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Advanced School on Understanding and Prediction of Earthquakes and other Extreme Events in Complex Systems

26 September - 8 October, 2011

Earthquakes and their Distribution in-Space-Time-Energy

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Earthquakes
and Their Distribution
in Space-Time-Energy Domain

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И.М. Гельфанд

ДВА АРХЕТИПА В ПСИХОЛОГИИ ЧЕЛОВЕЧЕСТВА

1989 Лекция при вручении премии INAMORI FOUNDATION (Киото, Япония)

Izrail M. Gelfand, Two archetypes in the psychology of Man. Nonlinear Sci. Today 1 (1991), no. 4, 11

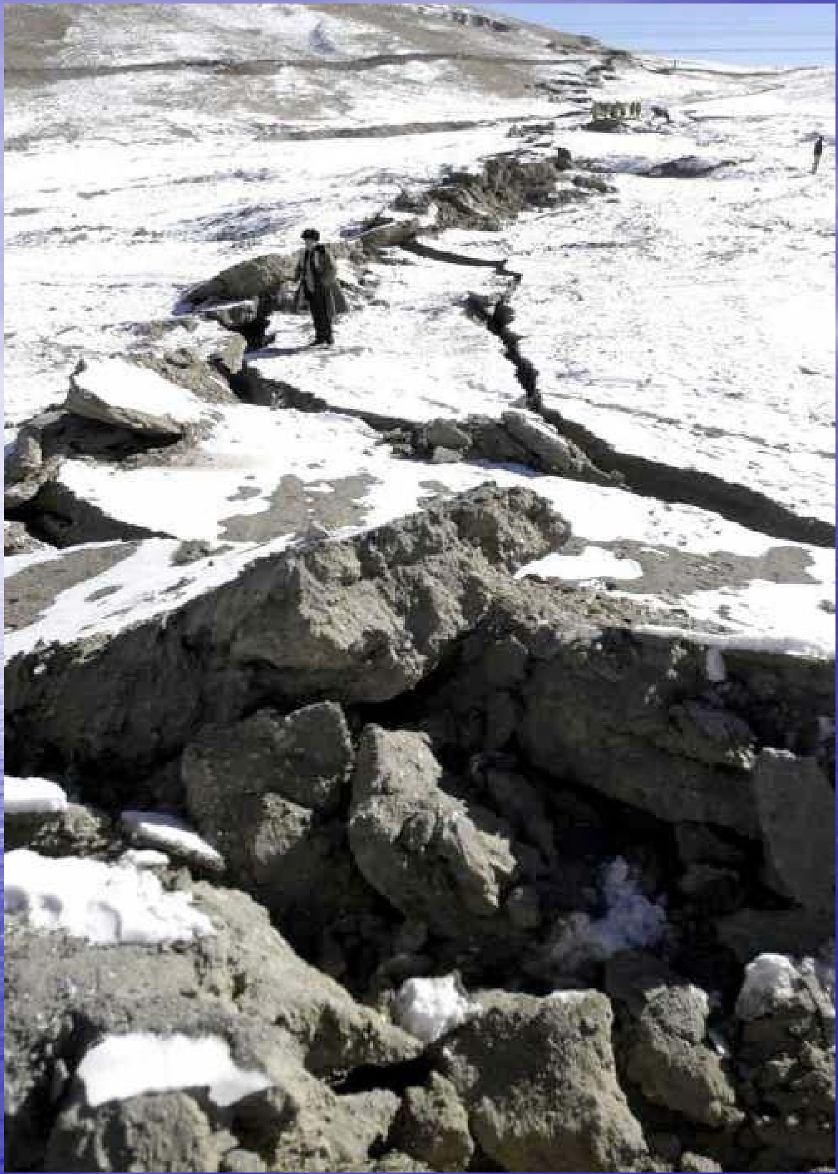
Izrail Moiseevich Gelfand (1913-2009)

It is frightening that in our technocratic times baseline principles are not subjected to questioning, so that when they built the basis of trivial or, conversely, delicately-designed model, it considered as a full replacement of natural phenomena. This made the better model, it is worse for its applications – you know that pressure of snatched "baseline principles" brings the model even further beyond its applicability.

What are earthquakes

Earthquakes are sudden fractures of the Earth’s crust that radiate seismic waves and cause ground shaking.

Although historical records on earthquakes are known from 2100 B.C., most of them before the middle of the 18th century are generally lacking a reliable description.



The extreme catastrophic nature of earthquakes is known for centuries due to resulted devastation in many of them.

The abruptness along with apparent irregularity and infrequency of earthquake occurrences facilitate formation of a common perception that earthquakes are random unpredictable phenomena.

The challenging questions remain pressing:

What happens during an earthquake?

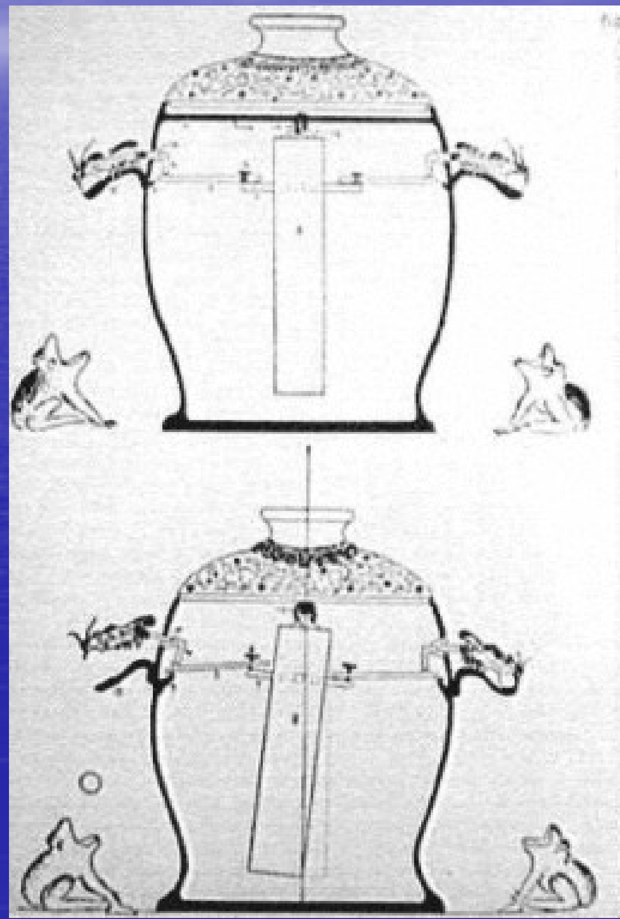
How to size earthquakes?

Why, Where and When do earthquakes occur?

The basic difficulty in answering these questions comes from the fact that no earthquake has been ever observed directly.

How to get info about earthquakes?

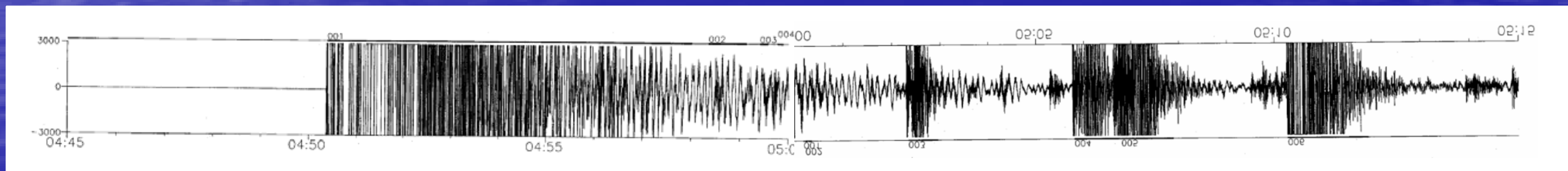
Chinese scientists created the first earthquake detector 2000 years ago



Recording earthquakes

- In 1870s the English geologist *John Milne* designed a forerunner of modern seismographs.

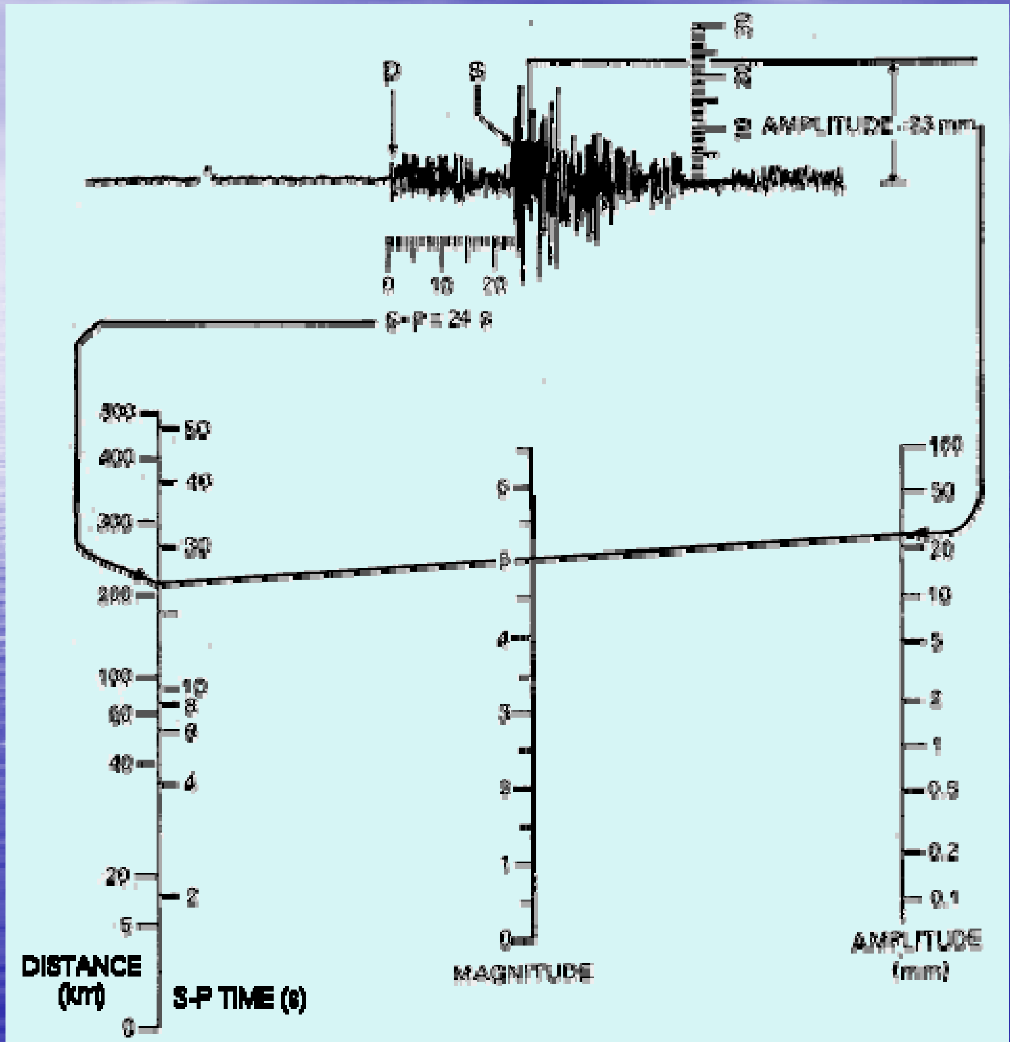
  A simple pendulum and a needle suspended above a smoked-glass plate allowed to distinguish primary and secondary earthquake waves and, basing on their timing, to derive an accurate statement about location of an earthquake source.
- The modern seismograph was invented in the early 20th century by the Russian Prince *Boris Golitzyn,* who improved similar instruments of the 1890's.
- At present, the classic image of a pen that writes a seismogram has been replaced by enhanced digital systems, but the principle remains the same.



Measuring size of an earthquake

- It was only in the 1930's that *Charles F. Richter*, a California seismologist, introduced the concept of earthquake magnitude.
- His original definition held only for California earthquakes occurring within 600 km of a particular type of seismograph (i.e., the *Woods-Anderson* torsion instrument).
- Richter's original magnitude scale (M_L) was then extended to observations of earthquakes of any distance and of focal depths ranging between 0 and 700 km.

Richter magnitude scale



The diagram demonstrates how to use Richter's original method to measure a seismogram for a magnitude estimate in Southern California.

Magnitude scales

- Because earthquakes excite both body waves, which travel into and through the Earth, and surface waves, which are constrained to follow the Earth's uppermost layers, two magnitude scales evolved - the m_b and M_S
- The standard body-wave magnitude formula is

$$m_b = \log_{10}(A/T) + Q(D,h) \,,$$

where *A* is the amplitude of ground motion; *T* is the corresponding period; and Q(*D*,*h*) is an empirical function of distance, *D*, between epicenter and station and focal depth, *h*.

- The standard surface-wave formula is

$$M_S = \log_{10}(A/T) + 1.66 \log_{10}(D) + 3.30 \,.$$

Seismic Moment, M_O

- The seismic moment is related to fundamental parameters of the faulting process.

$$M_O = \mu S \langle d \rangle,$$

where μ is the shear strength of the faulted rock,

S is the area of the fault, and ‹d› is the average displacement on the fault.

- These parameters are determined from waveform analysis of the seismograms produced by an earthquake.

Magnitude scale M_W

- This magnitude scale introduced recently is computed from seismic moment as

$$M_W = 2/3 \log_{10}(M_O) - 10.7$$

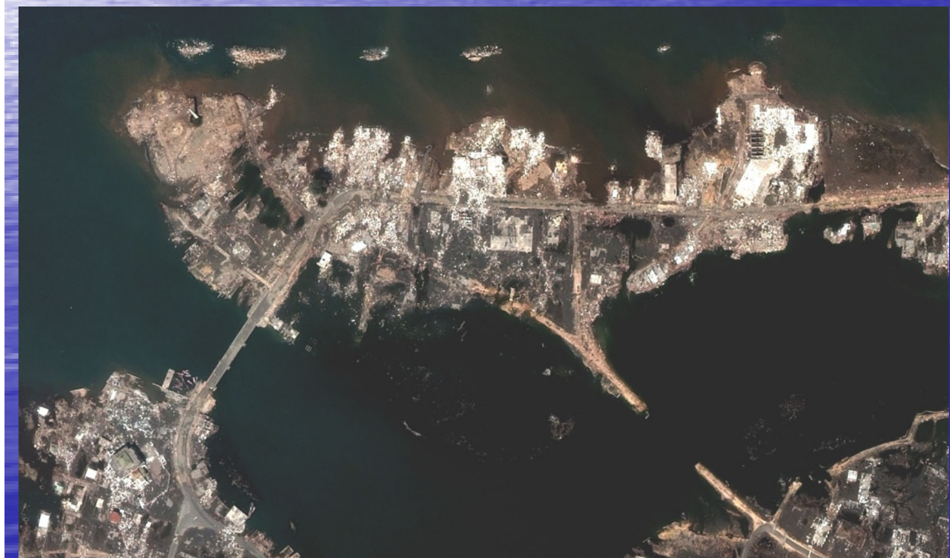
The largest reported moments are

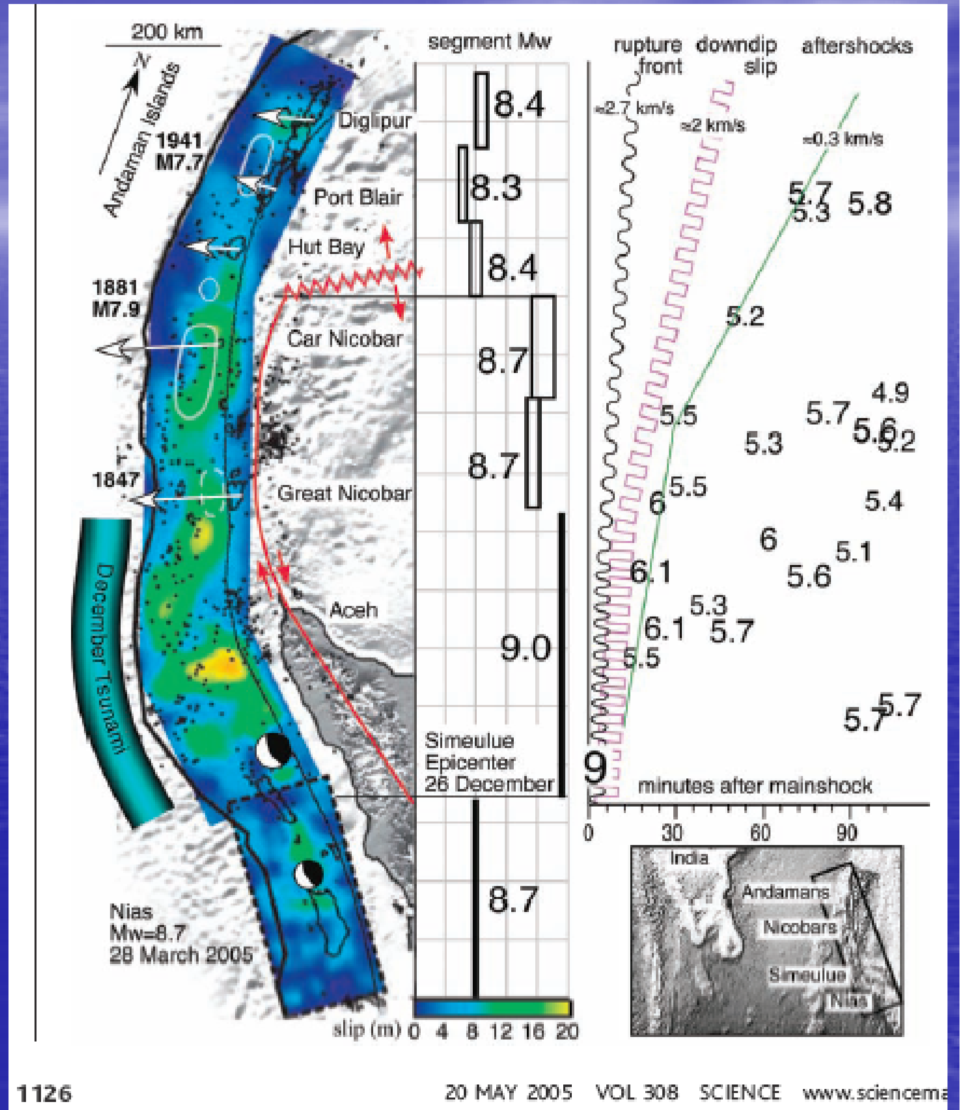
2.5×10^{30} dyn·cm for the 1960 Chile earthquake (M_S8.5; M_W9.6),

1.0×10^{30} dyn·cm for the 2004 Sumatra-Andaman earthquake (M_S8.8; M_W9.3),

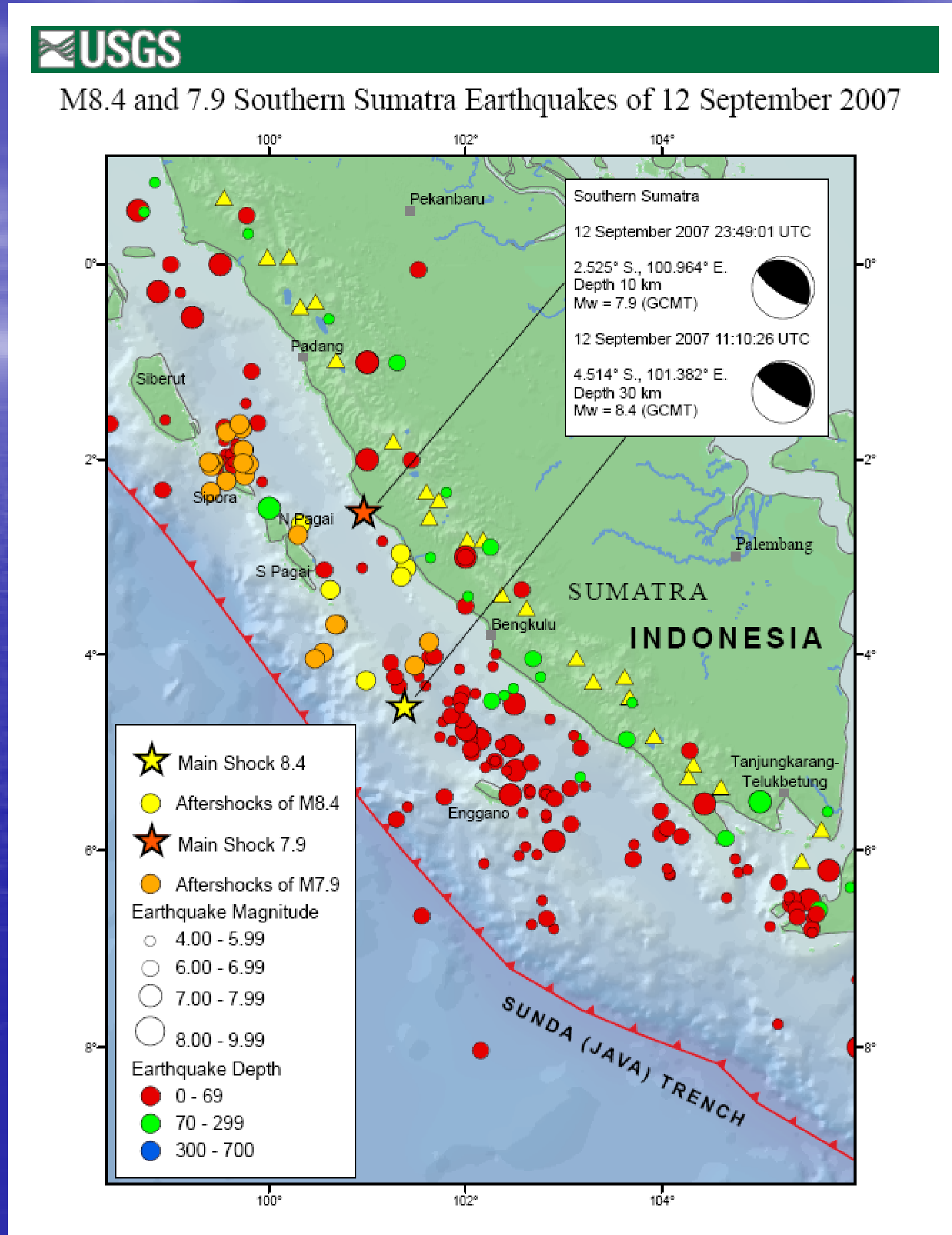
7.5×10^{29} dyn·cm for the 1964 Alaska earthquake (M_S8.3; M_W9.2).

December 26, 2004, Sumatra-Andaman, Mw=9.3



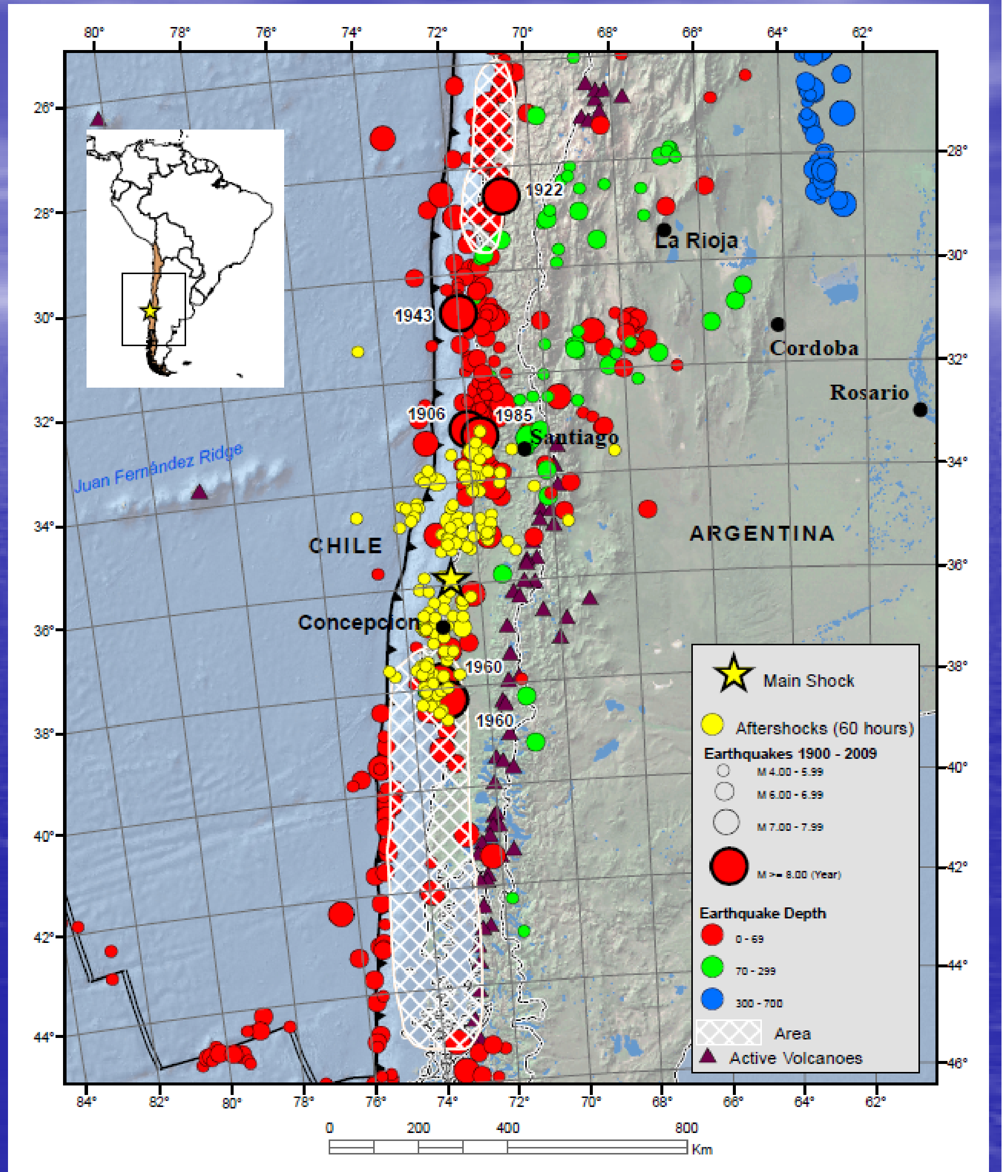


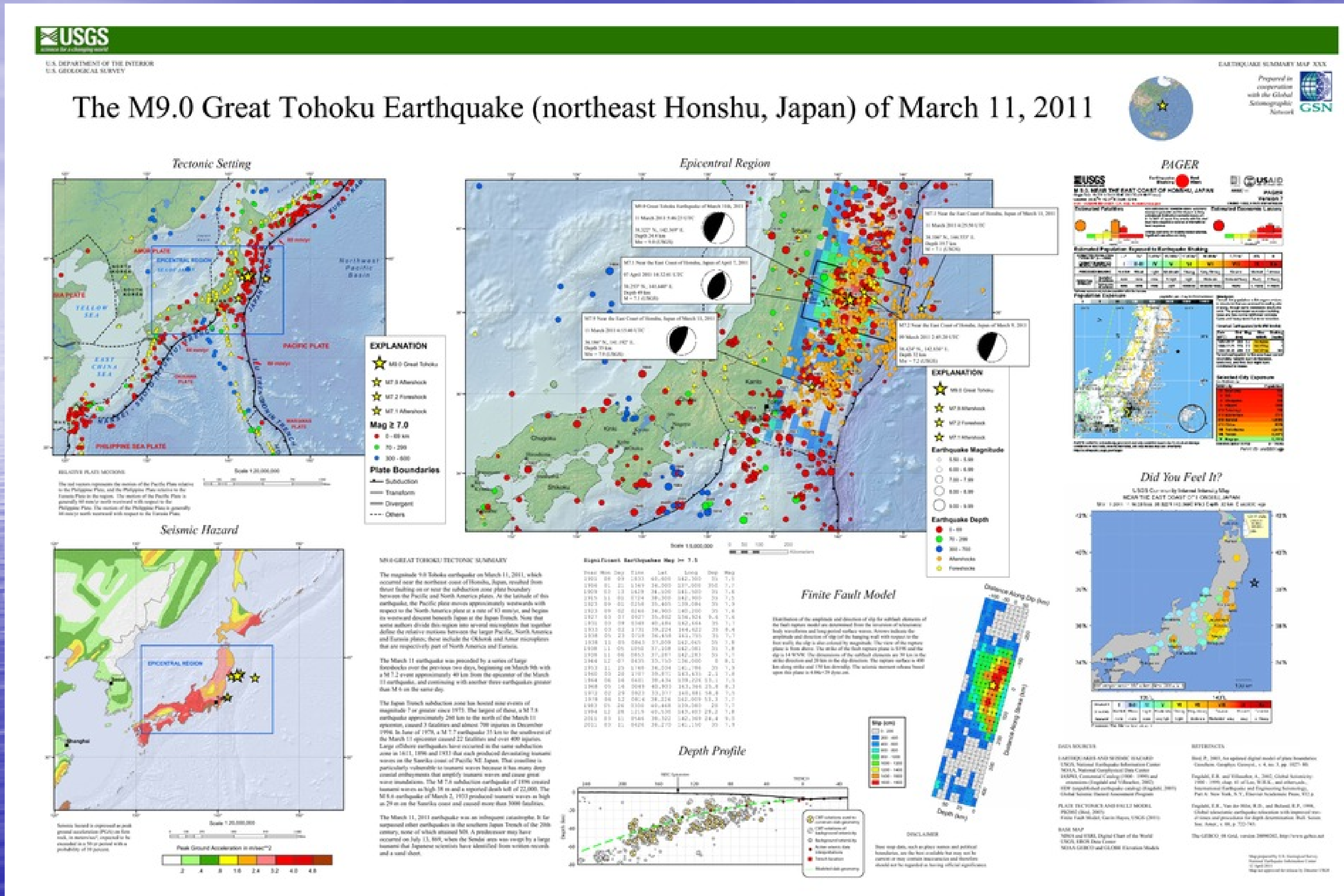
Selamat



USGS
M8.4 and 7.9 Southern Sumatra Earthquakes of 12 September 2007
Southern Sumatra
12 September 2007 23:49:01 UTC
2.525° S., 100.964° E.
Depth 10 km
Mw = 7.9 (GCMT)
12 September 2007 11:10:26 UTC
4.514° S., 101.382° E.
Depth 30 km
Mw = 8.4 (GCMT)
Pekanbaru
Padang
Siberut
Sipora
N Pagai
S Pagai
Palembang
SUMATRA
Bengkulu
INDONESIA
Enggano
Tanjungkarang-
Telukbetung
SUNDA (JAVA) TRENCH
Main Shock 8.4
Aftershocks of M8.4
Main Shock 7.9
Aftershocks of M7.9
Earthquake Magnitude
4.00 - 5.99
6.00 - 6.99
7.00 - 7.99
8.00 - 9.99
Earthquake Depth
0 - 69
70 - 299
300 - 700
100°
102°
104°
0°
2°
4°
6°
8°


O.CAMPOS


Juan Fernández Ridge
CHILE
Concepcion
Santiago
La Rioja
Cordoba
Rosario
ARGENTINA
1922
1943
1906
1985
1960
1960
Main Shock
Aftershocks (60 hours)
Earthquakes 1900 - 2009
M 4.00 - 5.99
M 6.00 - 6.99
M 7.00 - 7.99
M >= 8.00 (Year)
Earthquake Depth
0 - 69
70 - 299
300 - 700
Area
Active Volcanoes
0 200 400 800
Km


USGS
The M9.0 Great Tohoku Earthquake (northeast Honshu, Japan) of March 11, 2011
Tectonic Setting
Epicentral Region
PAGER
Seismic Hazard
Did You Feel It?
Finite Fault Model
Depth Profile
EXPLANATION
GSN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The US GS/NEIC Global Hypocenter Data Base

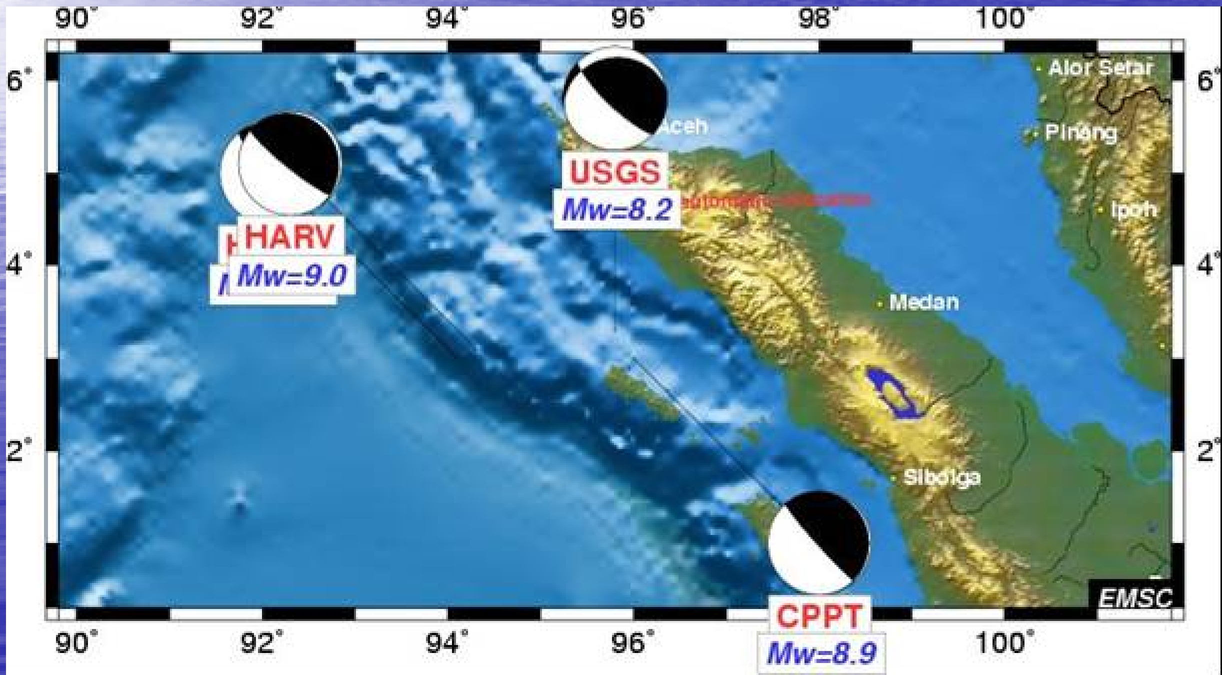
This database available from the US Geological Survey / National Earthquake Information Center at Denver, Colorado. It consists of the data on CD-ROM and its updates with Preliminary Determinations of Epicenters, PDE-monthly and PDE-weekly, and Quick Earthquake Determinations, QED.

P.N. Shebalin, using pattern recognition technique merged more than forty source catalogs of the NEIC GHDB into a composite one.

We shall use the updated version of this composite catalog in course the computer exercises of the Workshop.

The first determinations by USGS Earthquake Hazards Program: 26 December 2004 Sumatra-Andaman earthquake

Because of the size (M 9.0) of this earthquake, point-source methods that use only the body-wave portion of the seismogram are inadequate for measuring the true magnitude.




```
04/12/26 00:58:50.76
OFF W COAST OF NORTHERN SUMATRA
Epicenter:   3.298   95.778
MW 8.2

USGS MOMENT TENSOR SOLUTION
Depth   7          No. of sta: 31
Moment Tensor;    Scale 10**21 Nm
  Mrr= 0.91        Mtt=-0.89
  Mff=-0.02        Mrt= 1.78
  Mrf=-1.55        Mtf= 0.47
 Principal axes:
  T  Val=  2.53  Plg=55   Azm= 50
  N        0.09       8       308
  P       -2.61      34       213

Best Double Couple:Mo=2.6*10**21
 NP1:Strike=274 Dip=13 Slip=  55
 NP2:       130     79        98

              -------
         -----------------
       ---#############----
     --####################---
   ##-########################--
  #----########################--
  -------############   ########-
 ---------########### T #########-
 -----------#########   ##########
 -------------####################
 ---------------##################
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  ------------------############
  --------   -----------#########
   ------- P -------------#####
     -----   -----------------
       ---------------------
         -----------------
              -------
```

"This is a REVISED solution for today's earthquake near Sumatra. The solution includes approximately the first 9 hours of data recorded after the earthquake. Owing to the large size of the earthquake, the short-period cutoff for the analysis was set to 300 s. December 26, 2004, OFF W COAST OF NORTHERN SUMATRA, MW=9.0"

(Meredith Nettles, Goran Ekstrom)

```
CENTROID, MOMENT TENSOR SOLUTION
HARVARD EVENT-FILE NAME M122604A
DATA USED: GSN
MANTLE WAVES:    73S,202C, T=300
CENTROID LOCATION:
ORIGIN TIME        01:01: 9.0 0.3
LAT  3.09N 0.04;LON  94.26E 0.03
DEP  28.6 1.3;HALF-DURATION 95.0
MOMENT TENSOR; SCALE 10**29 D-CM
  MRR= 1.04 0.01; MTT=-0.43 0.01
  MPP=-0.61 0.01; MRT= 2.98 0.16
  MRP=-2.40 0.16; MTP= 0.43 0.00
 PRINCIPAL AXES:
 1.(T) VAL=  4.01;PLG=52;AZM= 36
 2.(N)      -0.12;    3;    130
 3.(P)      -3.89;   38;    222
BEST DOUBLE COUPLE:M0=4.0*10**29
 NP1:STRIKE=329;DIP= 8;SLIP= 110
 NP2:STRIKE=129;DIP=83;SLIP=  87

           -#######---
       #################--
     #####################--
    -########################--
   ----#############   #######--
  ------############ T ########--
  --------##########   #########-
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  ------------------############
  -------   ------------########-
   ------ P --------------#####-
    -----   -------------------
     -----------------------
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```
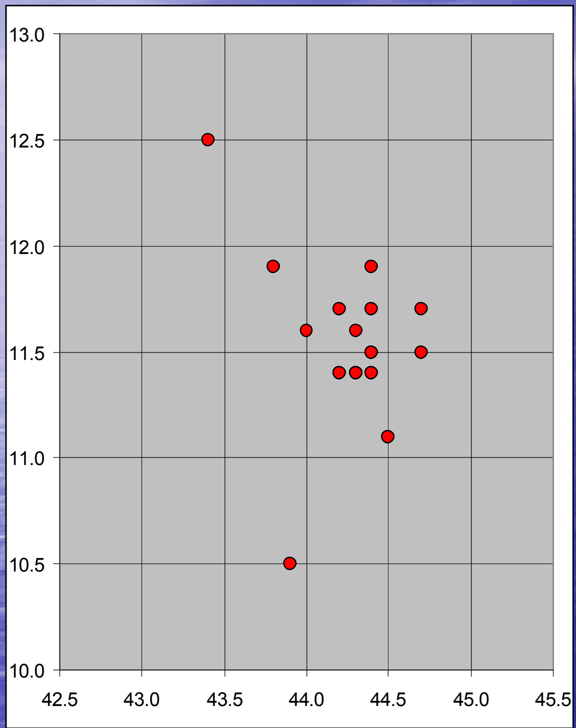
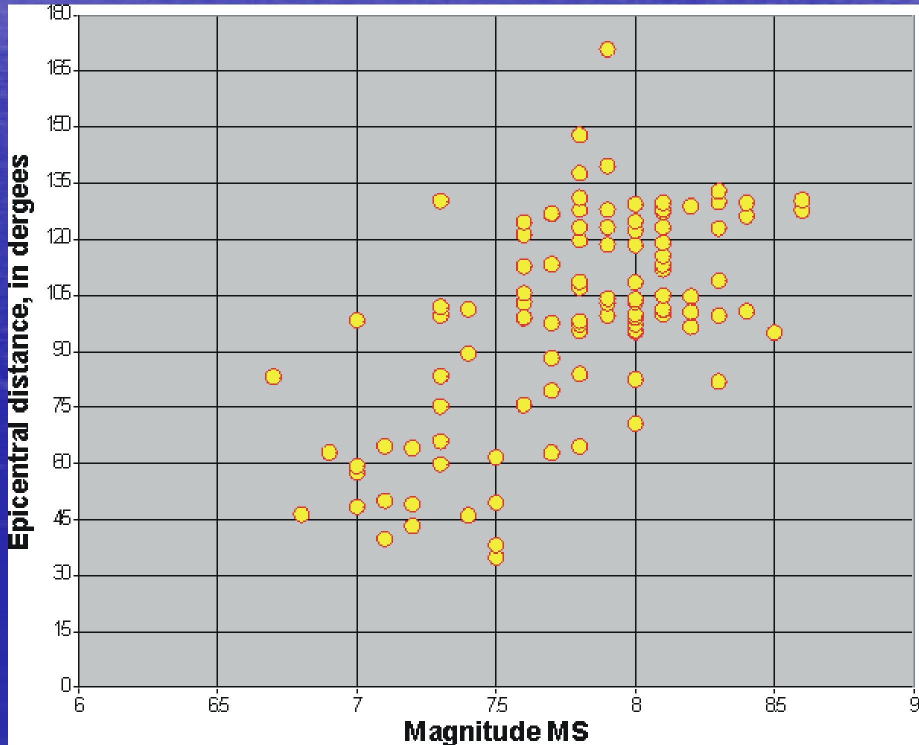

Uncertainties and errors



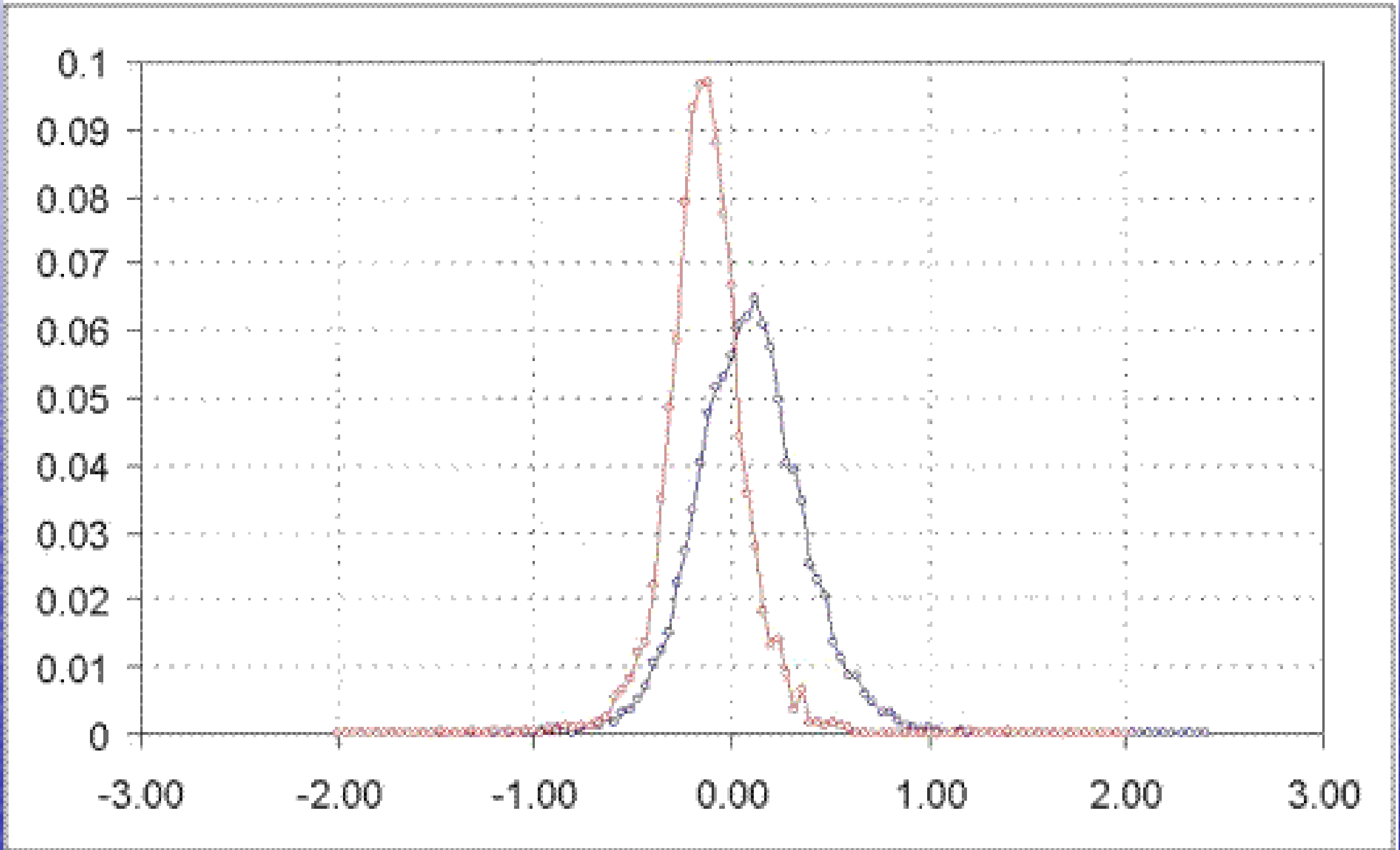
Fast determinations of the epicenter for the 14 September 2003 earthquake in Northern Italy by different seismological agencies to European-Mediterranean Seismological Centre (EMSC)

Epicenter distance vs. Station magnitude for the 108 determinations for the 08 September 2002 earthquake NEAR NORTH COAST OF NEW GUINEA, P.N.G.

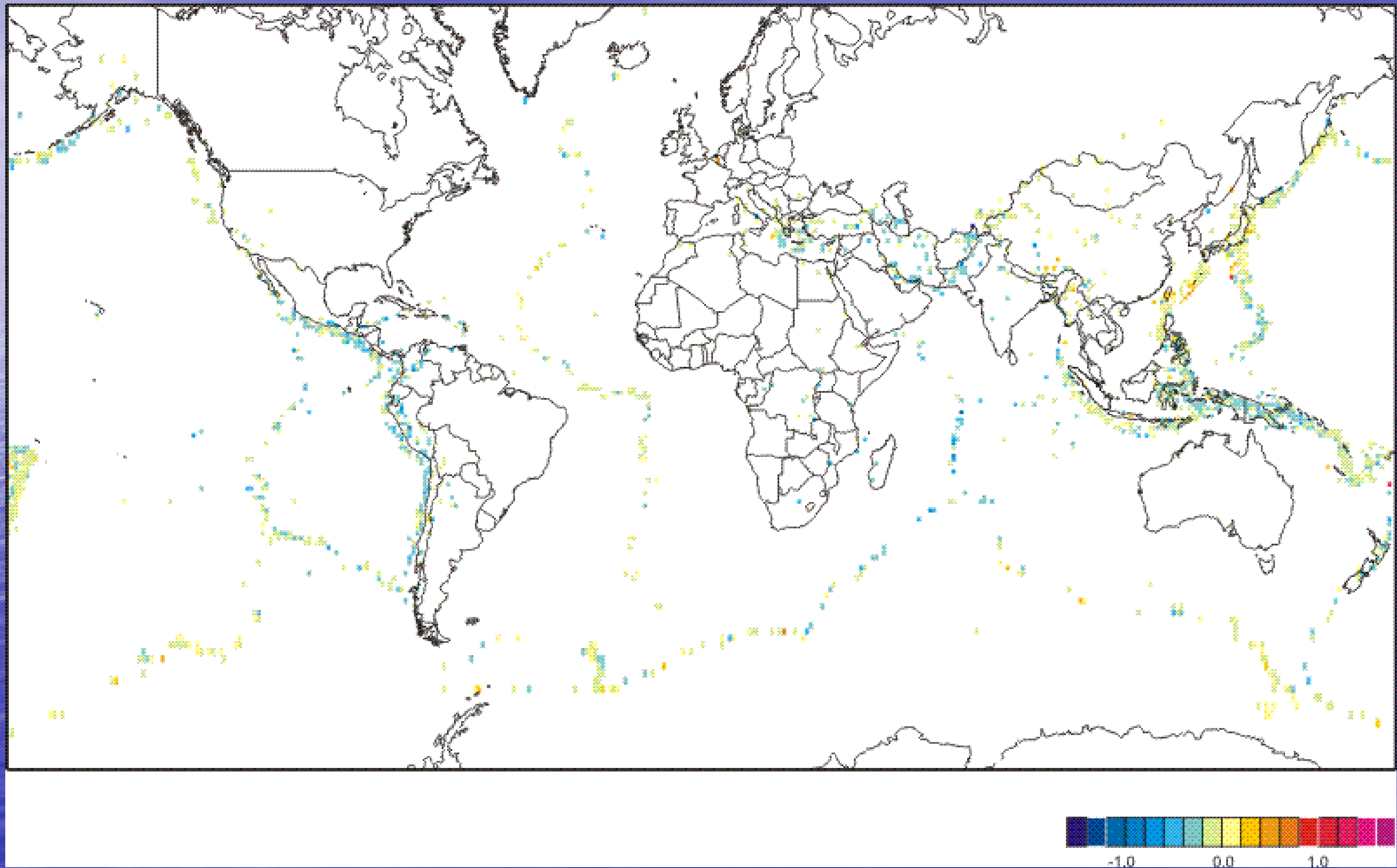


The distribution of the difference between average magnitudes in epicenter and antipodal hemispheres

(MCHEDR 1990-2000, all events that have three of more station magnitudes in each hemisphere). The violet curve corresponds to MSZ (4560 differences, Average = -0.147, σ = 0.198), while the blue one - to mb (8175 differences, Average = 0.074, σ = 0.274).



The territorial distribution of the difference between the two averages estimated over the stations from epicenter and antipodal hemispheres (for MSZ magnitudes).



Catalog Errors

All catalogs have errors, which may render invalid conclusions derived in a study based on a catalog of earthquakes.

Two ways to avoid the errors –

- Postpone the analysis until the data are refined;
- Use robust methods within the limits of their applicability.

"Undue precision of computations is the first symptom of mathematical illiteracy"

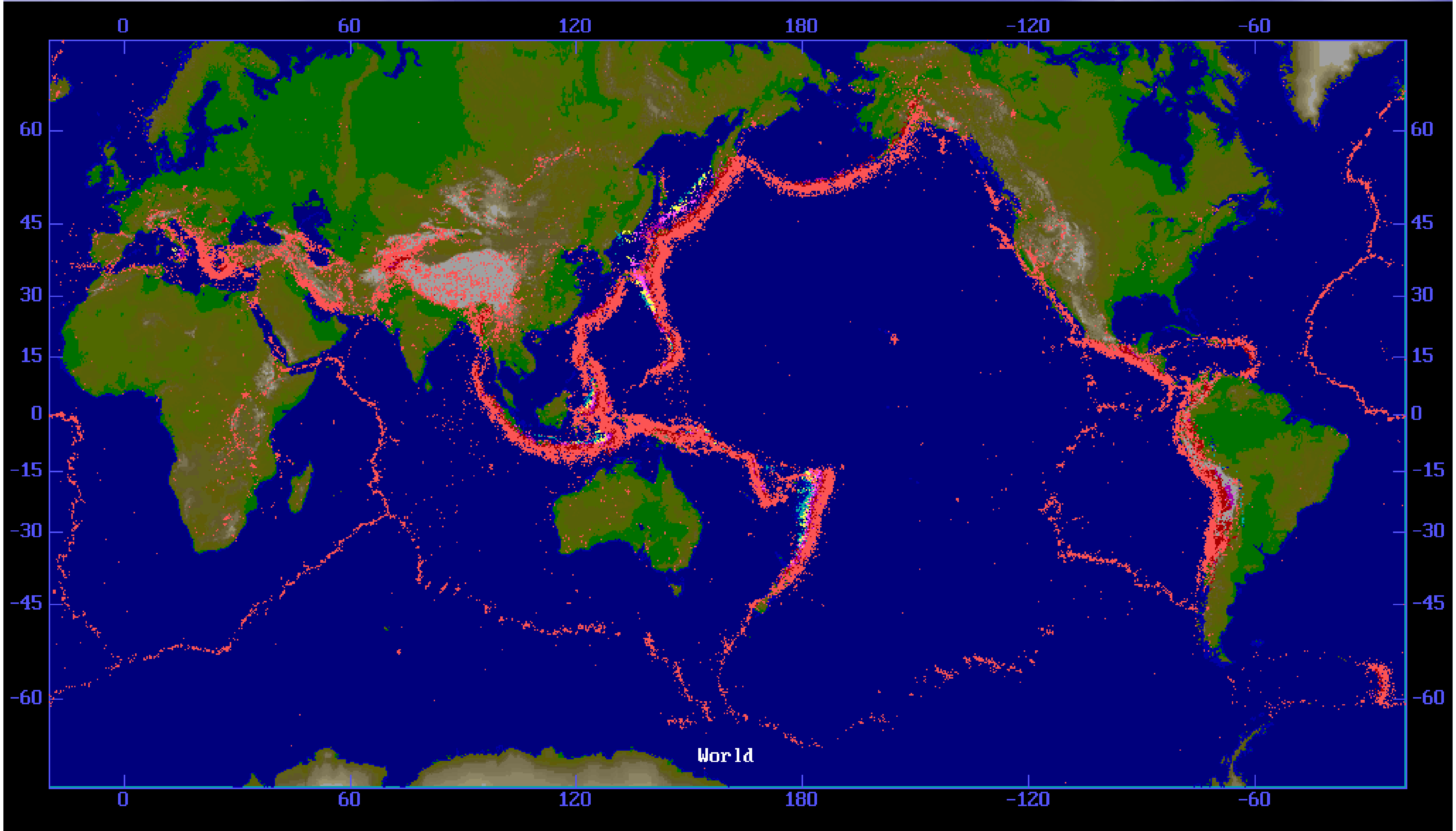
Alexei N.Krylov, famous Russian mathematician, naval engineer, specialist in non-linear mechanics

What can we learn from a catalog of earthquakes?

There are two extreme opinions on the subject –

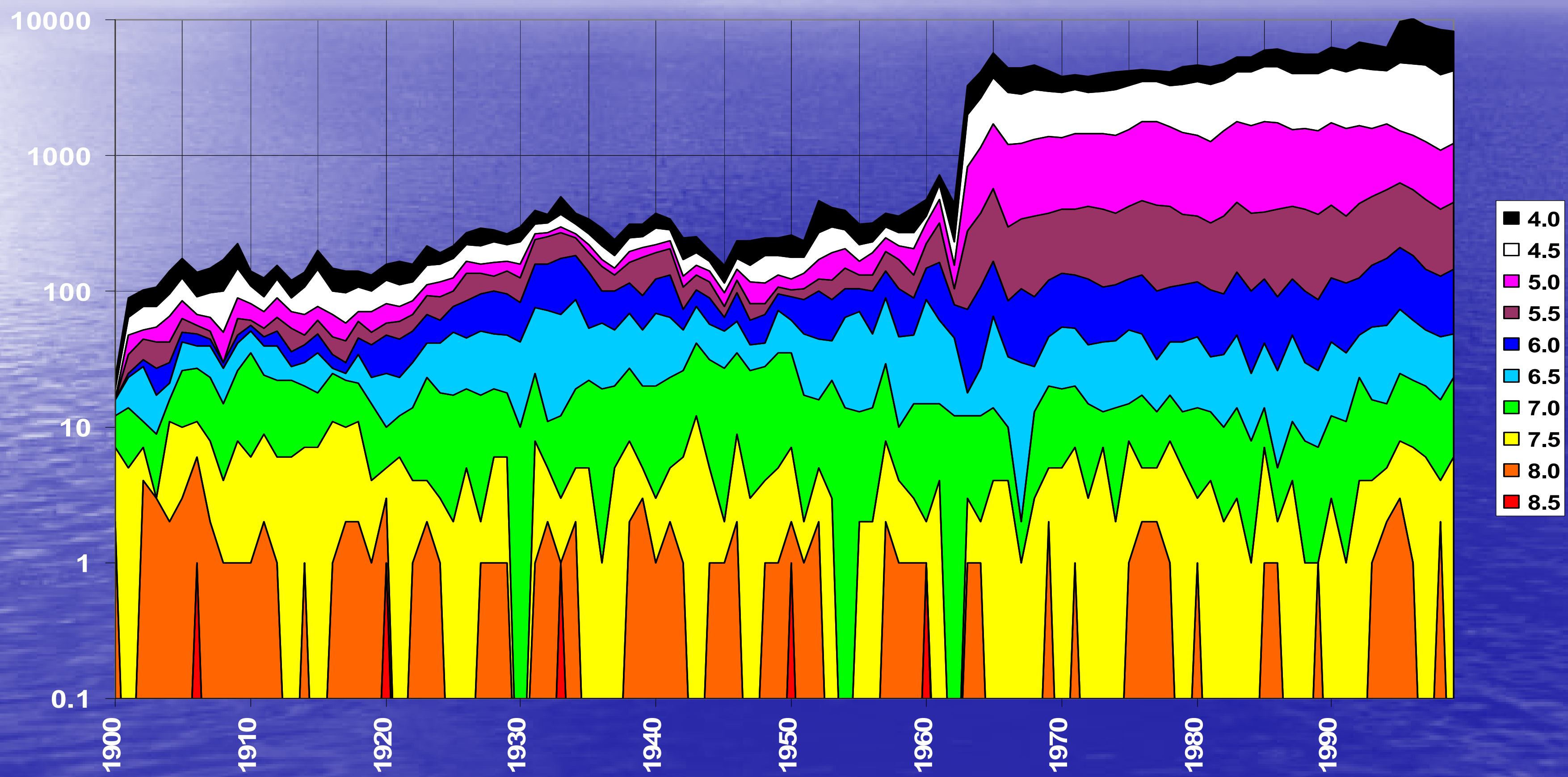
- *Pessimistic*: "… in the case of seismic data, most of the observed variations are, in fact, related to changes in the system for detecting and reporting earthquakes and not to actual changes in the Earth."
- *Optimistic*: Among existing data seismic catalogs remain the most reliable record on distribution of earthquakes of different size in space and time.

Distribution of earthquakes in Space



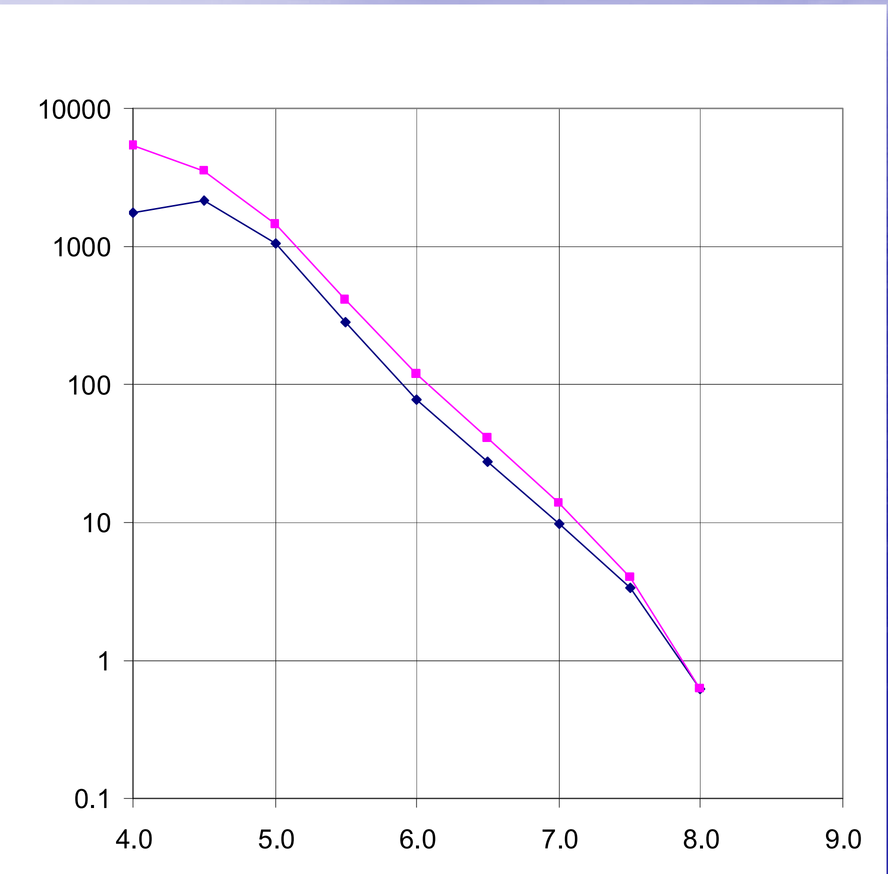
Distribution of earthquakes in Time:

Global Number of Earthquakes vs. Time



Distribution of earthquake size:

Gutenberg-Richter relation



- Averaged over a large territory and time the number of earthquakes equal or above certain magnitude, N(M) scales as

$$\log_{10}N(M) = A + B\times(8 - M)$$

This general law of similarity establishes the scaling of earthquake sizes in a given space time volume …but gives no explanation to the question how the number, N, changes when you zoom the analysis to a smaller size part of this volume.

The answer is not obvious at all.

Generalization of the G-R relation

$$\log_{10}N = A + B\cdot(5 - M) + C\cdot\log_{10}L$$

where $N = N(M, L)$ is the expected annual number of earthquakes with magnitude M in a seismic prone area of linear dimension L.

The first results (*Kossobokov and Mazhkenov, 1988*)

A simple box counting method tested successfully on artificial catalogs with prefixed A, B, and C, then applied to a dozen of selected seismic regions from the hemispheres of the Earth (*global scale*) down to a certain intersection of seismically active faults (*local scale*).

12 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

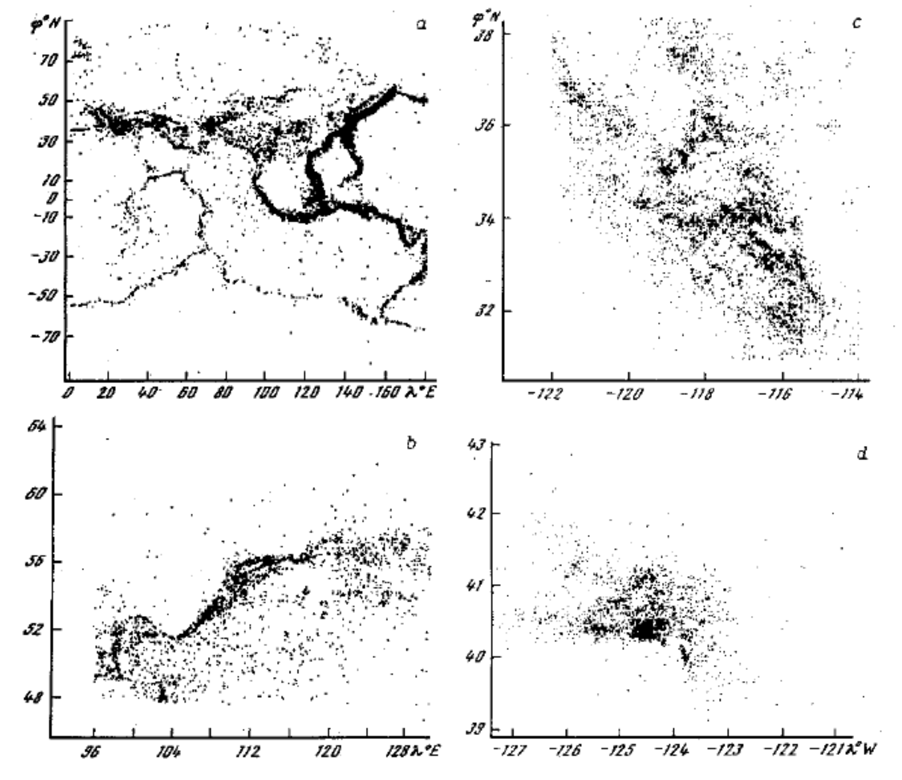


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

14 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

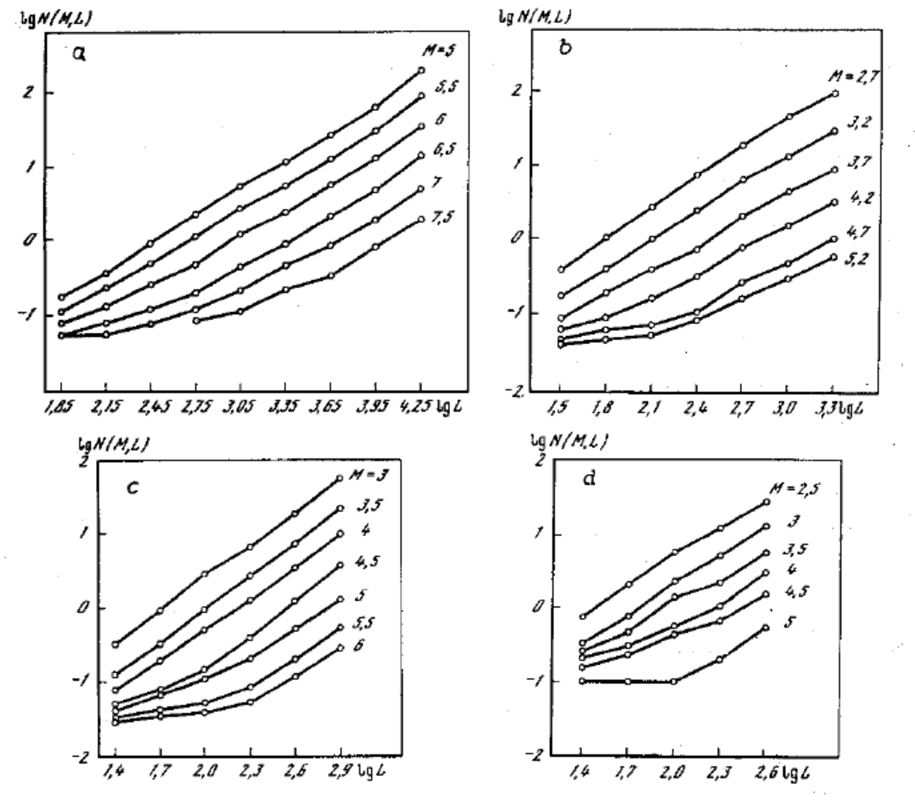
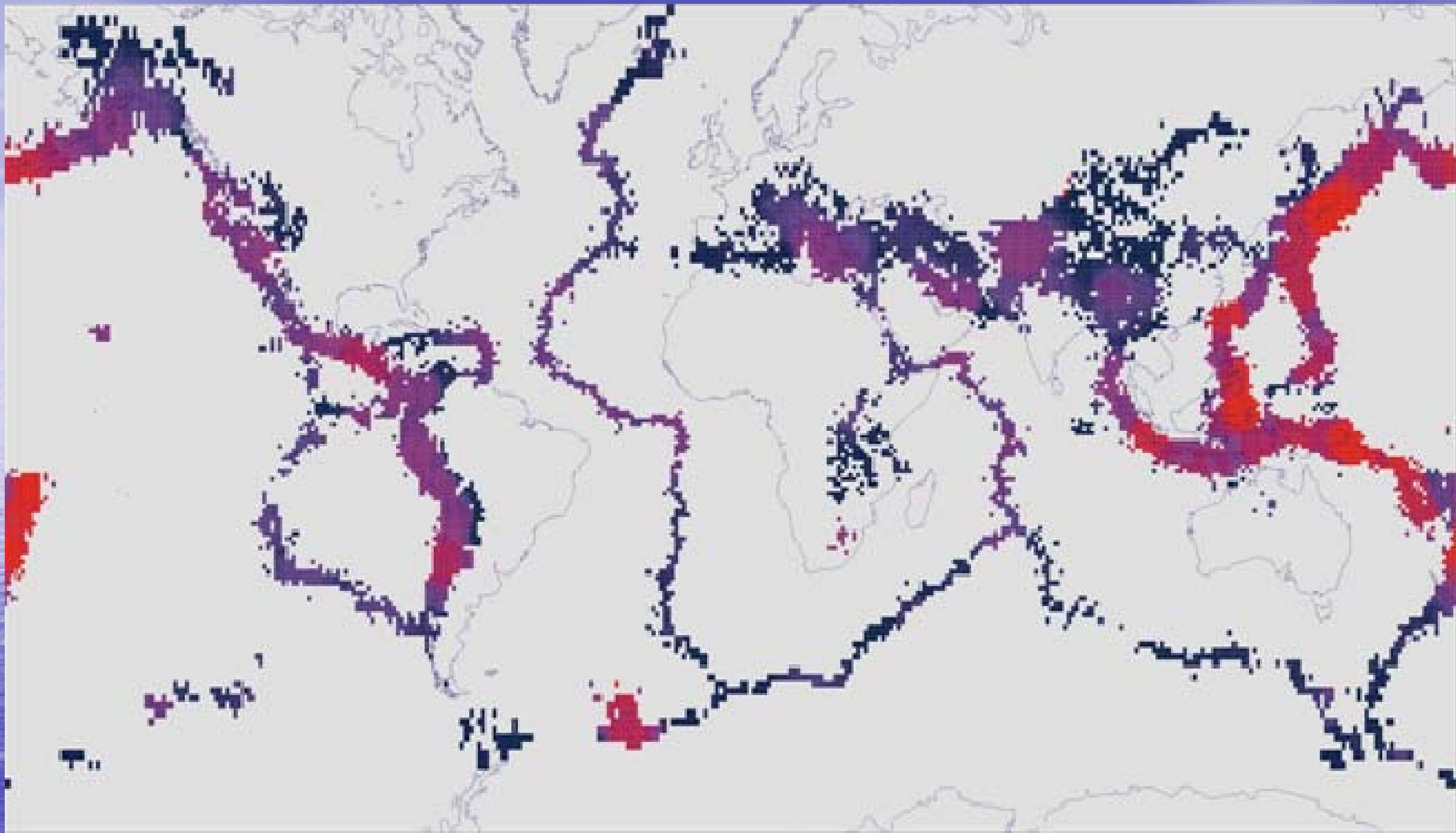


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

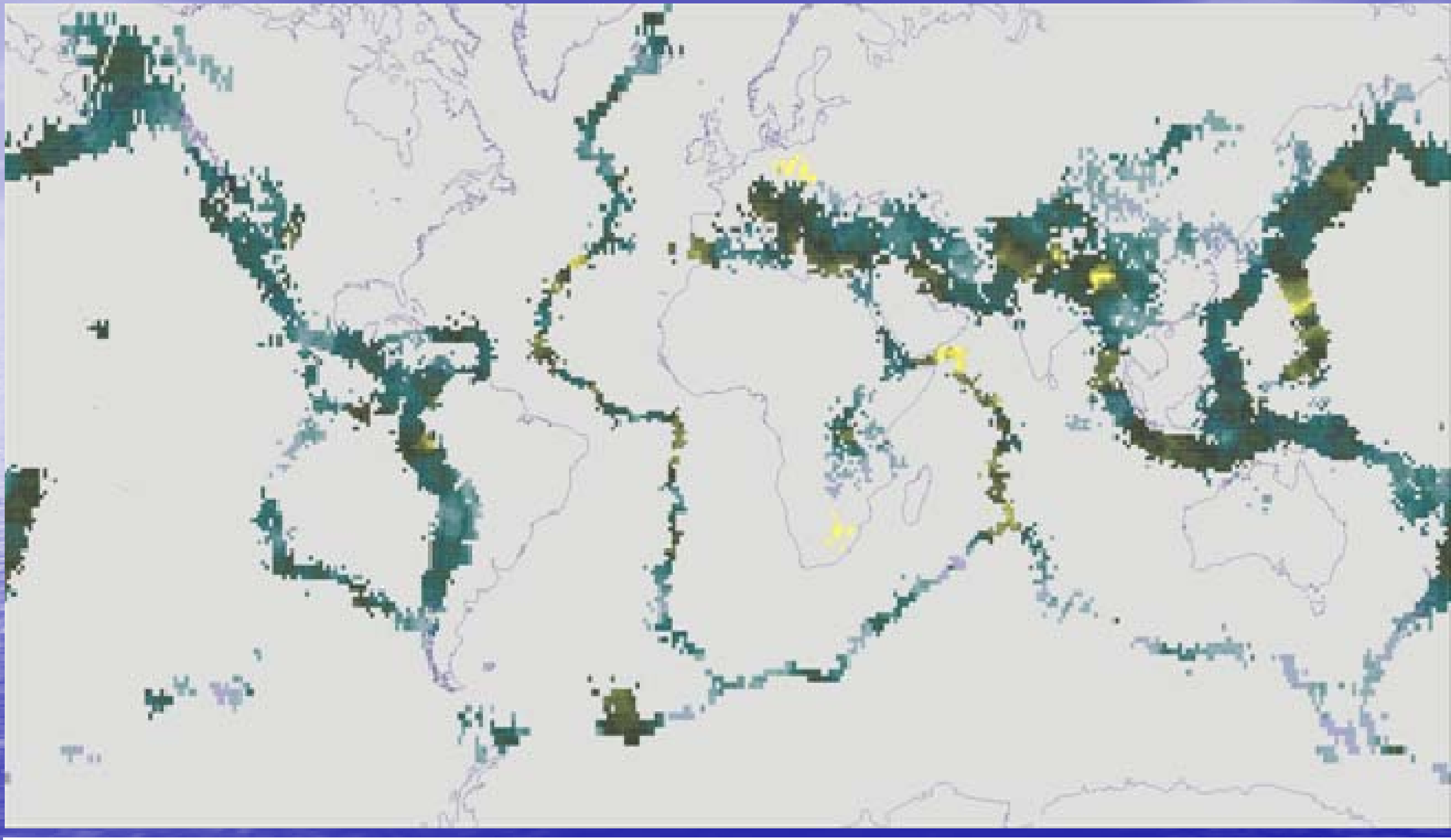
The Global Seismic Hazard map: Coefficient A



Logarithm of recurrence rate ***A***

year^{-1}

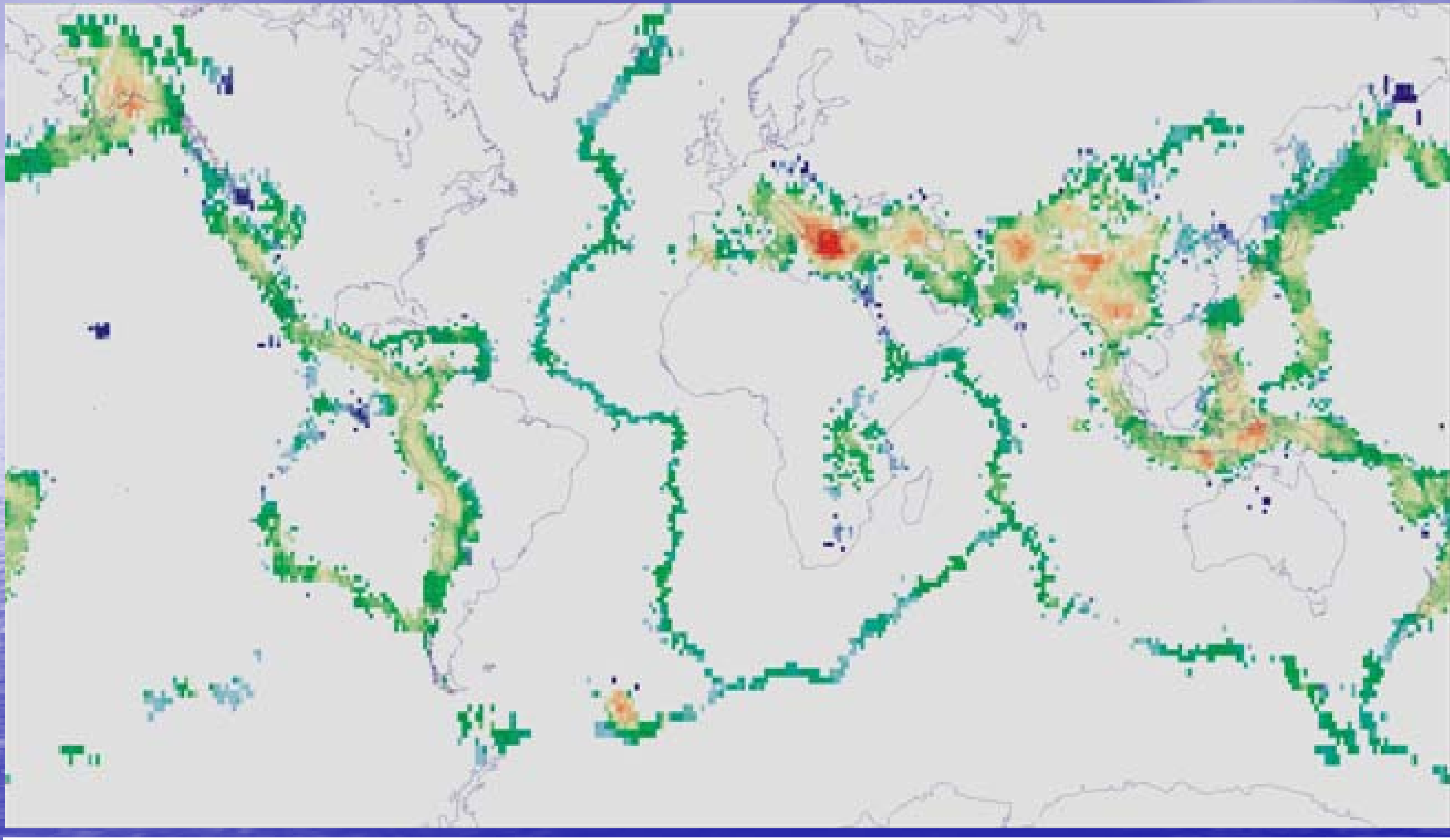
The Global Seismic Hazard map: Coefficient B



Magnitude balance relation ***B***

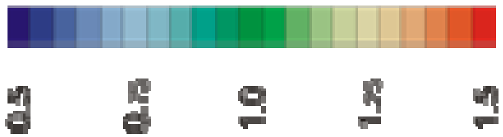
(magnitude unit)$^{-1}$

The Global Seismic Hazard map: Coefficient C



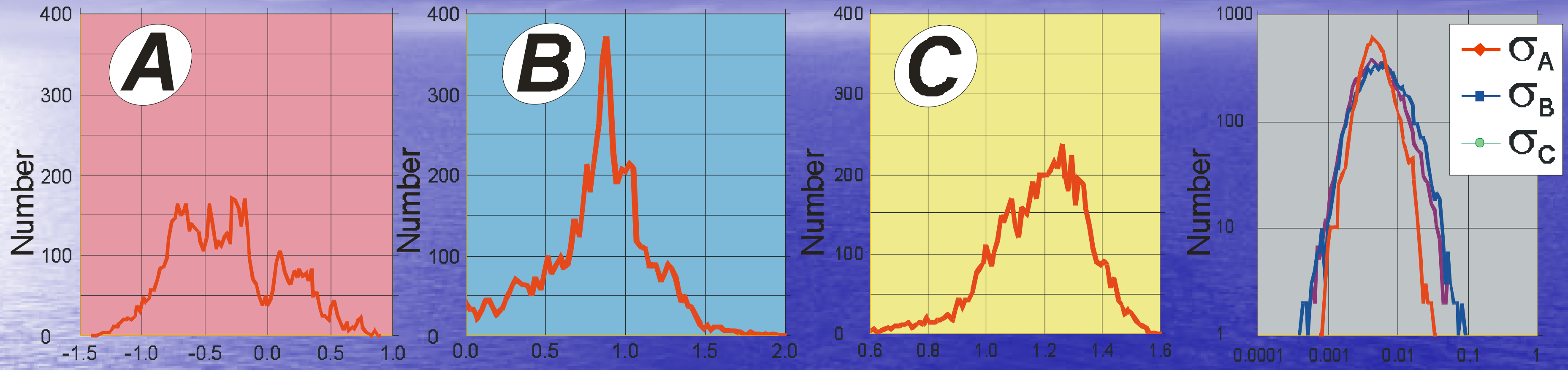
Fractal dimension of seismic locus

C



dimensionless

Histograms of A, B, C and σ's



- Note: The histograms of the coefficient value errors, σ's, (given in logarithmic scales here) suggest high degree of overall agreement with the assumption of self-similarity used in the computations.

Thus, confirming the Unified Scaling Law for earthquakes.

Recurrence of earthquakes

The recurrence of earthquakes in a seismic region, for a wide range of magnitudes and sizes, can be characterized with the following law:

$$\text{Log } N(M,L) = A + B\cdot(5 - M) + C\cdot\text{Log } L,$$

where N(M,L) is the expected annual number of main shocks of magnitude M within an area of liner size L.

For a wide range of seismic activity, A, the balance between magnitude ranges, B, varies mainly from 0.6 to 1.1, while the fractal dimension, C, changes from under 1 to above 1.4.

An estimate of earthquake recurrence rate per square km depends on the size of the territory that is used for averaging and may differ from the real one dramatically when rescaled in traditional way to the area of interest.

The Unified Scaling Law for Earthquakes has serious implications for estimation of seismic hazard, for the Global Seismic Risk Assessment, as well as for earthquake prediction.

Direct implications for assessing seismic hazard at a given location (e.g., in a mega city)

Our estimates for Los Angeles (SCSN data, 1984-2001) -

$$A = -1.28; \quad B = 0.95; \quad C = 1.21 \ (\sigma_{total} = 0.035)$$

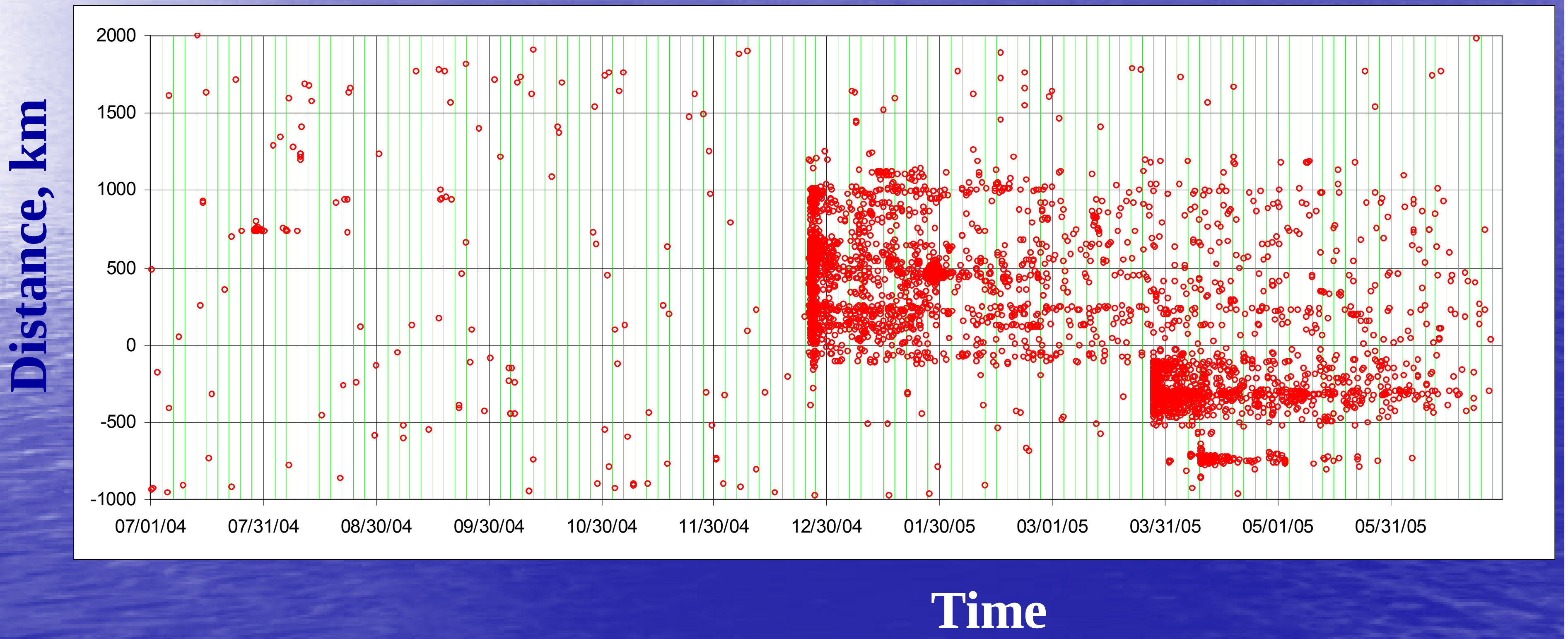
- imply a traditional assessment of recurrence of a large earthquake in Los Angeles, i.e., an area with L about 40 km, from data on the entire southern California, i.e., an area with L about 400 km, being underestimated by a factor of

$$10^{2} / 10^{1.21} = 10^{0.79} > 6 \ !$$

Similarly, underestimation is about a factor of 8 for Petropavlovsk (Kamchatka; A = 0.12, B = 0.86, C =1.26, σ_{total} = 0.04), about a factor of 10 for Irkutsk (Lake Baikal; A = -1.51, B = 0.88, C =1.38, σ_{total} = 0.03), etc.

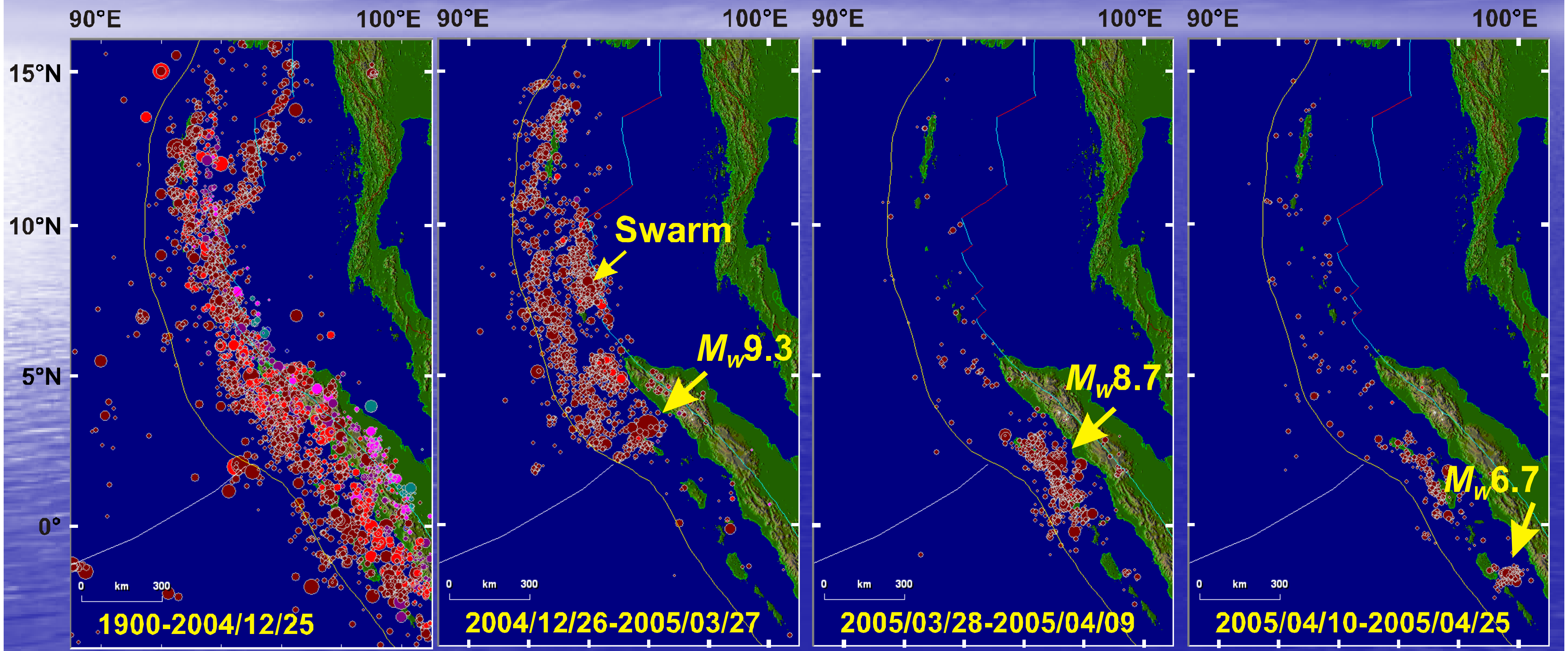
Distribution of earthquakes in Space and Time:

Sumatra-Andaman region



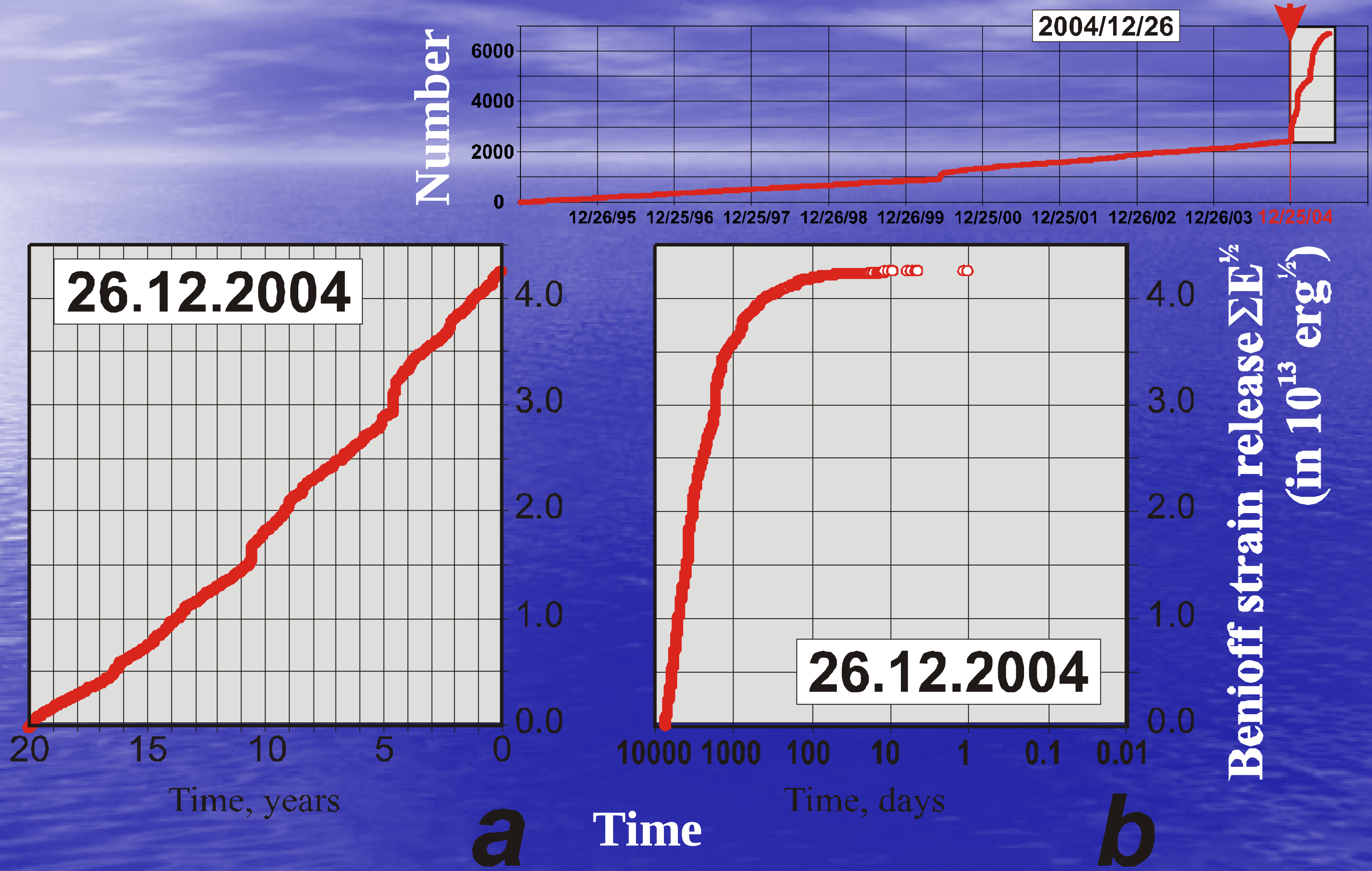
Distribution of earthquakes in Space and Time:

Clustering and cascades



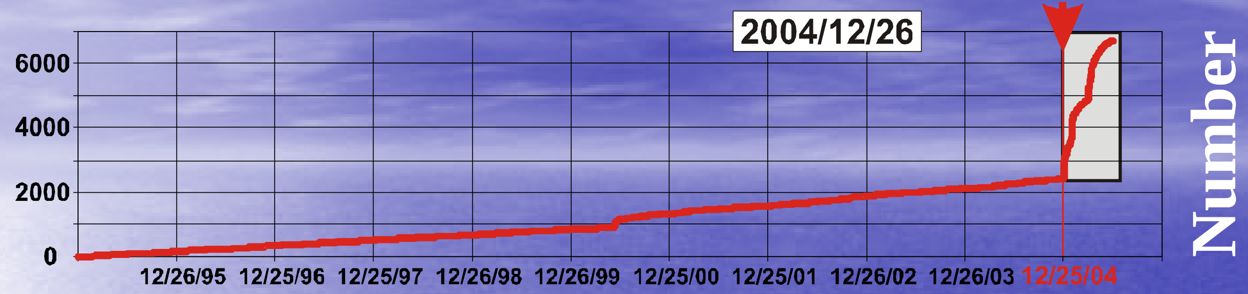
Distribution of earthquakes in Space and Time:

Clustering and cascades



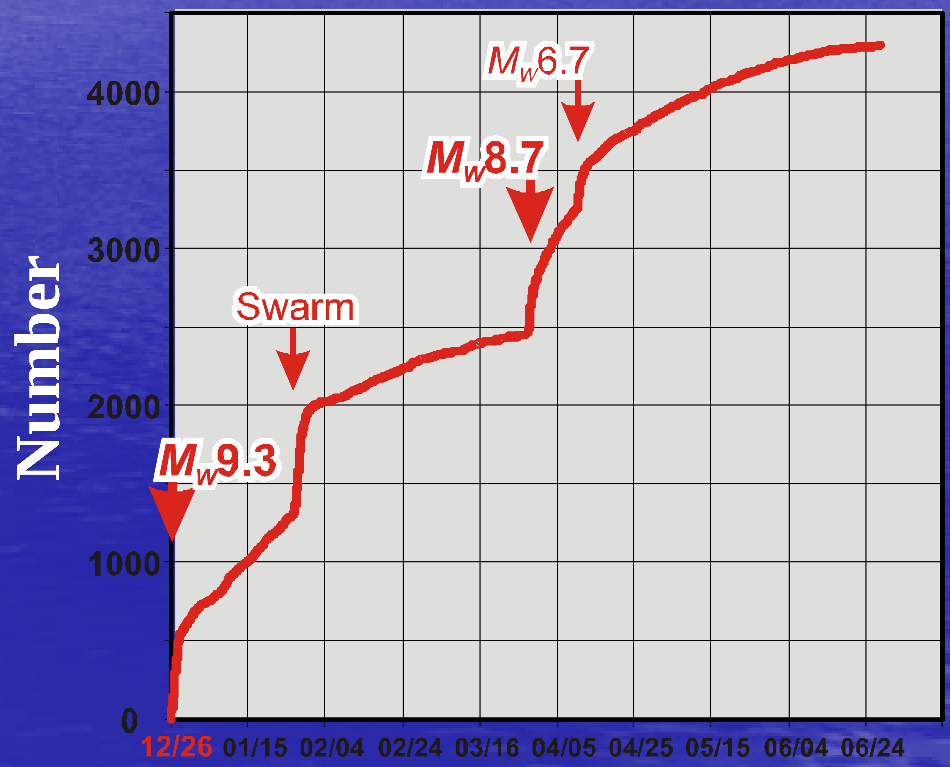
Distribution of earthquakes in Space and Time:

Clustering and cascades



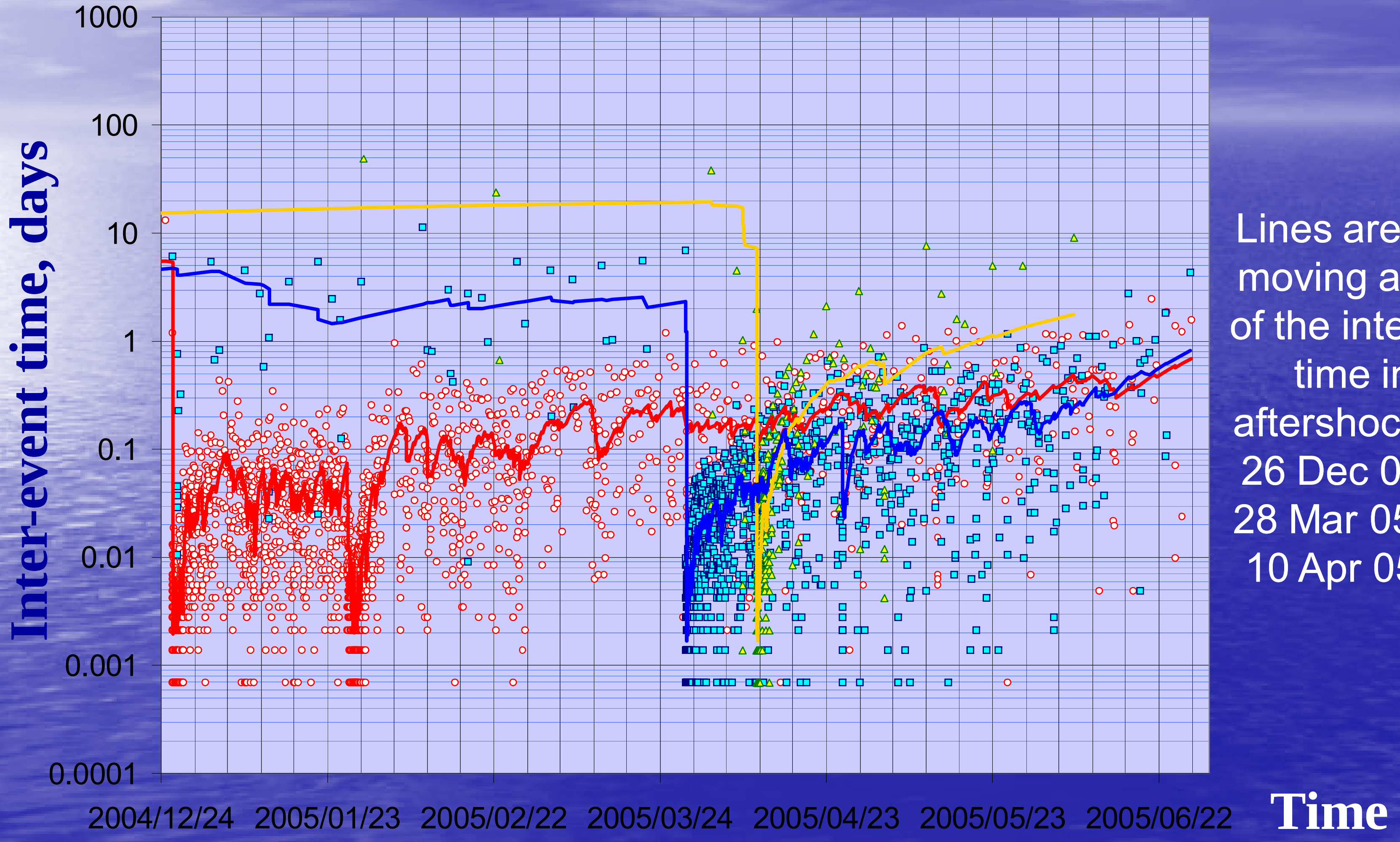
The rate of aftershocks did change in a step-wise manner from 10 (magnitude 4 or larger quakes) per hour to 1.1 per hour until the swarm of 25-27 January, which burst more than 500 events.

Then the rate has drop to about 11 per day during February, then drop again to 6 per day till 28 March 2005 Nias Mw8.7 earthquake.



Distribution of earthquakes in Space and Time:

Clustering and cascades

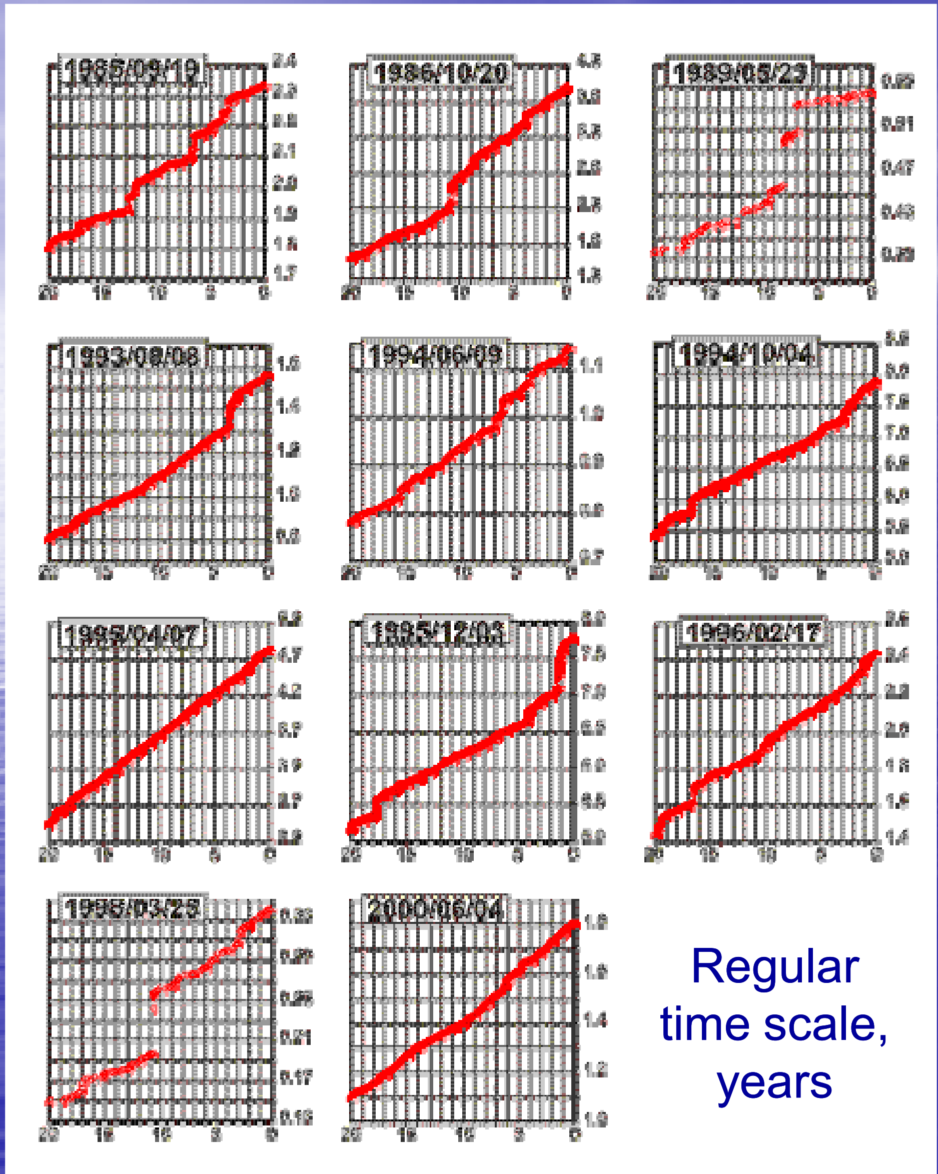


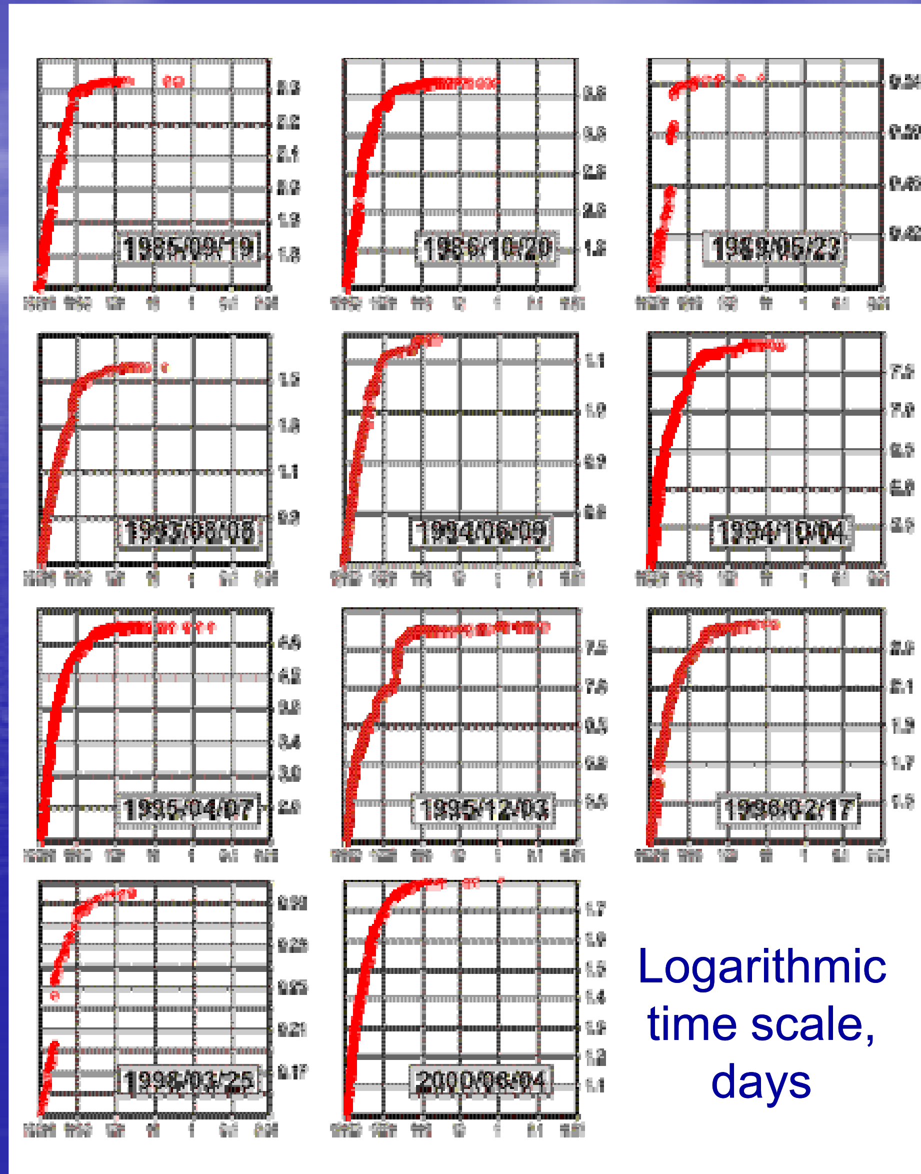
Lines are 20 per moving average of the inter-event time in an aftershock zone:
26 Dec 04 (red)
28 Mar 05 (blue)
10 Apr 05 (yellow)

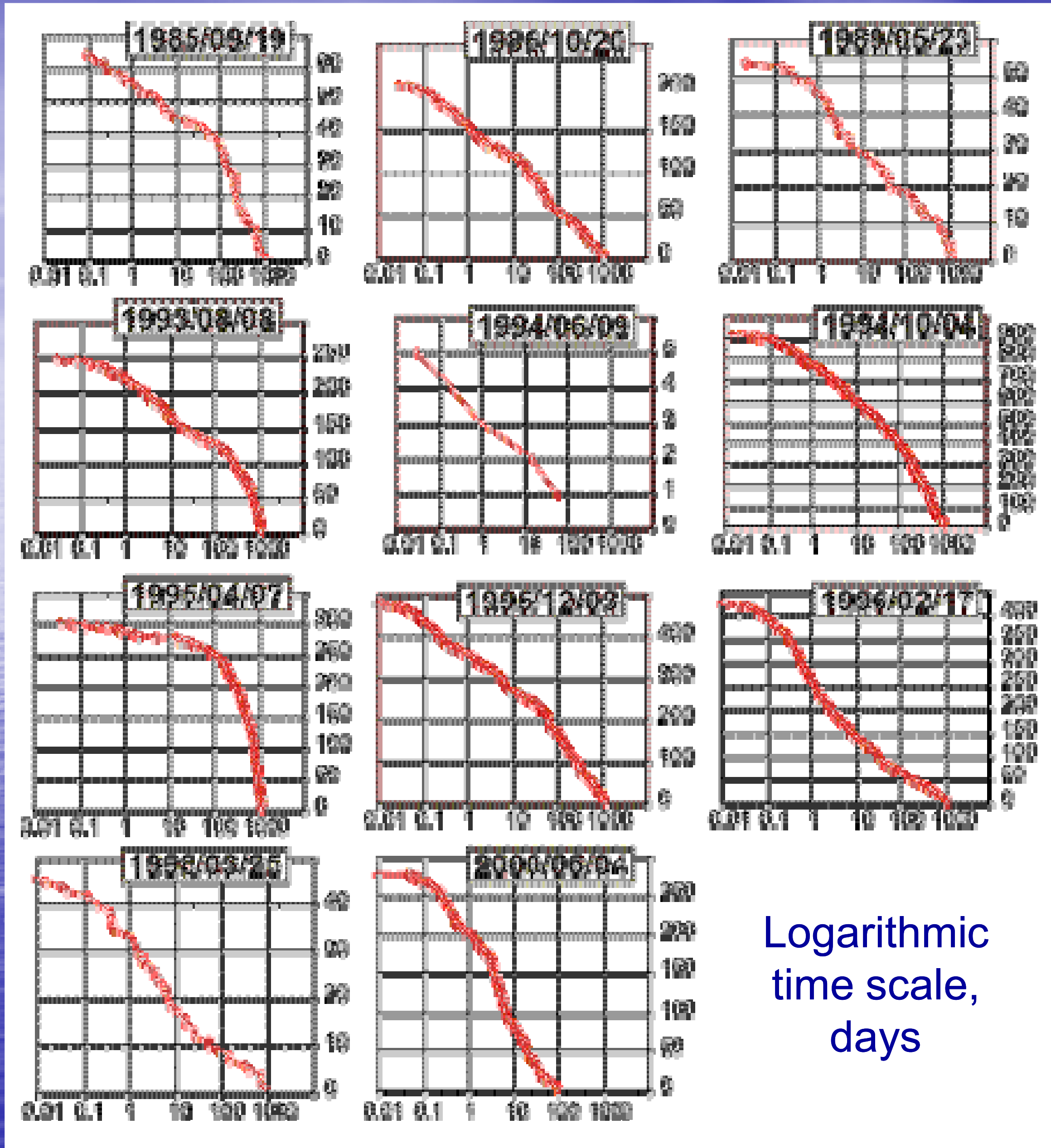
Catalogs of earthquakes make possible to study systematically seismic variability in space and time

- Earthquakes evidently cascade into aftershocks that re-adjust the hierarchical system of blocks-and-faults in the locality of the main shock rupture.
- Systematic analysis shows less evident inverse cascade in seismic activity prior to the recent greatest earthquakes.

Benioff strain release $\Sigma E^{1/2}$ (10^{12} erg$^{1/2}$) 20 years before the great shocks

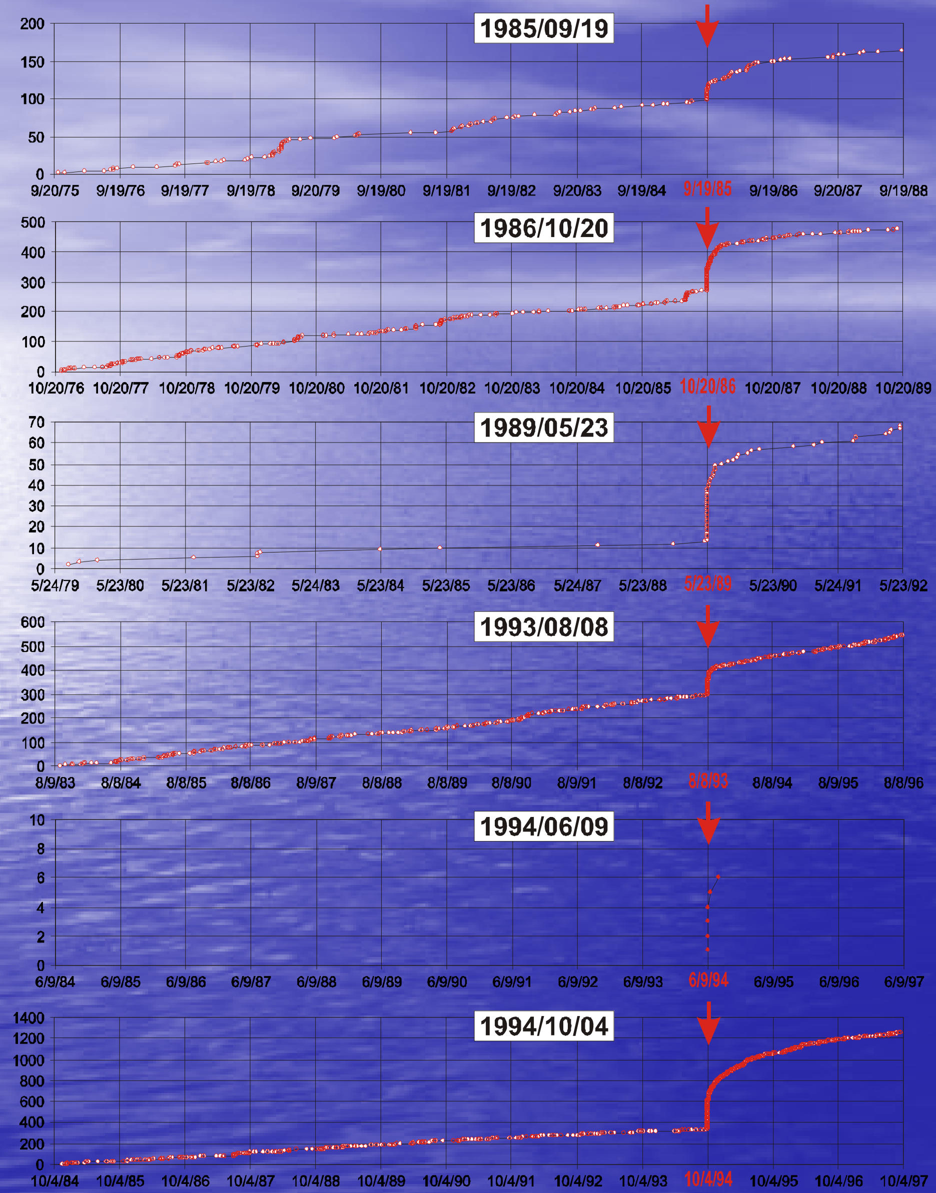


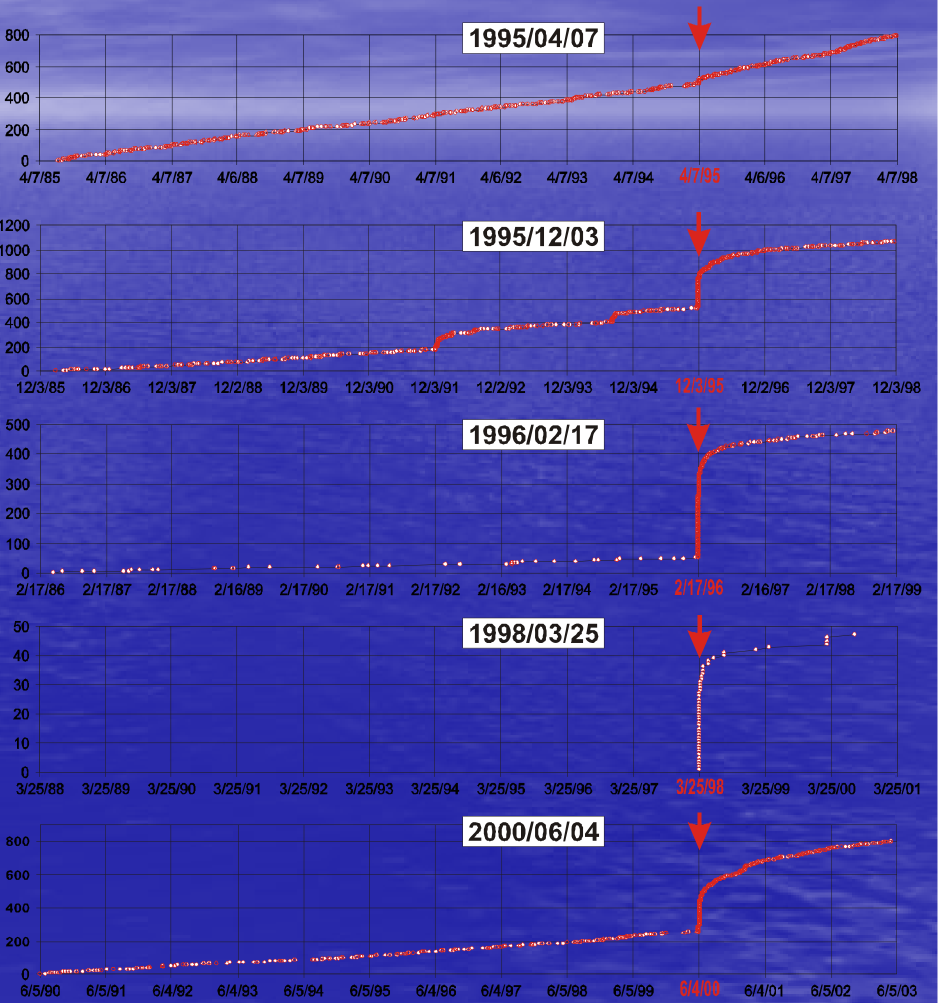




The number of aftershocks in the period from time τ to 3 years after the great shock

Activity in 10 years before and 3 years after the great shocks





Aftershock sequences of the great shocks (*summary*)

Date	Number, 100 days	Number, 3 years	Aftershocks decay 100 d	Aftershocks decay 3 y	Relaxation time, years
1985/09/19	29	65	Omori Law	Modified OL 3	284 days
1986/10/20	151	205	Modified OL 3	Modified OL 3	100 days, =1.5
1989/05/23	36	54	Omori Law	Modified OL 2	1.3 years, >3
1993/08/08	121	247	Modified OL 2	Modified OL 3	65 days, >1.5
1994/06/09	5	5	Modified OL 2	-	-
1994/10/04	515	919	Modified OL 2	Modified OL 3	2 years, >2.5
1995/04/07	52	302	Modified OL 2	Modified OL 2	14 days, >2
1995/12/03	311	483	Modified OL 2	Modified OL 3	1 year
1996/02/17	357	427	Modified OL 2	Modified OL 2	2 years, >2.5
1998/03/25	38	47	Omori Law	Modified OL 2	140 days
2000/06/04	278	799	Modified OL 2	Modified OL 2	2 years, >1.7

Combination of inverse and direct seismic cascades

- Apparently earthquakes display a phase transition of the system of blocks-and-faults from one steady stable seismic regime to another one.

Conclusions

- Catalogs evidence clear patterns in space-time-energy distribution of earthquakes, as well as consecutive stages of their inverse cascading to main shocks and direct cascading of aftershocks.
- The first may reflect coalescence of instabilities at the approach, while the second may indicate readjustment of a complex system of blocks-and-faults in a new state after a catastrophe.
- Despite evident difficulties of compilation in the real time, seismologists have no luxury of postponing usage of the existing earthquake catalogs to the benefit of population living in seismic regions.

Are earthquakes predictable?

Yes!

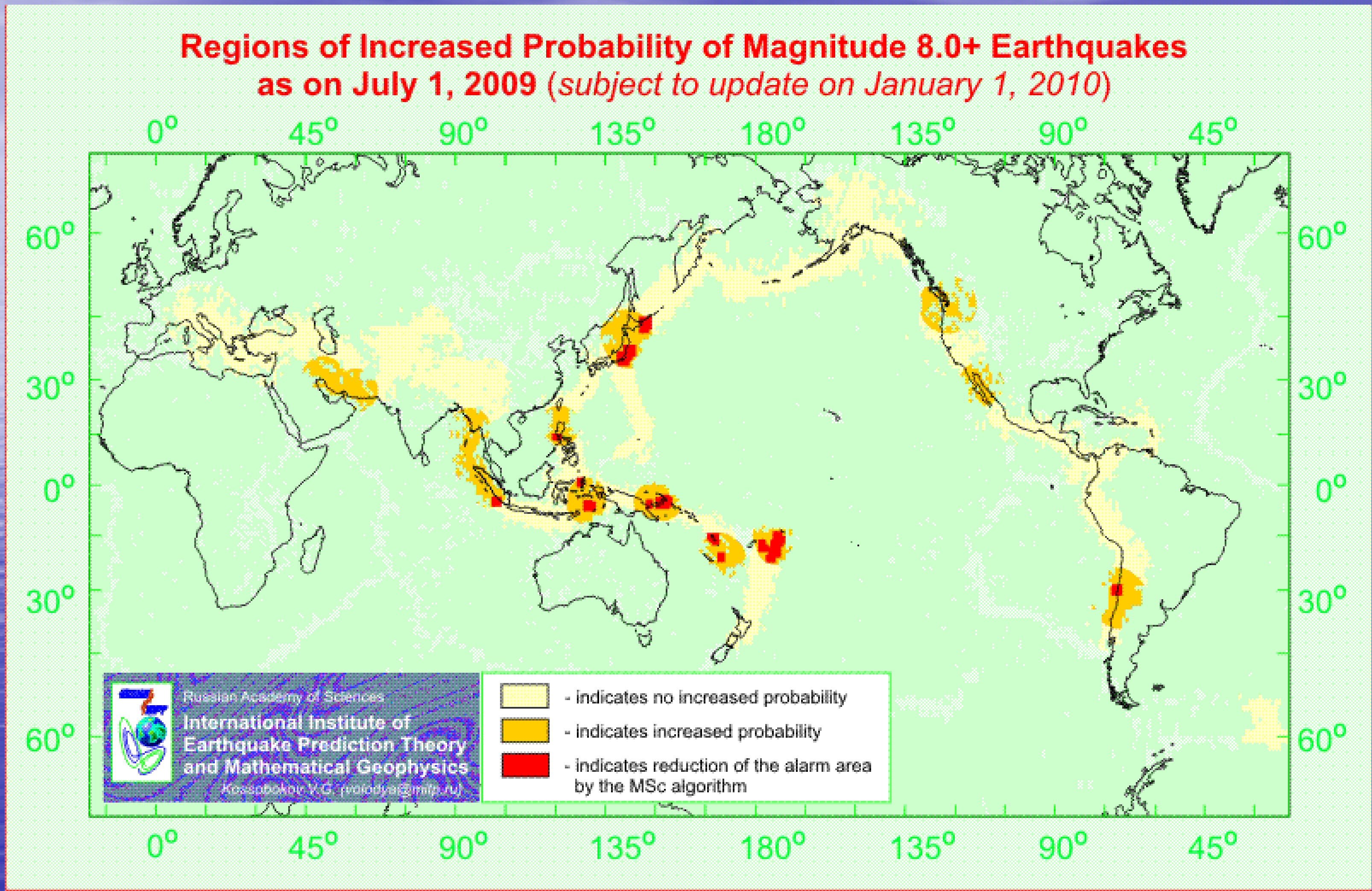
Real-time prediction of the world largest earthquakes: An experiment started in 1992 with a publication of

[Healy, J. H., V. G. Kossobokov, and J. W. Dewey. A test to evaluate the earthquake prediction algorithm, M8, *U.S. Geol. Surv. Open-File Report* **92-401**, 23 p. with 6 Appendices, 1992]

is in progress.

Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not easily accessed, although available on the web-pages of restricted access provided to about 150 members of the Mailing List.

Real-time prediction of the world largest earthquakes
(http://www.mitp.ru)

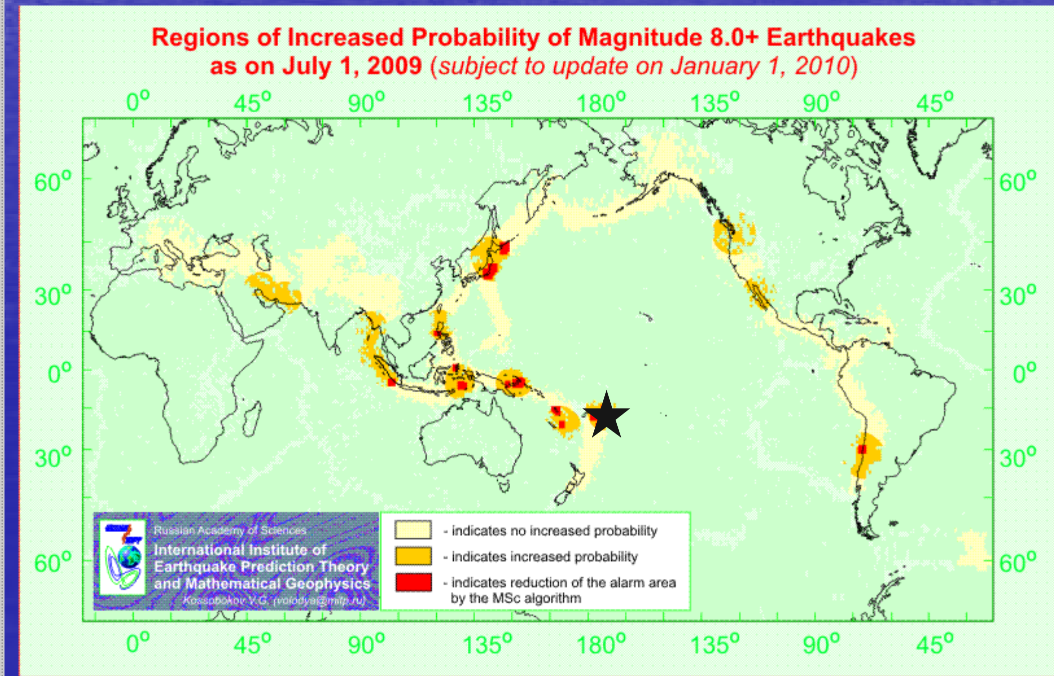


Real-time prediction of the world largest earthquakes

(http://www.mitp.ru)

Magnitude 8.0 - SAMOA ISLANDS REGION

2009 September 29 17:48:10 UTC



Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0+.

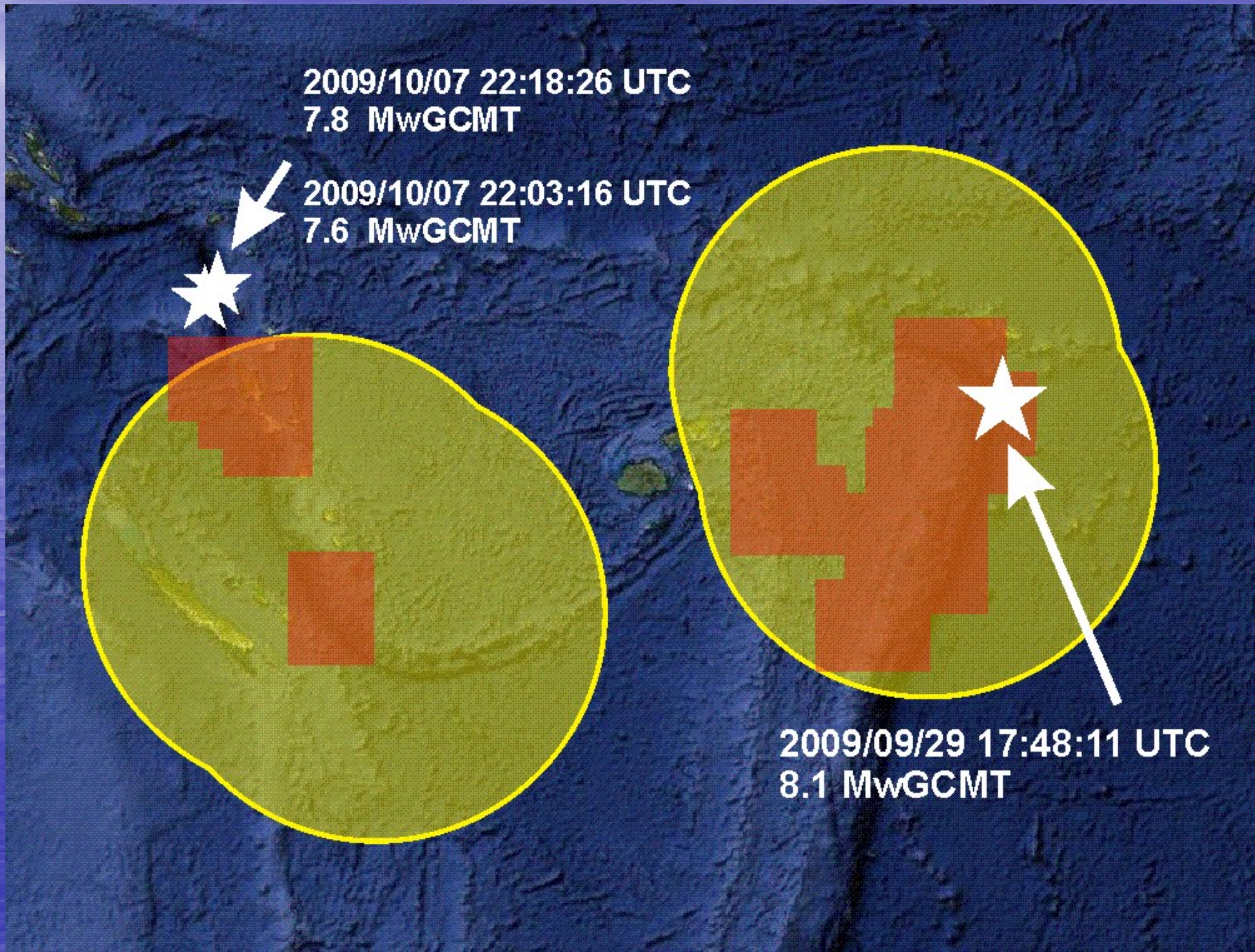
Test period	Target earthquakes			Measure of alarms, %		Confidence level, %	
	Total	Predicted by					
		M8	M8-MSc	M8	M8-MSc	M8	M8-MSc
1985-present	**19**	**14**	**10**	**33.16**	**16.89**	**99.96**	**99.96**
1992-present	**17**	**12**	**8**	**30.09**	**15.04**	**99.93**	**99.82**

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

To drive the achieved confidence level below 95%, the Test should encounter nine failures-to-predict in a row.

Real-time prediction of the world largest earthquakes

(http://www.mitp.ru)



Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 7.5 or more.

Test period	Target earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, % M8	Measure of alarms, % M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	65	38	16	28.73	9.32	99.99	99.98
1992-present	53	28	10	23.14	8.31	99.99	98.89

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

To drive the achieved confidence level below 95%, the Test should encounter 15(!) failures-to-predict in a row.

Real-time prediction of the world largest earthquakes

(http://www.mitp.ru)

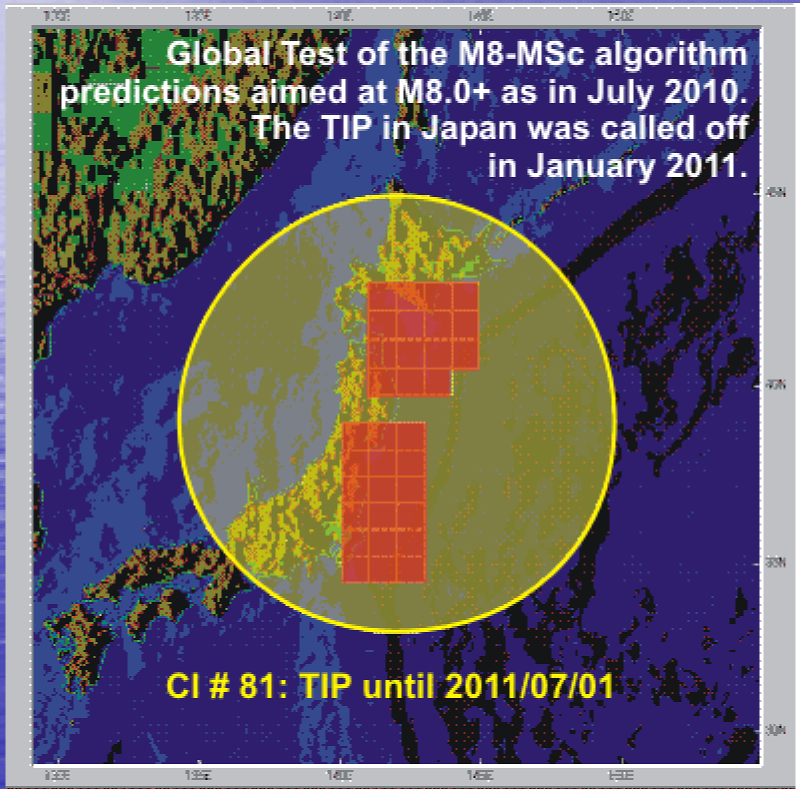
The 27 February 2010 mega-earthquake OFFSHORE MAULE, CHILE has ruptured the 600-km portion of the South American subduction zone, which was recognized (yellow outline) as capable of producing a magnitude M8.0+ event before mid-2012 in the regular 2010a Update. The earthquake epicenter missed the reduced area of alarm (red outline) diagnosed in the second approximation by algorithm MSc.

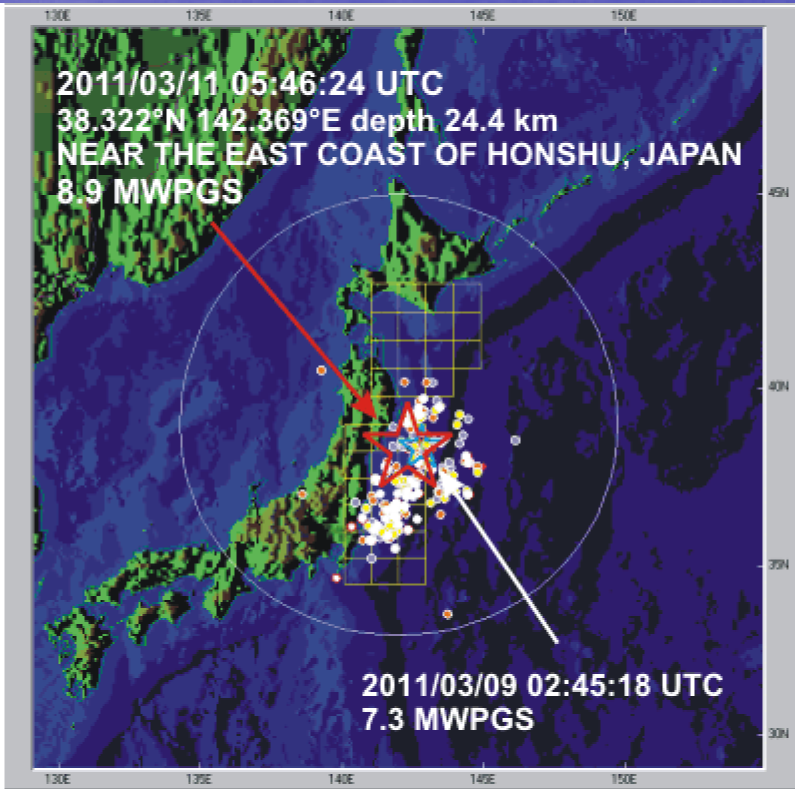
The failure of MSc algorithm is somewhat natural, taking into account the linear extent of the event, which is about a half of the area alerted in the first approximation.

Real-time prediction of the world largest earthquakes

(http://www.mitp.ru)

The 11 March 2011 MwGCMT 9.0 Tōhoku mega-thrust – the 2011 Great East Japan Earthquake





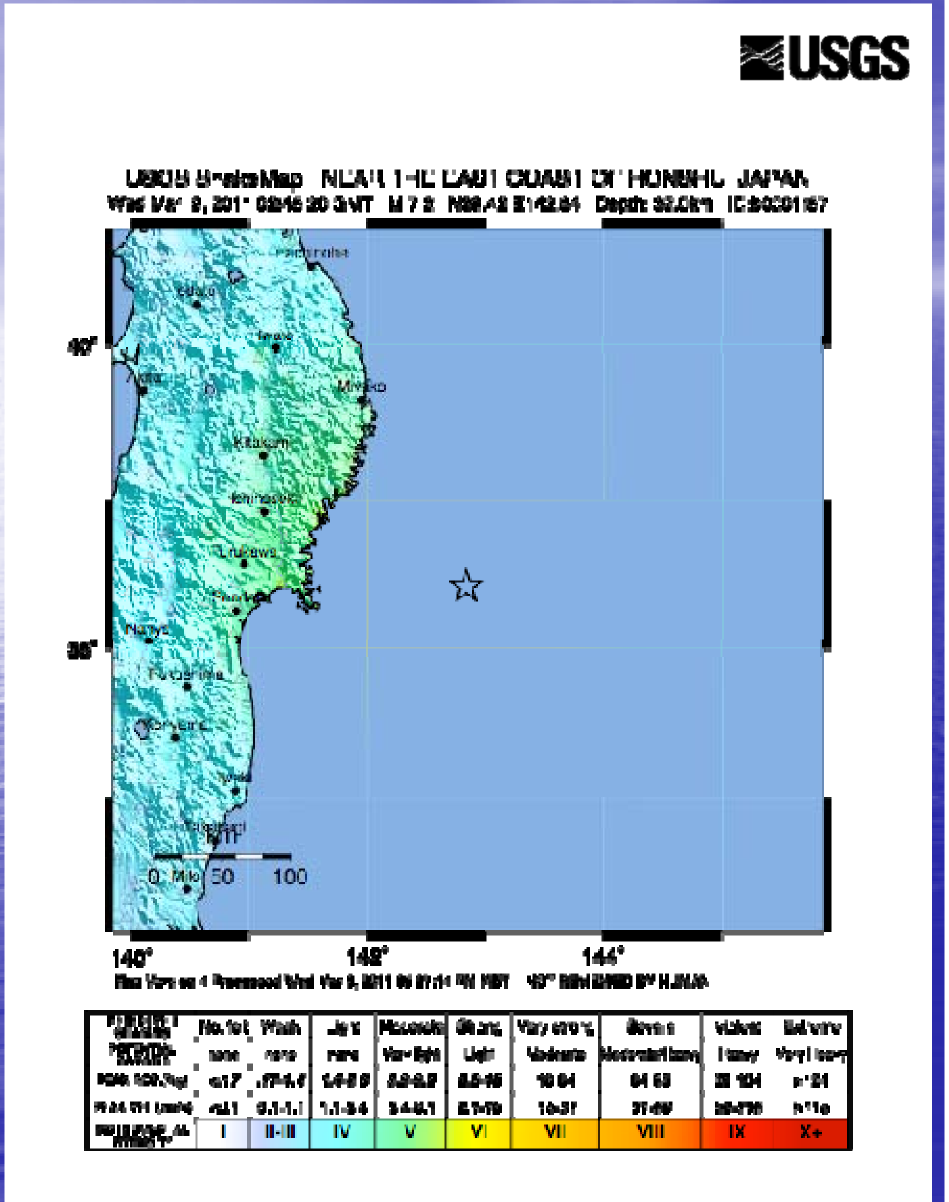
The 2011 earthquake off the Pacific coast of Tōhoku, also known as the 2011 Tōhoku earthquake or the Great East Japan Earthquake

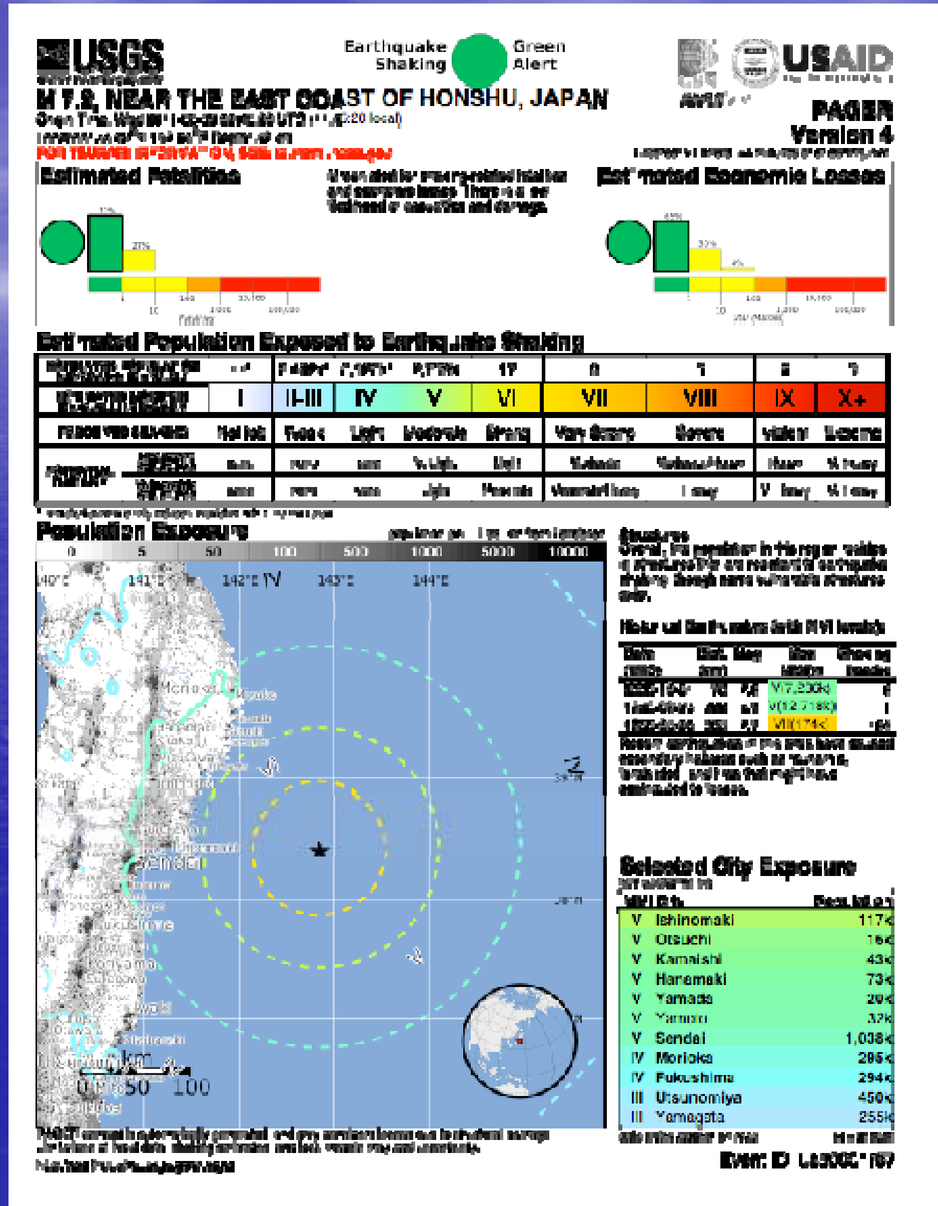
(Japanese: "Eastern Japan Great Earthquake Disaster" - 東日本大震災 - *Higashi Nihon Daishinsai*)

was a magnitude 9.0 (Mw) undersea mega-thrust earthquake off the coast of Japan that occurred at 14:46 JST (05:46 UTC) on Friday, 11 March 2011, with the epicenter approximately 70 km east of the Oshika Peninsula of Tōhoku and the hypocenter at an underwater depth of approximately 32 km. It was the most powerful known earthquake to have hit Japan, and one of the five most powerful earthquakes in the world overall since modern record-keeping began in 1900. It was so powerful the island of Honshu was moved 2.4 m eastward.

The earthquake triggered extremely destructive tsunami waves of up to 40.5 metres in Miyako, Iwate, Tōhoku. In some cases traveling up to 10 km inland. In addition to loss of life and destruction of infrastructure, the tsunami caused a number of nuclear accidents, primarily the level 7 meltdowns at three reactors in the Fukushima I Nuclear Power Plant complex, and the associated evacuation zones affecting hundreds of thousands of residents.

Offshore Honshu, Japan Earthquake, 03/09/2011, Mw 7.2





"Some seismologists are concerned with the following two problems.

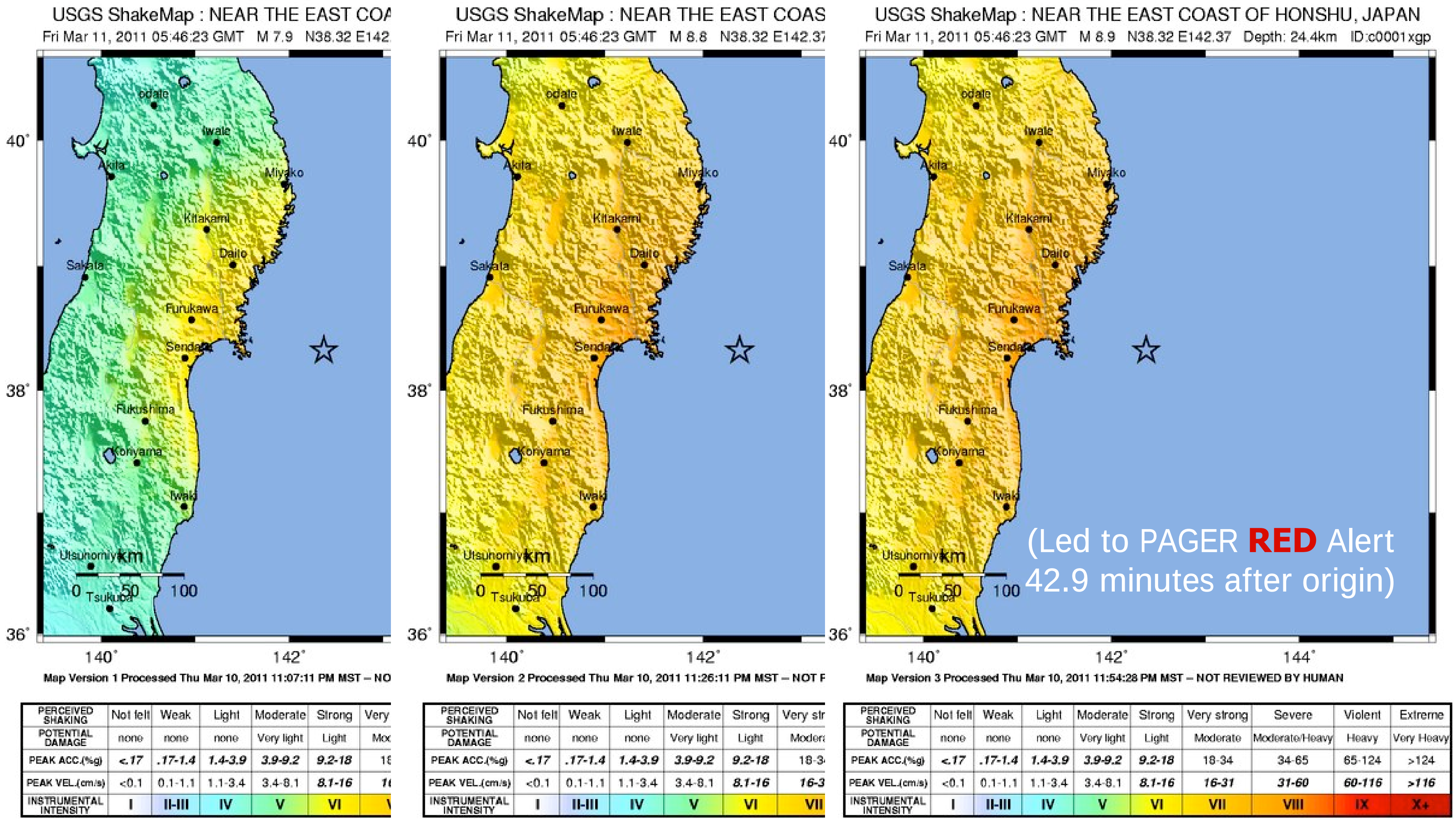
(1) The source region of the M7.5 class "expected" Miyagi-Ken-Oki EQ is 100 km east of the focal region of this EQ. Is this EQ a trigger of the expected one?

(2) In February, four M5 class EQs rocked around the focal region. Are these ones precursors of this M7.3 EQ?"

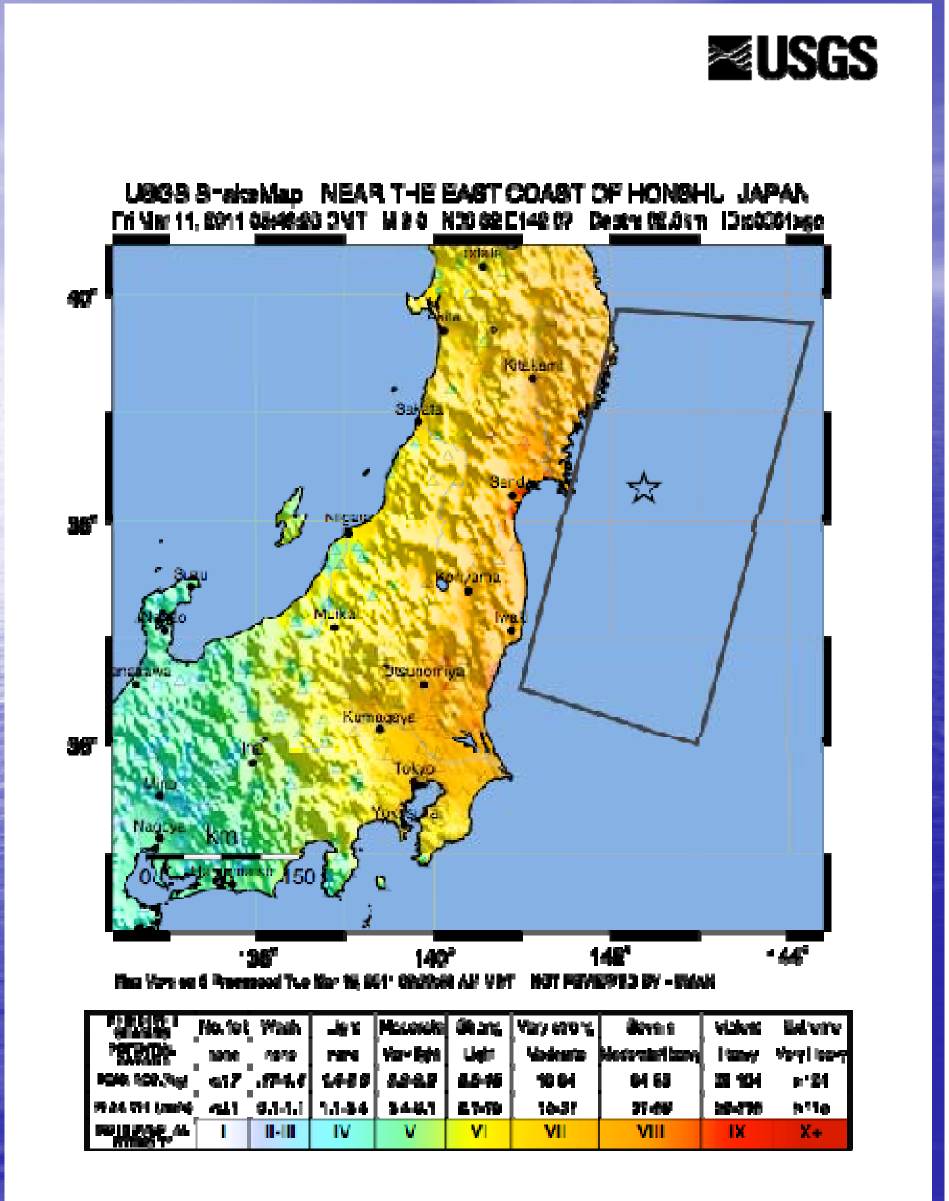
(Takeshi KUDO 工藤 健 kudo@isc.chubu.ac.jp; Thursday, March 10, 2011 09:12)

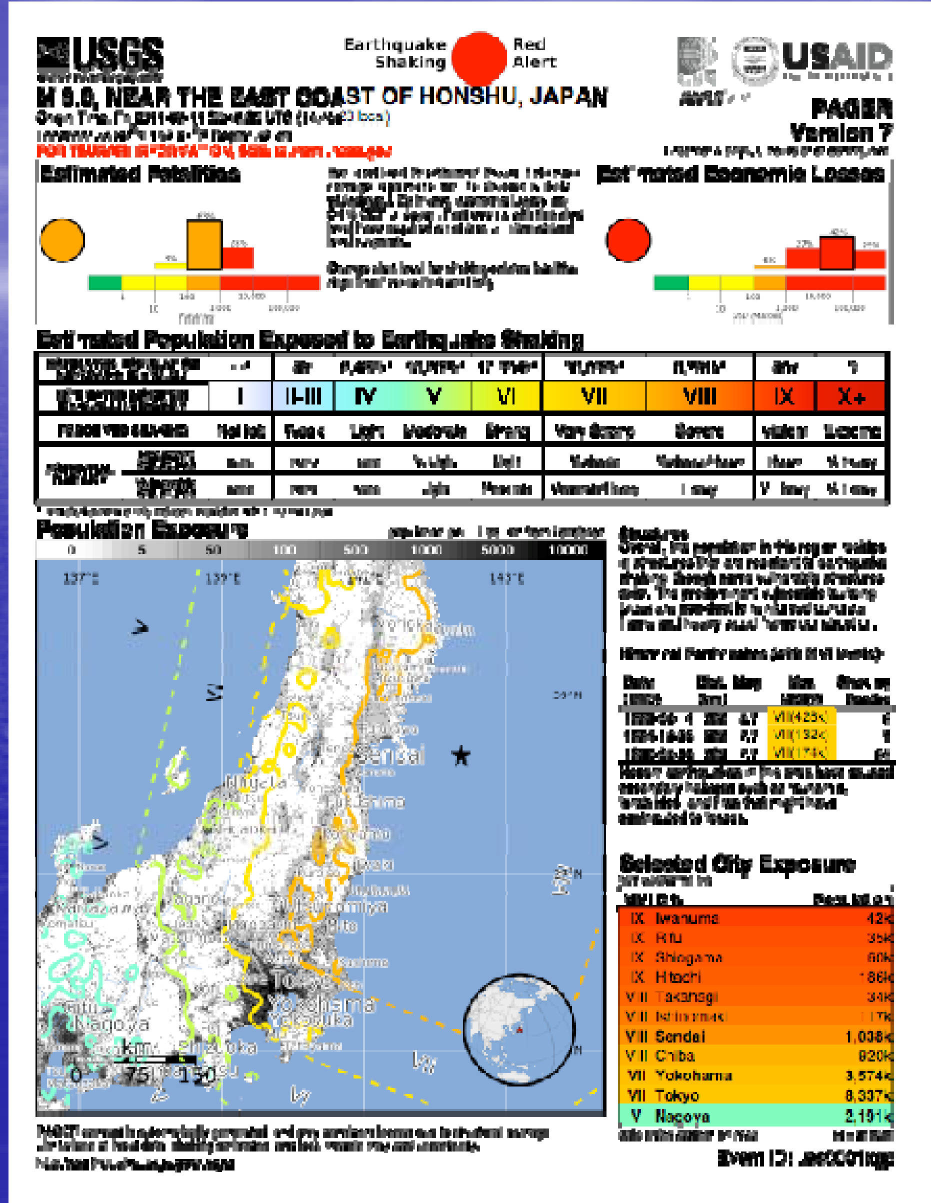
Tohoku, Japan Earthquake: Shake Map Evolution

V1: O.T. +21 min M7.9 V2: O.T. +40 min M8.8 V3: O.T. +1 hr 9 min M8.9



Tohoku, Japan Earthquake, 03/11/2011, Mw 9.0





DISASTER PREPAREDNESS

Japan faces up to failure of its earthquake preparations

Systems for forecasting, early warning and tsunami protection all fell short on 11 March.

BY DAVID CYRANOSKI IN TOKYO

Japan has the world's densest seismometer network, the biggest tsunami barriers and the most extensive earthquake early-warning system. Its population is drilled more rigorously than any other on what to do in case of earthquakes and tsunamis.

Yet this month's magnitude-9 earthquake surprised the country's forecasters. The grossly underestimated tsunami destroyed the world's deepest tsunami barrier and caught people by surprise. And the early-warning system for earthquakes largely failed. What went wrong?

The first problem was the earthquake forecast. Japan's seismic hazard map, the latest version of which was released in March 2009, breaks the offshore area of northeastern Japan into five seismic zones and envisages seven different earthquake scenarios. Each is assigned a probability based on the historical record of earthquakes. The southern Sanriku offshore region, which included the origin of this month's earthquake, was given a 30–40% chance of rupturing in the next 10 years and a 60–70% chance in the next 20 years.

As earthquake forecasting goes, these are very high numbers. "That basically means it could happen any day," says Yoshinori Suzuki of the Earthquake Disaster Reduction Research Division within the science ministry, which coordinates the map-making. But the fault was expected to unleash an earthquake of around magnitude 7.7 — about as large as any in the historical record for the area (see *Nature* **471**, 274; 2011).

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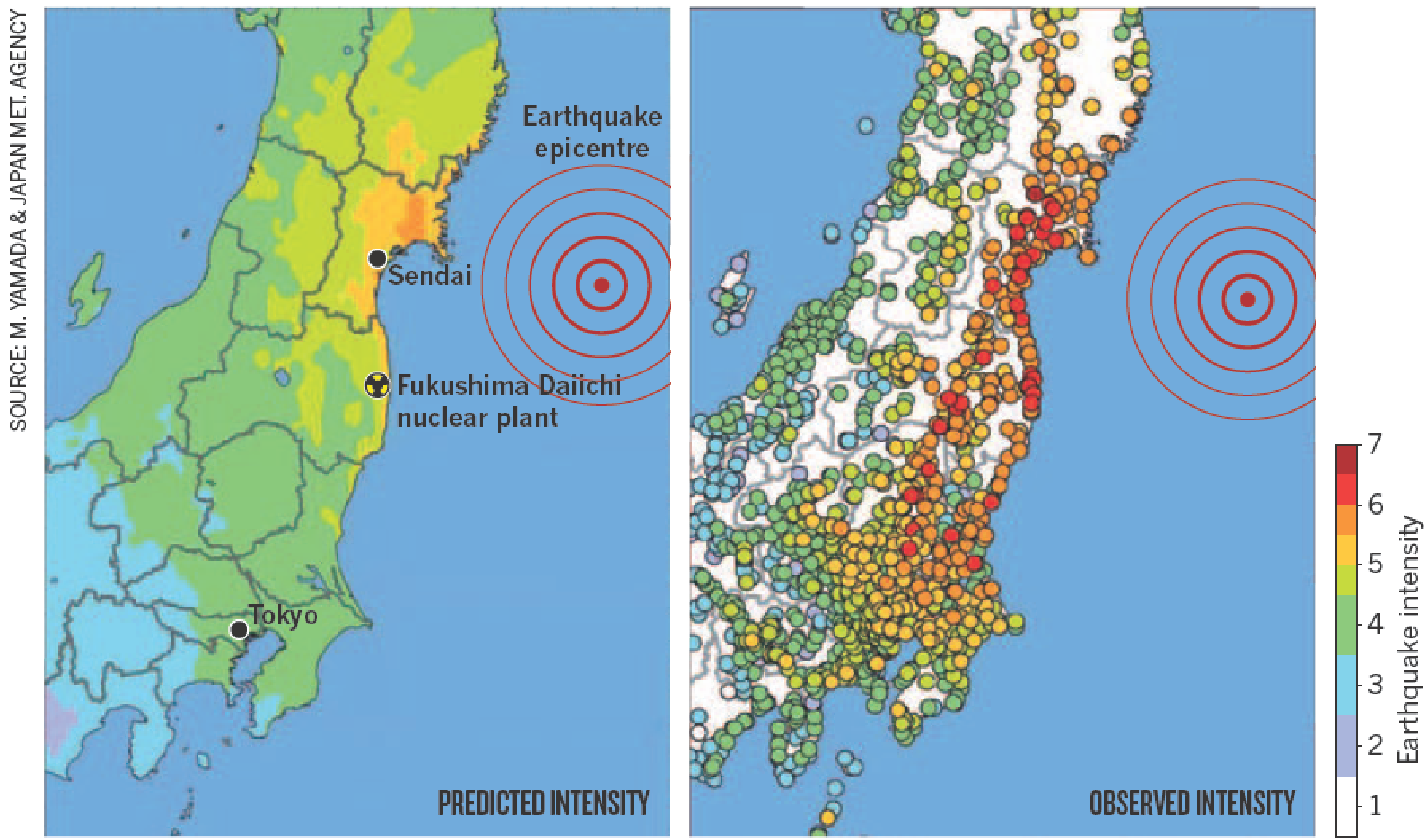
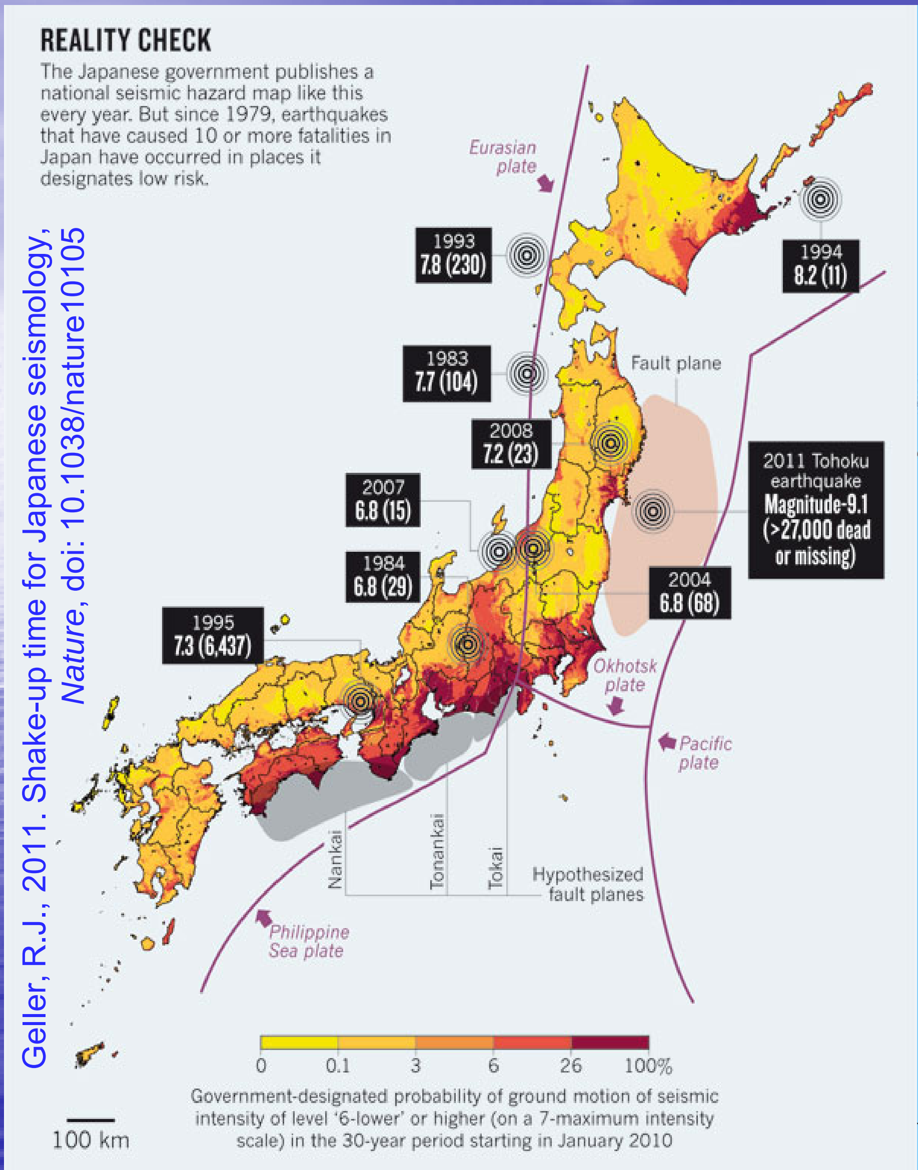
FALSE COMFORT

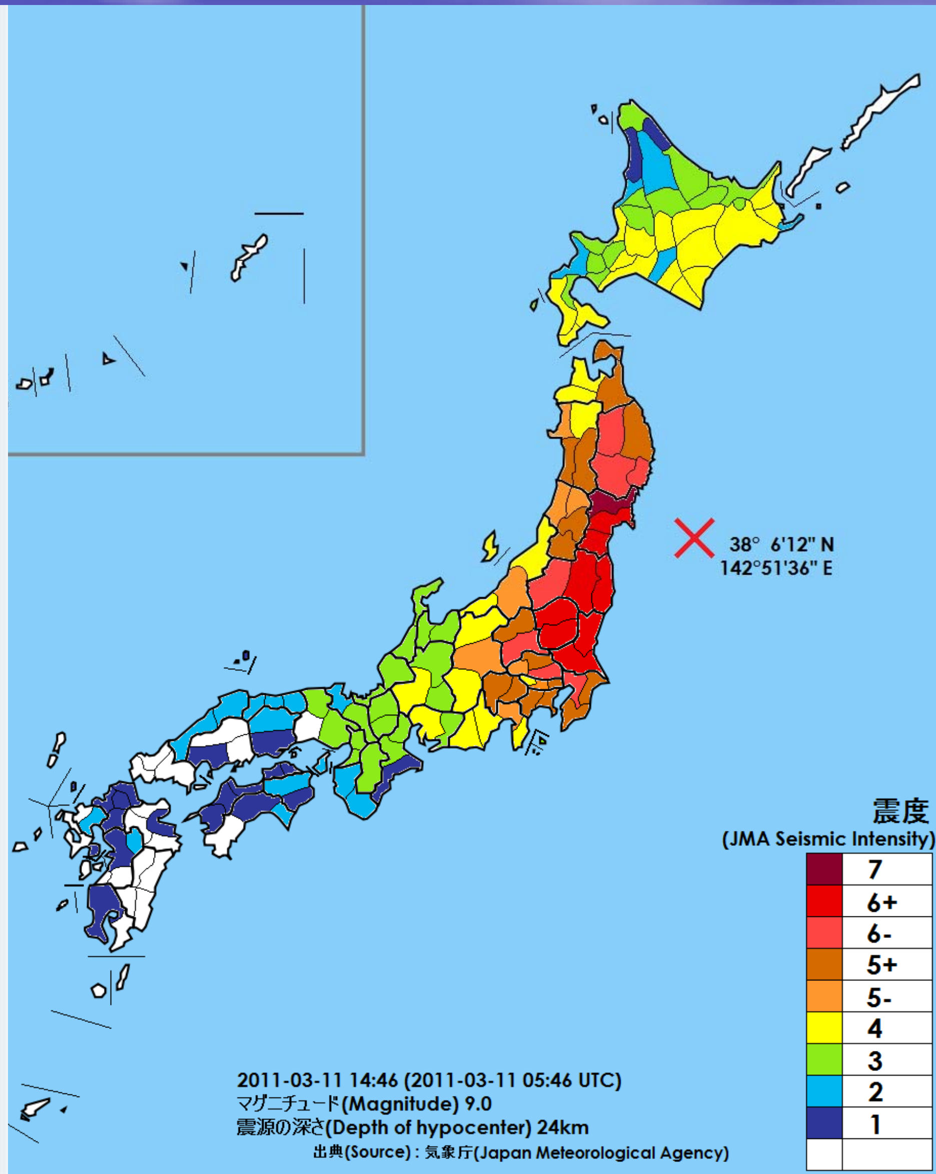
A warning system based on initial seismic signals predicted a limited region of intense shaking. The actual shaking was far more severe and widespread.

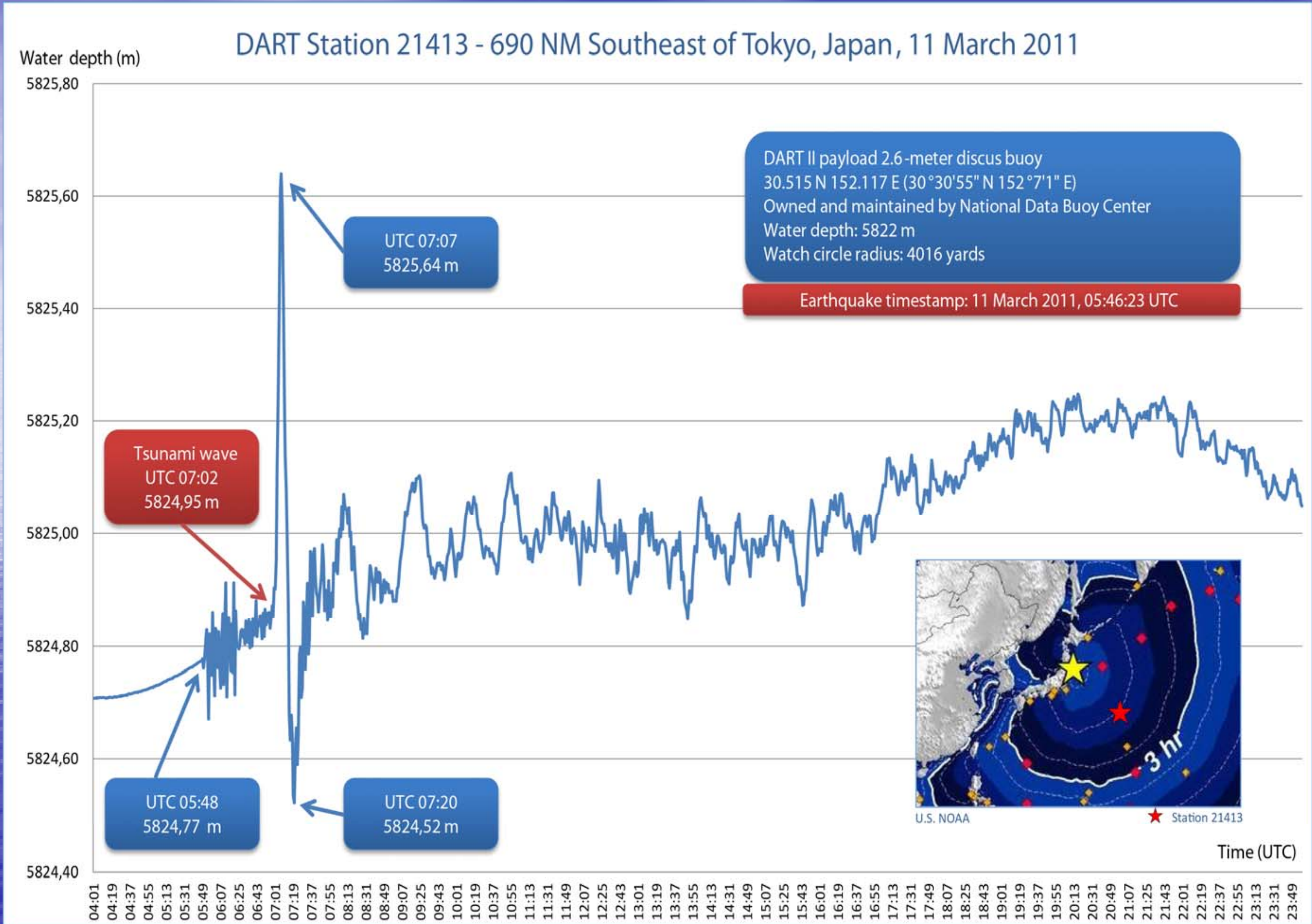


JMA macroseismic intensity

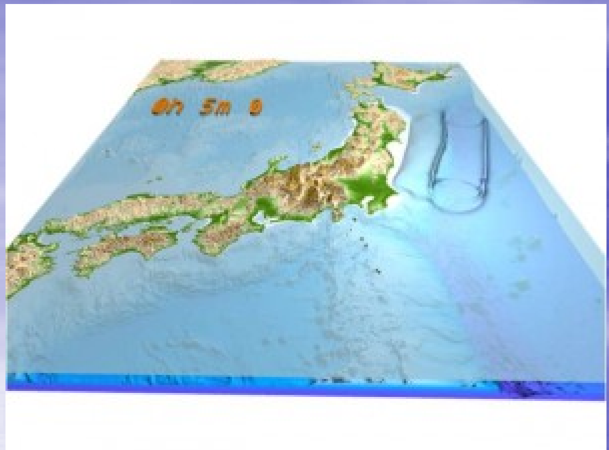


Geller, R.J., 2011. Shake-up time for Japanese seismology, *Nature*, doi: 10.1038/nature10105





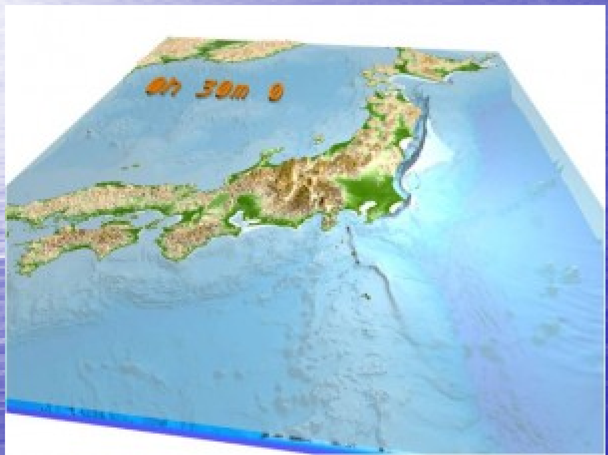
DART Station 21413 - 690 NM Southeast of Tokyo, Japan, 11 March 2011
Water depth (m)
5825,80
5825,60
5825,40
5825,20
5825,00
5824,80
5824,60
5824,40
DART II payload 2.6-meter discus buoy
30.515 N 152.117 E (30°30'55" N 152°7'1" E)
Owned and maintained by National Data Buoy Center
Water depth: 5822 m
Watch circle radius: 4016 yards
Earthquake timestamp: 11 March 2011, 05:46:23 UTC
UTC 07:07
5825,64 m
Tsunami wave
UTC 07:02
5824,95 m
UTC 05:48
5824,77 m
UTC 07:20
5824,52 m
3 hr
U.S. NOAA
Station 21413
Time (UTC)



The crustal change is calculated by referring to the source model of USGS, on the assumption of fault size 600km×250km and fault slip 17 m. The rise of seafloor surface causes tsunami and at the same time, sinking of the coastal regions nurtures the flooding from tsunami.

(Prof. Takashi Furumura and Project Researcher Takuto Maeda)

Snapshots:



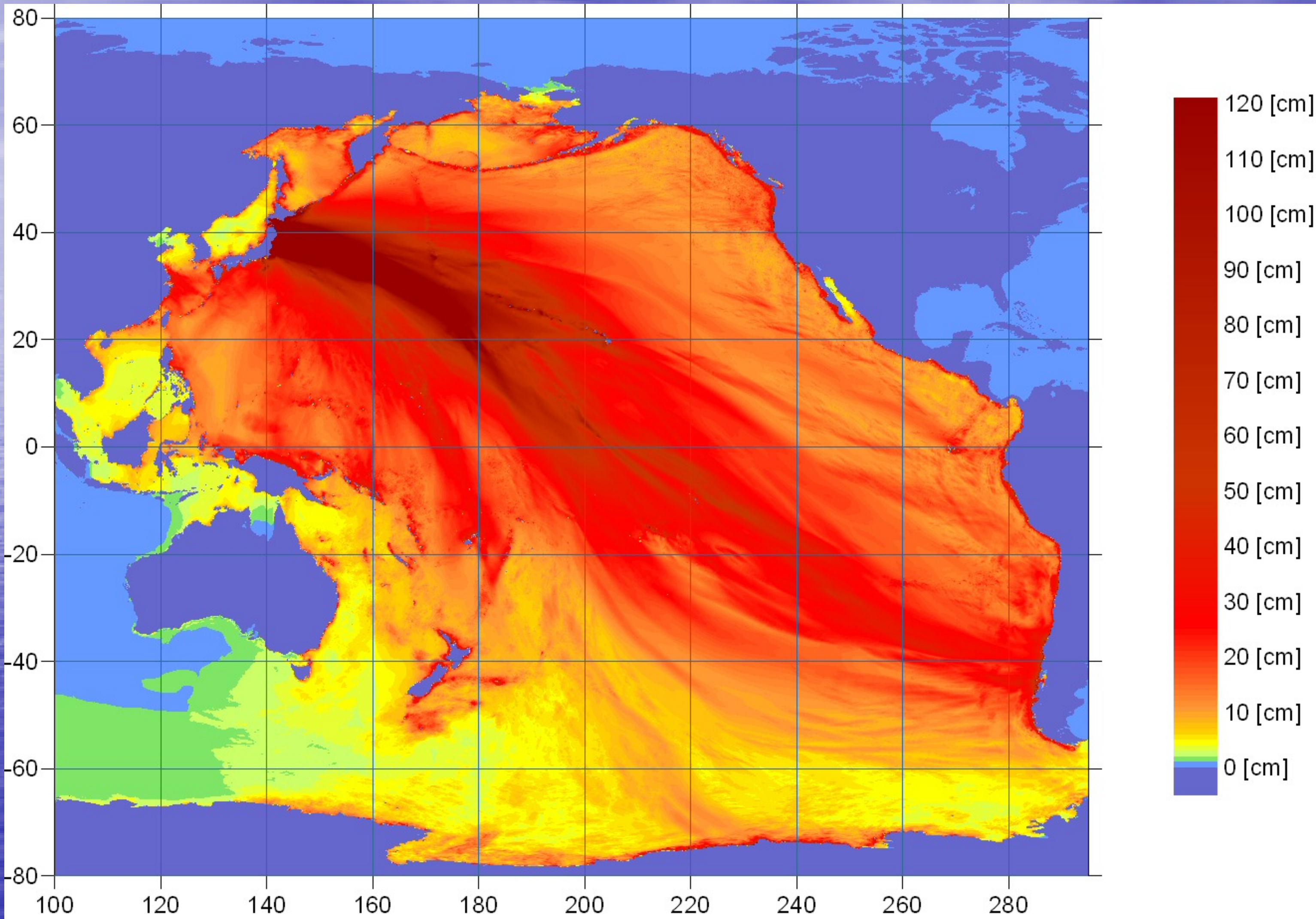
(after 5min) Tsunami extending slowly toward the land. A huge wave crest heading to the coast after a small drawback

(after30min) Tsunami surging in wide range from Hokkaido to Boso Peninsula

(after 2hours) Tsunami trapping along the coast and change in sea-level is lasting long

(after 1hour 10min) Tsunami reflected at the coast line focusing at Sendai bay

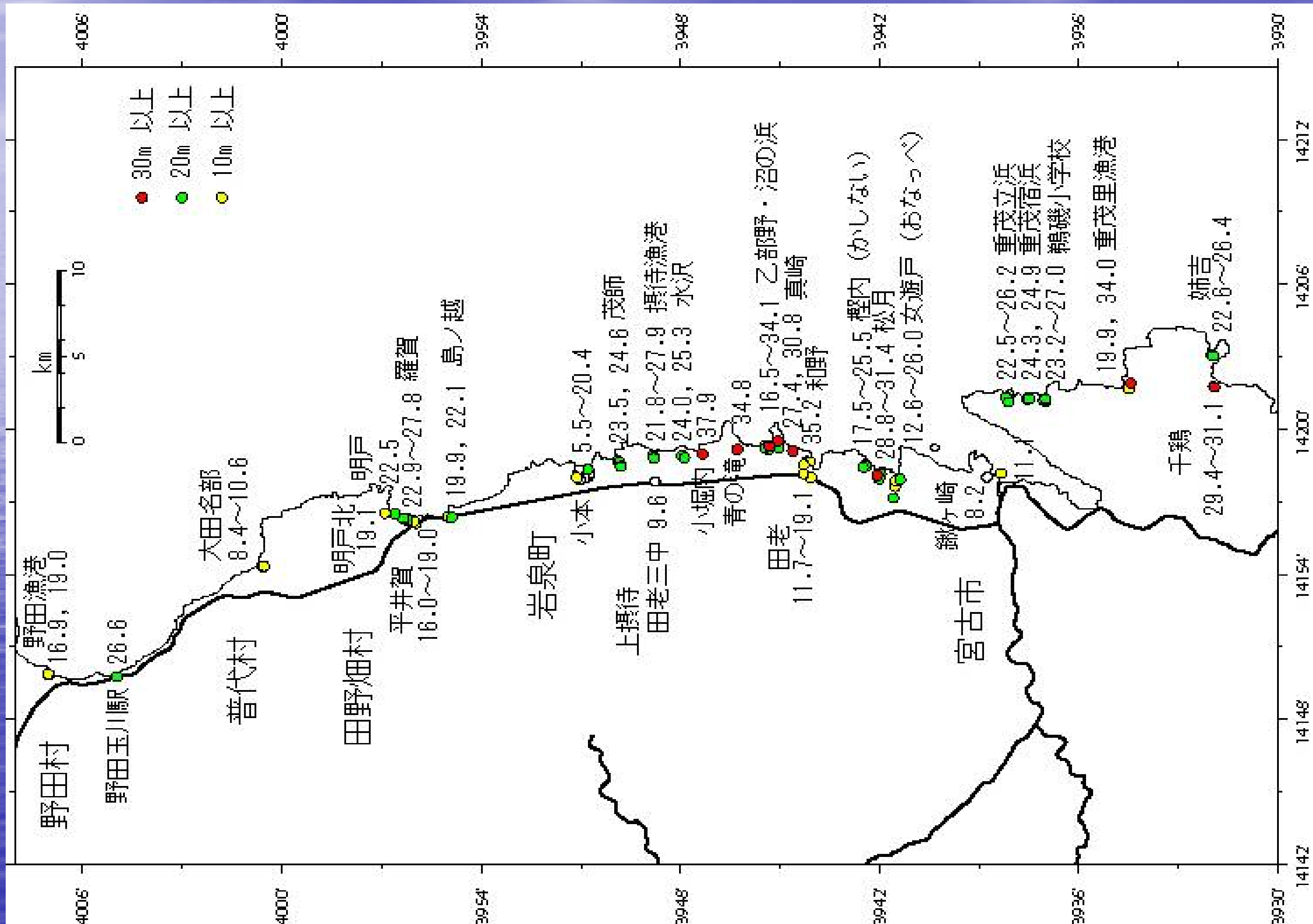
Energy map of the tsunami from NOAA

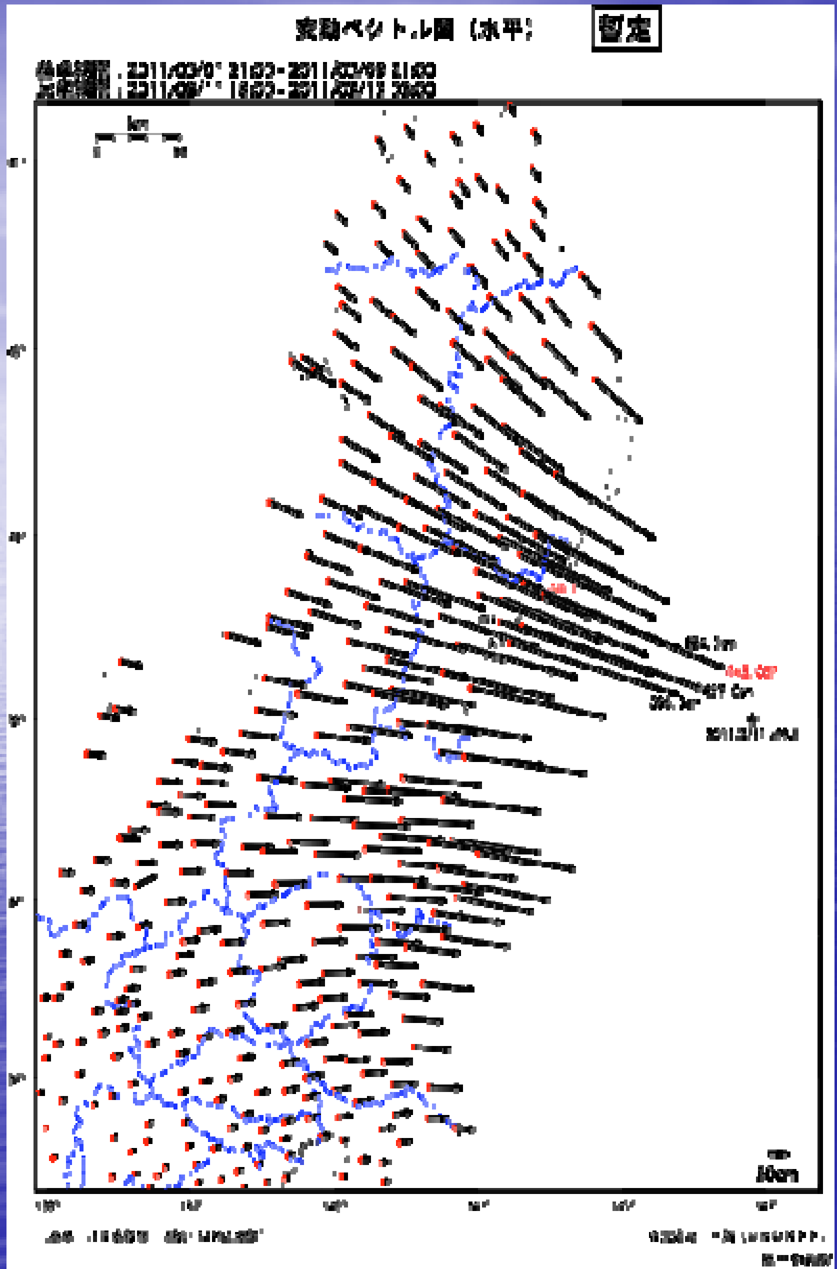


Tsunami Investigation of Northern Sanriku

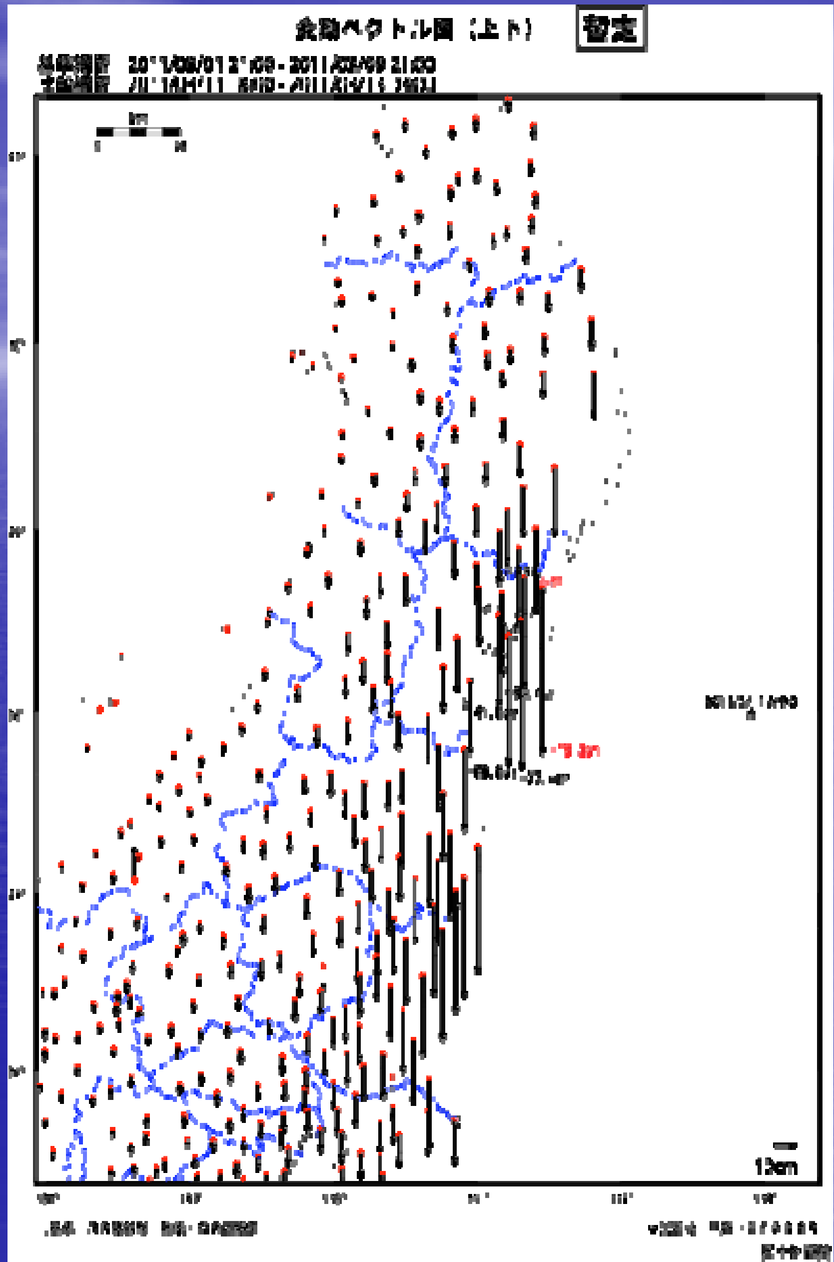
The measured results of: Otobeno-Numanohama, port Kashinai, Chikei of Omoe peninsula, Aneyoshi, port Omoe, Ymadamachi-Koyadori and Ryouri-Sanrikucho, Oofunato city.

（BY: Yoshinobu Tsuji (ERI）, Prof. B.H.Choi（SKKU）,Dr.Kyeong Ok Kim (KORDI), Mr Hyun Woo Kim(Marine Info Tech Co)）



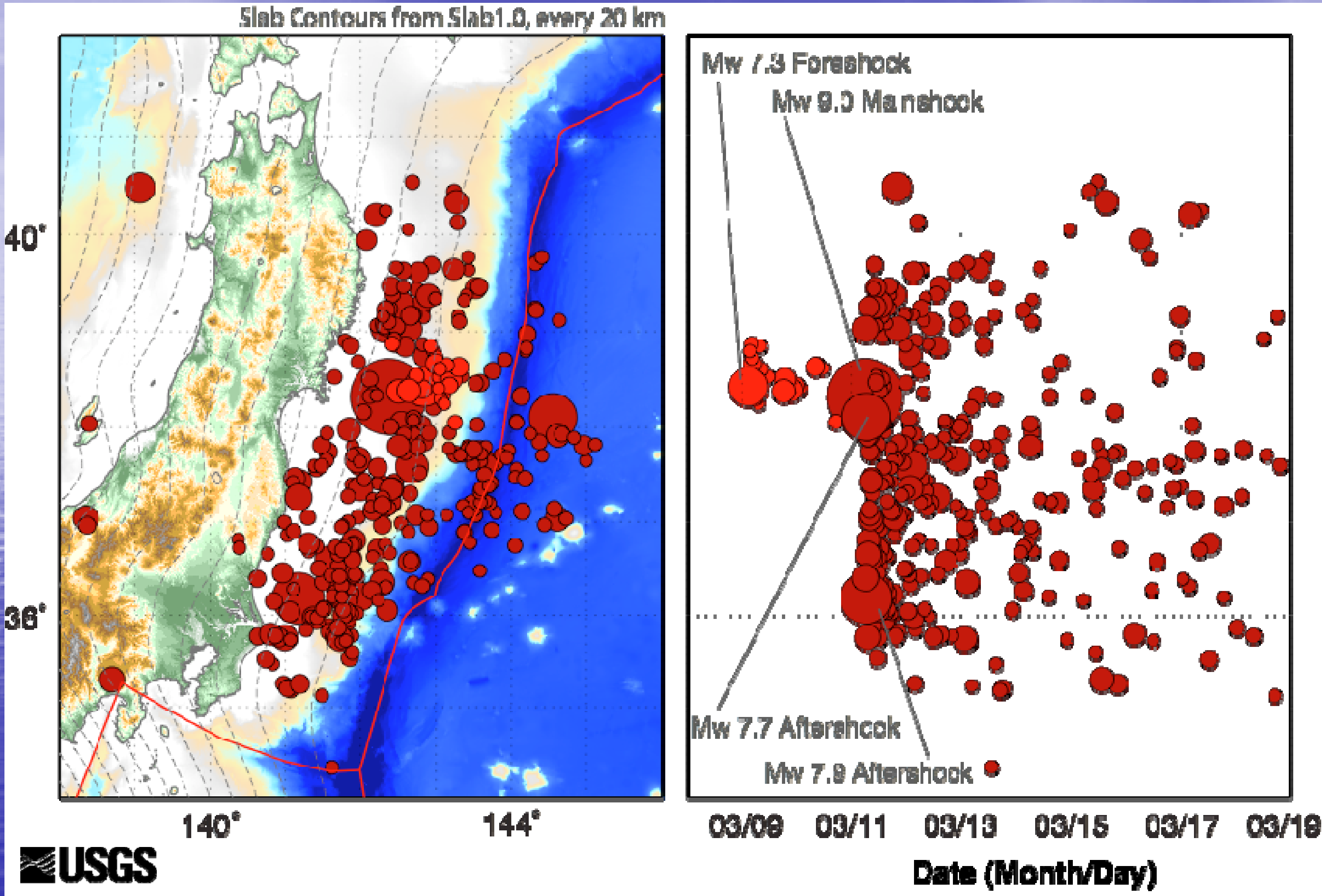


変動ベクトル図（水平）
暫定
50cm



変動ベクトル図（上下）
暫定
10cm

Tohoku, Japan Earthquake Sequence 03/08/11 - 03/16/11



2011 Tōhoku earthquake and tsunami
From Wikipedia, the free encyclopedia

- 1 Earthquake
- 2 Tsunami
- 3 Land subsidence
- 4 Casualties
- 5 Damage and effects
- 6 Aftermath

Sendai Airport

Land subsidence and soil liquefaction near Shin-Urayasu Station elevator shaft

The National Police Agency has confirmed 15,811 deaths, 5,932 injured, and 4,035 people missing across eighteen prefectures.

National Police Agency of Japan
Emergency Disaster Countermeasures Headquarters

Damage Situation and Police Countermeasures associated with 2011Tohoku district - off the Pacific Ocean Earthquake
September 26, 2011

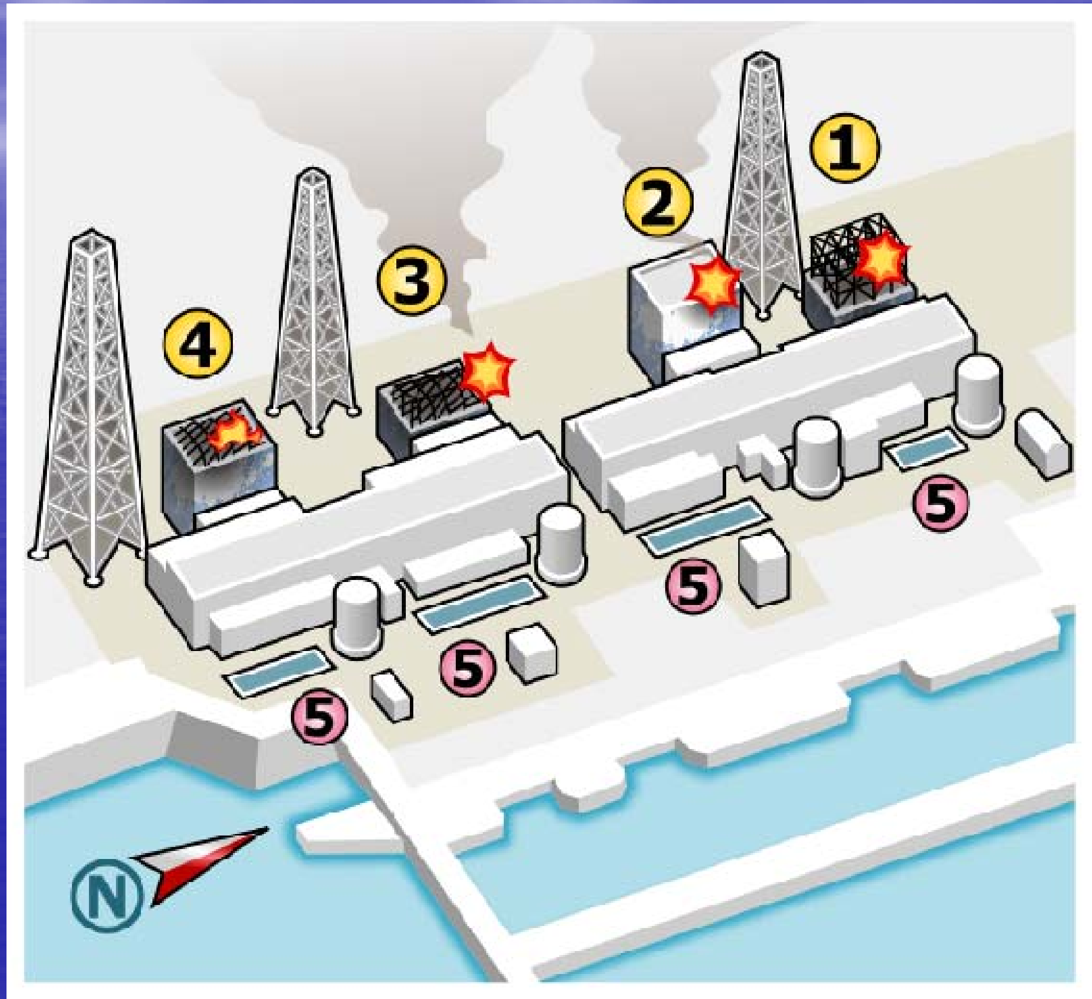
Type of damages / Prefecture	Personnel damages					Property damages									Damaged roads	Damaged bridges	Landslides	Break of dikes	Damaged railways
	Killed	Missing	Injured			Total collapse	Half collapse	Swept out	Total burn down	Partial burn down	Inundated above floor level	Inundated below floor level	Partially damaged	Non-dwelling houses					
			Severely injured	Slightly injured	Total														
	Person	Person	Person	Person	Person	Door	Door	Door	Door	Door	Door	Door	Door	Door	Place	Place	Place	Place	Place
Hokkaido	1			3	3		4				329	545	7	469					
Aomori	3	1	16	45	61	307	851						107	1,195	2				
Iwate	4,664	1,651			188	20,209	4,529		15		1,761	323	7,135	4,148	30	4	6		
Miyagi	9,477	2,141			4,000	75,391	91,411		135		7,068	10,982	172,788	27,394	390	29	51	45	26
Akita			4	8	12								3	3	9				
Yamagata	2		8	21	29	37	80								21		29		
Fukushima	1,604	239	87	154	241	17,740	48,977		77	3	62	339	139,310	1,052	19	3	9		
Tokyo	7		14	76	90		11		3				257	20	13		3		
Ibaraki	24	1	33	673	706	2,799	20,142		37		1,586	724	159,673	12,079	307	41			
Tochigi	4		7	125	132	262	2,083						64,155	295	257		40		2
Gunma	1		13	25	38		7						16,154	195	7		4		
Saitama			6	36	42		5		1	1		1	1,800	33	160				
Chiba	20	2	22	227	249	797	9,085		12		764	716	30,254	615	2,343		55		1
Kanagawa	4		17	112	129		7						279	1					
Niigata				3	3								9	7					
Yamanashi				2	2								4						
Nagano				1	1														
Shizuoka			1	3	4							7	4						
Gifu															1				
Mie				1	1						2			9					
Tokushima											2	9							
Kochi				1	1						2	8							
Total	15,811	4,035			5,932	117,542	177,192		284		11,576	13,654	591,939	47,515	3,559	77	197	45	29

＊ Unidentified information is included.

Panorama of Rikuzentakata area swept away

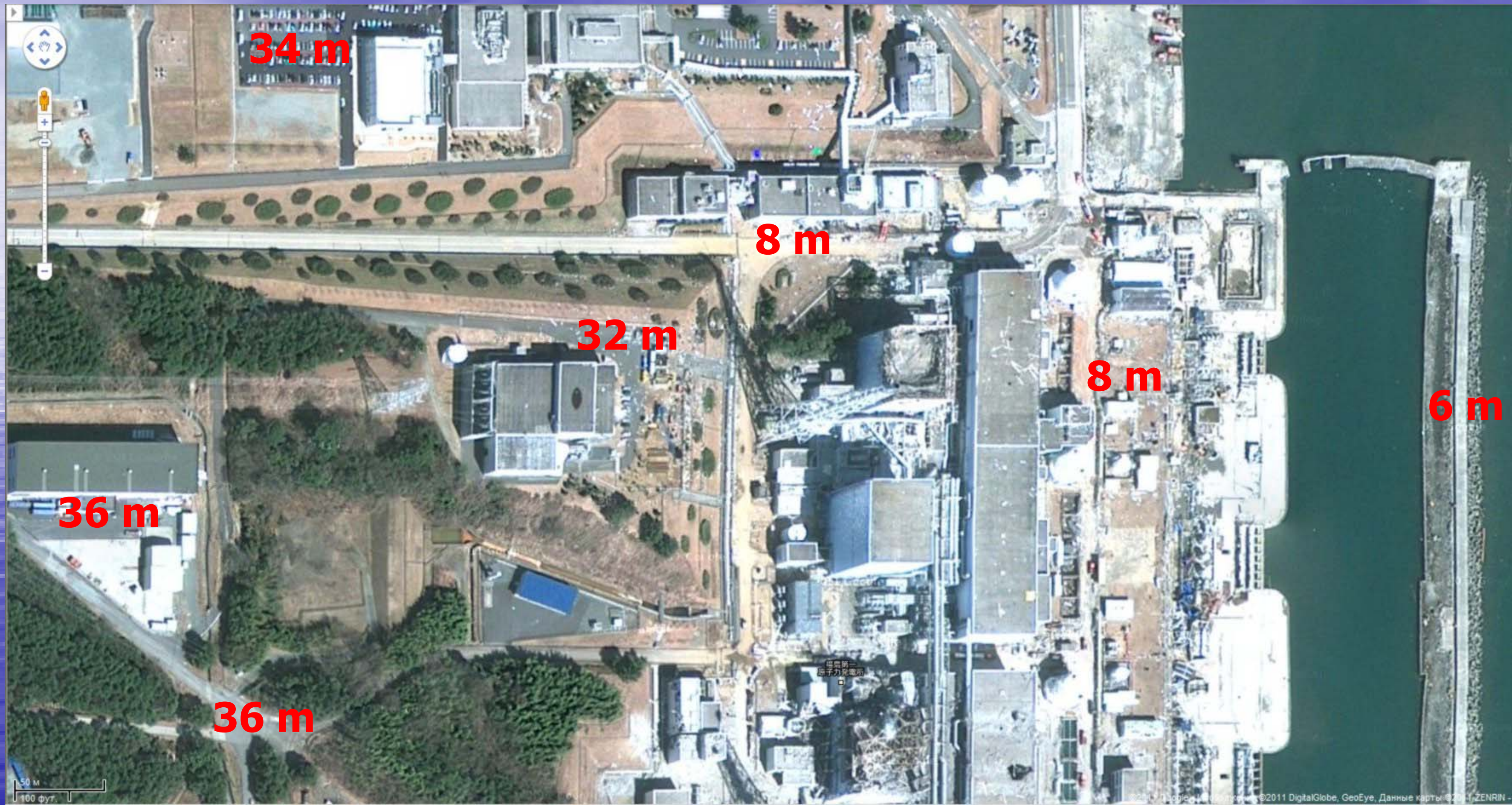
Aerial photo of Minato, devastated by both the earthquake and subsequent tsunami

Fukushima Daiichi NPP



Three of the reactors at Fukushima Daiichi overheated, causing meltdowns that eventually led to explosions, which released large amounts of radioactive material into the air

Fukushima Daiichi NPP by design was leveled down from 35 m above the sea.



Aftermath of the 2011 Tōhoku earthquake and tsunami

- **Humanitarian crisis**: The number of the evacuees has once passed 300,000; at the end of July 2011, the number of evacuees in Japan stood at 87,063
- **Nuclear accidents**: The accidents have drawn attention to ongoing concerns over Japanese nuclear seismic design standards and caused other governments to re-evaluate their nuclear programs.
- **Economic impact**: By April 12 2011 the Japanese government estimated that the cost of just the direct material damage could exceed ¥25 trillion ($300 billion).
- **Global financial impact**: In the immediate aftermath of the earthquake, Japan's Nikkei stock market index saw its futures slide 5% in after-market trading. The Bank of Japan said that they would do their utmost to ensure financial market stability. On Tuesday, 15 March, news of rising radiation levels caused the Nikkei to drop over 1,000 points or 10.6% (16% for the week).

Thank you!

"When sorrows come, they come not single spies, but in battalions"

(William Shakespeare, 1564-1616)