TSUNAMI PROCESSES: REFLECTIONS AND PROSPECTS FROM SUMATRA AND OTHER EVENTS

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TSUNAMI GENERATION

EARTHQUAKE

Deforms ocean bottom / Excites tsunami mode
Fast; Small motion over large areas

LANDSLIDE

Perturbs/destroys ocean bottom
Slow; Large motion over small areas

Documented: Nfld., 1929; Makran, 1945; Unimak, 1946; Fiji, 1953; Algeria, 1954, 1980; Amorgos, 1956; Skagway, 1994; PNG, 1998; Storrega, −7000.

→ *Reproducible in Laboratory*

VOLCANIC EXPLOSION

Documented: Krakatoa, 1883; Santorini, −1650.

BOLIDE IMPACT

Speculated: Chicxulub, (K/T)

EARTHQUAKE SCALING LAWS

Simple ideas:

- An earthquake source must grow both in space and time

* An enlarged slip, Δu requires a larger fault length L (the *strain* released ε must remain constant)

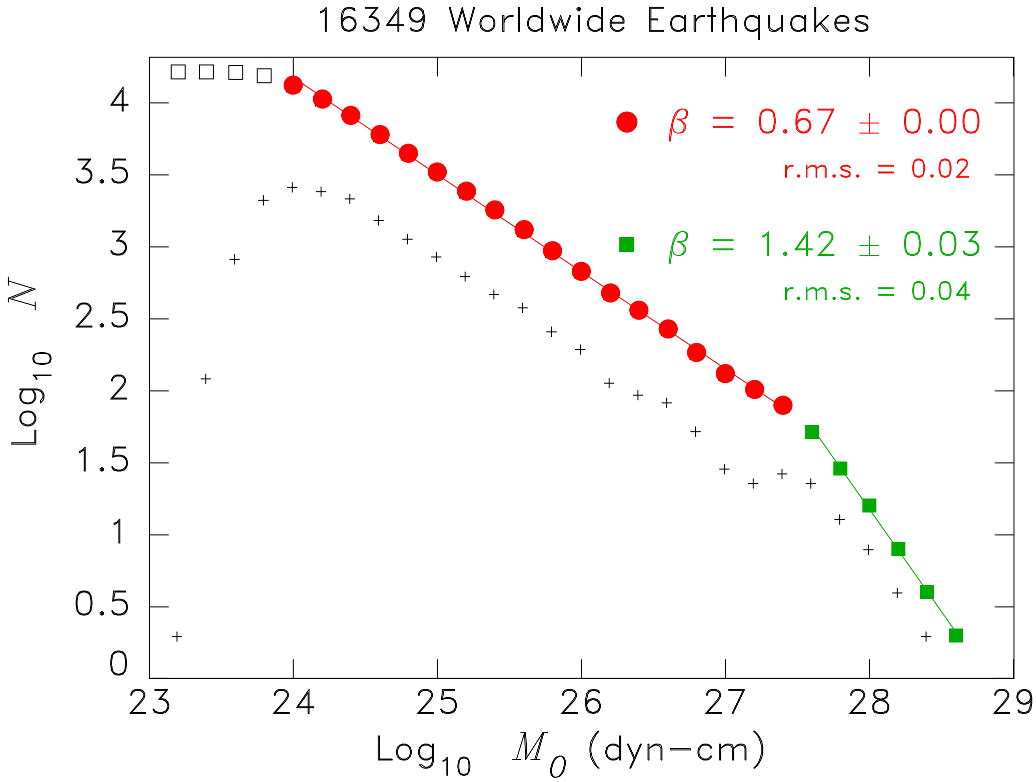
* A larger source must take a longer source or rupture time (Fault motion and rupture propagation involve constant speeds).

→ Thus, an earthquake must follow *SCALING LAWS* and might be well represented by a *SINGLE SCALAR*, its

SEISMIC MOMENT, M_0.

$$M_0 = \mu S \Delta u \sim L^3$$

Scaling laws may explain population statistics, such as frequency-size relations, useful to predict the occurrence of [large] events... although they are expected to break down at large moments.



LANDSLIDES may follow comparable (less well-known) SCALING LAWS, but with obviously different invariants.

SCALING TSUNAMIS in the NEAR FIELD

Okal and Synolakis [2004]

- **SIMPLE IDEAS:** Consider a seismic source

→ Everything else being equal, the maximum value of run-up on a beach should grow like the slip, Δu.

→ Everything else being equal, the lateral extent of run-up on the beach should grow like the size of the fault, L.

→ The ratio of the two, which is the *aspect ratio* of the distribution of run-up along the beach, should behave like $\Delta u / L$, which being the strain released, ε, should be invariant under seismic scaling laws.

- Thus we predict that all earthquakes should feature the *same distribution of run-up along a beach in the near field.*

→ TEST this theoretically.

→ COMPARE with data from tsunami surveys.

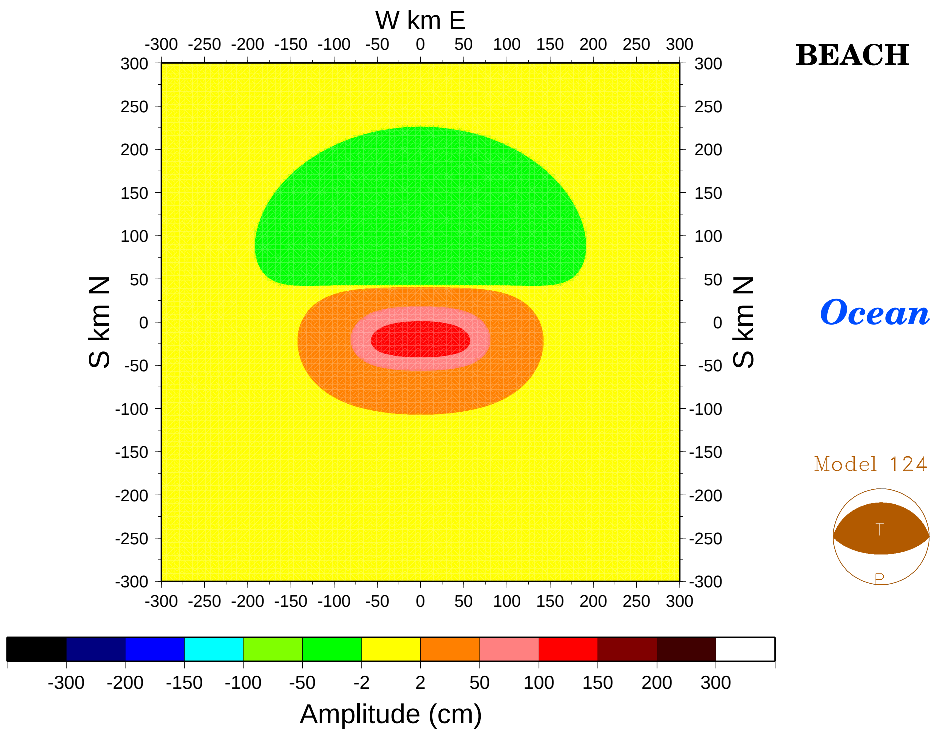
- If this invariant is violated, it means the source does not scale like an earthquake.

  It probably is not one !

[LANDSLIDE ?]

NEAR-FIELD: *The Earthquake Dislocation*

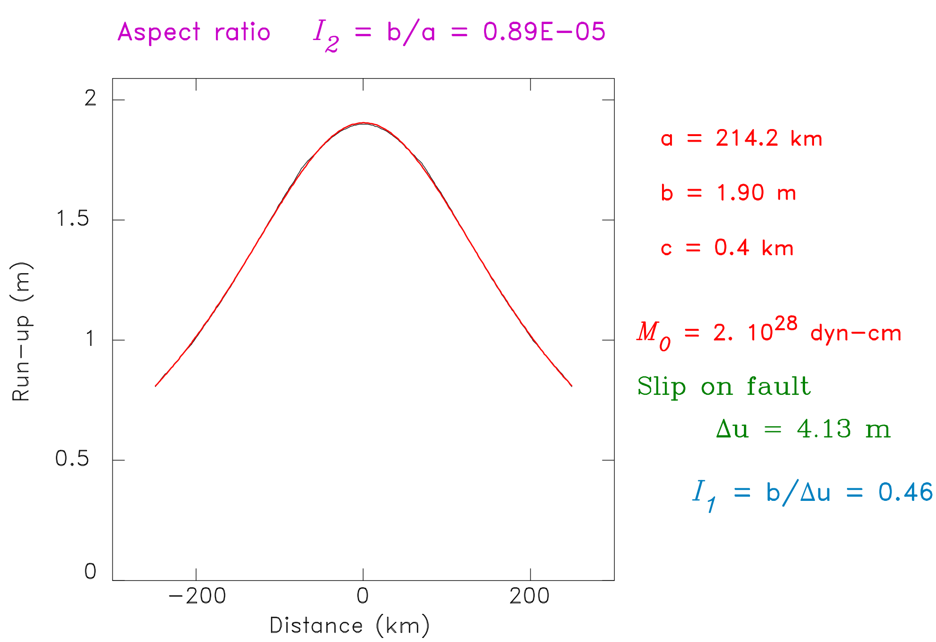
- Compute Ocean-Bottom Deformation due to Dislocation



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

$$\zeta = \frac{b}{\left(\frac{x-c}{a}\right)^2 + 1}$$



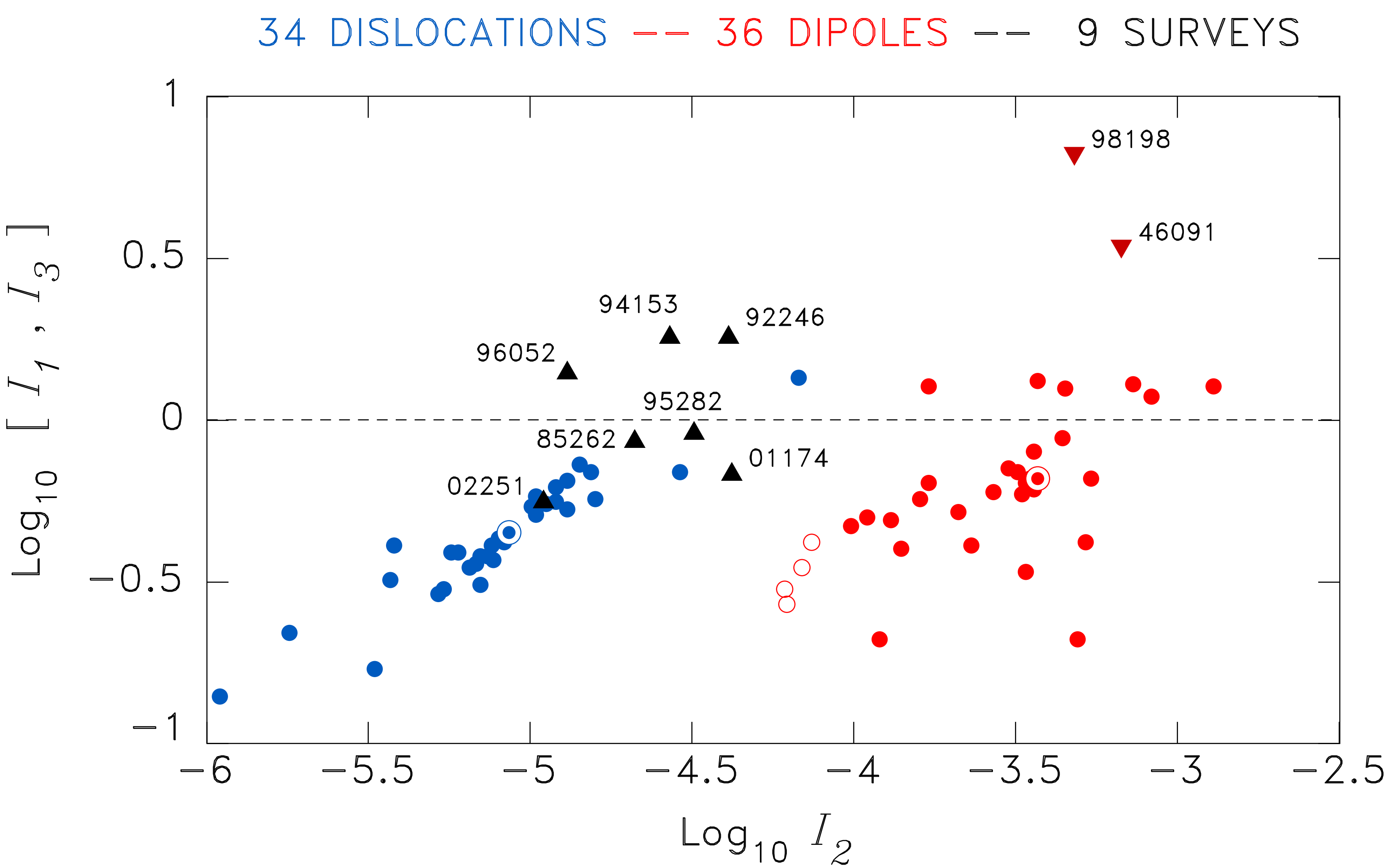
- Retain aspect ratio $I = b/a$

- Vary source parameters: I no greater than 2.3×10^{-5}.

In the near field, invariants I_1 and I_2 effectively separate earthquakes and landslides

MAX. RUN-UP SCALED TO FAULT SLIP

MAX. RUN-UP SCALED TO INITIAL TROUGH



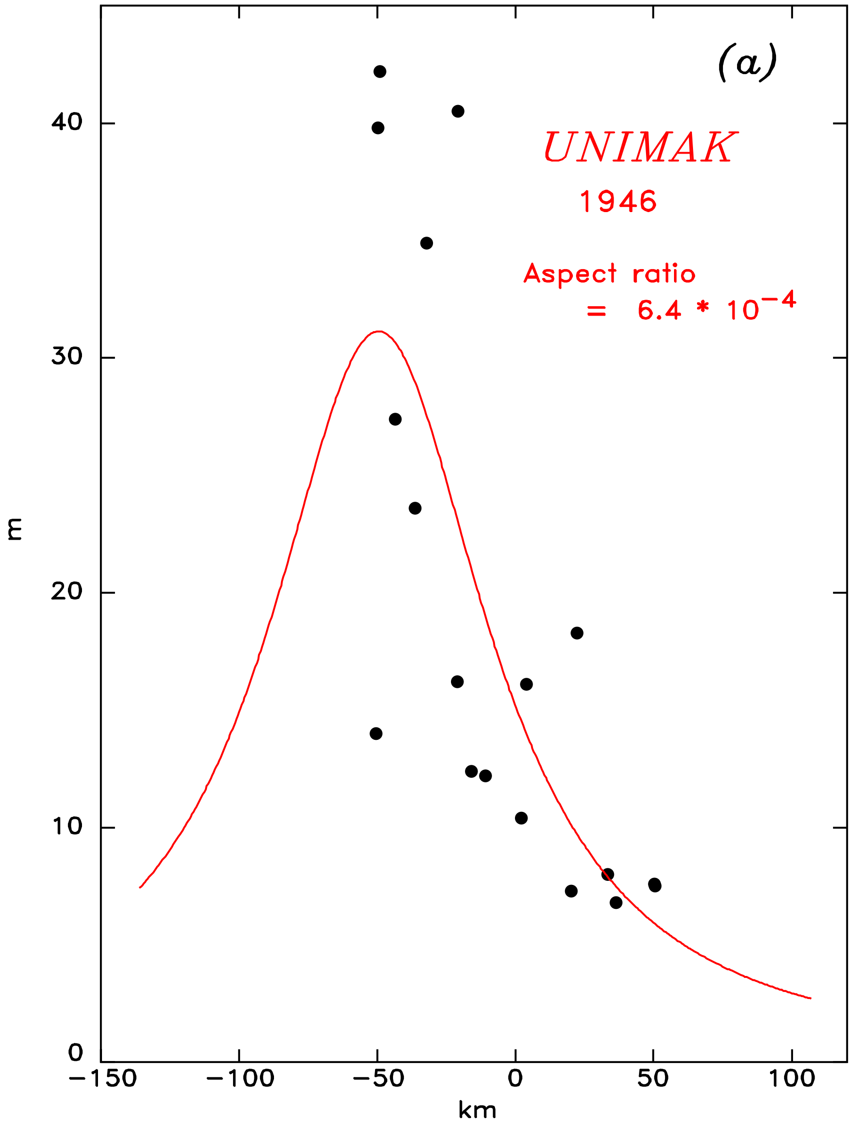
ASPECT RATIO OF RUN-UP DISTRIBUTION ALONG BEACH

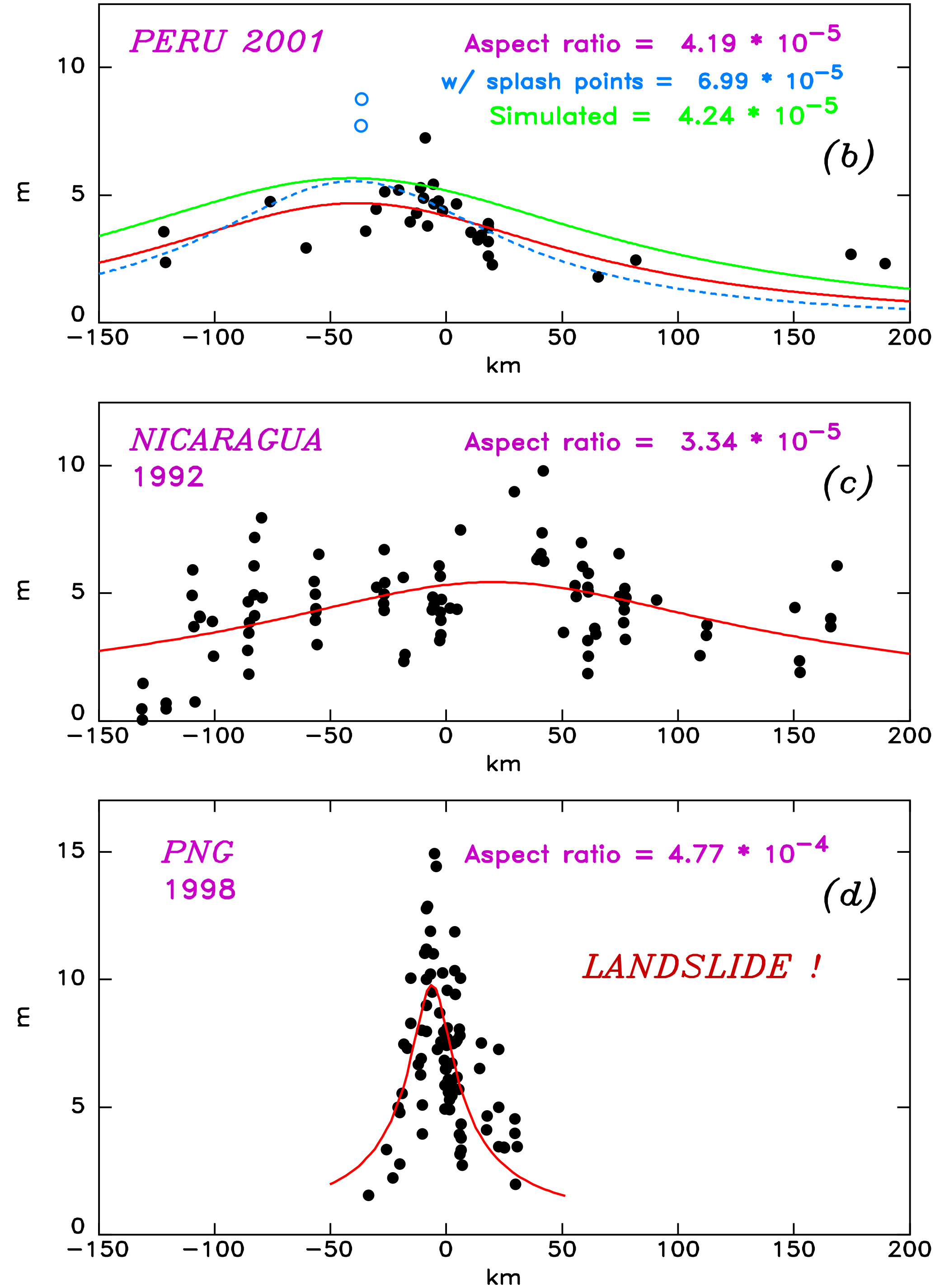
[*Okal and Synolakis*, 2004]

ALEUTIAN 1946: NEAR FIELD

Near-field *Aspect Ratio* of Run-up Distribution at Unimak (6.4×10^{-4}) even larger than for PNG-1998, thus

REQUIRING LANDSLIDE SOURCE

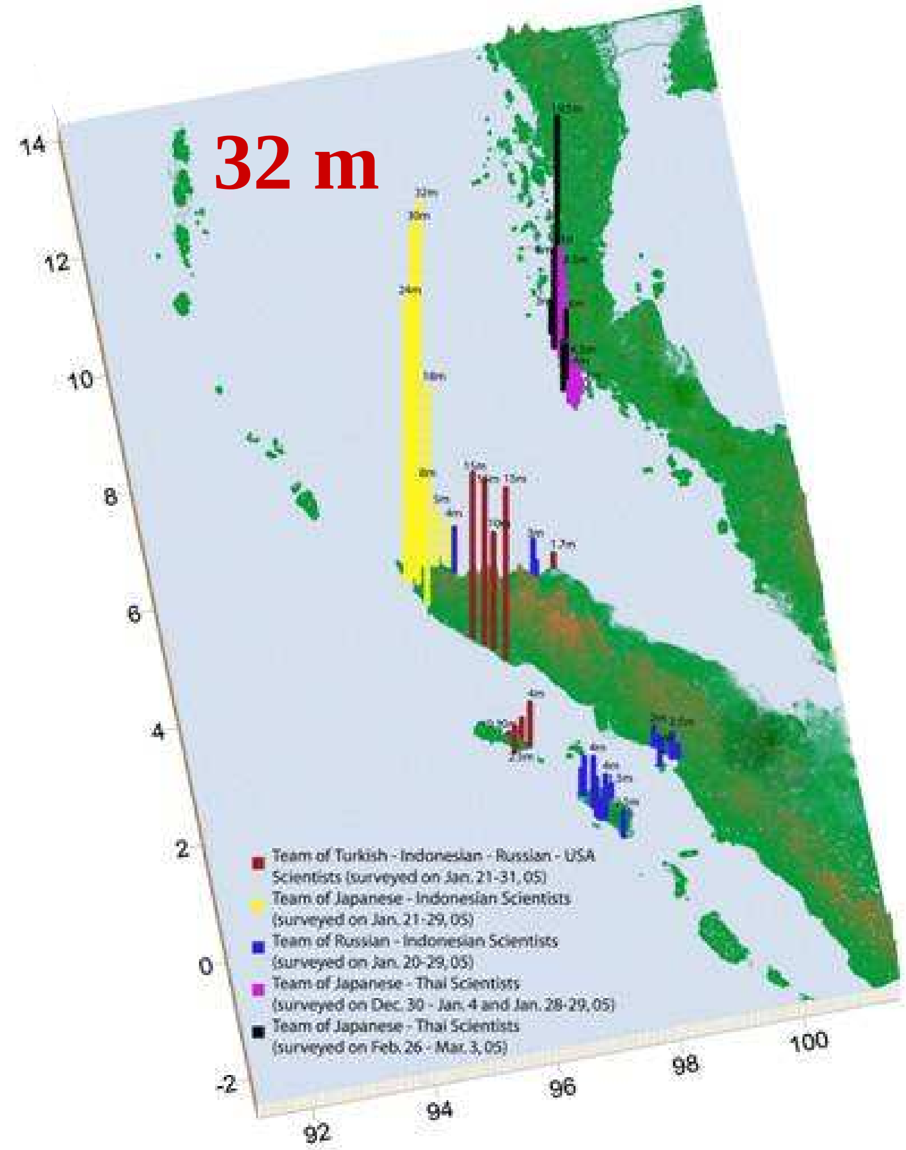




2. NEAR–FIELD RUN-UP : WELL EXPLAINED by DISLOCATION

(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 * Δu

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

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

MODELING LANDSLIDE SOURCES

- Motivation: PNG, 1998,
  but suggested as early as *Gutenberg* [1939].

WHAT IS DIFFERENT ?

* Moving much smaller masses
  Landslide: max. recorded 30 km; suggested 100 km
  (Earthquake: up to 1000 km)

* Moving over much greater distances
  Horizontally tens of km
  (Earthquake: at most 25 m)

* Physical process at extremity of rupture different
  Earthquake: Cohesive; continuous
  Landslide: Cohesion of material broken.

* Much slower process:

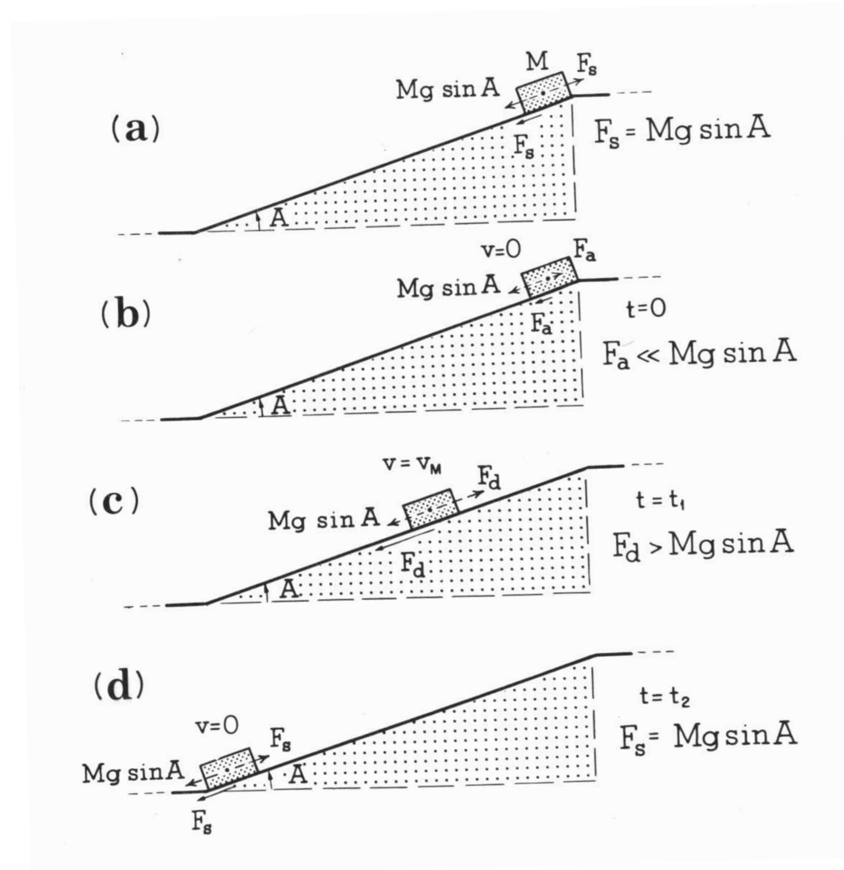
  Landslide: Maximum observed velocity: 40 m/s
  (suggested 70 m/s)
  Always very slow with respect to tsunami (220 m/s)

  Earthquake Rupture: 3.5 km/s;
  Even for "slow" earthquake, $v \geq 1$ km/s;
  remains HYPERSONIC with respect to tsunami.

PHYSICAL REPRESENTATION of LANDSLIDE

- Landslide modeled as *SINGLE FORCE* representing reaction by Earth to acceleration of sliding body.

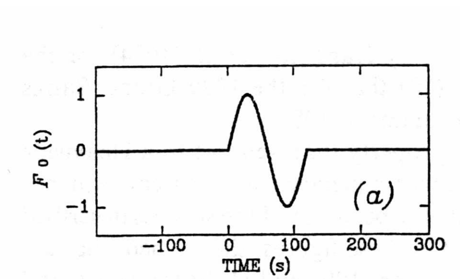
  [*Hasegawa and Kanamori*, 1987]

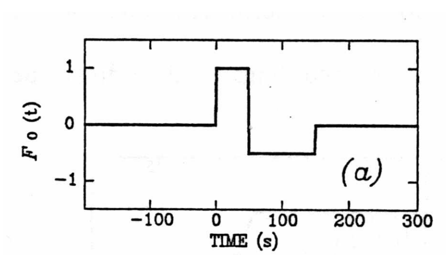


* Always nearly horizontal

* Zero impulse condition on Earth requires

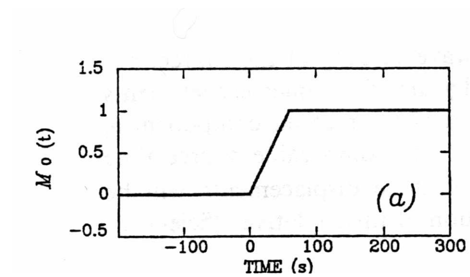
$$\int_{-\infty}^{+\infty} F(t) \cdot dt \;=\; 0$$





* Contrast with Seismic Moment for earthquake source

$$M(t) \;=\; \mu\, S\, \Delta u(t) \underset{t \to \infty}{\approx} M_0 \cdot H(t)$$



COMPARISON OF SPECTRAL AMPLITUDES

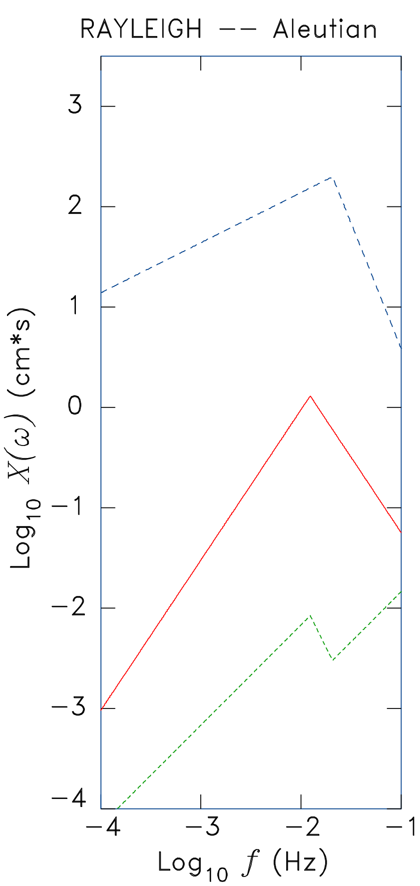
(Rayleigh and Tsunami)

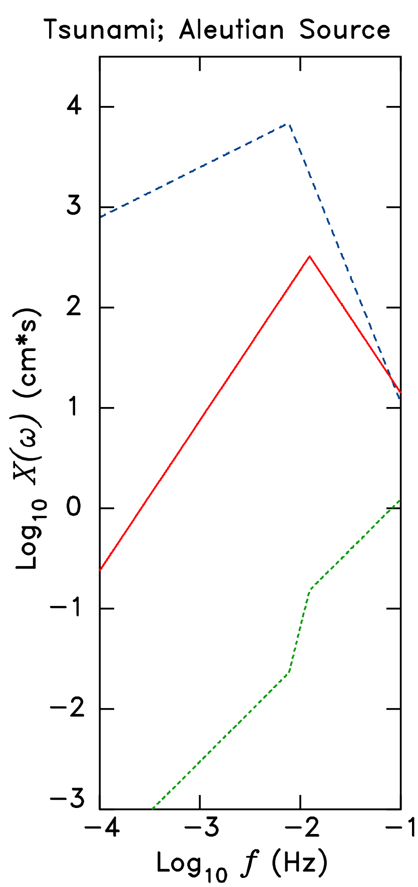
Landslide excitation, [**f · u**], proportional to *displacement,*
should be *INTEGRAL* of
Earthquake excitation, [$\boldsymbol{M} : \boldsymbol{\varepsilon}$], proportional to *strain.*

→ **BUT,** Source Time Function of Landslide is
SECOND DERIVATIVE of Earthquake Counterpart.

> → **Excitation by LANDSLIDE (SINGLE -FORCE)**
> **is DERIVATIVE of that by**
> **EARTHQUAKE (DOUBLE-COUPLE).**

EARTHQUAKE **LANDSLIDE**





RATIO

Note:

- Landslide Excitation Deficient by 1.5 orders of magnitude
- Landslide tsunami is

Higher-Frequency,

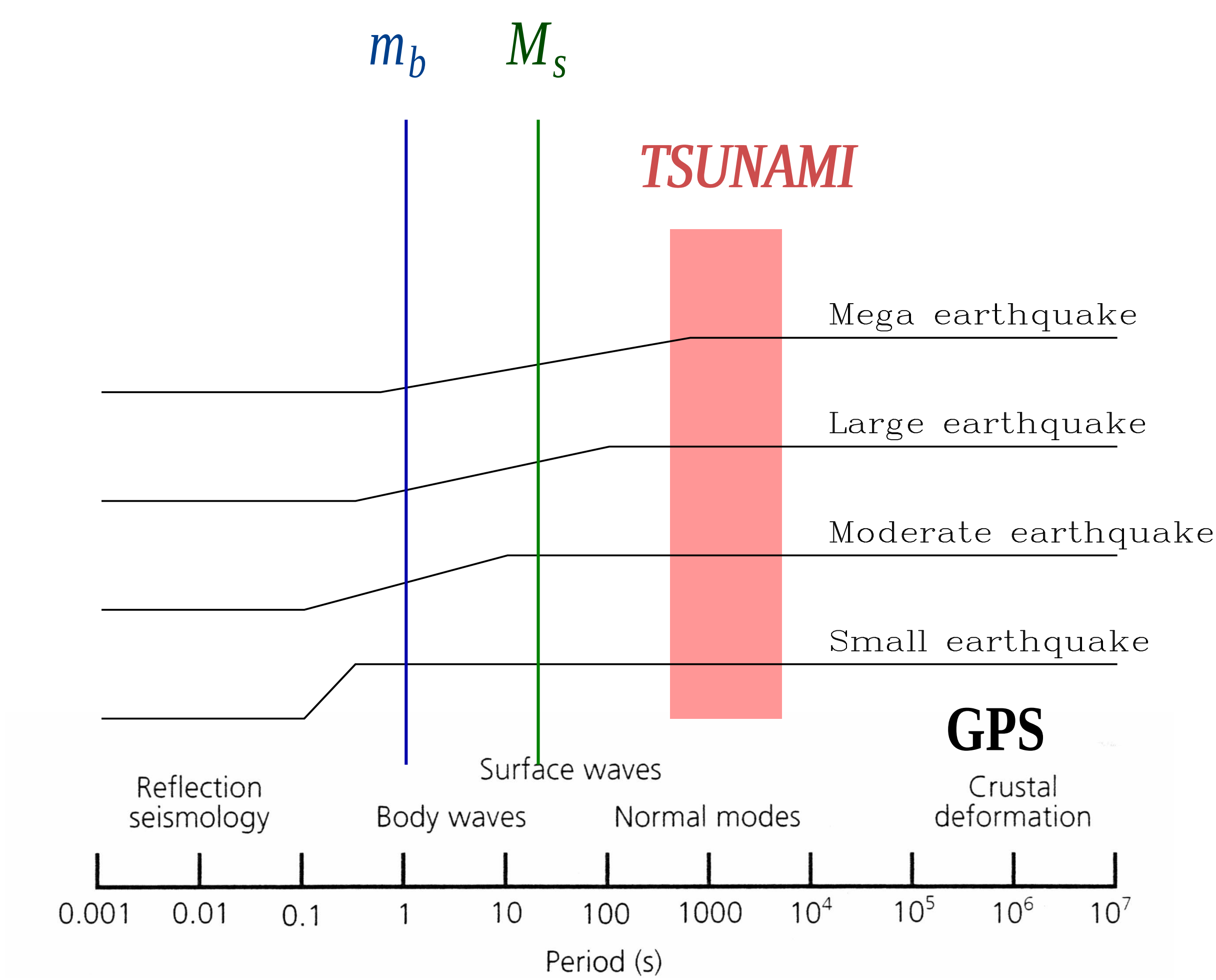
HENCE DISPERSIVE

ALGORITHMS are UNFIT
to MEASURE LARGE EARTHQUAKES

EARTHQUAKES TAKE TIME TO OCCUR

- The larger the earthquake, the longer the source *("Scaling Law")*.
- Measuring large earthquakes at small periods simply misses their true size.
- In the case of Sumatra, full size available only from normal modes.

- Measuring small earthquakes at long periods simply processes noise.



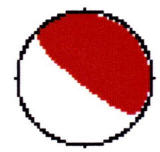
PROBLEMS with MANTLE WAVES (CMT; M_m)

2004 SUMATRA HARVARD CMT INVERSION (*T boosted to 300 s*)

Use automated process to invert 202 seismograms at 73 stations and retrieve best-fitting *POINT SOURCE* (in space and time).

Solution posted 05:25 GMT 26-DEC-2005, 4.5 hours after the event.

122604A OFF W COAST OF NORTHERN



```
Date: 2004/12/26   Centroid Time:  1: 1: 9.0 GMT
Lat=   3.09  Lon=  94.26
Depth= 28.6    Half duration=95.0
Centroid time minus hypocenter time: 139.0 seconds
```

```
Mw = 9.0                                   Scalar Moment = 3.95e+29 dyn-cm
Fault plane:  strike=329    dip=8    slip=110
Fault plane:  strike=129    dip=83    slip=87
```

Even with an inversion at T = 300 s,
the much longer source is drastically UNDERESTIMATED

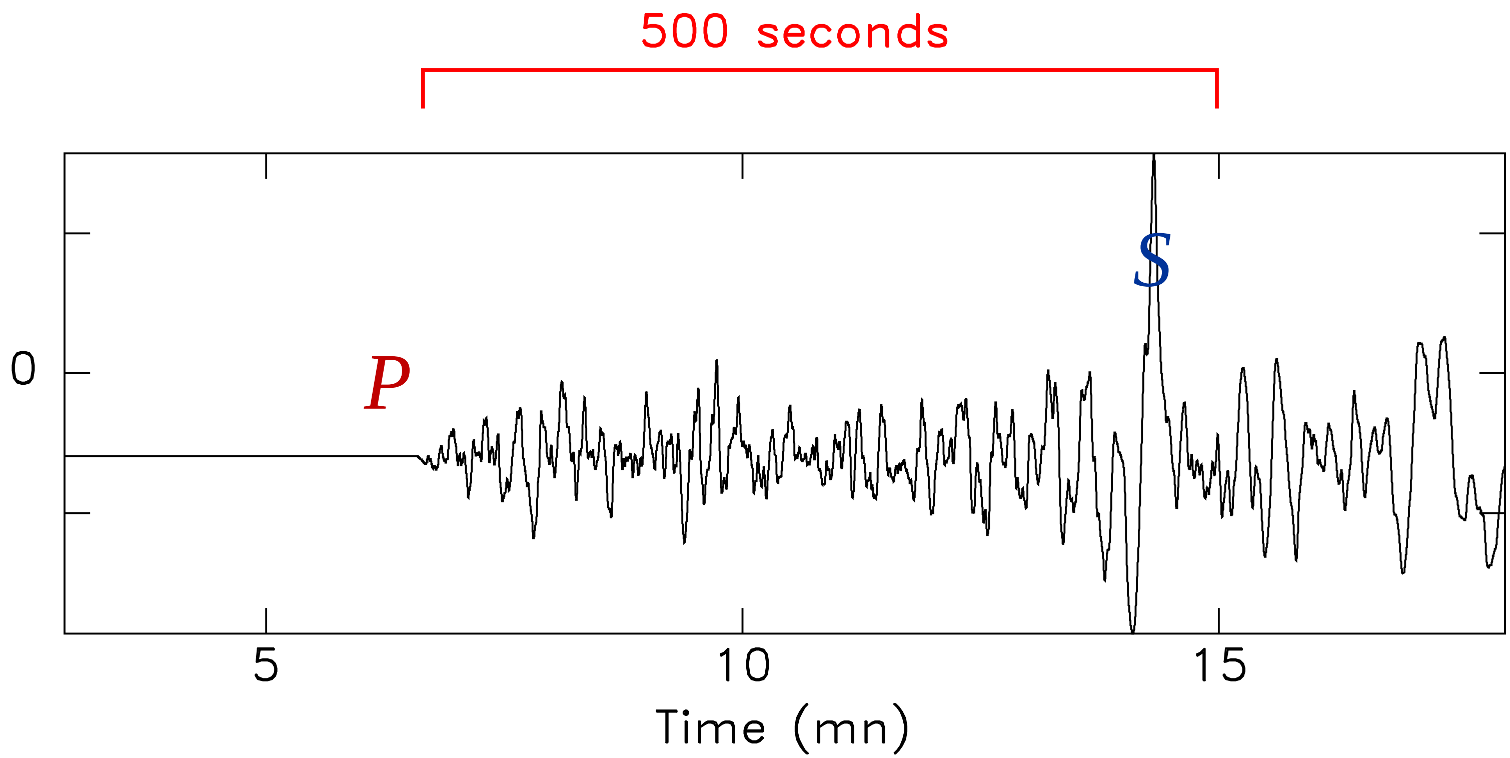
PROBLEM with BODY-WAVE TECHNIQUES for VERY LARGE EVENTS

- The duration of the source (and hence of the *P*-wave train may be so long that the *P* wave interferes with subsequent phases (*PP*, even *S*)

Example: Sumatra-Andaman Event, 26 DEC 2004

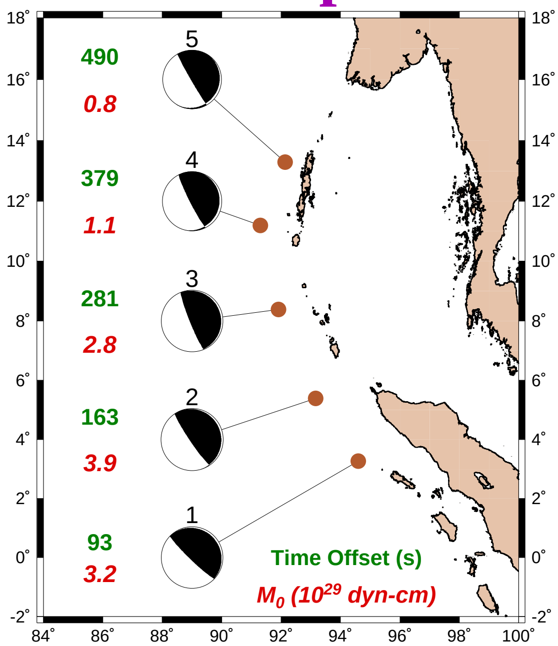
Station MSEY (Mahé, Seychelles; Δ = 41°**).**

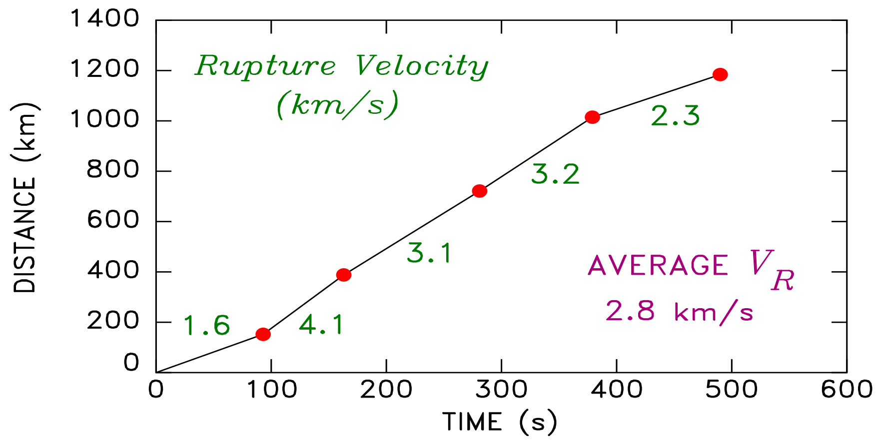
Duration of Source: 500 to 600 seconds (8 to 10 minutes)



IMPROVED ALGORITHMS to EXPLORE SUMATRA SOURCE

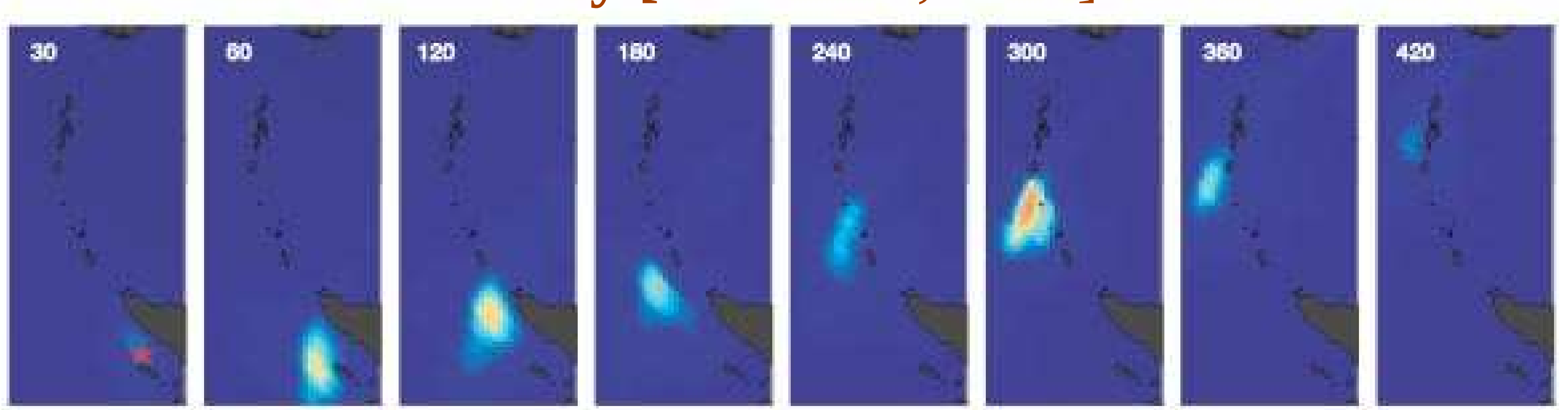
1. Composite CMT inversion [*Tsai et al.*, 2005]

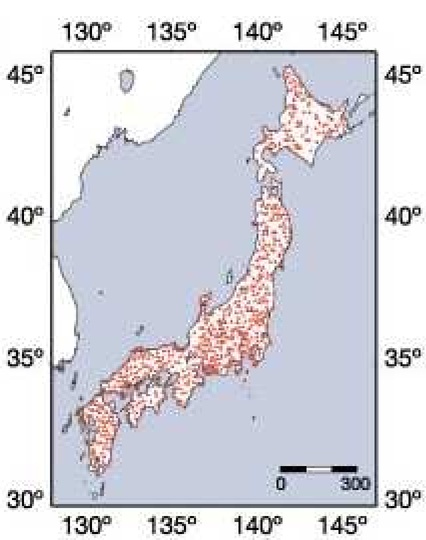




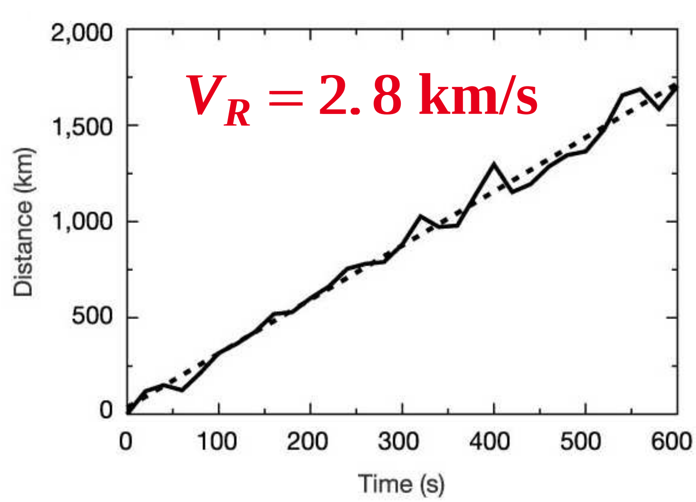
NOTE: **Sumatra 2004 has a slow source**

2. Back-tracking source history from distant seismic array [*Ishii et al.*, 2005]





Use
700−station
seismic array



{also *Krüger and Ohrnberger*, 2005; $V_R = 2.7$ km/s}

Q.: **Is it necessary** *(and hence worth)* **to resolve**

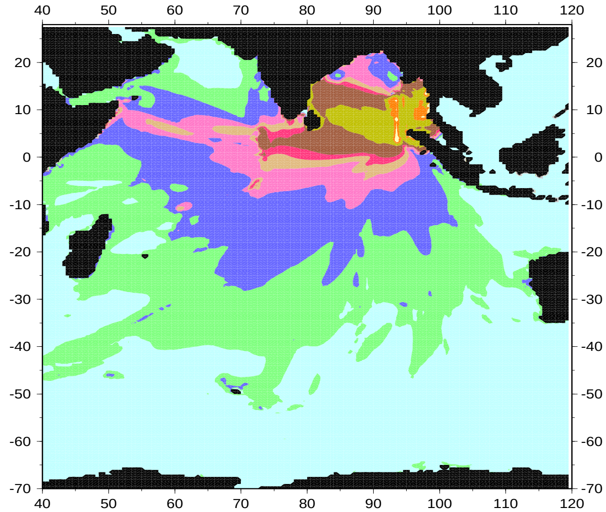
SOURCE DETAILS

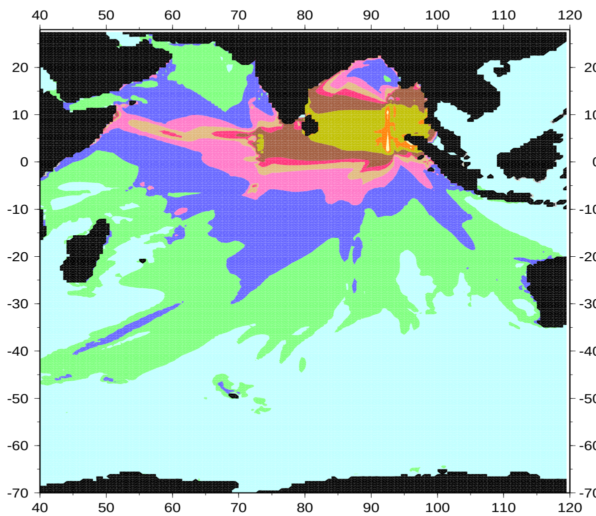
for FAR-FIELD TSUNAMI WARNING ?

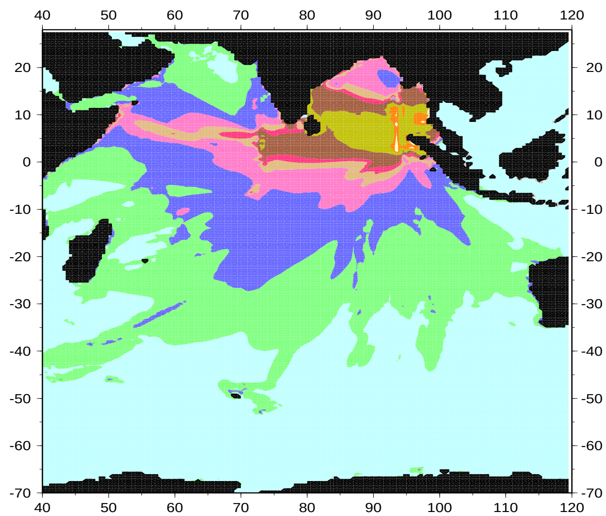
A.: *MAYBE NOT !!!*

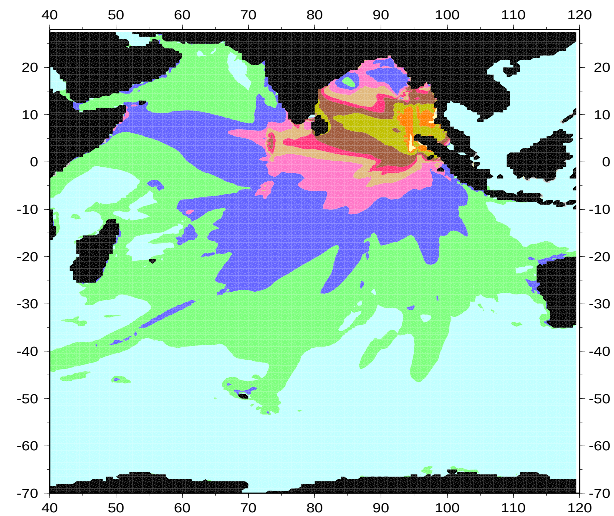
1. MOVE SOURCE

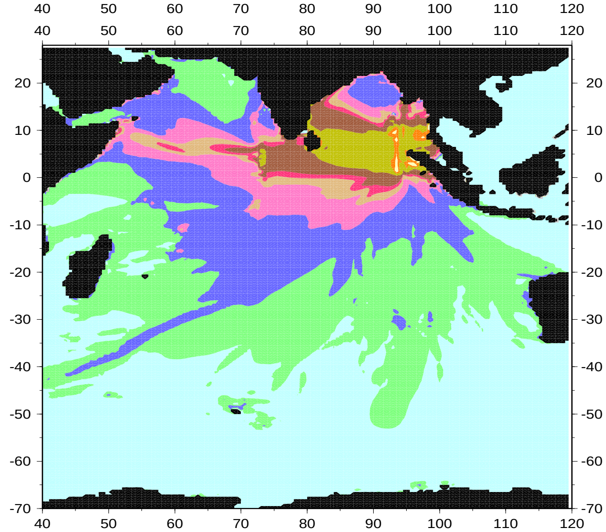
LATERALLY

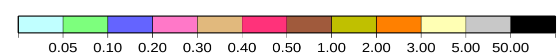






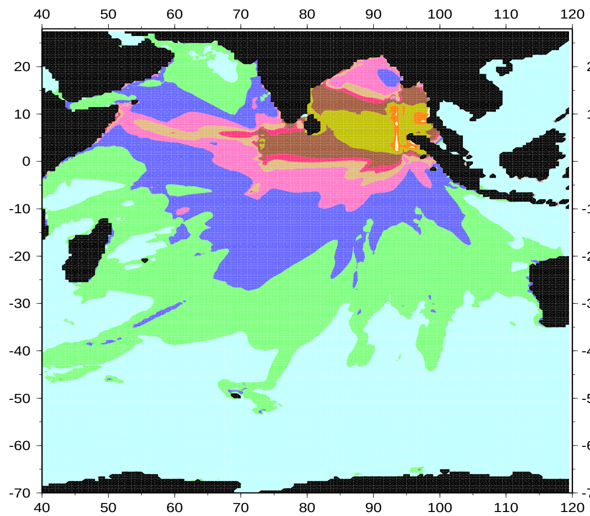




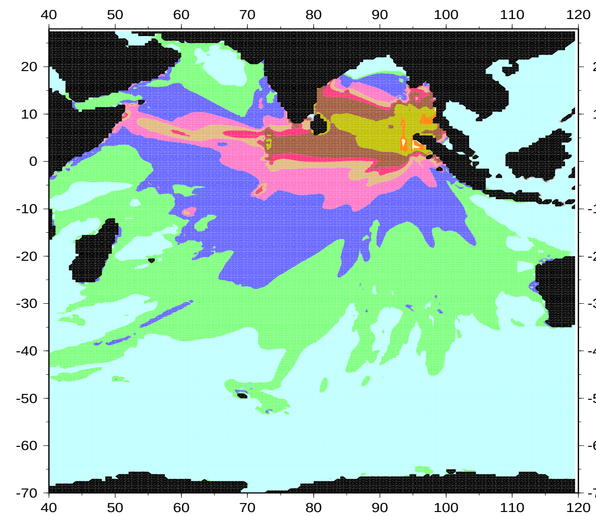


2. CHANGE SOURCE PARAMETERS

SUMATRA 2004 Original (before RUNUP)

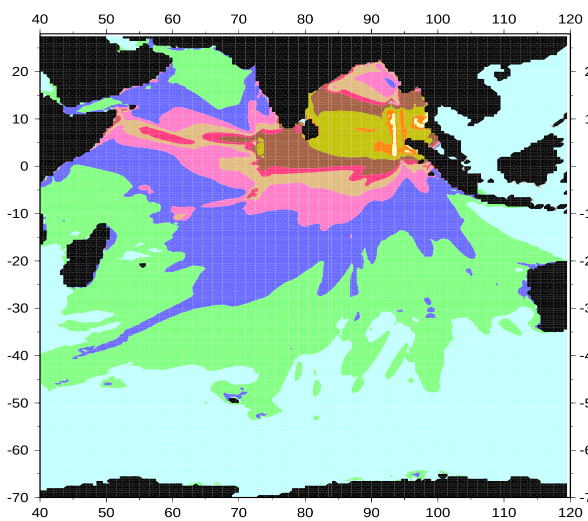


Heterogeneous Slip



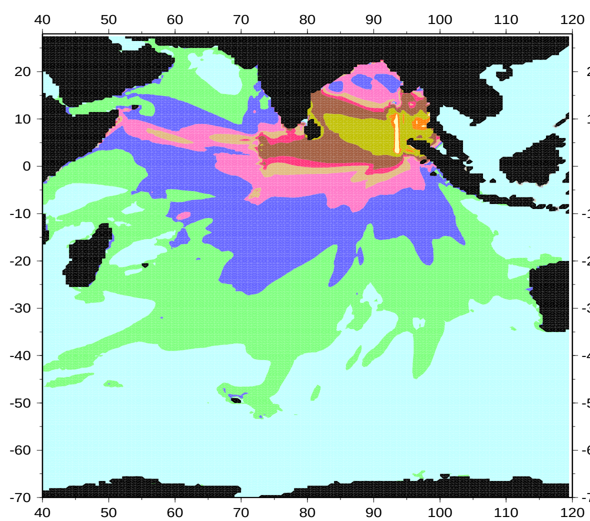
Depth

SUMATRA 2004; D = 20 km (before RUNUP)



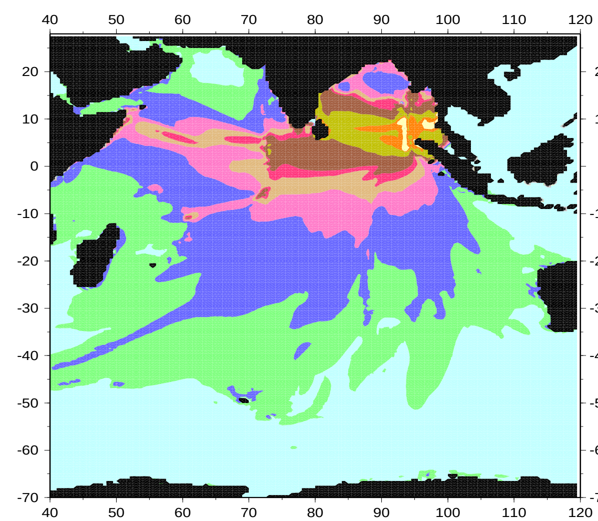
Fault Dip

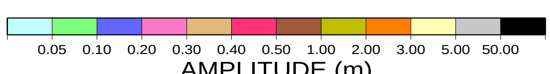
SUMATRA 2004 Dip = 12 deg. (before RUNUP)



Strain Released

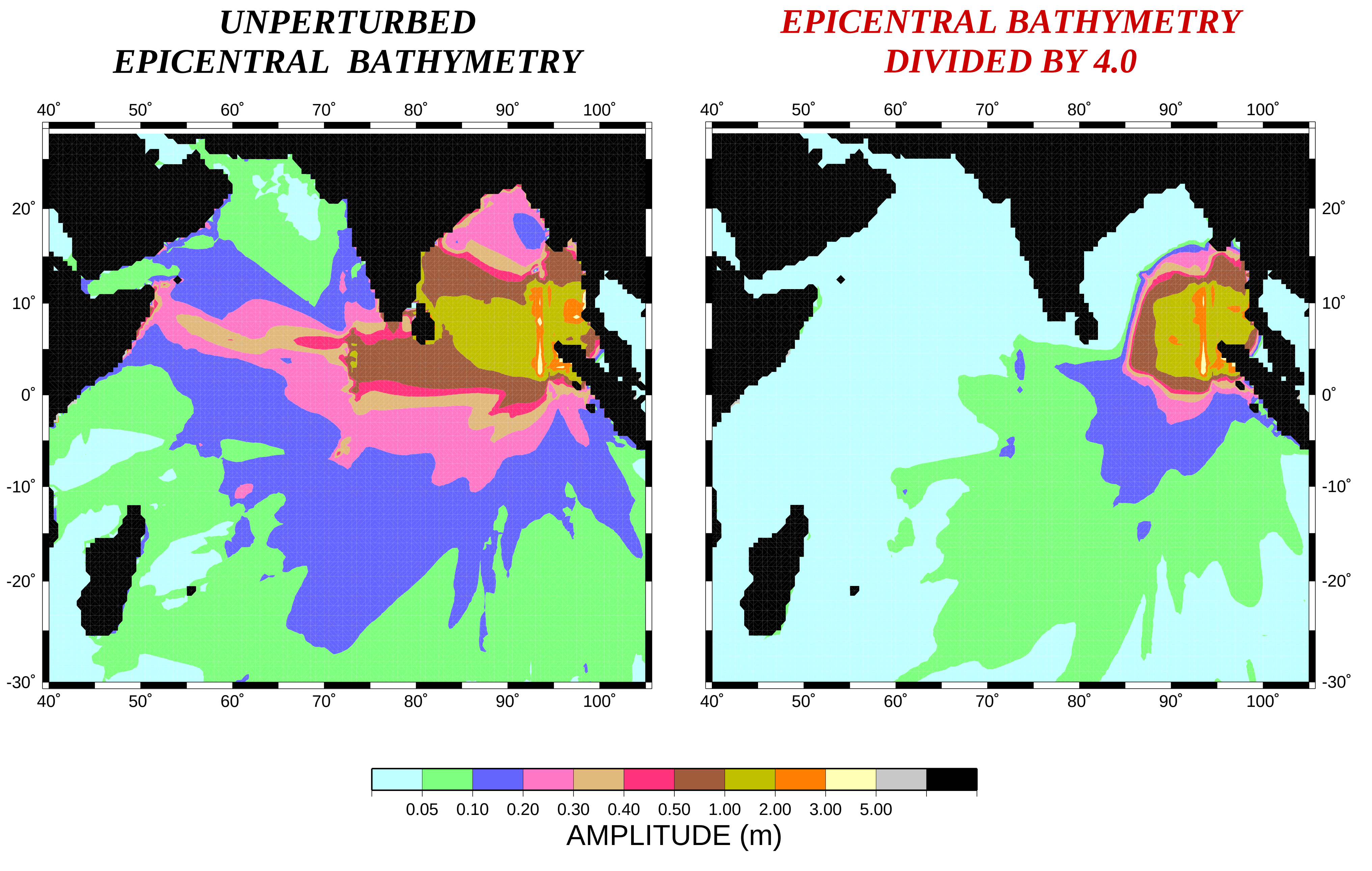
SUMATRA 2004 Large Strain (before RUNUP)





By CONTRAST, WATER DEPTH at the SOURCE PLAYS a CRUCIAL ROLE

NOTE: This explains the much smaller tsunami during the 2005 Nias earthquake



$\Sigma\, m_b$: A new, promising development

[*Bormann and Wylegalla*, 2005]

- Idea: Make standard measurements of m_b but keep adding their contributions throughout the P wavetrain, as long as enough energy is present.

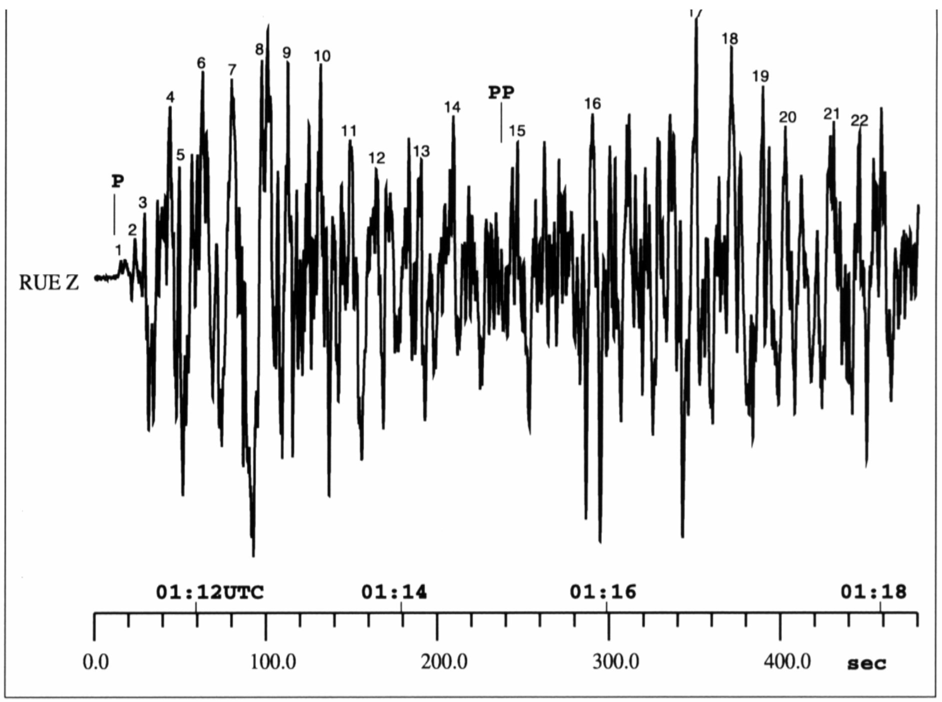


Fig. 1. Vertical component velocity-proportional broadband record at the Berlin seismic station RUE (D = 82.5°) of the P-wave group generated by the Sumatra earthquake of 26 December 2004. The times of the P and PP first arrivals have been marked. Numbered are the analyzed amplitudes originating from sub-events of the long progressing multiple rupture process.

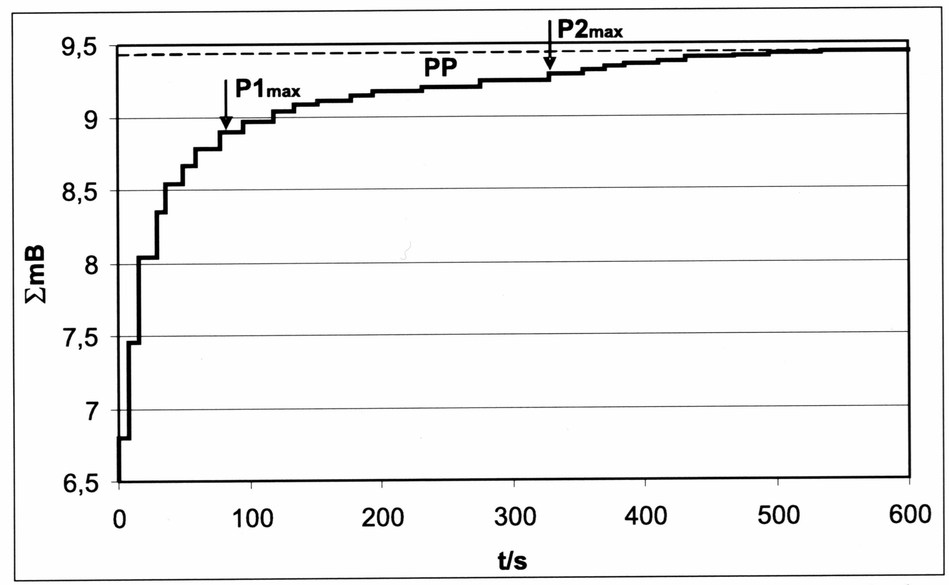


Fig. 2. Cumulative broadband body wave magnitude Σm_B as a function of time t in seconds after the first onset for the whole P-wave group of the Sumatra earthquake of 26 December 2004.

- Sumatra, 28 March 2005: $M_w = 8.6$, $M_e = 8.5$, $\Sigma m_B = 8.6$
- Hokkaido, 25 September 2003: $M_w = 8.3$, $\Sigma m_B = 8.4$
- Alaska, 3 November 2002: $M_w = 7.9$, $M_s = 8.5$, $\Sigma m_B = 8.4$
- Peru, 23 June 2001: $M_w = 8.4$, $\Sigma m_B = 8.4$.

- Seems to work fine, even for large earthquakes
- Drawbacks: Operational aspects of algorithm still largely *ad hoc*.

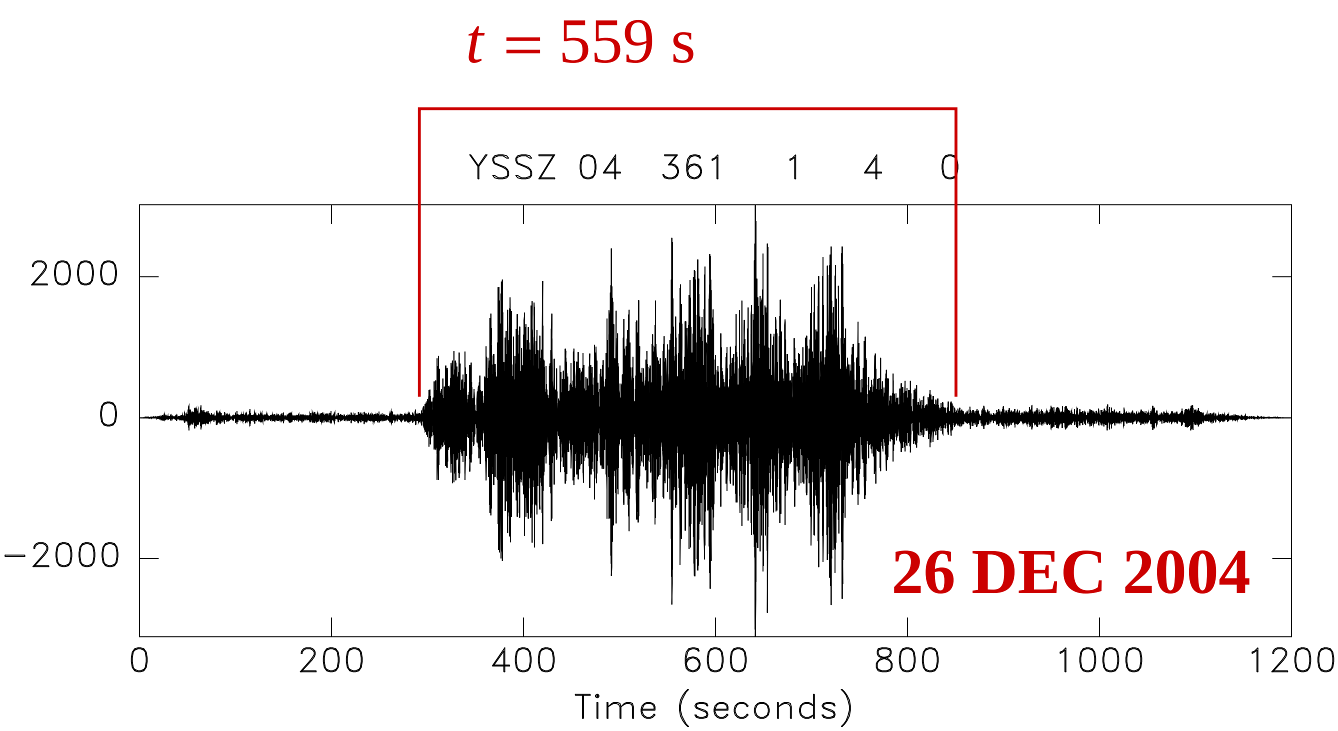
  Lacks theoretical justification.

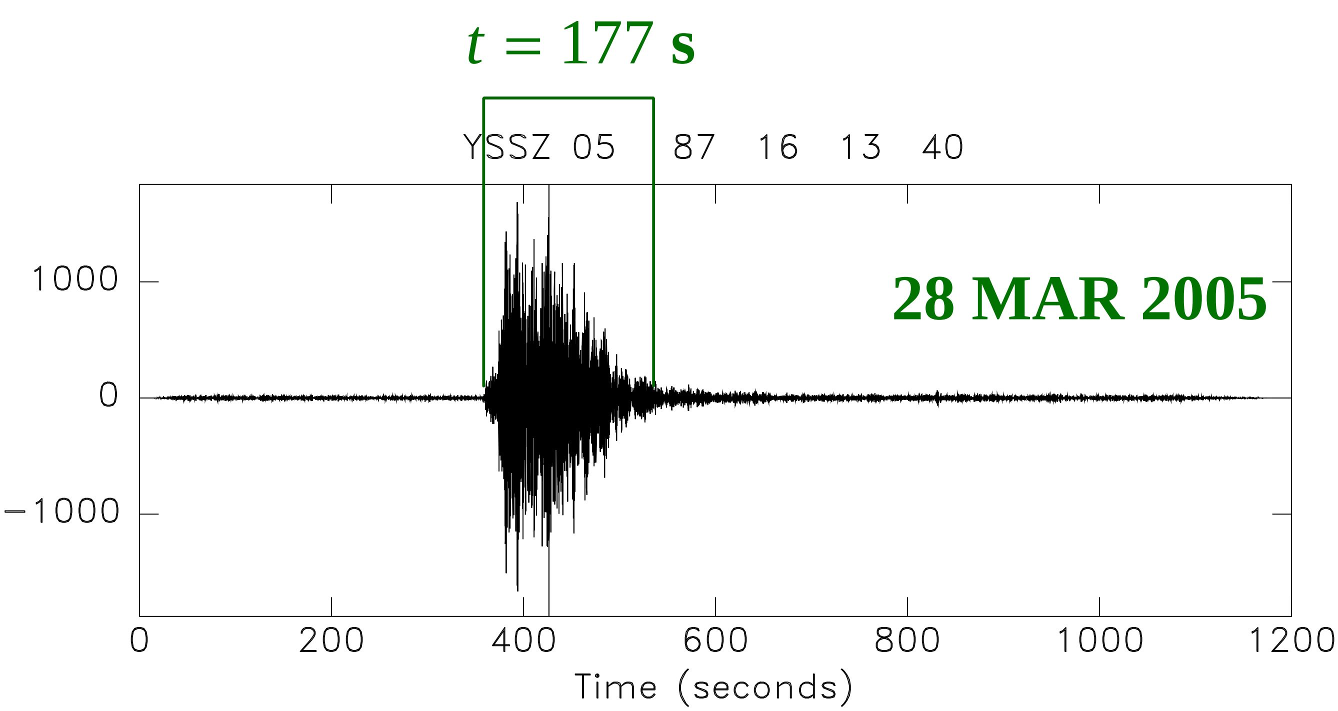
  Same problems as Θ, M_{wp} (duration of window).

A simple [trivial ?], robust measurement

[*Ni et al.*, 2005]

- Duration of source from High-Frequency (2−4 Hz) Teleseismic *P* wavetrain

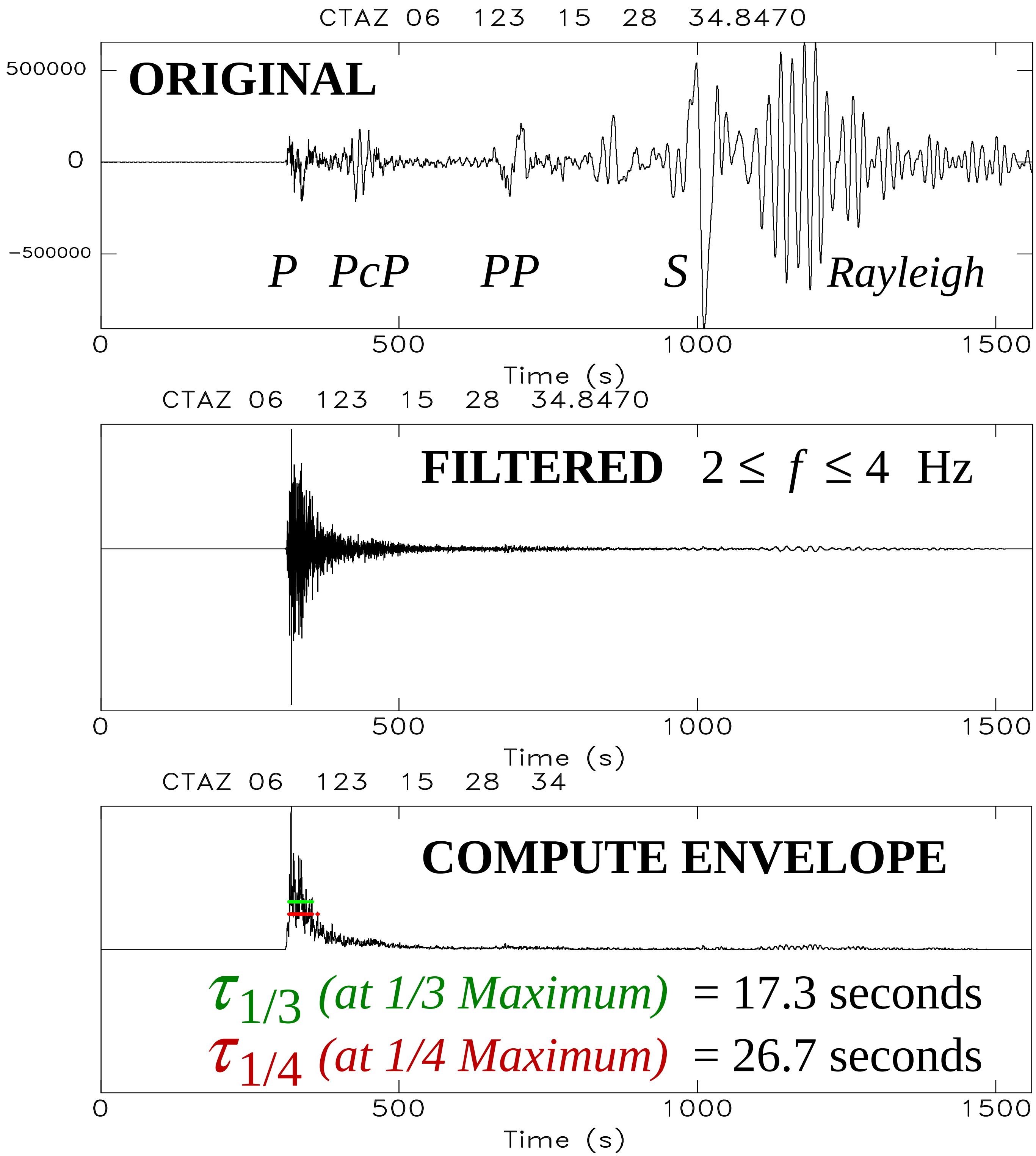




DEVELOP ALGORITHM TO MEASURE HIGH-FREQUENCY P−WAVE DURATION

TONGA, 3 May 2006 — Charter Towers (CTA)

$\Delta = 37°$

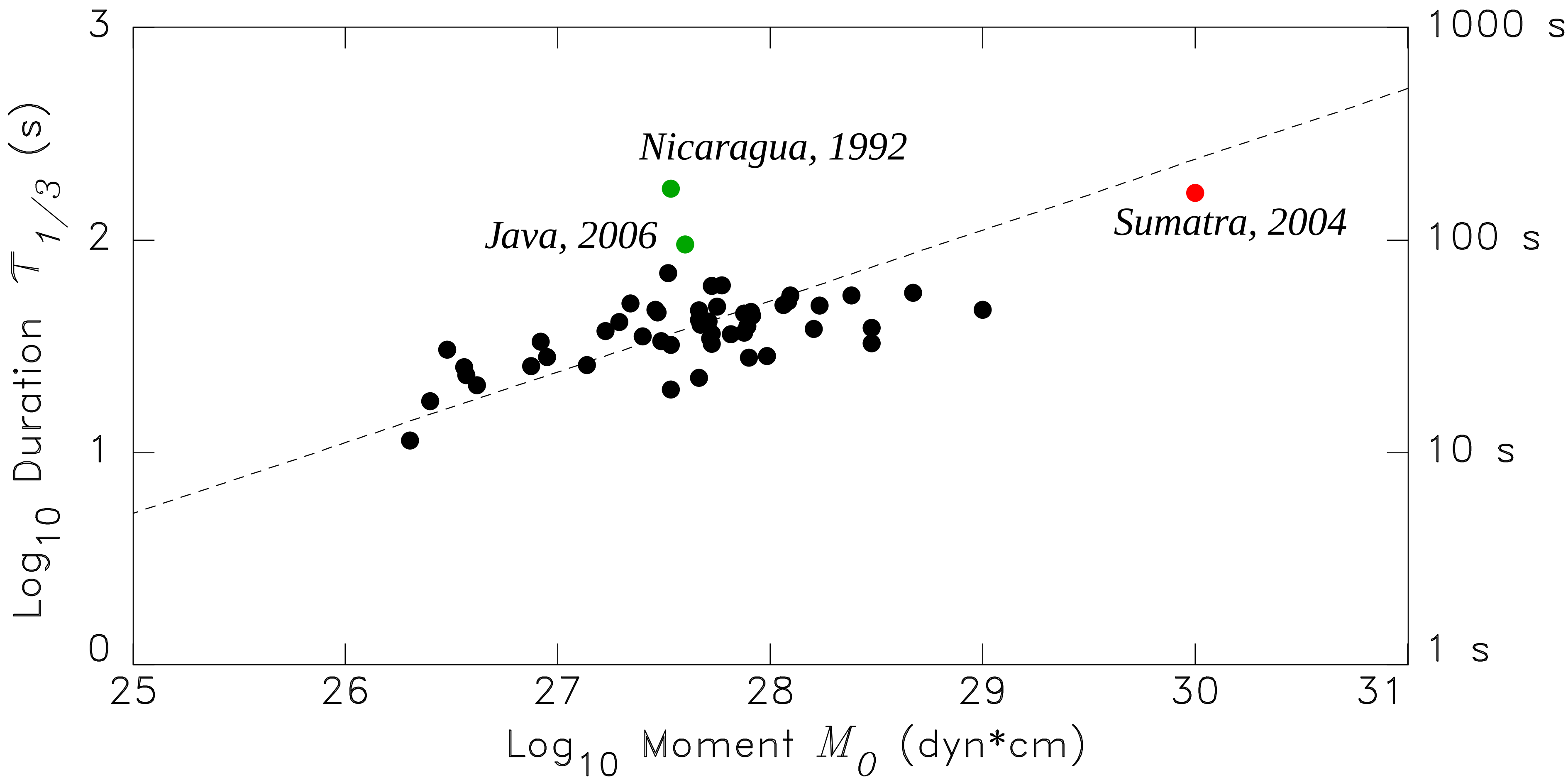


PRELIMINARY DATASET ($\tau_{1/3}$)

52 earthquakes; 1072 records

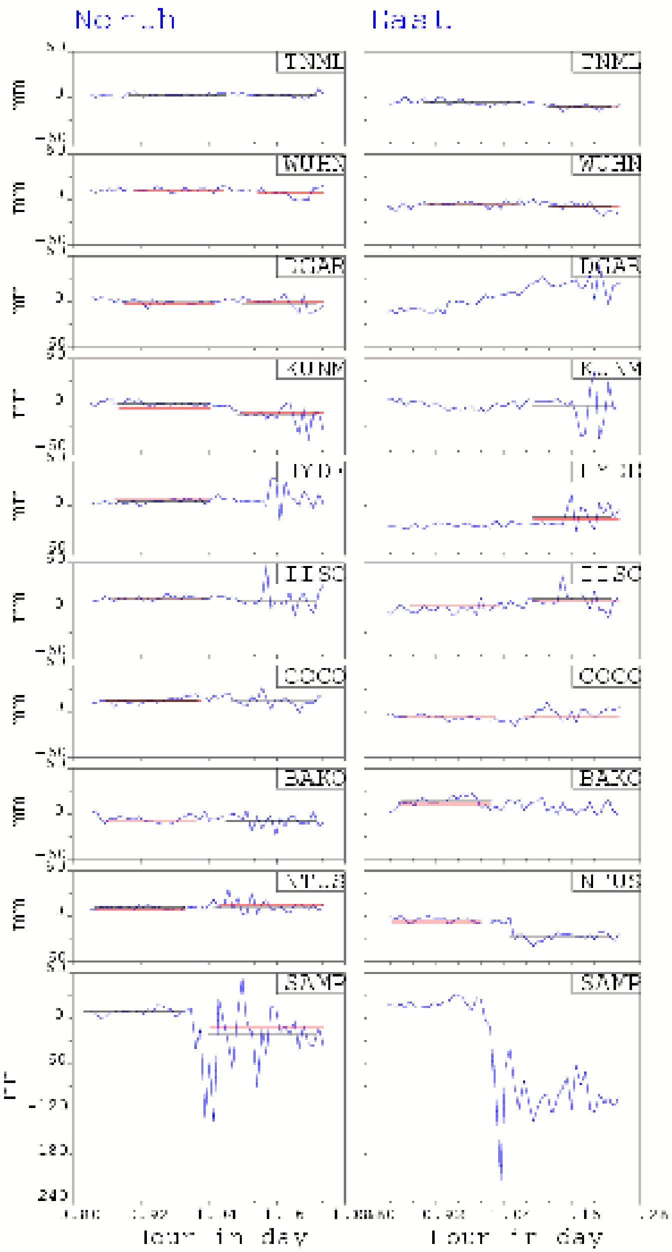
→ **2004 Sumatra event recognized as very long ($\tau_{1/3}$ = 167 s; $\tau_{1/4}$ = 291 s)**

→ *"Tsunami Earthquakes"* (Nicaragua 1992; Java 2006) **also identified.**



MODELING OF REAL-TIME GPS COULD PROVIDE QUICK ESTIMATE of SEISMIC MOMENT

[*Blewitt et al.*, submitted, rejected, resubmitted, 2006]

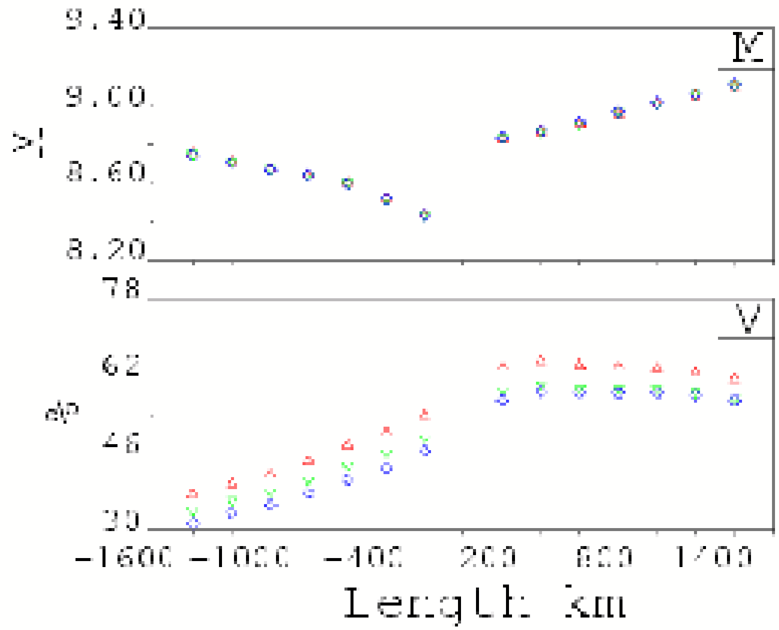


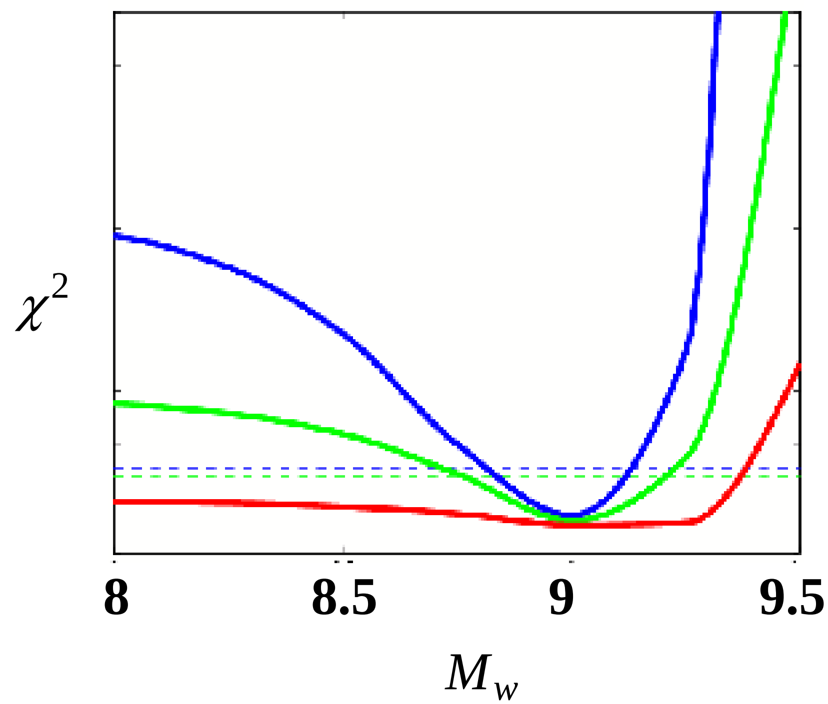
Fit Horizontal GPS data to various source models

Red: 10 mn

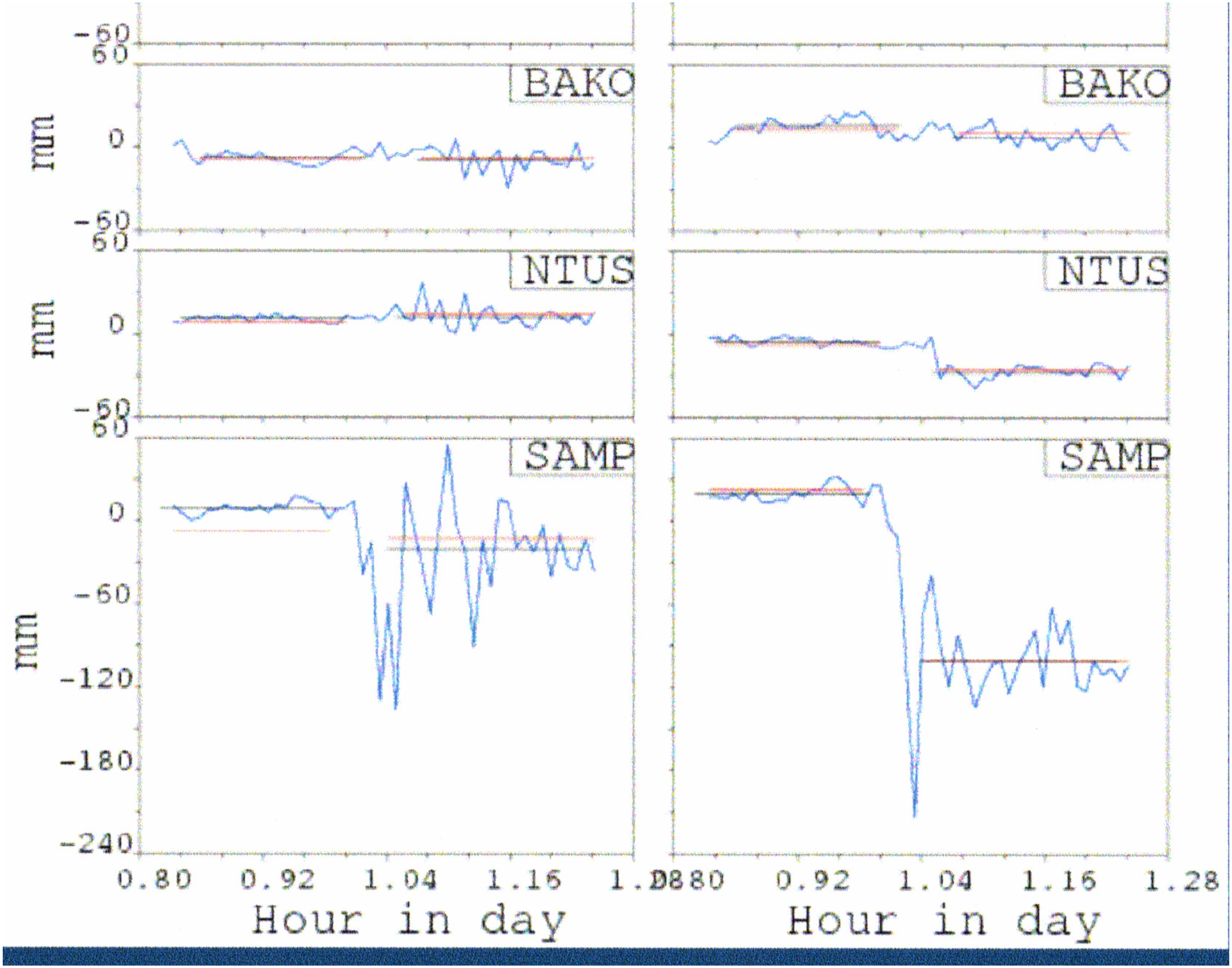
Green: 15 mn

Blue: 20 mn





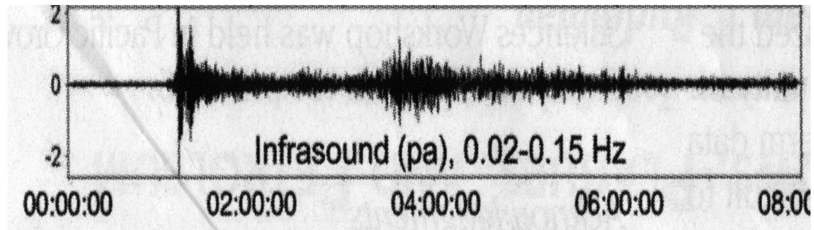
Zooming in on close-by stations...



INFRA SOUND ARRAYS (CTBT)

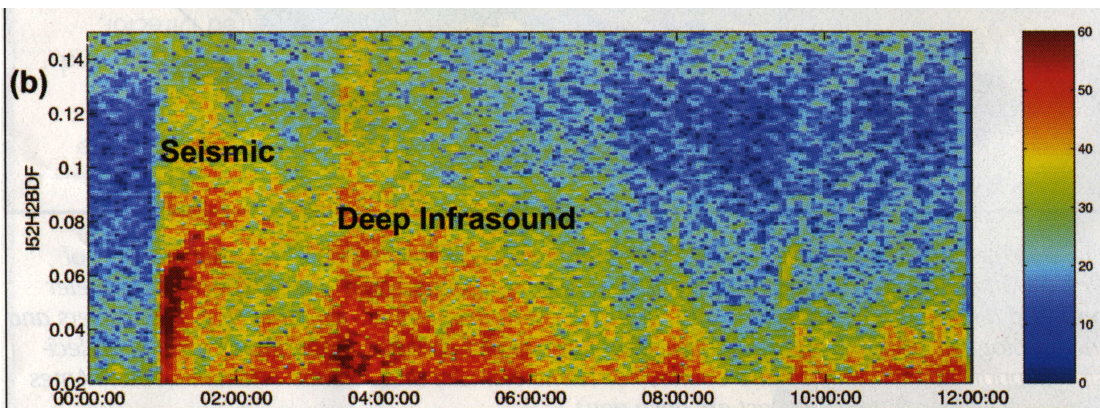
Arrays of barographs monitoring pressure disturbances carried by atmosphere.

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



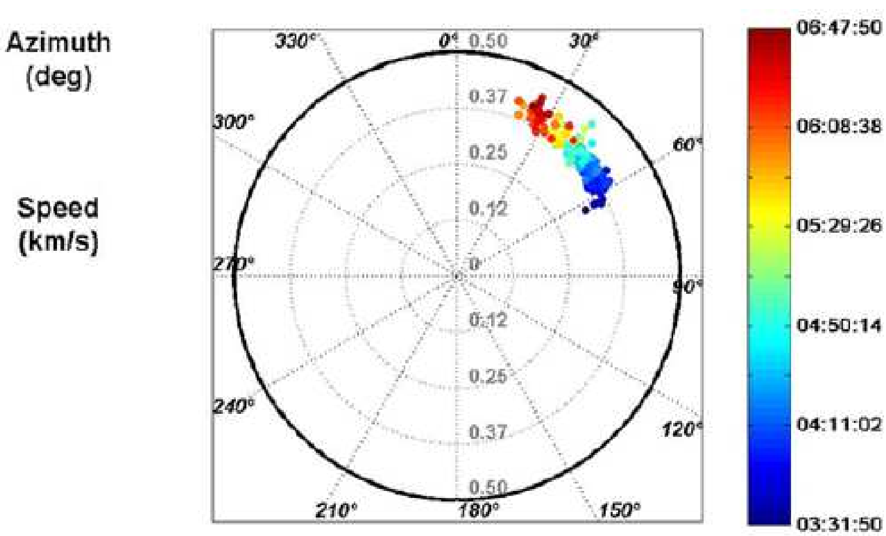
Diego Garcia, BIOT, 26 Dec. 2004

[*Le Pichon et al.*, 2005]

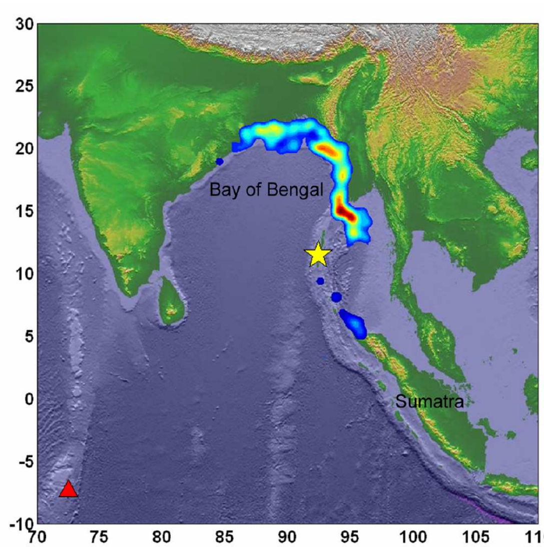


BEAM ARRAY to determine azimuth of arrival and velocity of air wave.

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



Time

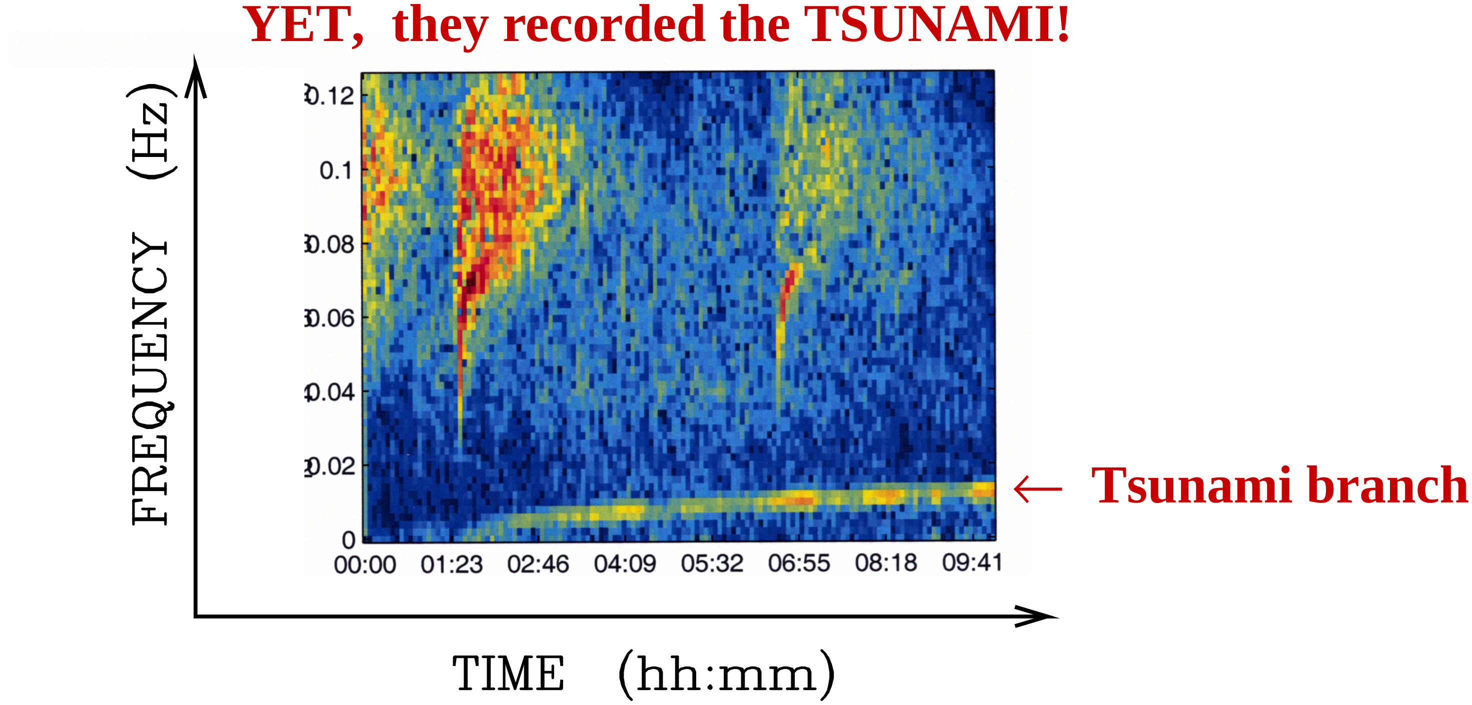


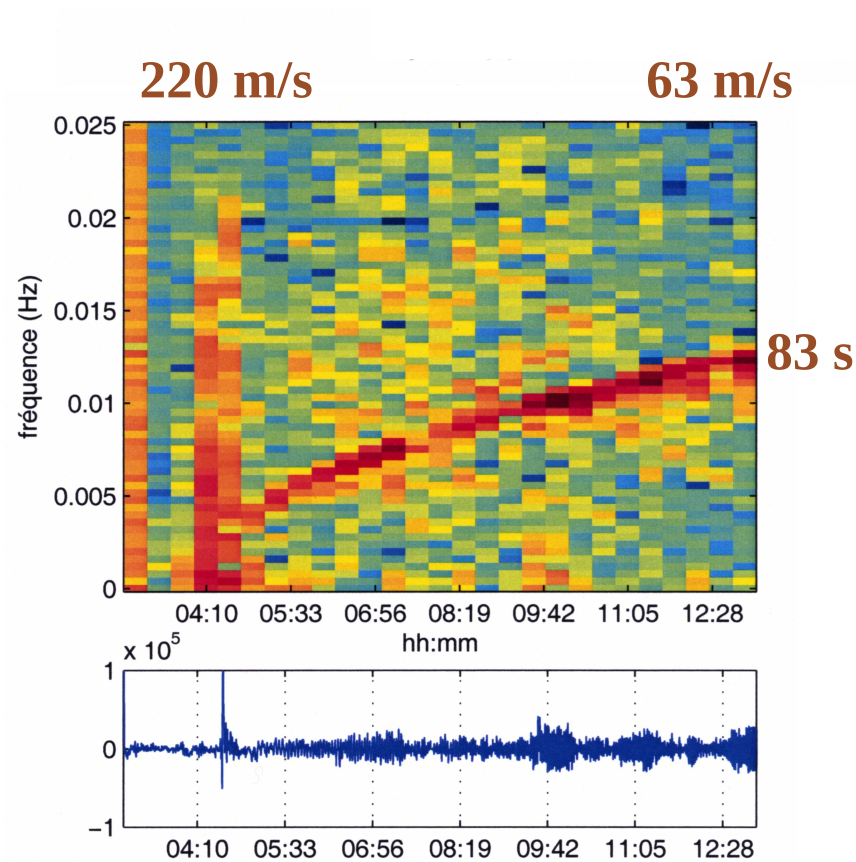
TSUNAMI recorded by HYDROPHONES of the CTBTO

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

→ Instruments are severely filtered at infra-acoustic frequencies.

YET, they recorded the TSUNAMI!





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

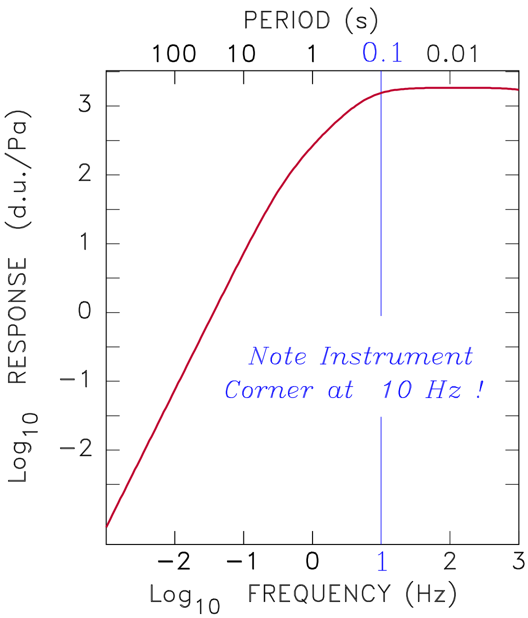
$$\omega^2 = g\,k \cdot \tanh(k\,h)$$

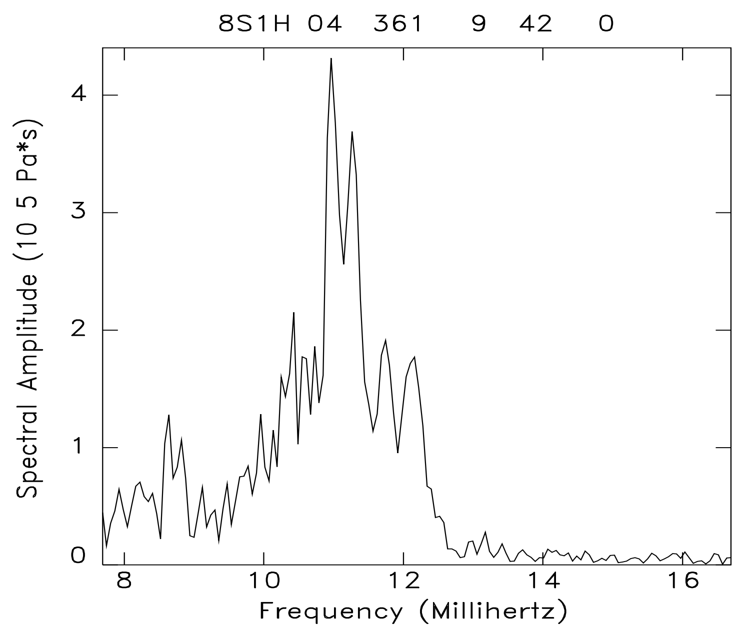
All of this on the high seas, unaffected by coastal response.

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





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

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

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

ACCEPTABLE !

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

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

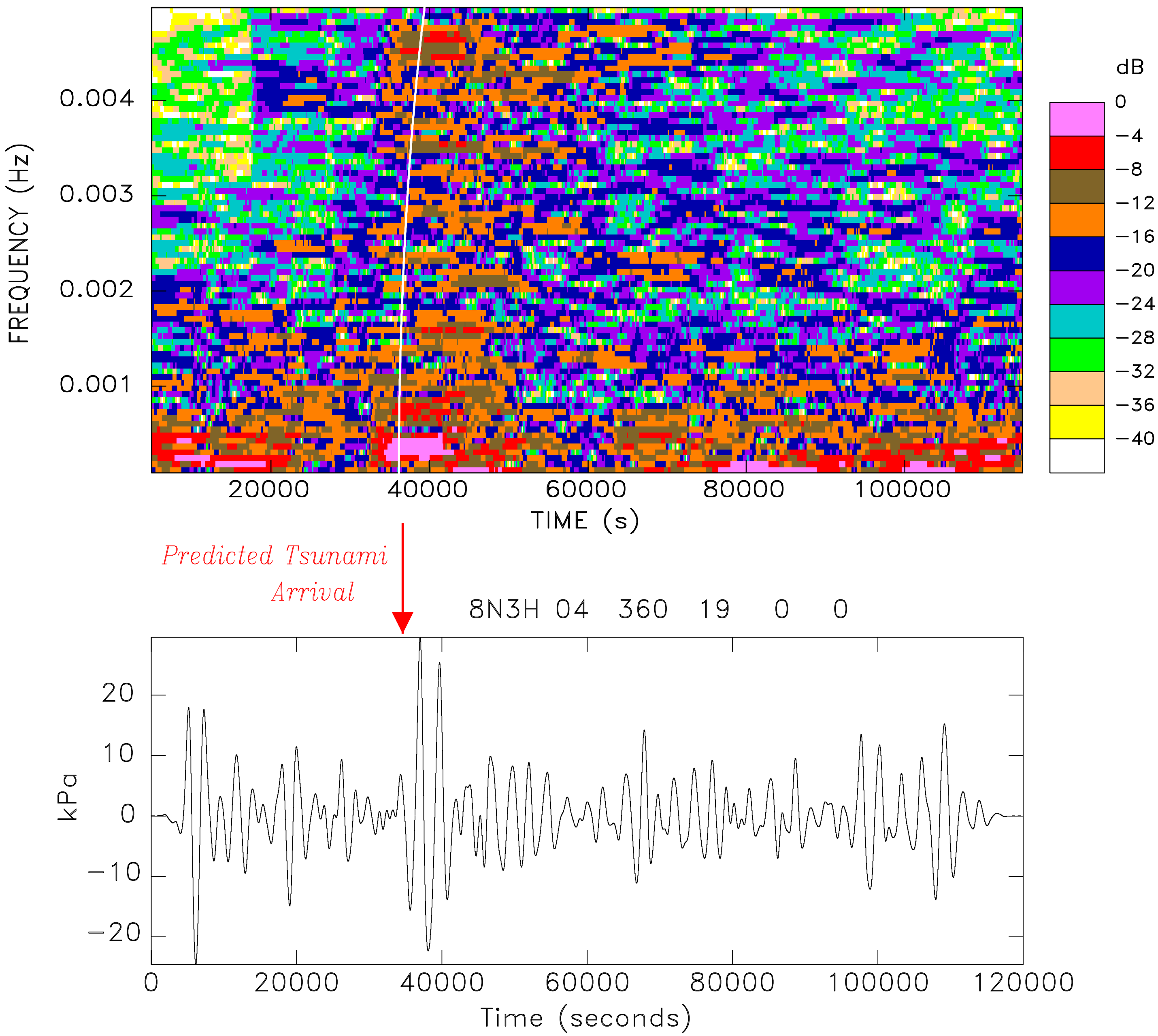
LONG-PERIOD ($T \approx 3000$ s) TSUNAMI

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.*

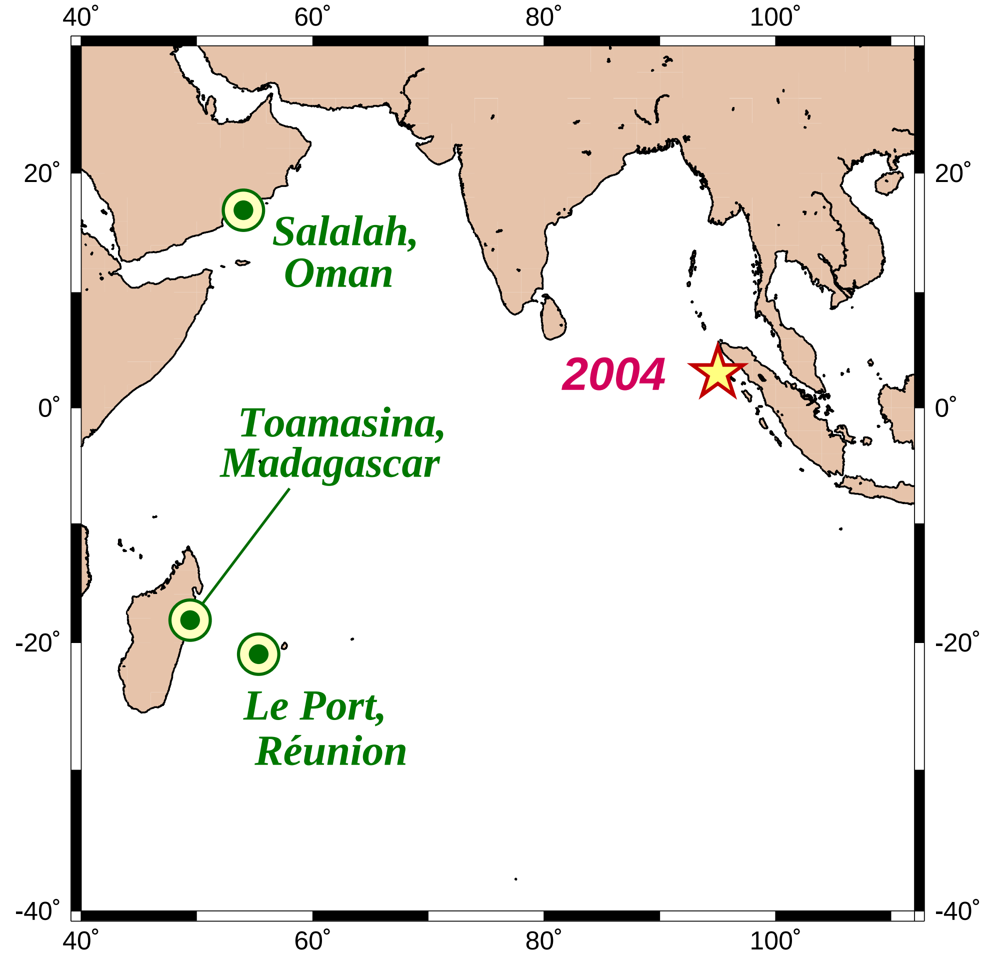
HYDROPHONES DESIGNED *WITHOUT HIGH – PASS FILTERS* COULD BE VALUABLE TSUNAMI DETECTORS



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.

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]

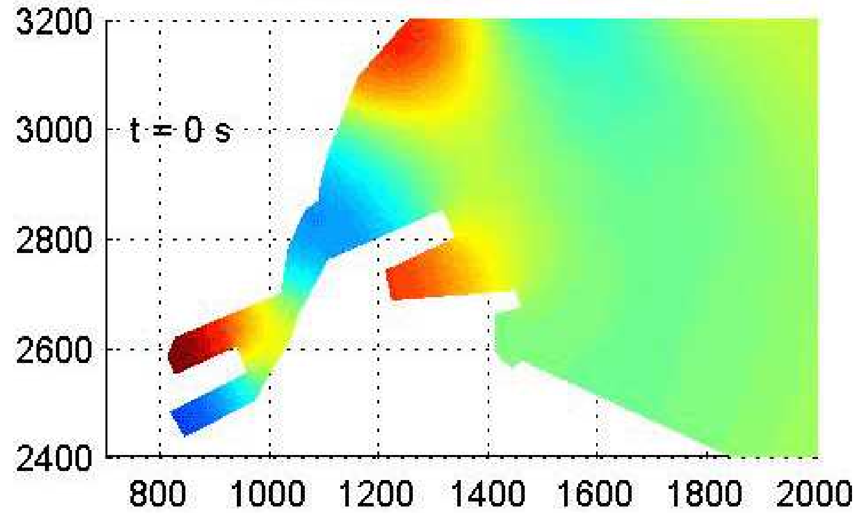
- Finite element modeling of the oscillations of the port of Toamasina reveals a fundamental mode of oscillation at *T* = 105 s, characterized by sloshing back and forth of water into the interior of the harbor, thus creating strong *currents* at the berth of *Soavina III*.

- 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.

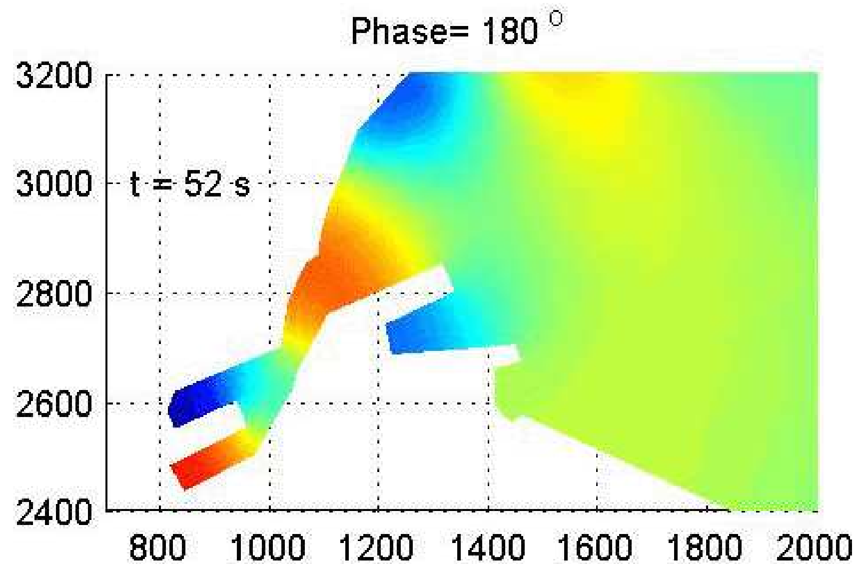
- This would correspond to an arrival at **16:55 GMT, or 19:55 Local Time**.

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

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



T = 105 seconds

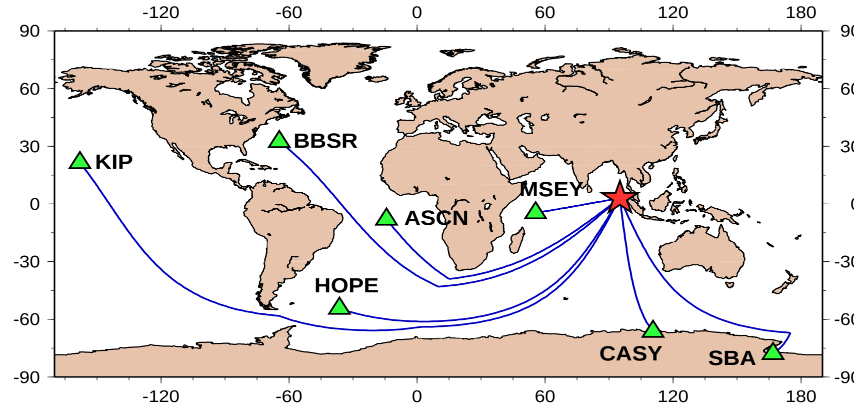


TSUNAMI RECORDED ON SEISMOMETERS

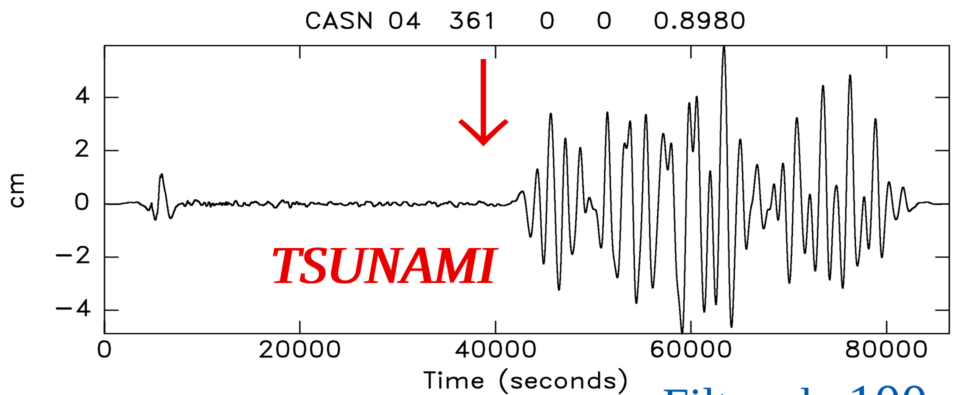
- Recording by shoreline stations is

  WORLDWIDE

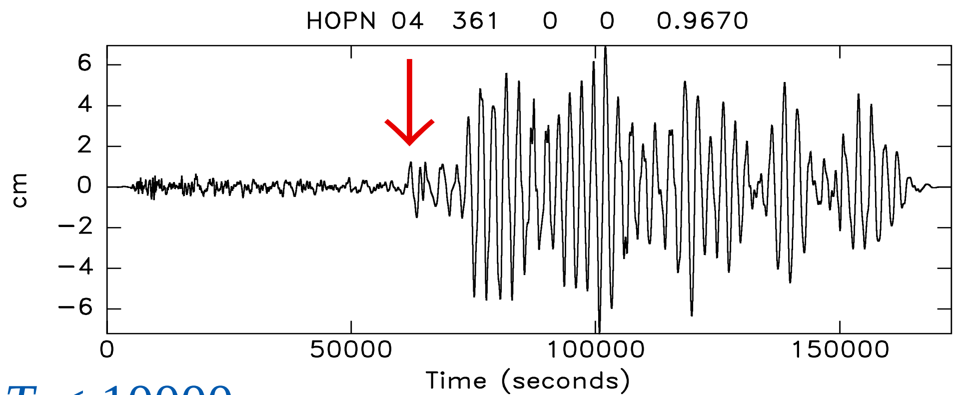
  including in regions requiring strong refraction around continents (Bermuda, Scott Base).



Casey, Antarctica, 8300 km

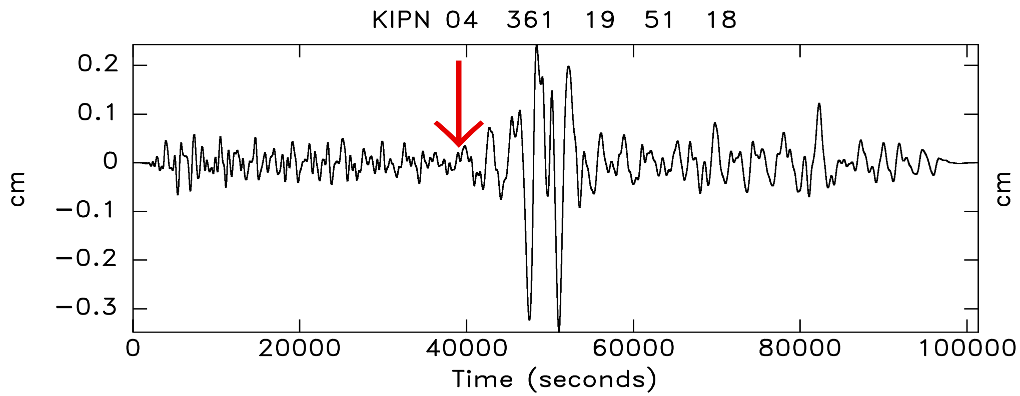


Hope, South Georgia, 13100 km

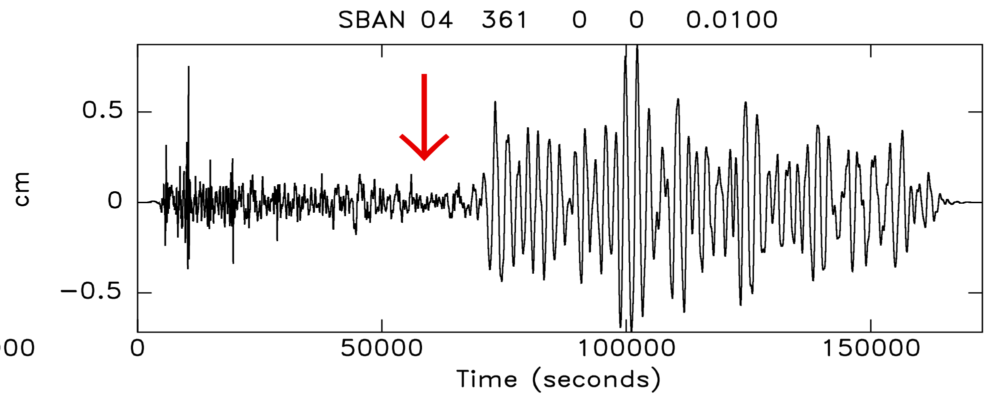


Filtered $100 < T < 10000$ s.

Kipapa, Hawaii, 27,000 km



Scott Base, Antarctica, 10400+ km



USING AN ISLAND SEISMOMETER AS A "DART" SENSOR?

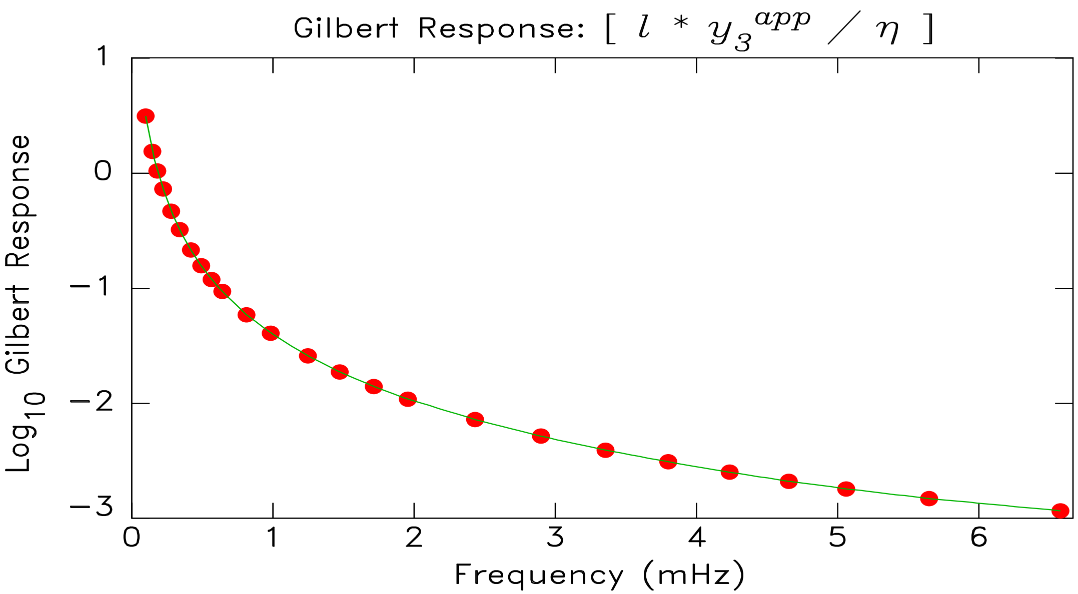
Example: Ile Amsterdam, 26 DEC 2004 (d= 5800 km)

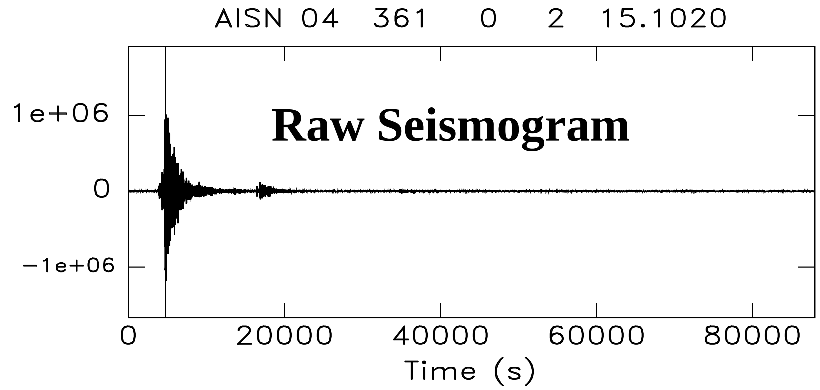
- A horizontal seismometer at a shoreline location can record a tsunami wave.

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

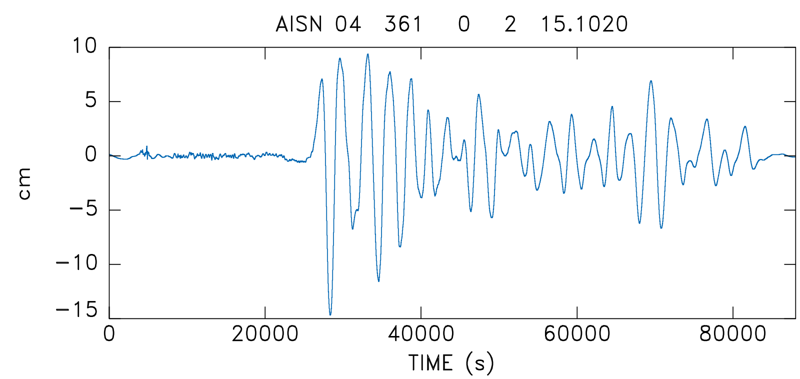
- Further deconvolve the *"**G**ilbert **R**esponse **F**actor"* $[l\, y_3^{app} / \eta]$ and obtain the time series of the surface amplitude of the tsunami.

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

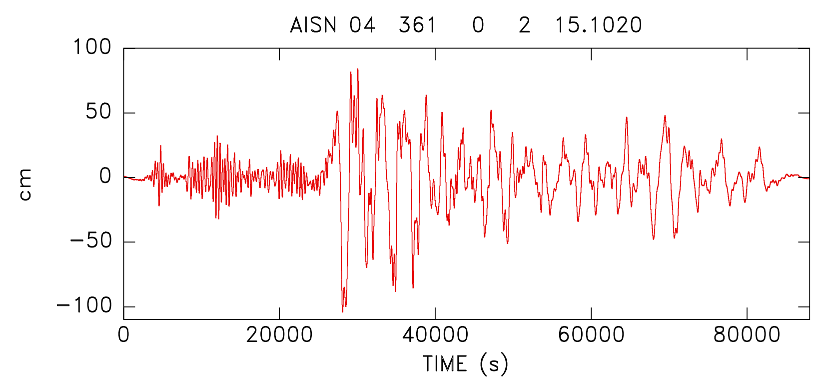




Deconvolve Instrument: **Apparent Ground Motion**



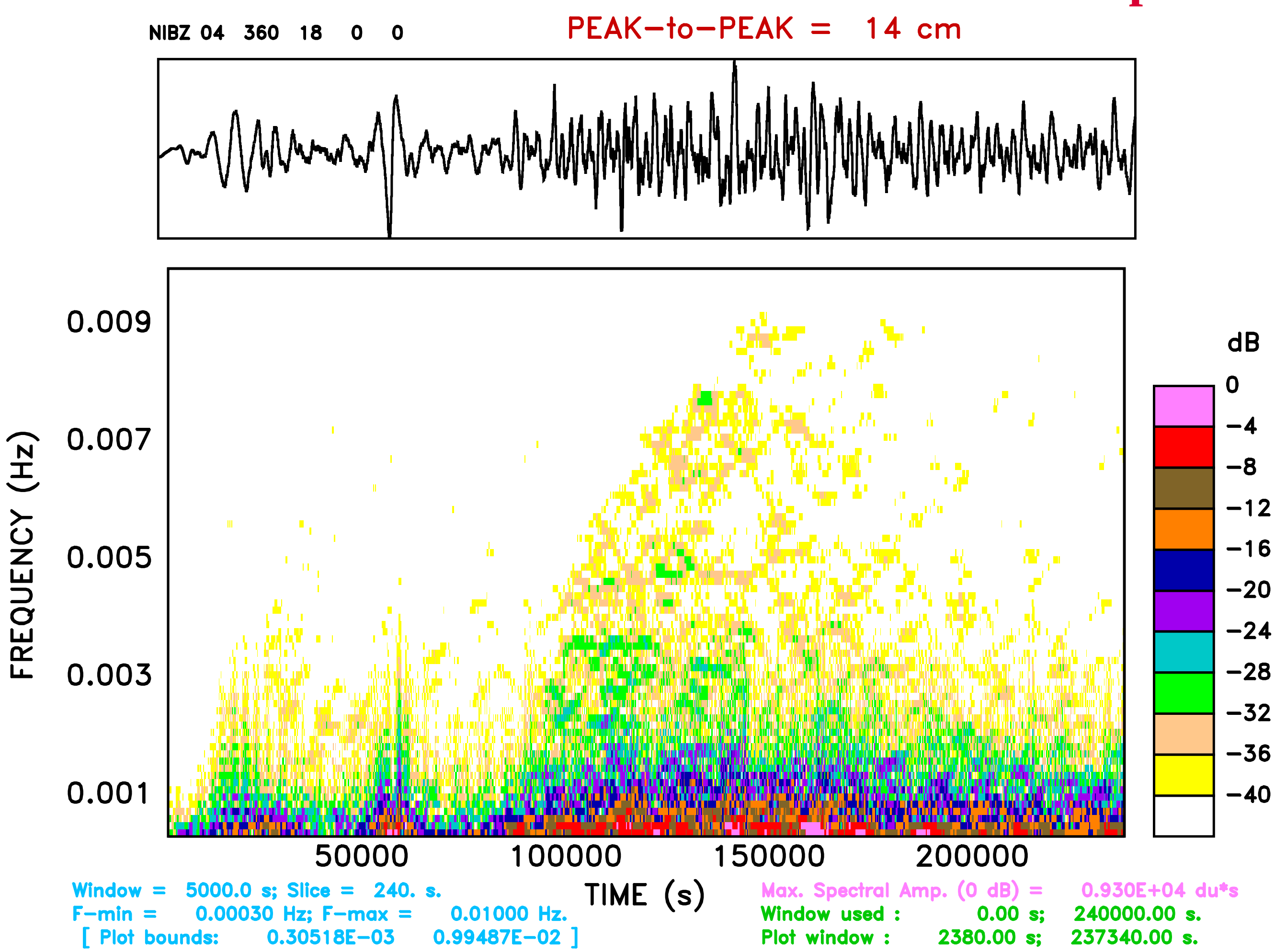
Deconvolve *GRF:* **"Tsunami Record"**

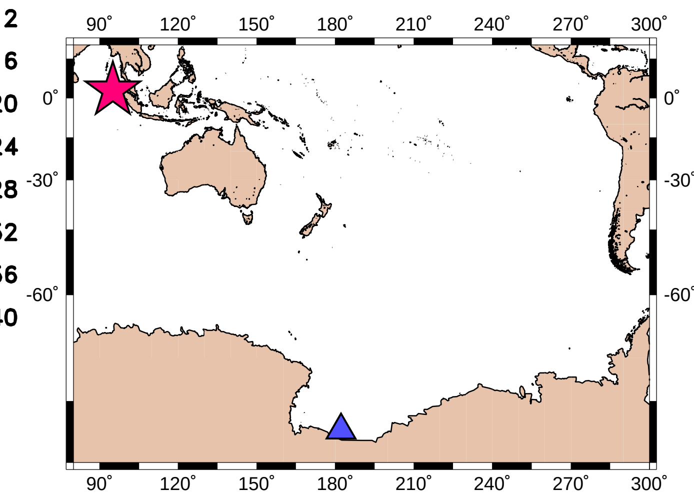


TSUNAMI RECORDED on ICEBERGS

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

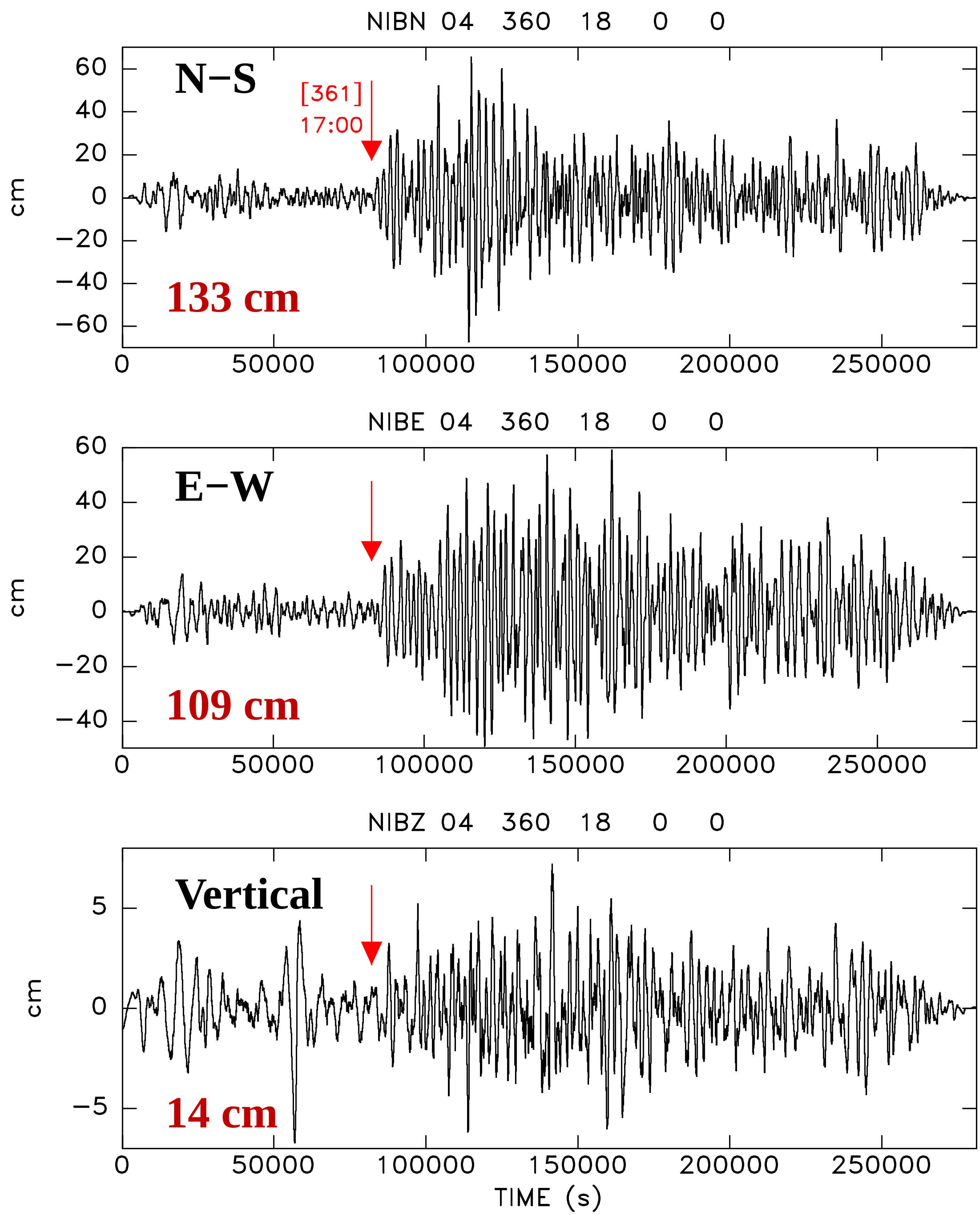
The tsunami was recorded by our 3 seismic stations, on all 3 components, with amplitudes of 10−20 cm.





Seismic recordings of 2004 Sumatra Tsunami

Nascent (NIB); *26 DECEMBER 2004*



ELLIPTICITY of TSUNAMI SURFACE MOTION

(Shallow Water Approximation)

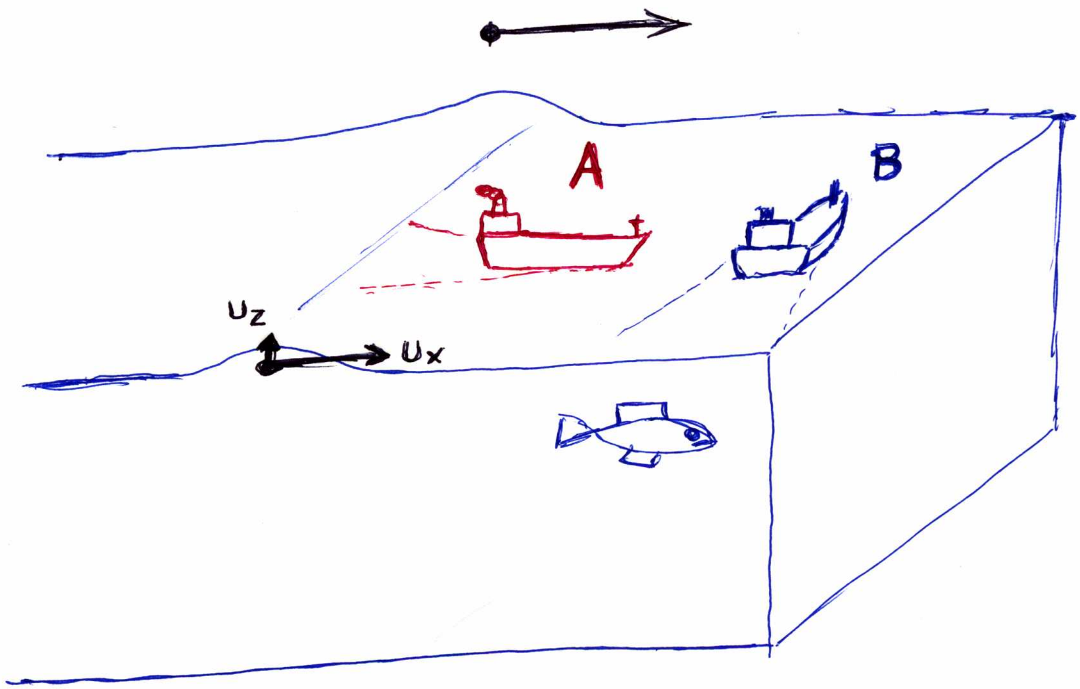
$$\frac{u_x}{u_z} = \frac{1}{\omega}\sqrt{\frac{g}{h}} = \text{typically} = 10 \text{ to } 30$$

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

$u_x \approx 15$ meters ?

Conceivable to use GPS-equipped ships to detect tsunami.

Tsunami



Ship A should see a perturbation in speed

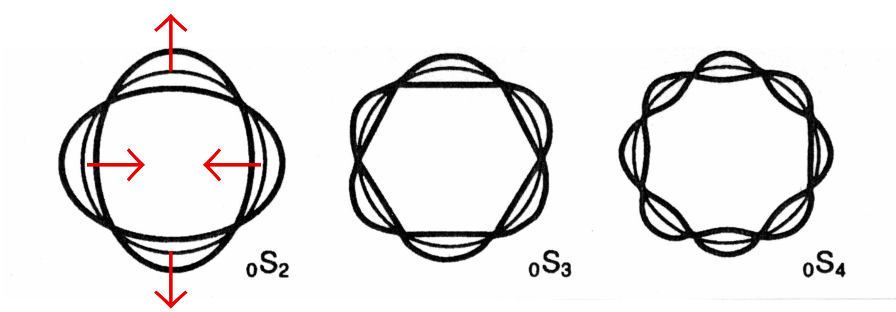
Ship B would show a zig-zag in trajectory

NORMAL MODE FORMALISM: A different approach

[*Ward*, 1980]

- At very long periods (typically 15 to 54 minutes), the Earth, because of its finite size, can ring like a bell.
- Such *FREE OSCILLATIONS* are equivalent to the superposition of two progressive waves travelling in opposite directions along the surface of the Earth.

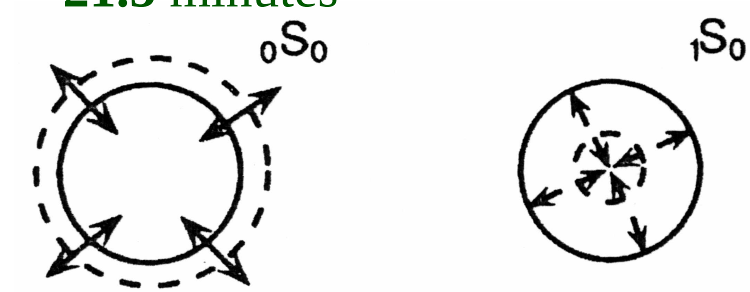
T = 54 minutes



"FOOTBALL Mode"

[After *Lay and Wallace*, 1995]

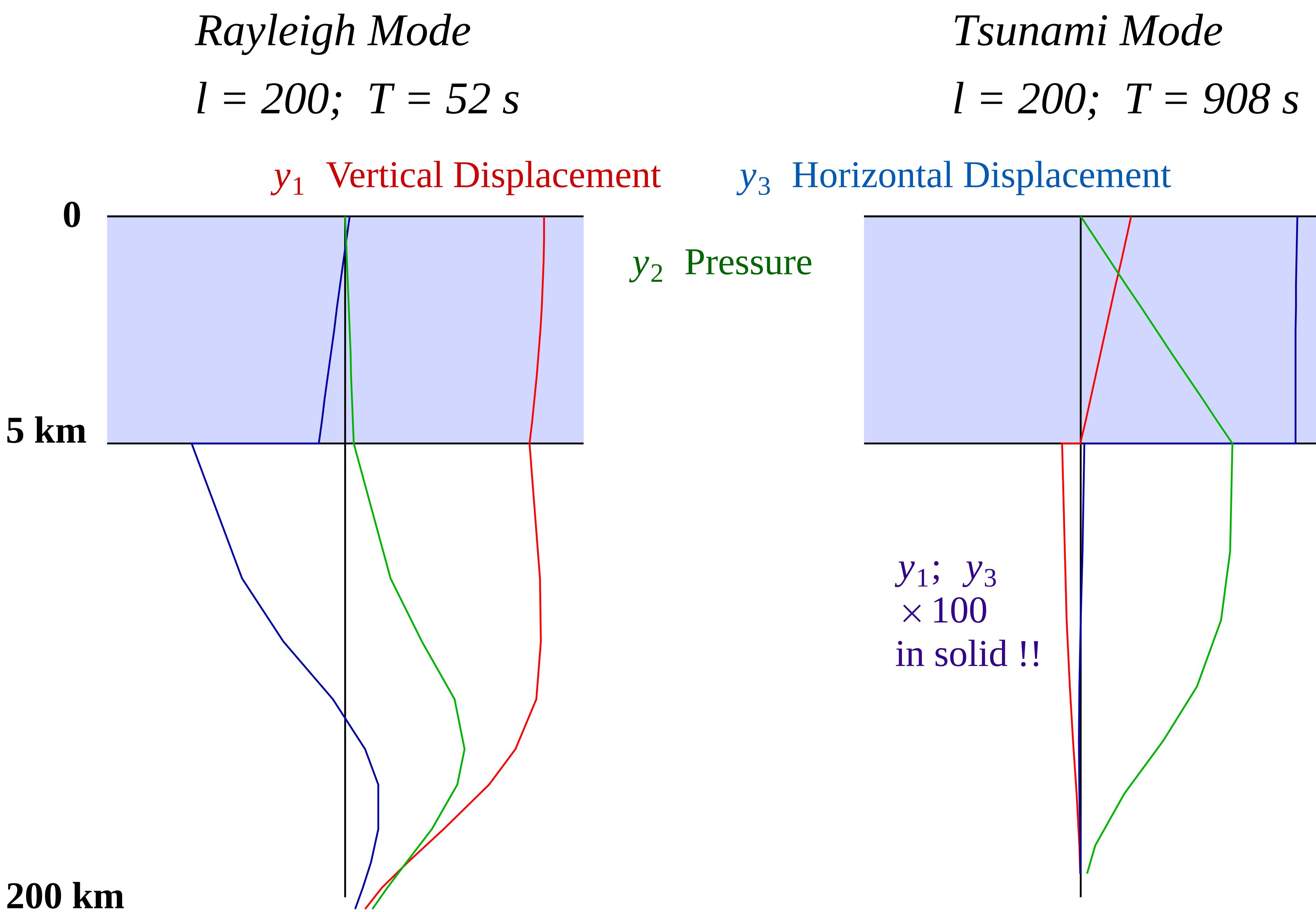
T = 21.5 minutes



"BREATHING Mode"

Ward [1980] has shown that **Tsunamis come naturally as a special branch of the normal modes of the Earth,** provided it is bounded by an ocean, and gravity is included in the formulation of its vibrations.

EIGENFUNCTIONS of SPHEROIDAL MODES



TSUNAMI EIGENFUNCTION is CONTINUED (SMALL) into SOLID EARTH