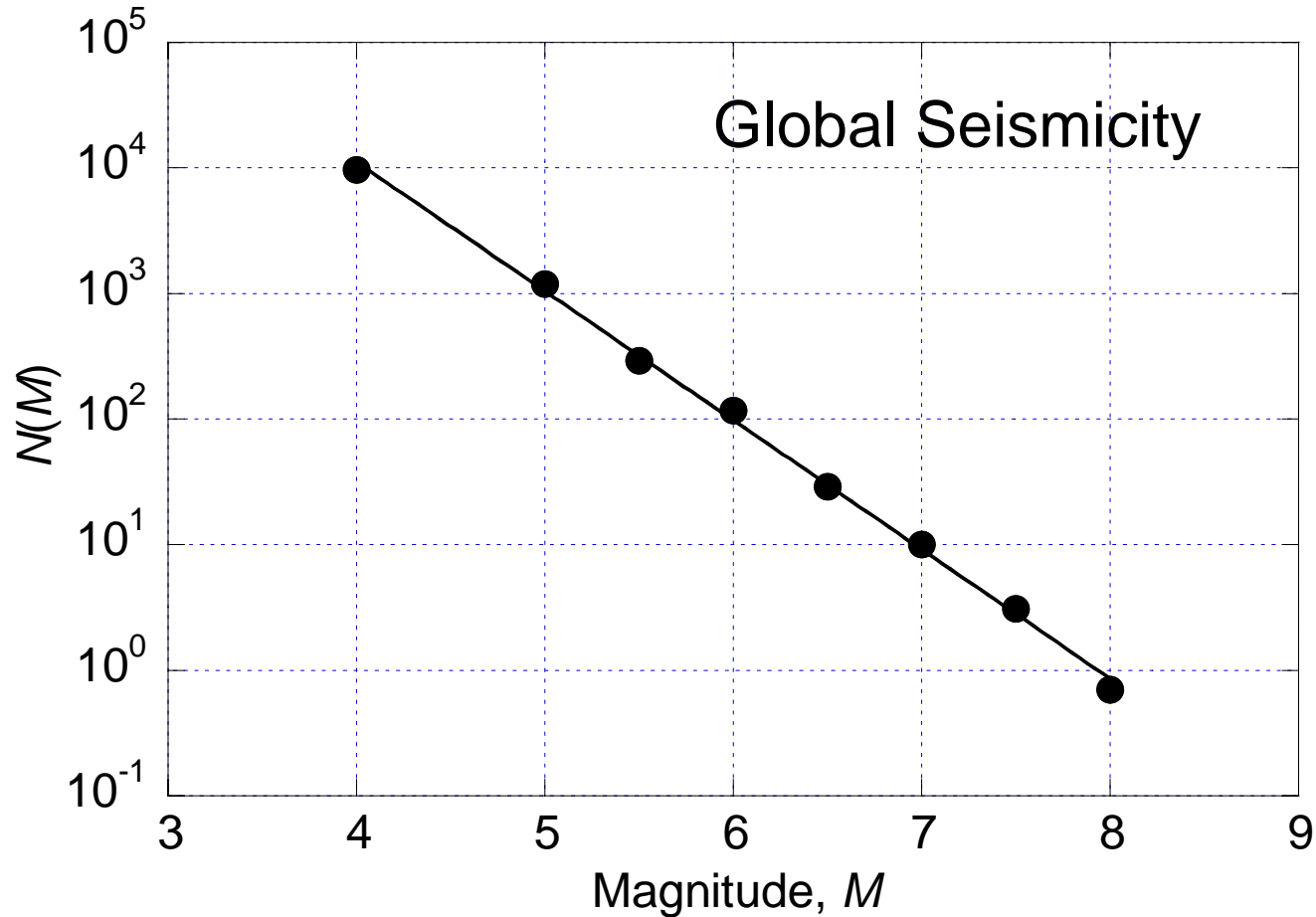


# Preparing for Rare, Great Earthquakes

Hiroo Kanamori  
Seismological Laboratory  
California Institute of Technology

# How rare are great earthquakes?

Only 4 events with  $M_w \geq 9$  in the past century



$M \geq 9$  earthquakes during the last 100 years

1952 Kamchatka (9.0), 1960 Chile (9.5), 1964 Alaska (9.2), 2004 Sumatra (9.2)

Great earthquakes are not necessarily most damaging, but some can be extremely damaging

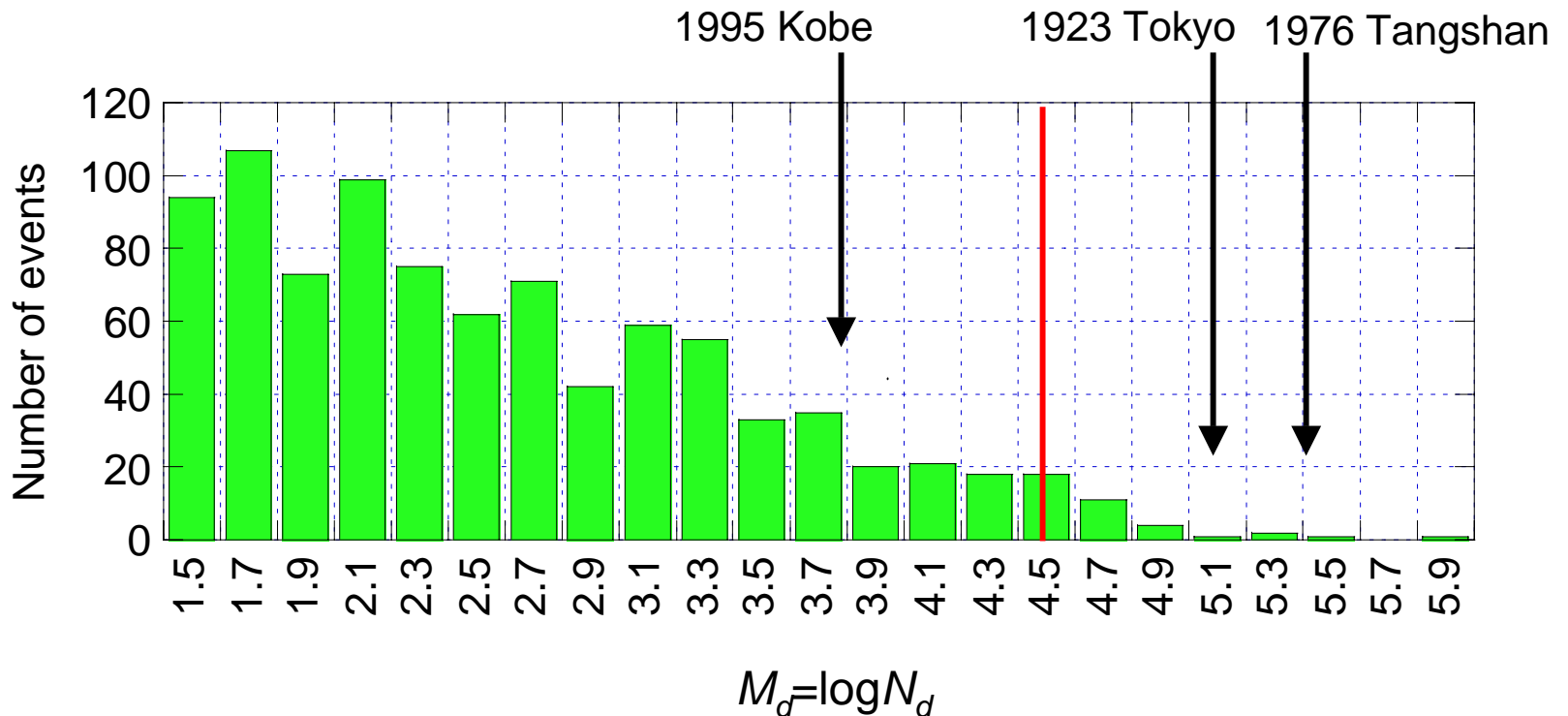
# Impact of Rare, Damaging Earthquakes on Society (1400-2000)

900 events with death toll > 30

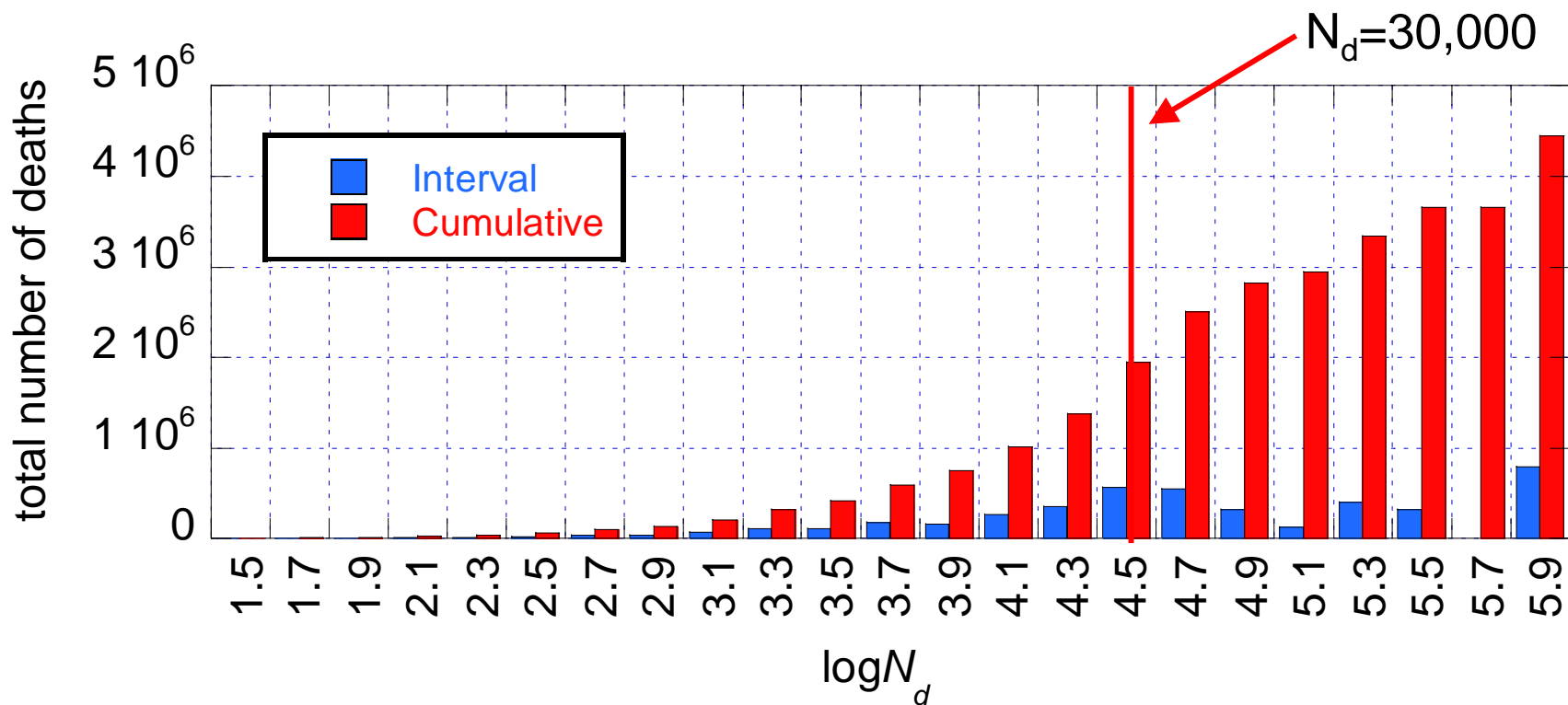
Only 36 out of the 900 events have death toll > 30,000

Utsu (2003)

$M_d = \log N_d$      $N_d = \text{Death toll}$ ,     $M_d = \text{“damage” Magnitude}$



Yet, 2 million out of 4 million died in these 36 events with death toll > 30,000



Example:

2004 Sumatra-Andaman Earthquake ( $M_w=9.2$ )

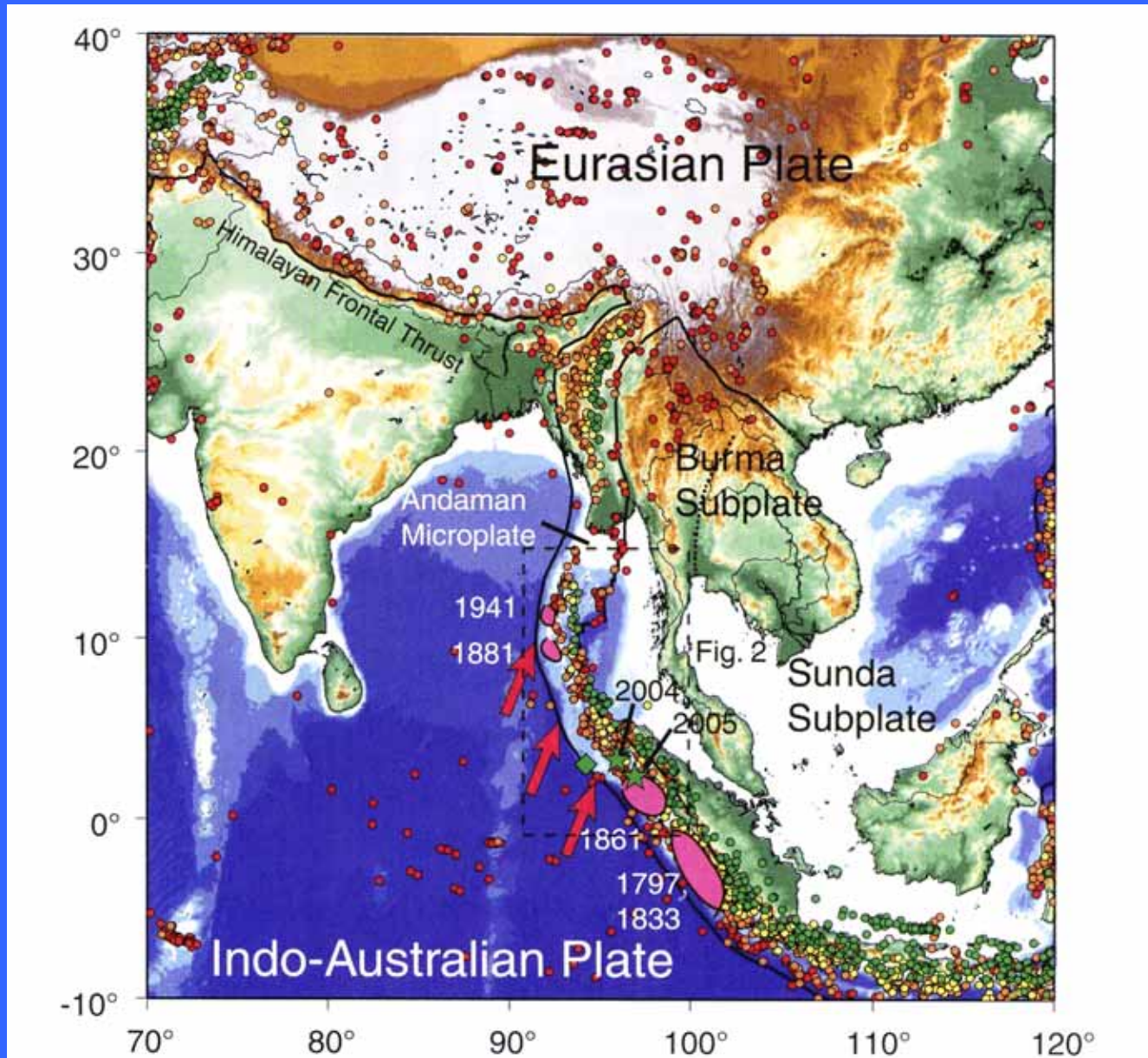
Physically, one of the largest.

One of the most damaging (death toll > 280,000).

Global Seismic Network worked well

Technical difficulty, Lack of knowledge

# The 2004 Sumatra-Andaman Earthquake





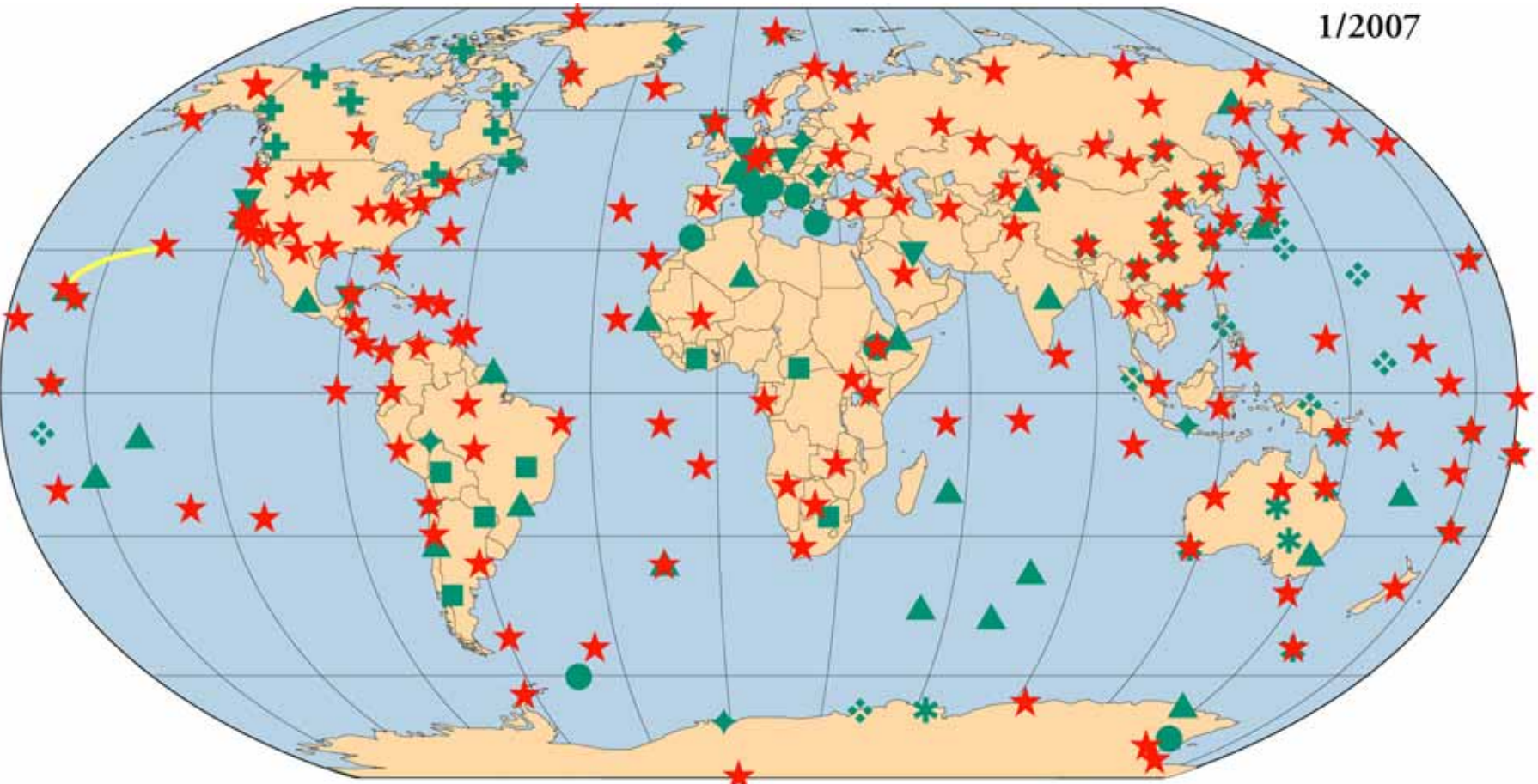
# Backbone Global Seismic Network and FDSN Stations (211 stations)

More than 500 stations, available online to seismologists

More than 100 stations, not easily available (requires special arrangement)

(FDSN: Federation of Digital Seismic Network)

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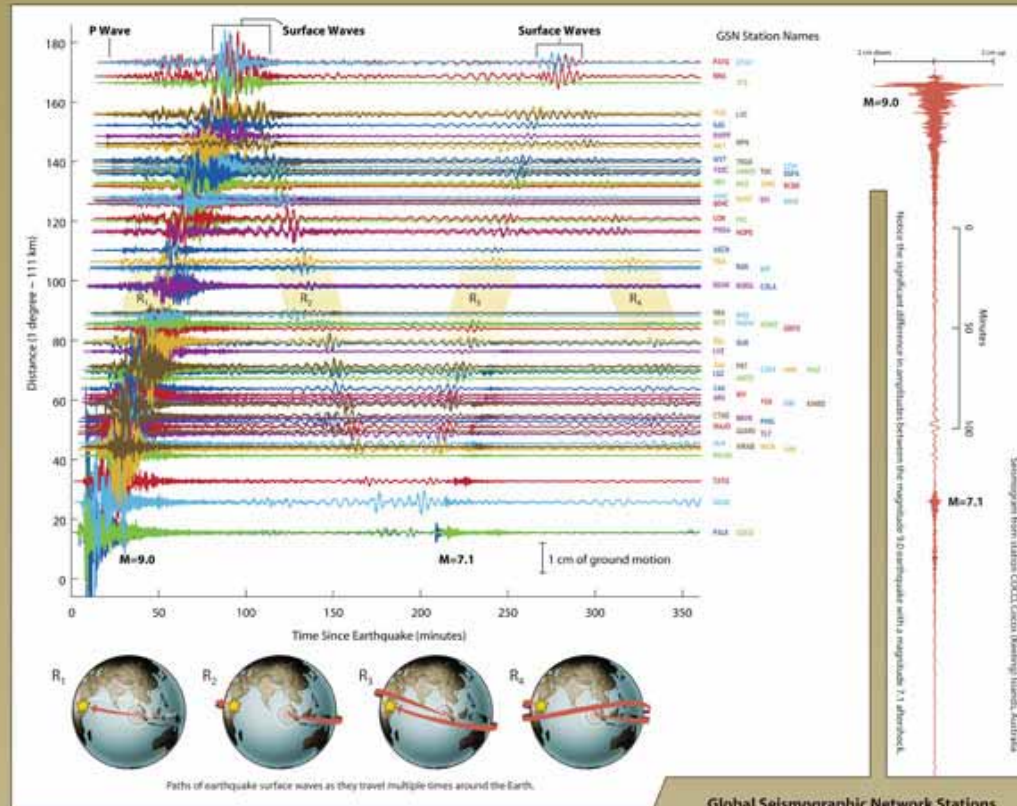


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|----------|-----------|--------|--------|---------|-------|-------|------|-------|
| IRIS GSN | Australia | Canada | France | Germany | Italy | Japan | U.S. | Other |
| ★        | *         | +      | ▲      | ◆       | ●     | ⋈     | ■    | ▼     |



# Global record section of the 2004 Sumatra-Andaman earthquake

## Sumatra - Andaman Islands Earthquake ( $M_w=9.0$ ) As Recorded by the Global Seismographic Network



The magnitude ( $M_w$ ) 9.0 earthquake near Sumatra on December 26, 2004 was one of the largest and most significant seismic events during the past 100 years. While earthquake damage and casualties were limited to the immediate vicinity of the epicenter, tsunamis generated by this event caused over 250,000 deaths in the Indian Ocean region spanning more than 10 nations.

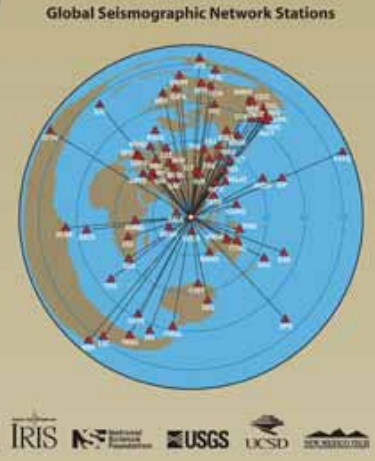
This assembly of seismograms displays the vertical movement of the Earth's surface due to seismic waves generated by the earthquake. The seismograms are plotted with respect to time since the start of the earthquake on the horizontal axis and are sorted vertically according to distance from the epicenter in degrees.

An earthquake generates many different types of seismic waves that travel through the earth simultaneously. At any particular station they are recorded at different times due to differences in the speed and in the paths that they travel. The earliest arriving signal is the compressional (P) wave. This P-wave takes about 21 minutes to reach the other side of the planet (the antipode, at 180 degrees). The largest amplitude signals are seismic surface (Rayleigh) waves that reach the antipode after about 95 minutes. The arrival of the surface waves at each seismic station above are labeled above as:

- $R_1$  - surface waves traveling the shortest route from the epicenter to the recording station;
- $R_2$  - surface waves traveling the longest route from the epicenter to the recording station;
- $R_3$  - surface waves traveling completely around the Earth, plus the  $R_1$  path;
- $R_4$  - surface waves traveling completely around the Earth, plus the  $R_2$  path.

The vertical ground motion as the surface waves passed was generally 1 cm or more. Though this movement occurred everywhere on the planet, you would not have noticed it since this oscillating ground motion occurred over periods of many tens of seconds. Signals from a large aftershock (magnitude 7.1) can be seen at the closest stations starting just after the 200-minute mark. Note the relative size of this aftershock (which would be considered a major earthquake under ordinary circumstances) compared to the mainshock.

Credits: Data provided by the IRIS Global Seismographic Network and distributed through the IRIS Data Management System. Seismic stations are operated by the US Geological Survey, Australian Geoscience Australia, and the University of California, San Diego. Support for this network is provided by the National Science Foundation through the IRIS Consortium and U.S. Geological Survey. Figure by Richard Allen, Rice Institute Institute of Mining and Geophysics.



# How large?

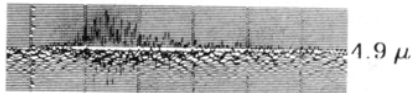
Source duration, about 500 sec

cf. 1960 Chile Earthquake ( $M_w=9.5$ ), 344 sec

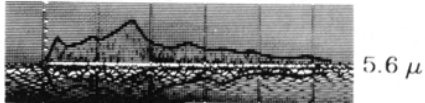
1964 Alaska Earthquake ( $M_w=9.2$ ), 338 sec

SAN FERNANDO Feb. 4, 1971  $M_o = 1 \times 10^{26}$   
MAT  $\Delta = 79.7^\circ \times 100000$

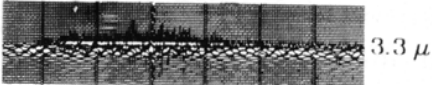
TOKACHI OKI May 16, 1968  $M_o = 2.8 \times 10^{28}$   
BKS  $\Delta = 69.3^\circ \times 25000$



KURILE IS. Oct. 13, 1963  $M_o = 7.5 \times 10^{28}$   
STU  $\Delta = 80.5^\circ \times 25000$



RAT ISLAND Feb. 4, 1965  $M_o = 1.4 \times 10^{29}$   
ESK  $\Delta = 73.7^\circ \times 12500$



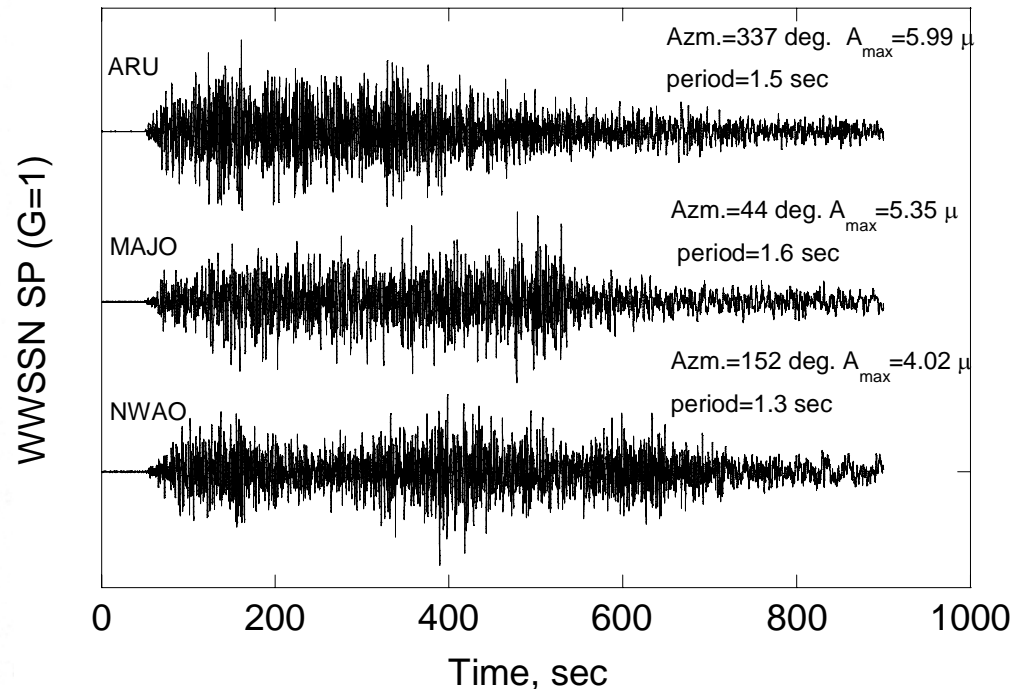
ALASKA Mar. 28, 1964  $M_o = 7.5 \times 10^{29}$   
BOG  $\Delta = 78.0^\circ \times 12500$



CHILE May 22, 1960  $M_o = 2.7 \times 10^{30}$   
PLM  $\Delta = 82.2^\circ \times 30000$



## 2004 Sumatra Earthquake



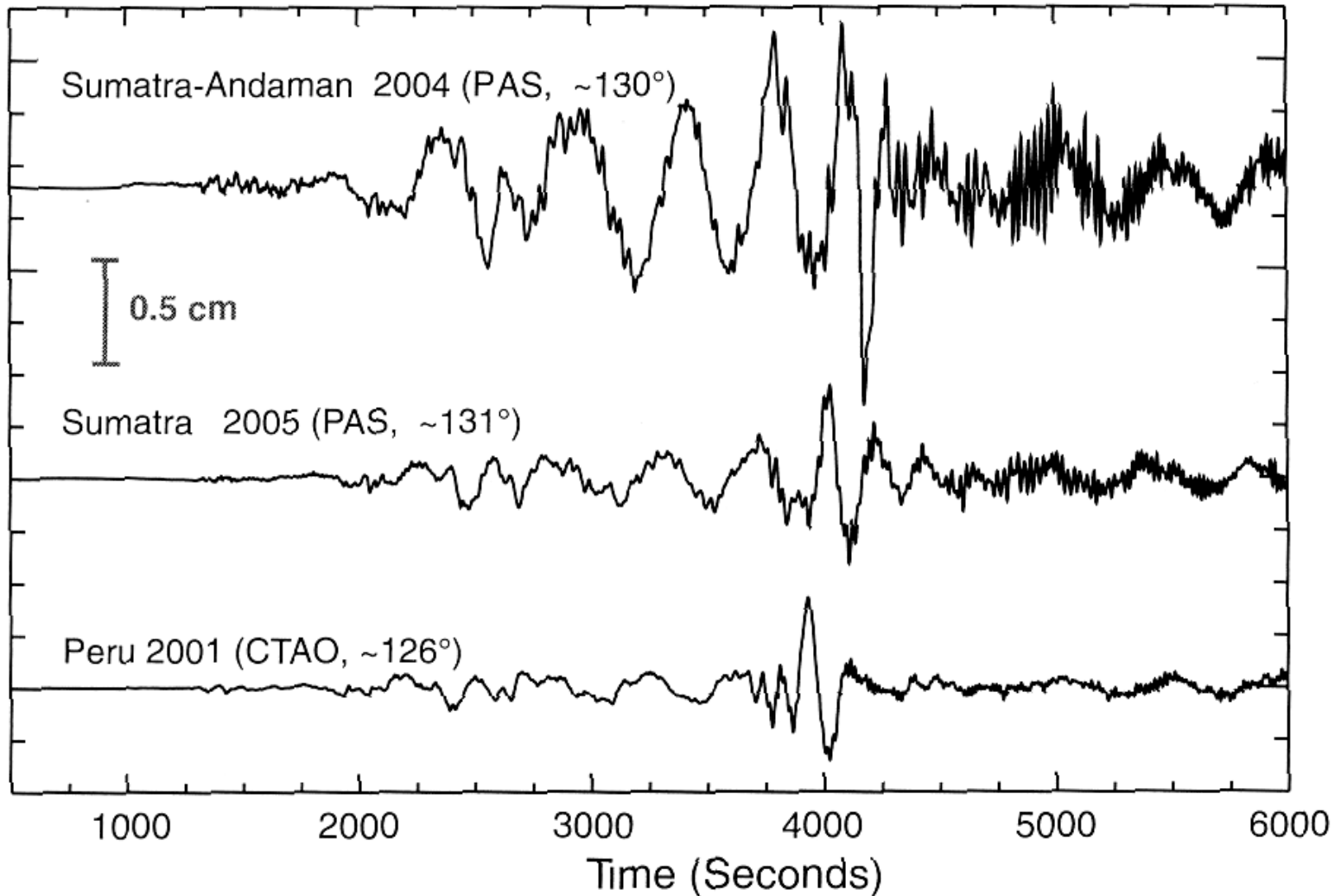
Houston and Kanamori, 1986

1964 Alaska

1960 Chile

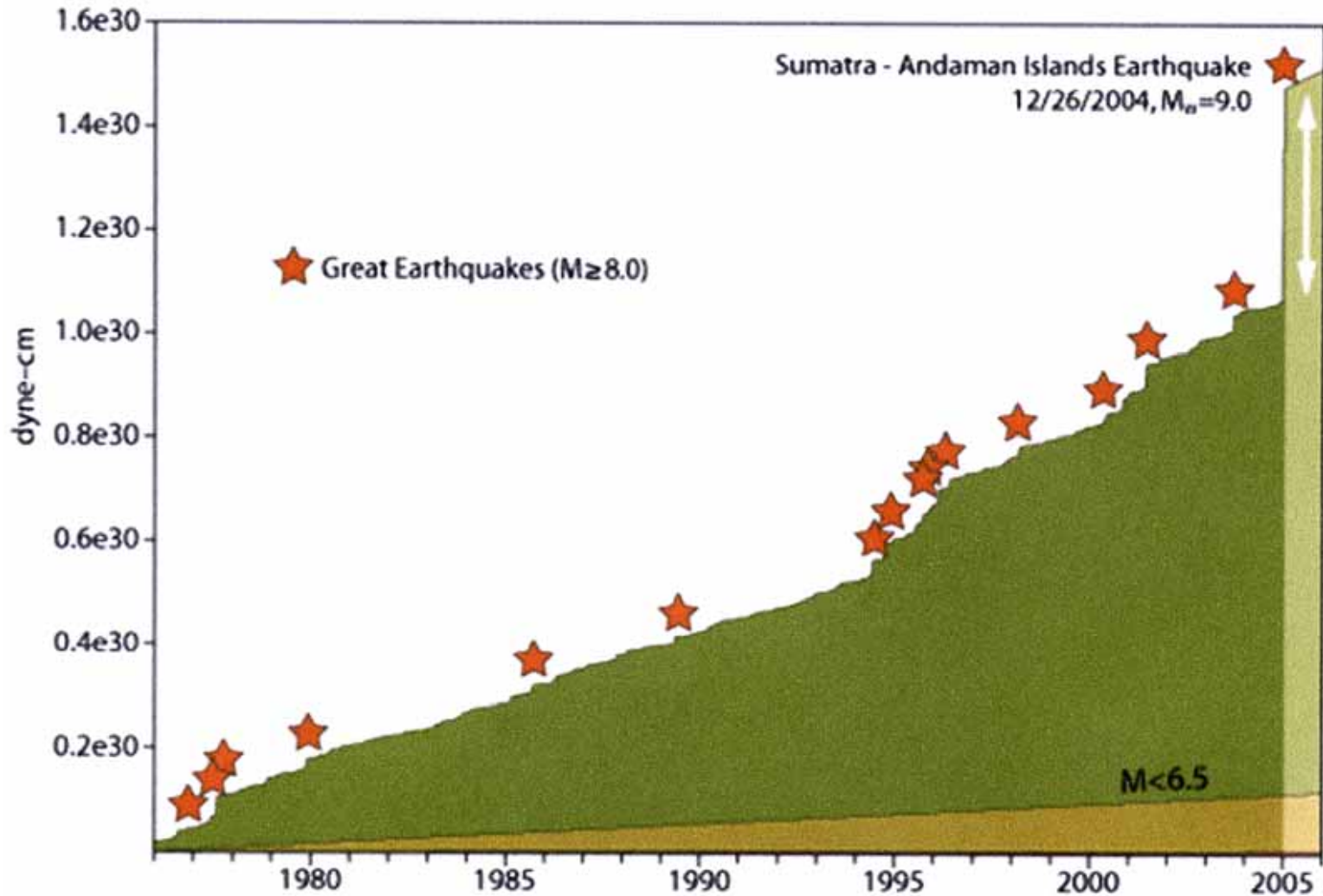
How large? Ground motion  $\geq 1$  cm anywhere on the planet.

Comparison with the 2<sup>nd</sup> and 3<sup>rd</sup> largest events



How large?

“Energy” release (about 1/3 of the total for the last 30 years.)



# 2004 Sumatra-Andaman Earthquake

Source duration in time, about 500 sec

(Ni et al., 2005; Ishii et al., 2005)

cf. 1960 Chile ( $M_w=9.5$ ), 344 sec

1964 Alaska ( $M_w=9.2$ ), 338 sec

(Houston and Kanamori, 1986)

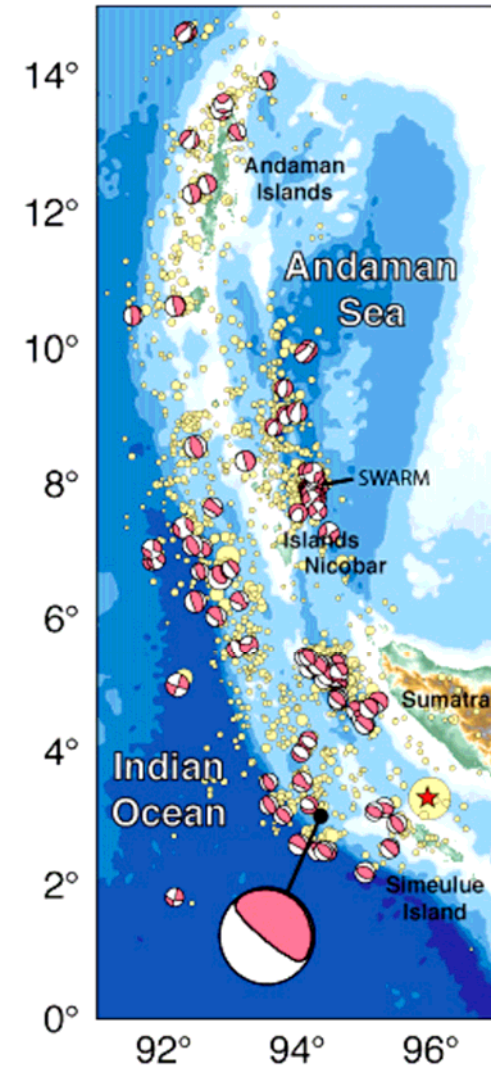
Rupture length, 1200 to 1300 km

cf. 1960 Chile ( $M_w=9.5$ ), about 1000 km

1964 Alaska ( $M_w=9.2$ ), about 700 km

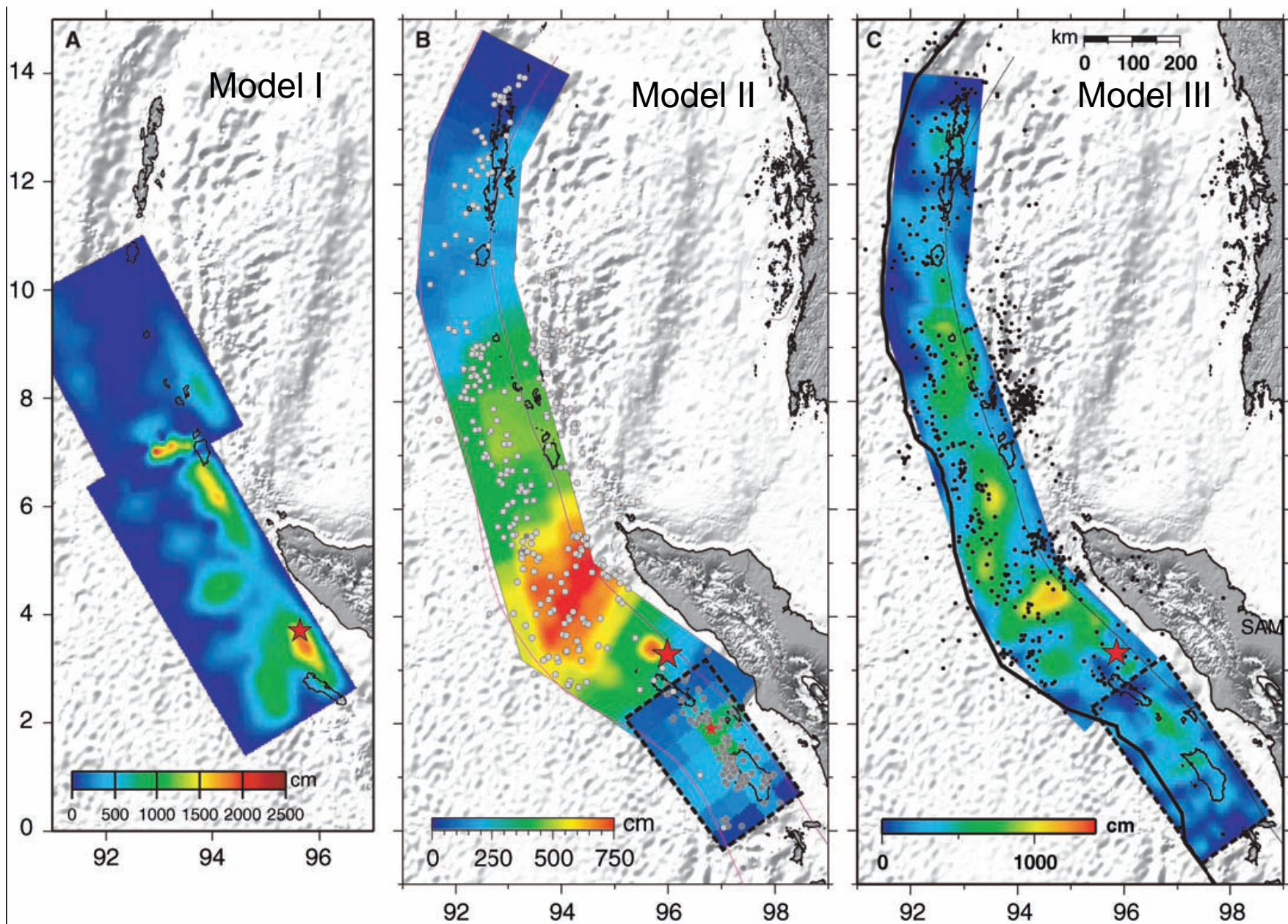
$M_w$  9.0 to 9.3

$M_t$  9.1

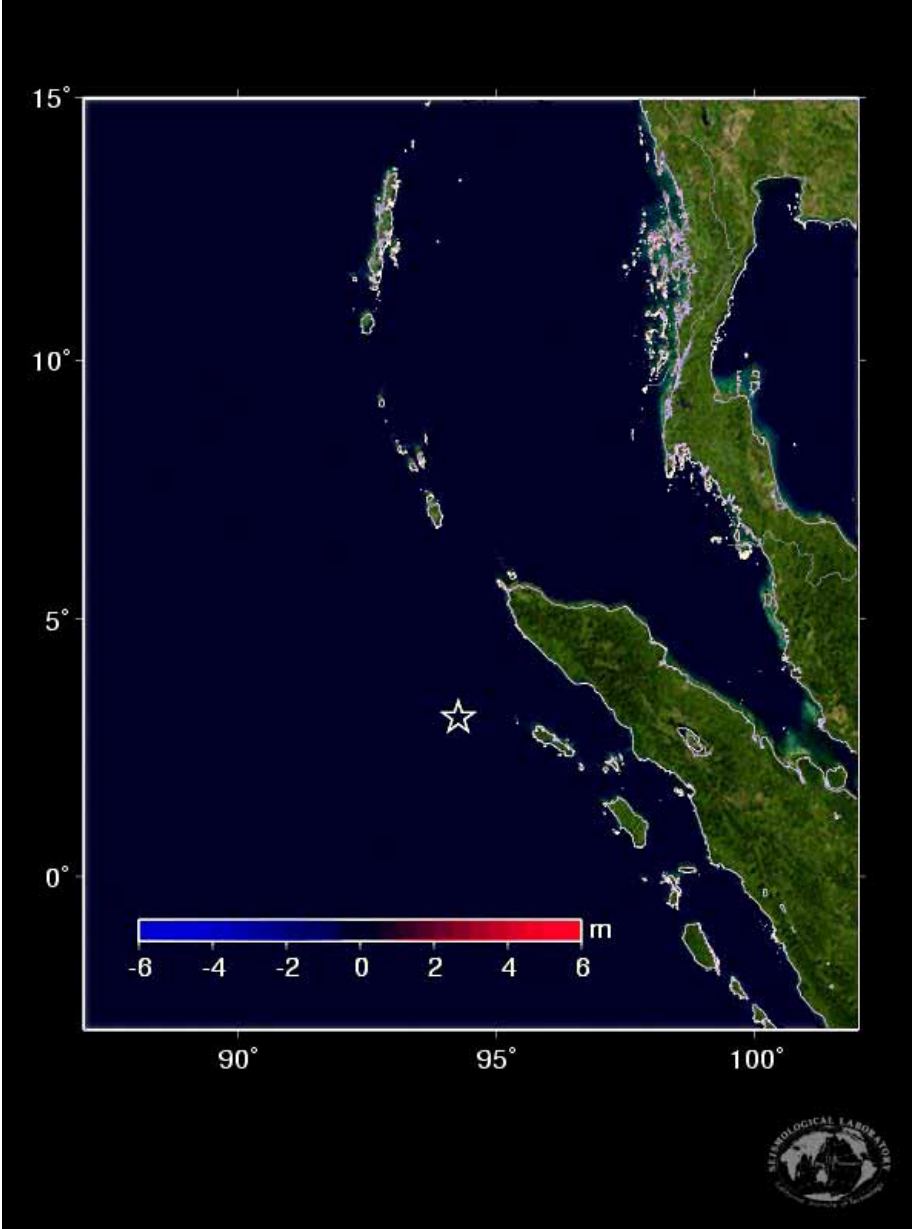




# Slip Distribution from Waveform Inversion



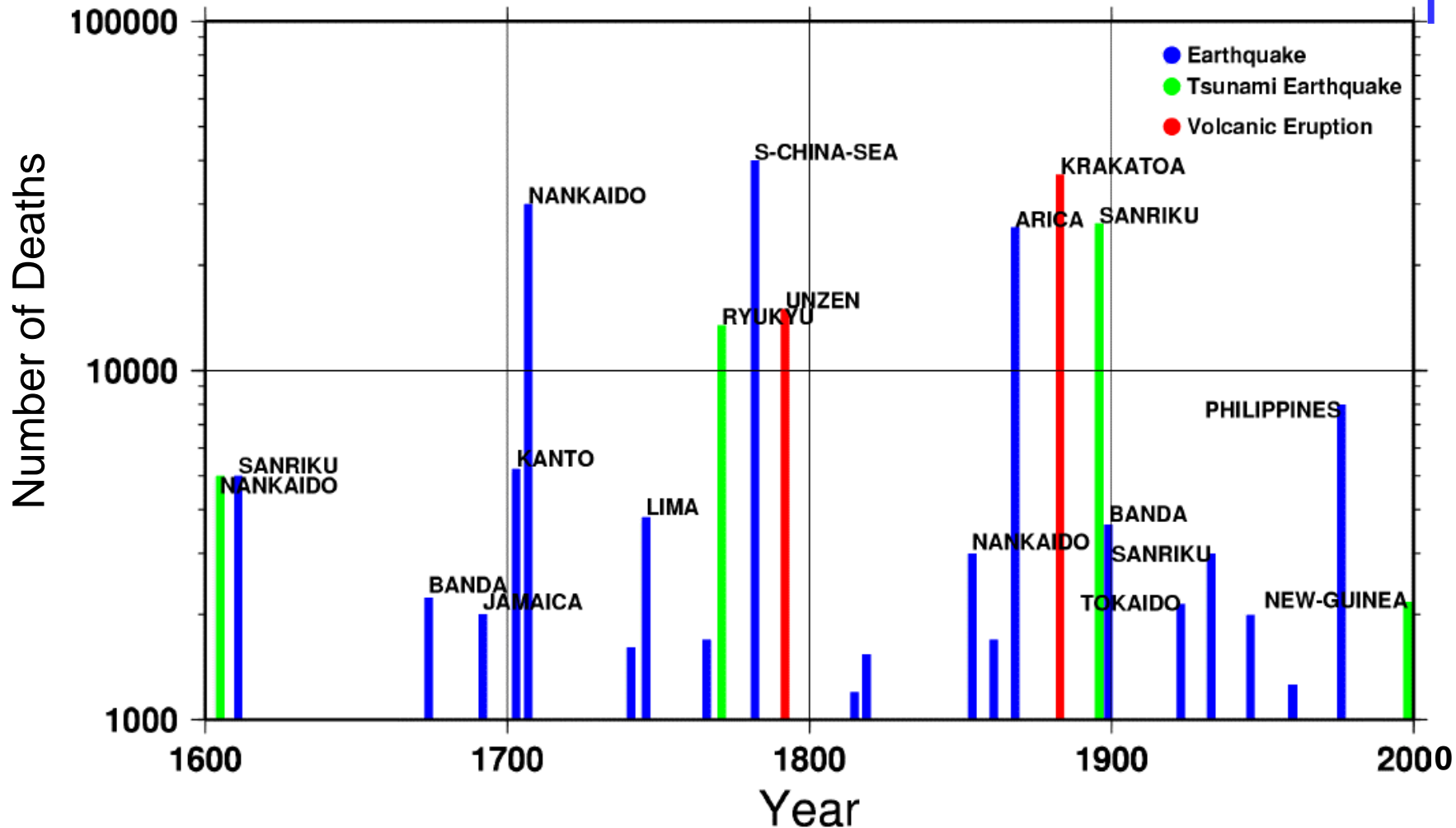
Ground displacement during the initial 10 min





# Damaging Tsunami

2004 Sumatra



## Technical problems

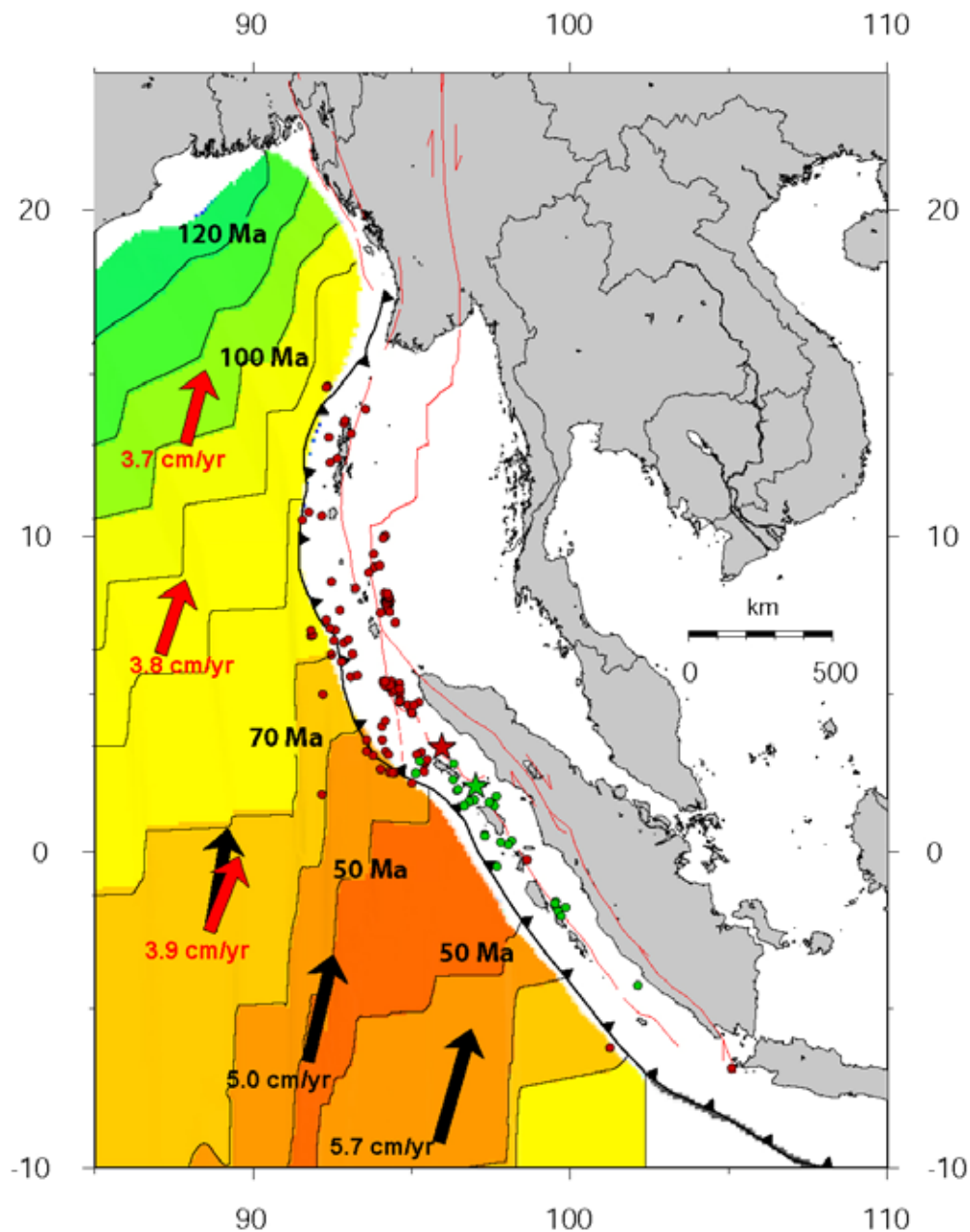
No real-time methods could handle the long duration and the long-period waves properly.

## Lack of Knowledge

Great earthquakes in the Andaman I s. not expected by most seismologists.

# Expected?

Zone	Age (My)	V (cm/y)	Mw
Chile	20	11	9.5
Alaska	40	6	9.2
Kamchatka	80	9	9.0
Sumatra	60	3	9.2



# Practical Difficulty

Long-term monitoring for such events is difficult.

The monitoring system needs to be maintained for very rare events.

Needs long-term financial support as well as sustained interest.

## Solution?

Deployment; Maintenance; Data Archive-Distribution-Exchange; Research should be budgeted together.

Data should be constantly used by researchers.

# An outstanding problem: Tsunami Warning

1. Seismic, Technically Feasible, 10 to 30 min, False Alarm
2. Water wave, Verification, Technically feasible,  
Expensive (Buoy, OB Cable)
3. Local infrastructure, Some exist (Hawaii, Alaska, Japan,  
.....)
4. Education and Training, Difficult for rare events

# Seismic Methods

## Merits:

Seismic networks and infrastructures exist

Long-range

Versatile

## Demerits:

Indirect (i.e., does not measure water waves) → false alarms

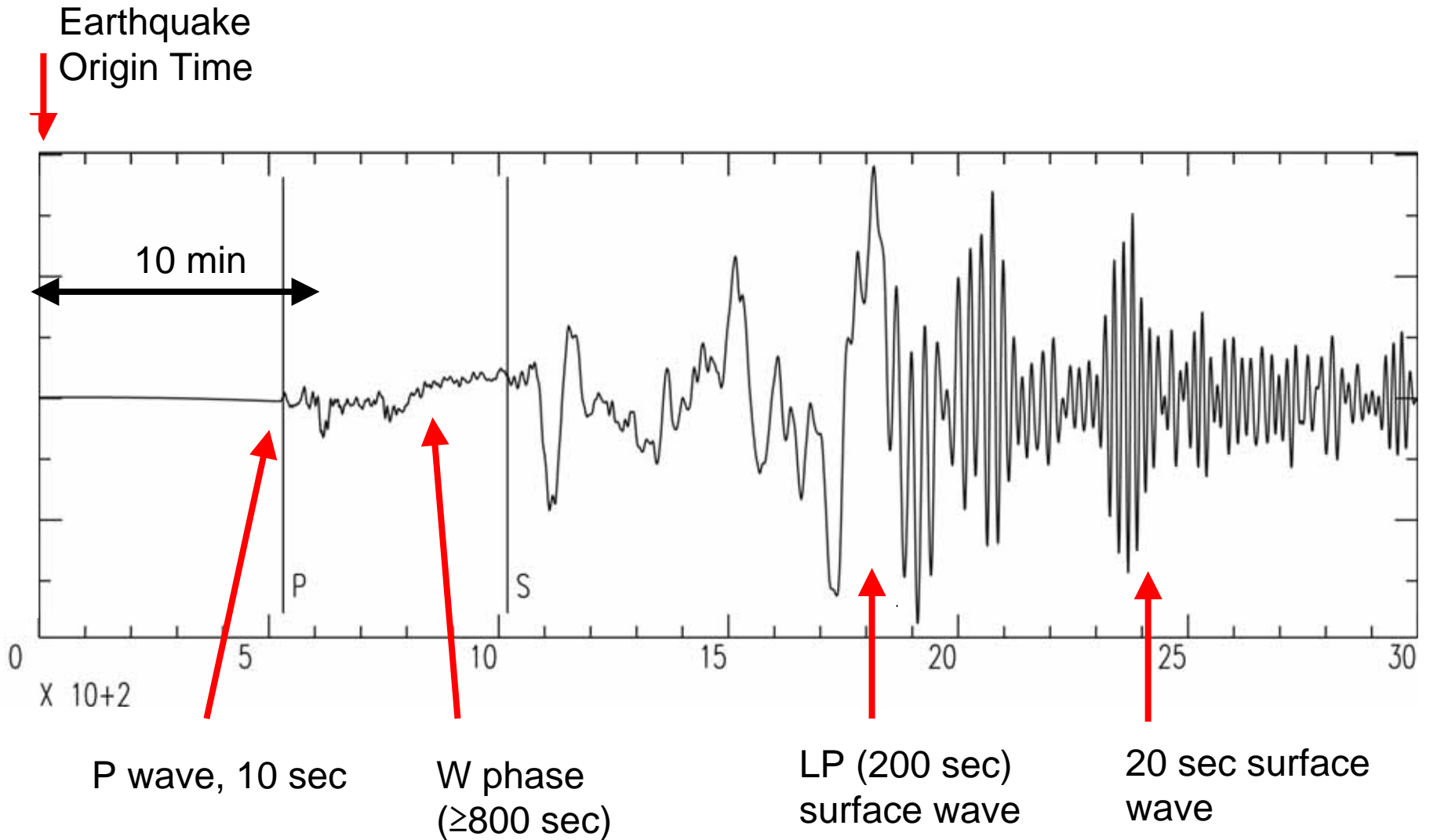
Too slow for near-field tsunami (finite wave propagation time)

## Future direction:

For  $M_w \geq 9$  (almost certainly tsunamigenic)

Use of very long-period waves ( $\geq 800$  sec)

# Illustration of Seismic Phases on a Seismogram at ~7000km



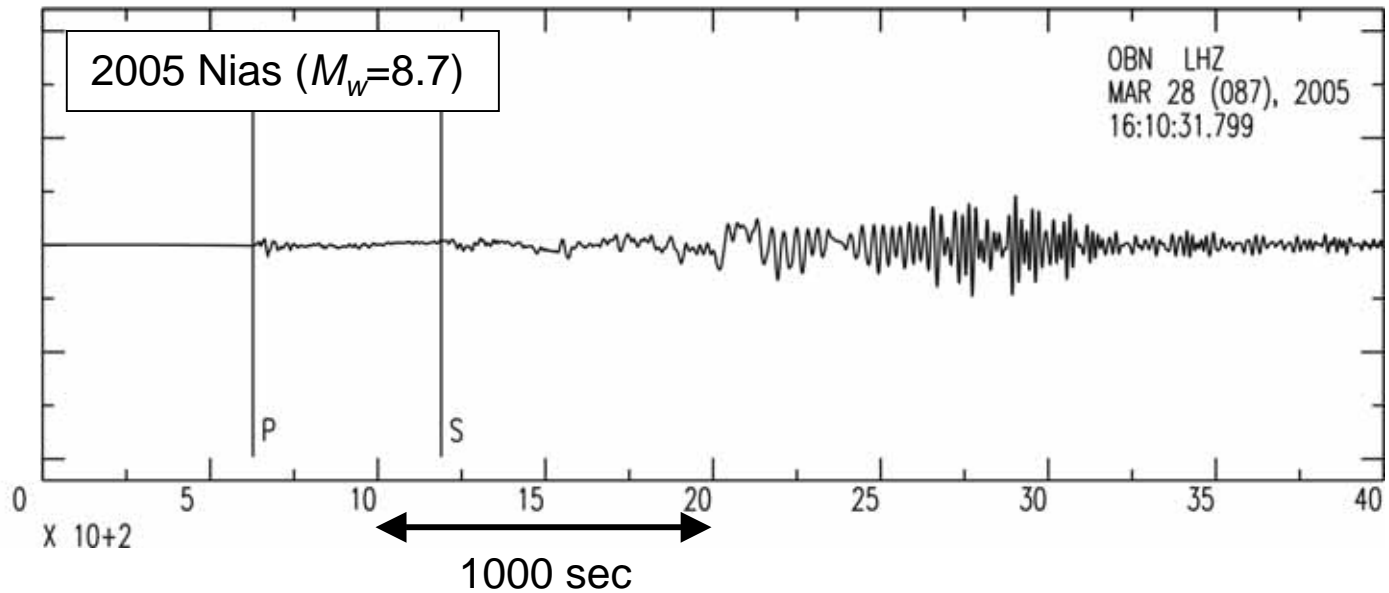
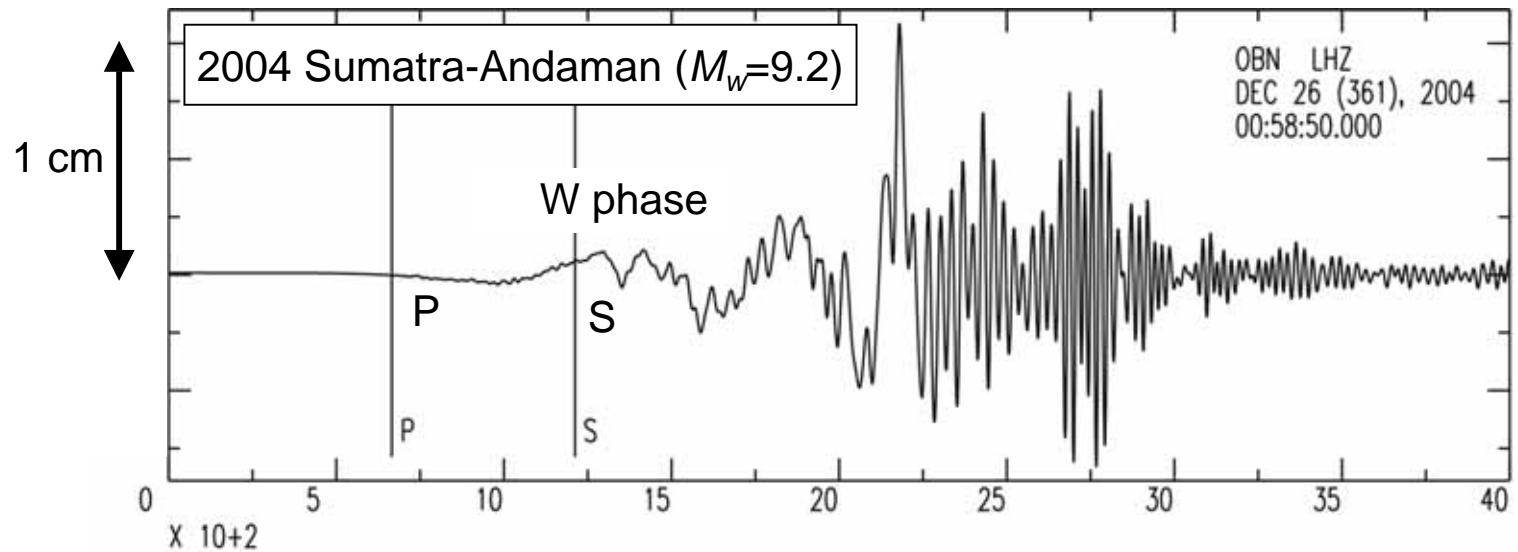


Problem with using short-period waves for tsunami warning of great earthquakes

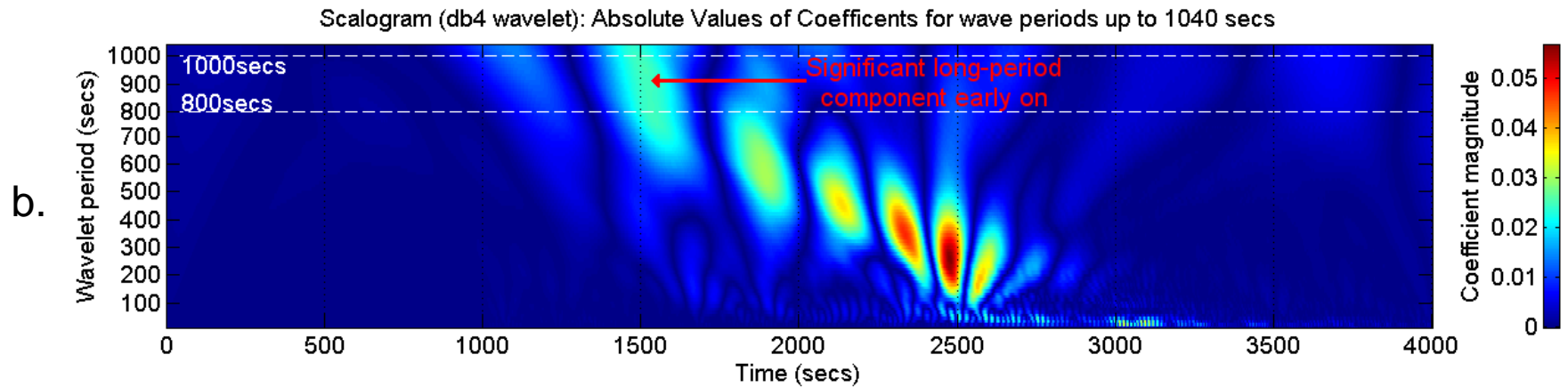
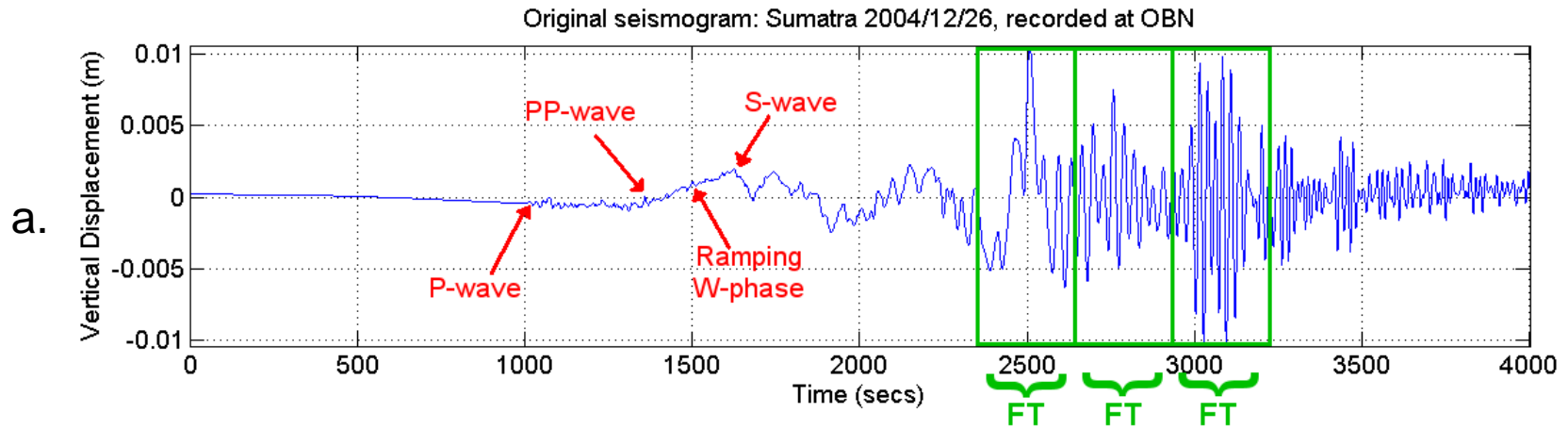
Short period ( $T \leq 200$  sec) magnitude saturates.

i.e., cannot assess the true tsunamigenic potential of great earthquakes

# Diagnostics of Tsunami Potential



# Wavelet Scalogram of the Sumatra-Andaman Earthquake

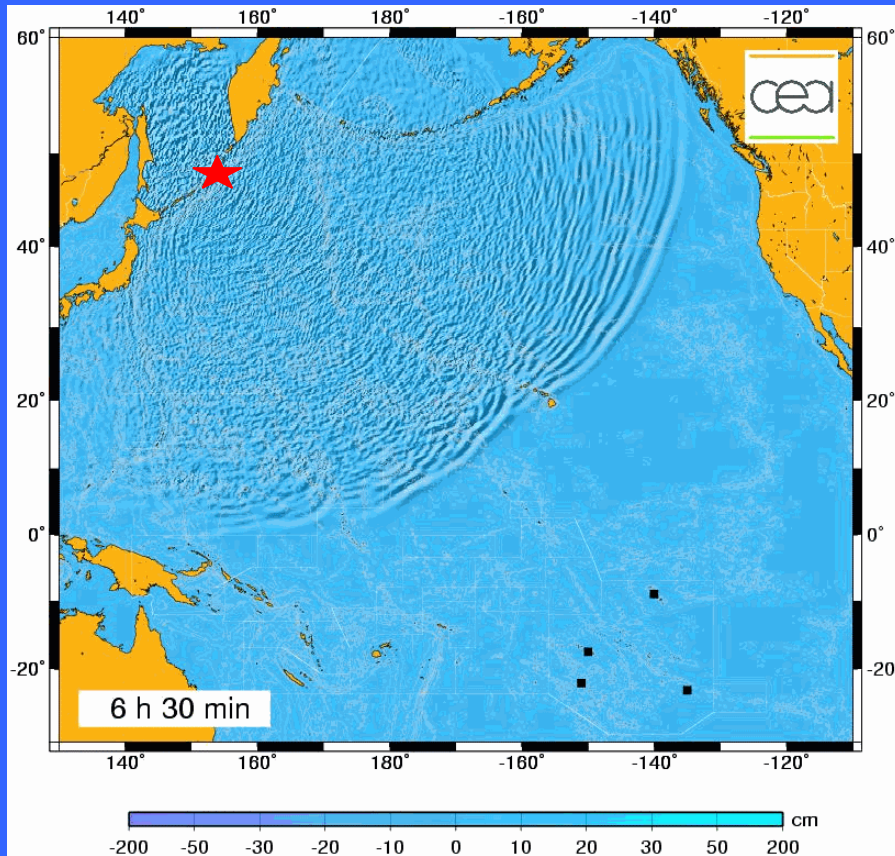


# Recent Accomplishments:

- Tsunami Warning of Nov. 15, 2006 Kuril Is. Earthquake ( $M_w=8.3$ )
- NIED/JMA Seismic Early Warning
- Tsunami Warning of July 17, 2006 Java Tsunami Earthquake

# Nov. 15, 2006 Kuril I s. Earthquake, $M_w=8.3$

## JMA Tsunami Warning



8:15 PM Origin time

8:29 PM Warning issued

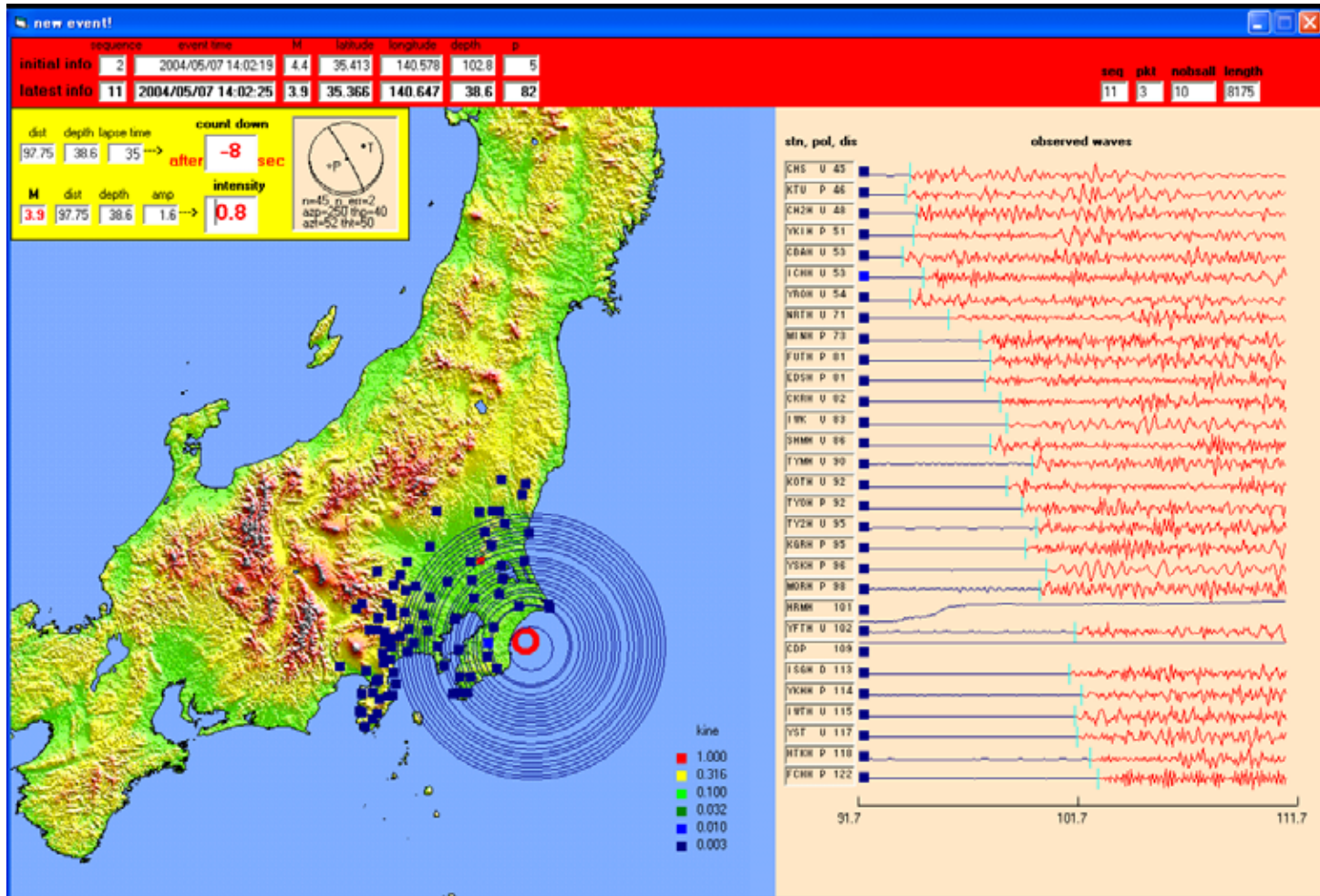
Wave height estimated

From this time on: NHK continuously broadcasted update of warning.

Entire Japanese population was given minute by minute update.

# Real-time Earthquake Information System (NIED)

## Warning for ground shaking before it starts





July 17, 2006, Java



15:19 Earthquake

~15:30 BMG announces that there is no danger of a tsunami (M6.8)

15:36 Pacific Tsunami Warning Center issues local watch for Indonesia and Australia (M7.2)

15:46 JMA issued tsunami watch for Indian Ocean (same as PTWC message)

~16:15 Tsunami hit Pangandaran

From Jim Mori



# Conclusion

- Great earthquakes are rare but can be extremely damaging
- Long-term monitoring for such events is difficult

Because of rarity,

Network for only monitoring purposes is impractical.

Insufficient knowledge, inadequate methodology

More research and development are necessary.

- Instrument Network

Data should be open to researchers and should be constantly used. Prerequisite for reliable operation.

Deployment-operation-maintenance-research should be supported as a whole.

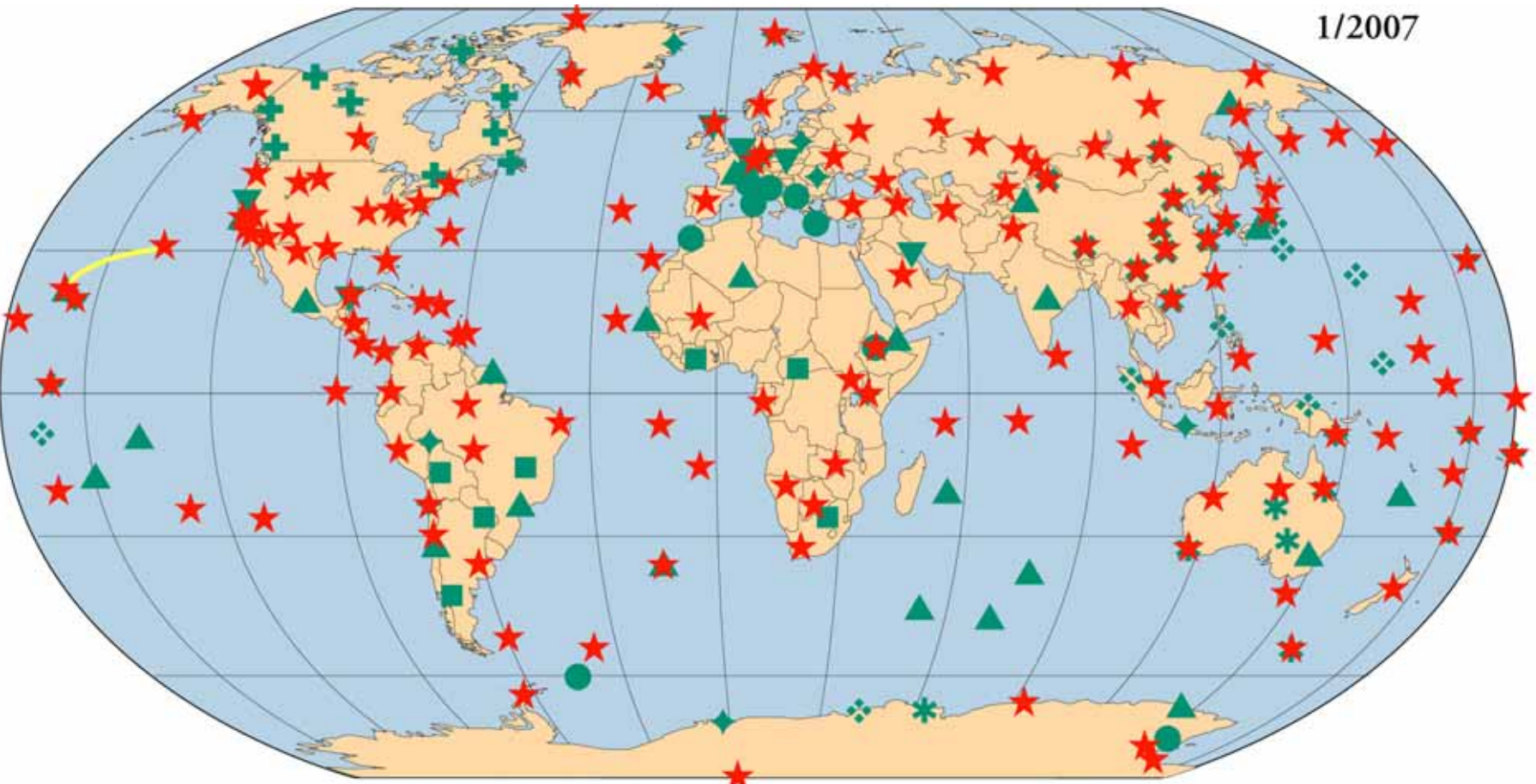
# Backbone Global Seismic Network and FDSN Stations (211 stations)

More than 500 stations, available online to seismologists

More than 100 stations, not easily available (requires special arrangement)

(FDSN: Federation of Digital Seismic Network)

1/2007



- |          |           |        |        |         |       |       |      |       |
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End

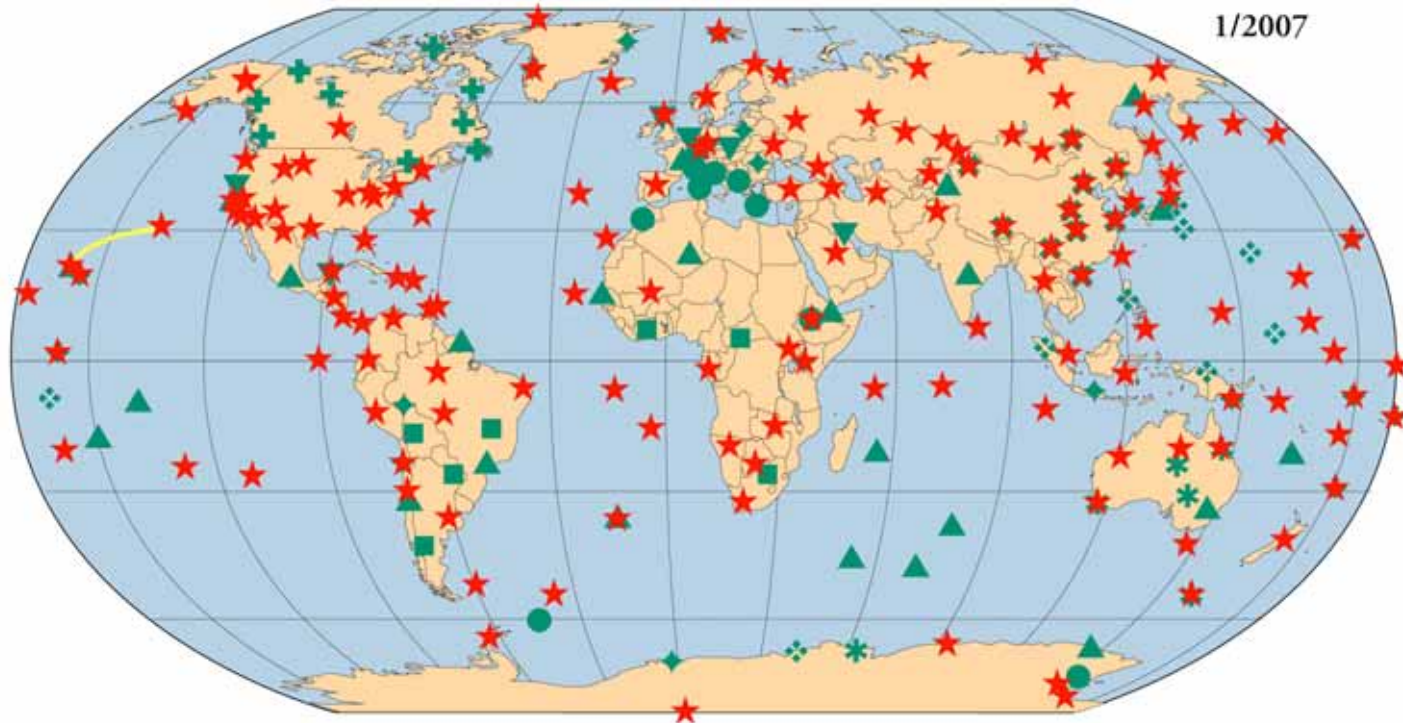
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## International Federation of Digital Seismograph Networks



IRIS GSN	Australia	Canada	France	Germany	Italy	Japan	U.S.	Other
★	✱	+	▲	◆	●	❖	■	▼





## Summary

- Great earthquakes are rare but can be extremely damaging
- Example: 2004 Sumatra-Andaman Earthquake ( $M_w=9.2$ )

Global Network worked well

Technical difficulty, Lack of knowledge

- Long-term monitoring for such events is difficult
- Instrument Network

Deployment; Maintenance; Data Archive, Distribution, Exchange; Research should be budgeted together

Data should be constantly used by researchers