# LECTURE 9

# LESSONS from the

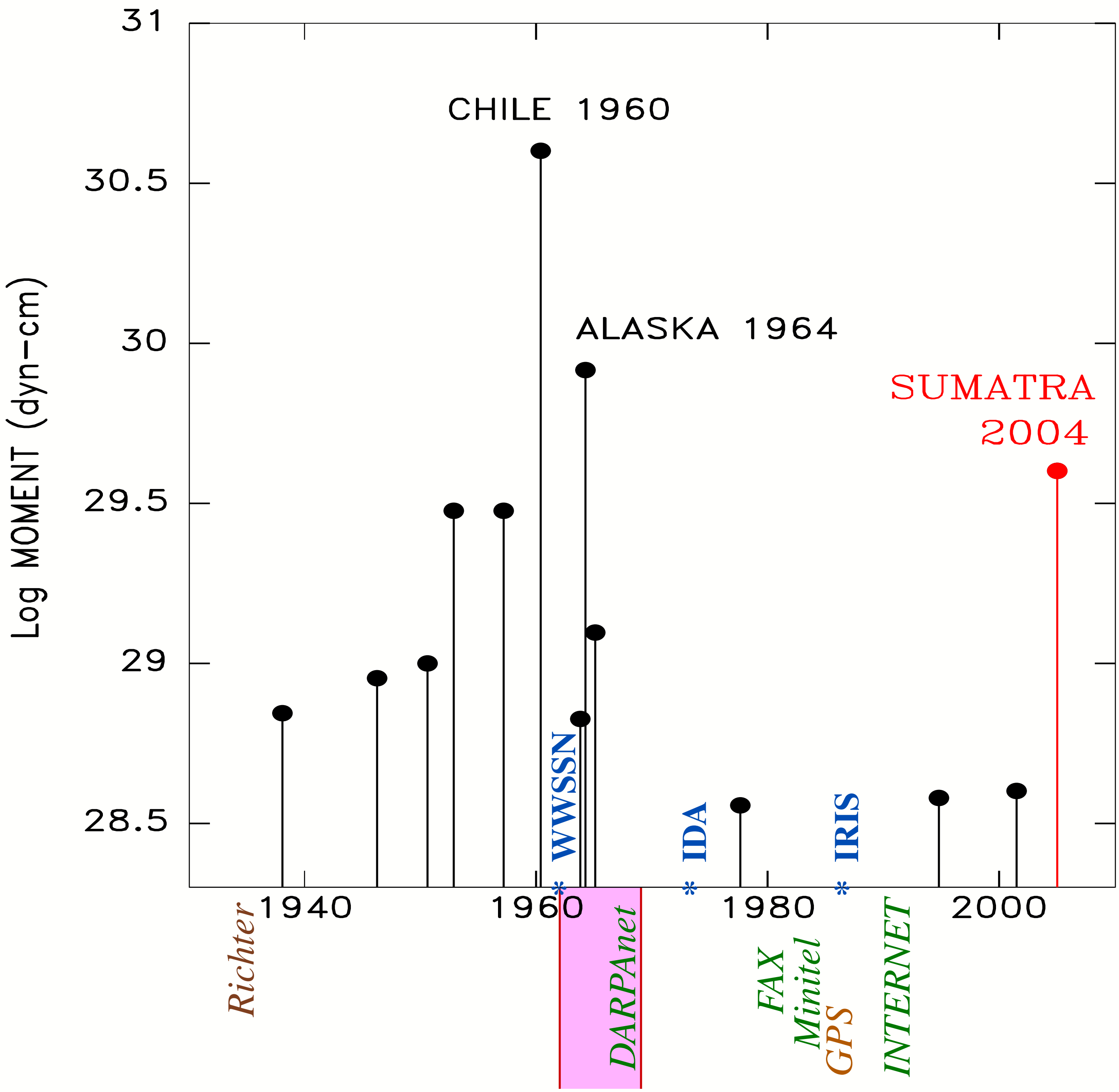
# 2004 SUMATRA DISASTER

# LESSONS in SEISMOLOGY

## 1. SUMATRA EARTHQUAKE VERY BIG

*(Slide Version* **I: 10 January 2005***)*

The 2004 Sumatra Earthquake is the largest seismic event in 40 years, and the third largest in 70 years.

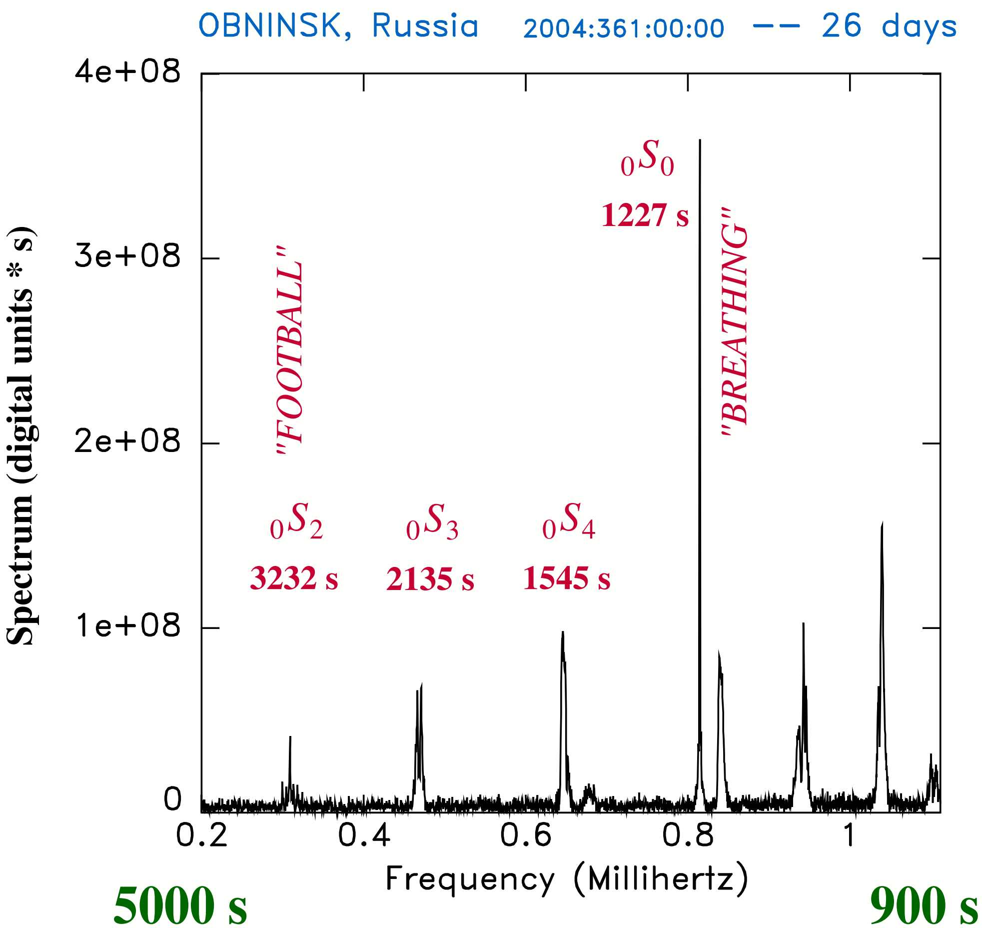



→ **The event is also the first mega-earthquake to occur after the** ***Plate Tectonics Revolution*****.**

# SPECTRUM of the EARTH's MUSIC PROMINENTLY EXCITED

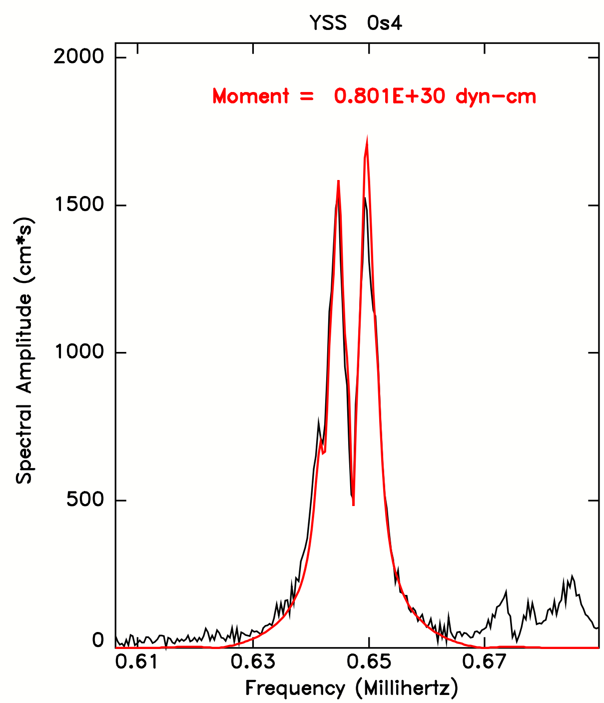
The gravest modes of the Earth are in the range

*1000–3230 s (1/4 hr. to 1 hour)*




- **Normal modes are split in a complex pattern by Earth's rotation and ellipticity.**

**YSS $_0S_4$ (1546 s)**



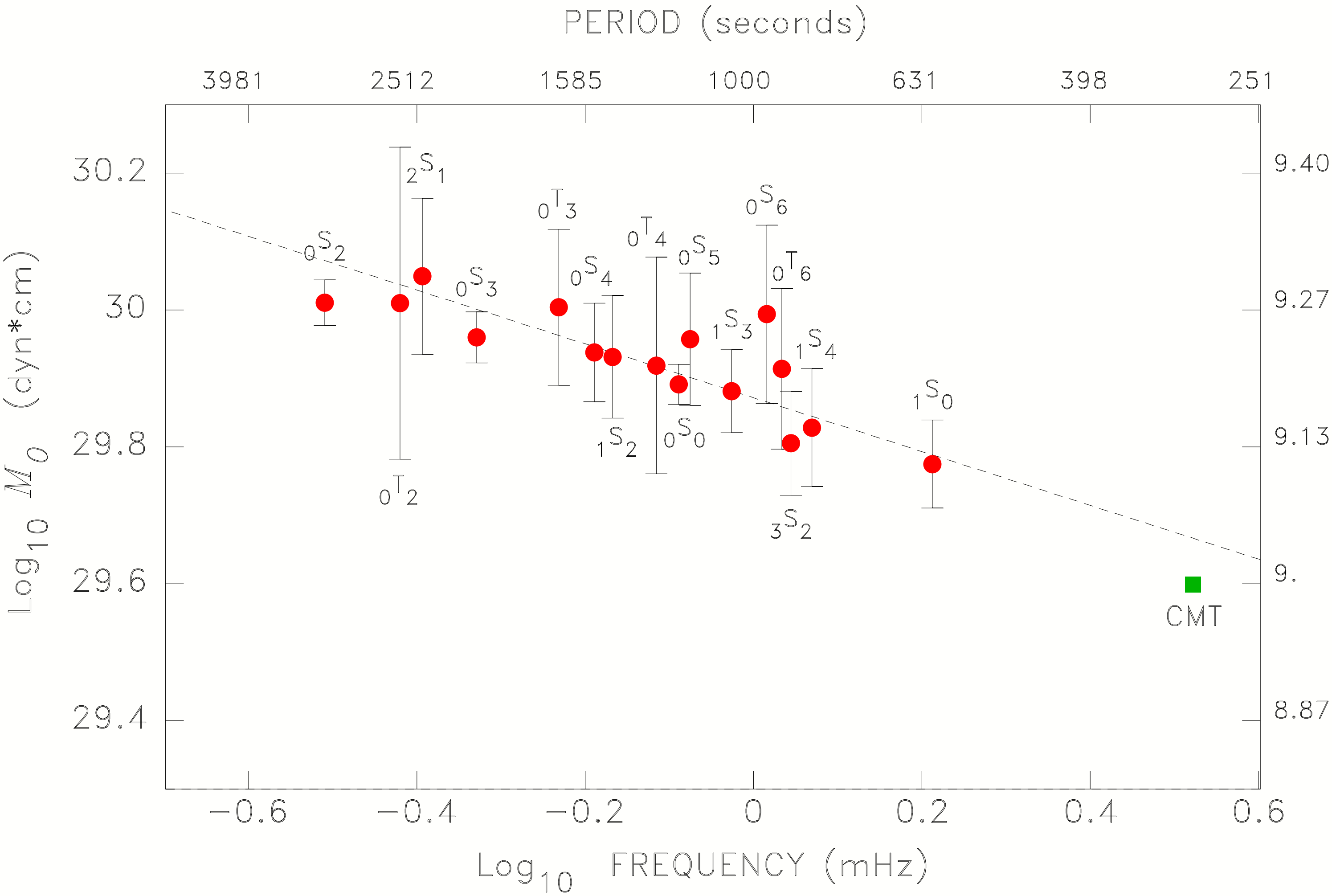

- Quantify excitation of modes (hence size of earthquake at very long periods) by fitting splitting pattern to exact geometry of source, station and focal mechanism.

→ **Theory developed in 1970s. *SUMATRA* is first opportunity to actually make measurement.**

[*Stein and Geller,* 1978]

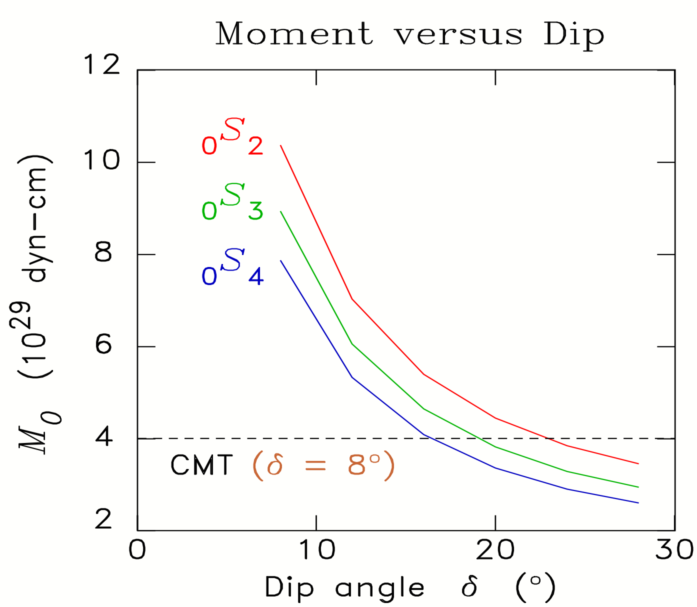
# RESULTS FROM 16 NORMAL MODES

- Size of Sumatra Earthquake keeps *INCREASING* with period when modeled as a *SINGLE SOURCE,* suggesting *SLOW* behavior.




→ The *ABSOLUTE* seismic moment could depend on fault dip (as does the CMT solution),

but the *RELATIVE* moments keep varying with period.



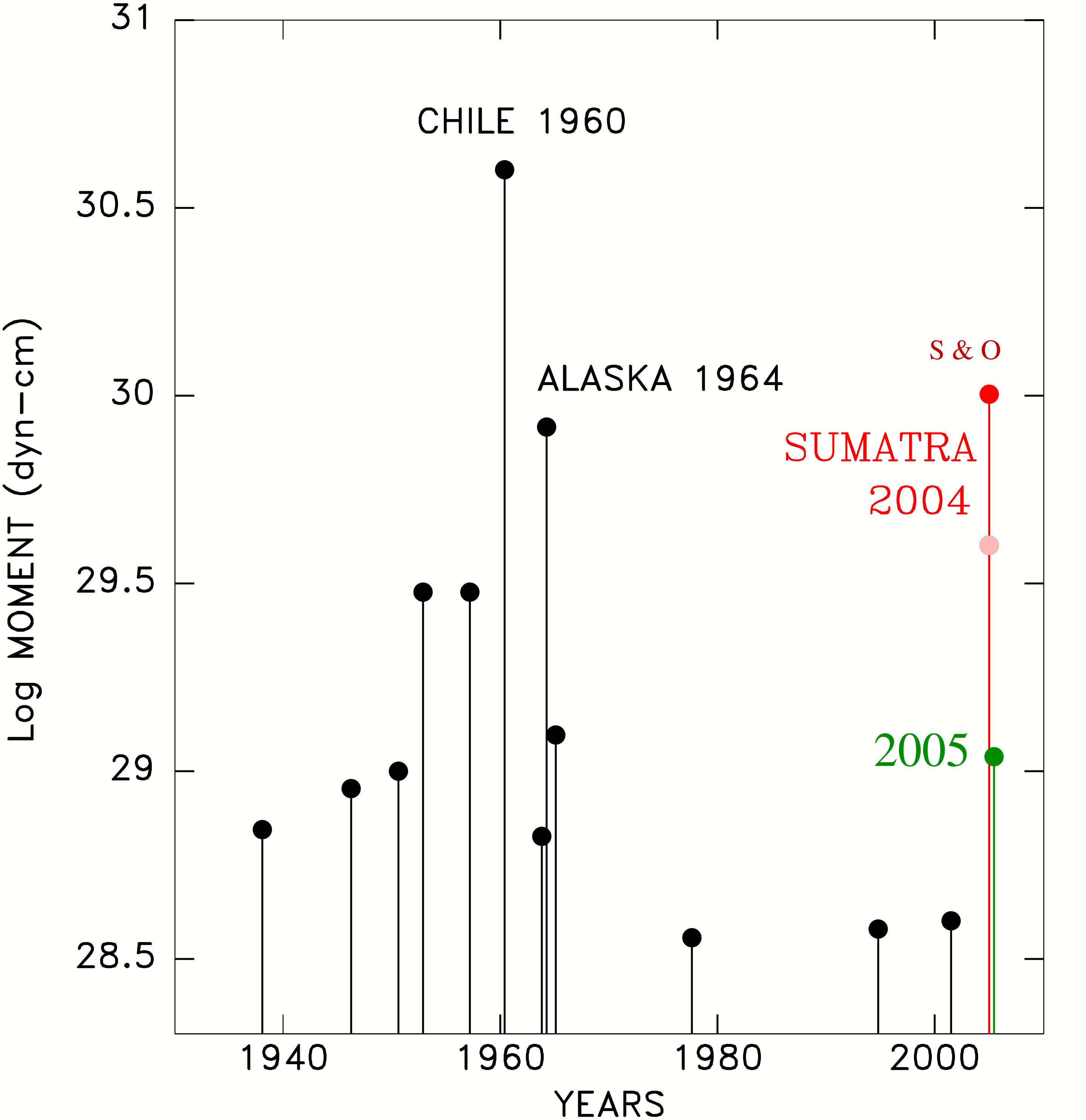
## 2. 2004 EARTHQUAKE BIGGER than THOUGHT

*(Slide Version* **II: 07 February 2005***)*

*(* **III: 28 March 2005***)*

The 2004 Sumatra Earthquake is the largest seismic event in 40 years, and the ~~third~~ **second** largest in 70 years.

[*Stein and Okal,* 2005]

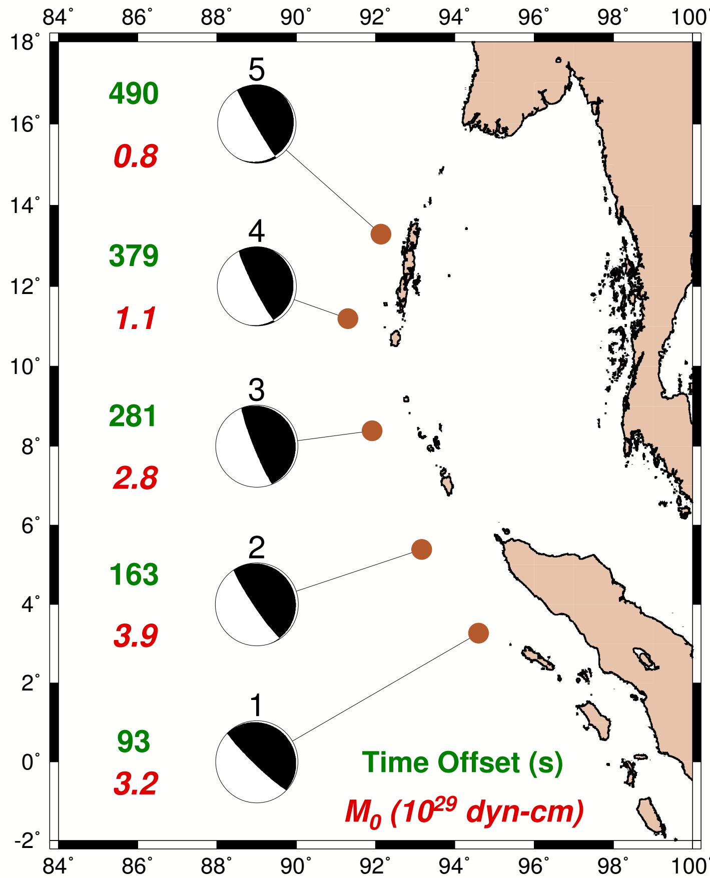


# COMPOSITE SOURCE [*Nettles et al.*, May 2005]

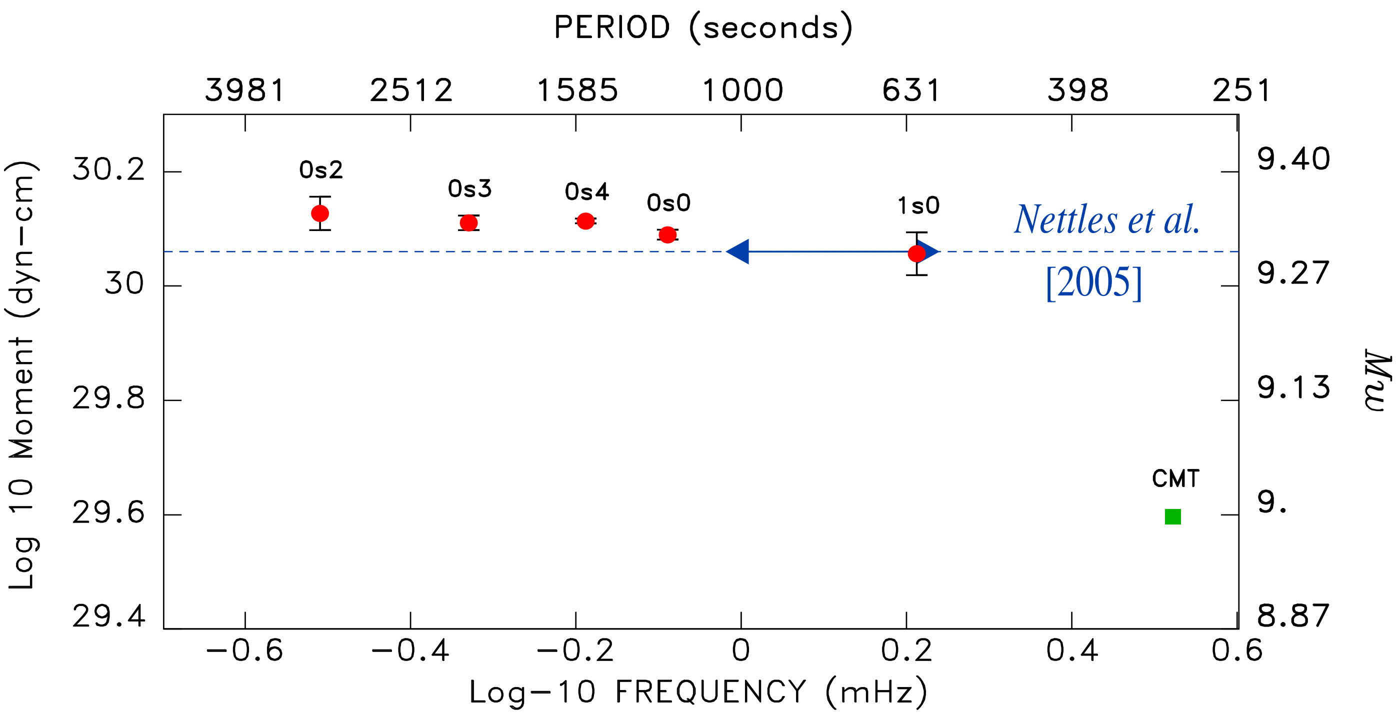
Total Moment

$$M_0 = 1.17 \times 10^{30}$$

dyn-cm




Composite solution provides an excellent fit to the mode data.



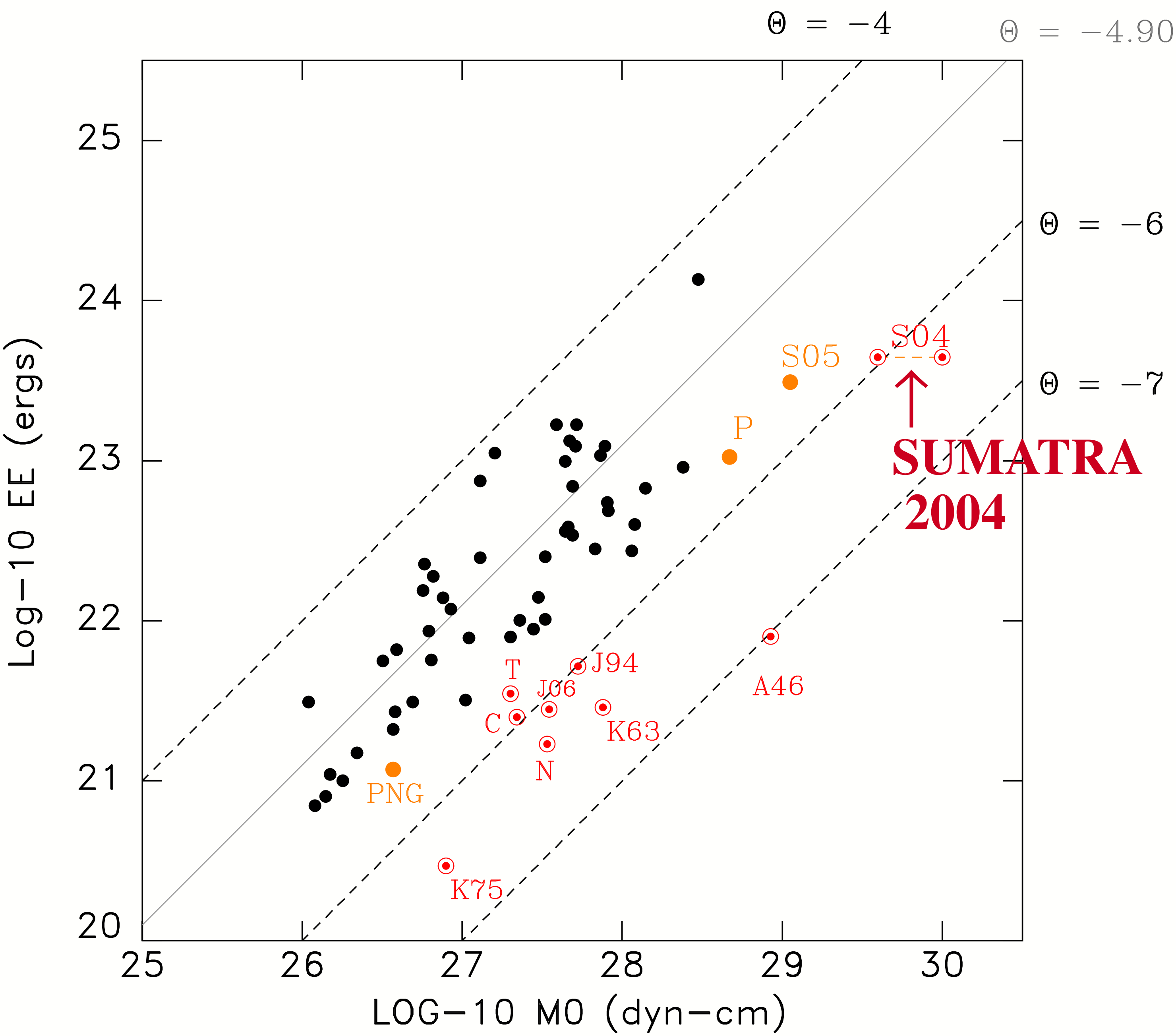

- **However, the price paid for a composite source is the violation of scaling laws.**

# OTHER PROOFS of SOURCE SLOWNESS

*Sumatra 2004*

**1.** Slowness Parameter $\Theta = \log_{10} E^E / M_0 \leq -6$

[*Newman and Okal,* 1998]




*(Characteristic of "Tsunami Earthquakes"* **in red***)*

# OTHER PROOFS of SOURCE SLOWNESS (ctd.)

*Sumatra 2004*

**2.** *Videos from Banda Aceh*


Buildings in Banda Aceh were standing intact during inundation, only 200 km from the epicenter of that magnitude $\geq 8$ earthquake.

*Suggestion:* **Little Energy at High Frequencies**

**[ Confirmed by a deficient parameter $\Theta$ ]**

# LESSONS in TECTONICS

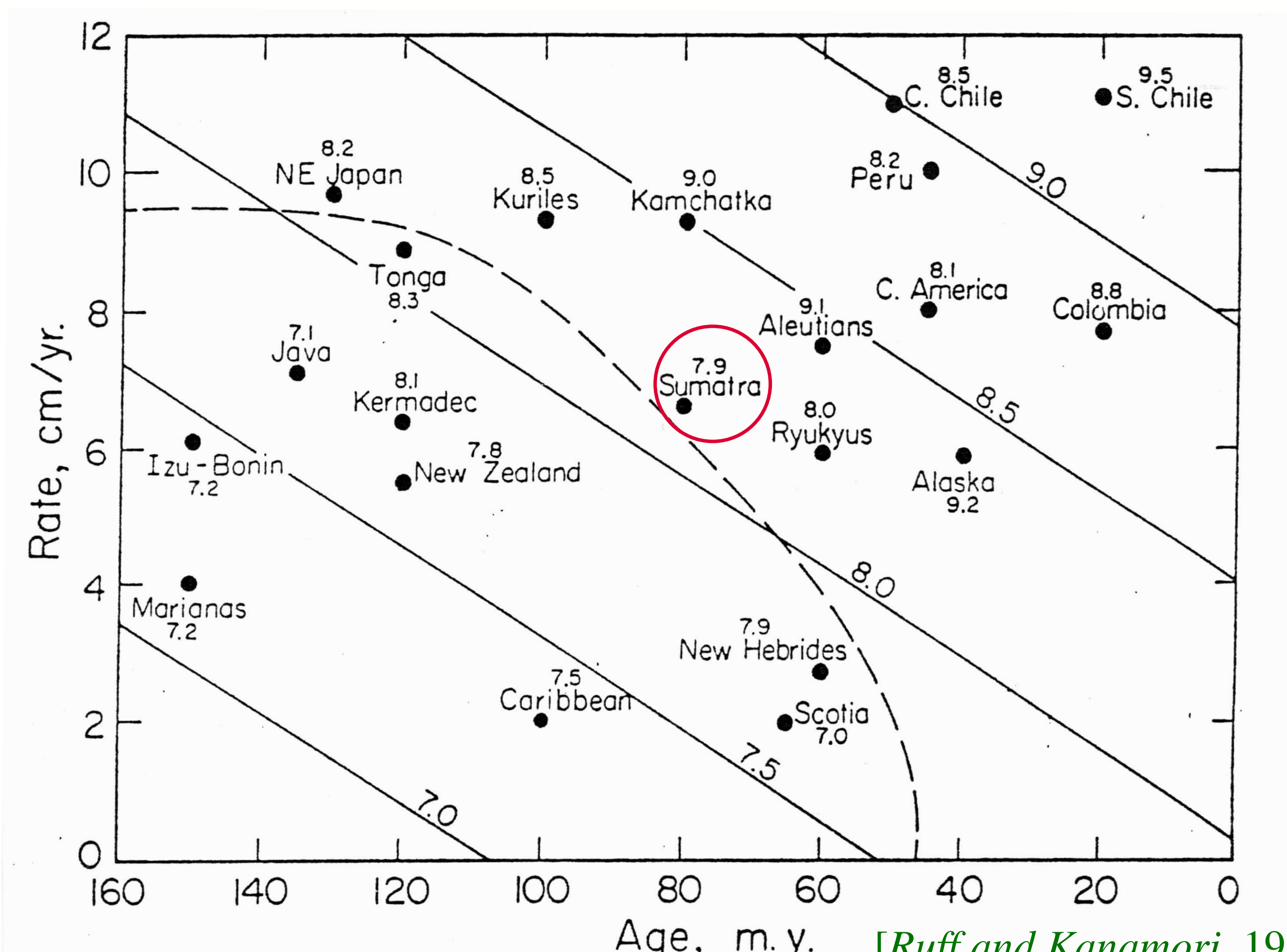
## 1. Mega-earthquakes occur in unsuspected areas

**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 ?

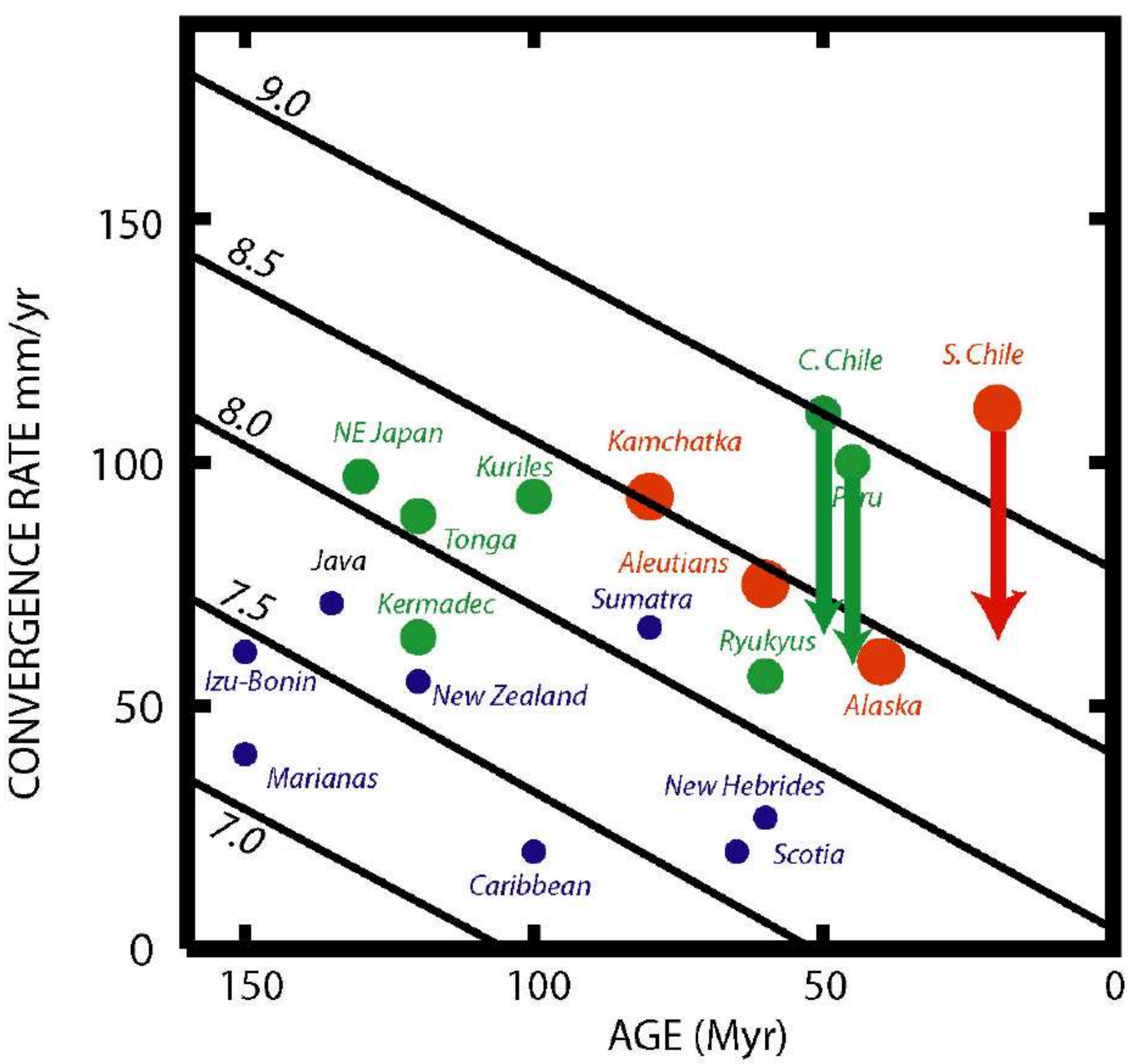
*Over the past 25 years...*

→ **We have obtained new rates**

Examples: South Chile **70** mm/yr *vs.* 111

South Peru: **67** mm/yr *vs.* 100

RUFF AND KANAMORI 1980



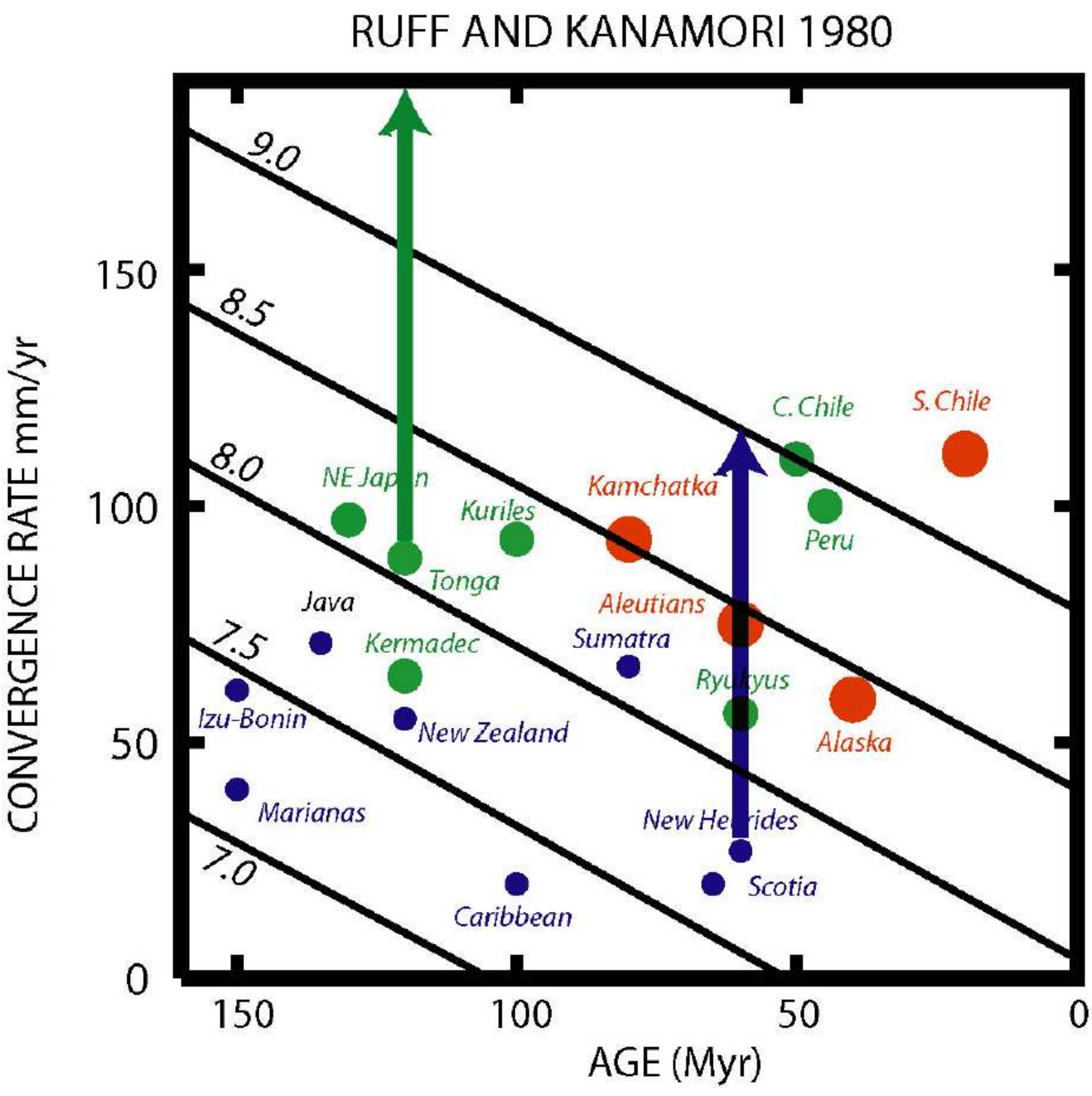
# UPDATING THE RUFF-KANAMORI DIAGRAM ?

*Over the past 25 years...*

→ **We have obtained new rates**

Examples: Tonga (20°S): **185** mm/yr *vs.* 89

Vanuatu: **103** mm/yr *vs.* 27



# UPDATING THE RUFF-KANAMORI DIAGRAM ?

*Over the past 25 years...*

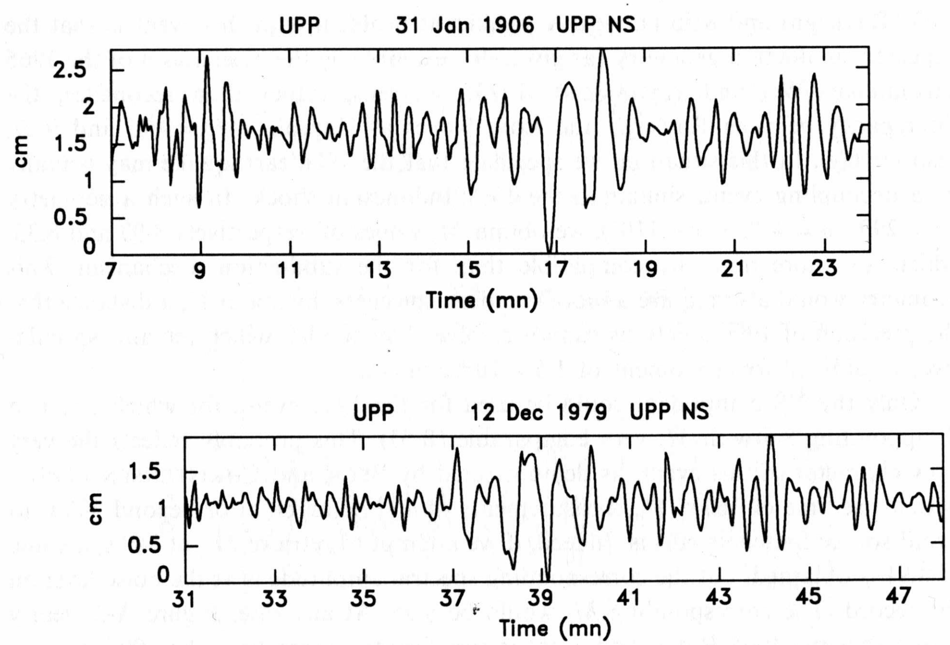
→ **We have revised the size of historical earthquakes**

Example: 1906 Colombia-Ecuador:

$$M_0 = 6 \times 10^{28} \text{ dyn-cm} \quad vs. \quad 2 \times 10^{29}$$

**1906**

**1979**




[*Okal,* 1992]

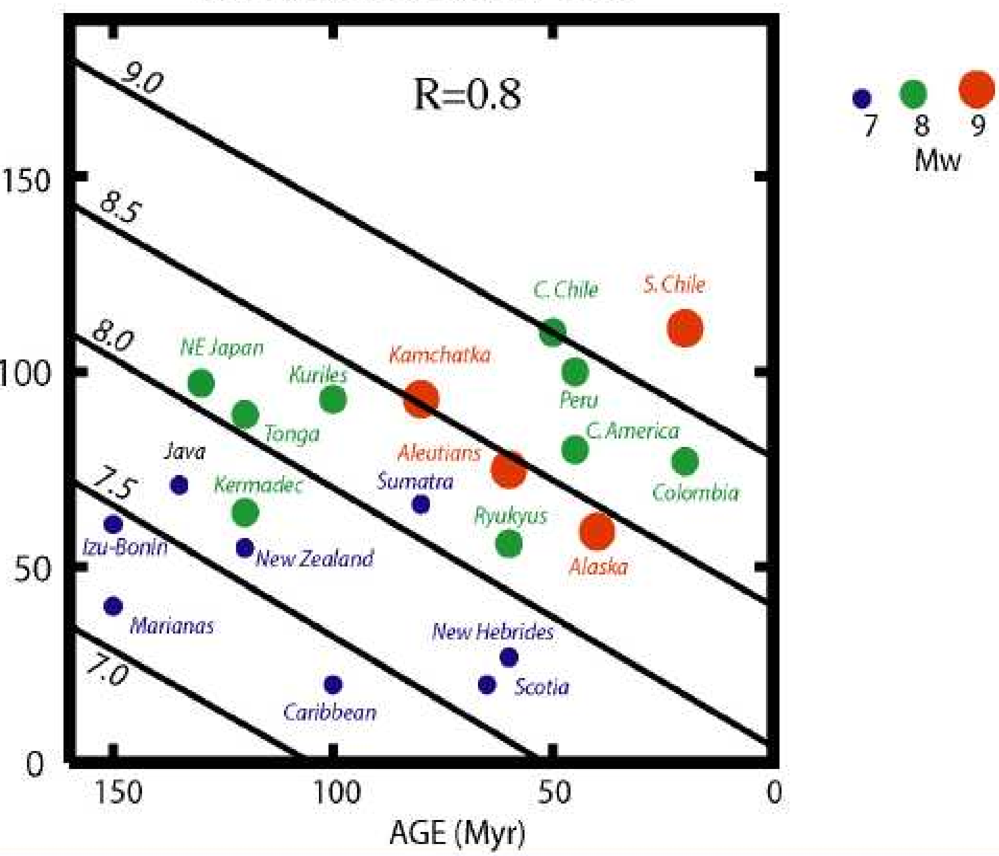
Figure A-1

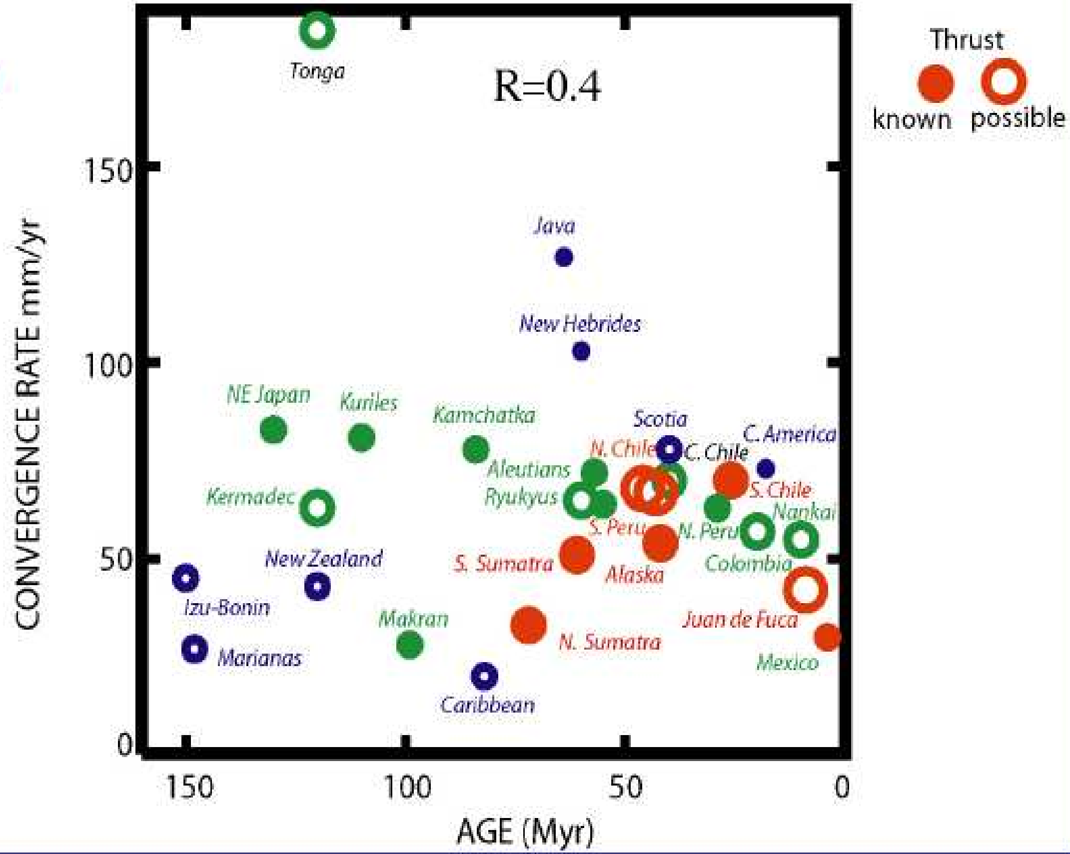
Comparison of the Love wavetrains $G_1$ of the 1906 and 1979 Ecuador-Colombia earthquakes, as recorded on the NS component of the Uppsala Wiechert. The records are plotted on the same scale, with the abcissæ offset so as to align the $G_1$ wavetrains, thus allowing a direct comparison of their relative sizes. Note that while the 1906 earthquake is undoubtedly the larger of the two, it cannot have a moment 10 times larger than the 1979 event.

# USING NEW RATES, AGES & MAGNITUDES

## MUCH OF THE CORRELATION VANISHES

RUFF AND KANAMORI 1980



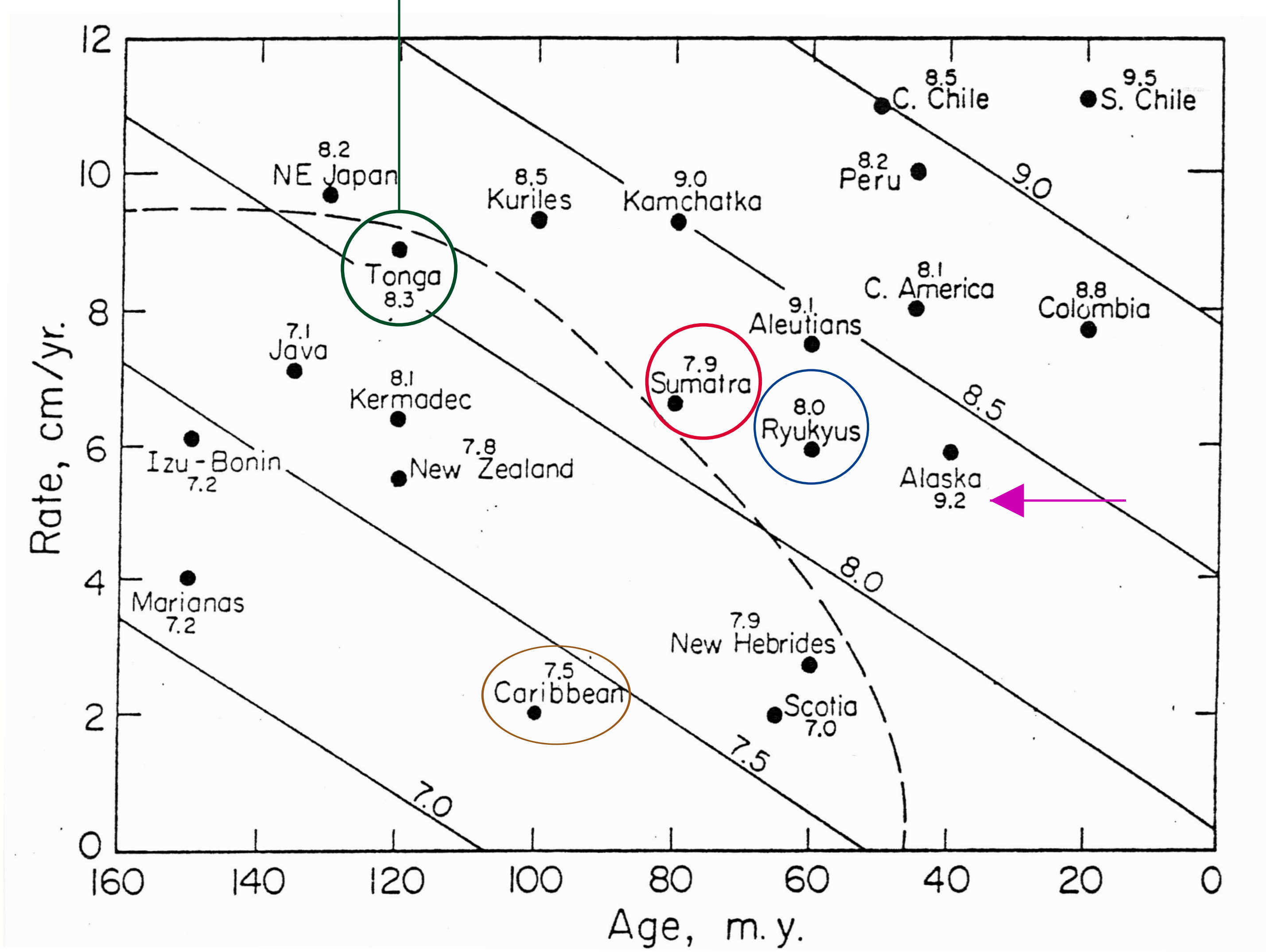
# 3. WHO COULD BE NEXT?

**23 cm/yr**
[*Bevis et al.*, 1995]

* TONGA: Could it rupture all the way from Samoa to T-K corner at 25°S?

* RYUKYU: Could it rupture all the way from Kyushyu to Taiwan?

* LESSER ANTILLES: Is a mega-thrust possible from Tobago to Anguilla?




[*Ruff and Kanamori*, 1980]

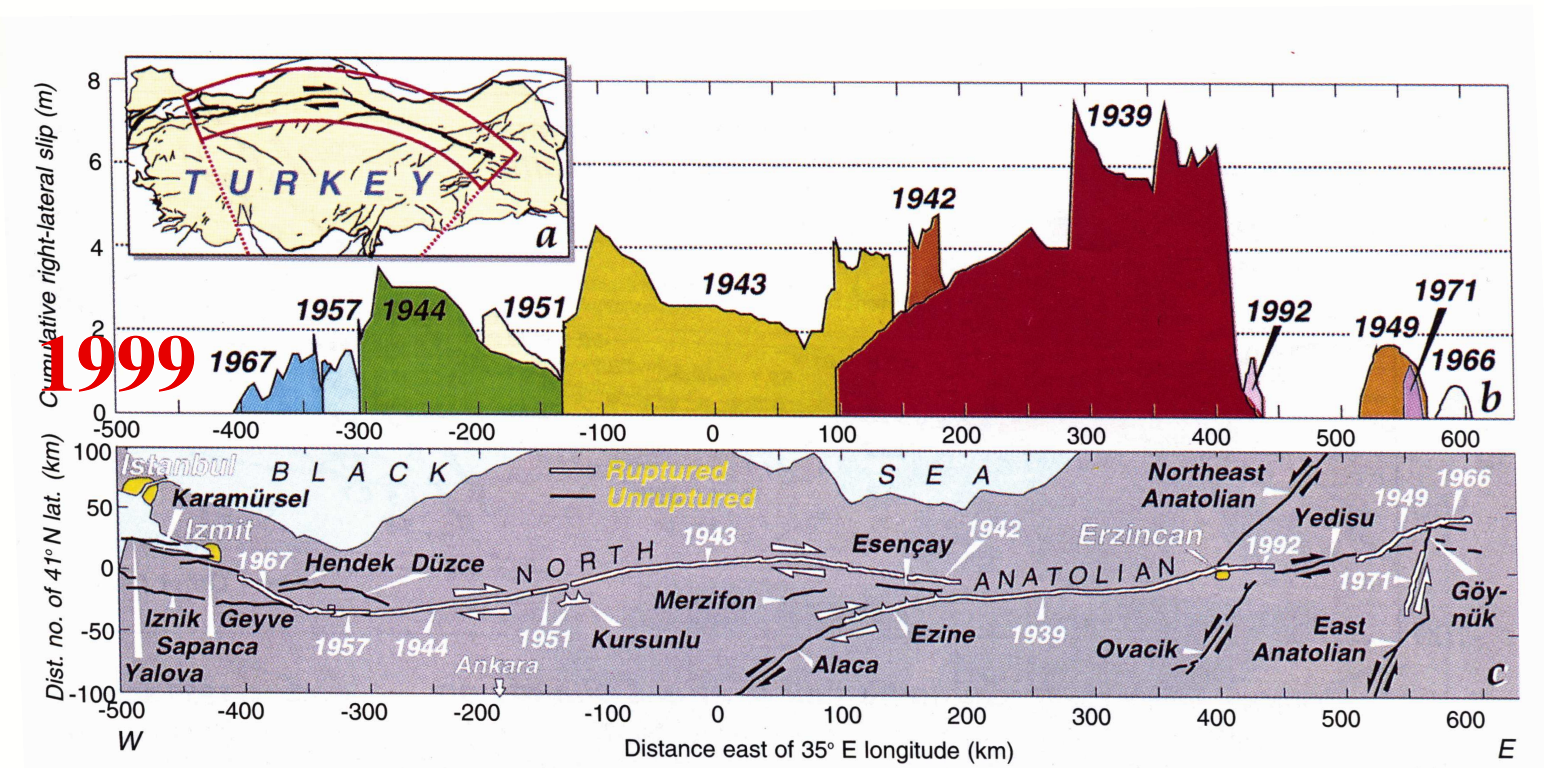
* ALASKA: Note that it really did not fit

# LESSONS in TECTONICS

## 4. 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.

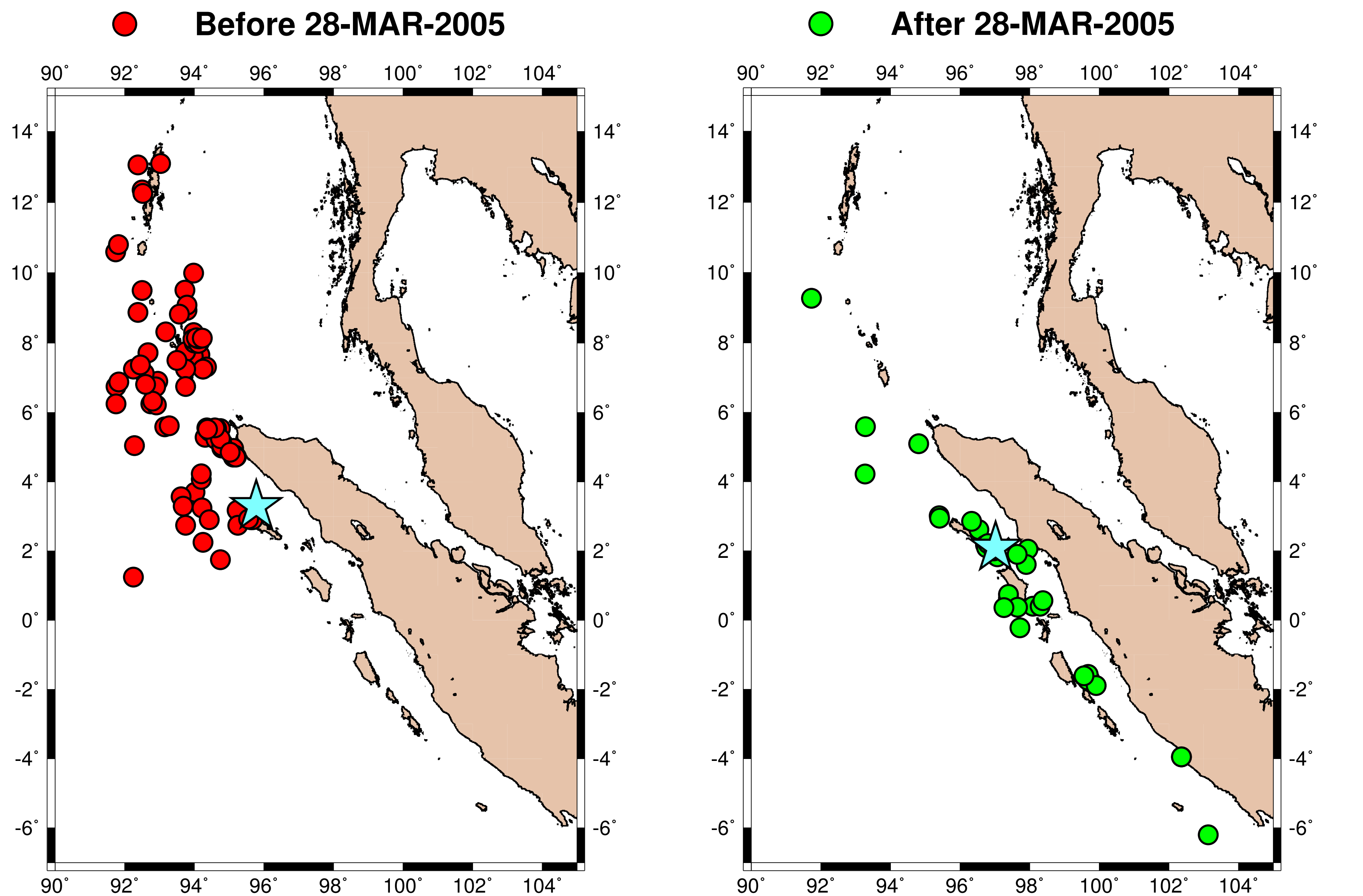
Recall Anatolian Fault from 1939 (east) to 1999 (Izmit) to 20xx (Marmara-Istanbul?)




[*Stein et al.*, 1997]

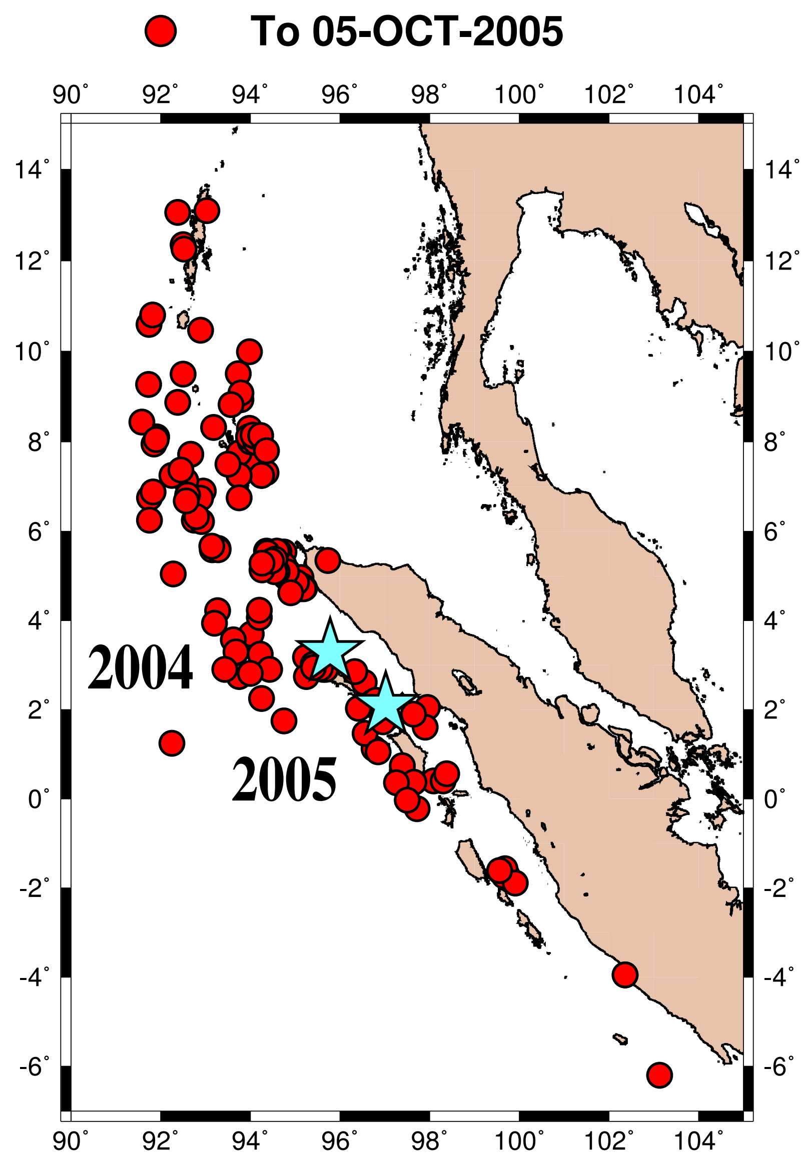
# 28-MAR-2005 (SUMATRA-II) EARTHQUAKE PREDICTED ON THE BASIS of STRESS TRANSFER by McCLOSKEY *et al*. [*Nature*, 17 MAR 2005].

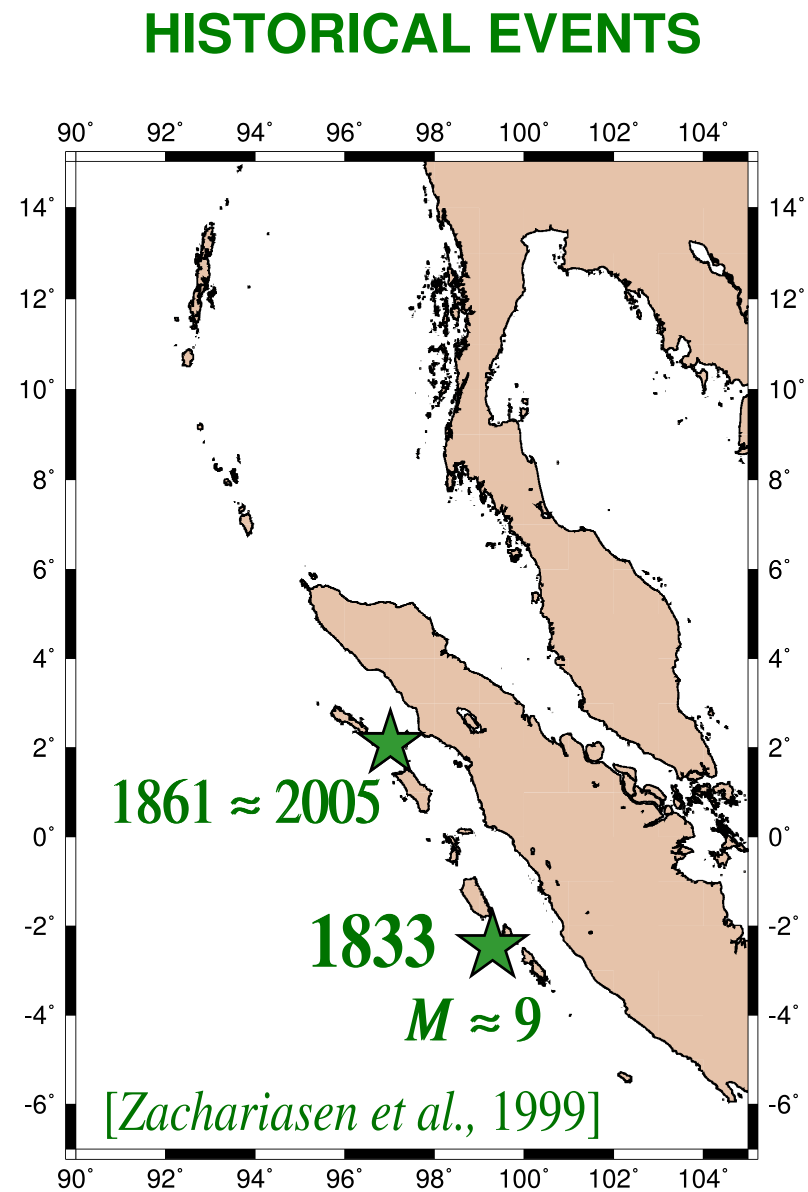
## *Events with CMT Solution (To 20-MAY-2005)*



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

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



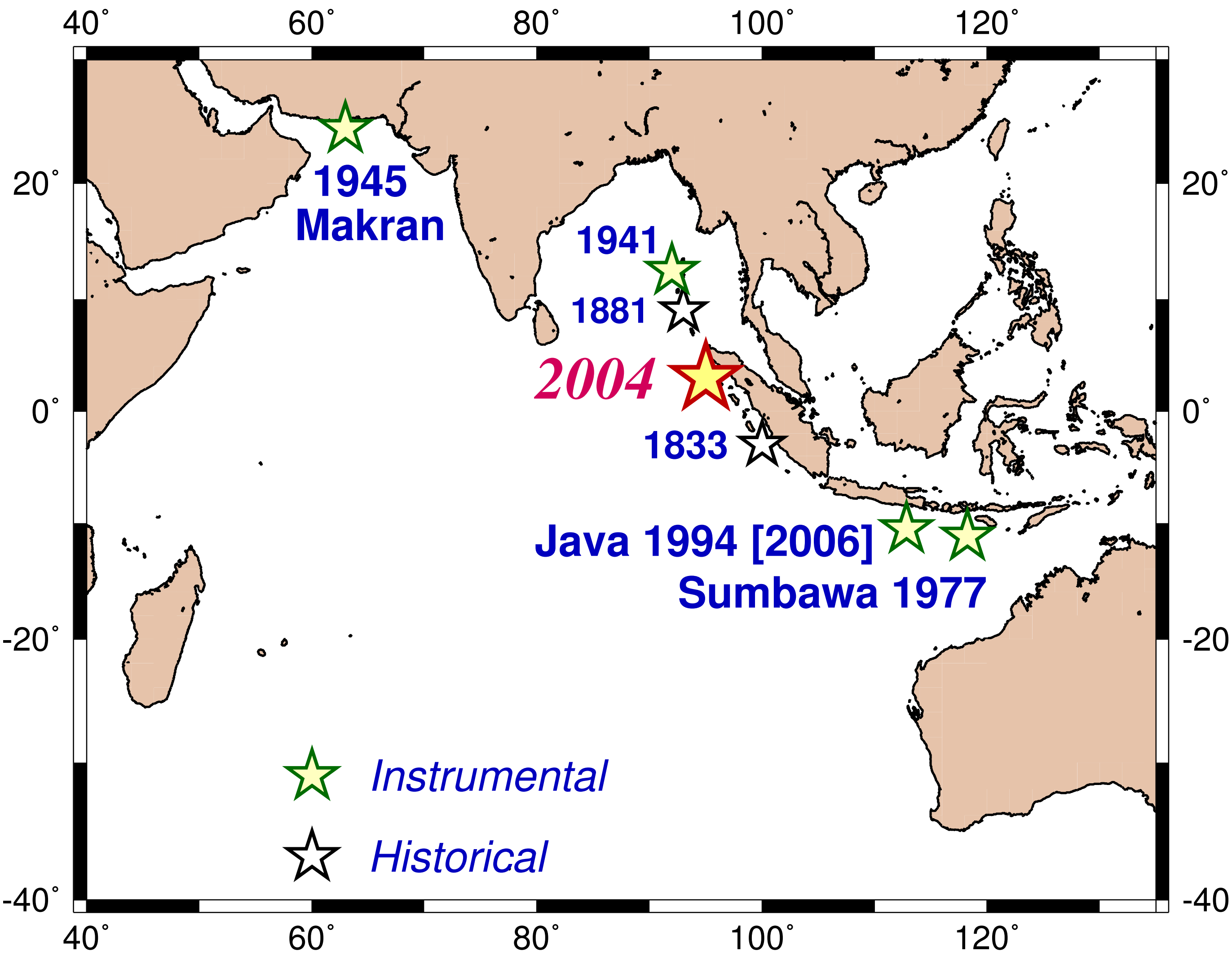



# SCIENTIFIC LESSONS from TSUNAMI

## 1. CATASTROPHIC FAR-FIELD TSUNAMI HAZARD EXISTS in the INDIAN OCEAN

### * Previous events:

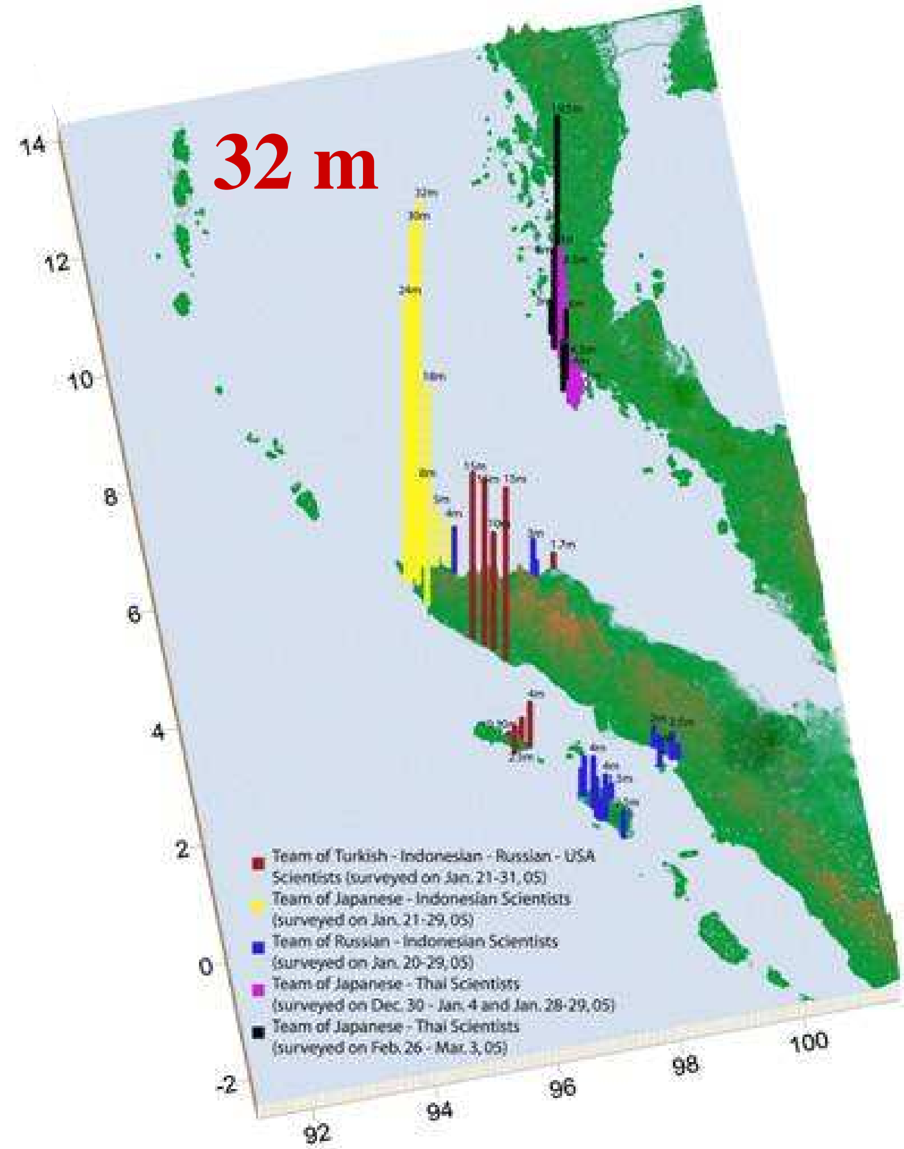
- **1977, 1994 [2006]** *Sunda:* Damage in NW Australia; regional field.
- **1945** *Makran:* Decimetric in Seychelles, damage reported (unassessed) in Oman.
- **1941** *Andaman:* Reported damage in India [*Murty and Rafiq,* 1991], unconfirmed [*Ortiz and Bilham,* 2003].
- **1881** *Nicobar:* Decimetric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



# 2. NEAR–FIELD RUN-UP : WELL EXPLAINED by DISLOCATION

*(No need to invoke major landslides)*

[*R. Davis,* AusAID]




[*A.C. Yalçıner,* 2005]

As high as these run-up values may seem, they fall within the so-called *"Plafker Rule of Thumb"*

MAX RUN-UP $<$ 2 * $\Delta u$

{Justified theoretically by *Okal and Synolakis* [2004]}

For Sumatra, $\Delta u \approx 20$ m

# LESSONS from TSUNAMI

## TSUNAMI recorded by many "INADEQUATE" instruments

**(NOT DESIGNED to pick up such signals)**

→ Satellite altimeters.

→ Hydrophones floating inside the SOFAR channel (IMS/CTBTO).

→ Infrasound stations of the International Monitoring System of the CTBTO.

→ Upwards continuation of tsunami detected in ionosphere by GPS technology

→ Impact of tsunami on shorelines detected by seismic stations and *perhaps* by land GPS stations.

→ Tsunami waves reaching beach on Sri Lanka (Sunglit) photographed directly from satellite.

## *OUTLOOK*:

Some of these observations hold the promise of furthering our understanding of the *coupling* of the tsunami between various media (*e.g.*, atmosphere).

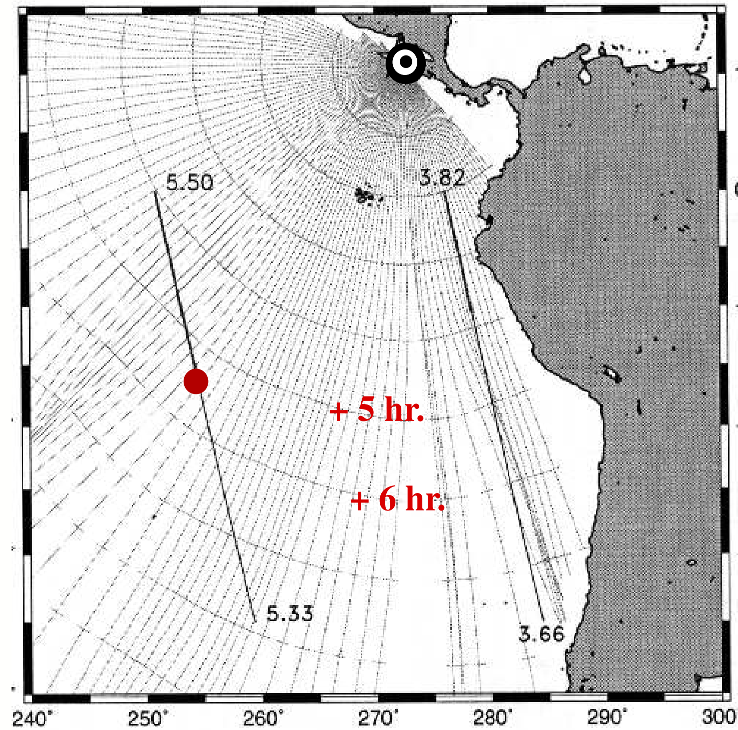
# TOWARDS DIRECT DETECTION of a TSUNAMI on the HIGH SEAS

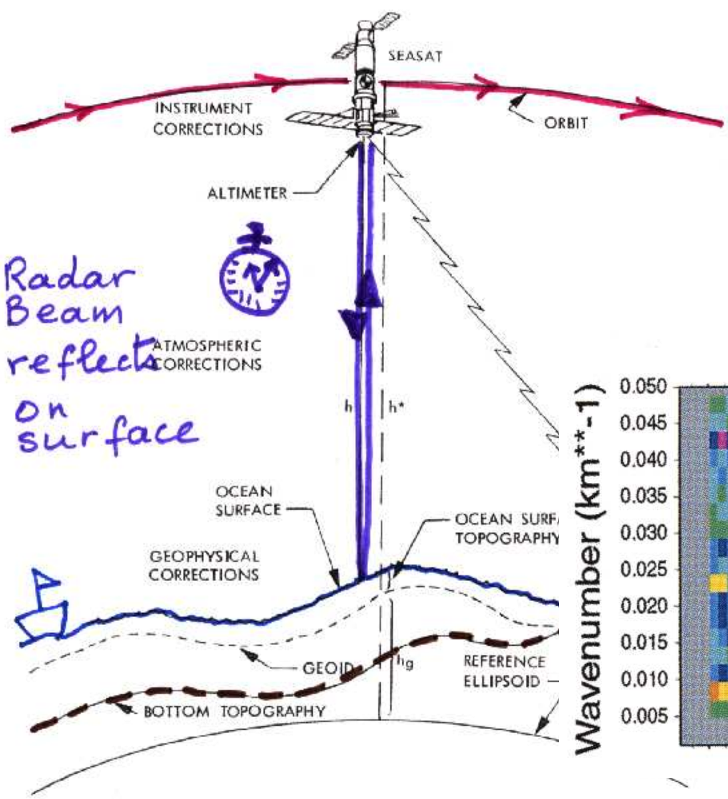
## 2. TSUNAMI DETECTION by SATELLITE ALTIMETRY

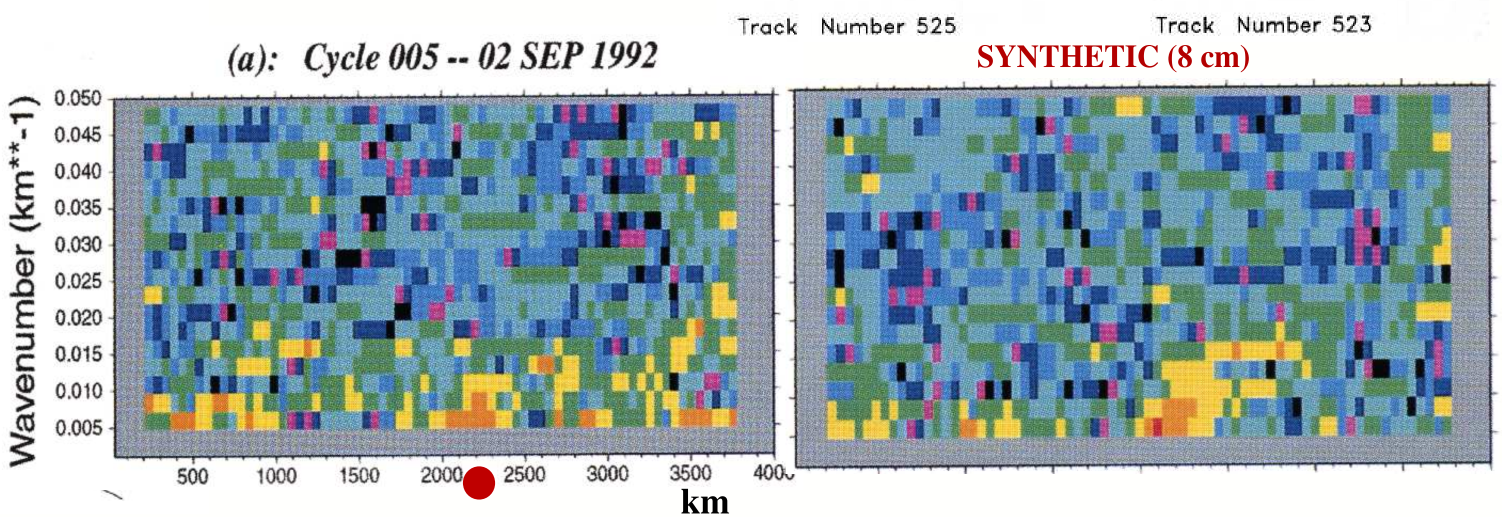
*E.A. Okal, A. Piatanesi and P. Heinrich,* 1999

- Altimetric satellites constantly map sea-surface height variability
- Tsunami wave may be detected if satellite flies over it.
- 8-cm signal confirmed for 1992 Nicaragua tsunami.

→ *Problem:* Satellite must be at right place at right time...



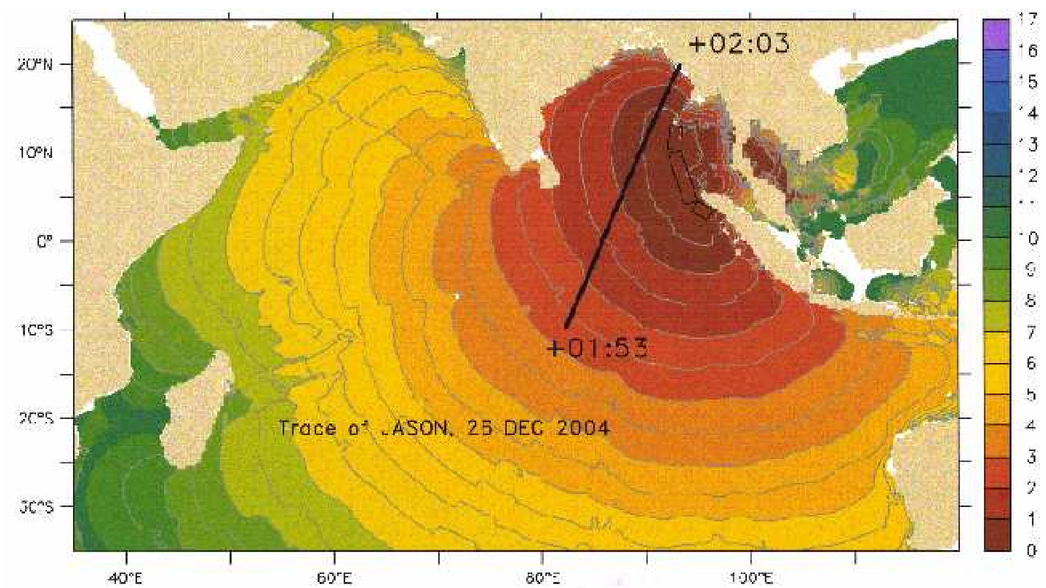



**DETECTION by SATELLITE ALTIMETRY** gives first definitive measurement of *MAJOR* tsunami on *HIGH SEAS*

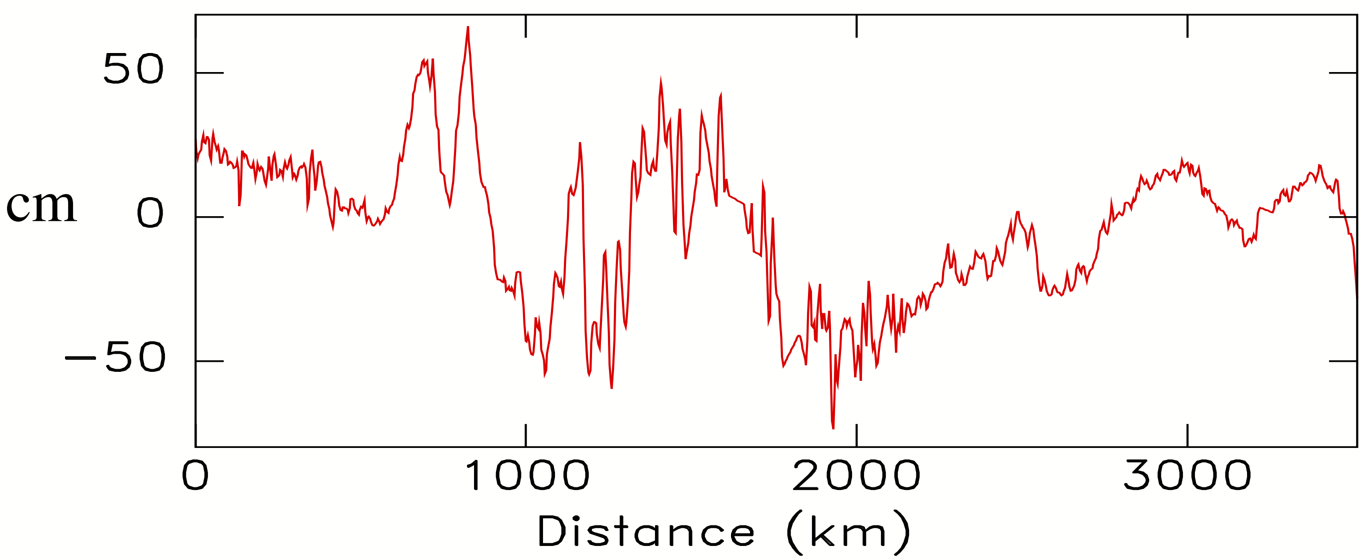
(previous detection by *Okal et al.* [1999] during 1992 Nicaragua tsunami -- 8 cm -- at the limit of noise).

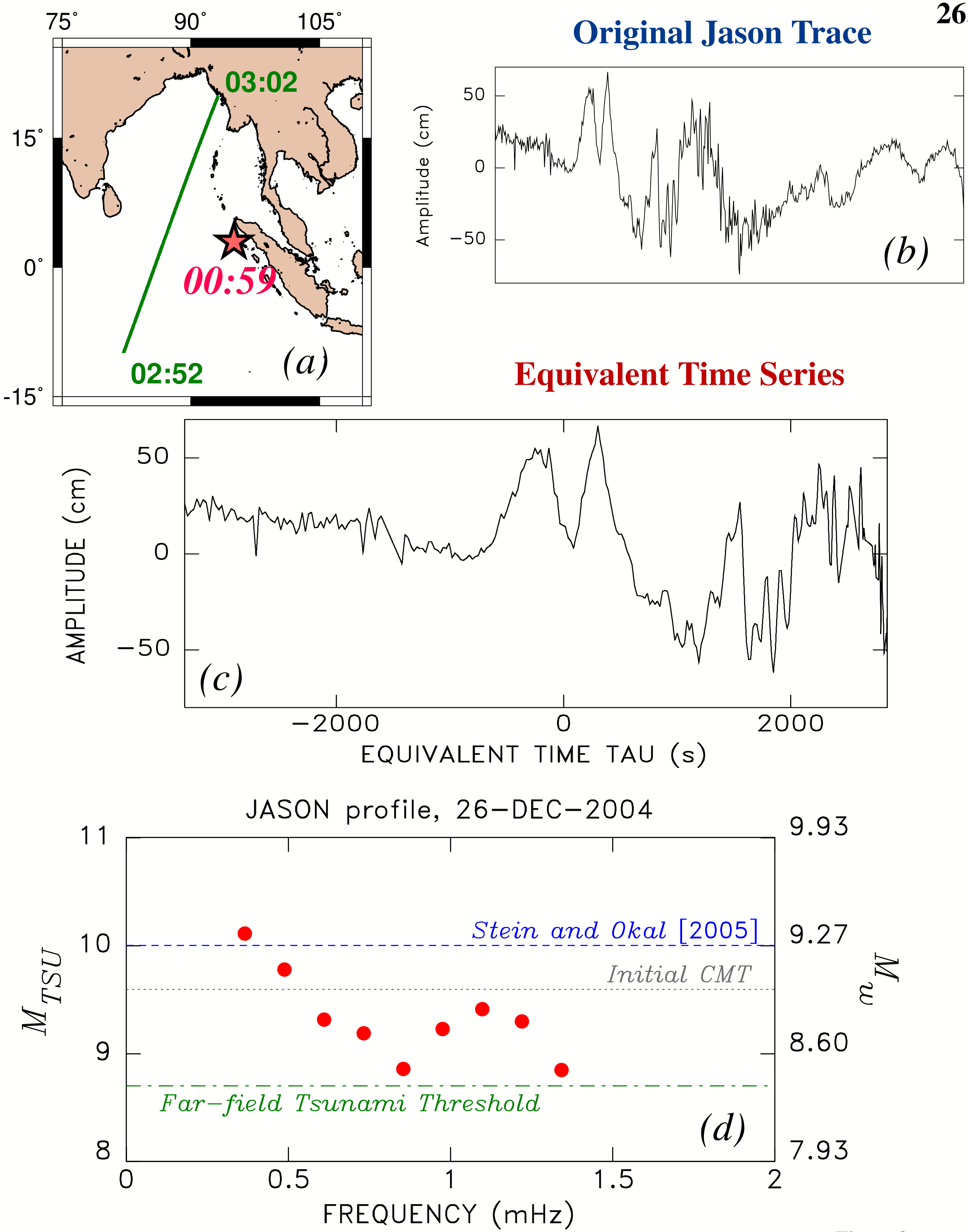
**TRACE of ALTIMETRY SATELLITE OVER INDIAN OCEAN**




*Satellite at the right place at the right time!*

**measures 70 cm across Bay of Bengal**





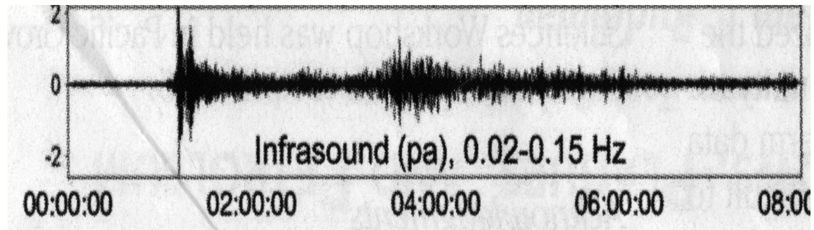
75°
90°
105°
15°
0°
-15°
03:02
00:59
02:52
(a)
Original Jason Trace
Amplitude (cm)
50
0
−50
(b)
Equivalent Time Series
AMPLITUDE (cm)
50
0
−50
(c)
−2000
0
2000
EQUIVALENT TIME TAU (s)
JASON profile, 26−DEC−2004
11
10
9
8
$M_{TSU}$
9.93
9.27
8.60
7.93
$M_m$
Stein and Okal [2005]
Initial CMT
Far−field Tsunami Threshold
(d)
0
0.5
1
1.5
2
FREQUENCY (mHz)


Figure 8

# INFRA SOUND ARRAYS (CTBT)

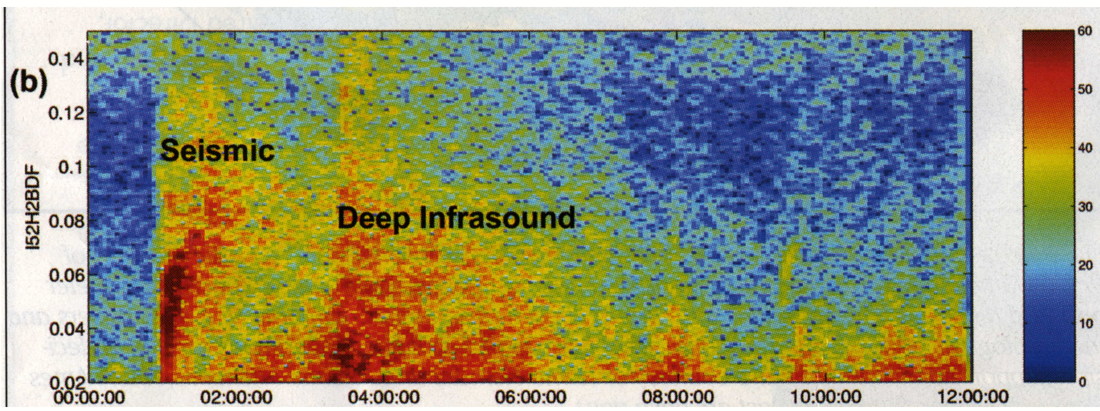
Arrays of barographs monitoring pressure disturbances carried by atmosphere.

(Deployed as part of International Monitoring System of CTBT.)

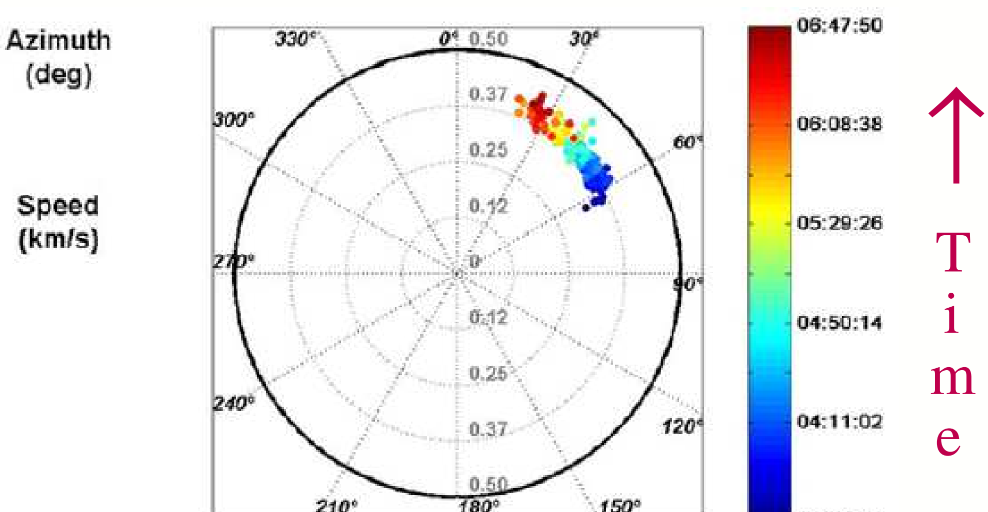

**Diego Garcia, BIOT, 26 Dec. 2004**

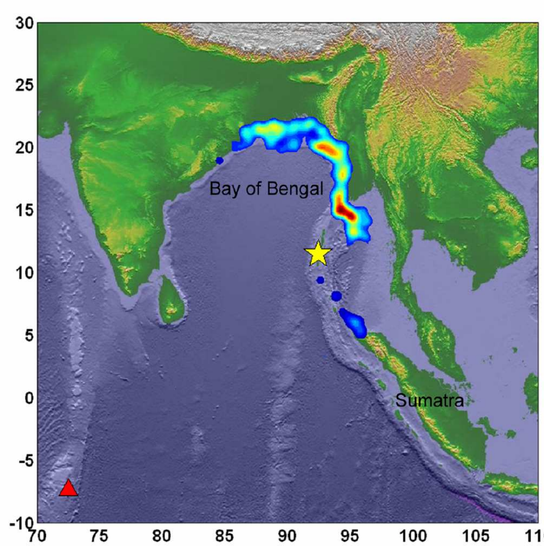
[*Le Pichon et al.*, 2005]




BEAM ARRAY to determine azimuth of arrival and velocity of air wave.

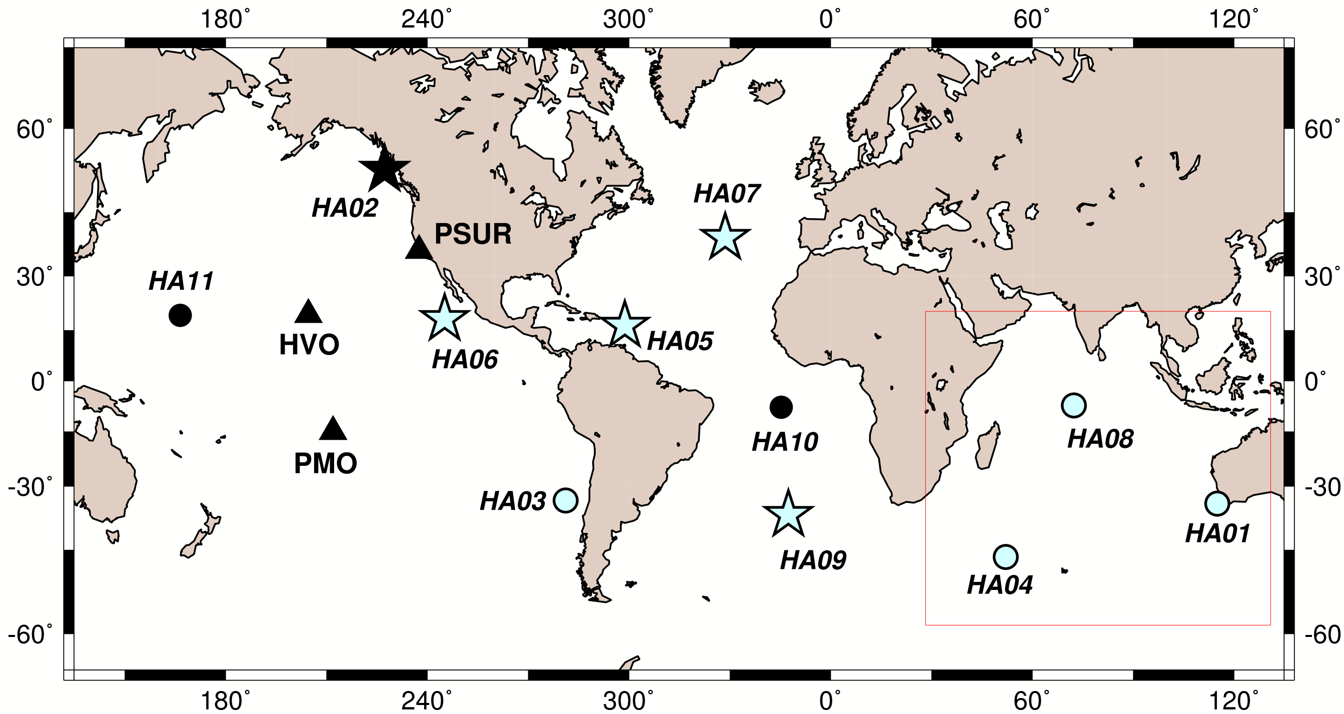
**USE TIMING** of arrival to infer source of disturbance as *TSUNAMI HITTING CONTINENT* then continent shaking atmosphere.



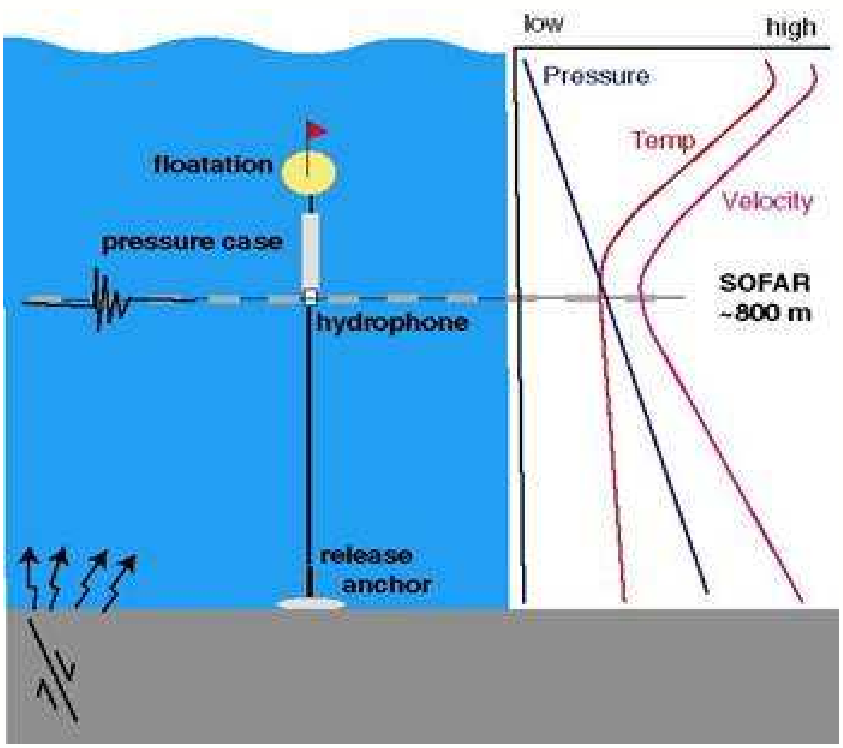



# CTBT HYDROPHONE RECORDS

In the context of the CTBTO ("Test-Ban Treaty Organization"), the **I**nternational **M**onitoring **S**ystem comprises six hydrophone stations deployed in the SOFAR channel, including three in the Indian Ocean.




Each station features several (3–6) sensors, allowing *beaming* of the array




These instruments recorded not only the hydroacoustic ("***T***") waves generated by the earthquake, but also its conventional seismic waves (Rayleigh), and most remarkably,

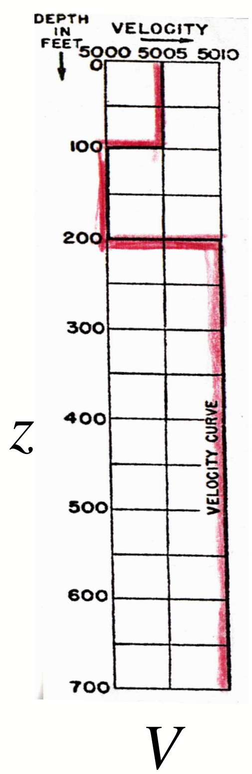
*the tsunami itself.*

[*M. Tolstoy,* Columbia University]

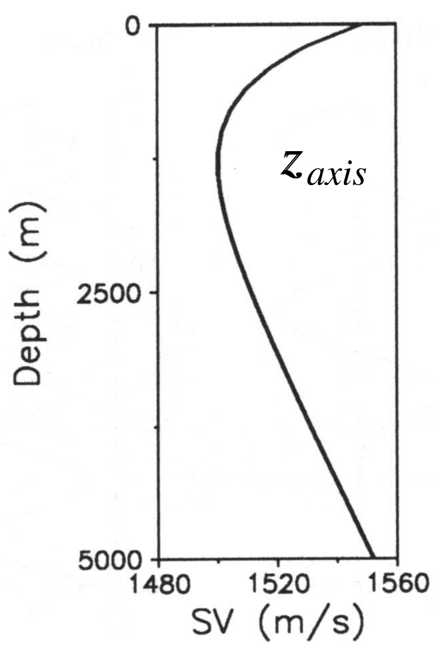
# THE SOFAR CHANNEL

- Variations in pressure, temperature and salinity of sea-water with depth create a *channel of minimum velocity* around $z = 1000$ m.
- This acts as a *WAVEGUIDE* allowing exceptionally efficient propagation of acoustic energy in the ocean basins ($f \geq 3$ Hz).

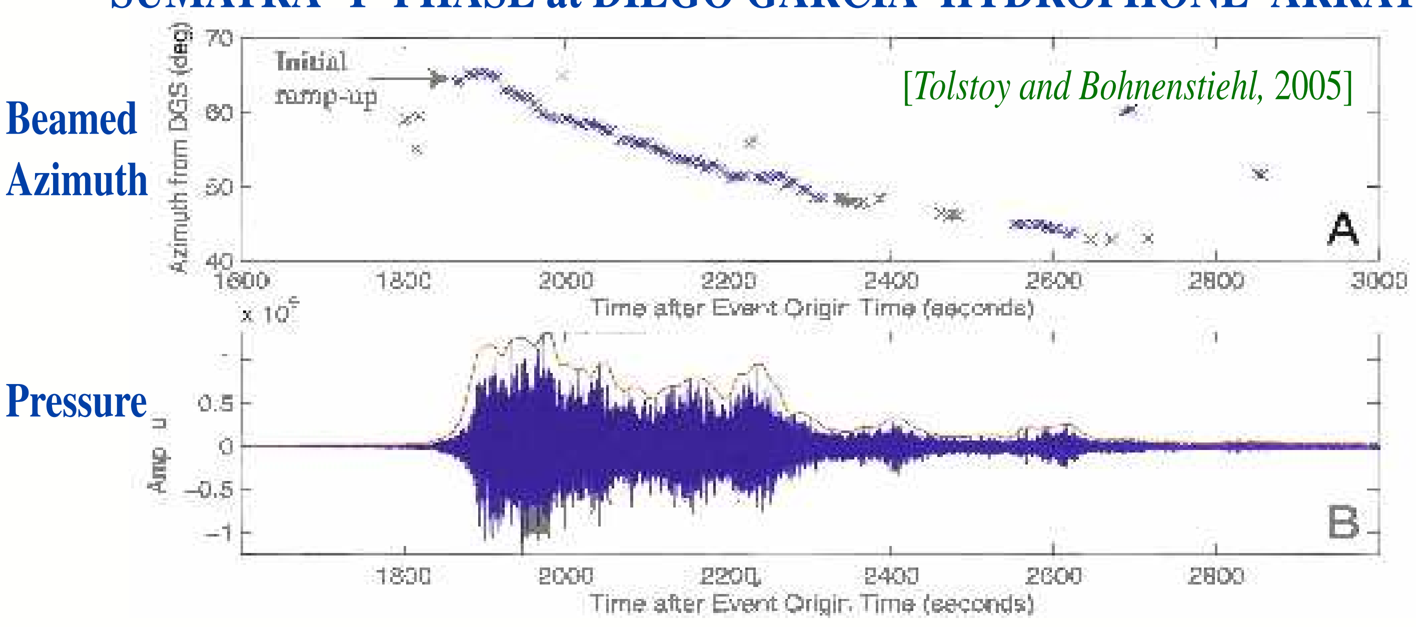
[*Pekeris,* 1948]




[*Munk,* 1972]



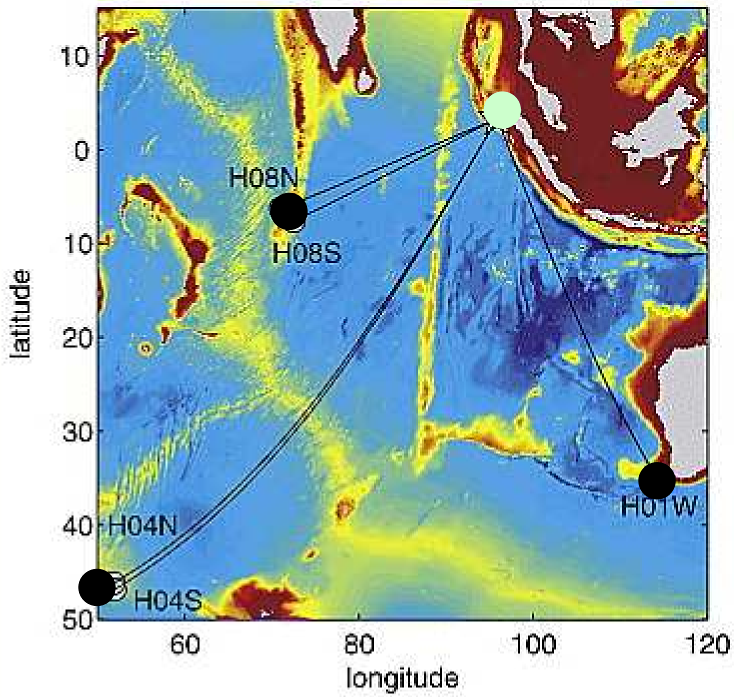

## SUMATRA T PHASE at DIEGO GARCIA HYDROPHONE ARRAY

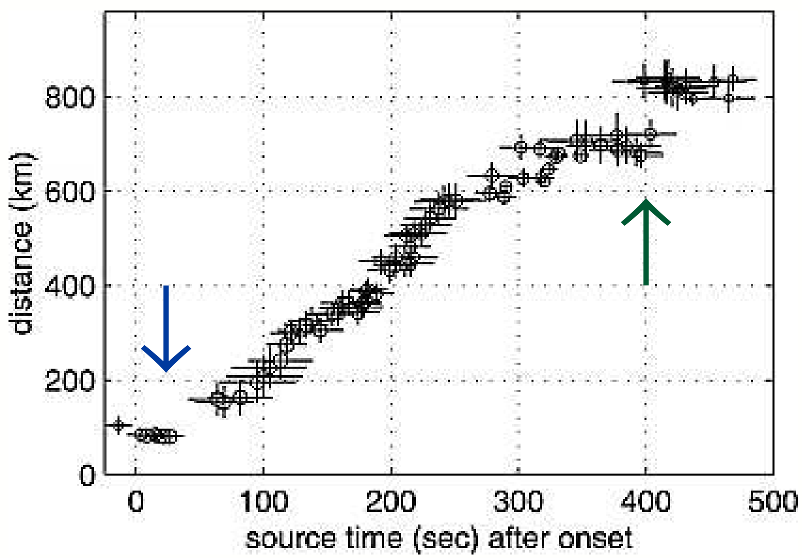


# "HYDROACOUSTIC TOMOGRAPHY"

Use CTBT hydrophone triads to back-track the temporal evolution of $T$−wave energy into individual elements of the rupture.

[deGroot-Hedlin, 2005]



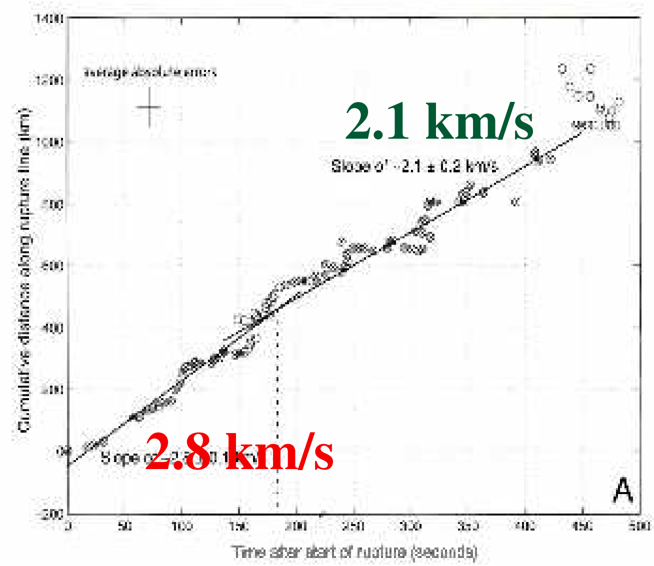




These studies confirm:

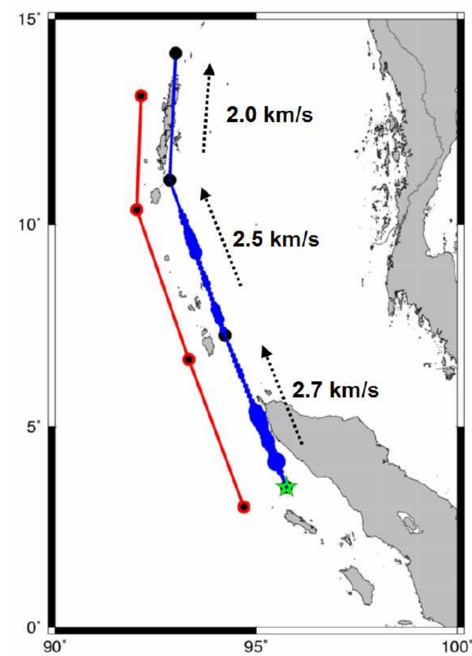
- **1000(+)-km rupture**
- **Slow rupture**
- **Slower in the North**

[Perhaps slower initially]

[Tolstoy and Bohnenstiehl, 2005]




[Guilbert et al., 2005]

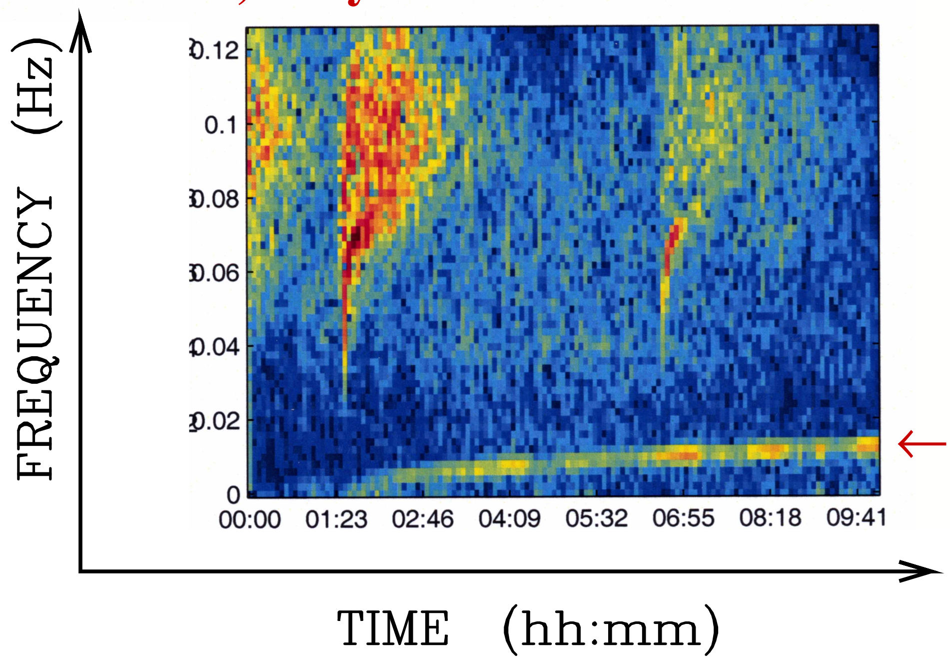


# TSUNAMI recorded by HYDROPHONES of the CTBTO

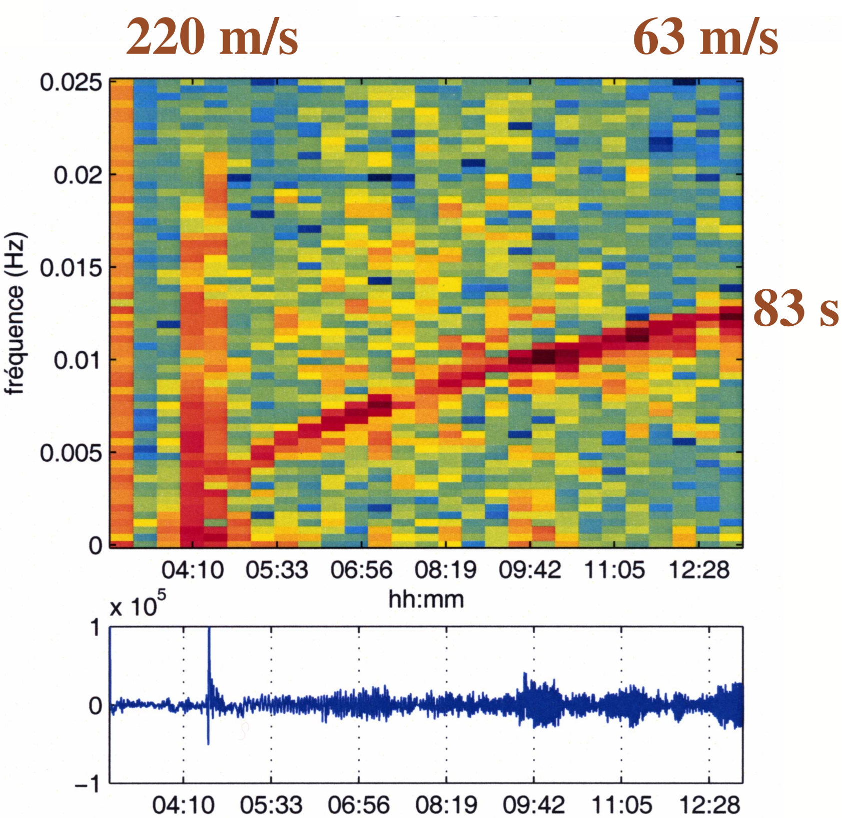
**(hanging in ocean at 1300 m depth off Diego Garcia)**

→ Instruments are severely filtered at infra-acoustic frequencies.

**YET, they recorded the TSUNAMI!**




← **Tsunami branch**




**Note first ever observation of** *DISPERSION* of tsunami branch at *VERY HIGH* [tsunami] frequencies in the far field

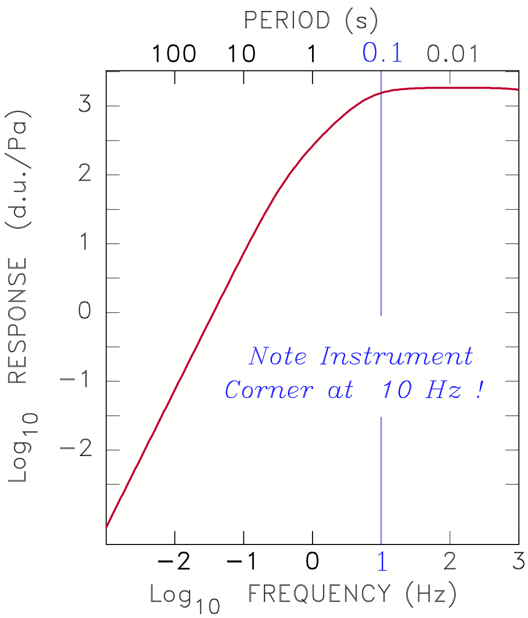
$$\omega^2 = g\,k \cdot \tanh(k\,h)$$

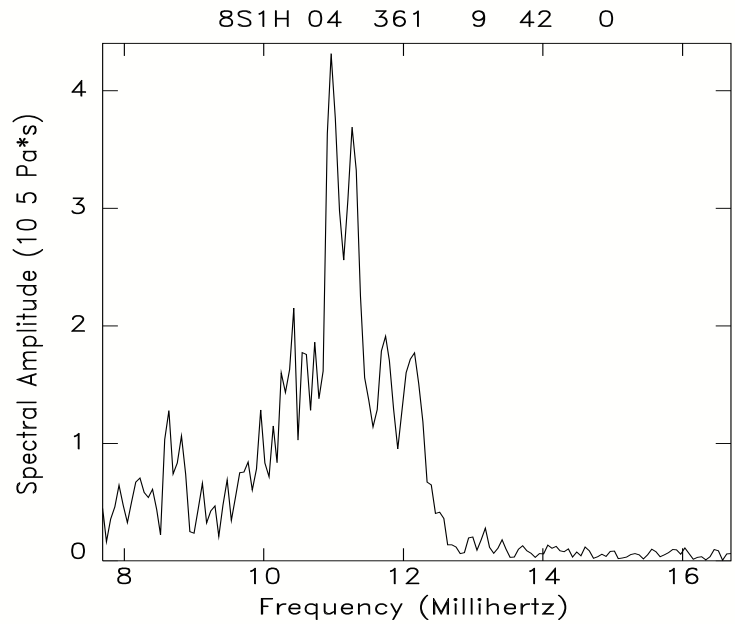
All of this on the high seas, unaffected by coastal response.

**NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS**

# Retrieving Seismic Moment from High-Frequency Tsunami Branch

- Use Hydrophone H08S1 from IMS at Diego-Garcia (BIOT)
- Deconvolve instrument and retrieve pressure spectrum




$$P(\omega) \ = \ 0.35 \ \mathrm{MPa} * \mathrm{s} \ \ \mathrm{at} \ \ 87 \ \mathrm{s}$$

- Use *Okal* [1982; 2003; 2006] to convert overpressure at 1300 m depth to surface amplitude $\eta$ ,

*outside classical Shallow-Water Approximation.*

Find $\eta(\omega) = 78000$ cm*s at $T = 87$ s.

- Use *Haskell* [1952], *Kanamori and Cipar* [1974], *Ward* [1980], *Okal* [1988; 2003] in normal mode formalism to compute excitation coefficients.

Find $\boldsymbol{M_0 \ = \ 8 \times 10^{29}}$ **dyn – cm**

*ACCEPTABLE !*

(Moment from Earth's free oscillations: **$1$ to $1.2 \times 10^{30}$ dyn-cm**)

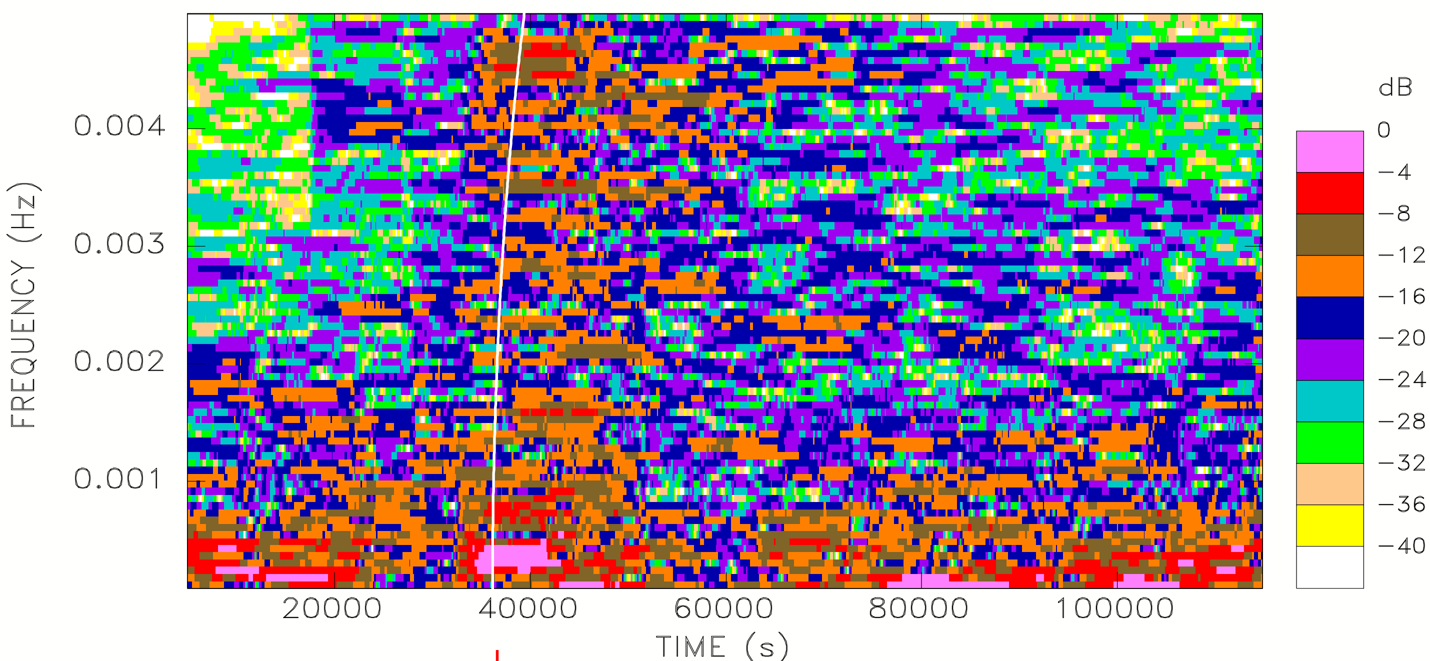
[*Stein and Okal,* 2005; *Nettles et al.,* 2005]

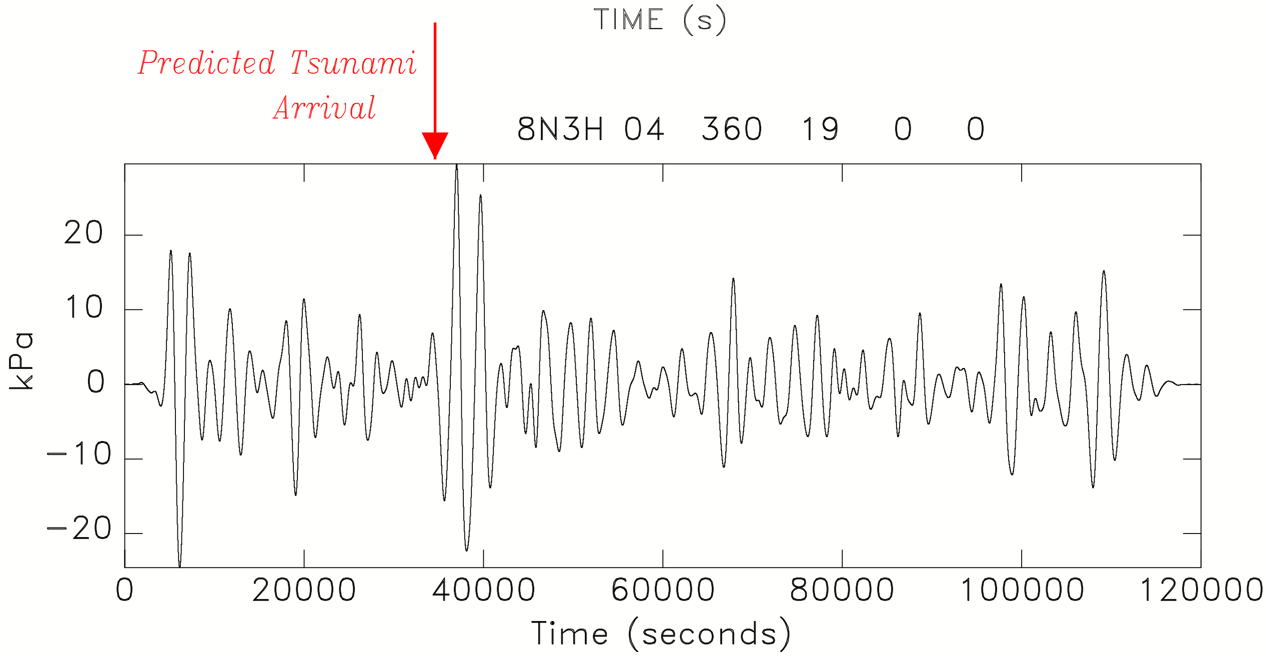
# LONG-PERIOD ($T \approx 3000$ s) TSUNAMI

# ALSO RECORDED BY DIEGO GARCIA HYDROPHONES

- However, such periods are 30,000 times the corner of the filter and the response of the instrument is expected to be down by $\approx 5 \times 10^8$, to the extent that digital noise strongly affects the spectrum.

→ *IT DOES NOT APPEAR POSSIBLE TO FURTHER INTERPRET THESE SIGNALS QUANTITATIVELY.*

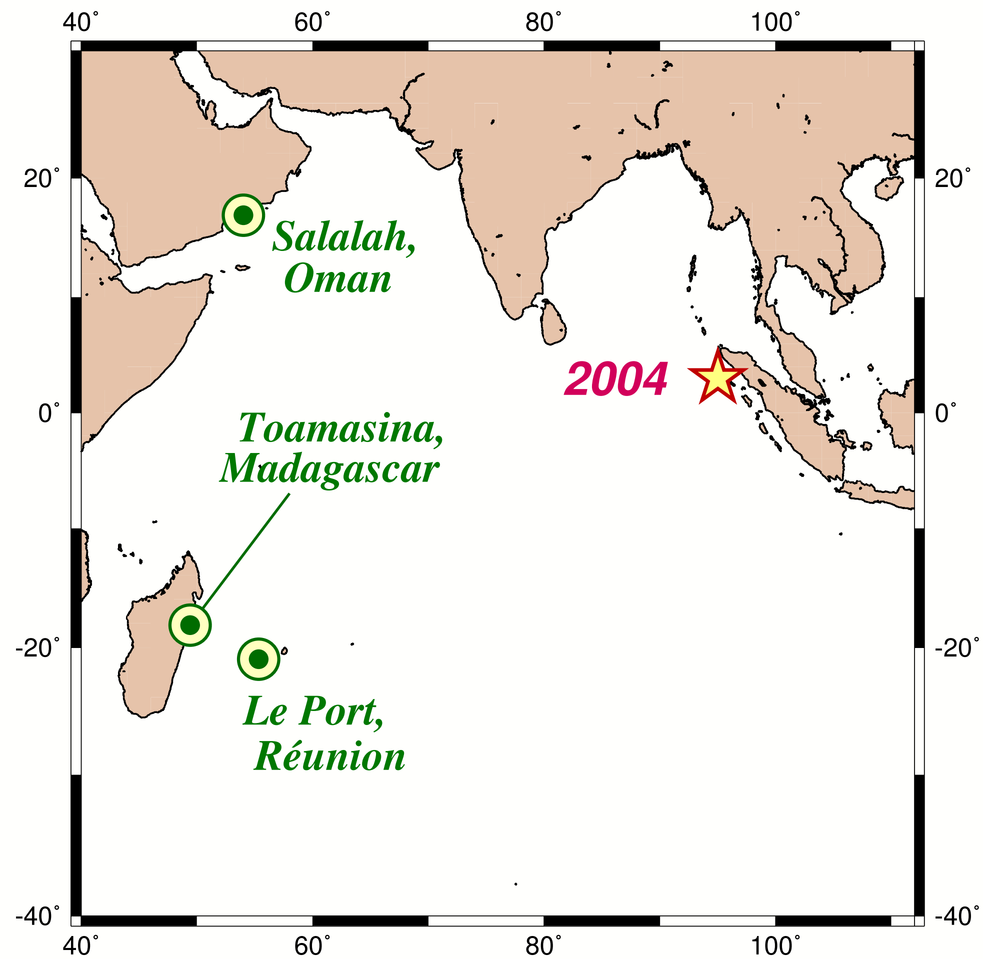


# HIGH–FREQUENCY COMPONENTS of the TSUNAMI WAVE and HAZARD to HARBOR ENVIRONMENTS

- In at least three harbors of the Western Indian Ocean where the tsunami was otherwise benign, large vessels broke their moorings and drifted for several hours inside port facilities.
- Miraculously, this led to no casualties and only minor damage to ships and infrastructure.
- In two instances, this happened *SEVERAL HOURS AFTER* the arrival of the main tsunami waves.
- This has severe consequences for Civil Defense in harbor environments, especially with respect to the sensitive issue of the *"all clear"* after an alert.

→ It may be due to the resonant oscillation of the harbors excited by the shorter components of the tsunami wave, delayed by the dispersion of their group velocity outside the limits of the shallow-water approximation.



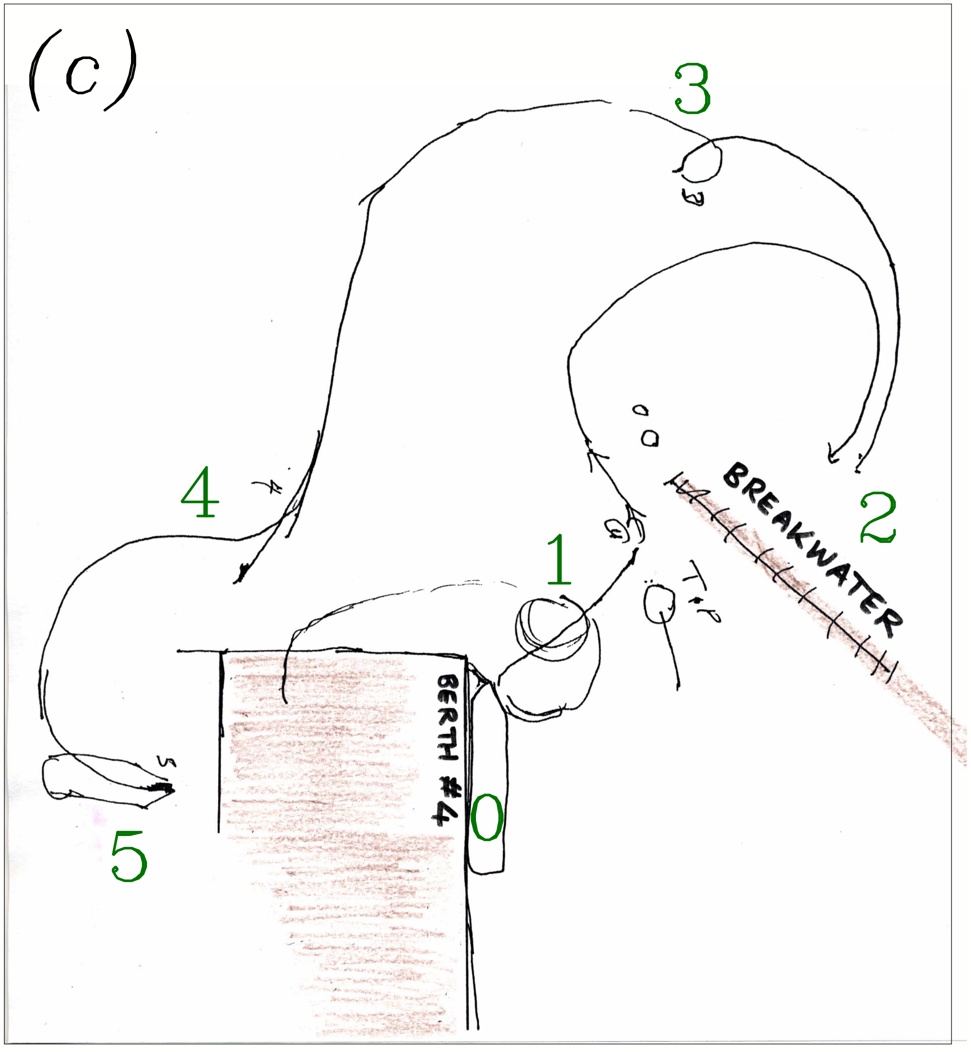

**→ The study of this part of the tsunami spectrum should become a priority.**

# SALAHAH, Oman

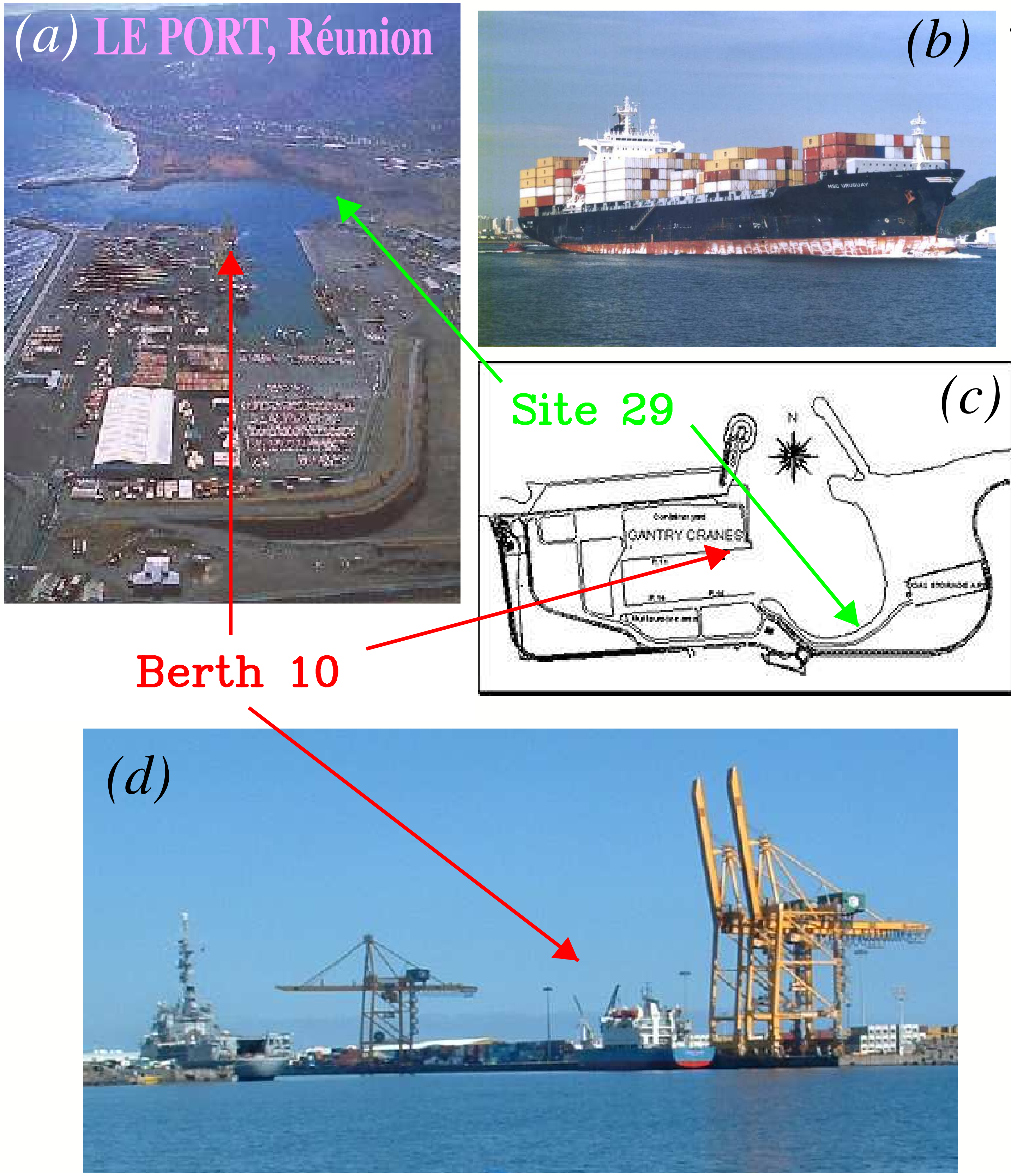
(a)

(b)


(c)




- **285–m CONTAINER SHIP BROKE MOORINGS at 13:42 (GMT+4), during MAXIMUM TSUNAMI WAVES,**
- **DRIFTED INSIDE and OUT OF HARBOR**
- **SISTER SHIP WAS CAUGHT in EDDIES and HIT BREAKWATER WHILE WAITING to ENTER HARBOR AROUND 22:00**




**196–m CONTAINER SHIP BROKE MOORINGS**

**around 15:45 (GMT+4), 1.5 HOURS after MAXIMUM WAVES,**

**THEN a 2nd TIME at 18:30, FOUR HOURS after Maximum.**

**CAUSED DAMAGE TO GANTRY CRANES**

# TOAMASINA, Madagascar

(a)

(b)


(c)


**Figure 5.** *(a):* The 50–m freighter *Soavina III* photographed on 2 August 2005 in the port of Toamasina. *(b):* Sketch of the port of Toamasina showing its complex geometry. *(c):* Captain Injona uses a wall map of the port (ESE at top) to describe the path of *Soavina III* from her berth in Channel 3B (pointed on map), where she broke her moorings around 7 p.m., wandering in the channels up to the location of the red dot (also shown on Frame *b*), before eventually grounding in front of the Water-Sports Club Beach (white dot; Site 17).

## 50–m SHIP BROKE MOORINGS around 19:00 (GMT+3), FOUR HOURS AFTER MAXIMUM WAVES

# Preliminary modeling for Toamasina [Tamatave], Madagascar

[*D.R. MacAyeal*, pers. comm., 2006]

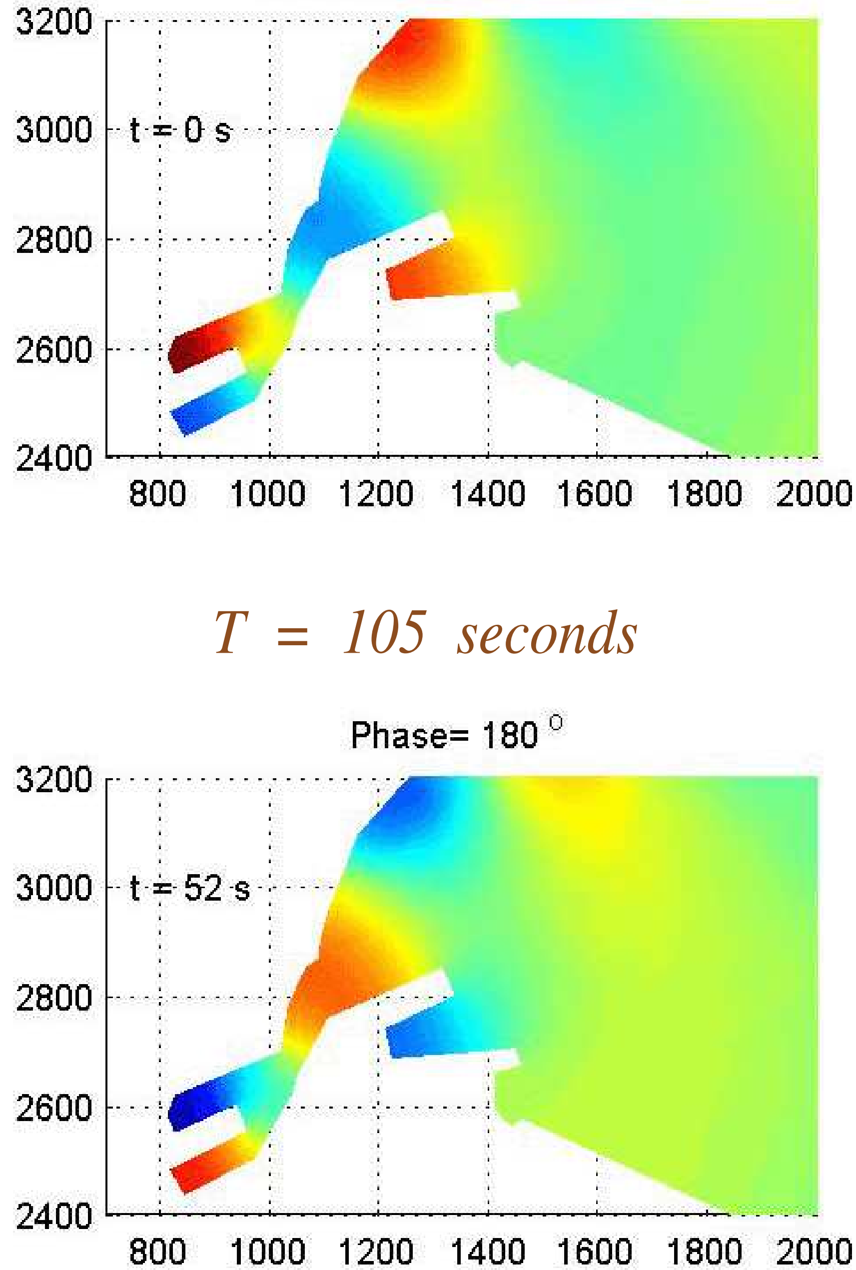
- Finite element modeling of the oscillations of the port of Toamasina reveals a fundamental mode of oscillation at $T$ = 105 s, characterized by sloshing back and forth of water into the interior of the harbor, thus creating strong *currents* at the berth of *Soavina III*.

- At this period, the group velocity of the tsunami wave is found to be **97 m/s** for an average ocean depth of 4 km.

- This would correspond to an arrival at **16:55 GMT, or 19:55 Local Time**.

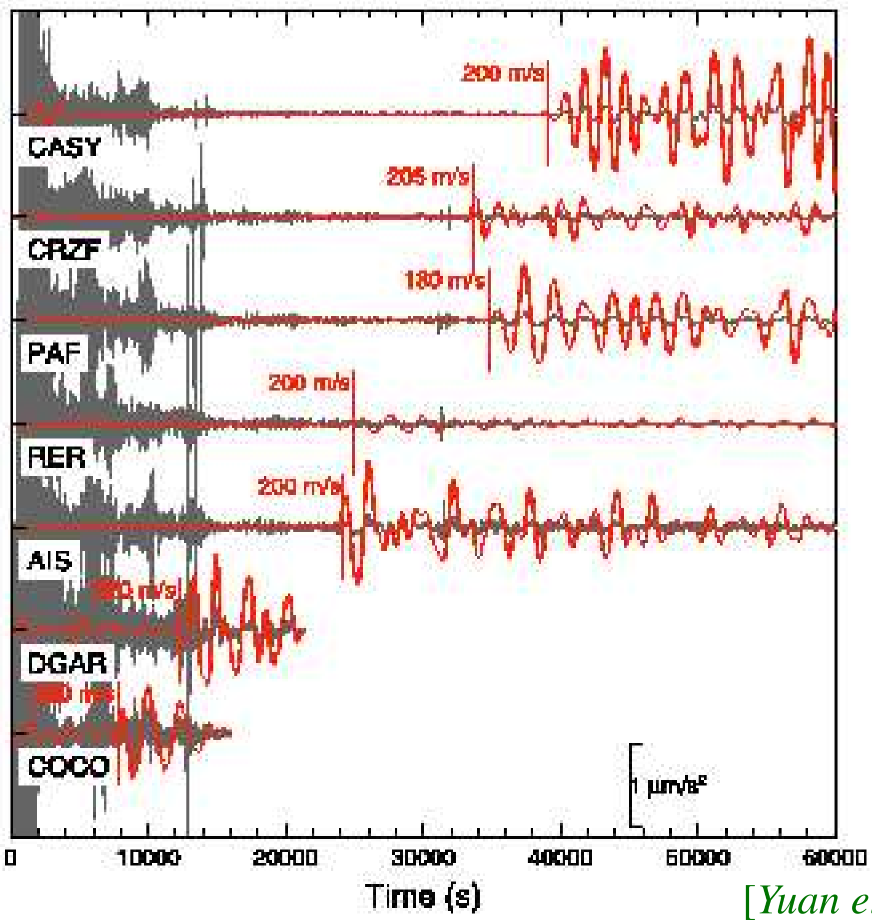
- This is in good agreement with the Port Captain's testimony

*"After 7 p.m. and lasting several hours"*

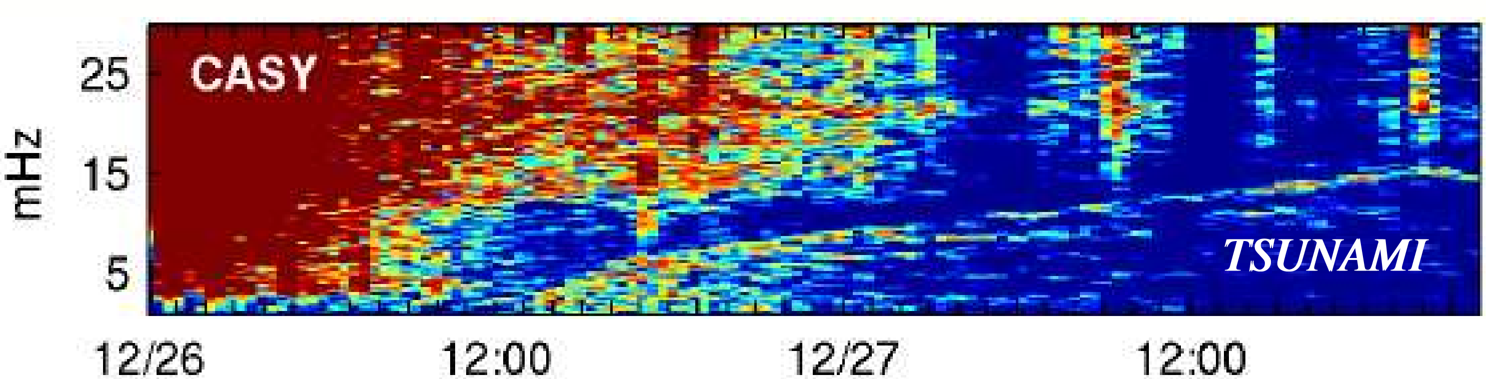


# TSUNAMI RECORDED ON SEISMOMETERS

- Horizontal long-period seismometers (GEOSCOPE, IRIS...) record ultra-long period oscillations following arrival of tsunami at nearby shores [*R. Kind,* 2005].
- Energy is mostly between 800 and 3000 seconds
- Amplitude of equivalent displacement is **centimetric**




[*Yuan et al.,* 2005]




[*Hanson and Bowman,* 2005]

# TSUNAMI RECORDED ON SEISMOMETERS (ctd.)

**Enhanced Study** [*E.A. Okal,* 2005–06].

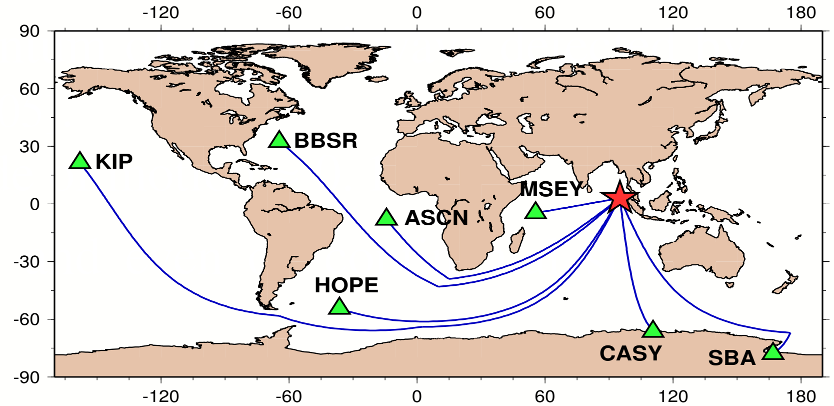
- *RECORDED* **WORLDWIDE** (On Oceanic shores)
- ***HIGHER FREQUENCIES*** (up to 0.01 Hz) *PRESENT* (in regional field)
- Tsunami detectable during **SMALLER EVENTS**
- *CAN BE* **QUANTIFIED** (Variation of $M_{TSU}$ )

# 8. TSUNAMI RECORDED ON SEISMOMETERS

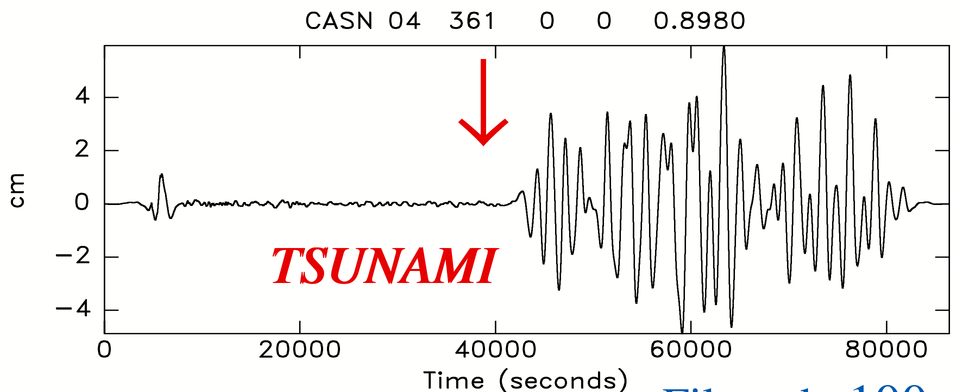
- Recording by shoreline stations is

  **WORLDWIDE**

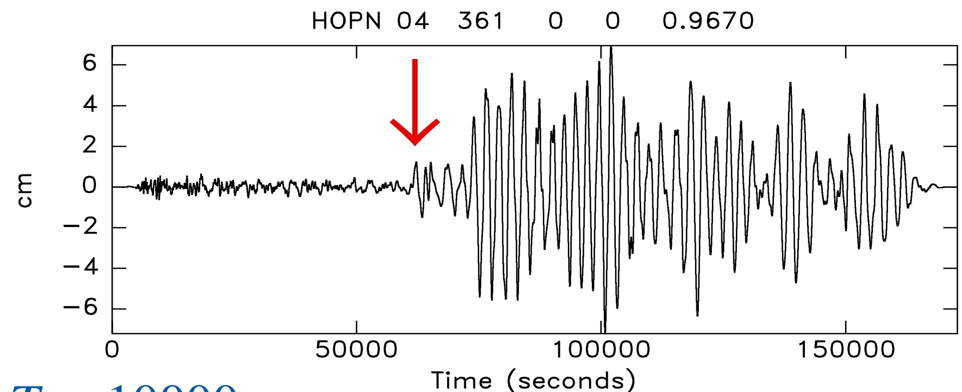
  including in regions requiring strong refraction around continents (Bermuda, Scott Base).




## Casey, Antarctica, 8300 km

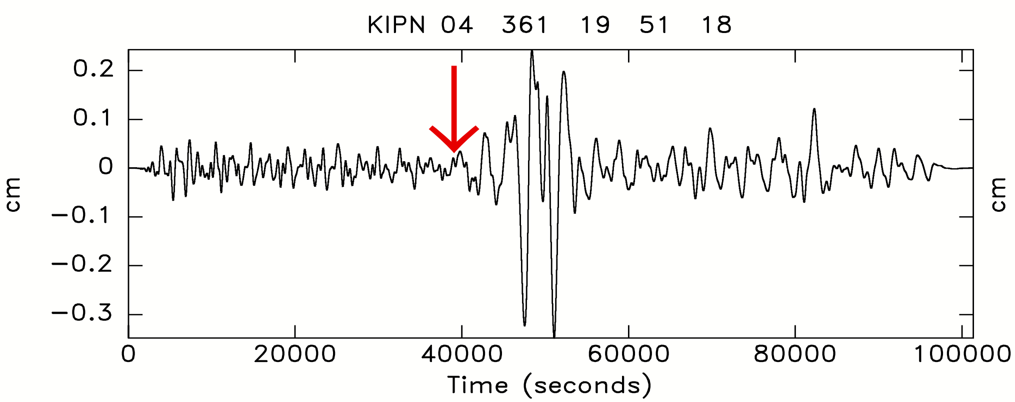



## Hope, South Georgia, 13100 km

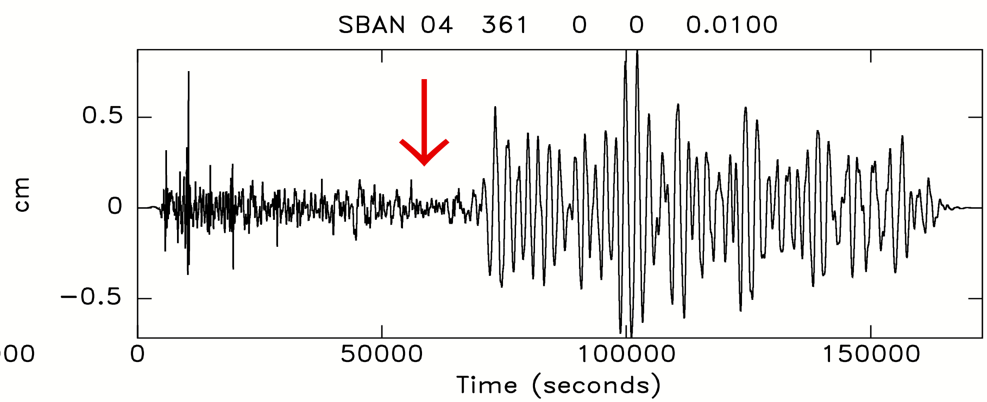



Filtered 100 < $T$ < 10000 s.

## Kipapa, Hawaii, 27,000 km

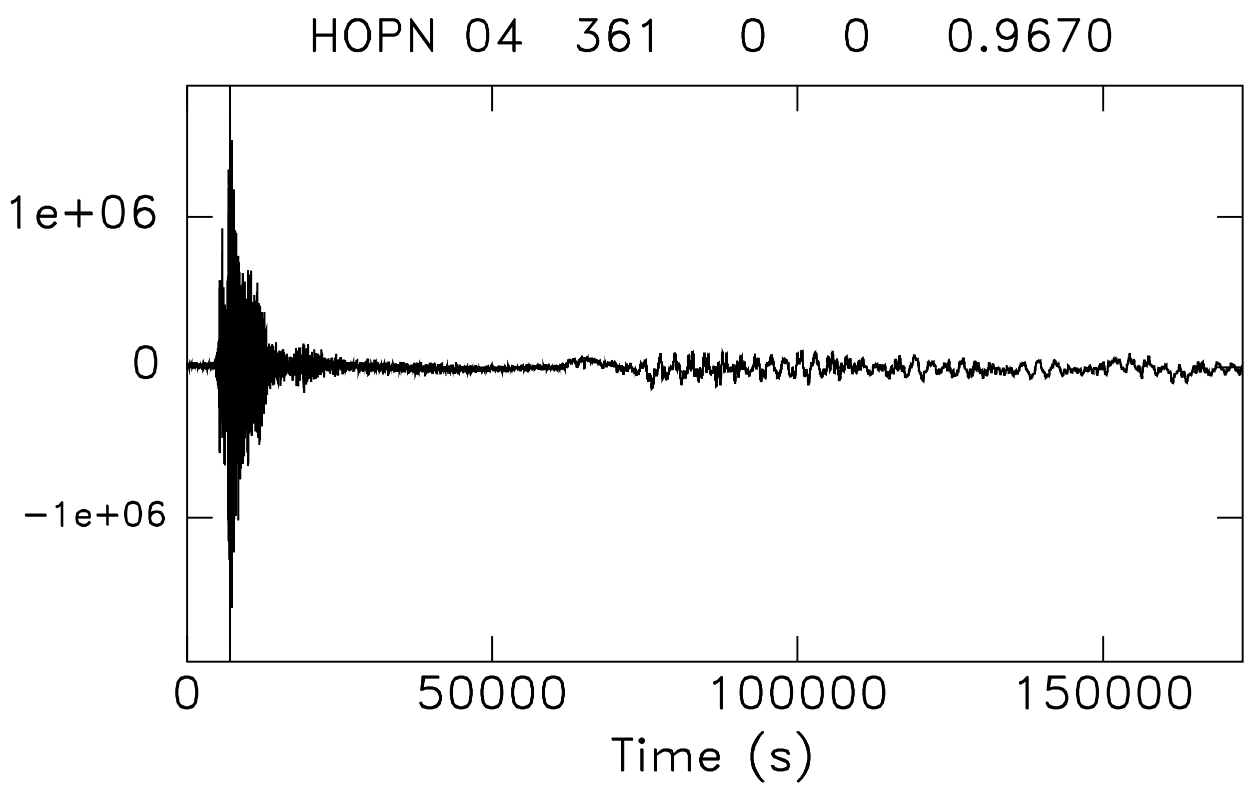



## Scott Base, Antarctica, 10400+ km



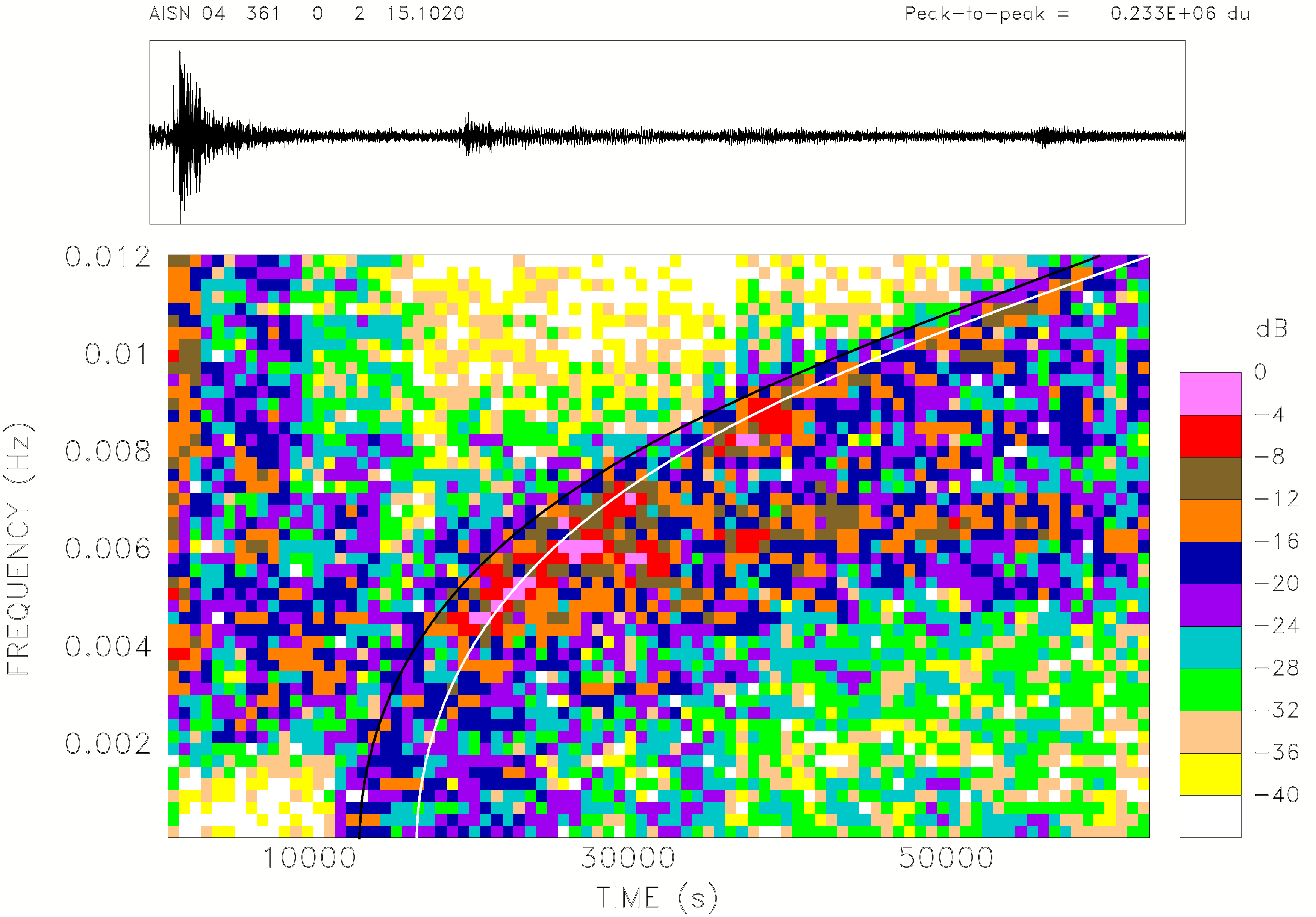
- *On some of the best records, (e.g., HOPE, South Georgia), the tsunami is actually visible* ***on the raw seismogram!!***

[But who "reads" seismograms in this digital age, let alone that of HOPE, South Georgia...]



# Dispersed energy resolved down to $T$ = 80 s.

## Ile Amsterdam, 26 Dec. 2004




**NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS**

# SEISMIC RECORD at CASY

- Assume that seismic record (*e.g.,* at CASY) reflects response of seismometer to the *deformation of ocean bottom.*

- Use *Gilbert*'s [1980] combination of displacement, tilt and gravity;

Apparent Horizontal Acceleration (*Gilbert*'s [1980] Notation):

$$AV = \omega^2 V - r^{-1} L ( g U + \Phi )$$

or (*Saito*'s [1967] notation):

$$y_3^{APP} = y_3 - \frac{1}{r \omega^2} \cdot ( g y_1 - y_5 )$$

- Use *Ward*'s [1980] normal mode formalism;

Evaluate Gilbert response on solid side of ocean floor, and derive equivalent spectral amplitude of surface displacement $y_1(\omega) = \eta(\omega)$.

- Use *Okal and Titov*'s [2005] Tsunami Magnitude, inspired from *Okal and Talandier*'s [1989] $M_m$ ;

- Apply to CASY record at maximum spectral energy
  ($S(\omega)$ = 4000 cm*s at $T$ = 800 s).

→ Find $\mathbf{M_0 = 1.7 \times 10^{30}}$ **dyn – cm.**

Acceptable, given the extreme nature of the approximations.

→ Suggests that the signal is just the expression of the horizontal deformation of the ocean floor, and that

CASY functions in a sense like an OBS !!

# QUANTIFICATION OF SEISMIC TSUNAMI RECORDS

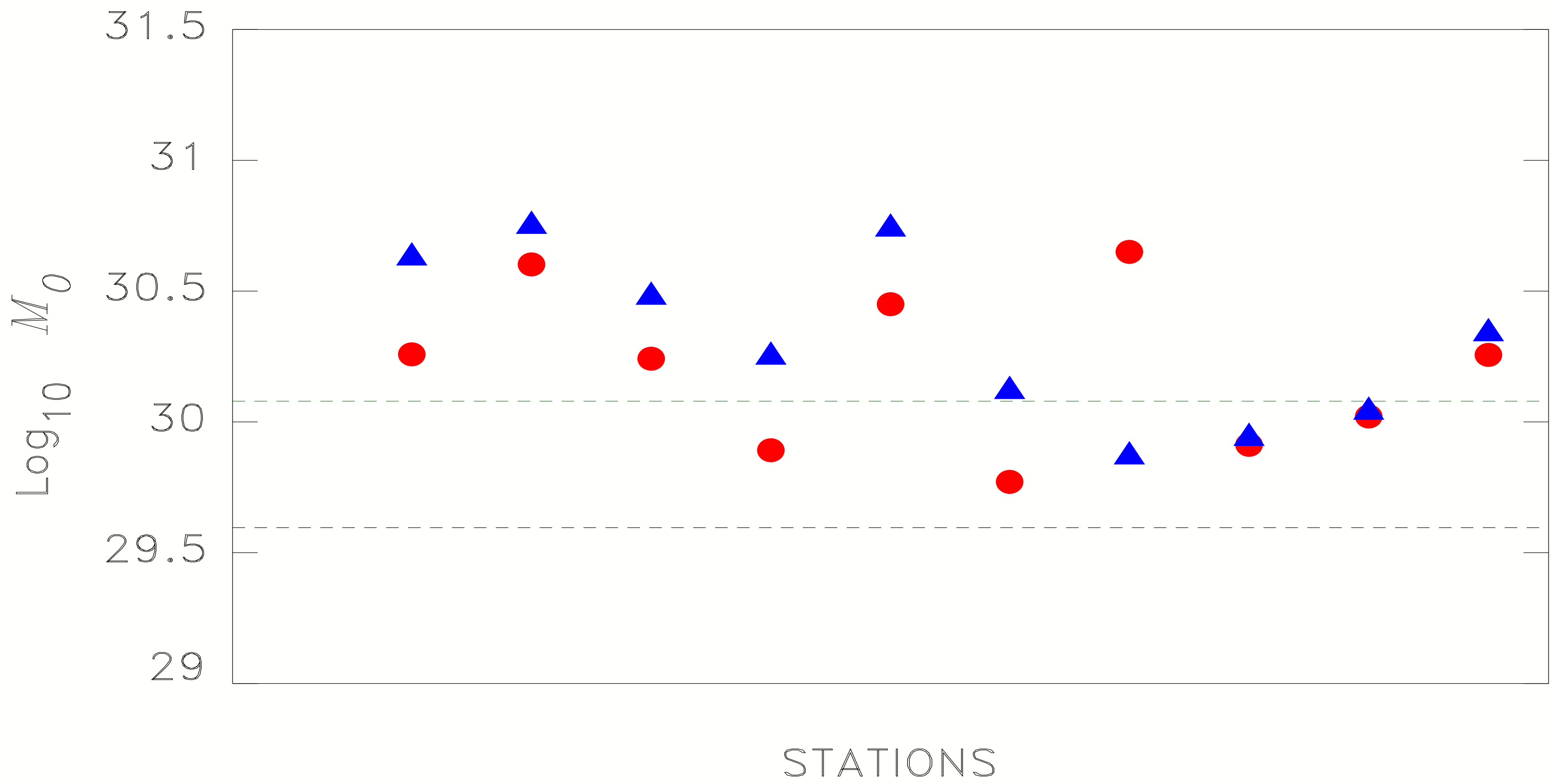
- Apply technique to dataset of 10 stations with direct great circle path
- Use either Full Source computation (**Red Symbols**)

$$\overline{M_0} = 1.6 \times 10^{30} \text{ dyn} - \text{cm}$$

or $M_{TSU}$ magnitude approach (**Blue Symbols**)

$$\overline{M_0} = 2.1 \times 10^{30} \text{ dyn} - \text{cm}$$

In good agreement with *Nettles et al.* [2005] and *Stein and Okal* [2005] (green dashed line)



# USING AN ISLAND SEISMOMETER AS A "DART" SENSOR?

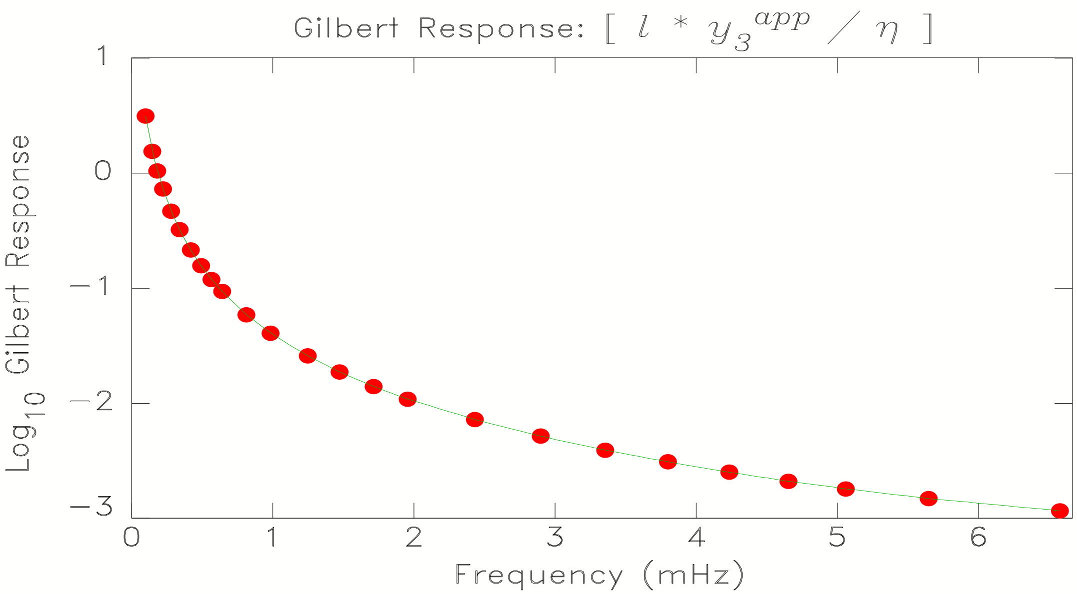
*Example: Ile Amsterdam, 26 DEC 2004 (d= 5800 km)*

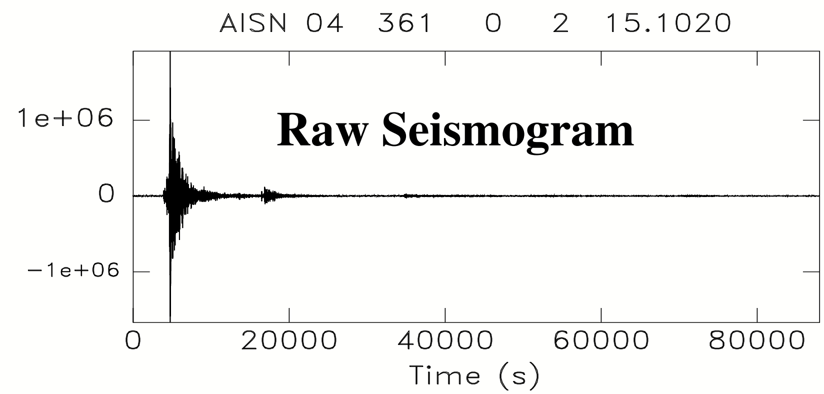
- A horizontal seismometer at a shoreline location can record a tsunami wave.

- Once the instrument is deconvolved, we obtain an apparent horizontal ground motion of the ocean floor

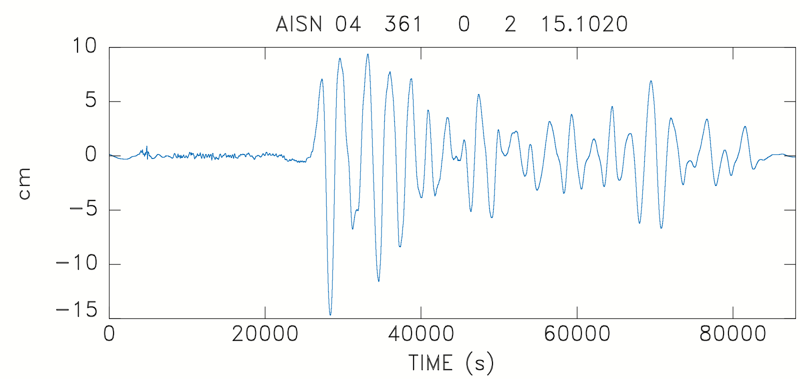
- Further deconvolve the *"**G**ilbert **R**esponse **F**actor"* $[l\, y_3^{app} / \eta]$ and obtain the time series of the surface amplitude of the tsunami.

- The ***G*** *R F* can be computed from normal modes

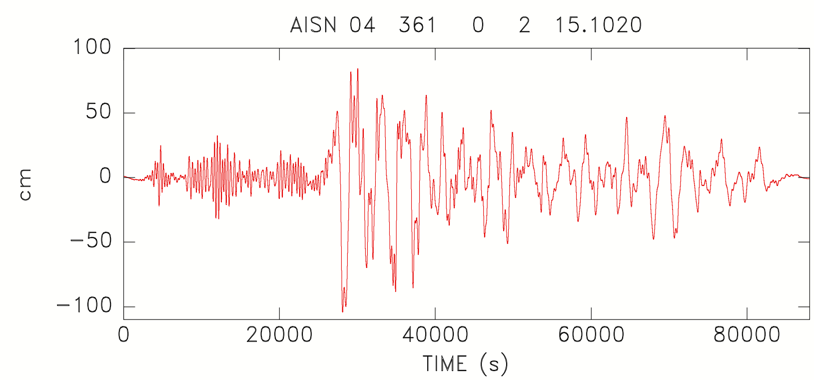


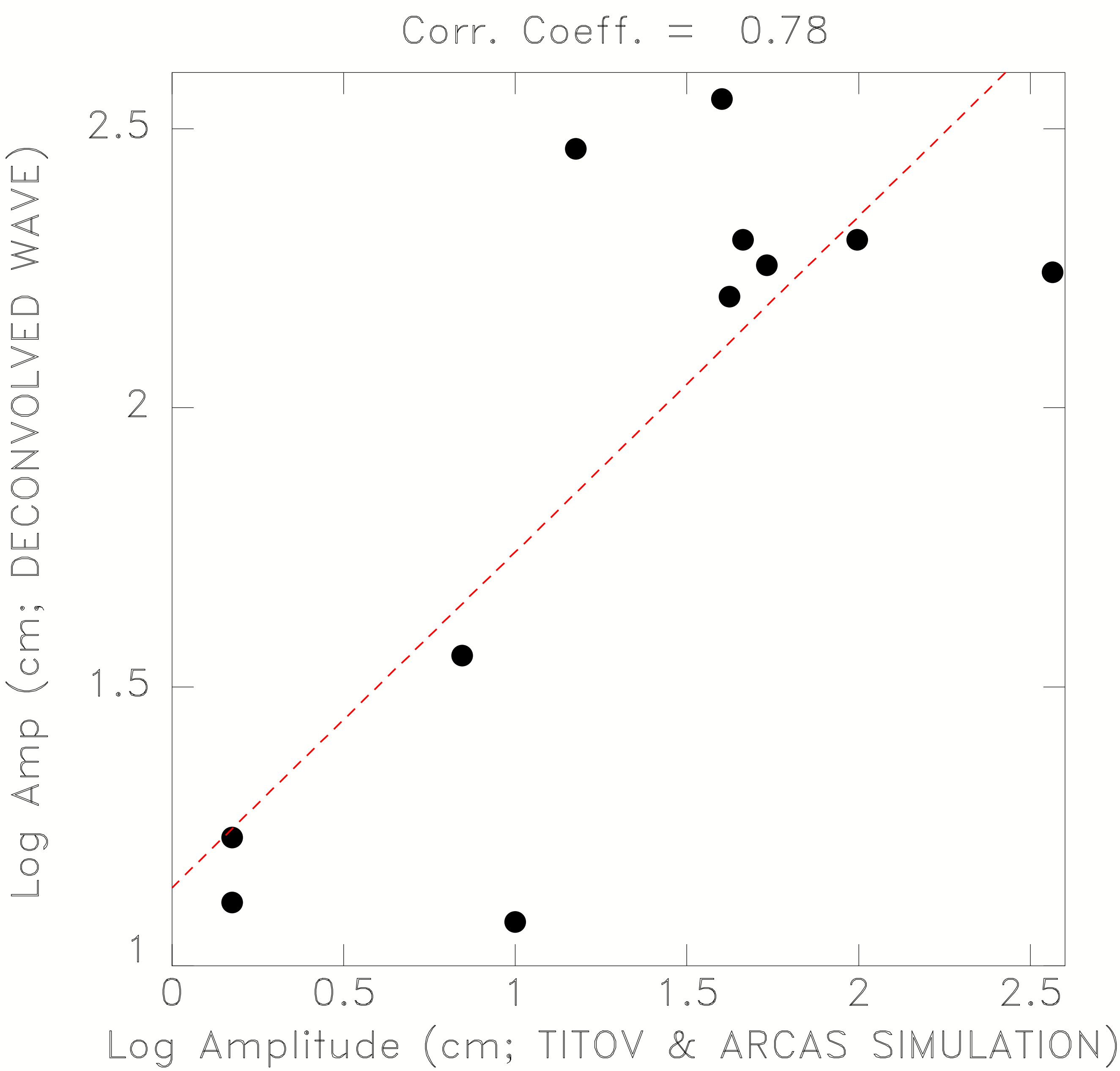

Deconvolve Instrument: **Apparent Ground Motion**




**Deconvolve *GRF*: "Tsunami Record"**



- Indeed, we find a good correlation between tsunami heights deconvolved from seismometers and tsunami amplitudes from the worlwide simulation of *Titov and Arcas* [2005], computed at deep-ocean locations in the neigborhood of the recording seismometers.



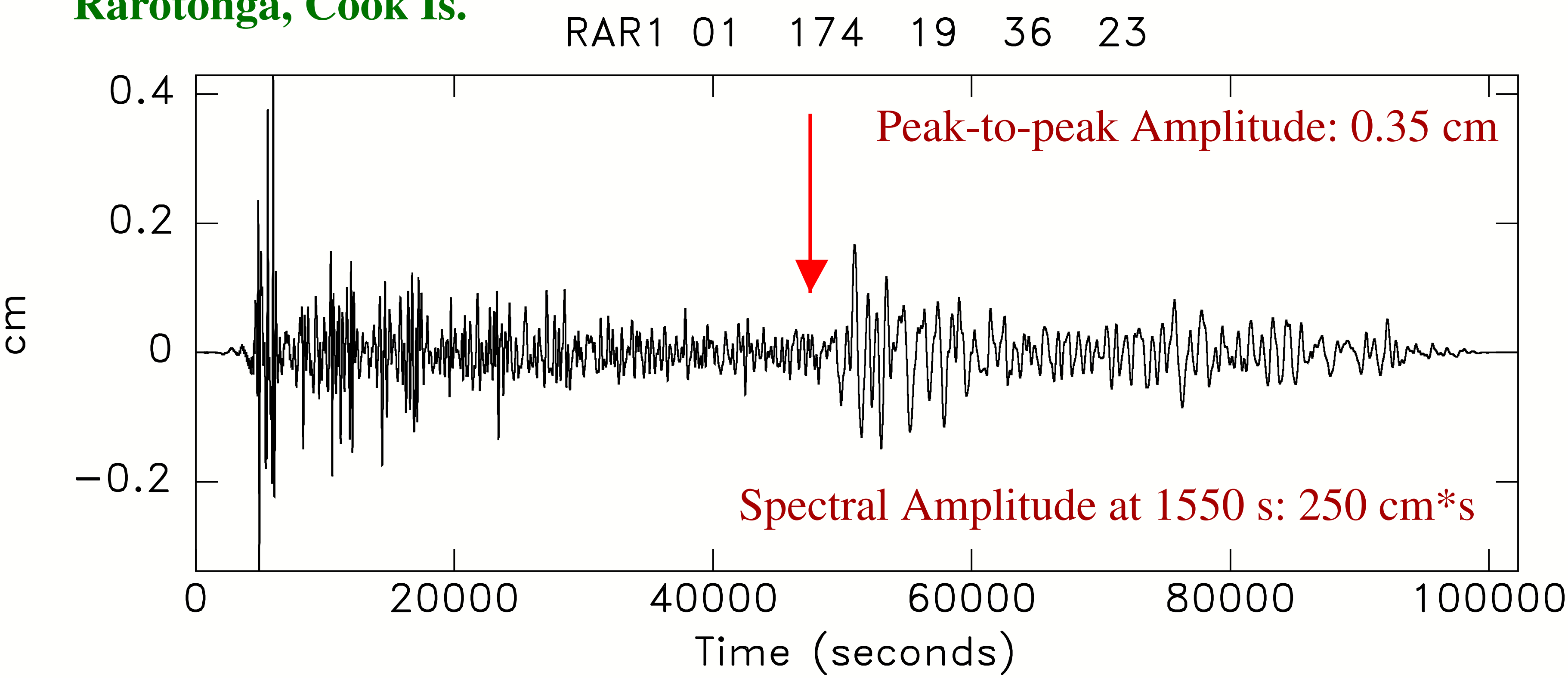
# TSUNAMI DETECTED FOLLOWING SMALLER EVENT

*Camaná, Perú, 23 June 2001*

Harvard CMT: $M_0 = 4.7 \times 10^{28}$ dyn-cm

FILTERED, Tmax = 10000. s; Tmin = 100. s.

**Rarotonga, Cook Is.**

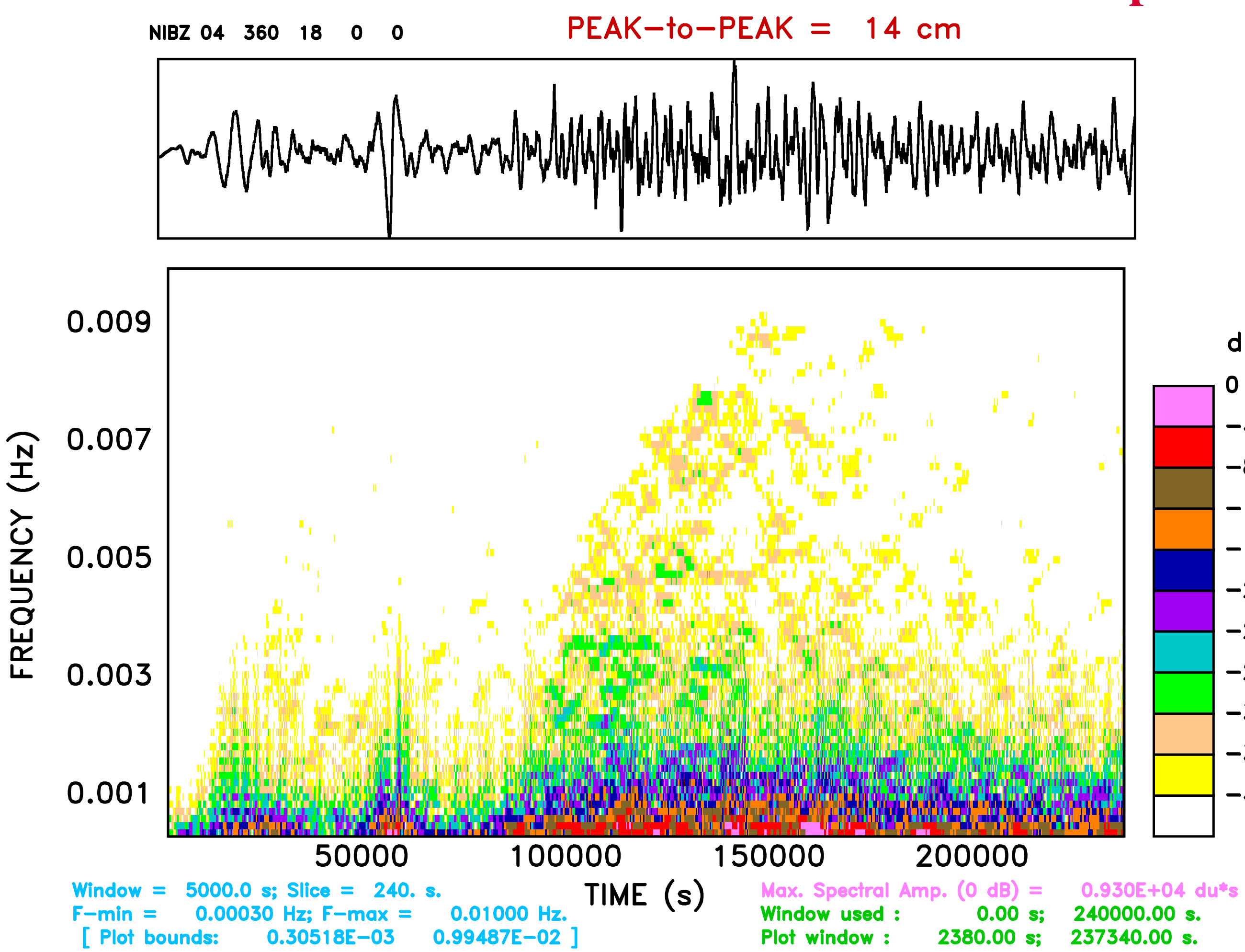


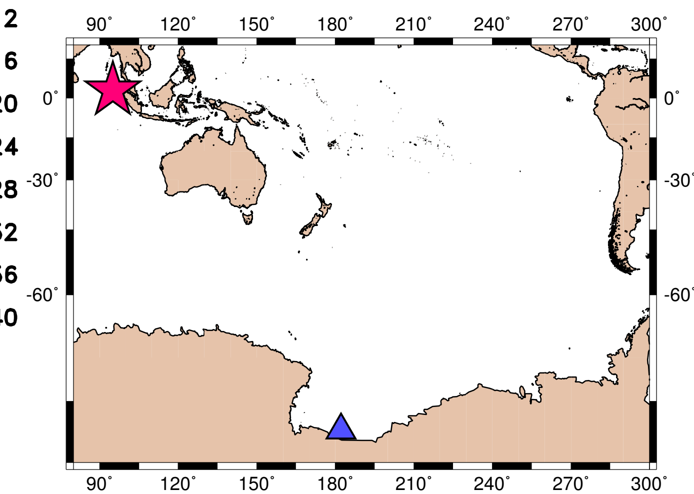

**Computed Moment: $M_0 = 4.6 \times 10^{28}$ dyn-cm**

# TSUNAMI RECORDED on ICEBERGS

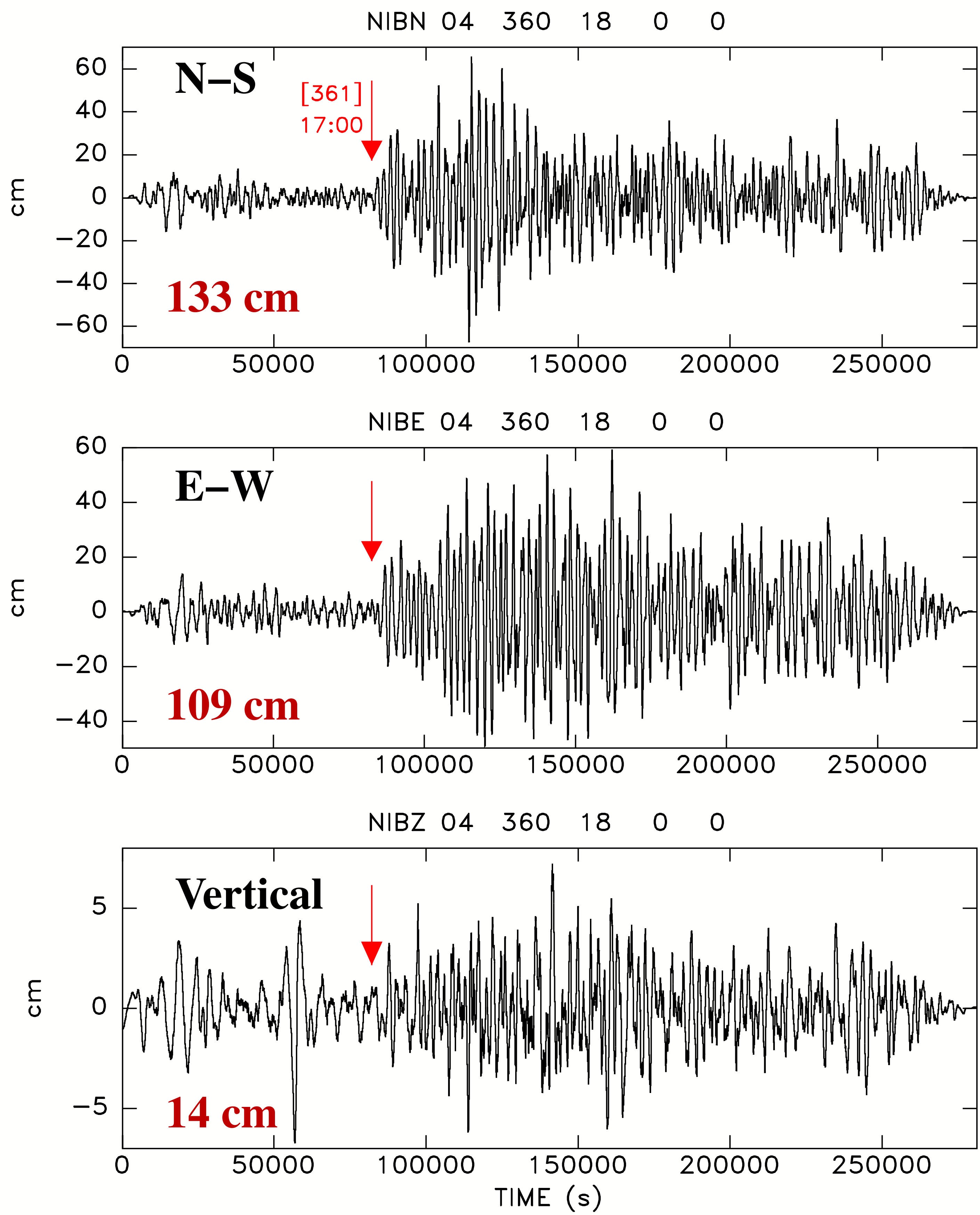
Since 2003, we have operated seismic stations on detached and nascent icebergs adjoining the Ross Sea.

**The tsunami was recorded by our 3 seismic stations, on all 3 components, with amplitudes of 10–20 cm.**



# Seismic recordings of 2004 Sumatra Tsunami
## **Nascent (NIB);** *26 DECEMBER 2004*



# ELLIPTICITY of TSUNAMI SURFACE MOTION

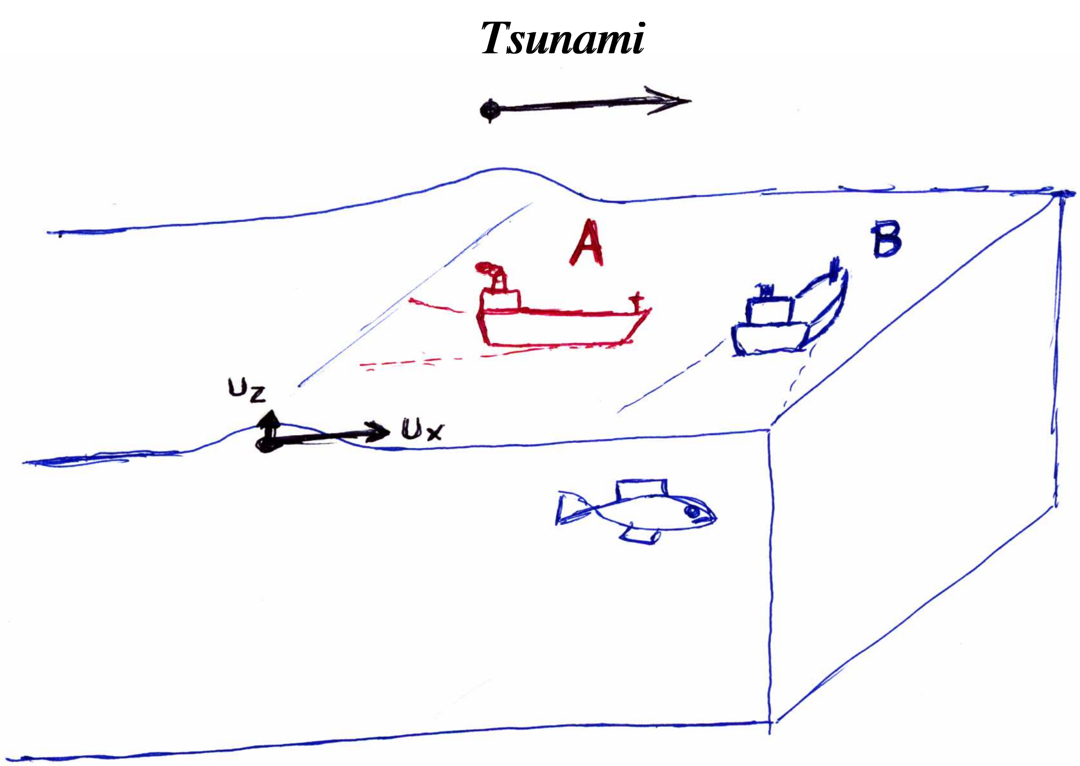
*(Shallow Water Approximation)*

$$\frac{u_x}{u_z} = \frac{1}{\omega}\sqrt{\frac{g}{h}} = \text{typically} = 10 \text{ to } 30$$

Sumatra 2004: $u_z \approx 1$ m (JASON; seismic stations)

$u_x \approx 15$ meters ?

Conceivable to use GPS-equipped ships to detect tsunami.




**Ship A** should see a perturbation in speed

**Ship B** would show a zig-zag in trajectory

## LESSONS in OPERATIONS

**1.**

# WE FAILED

# LESSONS in OPERATIONS

## 2. SCIENCE did not FAIL; COMMUNICATIONS DID.

To a large extent, the scientific processing of the 2004 earthquake did not fail

Even though the final moment took one month to assess, a value (8 to 9 times $10^{28}$ dyn-cm; $M_w = 8.5$), sufficient to trigger a tsunami alert if the earthquake had been in the Pacific Basin, was recognized in due time.

- *COMMUNICATIONS INFRASTRUCTURE CANNOT BE IMPROVISED AND MUST BE DESIGNED, BUILT AND TESTED AHEAD OF TIME.*

- The development of reliable tsunami systems in the Atlantic and Indian Oceans must focus on

  **COMMUNICATIONS,**

  to a greater extent than on additional seismic sensors.

- New observations (or the lack of data) point out to the potential value of a synergy between various technologies.

# 3. FINAL LESSONS

## EDUCATION WORKS

*C. Ruscher,* Vanuatu, November 1999.

- The Moken people of the Surin Islands
- Little 10-year old English girl in Phuket
- Professor C.H. Chapman in Sri Lanka
- Japanese tourists in high-rise hotels

## EDUCATION is NEEDED !

**DO NOT EXPLORE**


**Sumatra Tsunami, Madagascar, 26 Dec. 2004**

## RUN TO SAFETY ON HIGHER GROUND !!