LECTURE 10

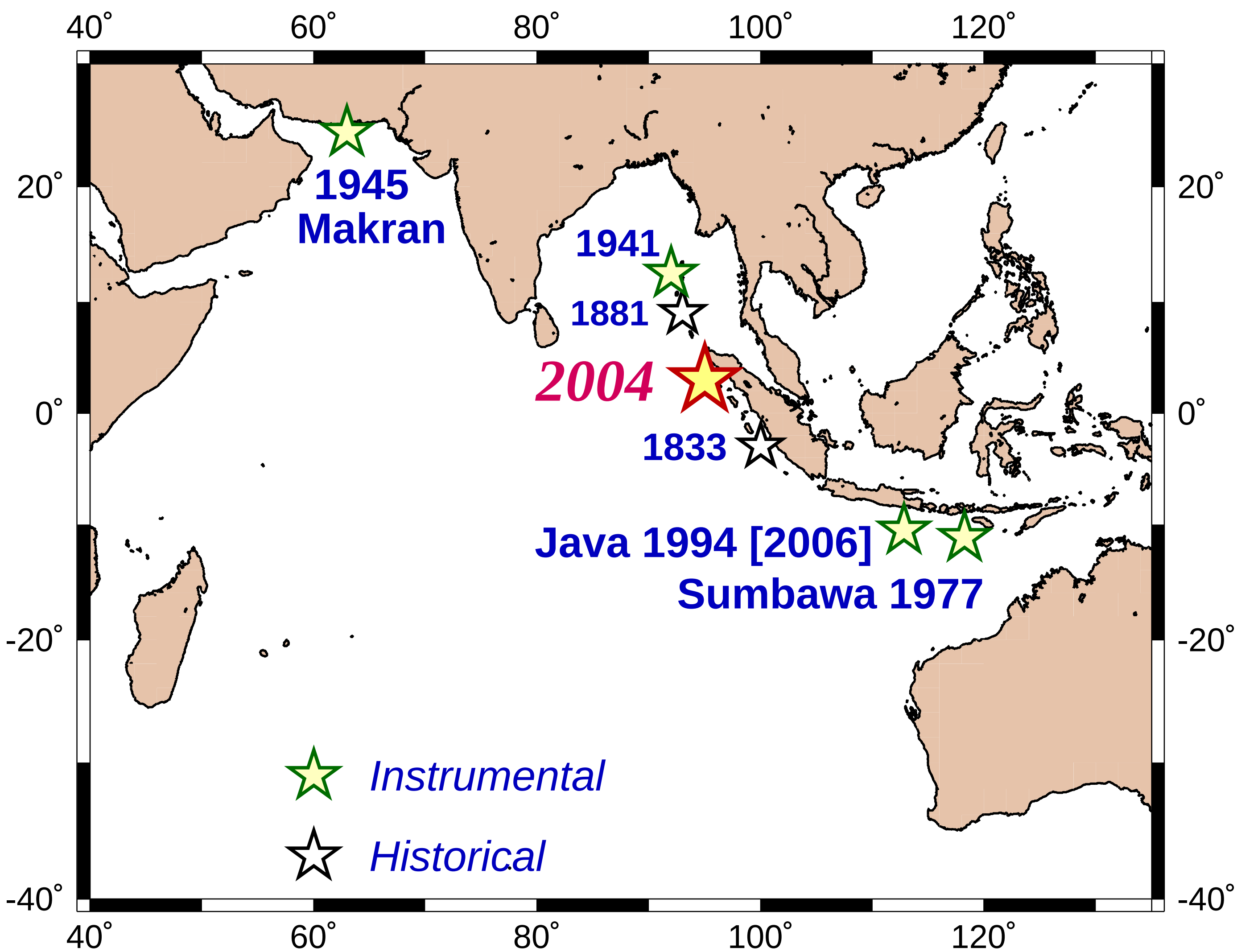
THE INDIAN OCEAN:

CASE STUDIES

and SCENARIOS

PREVIOUS FAR-FIELD TSUNAMIS KNOWN in the INDIAN OCEAN

- **1977, 1994 [2006]** *Sunda:* Damage in NW Australia; regional field.
- **1945** *Makran:* Decimetric in Seychelles, damage reported (unassessed) in Oman.
- **1941** *Andaman:* Reported damage in India [*Murty and Rafiq*, 1991], unconfirmed [*Ortiz and Bilham*, 2003].
- **1881** *Nicobar:* Decimetric in India.
- **1833** *Sumatra:* Damage reported in Seychelles — No instrumental records.



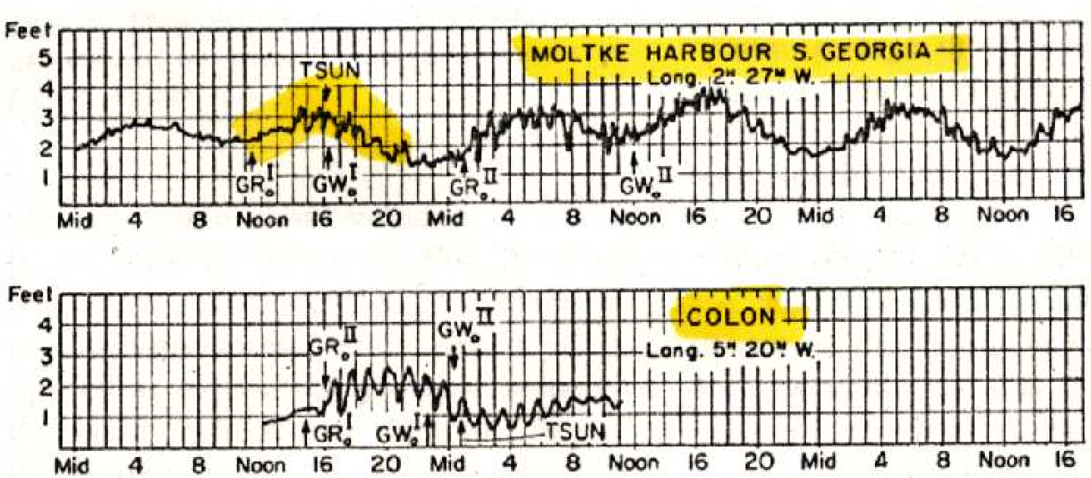
Volcanic Explosion at Sea

Krakatoa [Sunda Straits], 27 August 1883

Air-Sea Waves from the Explosion of Krakatoa

Abstract. *The distant sea disturbances which followed the explosion of Krakatoa are correlated with recently discovered atmospheric acoustic and gravity modes having the same phase velocity as long waves on the ocean. The atmospheric waves jumped over the land barriers and reexcited the sea waves with amplitudes exceeding the hydrostatic values. An explosion of 100 to 150 megatons would be required to duplicate the Krakatoa atmospheric-pressure pulse.*

[*Press and Harkrider*, 1966]



Catastrophic local tsunami

36,000 deaths, many of them in Batavia [Jakarta].

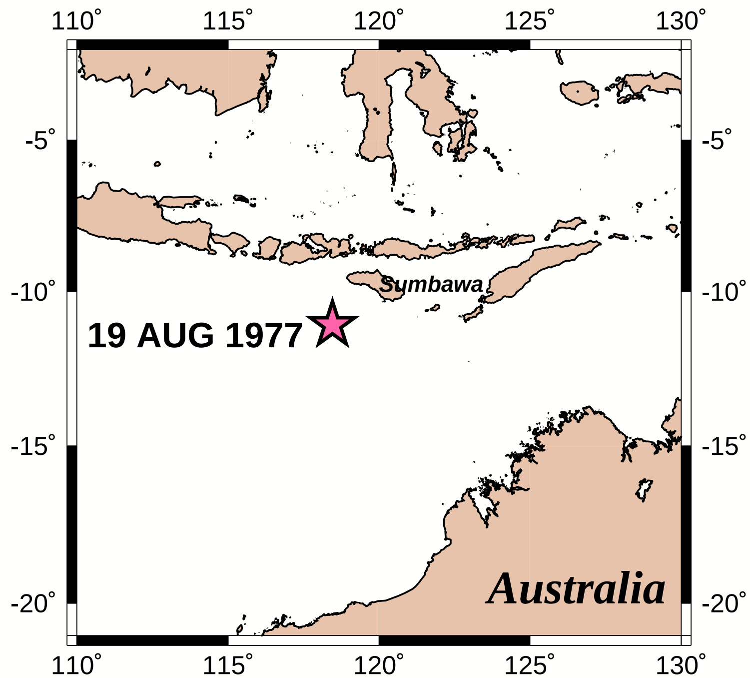
Tsunami recorded (on tide gauges) worldwide.

Locally, tsunami heights as great as 40 m, but relatively benign in the far field (10s of cm to 1 m).

Hint: Shorter wavelengths are dispersed during propagation.

SUMBAWA, Indonesia — 19 AUGUST 1977

- This was a normal faulting earthquake occurring seaward (South) of the trench in the buckling Australian plate.
- The tsunami was damaging locally, with several hundred fatalities and waves reported to reach 15 m on Sumbawa, as well as on the sparsely populated Northwestern coast of Australia, reaching 6 m at Cape Leveque (220 km North of Broome).



above - Coastal area of Sumbawa Island, near Lunyuk, devastated by August 19, tsunami wave.

below - Lunyuk Village, Sumbawa Island, destroyed by the August 19 tsunami. (Associated Press, Jakarta, Indonesia)

[*ITIC*, 1977]

FLORES, Indonesia — 12 DEC 1992

- This tsunami killed approximately 2000 people.

→ It featured very singular and interesting aspects.

The CASE of BABI ISLAND

Major Destruction in the Lee of the Wave

Direction of Tsunami Arrival

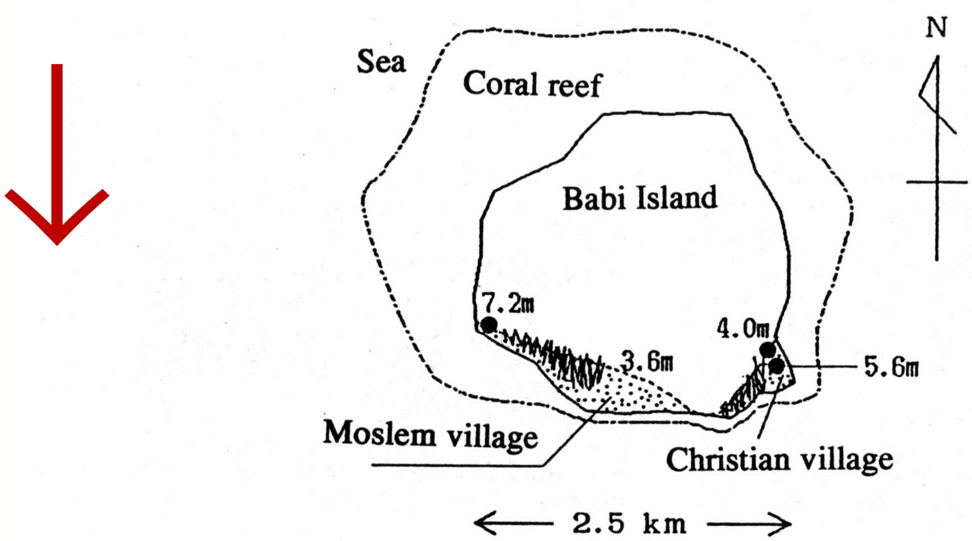


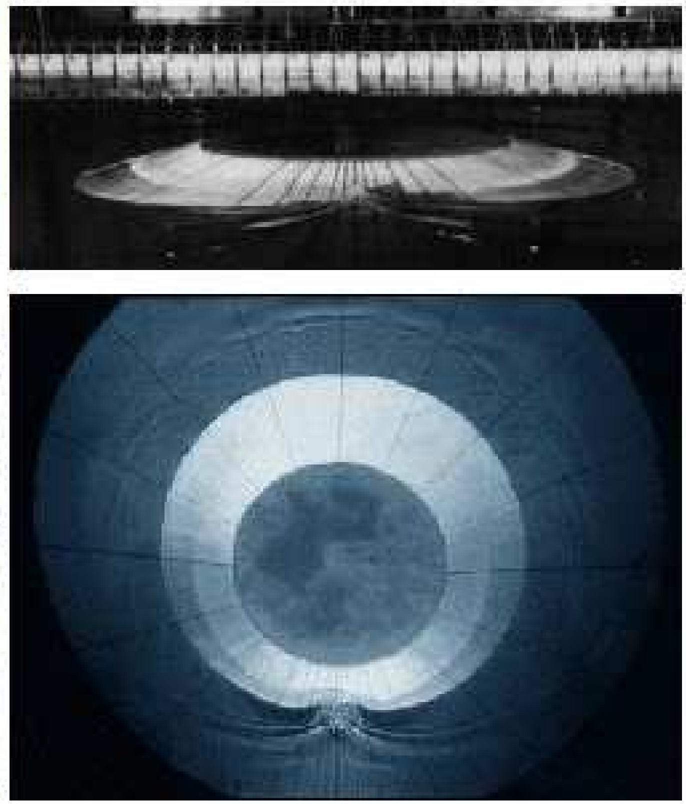
Figure 8
Map of Babi Island. There are two villages on the southern coast of this island. The observed tsunami heights are not extremely high and yet damage to the two villages was considerable.

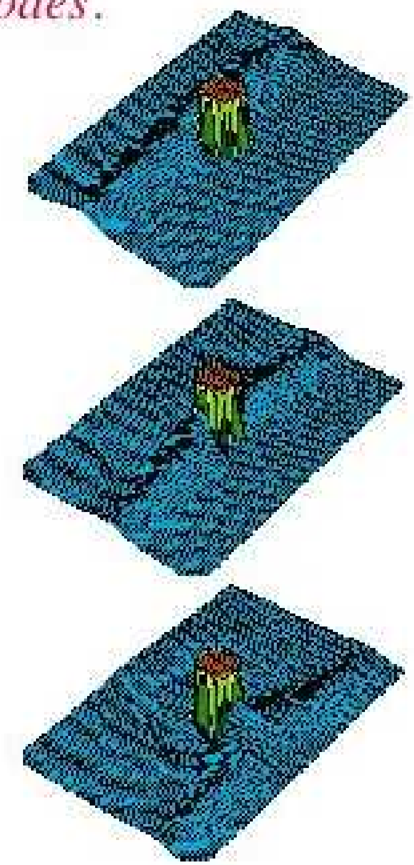
Flores, 1992: BABI Island (ctd.)

Enhanced runup on the lee side of Babi Island.

Realization of flow pattern in the laboratory.

Validation of first 2+1 D runup codes.





Flores, 1992: The case of **RIANGKROKO**

Locally Enhanced Run-up Reaches Catastrophic Height of

26 m

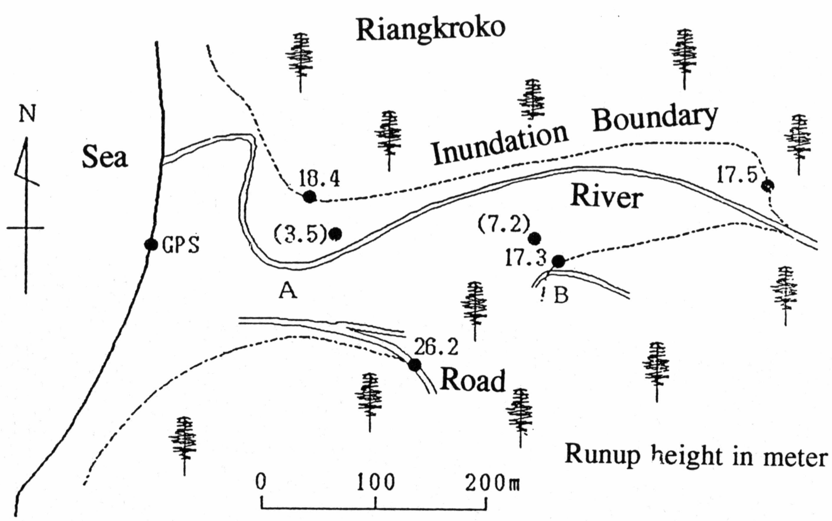
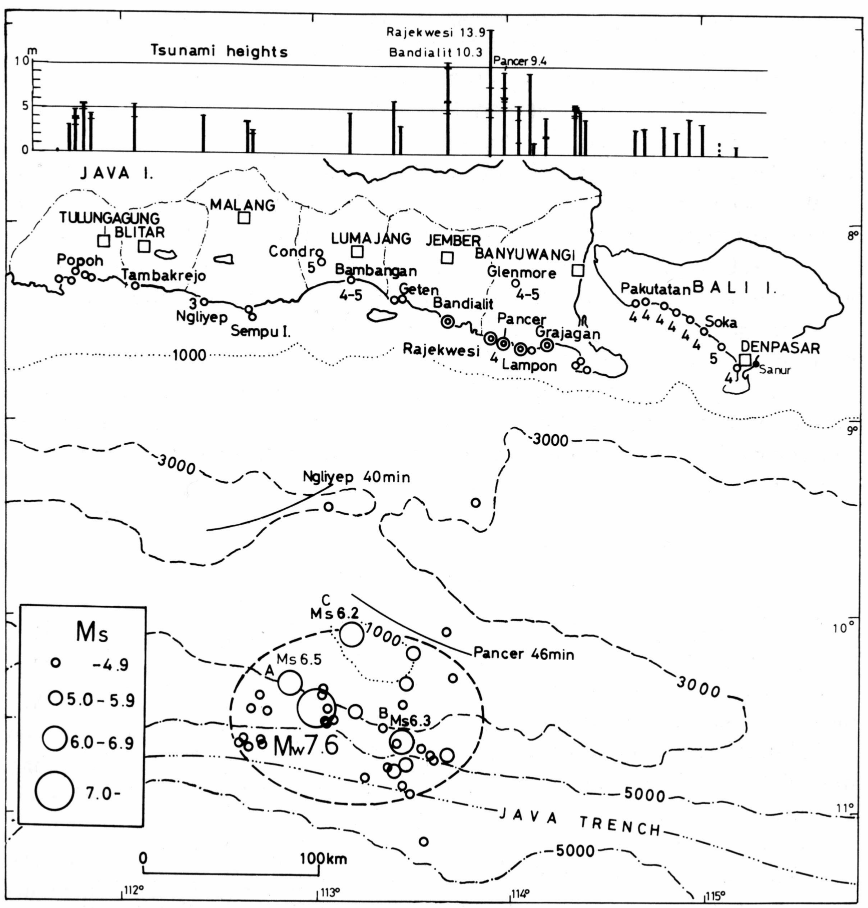


Figure 6
Inundation area and tsunami runup at Riangkroko. A maximum tsunami height of 26.2 m was measured. All houses were completely washed away by the tsunami. Numerals in parenthesis are the inundated tsunami heights.

Interpreted as due to local submarine landslide

EAST JAVA — 02 JUNE 1994

- "Tsunami Earthquake" in an area where no large interplate thrust events are known.
- Tsunami reached 13 m on coast and killed about 260 people.
- Tsunami emphasized danger of overflow from both sides of a low-lying isthmus [harbinger of the Banda Aceh situation].



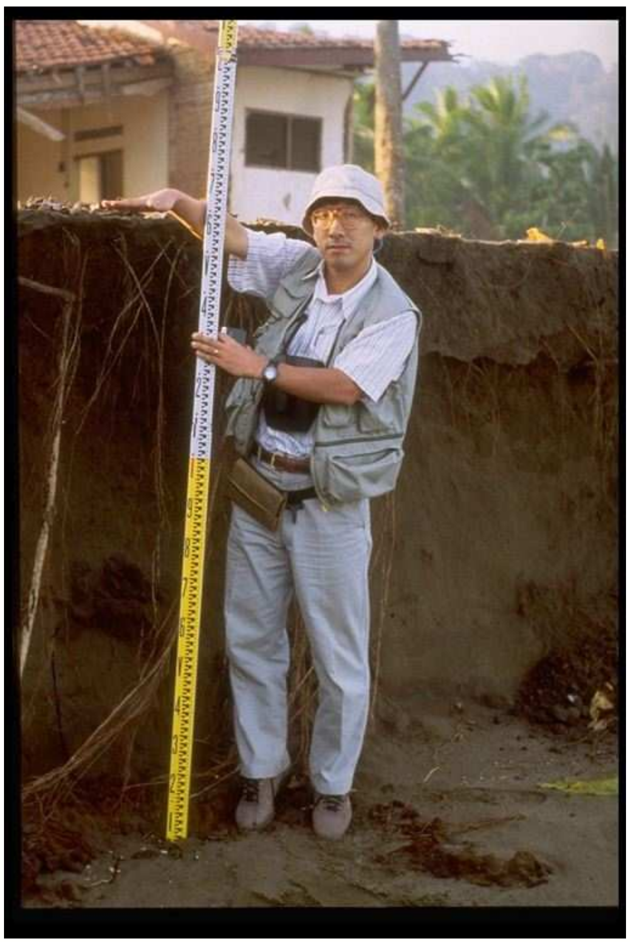
EAST JAVA — 02 JUNE 1994 (ctd.)

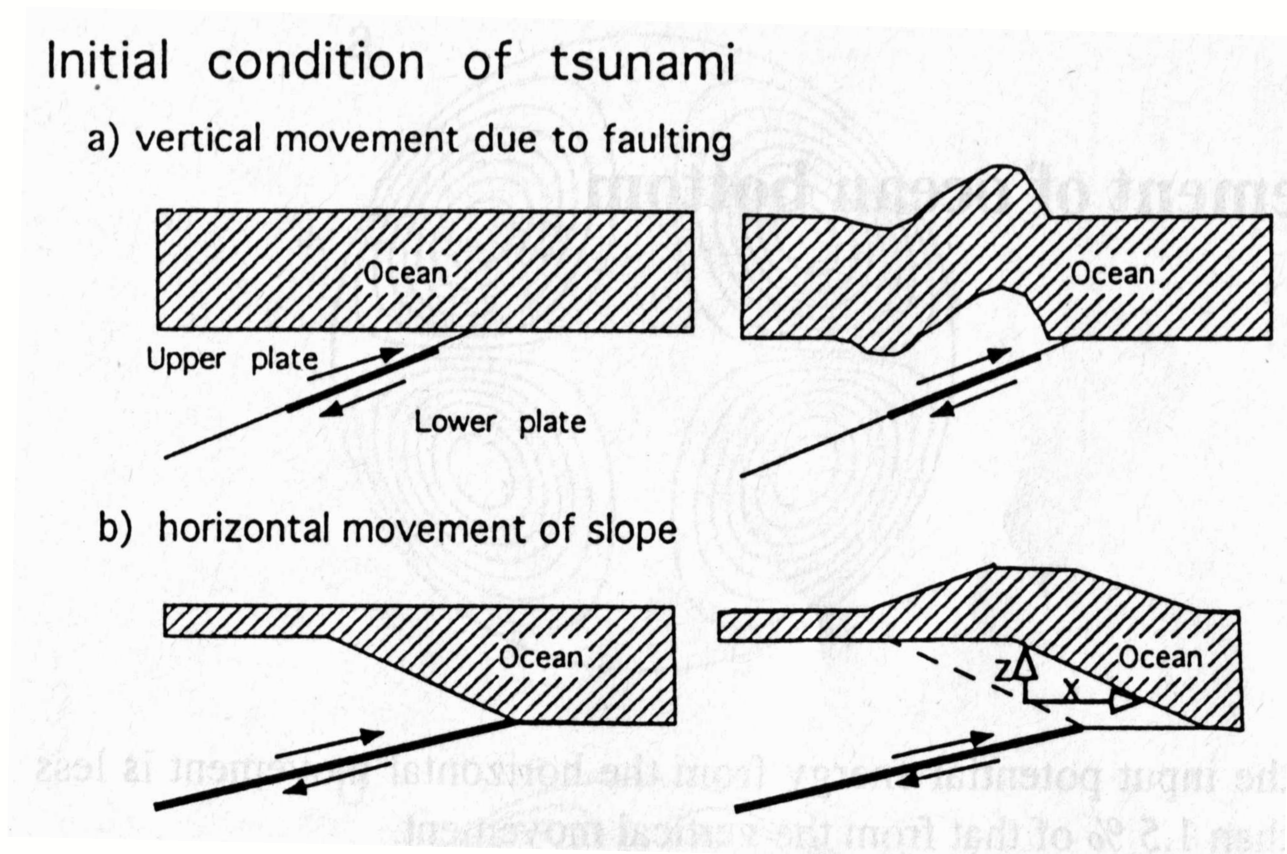
- Tsunami provided spectacular cases of deep scouring on affected beaches.

  [*F. Imamura*]

- Epicenter location in the vicinity of steep sea floor (including major seamount) suggested the contribution of horizontal ground displacement to the mechanism of tsunami generation.

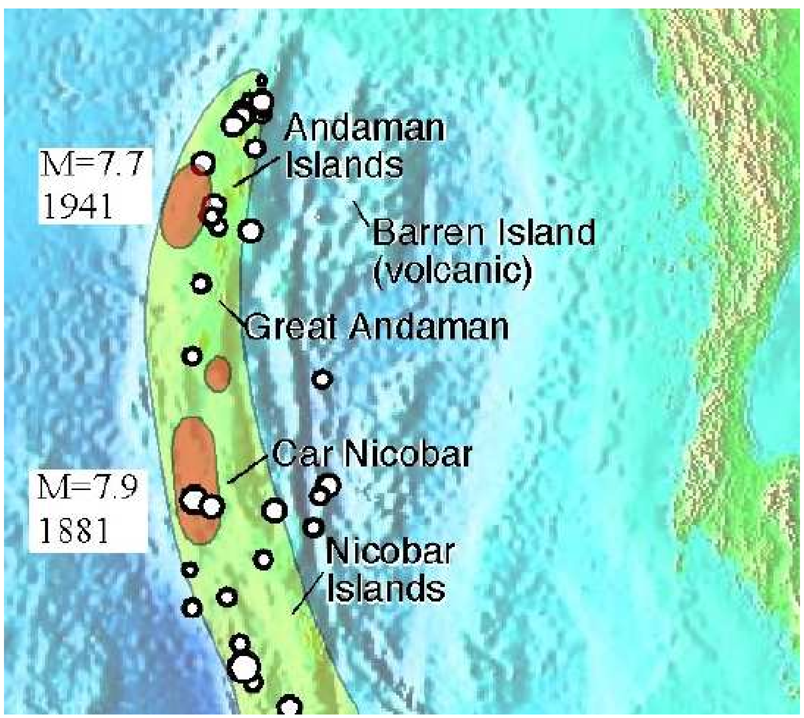
  [*Tanioka and Satake*, 1996]

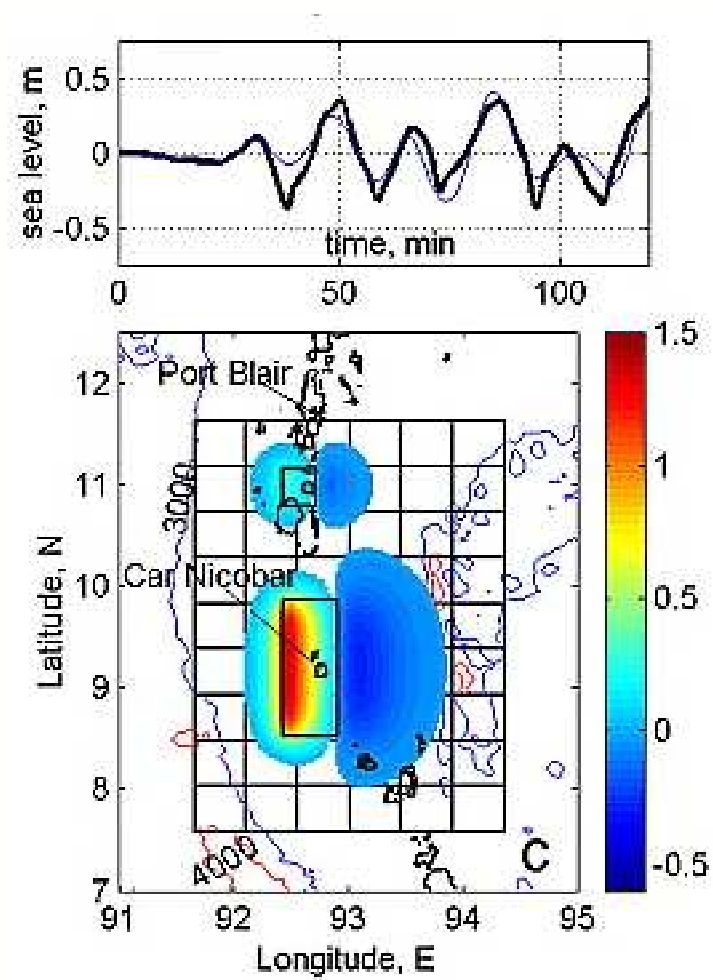




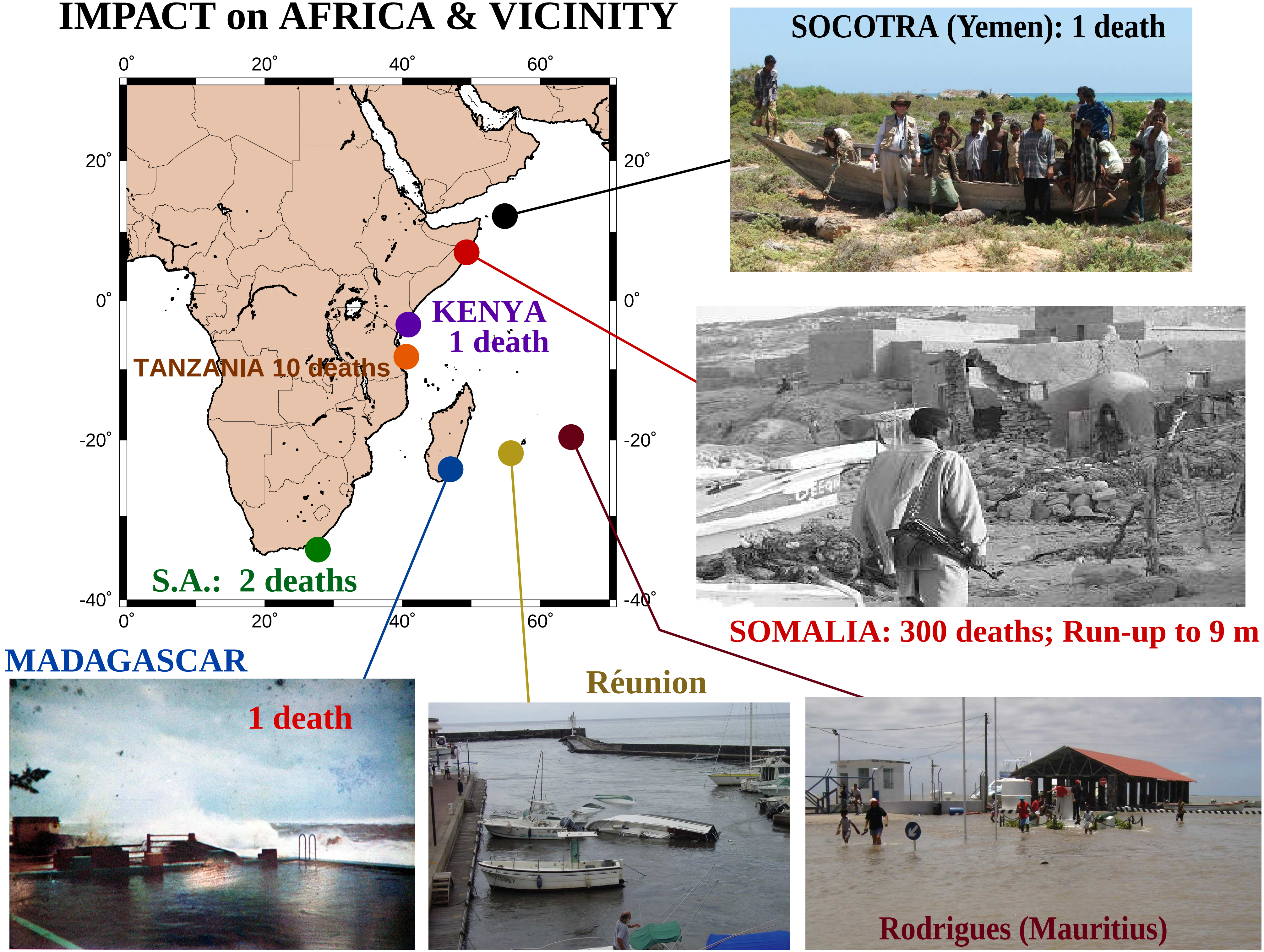
The HISTORICAL ANDAMAN EARTHQUAKES 31 DEC 1881 and 26 JUNE 1941

- These two events are reported as having generated local and regional tsunamis.
- For the 1881 event, *Ortiz and Bilham* [2003] modeled tidal gauge data to infer a relatively moderate seismic moment ($M_0 = 7 \times 10^{27}$ dyn-cm).
- By contrast, it seems that the 1941 event was smaller, and reports of its tsunami in India could not be confirmed.





IMPACT on AFRICA & VICINITY

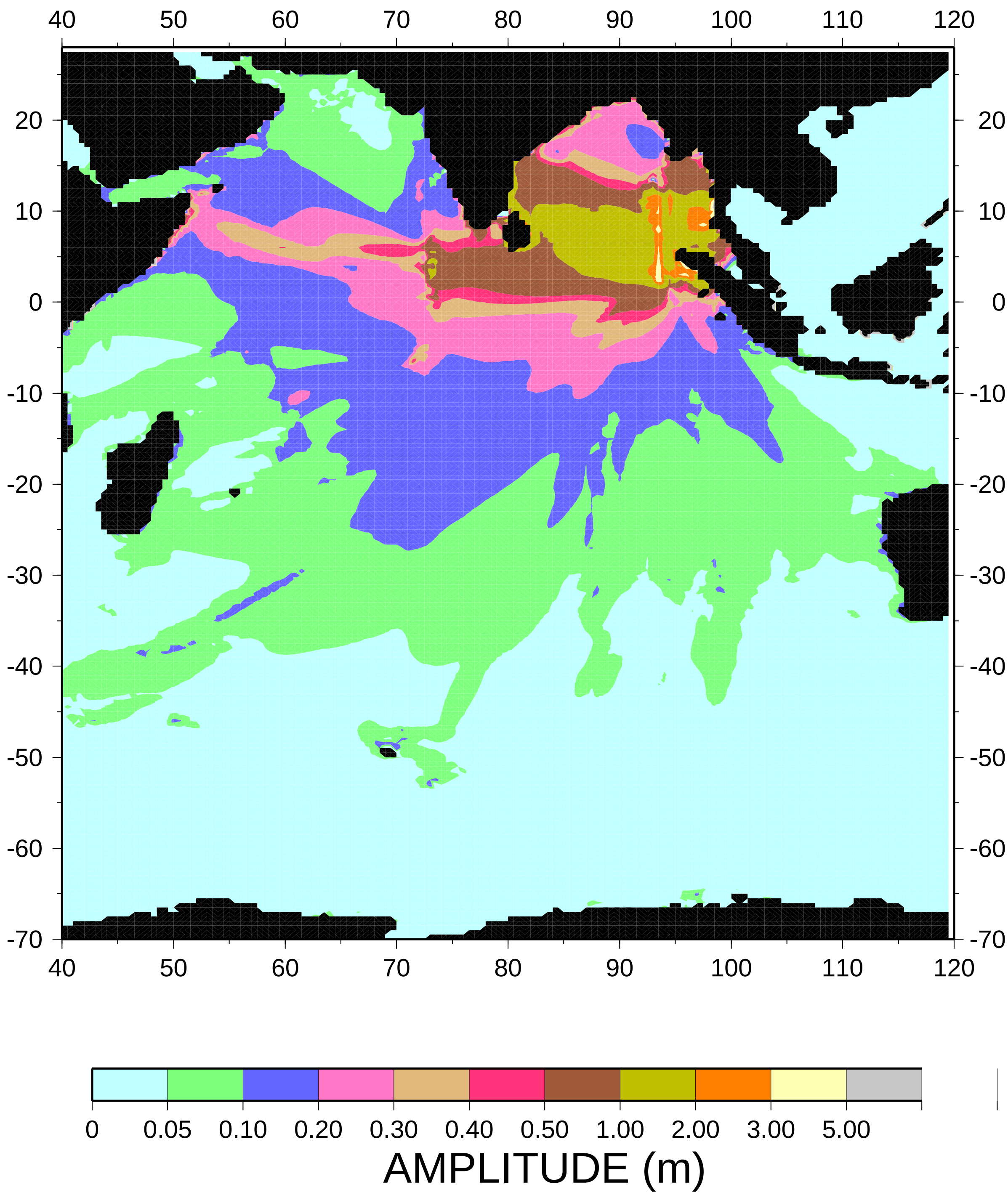


ORIGIN of TSUNAMI FAR-FIELD DISTRIBUTION

- *Source Directivity*

  Perpendicular to Fault

- *Focusing* by Bathymetry



WHAT CAN WE EXPECT IN THE FUTURE ?

Problem : Predict Largest Earthquake which may occur along a given subduction zone

$\longrightarrow$ We thought we knew how to do it in the context of Plate Tectonics

SUMATRA CHANGED IT ALL

LESSONS in TECTONICS

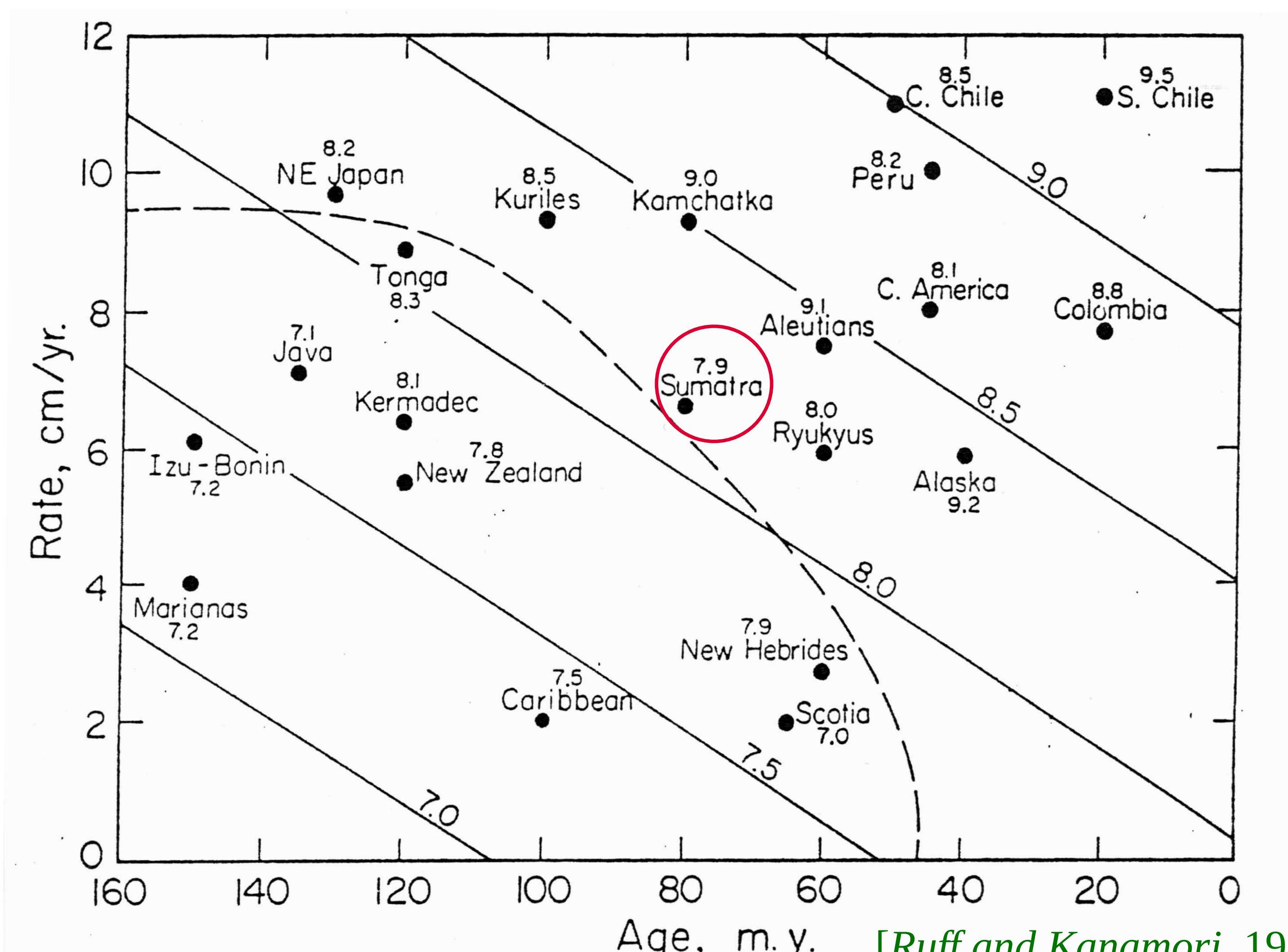
1. Mega-earthquakes occur in unsuspected areas

The 2004 [and 2005] **Sumatra earthquake[s] violated the concept of a**

maximum expectable

subduction earthquake controlled by

***plate age* and *convergence rate*.**

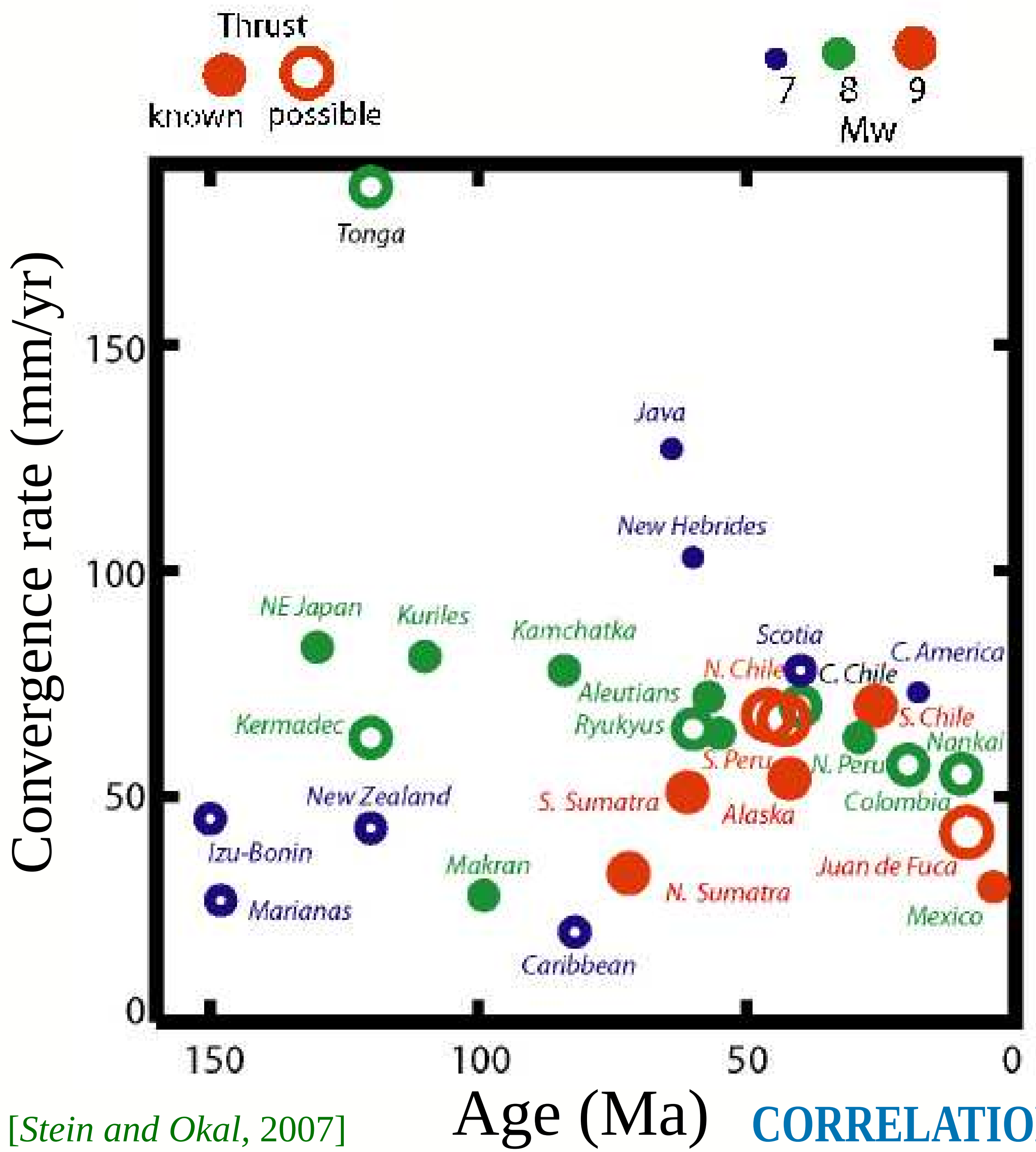


[*Ruff and Kanamori*, 1980]

Modern parameters: **> 55 Ma; 5 cm/yr**

Would predict Maximum **8.0−8.2 not ≥ 9...**

UPDATING the RUFF-KANAMORI DIAGRAM ?



[*Stein and Okal*, 2007]

Over the past 25 years:

→ **NEW RATES**

e.g., South Chile: **70** mm/yr *vs.* 111
South Peru: **67** mm/yr *vs.* 100
Tonga (20°S): **185** mm/yr *vs.* 89
Vanuatu: **103** mm/yr *vs.* 27

→ **NEW AGES**

e.g., Central America **18** Ma *vs.* 45

→ **OLD EVENTS REVISED**

e.g., 1906 Colombia [*Okal*, 1992]
1868 South Peru [*Okal et al.*, 2005]

→ **NEW LARGE E.Q. IDENTIFIED**

1700 Juan de Fuca [*Satake et al.*, 1996]
Tonga 1865 [*Okal et al.*, 2004]

→ **NOT ALL LARGEST E.Q. are INTERPLATE THRUSTS !**
Lesser Antilles, 1974 [*Stein et al.*, 1982]

CORRELATION: ONLY 40% *vs.* 80% [R & K]

- All attempts to correlate maximum observed earthquakes with simple physical parameters of plate boundaries have failed.

→ Maximum Earthquake could be controled

ONLY by AVAILABLE FAULT LENGTH

along plate boundary.

AND THEN, ...

Fragmentation of Rupture among subsequent earthquakes is

capricious

[*Ando*, 1975]

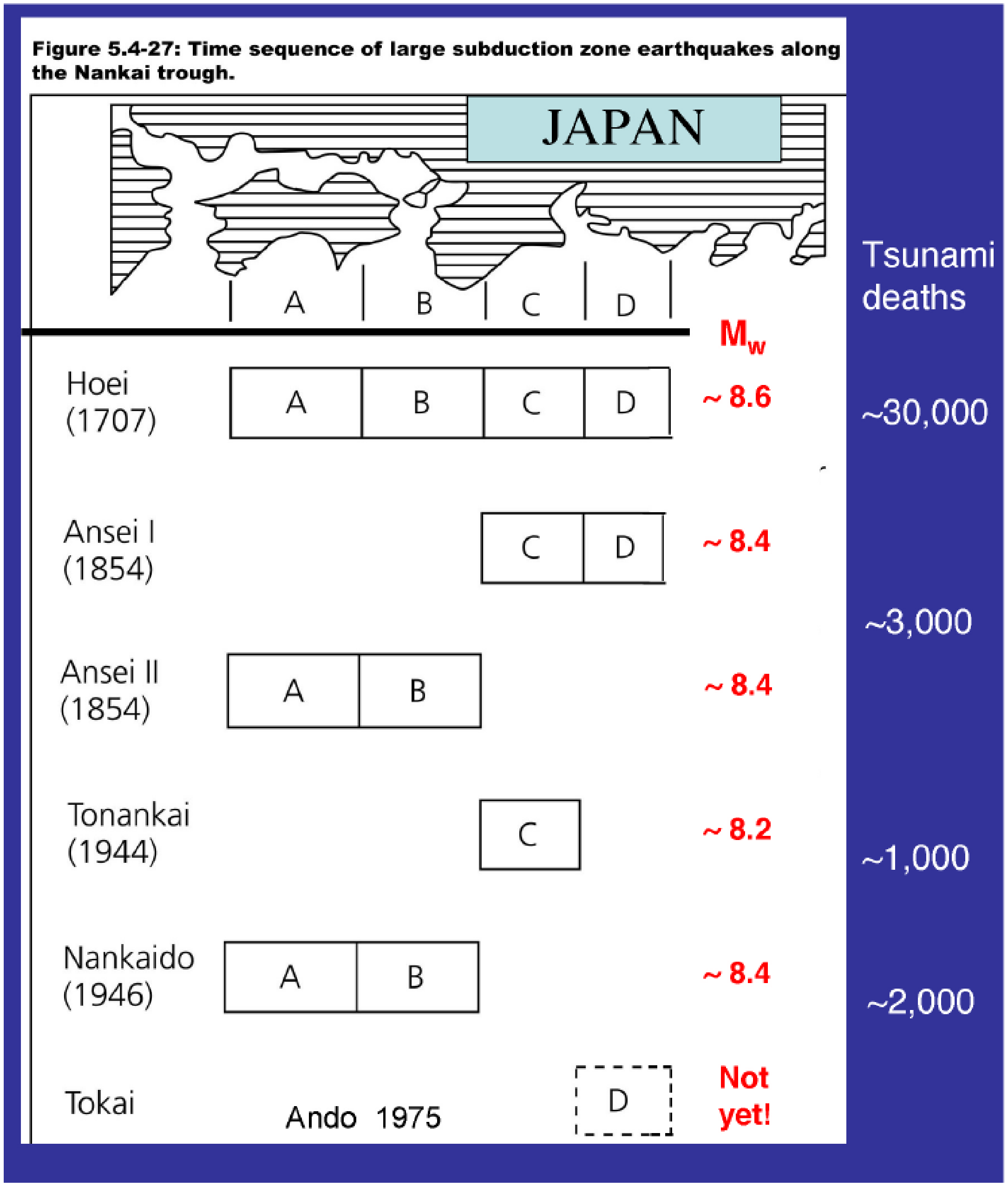
FAULT FRAGMENTATION is IRREGULAR: ANDO [1975]

Large earthquakes in Nankai province (SW Japan) may rupture through

one or **more** of **up to 4**

segments of the plate boundary.

Apparently, the pattern is random and cannot be predicted.



SIMULATING FAR-FIELD TSUNAMI RISK

in the INDIAN OCEAN

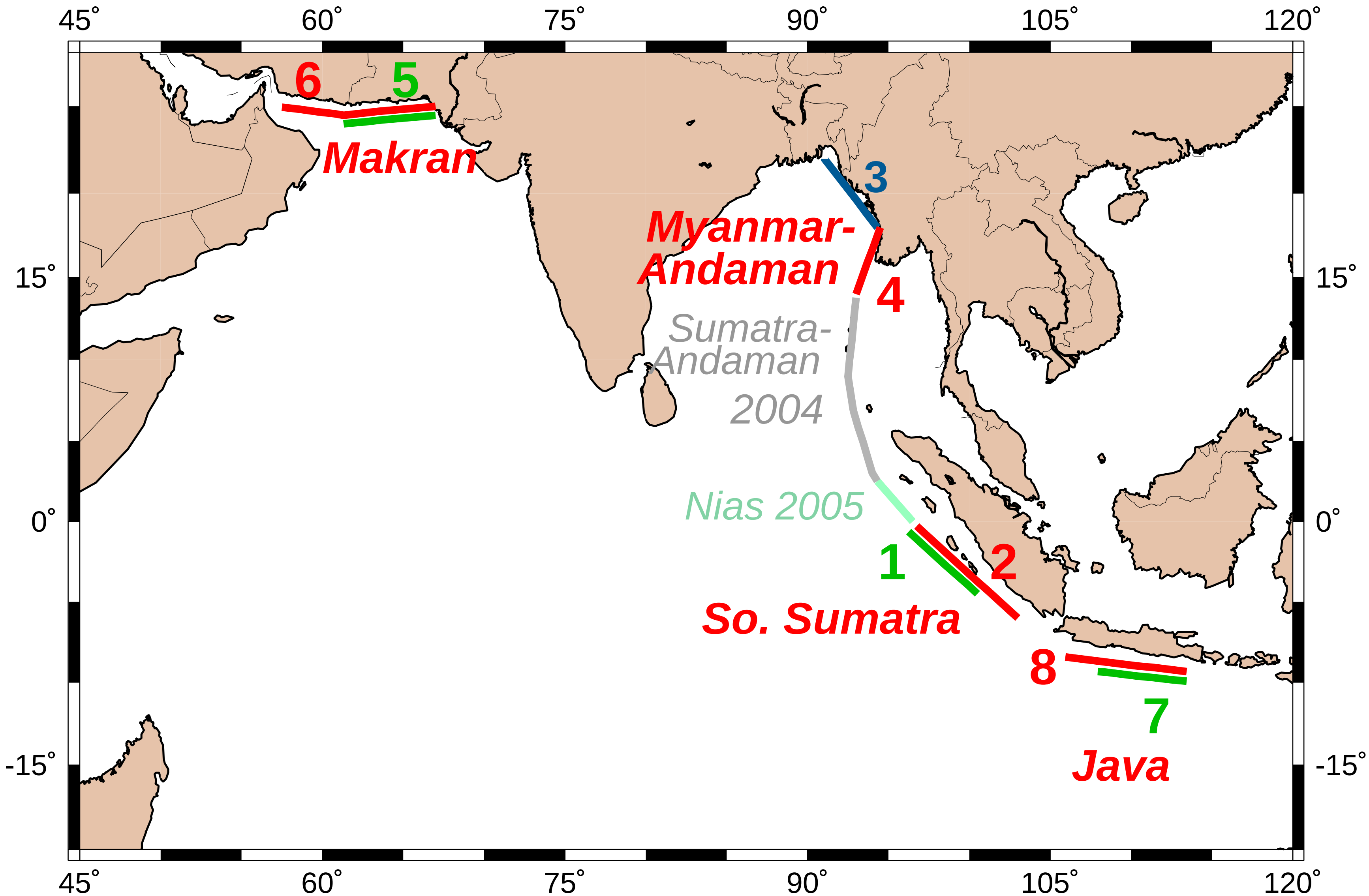
1. For each subduction zone, assess historical seismicity (mega-earthquakes only).

2. Define possible models of extreme events based on known tectonic features.

3. Run numerical simulations of propagation of tsunami generated in each scenario.

[**4.** *NOT PRESENTED HERE* -- On a small scale, run simulation of interaction of resulting waves with local structures — ports, bays, etc.]

SUBDUCTION ZONES CONSIDERED AS POTENTIAL SOURCES

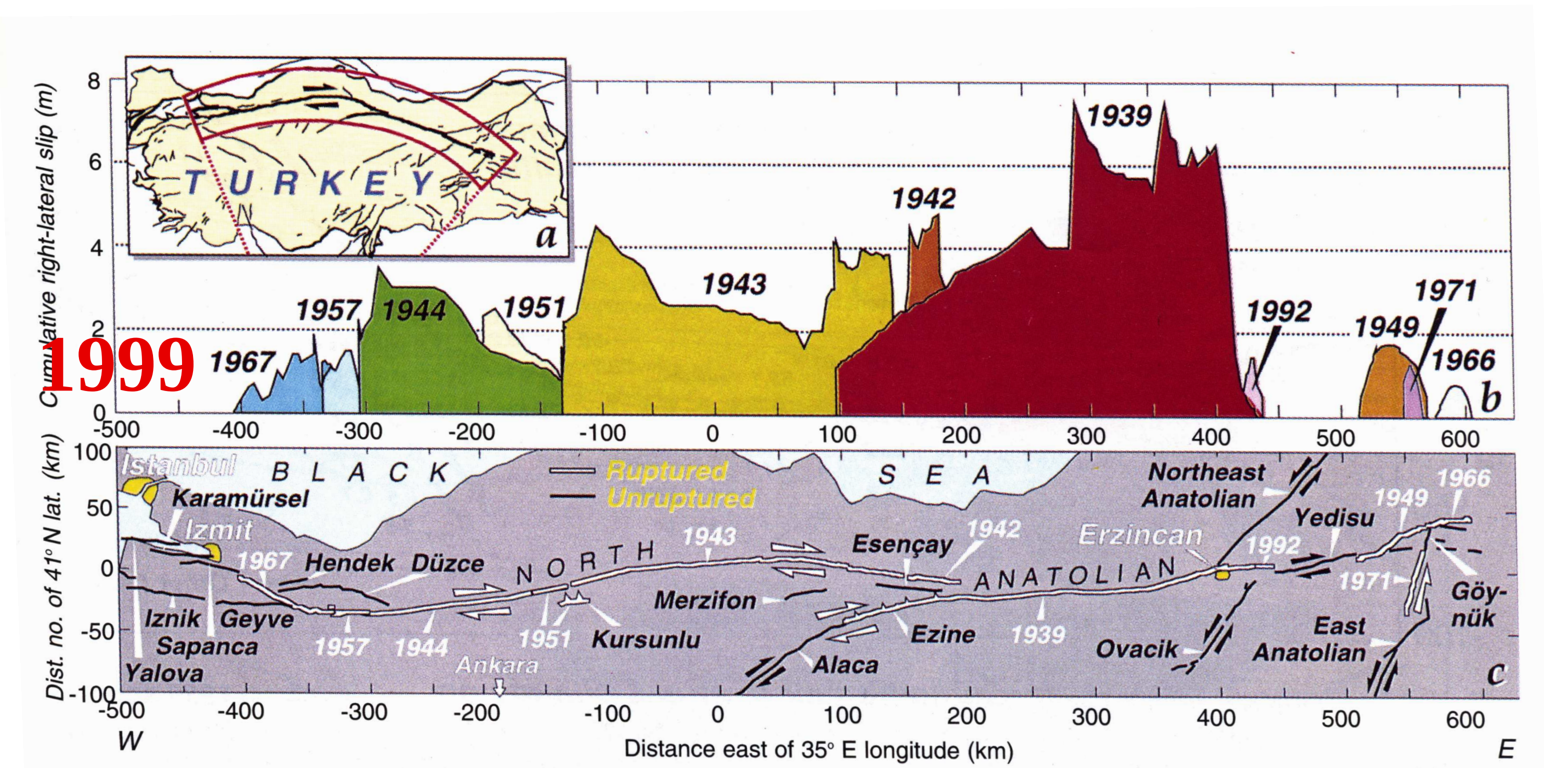


1. SOUTH SUMATRA

COULOMB STRESS TRANSFER WORKS !

Stress release during a major earthquake along one segment of fault can result in *transfer of Coulomb stress* to adjacent, "ripe" segment, thus precipitating (*"triggering"*) next earthquake.

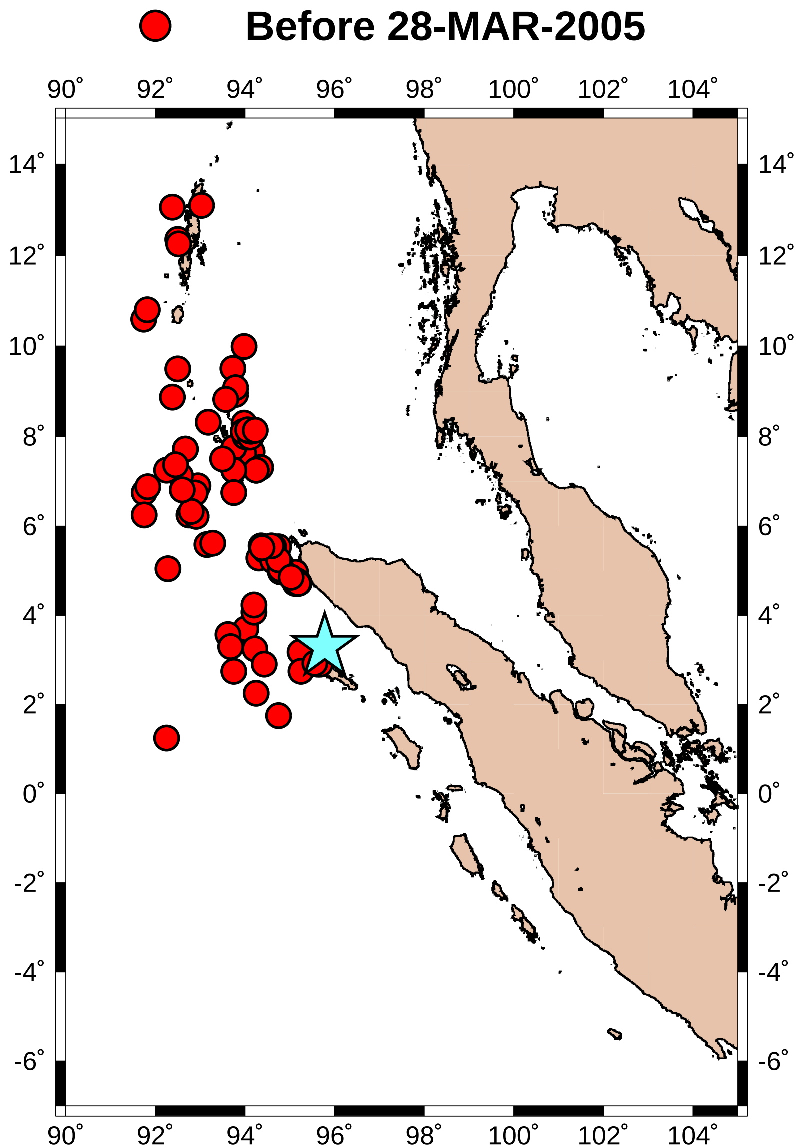
Recall Anatolian Fault from 1939 (east) to 1999 (Izmit) to 20xx (Marmara-Istanbul?)

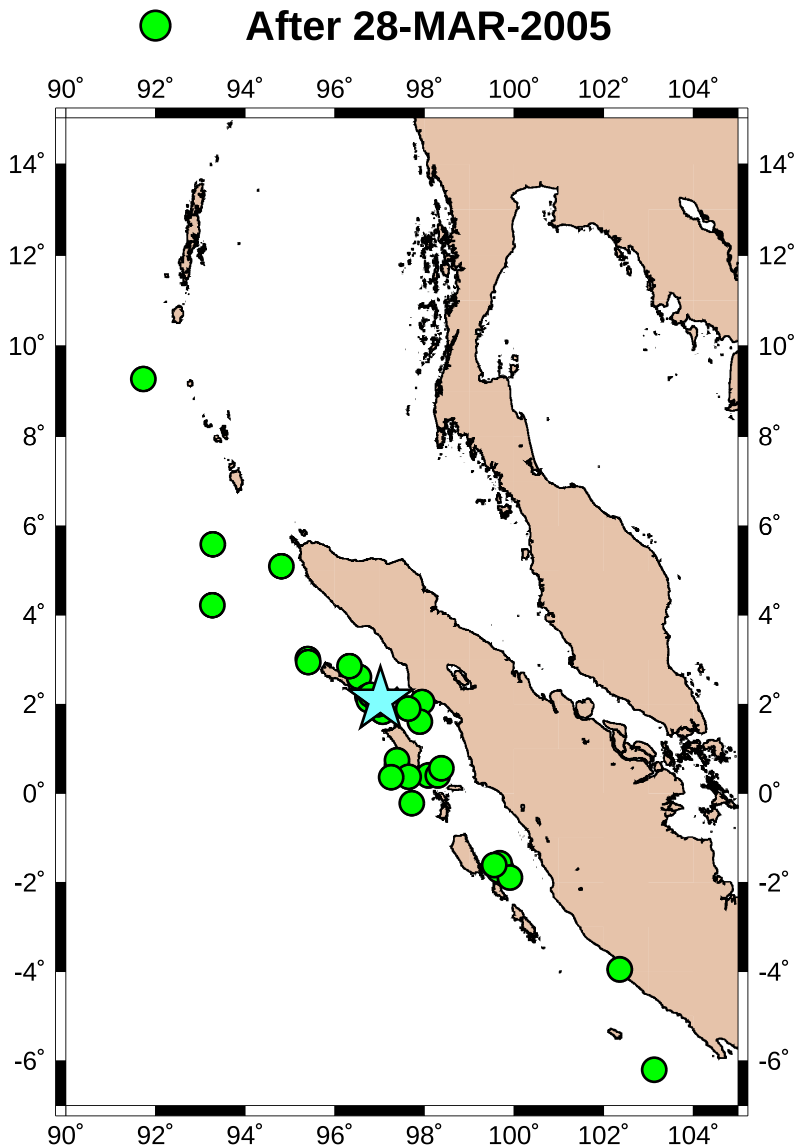


[*Stein et al.*, 1997]

28-MAR-2005 (SUMATRA-II) EARTHQUAKE PREDICTED ON THE BASIS of STRESS TRANSFER by McCLOSKEY *et al*. [*Nature*, 17 MAR 2005].

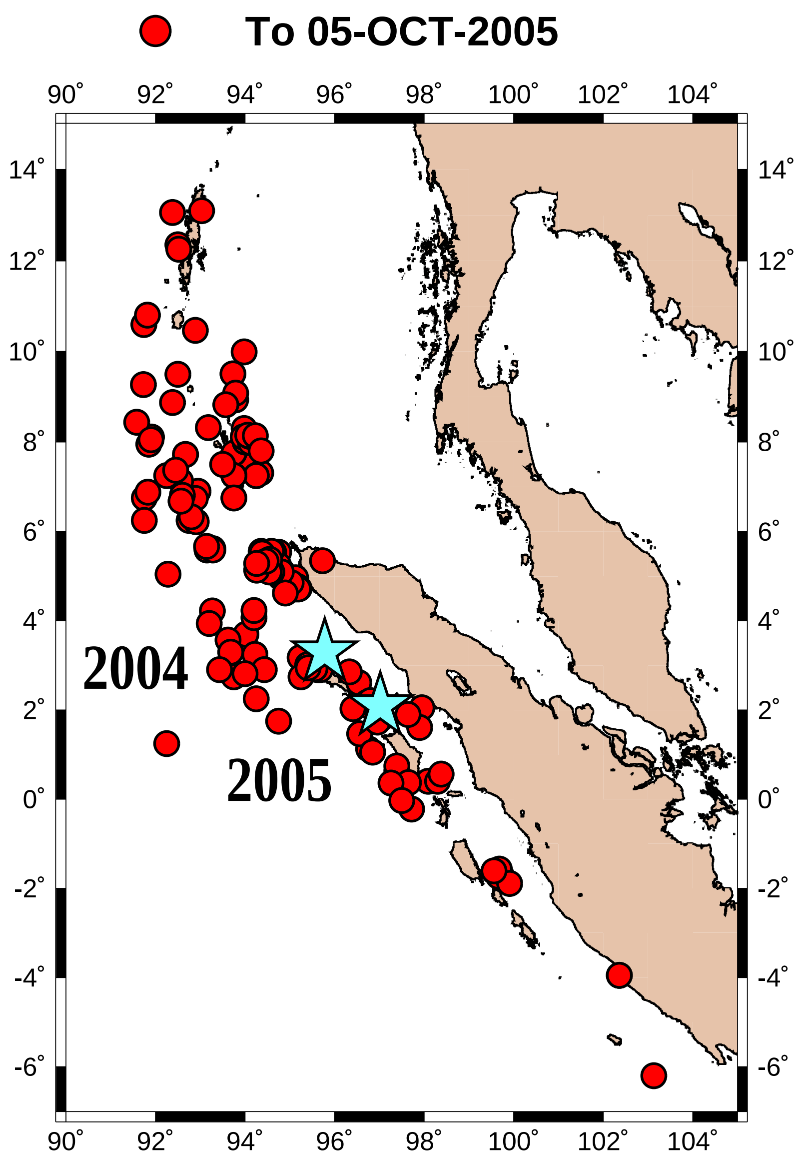
Events with CMT Solution (To 20-MAY-2005)



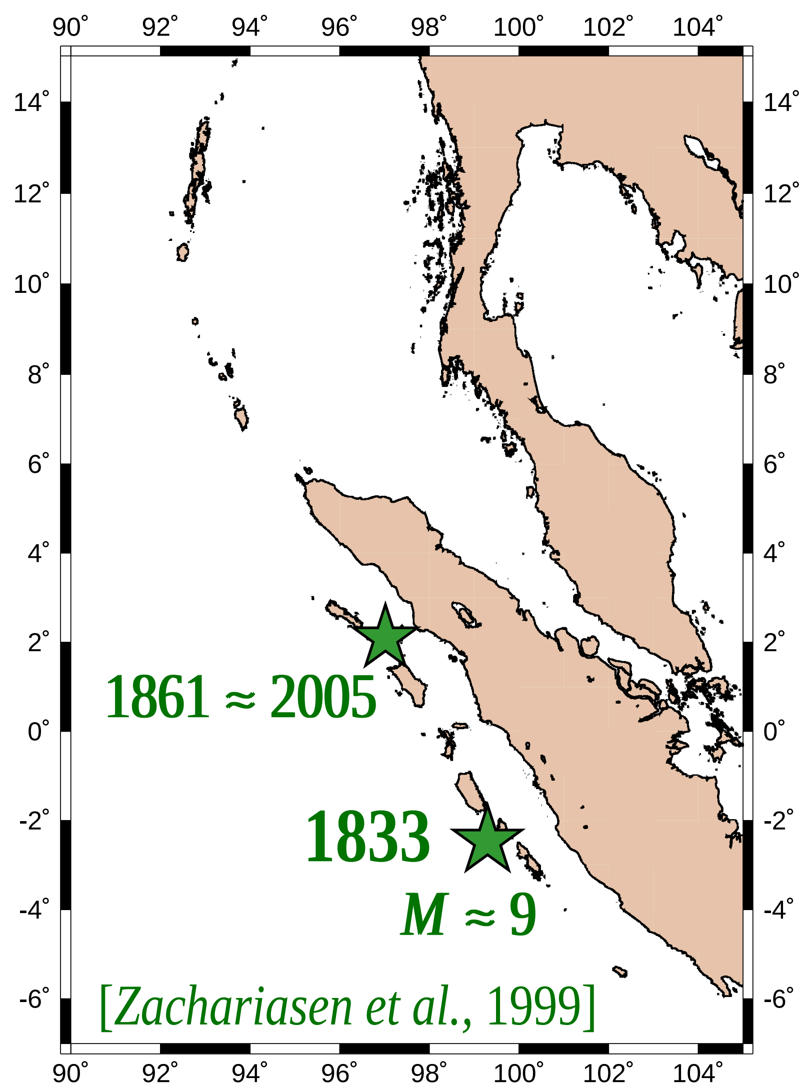


5. WHAT NEXT ?? KEEP LOADING FARTHER SOUTH...

PREDICT REPEAT of 1833 EARTHQUAKE ?? [*Nalbant et al.*, 2005].



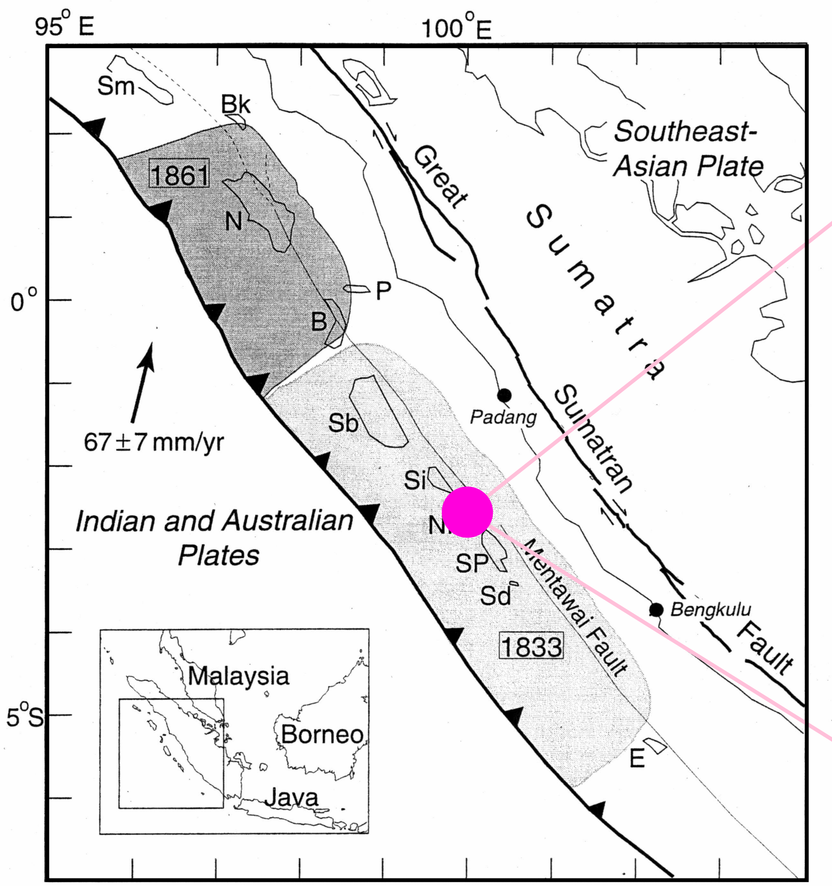
HISTORICAL EVENTS

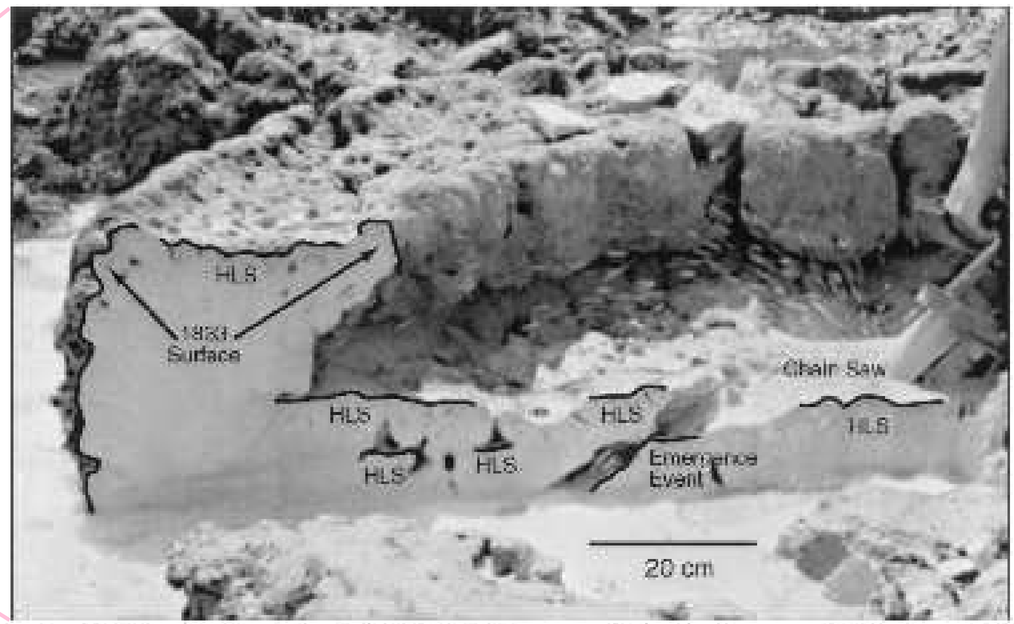


SOUTH SUMATRA: The 1833 Evidence

- *Zachariasen et al.* [1999] have used radiometric dating on corals uplifted on the islands lying off the coast of South Sumatra to quantify the 1833 earth-quake as involving a slip of 13 m.

This event generated a tsunami reported in the Seychelles [*Jackson et al.*, 2005].





[*Zachariasen et al.*, 1999]

- Our study models a repeat of the 1833 earthquake along the coast of Southern Sumatra.

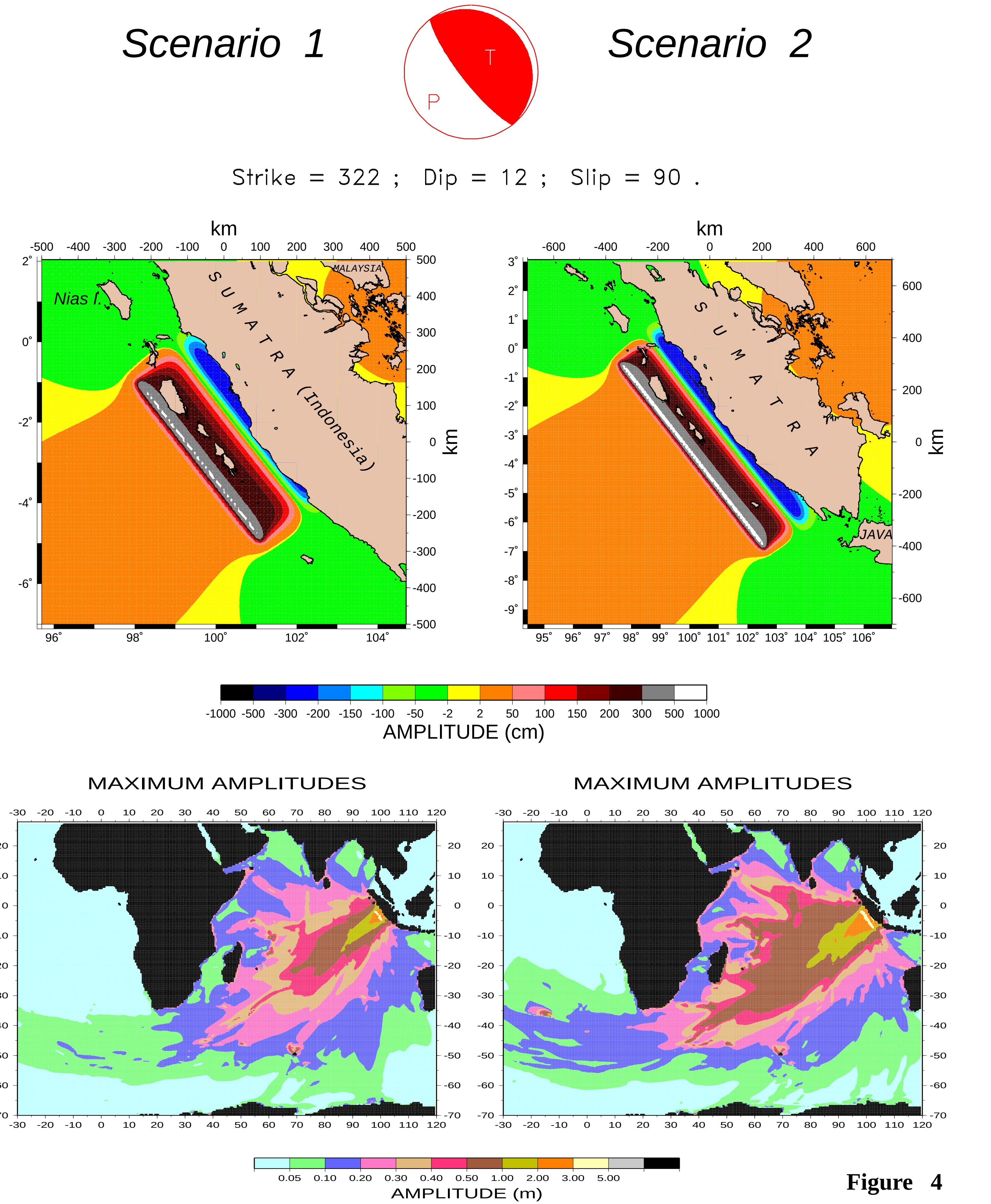
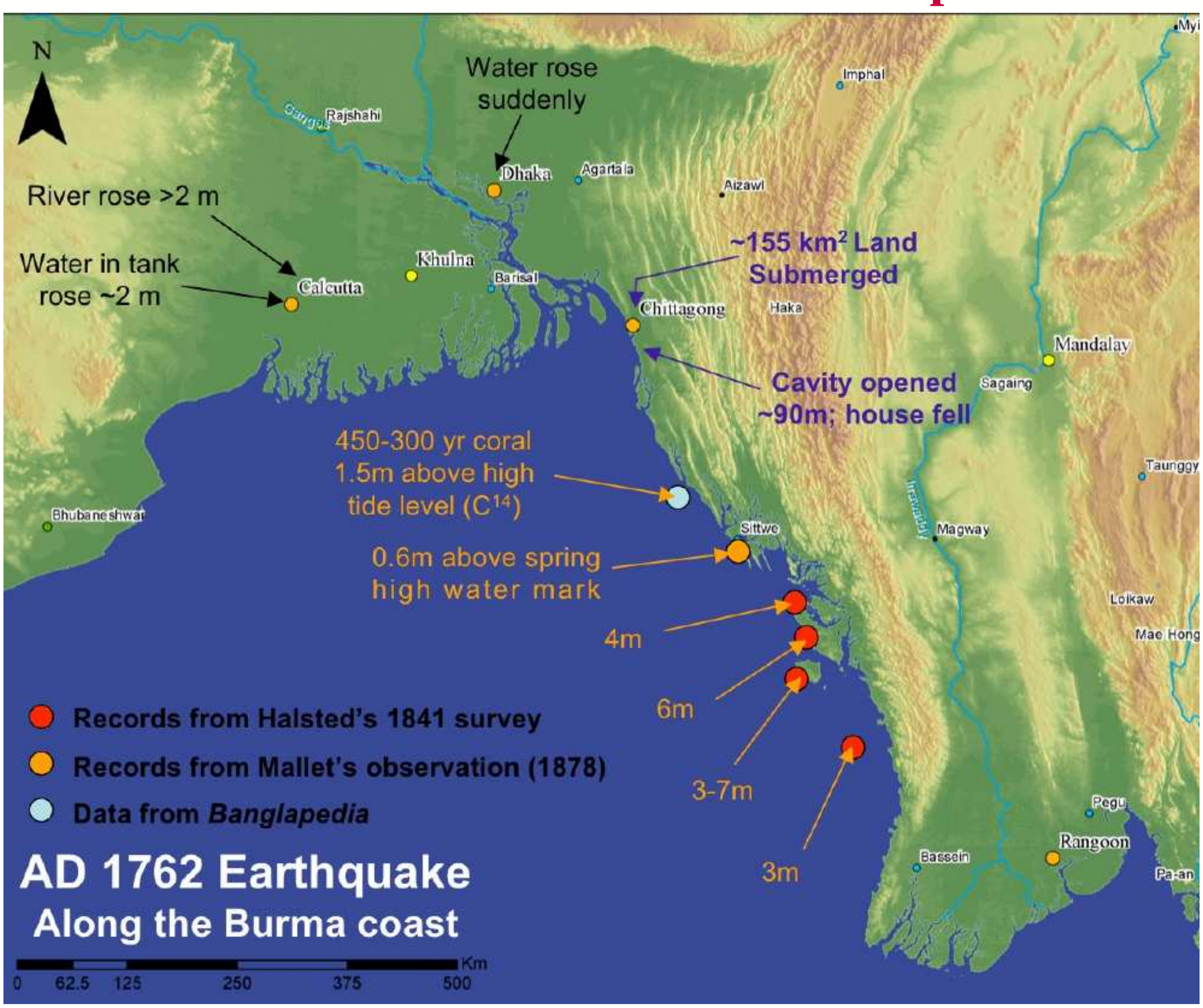

Scenario 1
Scenario 2
T
P
Strike = 322 ; Dip = 12 ; Slip = 90 .
km
km
Nias I.
MALAYSIA
S U M A T R A (Indonesia)
S U M A T R A
JAVA
AMPLITUDE (cm)
MAXIMUM AMPLITUDES
MAXIMUM AMPLITUDES
AMPLITUDE (m)

Figure 4

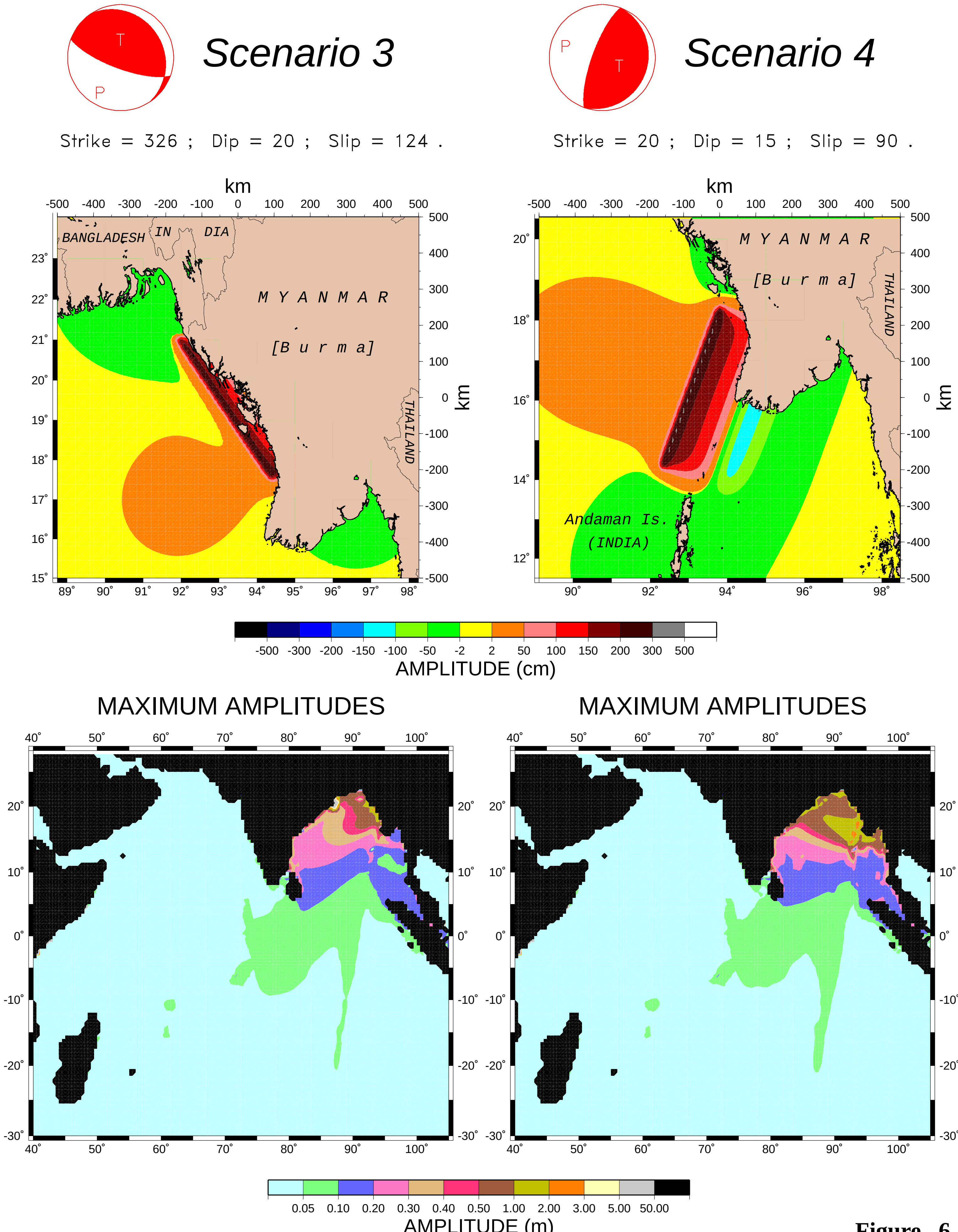
2. THE BURMA−ANDAMAN REGION

- While no major earthquake is known in the instrumental period North of the 2004 rupture, a very large event occurred in 1762, described by *Oldham* [1883], based on an 1841 survey by Captain Halsted, which reports the generation of a tsunami.
- Recent paleoseismological work has identified emerged coral structures of a compatible age [*K. Sieh*, pers. comm., 2006].
- We elect to model a possible rupture extending North of the 2004 Sumatra-Andaman fault, and along the Southern coast of Myanmar.

→ **This region is undergoing enhanced stress, due to Coulomb stress transfer from the 2004 rupture.**



[Map courtesy of **K. Sieh and W. Yu,** *Calif. Inst. Tech.*, Dec. 2006]

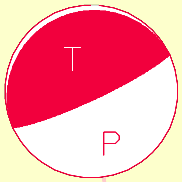


Scenario 3
T
P
Strike = 326 ; Dip = 20 ; Slip = 124 .
Scenario 4
P
T
Strike = 20 ; Dip = 15 ; Slip = 90 .
km
km
BANGLADESH
IN DIA
M Y A N M A R
[B u r m a]
THAILAND
Andaman Is.
(INDIA)
-500 -300 -200 -150 -100 -50 -2 2 50 100 150 200 300 500
AMPLITUDE (cm)
MAXIMUM AMPLITUDES
MAXIMUM AMPLITUDES
0.05 0.10 0.20 0.30 0.40 0.50 1.00 2.00 3.00 5.00 50.00
AMPLITUDE (m)

Figure 6

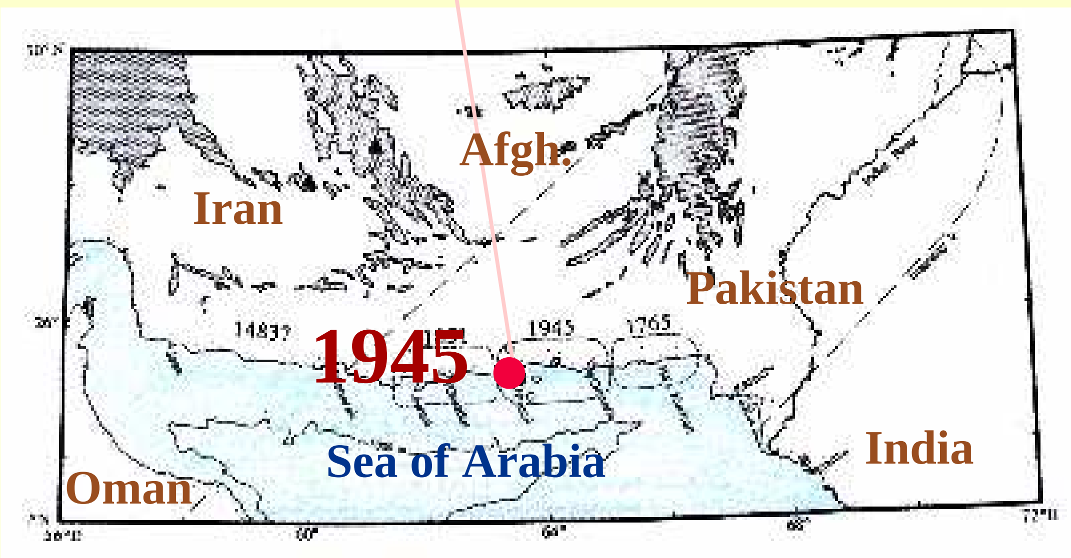
3. MAKRAN (Pakistan) — 27 NOV 1945

The *"forgotten (?)"* Indian Ocean Subduction Zone



$M_0 = 2 \times 10^{28}$ dyn-cm [*Byrne et al.*, 1992]

- Regionally destructive on the coast of Baluchistan (run up reached 12 m), killing perhaps 3000 people, and reaching as far as Bombay (2 m).



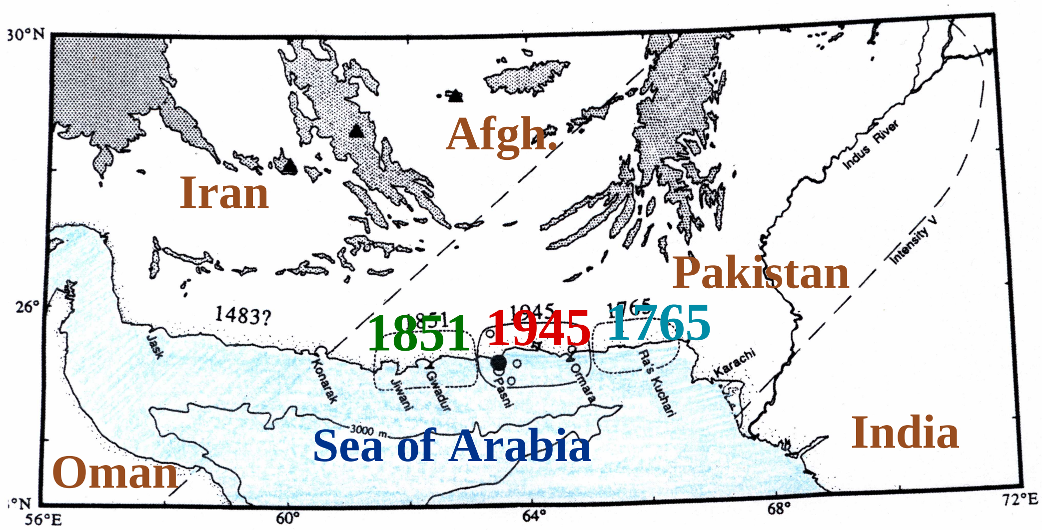
- Recorded on a tidal gauge in the Seychelles.

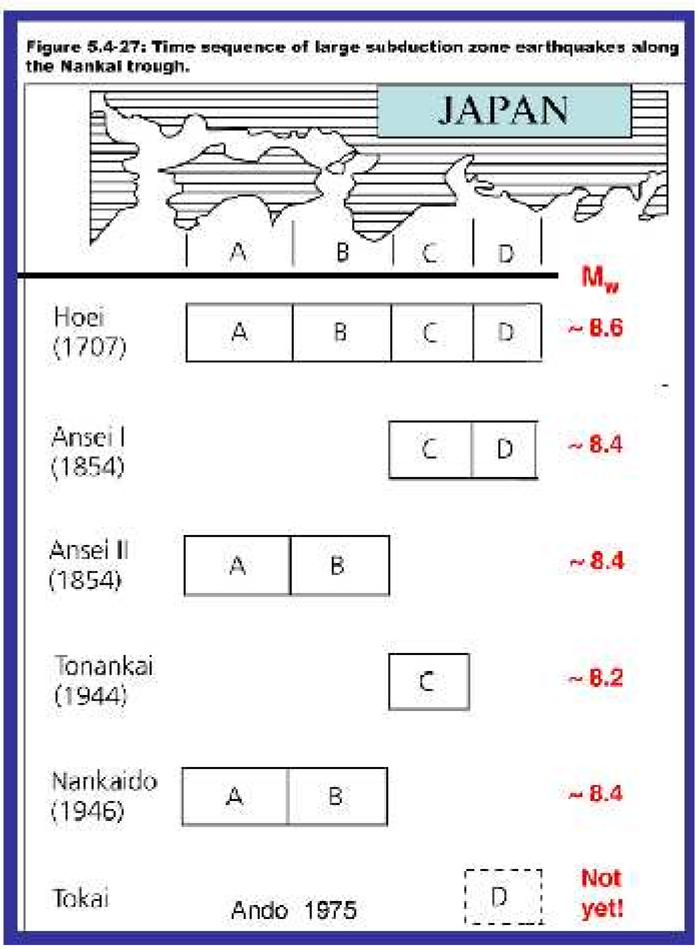
- Triggered eruption of mud volcanoes in the Makran.

- Descriptions of waves separated by 2 hours and rupture of the Bombay−London telegraphic cable suggest delayed triggering of underwater landslides.

Historical data [*Ambraseys*, 1981; *Byrne et al.*, 1992]

suggests large neighboring events





COULD a

COMPOSITE EARTHQUAKE

(Ando's "A−B−C" Scenario)

OCCUR IN MAKRAN ?

[*Ando*, 1975]

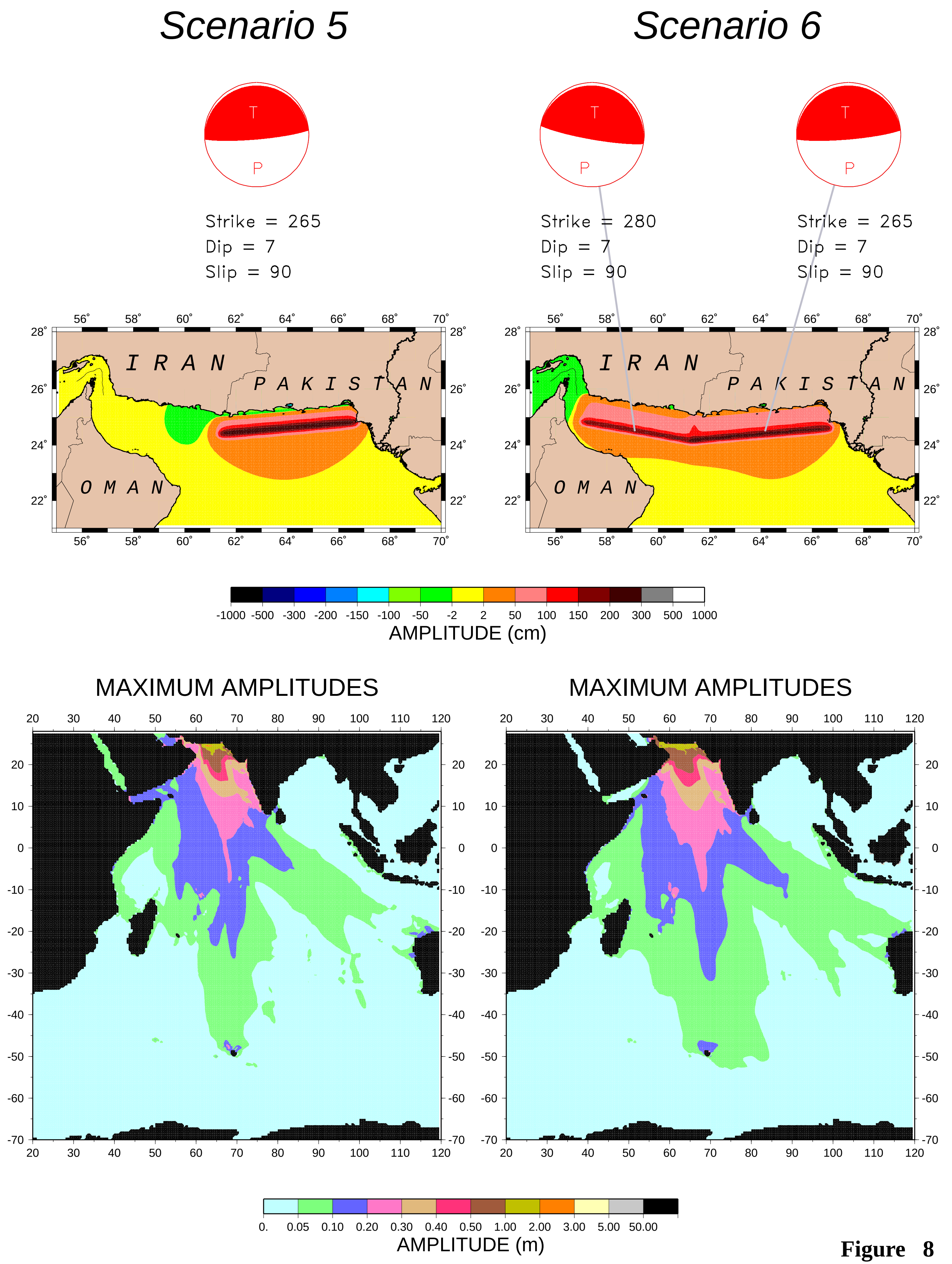

Scenario 5
Scenario 6
T
P
Strike = 265
Dip = 7
Slip = 90
Strike = 280
Dip = 7
Slip = 90
Strike = 265
Dip = 7
Slip = 90
I R A N
P A K I S T A N
O M A N
-1000 -500 -300 -200 -150 -100 -50 -2 2 50 100 150 200 300 500 1000
AMPLITUDE (cm)
MAXIMUM AMPLITUDES
MAXIMUM AMPLITUDES
0. 0.05 0.10 0.20 0.30 0.40 0.50 1.00 2.00 3.00 5.00 50.00
AMPLITUDE (m)

Figure 8

SUBSEQUENT TSUNAMIS (ctd.)

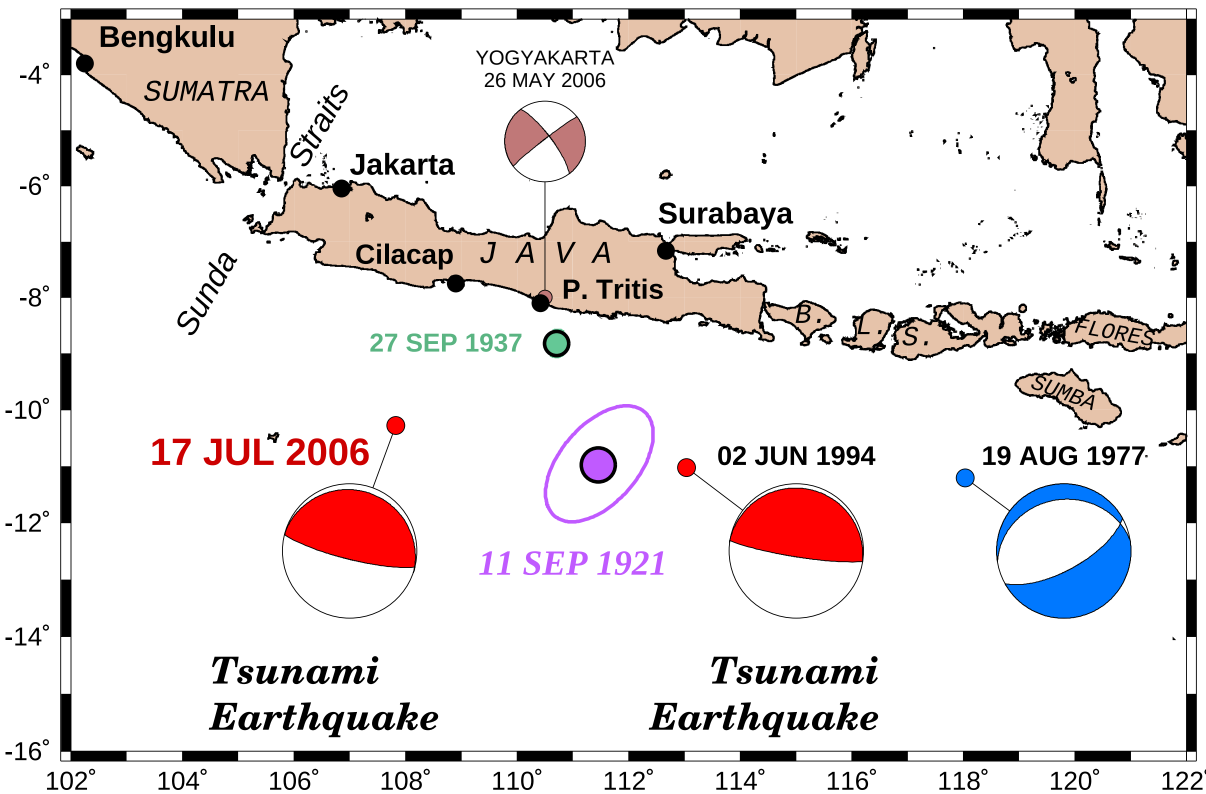
4. *Java, 17 July 2006*

$M_0 = 4.6 \times 10^{27}$ dyn*cm *Slow event,* $\Theta = -6.13$

Typical "Tsunami Earthquake"; — 700 killed by tsunami

Carbon copy of 1994 event, 600 km to the East

T.E. : Event whose tsunami is stronger than suggested by its seismic magnitudes [*Kanamori*, 1972].



This event suggests that *"tsunami earthquakes"* could feature a regional character.

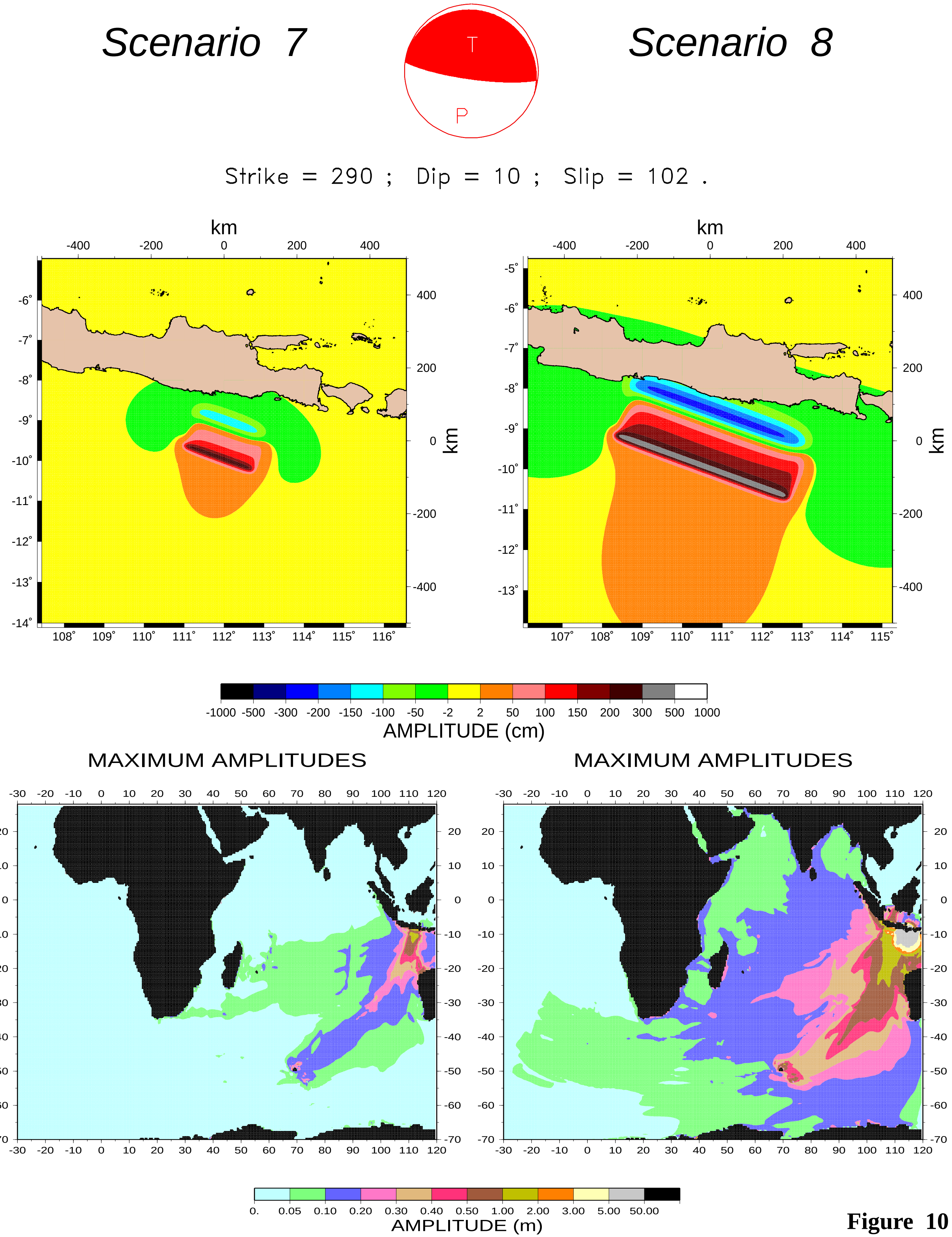
Question: **Does this exclude the danger of a subduction mega-thrust earthquake in Java ???**

* **What is the role of the 1921 shock (contrary to the T.E.s, strongly felt, but with benign tsunami) ?**

• *Lesson:* Total Failure

(i) of the new, allegedly operational, systems;

(ii) of the response of the Governement officials involved.



Scenario 7
Scenario 8
T
P
Strike = 290 ; Dip = 10 ; Slip = 102 .
km
km
AMPLITUDE (cm)
-1000 -500 -300 -200 -150 -100 -50 -2 2 50 100 150 200 300 500 1000
MAXIMUM AMPLITUDES
MAXIMUM AMPLITUDES
AMPLITUDE (m)
0. 0.05 0.10 0.20 0.30 0.40 0.50 1.00 2.00 3.00 5.00 50.00

Figure 10

OTHER SOURCES ??

- *Earthquakes at Mid-Oceanic Ridges.*

  They are simply too small to generate transoceanic tsunamis.

  Even the largest one (Prince Edward FZ, 1942) remains benign for South Africa.

- *South Sandwich Islands Subduction Zone*

  While no mega-earthquake is known in the SSI, the subduction zone could conceivably host a rupture of 400-500 km. Such a source could threaten South Africa.

→ Largest SSI event (27 June 1929, quoted as $M = 8.3$) should be investigated with modern techniques.