barenblatt et al., 1983) affects rock strength through lubrication, stress corrosion, destabilization waves, and redistribution of hydrostatic pressure; hydrodynamic waves in the upper mantle (Pollitz et al., 1998) which propagate through thousands of kilometers during decades and may trigger large earthquakes connecting seismicity over the globe; creep strain in the ductile part of the lithosphere (Aki, 1996) increases the stress in its brittle part; inelasticity and inhomogeneity of the lithosphere (Barenblatt, 1993; Shaw, 2000) may cause redistribution of stress after a fracture to much greater distances than in a homogeneous elastic earth.

On the other hand, long-range correlation is a general feature of complex systems in a near-critical state. The above mechanisms and many other factors make for greater complexity of the lithosphere. The concepts of "self-organized criticality", "critical point behavior", "finite-time singularity" (Sadovsky and Pisarenko, 1989; Knopoff, 1993; Bak, 1996; Turcotte, 1997; Sornette, 2000; Rundle et al., 2000; Narteau et al., 2000) are helpful in the detection and study of different phenomena in the lithosphere considered as a complex system. One such phenomenon is the increase in the correlation range of seismicity prior to large earthquakes. It was first found in simulated seismicity by Pepke et al. (1994), Shaw (2000), Gabrielov et al. (2000), Zaliapin et al. (2003) and then in observed seismicity (Shebalin et al., 2000; Zöller et al., 2001; Zaliapin et al., 2002; Keilis-Borok et al., 2002).

2. Earthquake chains

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

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

In application to real seismicity, ROC and ACCORD were found in retrospective analysis, with an a posteriori choice of the area of study. A similar problem arises in application to other long-range premonitory seismicity patterns, for example, Accelerating Moment Release (Bowman et al., 1998) and the M8 algorithm (Kossobokov et al., 1999). Earthquake chains provide a solution of this problem: they not only reflect the increase of earthquake correlation range, but also give the location, size and shape of the area where the phenomenon is observed. The author previously used earthquake chains in a modification of the Seismic Reversal prediction algorithm (Shebalin and Keilis-Borok, 1999; Kossobokov and Shebalin, 2003).

2.1. Earthquake chains defined

We consider a catalog of main shocks with magnitude $M \geq M_{\min}$, the aftershocks being removed using the coarse window method (Gardner and Knopoff, 1974). Let us call two earthquakes "neighbors" if their inter-epicenter distance is less than r and their origin times differ by less than τ_0. A chain is a sequence of earthquakes where each has at least one neighbor belonging to that sequence and, therefore, no neighbors outside the sequence. The average epicenter density decreases with increasing magnitude. Accordingly, r is normalized as $r = r_0 10^{c(m-2.5)}$, where m is the smaller magnitude in the pair, and c is a dimensionless constant.

There is no scaling for the parameter τ_0. We consider only the chains with two sufficiently large characteristics: the number of earthquakes involved $k \geq k_0$ and the greatest 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 radius R centered at all epicenters 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, 2006). This algorithm is designed to predict large earthquakes a few months in advance. The RTP

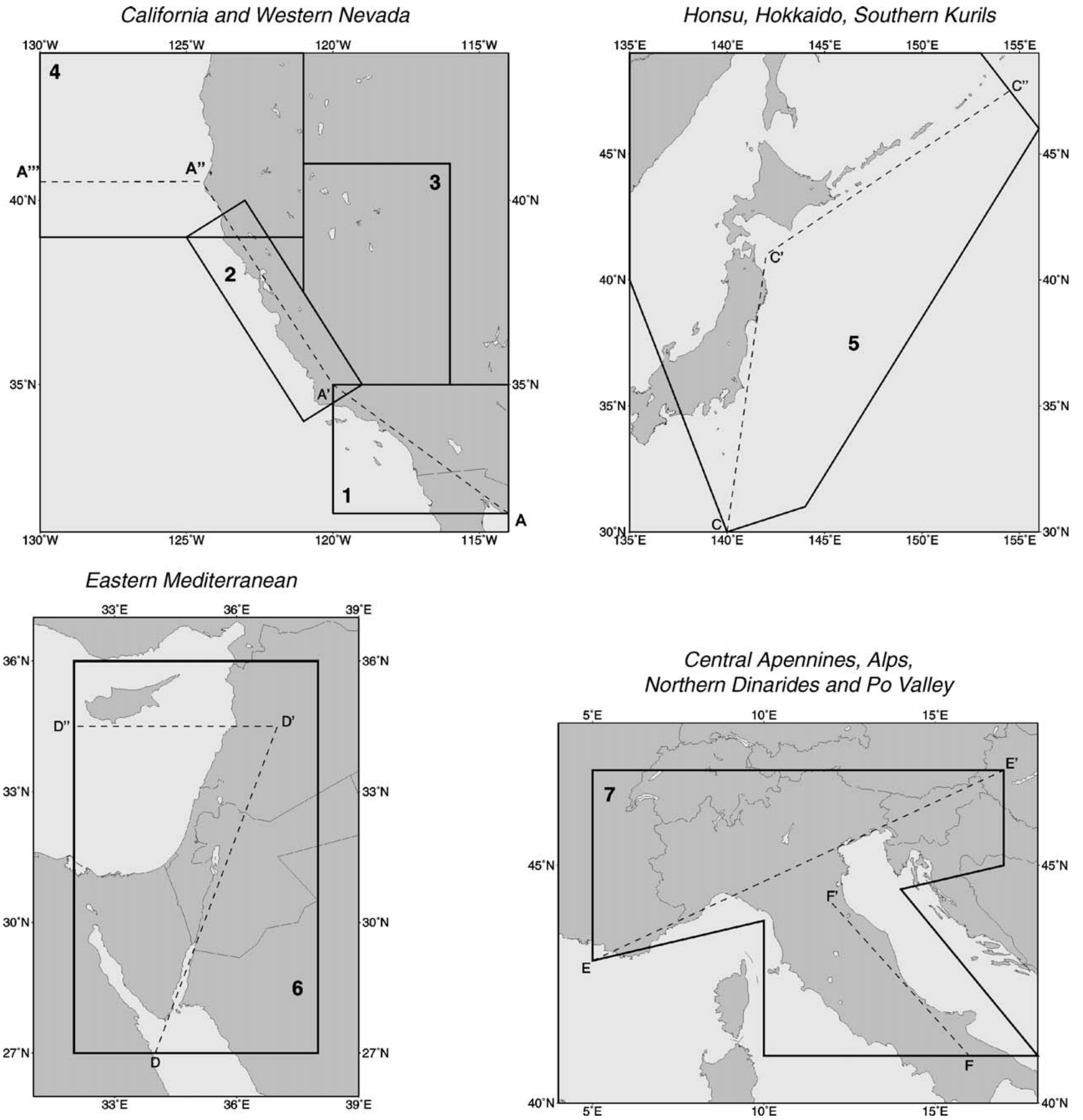

Fig. 1. Regions for analysis of earthquake chains (cases 1 to 7 in Table 1, here marked by numerals). The regions are the same as those where the algorithm RTP is being tested by predictions documented in advance. Dashed lines indicate lines of projections for subsequent figures.

algorithm must include a second step, because up to 90% of the chains are not followed so closely by large earthquakes, and these would technically be 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 chain are determined in the space indicated by the chain. Pattern recognition is used to separate precursory chains from false alarms. Precursors are analyzed in the reverse temporal order: first, shorter-term precursors, i.e., earthquake chains that appear months prior to large earthquakes, and second, intermediate-term precursors having lead times of a few 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, occur in approximately the same space. The advantage of the RTP approach is obvious, if this hypothesis is true: an earthquake chain automatically indicates the location, size and shape of the area where intermediate-term precursors are expected to have the most contrasting manifestation as compared with any alternative approach, for example, scanning the area of interest by circles. In Section 5 we shall show that the size of a precursory chain correlates with the magnitude of the large earthquake it precedes; this gives an important corroboration of the hypothesis.

The RTP algorithm is now tested by documented predictions made in advance for several seismic regions (Shebalin et al., 2006) 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 do not discuss the complete RTP algorithm, but study two important questions concerning its first step only: (1) (Section 4) are earthquake chains short-term (time scale of months) precursors, or do they just give an unambiguous formalized rule to choose an area of study for the analysis of intermediate-term precursors? (2) (Section 5) do precursory chains have scaling properties based on the magnitudes of large earthquakes they precede?

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

We consider the same regions (Fig. 1) as in the test of documented forward predictions using the RTP method (Shebalin et al., 2006). Parameters of the chains as well as magnitudes of target earthquakes (Table 1) are also the same as in the RTP test. In addition, we consider chains with modified parameters supposed to be precursors of only very large earthquakes in California ($M \geq 7.4$) and in Honshu–Hokkaido–Southern Kurils ($M \geq 8.0$). 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 the three regions.

After the catastrophic earthquake near Sumatra, Indonesia, 26 December 2004, $M=9.0$ we naturally tried to find a precursory chain preceding the earthquake.

Table 1
Parameters of the chains supposed 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 and 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

Such a chain was found in a large area surrounding the epicenter. After that it was found that chains with the same parameters occurred before all eight $M_w \geq 8.3$ earthquakes that have occurred worldwide 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 region considered, Vrancea, Rumania (target earthquakes with $M_w \geq 5.2$) is very specific. The large earthquakes in the region occur at depths below 100 km, and the seismicity is concentrated in an almost vertical plane crossing the Earth's surface in SW–NE direction. Accordingly, here we consider chains in this plane, and not at the Earth's surface as in the other regions.

The catalogs used for each of the regions are indicated in Table 1. The ANSS catalog is the composite catalog produced by the Advanced National Seismic System (ANSS) and hosted by the Northern

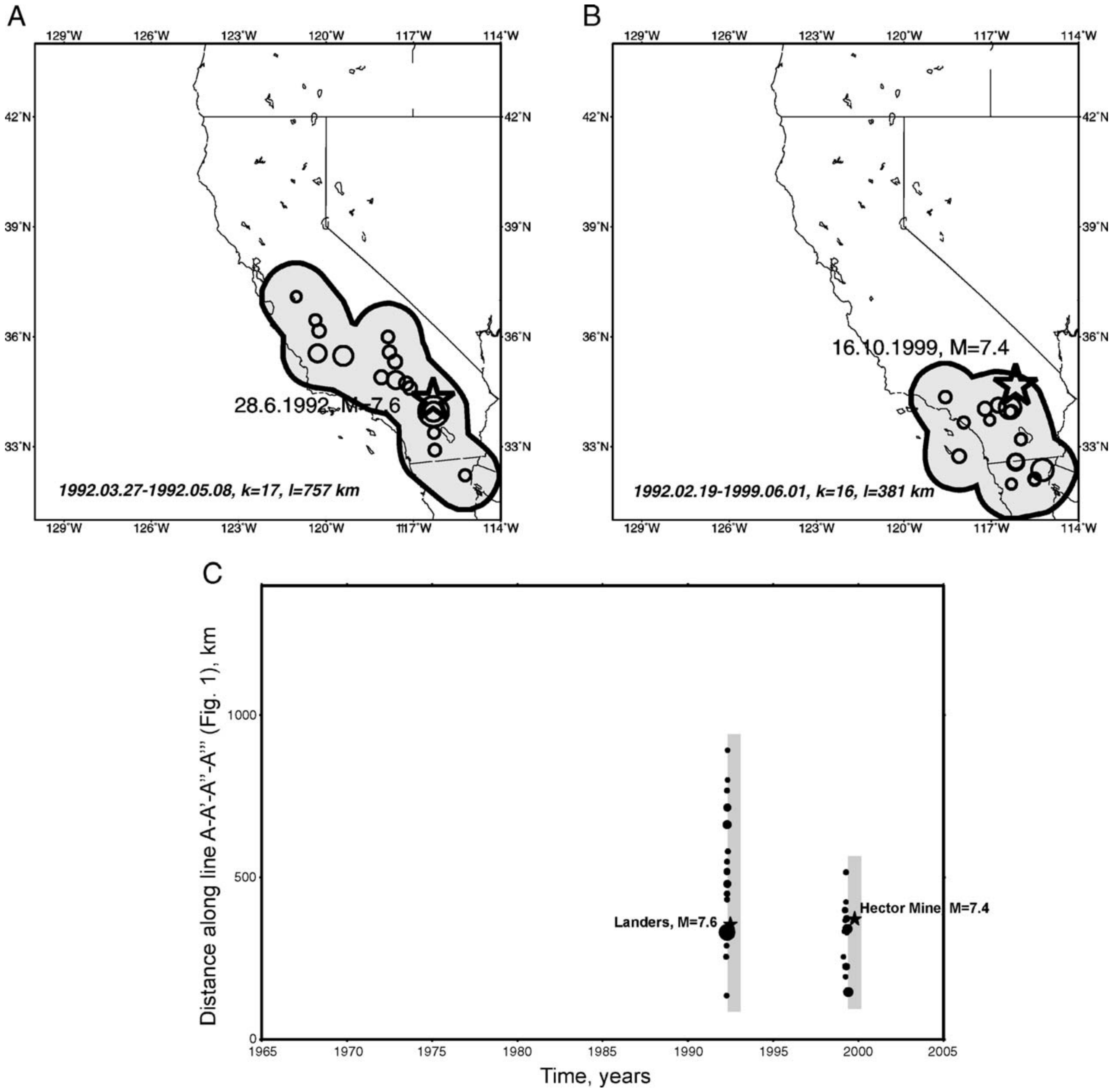

Fig. 2. Earthquake chains before very large earthquakes ($M \geq 7.4$) in California, 1965–2005 (case 8 in Table 1): (A and B) maps of the chains and their 75 km vicinities; (C) time–space diagram of the chains. Circles indicate epicentres forming the chains, larger size corresponding to larger magnitude, stars denote target earthquakes, grey areas mark 75 km vicinities of the chains. Dates of the beginning and end, number of epicentres, and linear size of the chains are indicated in relevant maps. The grey strip in the time–space diagram corresponds to a 9-month interval.

California Earthquake Data Center (NCEDC), and is available at the web site hhttp://quake.geo.berkeley.edu/cnss/catalog-search.html. The PDE catalog is the NEIC/USGS catalog. We used data in the EHDR format: PDE monthly (ftp://hazards.cr.usgs.gov/pde/) updated by PDE weekly and by QED (ftp://hazards.cr.usgs.gov/weekly/). The JMA catalog is the Japan Meteorological Agency earthquake catalog received through the Japan Meteorological Business Support Center. GII is the earthquake catalog of Geophysical Institute of Israel, Holon, covering the eastern Mediterranean region. The NIEP catalog is produced by National Institute for Earth Physics, Bucharest, Romania.

The chain parameters for all 14 cases are listed in Table 1. Two parameters are common, with few exceptions, to all cases: $r_0 = 50$ km, $c = 0.35$. The other

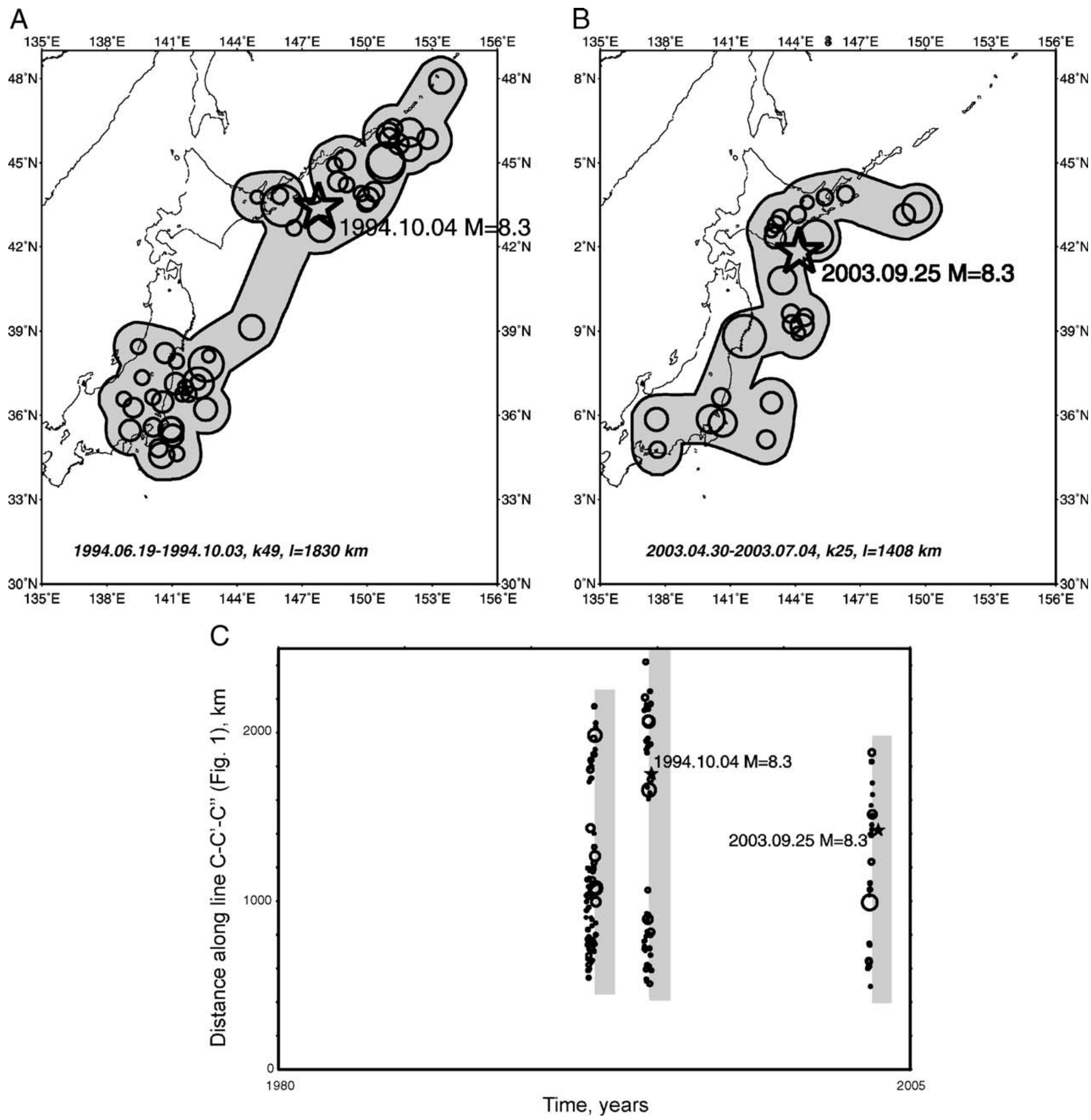

Fig. 3. Earthquake chains before very large ($M \geq 8$) earthquakes in Honshu–Hokkaido–S. Kurils, 1980–2005 (case 9 in Table 1). The other notation is as in Fig. 2.

parameters are common to all chains within a region, but differ between regions.

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 times of a few months. Any of the following cases could also give non-random RTP results: (a) earthquake chains are completely random, they just give an unambiguous way to specify a complex-shaped area 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 can best be seen; (c) the chains are shorter-term precursors, but the space they highlight is not necessarily that of the future large earthquake nor the area of manifestation of intermediate-term precursors. What is the contribution of the chains to the aggregate RTP result? The results of the next four subsections corroborate the hypothesis that the chains are precursors of large earthquakes, with lead times of a few months.

4.1. Earthquake chains preceding great earthquakes

First, we try to change the parameters of the chains in order to "predict" only very large ("great") earthquakes and also to decrease the total number of chains. We tried to do this in California and Honshu–Hokkaido–S. Kurils regions (cases 8 and 9 in Table 1), and this proved possible. For California we increased the magnitude cut-off $M_{\min}$, the spatial parameters r_0 and l_0, and the minimum number of epicenters in a chain k_0 (compare cases 1 to 4 and case 8 in Table 1). As a result, only two chains remain, both preceding two great earthquakes ($M \geq 7.4$) (Fig. 2). In Honshu–Hokkaido–S. Kurils we have increased the magnitude cut-off $M_{\min}$ and the value l_0 alone (compare cases 5 and 9 in Table 1). Three chains are found, two of them preceding both of the great earthquakes in the region, $M \geq 8$ (Fig. 3). Below we shall show that both results are significantly non-random and stable under variation of the parameters.

4.2. Tests with randomized earthquake catalogs

The first columns in Table 2 give statistics of the chains for all 14 cases specified in Table 1. In all the 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 Table 2). Except for the two cases described above and the case of Vrancea, the number of chains is significantly larger than the number of target earthquakes, the ratio varying between 3.27 and 7.86. The number of non-precursory chains is large, but the chains occupy only some part of the regions, so that the time–space of hypothetic alarms (*R*-vicinity of chains in space, and a period of *T* months in time) takes less than a half of the total time–space considered for all cases. What is the probability of obtaining similar results by chance? For the estimate of this probability, α, in each of 14 cases we generated 1000 samples of a random catalog, and used these to detect chains, and then we calculated the fraction of the target earthquakes that have occurred in the time–space of

Table 2
Results of the tests with a randomized catalog

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

hypothetic alarms given by those chains; the corresponding average rate p is shown in Table 2. Finally, we used the binomial model to calculate α from p (see the last column of Table 2). The binomial model gives a crude estimate, because it disregards the fact that some large earthquakes are preceded more often by random chains than others due to the heterogeneity of seismicity. For relatively large estimates $\alpha > 0.02$ (cases 2, 3 and 4) we verified them directly, increasing the number of samples of the random catalog to reach 5000, and calculating the number of samples giving 3 "successes" of 3 "trials", 7 "successes" of 8, and 8 "successes" of 9 (see Table 2; the relevant estimate of α is given in brackets). The direct estimates well agree with those obtained from the binomial model.

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

4.3. Testing the stability of chains under variation of chain parameters

The results obtained here are retrospective. Choosing parameters of the chains, we tried to avoid their over-optimization (data fitting); the crude rounded-off values chosen here are sufficient for our purposes.

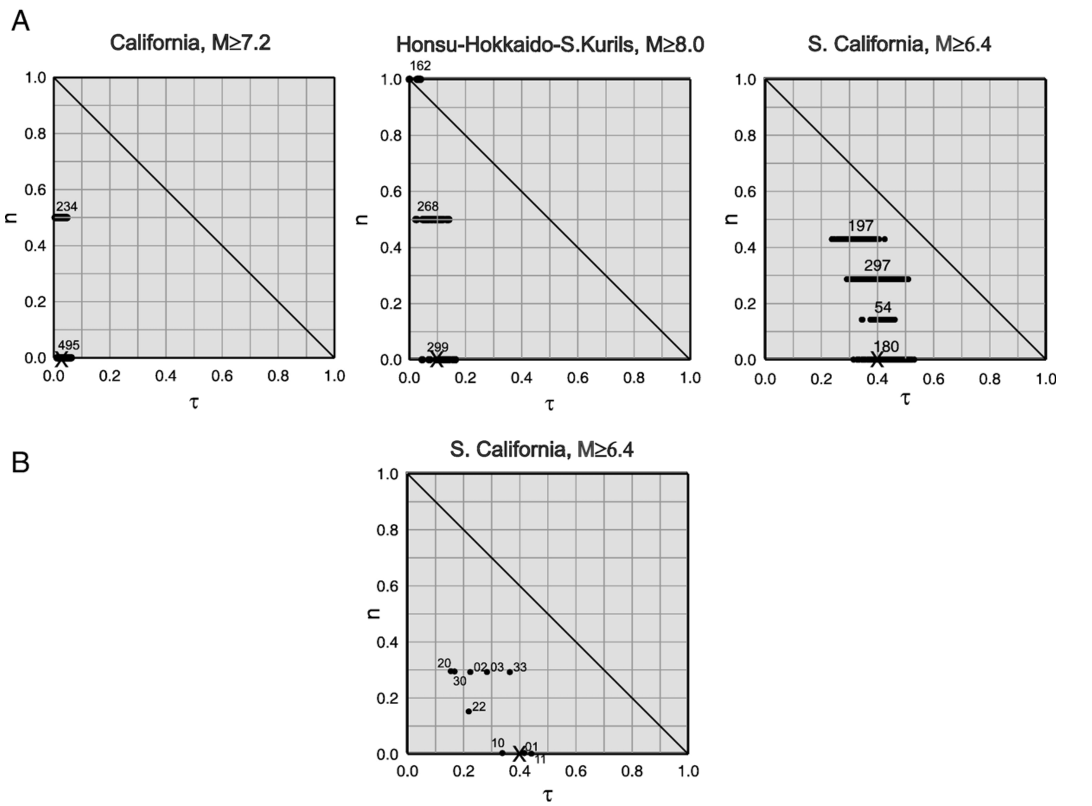

Fig. 4. Examples of error diagrams. (A) Stability tests (for the cases 8, 9 and 1 in Table 1). The total number of points in each plot is 729, which corresponds to all combinations of three values for each of the six parameters. The numbers indicate the number of points in the cluster. The cross marks the main result. For other explanations see main text. (B) Tests with variation of the aftershock parameters. All 9 tests are marked by circles with an index. First digit of the index corresponds to time window, second digit to spatial window. Digits 0, 1, 2, and 3 indicate proportional change of the corresponding window by the factors 1, 1/2, 1/3, 3/2, respectively.

Still, some danger of over-optimization remains, but in that case results should be sensitive to variation of parameters. We tested stability by independent variation of parameter values within at least 10% (0.2 magnitude units for the parameter $M_{\min}$). Each of the six parameters was represented by 3 values: the standard one, a smaller value, and a larger value, $729=3^6$ variants in all. 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 afforded by Molchan's (2003) error diagrams. We calculated two interdependent measures: the fraction of target earthquakes that occurred outside the time–space of hypothetic alarms (*R*-vicinity of a chain during *T* months), *n*; and the time–space τ covered by all the alarms normalized by the whole space–time considered. The space is measured, not in km^2, but in the long-term average seismicity rate. We used the average rate of $M\geq4$ main shocks (Kossobokov and Shebalin, 2003). The meaning of τ is the conditional probability that a target earthquake occurs randomly within the alarm time–space, given it has occurred. We assume the Poisson distribution of target earthquakes in time. We do not know the distribution of target earthquakes in space because of very poor statistics; that is why we replace this distribution by the distribution of $M\geq4$ main shocks. The line (0,1; 1,0) in the (n,τ) diagram corresponds to a random result, the ideal prediction is the point (0,0).

Each of the 729 variants of the stability test gives one point in the (n,τ) diagram. For all 14 cases, all or most of the points lie far from the line of a random result; several examples are shown in Fig. 4A. 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 also studied how large are admissible ranges of the variation of parameters. We varied every parameter in a wide range, and each time corrected, if necessary, the value of only one more parameter with the goal of obtaining approximately the same number of chains with approximately identical location, size and shape

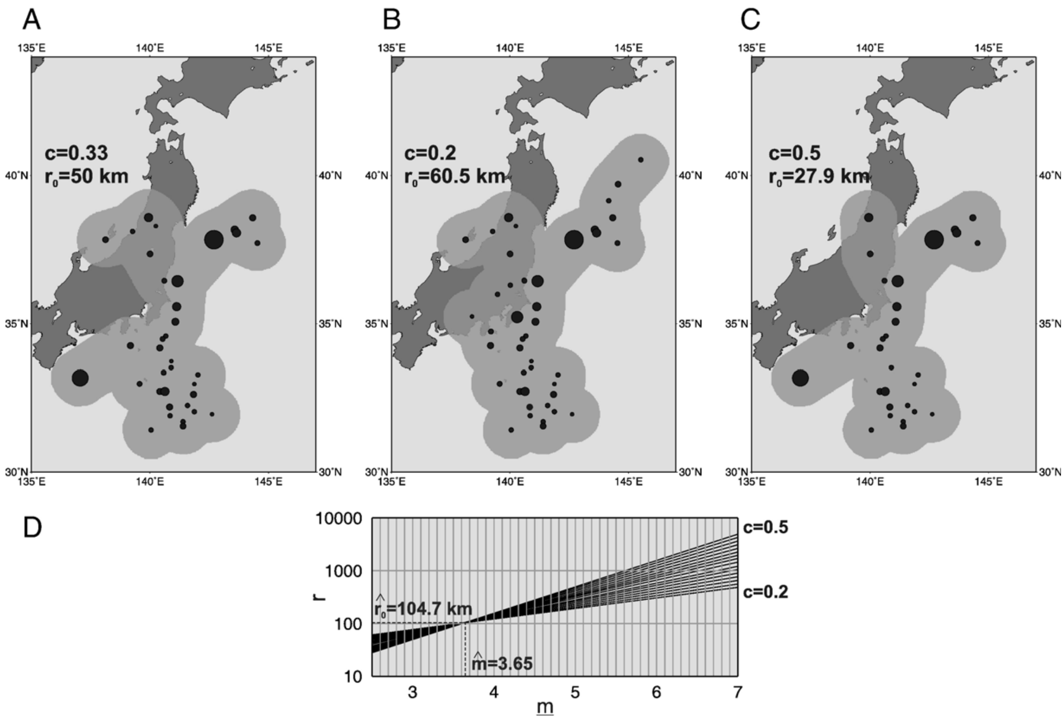

Fig. 5. Variants of the chain preceding two earthquakes with $M=7.2$ and $M=7.4$ in the southern Honshu, Japan, 5 September 2004: (A) chain with standard values of parameters, (B) with $c=0.2$ ($r_0=60.5$ km), (C) with $c=0.5$ ($r_0=60.5$ km), (D) plots of $r=r_0 10^{c(m-2.5)}$ for the whole range of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

compared with the main result. The criterion of a small difference from the main result was as follows: at least 80% of the chains obtained with modified parameters should have at least 80% of the epicentres that make this chain coinciding with those in the main result. We defined the admissible range of a parameter as the range of its values for which we could obtain the small difference from the main result. In all regions we found those ranges to be very large: 0.5 to 2 units of magnitude for the parameter $M_{\min}$, 30% to 150% of relative change for other parameters, dependent on the region.

4.4. The role of the aftershock elimination rule

The simple rule to eliminate aftershocks we use here was proposed by Gardner and Knopoff (1974). Let us denote t_j the origin time of the jth earthquake in the catalog, M_j its magnitude, r_{ij} is distance between epicentres with indexes j and i. By definition, if $t_j > t_i$, $M_j < M_i$, $t_j - t_i < \Delta t(M_i)$, and $r_{ij} \le \Delta r(M_i)$, then the earthquake with the index j is an aftershock of the earthquake with index i, the main shock. If a main shock happens to be an aftershock of another main shock, then we remove the aftershocks of this earlier main shock alone. The "windows" $\Delta t(M)$ and $\Delta r(M)$ increase with main shock magnitude, we use the same values as Gardner and Knopoff (1974). In more complex rules aftershocks are also defined in time and space that are scaled by the magnitude of the main shock, (see Molchan and Dmitrieva, 1992, and references therein, and Baesi and Paczuski, 2005). The major difference of the definition of earthquakes chains is the scaling of the spatial parameter by the lower magnitude in a pair of earthquakes, not by the magnitude of the earlier event. Due to this difference and to the actual values of parameters, the definition of aftershocks is not drastically important for the shape and duration of the chains. Let us check this using chains in southern California.

We changed proportionally the windows $\Delta t(M)$ and $\Delta r(M)$, multiplying them by the factors c_t and c_r, respectively. Those modifications affected the number of main shocks in the catalog; we readjusted the parameters τ and k_0 accordingly. The results are summarized in the error diagram (Fig. 4B). We see that the decrease of either time windows or spatial windows or even both by the factor 2 gives results very similar to the main one. Results are slightly worse in the cases $c_t = 1/3$ or $c_r = 1/3$. Still worse results were obtained

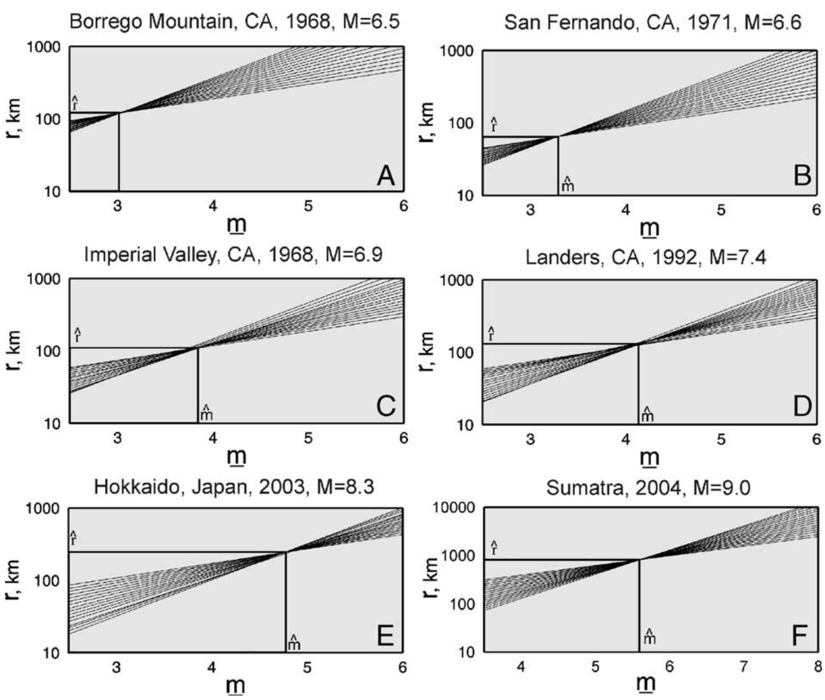

Fig. 6. Sample plots of $r = r_0 10^{c(m-2.5)}$ for the whole range of c from 0.2 to 0.5 with the appropriate value of r_0 (see main text). Six precursory chains preceding large earthquakes.

with enlarged windows, $c_t = 3/2$ or $c_r = 3/2$. The same tendency we observe in other regions: with $c_t = 1/2$ or $c_r = 1/2$ results are only slightly different from the main one, more different with $c_t = 1/3$ or $c_r = 1/3$, and significantly worse with enlarged windows. It is interesting to note that acceptable results were obtained also with the complete catalog, without elimination of aftershocks at all.

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

Studying admissible limits of parameter values, we found an interesting property of earthquake chains. If one varies the value of c from 0.2 to 0.5, and then finds an appropriate value of r_0, leaving the other parameters unchanged, the chain remains the same or only slightly

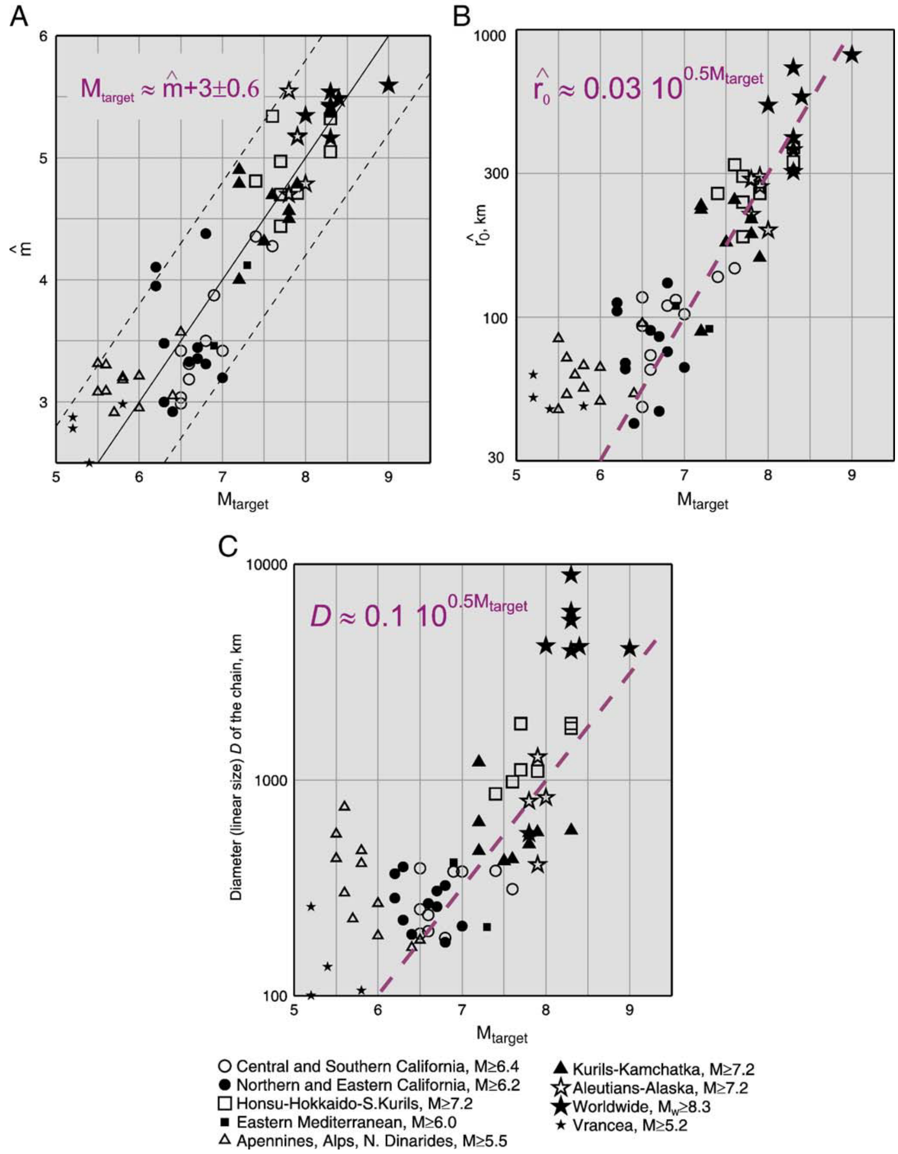

Fig. 7. Correlation of the chain parameters $\hat{m}$, $\hat{r}_0$ and D (linear size) with the magnitudes of target earthquakes. Different symbols represent the values for different cases (see Table 1).

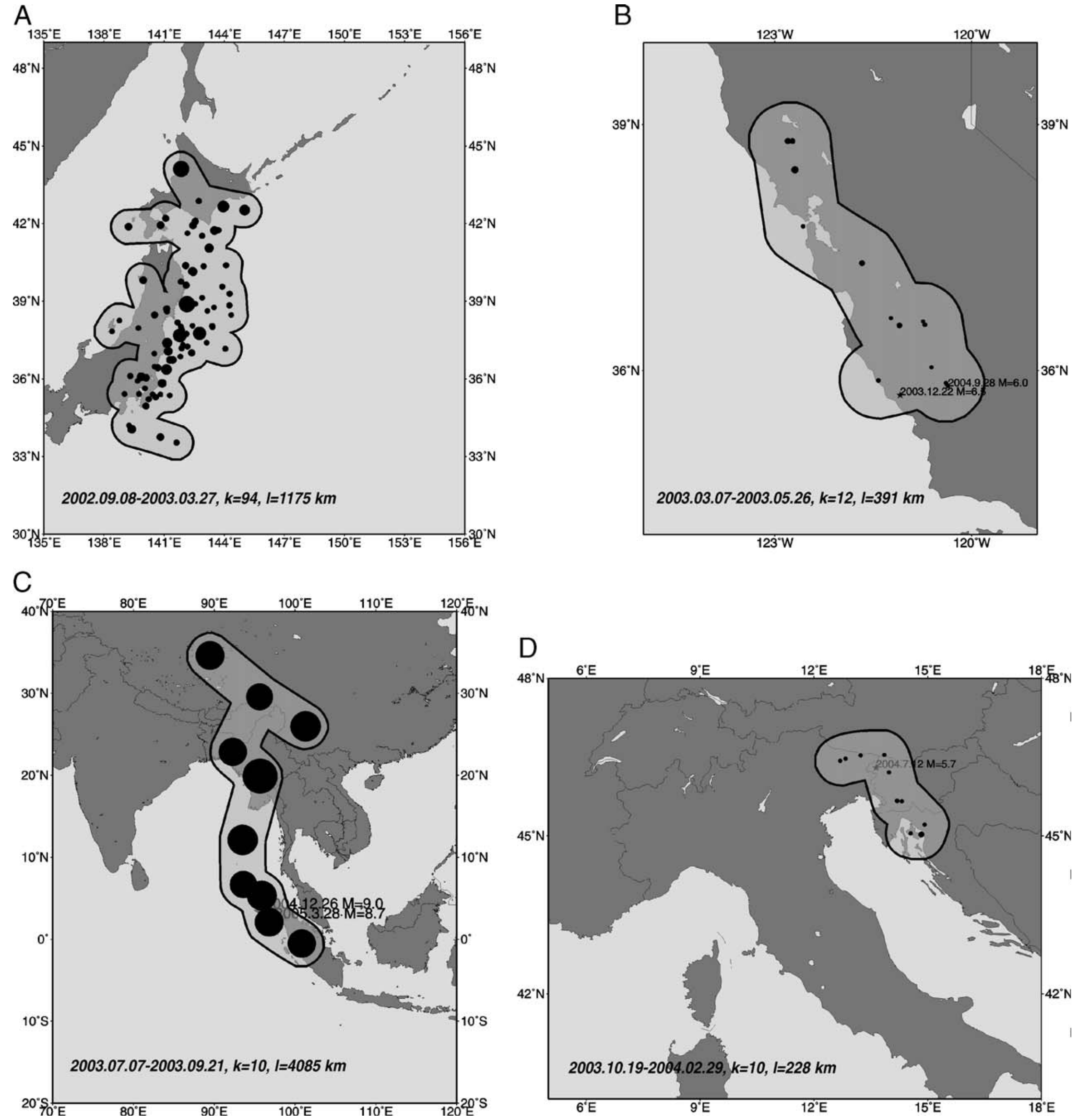

Fig. 8. Examples of precursory chains. See the notation in Fig. 2.

different (as in the example in Fig. 5). The small difference criterion is similar to that described in the previous paragraph: at least 80% of the epicenters forming the modified chain should coincide with those in the initial chain. Usually values of r_0 in some range are appropriate, and we take the minimum among these. The plots of $r = r_0 10^{c(m-2.5)}$ (see the definition of a chain in Section 2.1) made for the resulting pairs (c, r_0), intersect as a rule at one point ($\hat{m}$, $\hat{r}_0$); those values vary from chain to chain (see examples in Fig. 6). This rule makes the values of $\hat{m}$ and $\hat{r}_0$ convenient parameters for the energy scale and the range of earthquake correlation, respectively. The statistics of both $\hat{m}$ and $\hat{r}_0$ are given in Fig. 7 (A, B). Both demonstrate good correlation with magnitudes of target earthquakes, while $\hat{r}_0$ is approximately proportional to the linear size of the target earthquake fault.

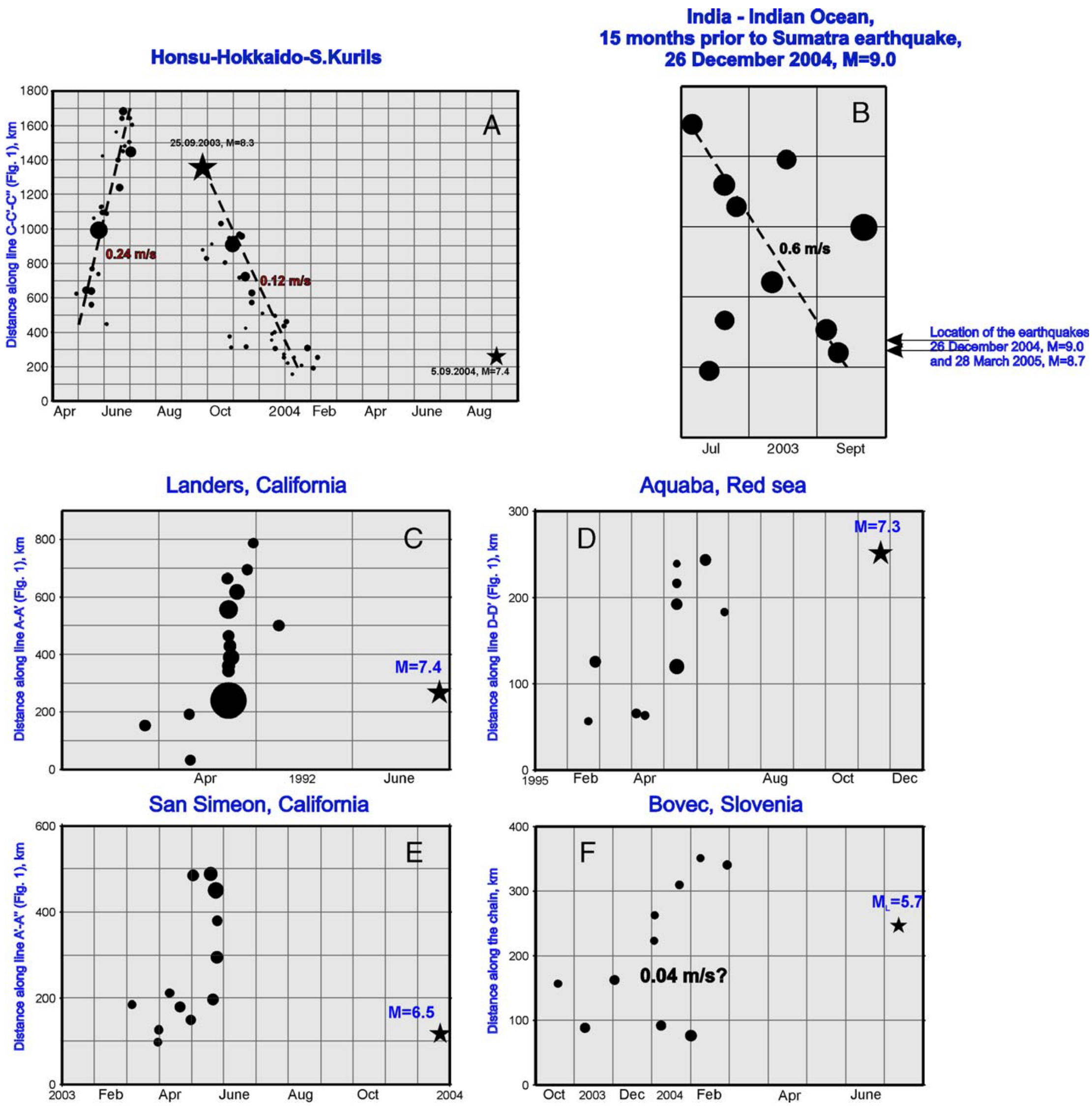

Fig. 9. Examples of time–space diagrams of precursory chains. See comments in the text.

Although points in this figure form clusters corresponding to different regions, and accordingly, to different target magnitudes, this correlation is not explicitly included in our assumptions. Remarkably, the same correlation is observed in a single region, southern California (open circles in the figure), where the parameters of all chains are identical. In the other regions the spatial parameters r_0 and c are also identical with few exceptions. The parameter l_0 is used to select large chains; we found that the use of the value $l_0 = 175$ km for all regions (see Table 1) will add few points to the figure without affecting the statistics. The estimates $\hat{m}$ and $\hat{r}_0$ could be significantly affected by the parameter $M_{\min}$, but our experiments have shown that actually $\hat{m}$ and $\hat{r}_0$ vary very little in a wide range of $M_{\min}$, if $M_{\min} < \hat{m}$.

The correlation between the linear sizes of chains and the target magnitudes (Fig. 7C) is slightly lower. The scaling of $\hat{m}$ and $\hat{r}_0$ by target magnitudes suggests that this is not just a result of larger values of l_0 in the regions with larger M_{target}, but that in general larger chains precede larger earthquakes.

6. Discussion and conclusions

The results of this paper confirm that in a vast majority of cases, large earthquakes are preceded, months in advance, by earthquake chains. The statistical significance of non-randomness of the result is high.

Earthquake chains are manifestations of an increased range of correlation for earthquakes of medium magnitudes. Accordingly, they give additional evidence of a premonitory increase of the correlation range.

The chosen definition of earthquake chains ensures high stability under the variation of their parameters within wide limits of variation.

The invariant parameters of the chains found, $\hat{m}$ and $\hat{r}_0$, characterize the energy and spatial scales of the correlation. The parameter $\hat{r}_0$ can be used as the definition of correlation range in earthquake chains. The parameter $\hat{m}$ could be used in the RTP prediction algorithm 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 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 extended shape, a few examples being shown in Fig. 8. This explains why we prefer the term "chains". It is interesting that the chains obtained from a randomized catalog are usually less regular. This fact is additional evidence for the phenomenon of the premonitory increase of earthquake correlation range.

Earthquake chains have various time–space structures. Some of them demonstrate a well-organized, directional, wave-like arrangement. For example, the chain prior to the Tokachi-Oki, Hokkaido earthquake of 26 September 2003, $M = 8.3$ clearly developed from south to north (Fig. 9A). The earthquake occurred in the northern part of the chain three months later. After the quake, a new chain started to develop from north to south, and 7 months later two earthquakes ($M = 7.2$ and $M = 7.4$) occurred in the south. The rates of motion of the chains are 0.24 m/s and 0.12 m/s, respectively. The propagation of the chain preceding the Sumatra earthquake of 26 December 2004, $M = 9.0$ is less evident (Fig. 9B), but its rate of motion is higher (0.6 m/s). The example of the chain prior to the Landers, California, earthquake of 28 June 1992, $M = 7.6$ is a sequence of long-range "aftershocks" occurring almost at once after the Joshua Tree earthquake of 23 April 1992, $M = 6.1$, propagating over distances of 600 km (Fig. 9C). The chains prior to the San Simeon, central California, earthquake of 22 December 2003, $M = 6.5$, also demonstrates very fast propagation over large distances (300 km), but the sequence was not initiated by a larger quake (Fig. 9D). Such 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 an acceptable physical interpretation of premonitory earthquake chains is still to be devised.

Acknowledgements

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