TSUNAMI

When Great Earthquakes Couple Eclectic Media

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TSUNAMI

Gravitational oscillation of the mass of water in the ocean, following a *DISTURBANCE* of the ocean floor [or surface].

Improperly called

- *Tidal* wave
- Raz-de-*marée* [French]
- *Flut*wellen [German]

Properly called

→ Maremoto [Spanish, Italian]

→ Taitoko [Marquesan]

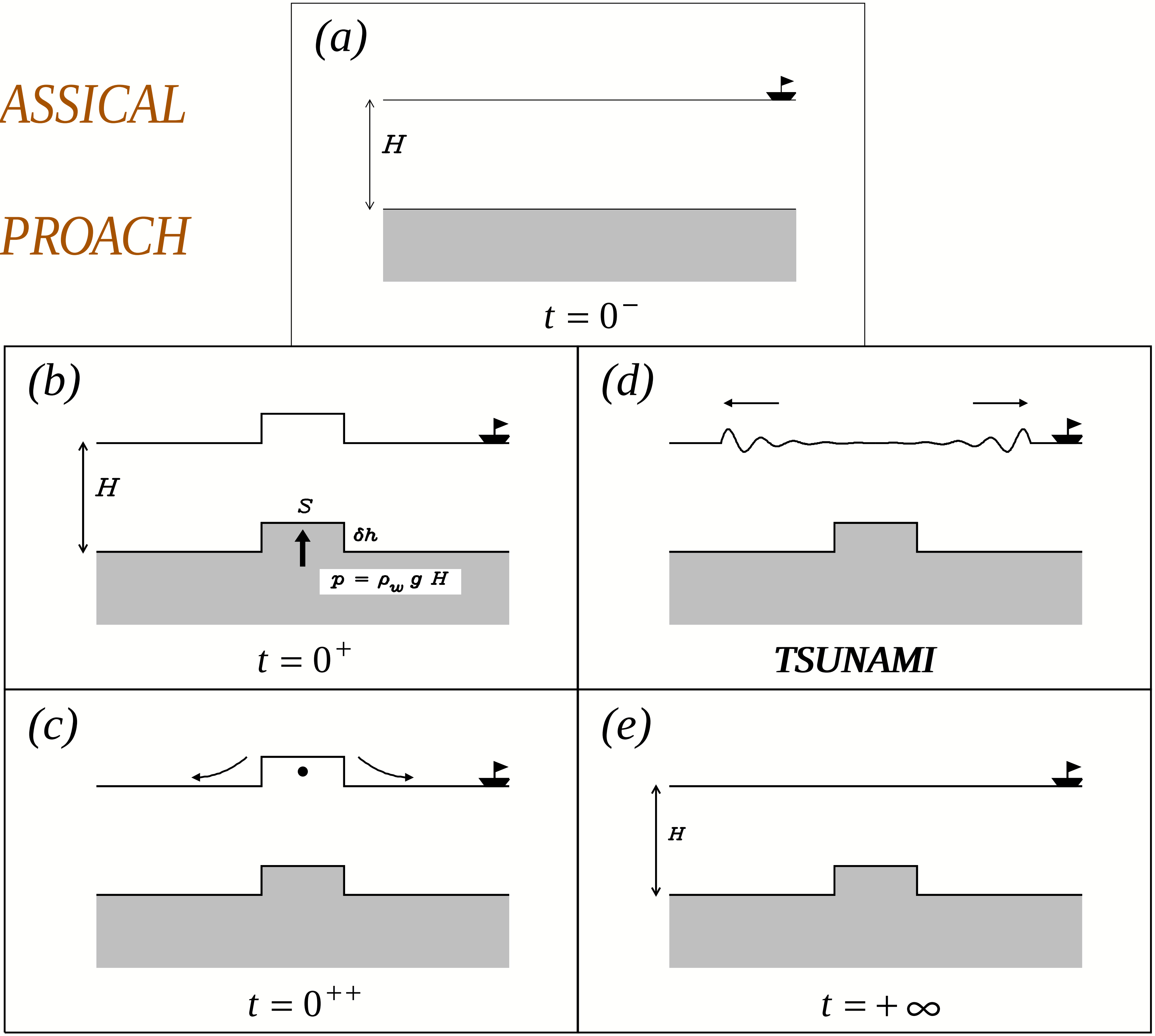
→ Tsu Nami (Harbor wave) [Japanese]

TSUNAMIS GENERATED BY

- **Earthquakes**
- **Landslides**
- **Volcanic Explosions**
- **Bolide Impacts**

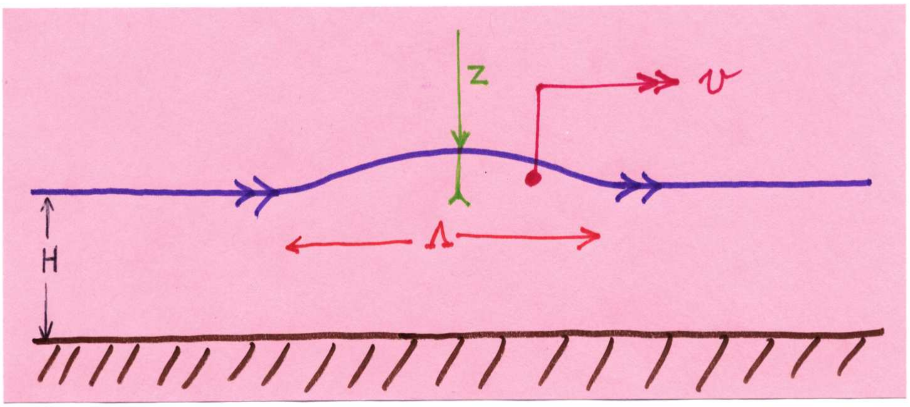
→ ***Meteo – Tsunamis***

CLASSICAL APPROACH



TSUNAMI WAVE CHARACTERISTICS

- *Propagation on the High Seas*



* *VELOCITY depends on DEPTH of Water, H*

$$v = \sqrt{g \cdot H}$$

In practice for $H = 5$ km, $v = 220$ m/s = 800 km/h

(i.e., the speed of a modern airliner)

* *Maximum AMPLITUDE, z (poorly known),* is a few, to a few tens of centimeters.

* *WAVELENGTH, Λ,* is typically 300 km

(PERIODS: 600 to 3000 s)

- *Interaction with Coastlines — Shoaling*

Upon shoaling, the wave slows down considerably ($v = \sqrt{g\,H}$), and its energy, which was spread over the deep ocean column, must be squeezed into a now shallow water layer.

→ Hence, **the wave amplitude increases considerably,** often to **several meters, or tens of meters.**

→ It can penetrate as much as several km inland.

Sumatra, 2004

INUNDATION:

2 km

[*R. Davis*, AusAID]

FLOW DEPTH:

32 m

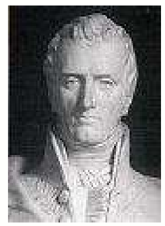
[*J.C. Borrero*, USC]

PHYSICAL PRINCIPLES

Like in all branches of Physics, the equations of motion of Hydrodynamics are derived from the application of Newton's Law and of conservation of mass.

We can start with the most general *Navier-Stokes* equations

$$\frac{D(\rho\,\mathbf{u})}{Dt} = \rho\,\mathbf{f} - \mathbf{grad}\,p + \mathbf{div\,T}$$



where $\mathbf{u}$ is the velocity field, $\frac{D}{Dt}$ is the full *particle* derivative, $\mathbf{f}$ the body force per unit mass (*e.g.*, gravity), p pressure, and $\mathbf{T}$ the tensor of shear stress density in the general case of a viscous fluid.

The following approximations are almost always assumed in tsunami applications:

- The fluid is *incompressible:* ρ is constant in space in time. Conservation of mass then requires div $\mathbf{u} = 0$.

- The shear stress $\mathbf{T}$ (to be added to the opposite of the pressure, $-p \cdot \delta_{ij}$) is given by

$$T_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

If the viscosity μ is constant (in space and time), then the fluid is called *Newtonian* and the Navier - Stokes Equations become

$$\rho\,\frac{D\,\mathbf{u}}{Dt} = \mu\,\nabla^2\mathbf{u} - \mathbf{grad}\,p + \rho\,\mathbf{f}$$

- If the fluid can be considered *inviscid* ($\mu = 0$), then we get the *Eulerian* form of the Navier-Stokes Equations

$$\rho\,\frac{D\,\mathbf{u}}{Dt} = -\,\mathbf{grad}\,p + \rho\,\mathbf{f}$$

Note that the full derivative introduces *NON-LINEARITY*:

$$\frac{D\,\mathbf{u}}{Dt} = \frac{\partial\mathbf{u}}{\partial t} + (\mathbf{u}\cdot\mathbf{grad})\,\mathbf{u}$$

More approximations can be introduced depending on the scaling between three essential *LENGTHS*:

* Amplitude of Wave
* Depth of Water
* Wavelength

SHALLOW WATER APPROXIMATION

- Assume

  DEPTH $(h(x,y,t)) \ll$ *WAVELENGTH*

- Characterize wave with

  * Velocity field Averaged over Depth

  $\bar{u}(x,y,t)$ in x direction;
  $\bar{v}(x,y,t)$ in y direction;

  * Vertical amplitude at surface, $\eta(x,y,t)$

Then,

$$\frac{\partial}{\partial t}(\eta+h)+\frac{\partial}{\partial x}[(\eta+h)\bar{u}]+\frac{\partial}{\partial y}[(\eta+h)\bar{v}] = 0$$

$$\frac{\partial}{\partial t}[(\eta+h)\bar{u}]+\frac{\partial}{\partial x}[(\eta+h)(\bar{u})^2]+\frac{\partial}{\partial y}[(\eta+h)\bar{u}\,\bar{v}] = -g\frac{\partial\eta}{\partial x}\cdot(\eta+h)$$

$$\frac{\partial}{\partial t}[(\eta+h)\bar{v}]+\frac{\partial}{\partial x}[(\eta+h)\bar{u}\,\bar{v}]+\frac{\partial}{\partial y}[(\eta+h)(\bar{v})^2] = -g\frac{\partial\eta}{\partial y}\cdot(\eta+h)$$

This combination of equations (*Non-Linear Shallow Water Approximation*) constitute the basis for the modeling of long-distance (transoceanic) tsunami propagation.

They can be solved, for example using finite difference algorithms, as developed in the **MOST** code [*Titov and Synolakis*, 1997].

LINEAR SHALLOW WATER Approximation

- In simple, two-dimensional formalism, the Shallow Water Approximation is:

$$\frac{\partial}{\partial t}[(\eta+h)\bar{u}]+\frac{\partial}{\partial x}[(\eta+h)(\bar{u})^2] = -g\cdot(\eta+h)\cdot\frac{\partial\eta}{\partial x}$$

- Consider *SMALL DEFORMATIONS* [neglect $(\overline{u})^2$]

Then combine with conservation of mass

$$\frac{\partial}{\partial t}(\eta+h) + \frac{\partial}{\partial x}[(\eta+h)\bar{u}] = 0,$$

- Take further time derivative

$$\frac{\partial^2}{\partial t^2}(\eta+h) - g\cdot\frac{\partial}{\partial x}\left[(\eta+h)\frac{\partial\eta}{\partial x}\right] = 0.$$

If the bottom does not deform,

$$\frac{\partial^2\eta}{\partial t^2} = g\,h\cdot\frac{\partial^2\eta}{\partial x^2}$$

Linear Shallow Water Wave Equation

Propagation at *UNDISPERSED VELOCITY*

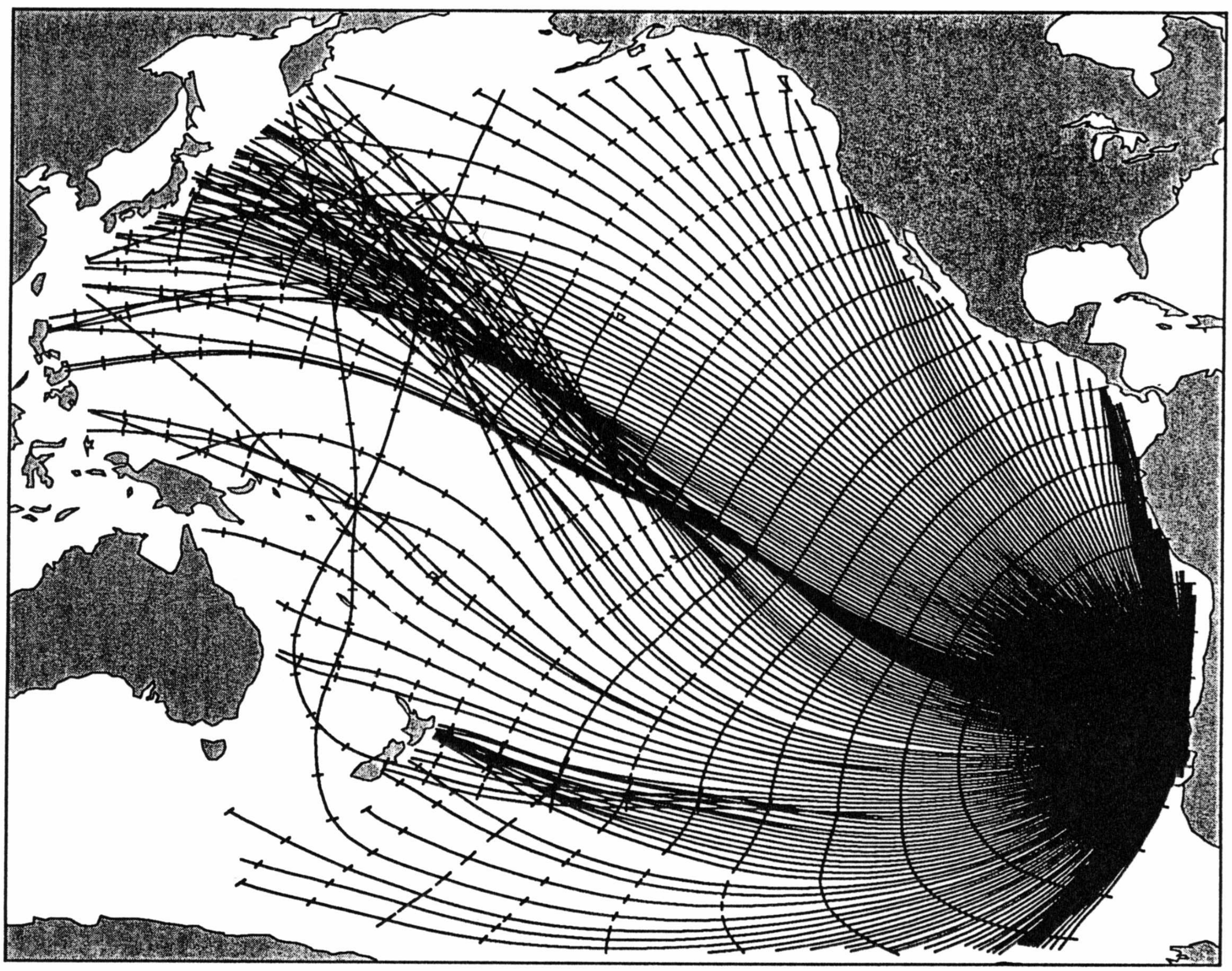
$$\underset{phase}{C} = \underset{group}{U} = \sqrt{g\,h}$$

Consequence: Shallow bathymetry *focuses* tsunami waves

$$C = \sqrt{g \cdot h}$$

Geophysical
Research
Letters

[*Woods and Okal*, 1987]



JULY
1987

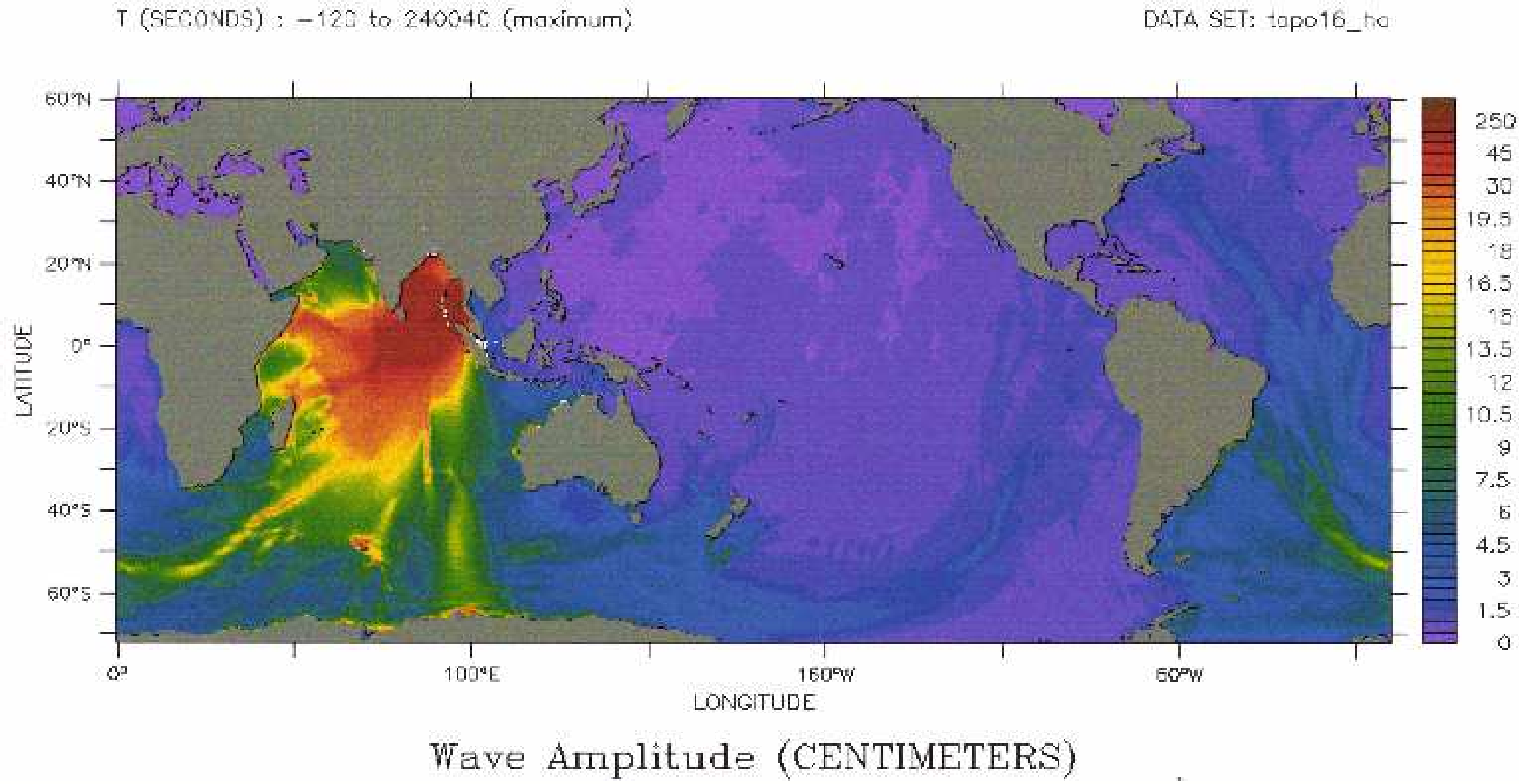
volume 14
number 7

SIMULATION of 2004 SUMATRA TSUNAMI (35 hours):

Global model of Maximum Wave Height

(before interaction with coastlines)

Note Remarkable FOCUSING of Tsunami Energy by Southwest Indian Ocean Ridge



[*V.V. Titov and D. Arcas, NOAA,* pers. comm., 2005].

HYDRODYNAMIC SIMULATIONS

1. Obtain model of Earthquake Rupture

2. Compute Static Deformation of Ocean Bottom

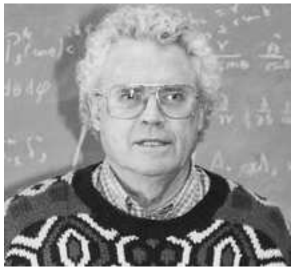
3. Use as Initial Conditions of

Vertical Surface Displacement with Zero Initial Velocity

4. Run Hydrodynamic Model (*e.g.*, **MOST**)

5. Propagate, up to and including

INUNDATION of Receiving Shore



STATIC DEFORMATION OF OCEAN BOTTOM

Straightforward, if somewhat arcane analytical formulæ

[*Mansinha and Smylie*, 1971; *Okada*, 1985]

1906 CHILEAN EVENT

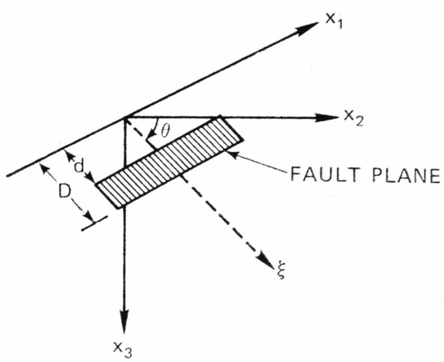
(1) Displacements

For strike-slip

$$\begin{cases} u_x = -\frac{U_1}{2\pi}\left[\frac{\xi q}{R(R+\eta)} + \tan^{-1}\frac{\xi\eta}{qR} + I_1 \sin\delta\right]\Big\| \\ u_y = -\frac{U_1}{2\pi}\left[\frac{\tilde{y} q}{R(R+\eta)} + \frac{q\cos\delta}{R+\eta} + I_2 \sin\delta\right]\Big\| \\ u_z = -\frac{U_1}{2\pi}\left[\frac{\tilde{d} q}{R(R+\eta)} + \frac{q\sin\delta}{R+\eta} + I_4 \sin\delta\right]\Big\| . \end{cases}$$

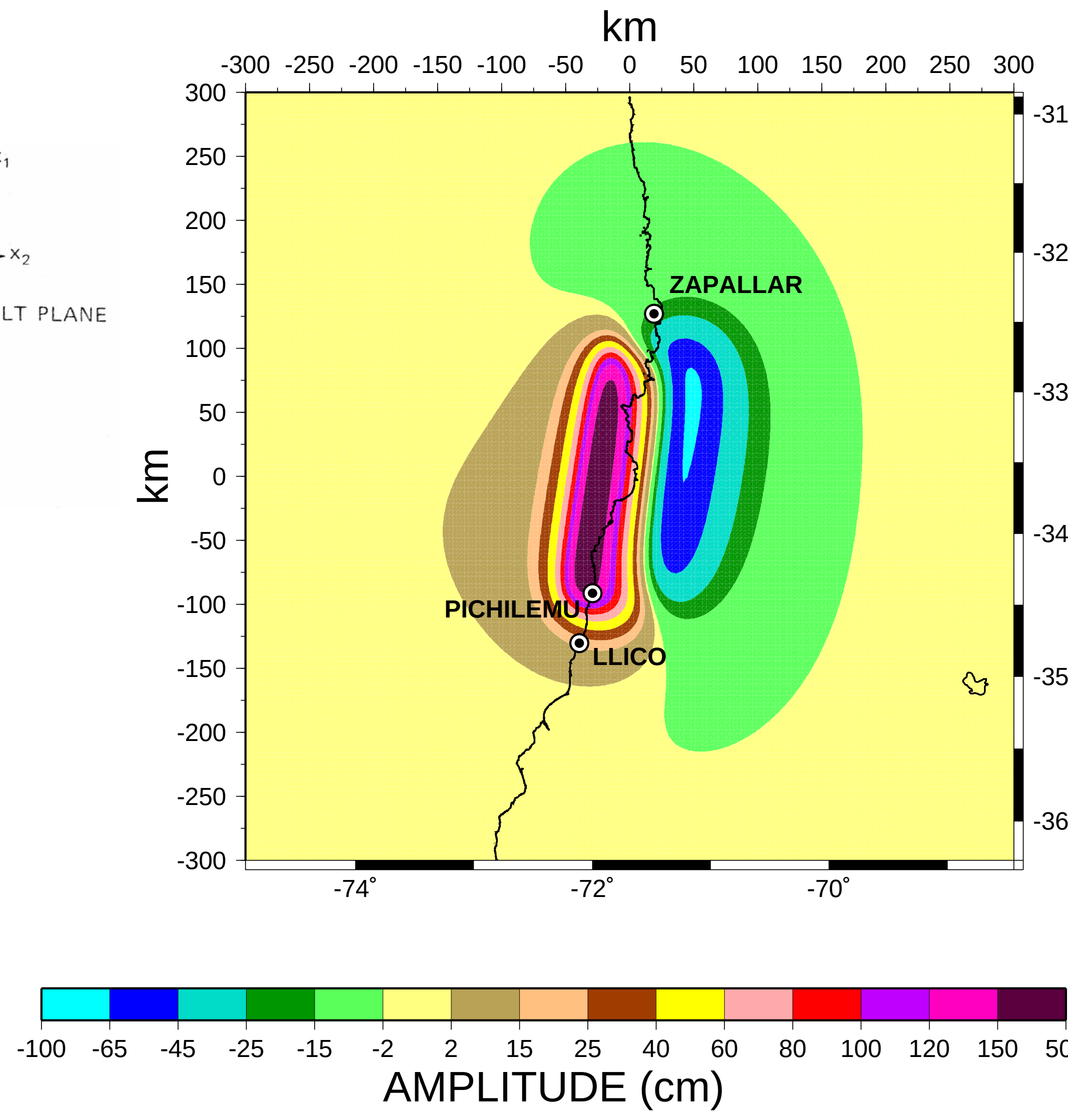
For dip-slip

$$\begin{cases} u_x = -\frac{U_2}{2\pi}\left[\frac{q}{R} - I_3 \sin\delta\cos\delta\right]\Big\| \\ u_y = -\frac{U_2}{2\pi}\left[\frac{\tilde{y} q}{R(R+\xi)} + \cos\delta\tan^{-1}\frac{\xi\eta}{qR} - I_1 \sin\delta\cos\delta\right]\Big\| \\ u_z = -\frac{U_2}{2\pi}\left[\frac{\tilde{d} q}{R(R+\xi)} + \sin\delta\tan^{-1}\frac{\xi\eta}{qR} - I_5 \sin\delta\cos\delta\right]\Big\| . \end{cases}$$



where

$$\begin{cases} I_1 = \frac{\mu}{\lambda+\mu}\left[\frac{-1}{\cos\delta}\frac{\xi}{R+\tilde{d}}\right] - \frac{\sin\delta}{\cos\delta} I_5 \\ I_2 = \frac{\mu}{\lambda+\mu}[-\ln(R+\eta)] - I_3 \\ I_3 = \frac{\mu}{\lambda+\mu}\left[\frac{1}{\cos\delta}\frac{\tilde{y}}{R+\tilde{d}} - \ln(R+\eta)\right] + \frac{\sin\delta}{\cos\delta} I_4 \\ I_4 = \frac{\mu}{\lambda+\mu}\frac{1}{\cos\delta}[\ln(R+\tilde{d}) - \sin\delta\ln(R+\eta)] \\ I_5 = \frac{\mu}{\lambda+\mu}\frac{2}{\cos\delta}\tan^{-1}\frac{\eta(X+q\cos\delta)+X(R+X)\sin\delta}{\xi(R+X)\cos\delta} \end{cases}$$



MOST Hydrodynamic Code

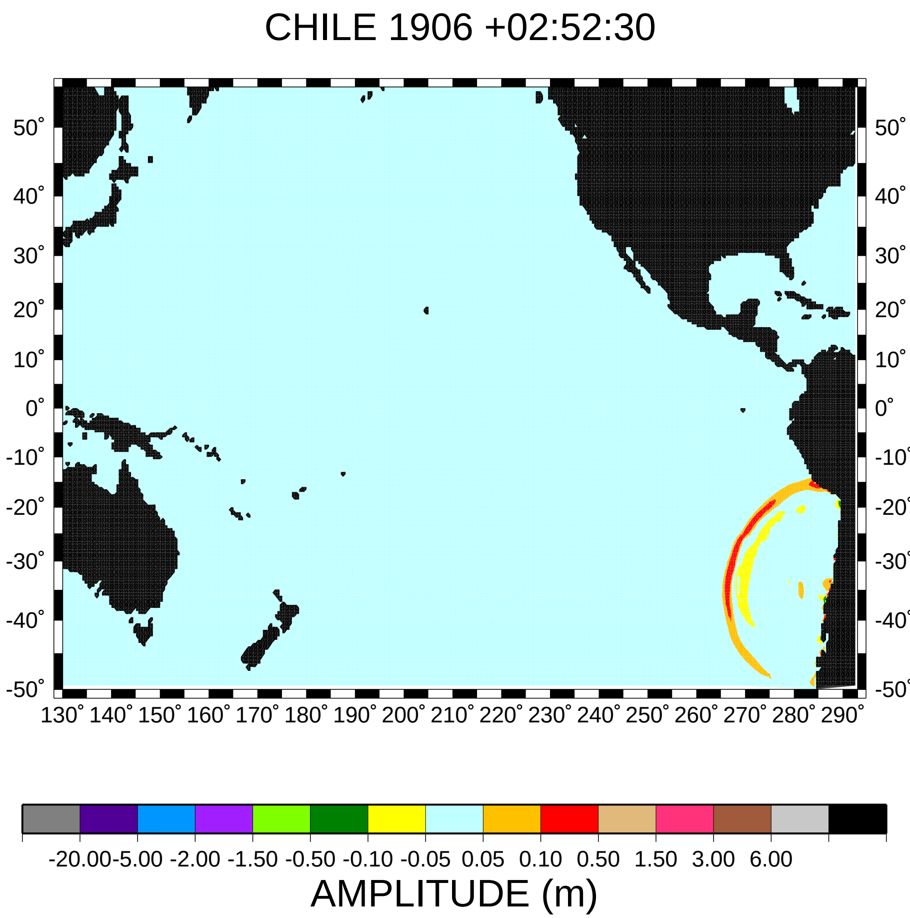
(**M**ethod **O**f **S**plitting **T**sunamis)

[*Titov and Synolakis,* 1998]

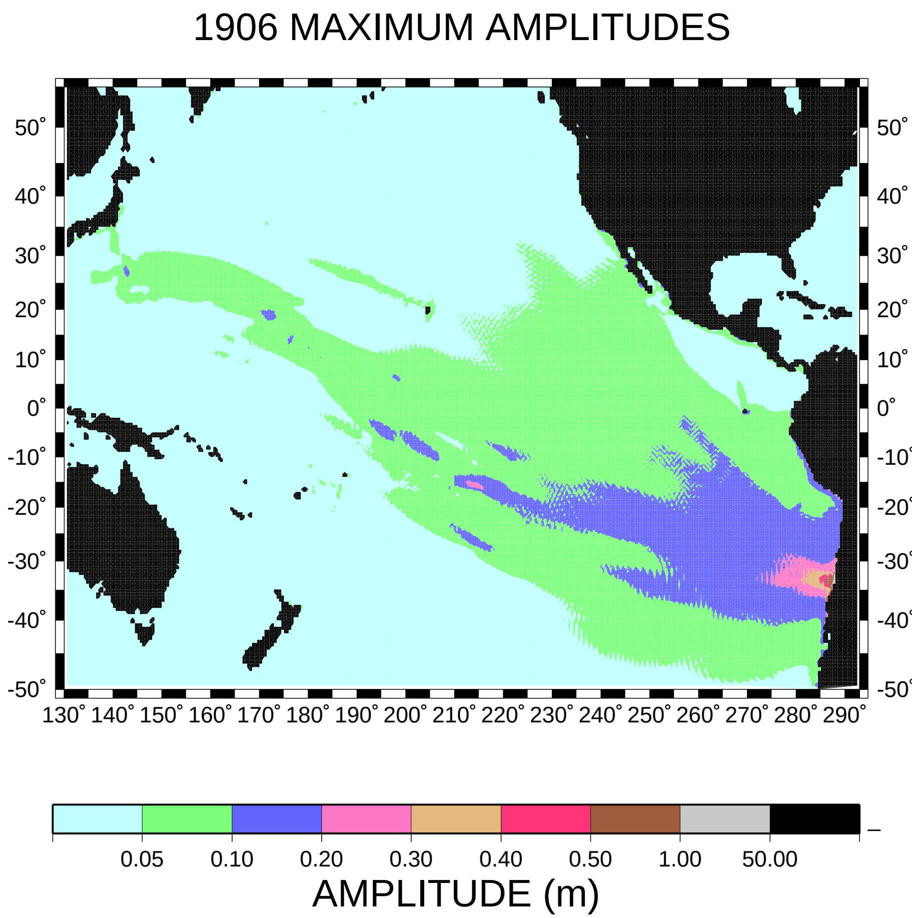
Solves the Non-Linear Shallow Water Equations

Example: *1906 Valparaiso, Chile Tsunami* [*Okal*, 2005]

INSTANTANEOUS SURFACE SNAPSHOT



MAXIMUM SEA SURFACE AMPLITUDES



HYDRODYNAMIC SIMULATIONS

Some Embarrassing, Incompatible Assumptions

1. Obtain model of Earthquake Rupture

2. Compute Static Deformation of Ocean Bottom

[*NOTE:* **Ocean absent !]**

3. Use as Initial Conditions of

Vertical Surface Displacement with Zero Initial Velocity

4. Run Hydrodynamic Model (*e.g.*, **MOST**)

[*NOTE:* **Rigid Ocean Floor !]**

5. Propagate, up to and including

INUNDATION of Receiving Shore

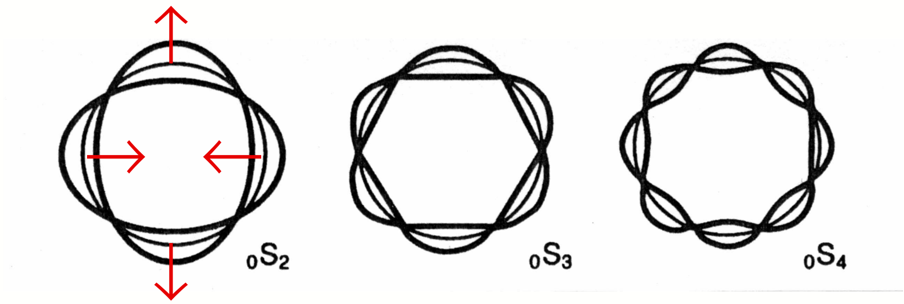
TSUNAMIS: The NORMAL MODE FORMALISM

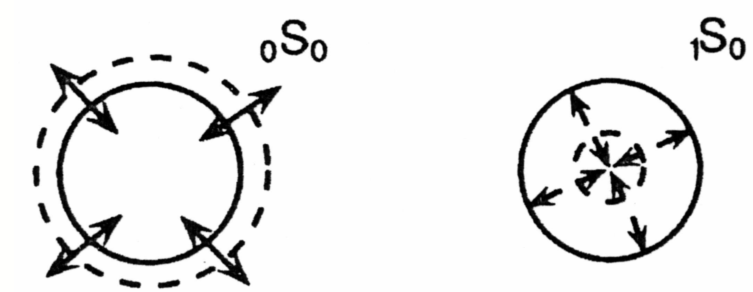
[*Ward*, 1980]

- 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

T = 21.5 minutes





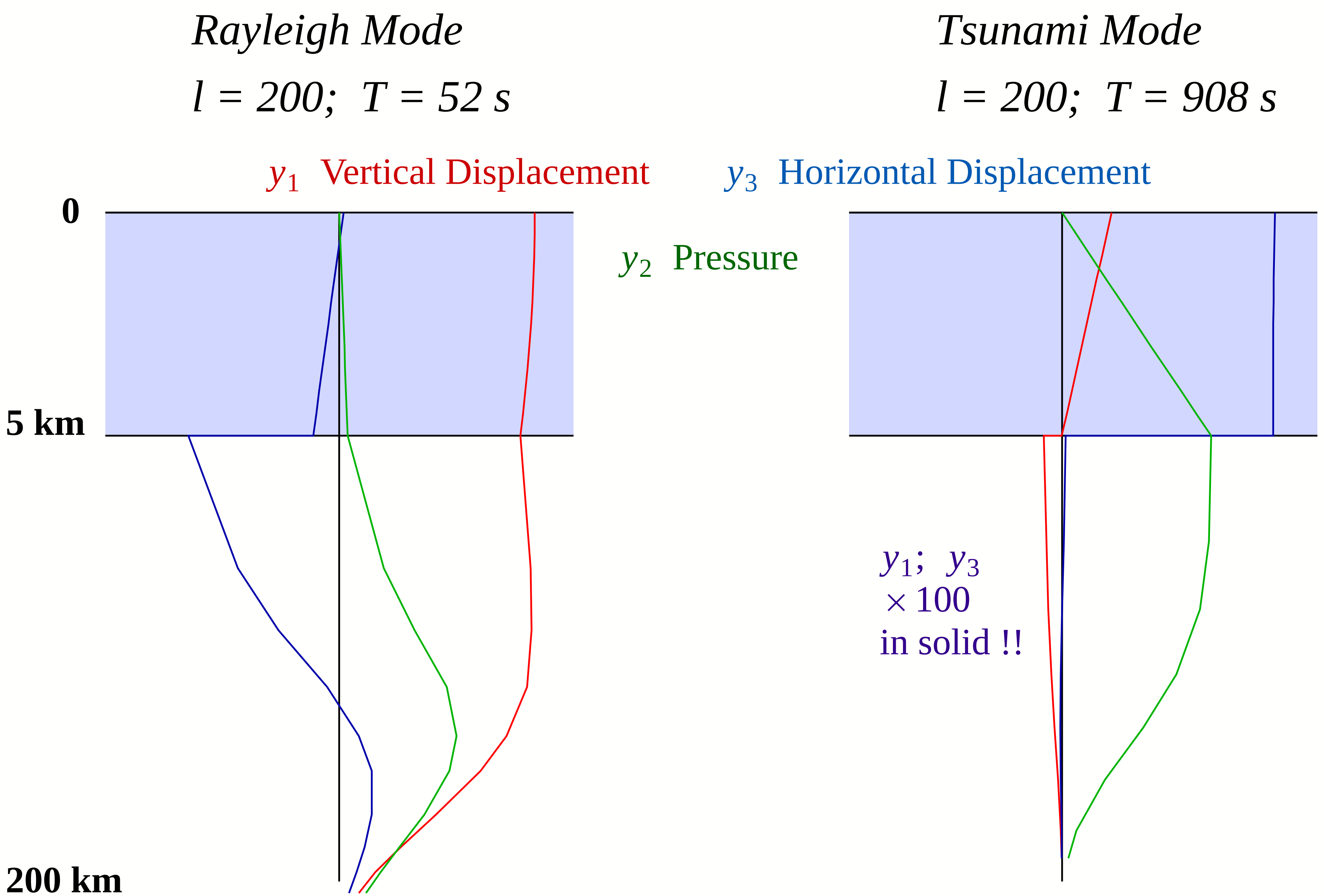
"FOOTBALL Mode"

[After *Lay and Wallace*, 1995]

"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.

TSUNAMI as SPHEROIDAL MODE : STRUCTURE of the EIGENFUNCTION



TSUNAMI EIGENFUNCTION is CONTINUED (SMALL) into SOLID EARTH

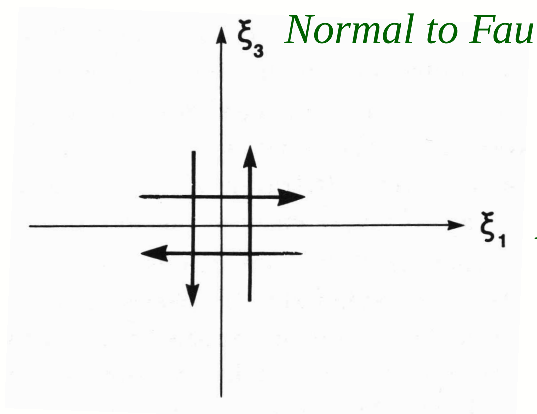
EXCITATION OF TSUNAMI in NORMAL MODE FORMALISM

- *Gilbert* [1970] has shown that the response of the Earth to a point source consisting of a single force **f** can be expressed as a summation over all of its normal modes

$$\mathbf{u}(r,t) = \sum_N \mathbf{s}_n(\mathbf{r}) \left(\mathbf{s}_n^*(\mathbf{r_s}) \cdot \mathbf{f}(\mathbf{r_s}) \right) \cdot \frac{1 - \cos\omega_n t \exp(-\omega_n t / 2Q_n)}{\omega_n^2} \quad ,$$

the *EXCITATION* of each mode being proportional to the *scalar product of the force* **f** *by the eigen-displacement* **s** *at location* $\mathbf{r_s}$.

- Now, an *EARTHQUAKE* is represented by a system of forces called a ***double – couple***:



The response of the Earth to an earthquake is thus

$$\mathbf{u}(r,t) = \sum_N \mathbf{s}_n(\mathbf{r}) \left(\varepsilon_n^*(\mathbf{r_s}) : \boldsymbol{M}(\mathbf{r_s}) \right) \cdot \frac{1 - \cos\omega_n t \exp(-\omega_n t / 2Q_n)}{\omega_n^2}$$

where the *EXCITATION* is the *scalar product* of the earthquake's **MOMENT *M*** with the local *eigenstrain* ε at the source $\mathbf{r_s}$.

This formula is directly applicable to the case of a tsunami represented by normal modes of the Earth.

ADVANTAGES of NORMAL MODE FORMALISM

- Handles any Ocean-Solid Earth Coupling
  Including Sedimentary Layers
- Works well at Higher Frequencies
  No need to assume Shallow-Water Approximation

IMMEDIATE RESULTS

- Eigenfunction very small in Solid
  Requires ***HUGE*** *Earthquake*
- Eigenfunction decays slowly in Solid
  Depth has ***minimal influence*** *on tsunami excitation* ($h \leq 70$ *km*)
- y_3 present in solid. *All geometries,* ***including strike – slip*** *excite tsunamis.*

DRAWBACKS of NORMAL MODE FORMALISM

- Must assume Laterally Homogeneous Structure
- Linear Theory -- Does not allow for Large Amplitudes

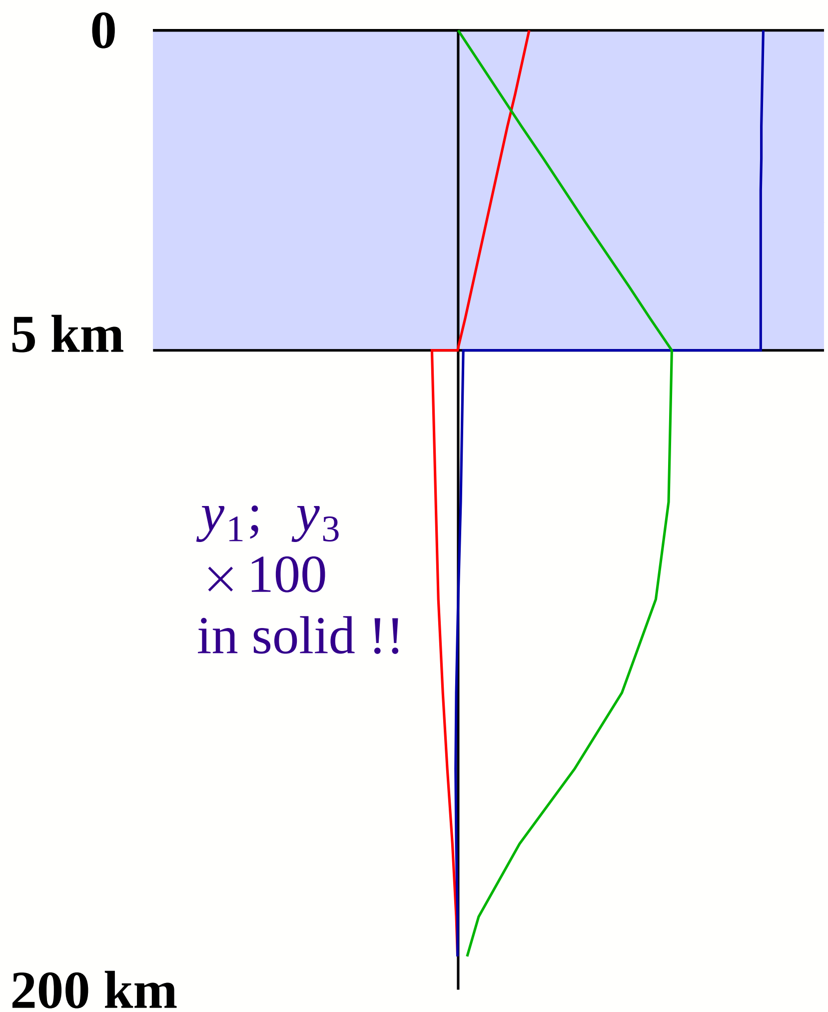
Tsunami Mode

$l = 200; \; T = 908$ s

y_1 Vertical Displacement

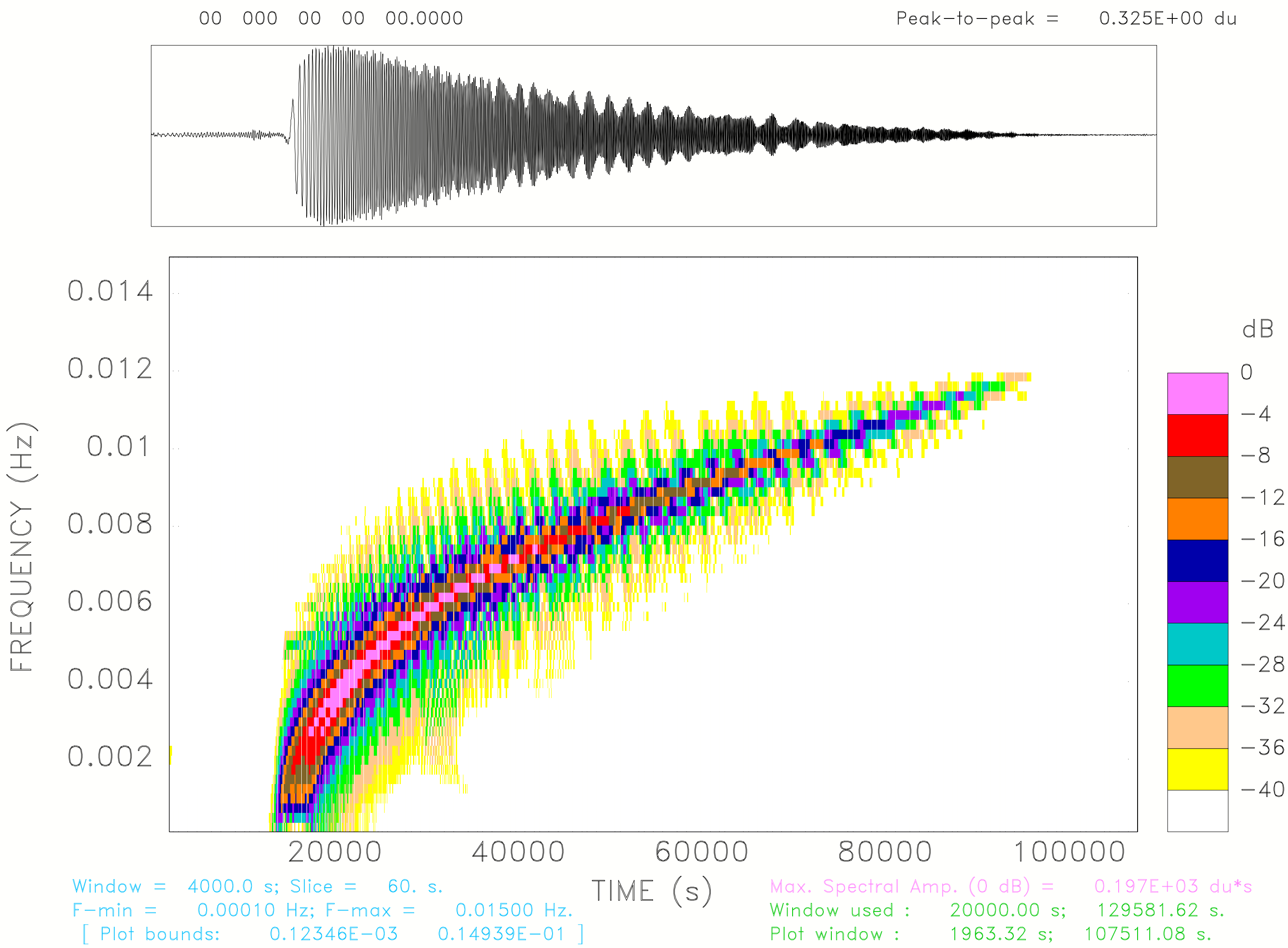
y_2 Pressure

y_3 Horizontal Displacement



EXAMPLE of NORMAL MODE TSUNAMI SYNTHETIC

$$\Delta = 70°$$



The spectrogram illustrates the dispersion of the tsunami outside the Shallow-Water Approxiamtion.

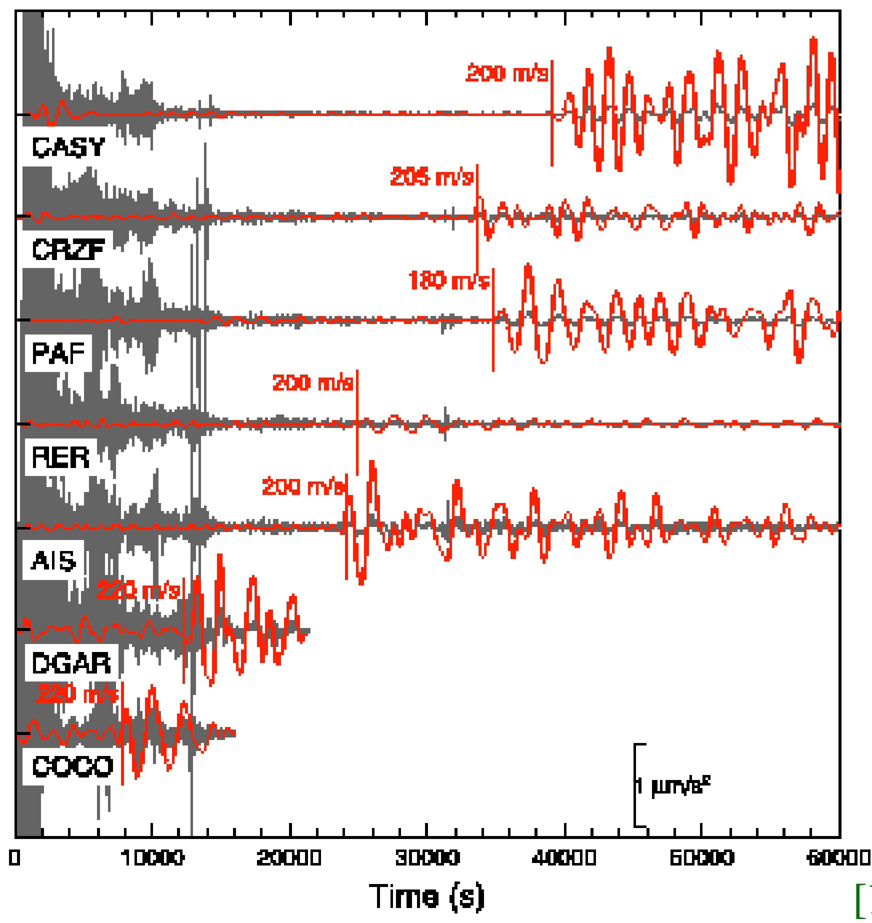
Note that high-frequency components (f = 10 mHz or T = 100 seconds) take *close to one day* to reach the receiver.

This computation is equivalent to a

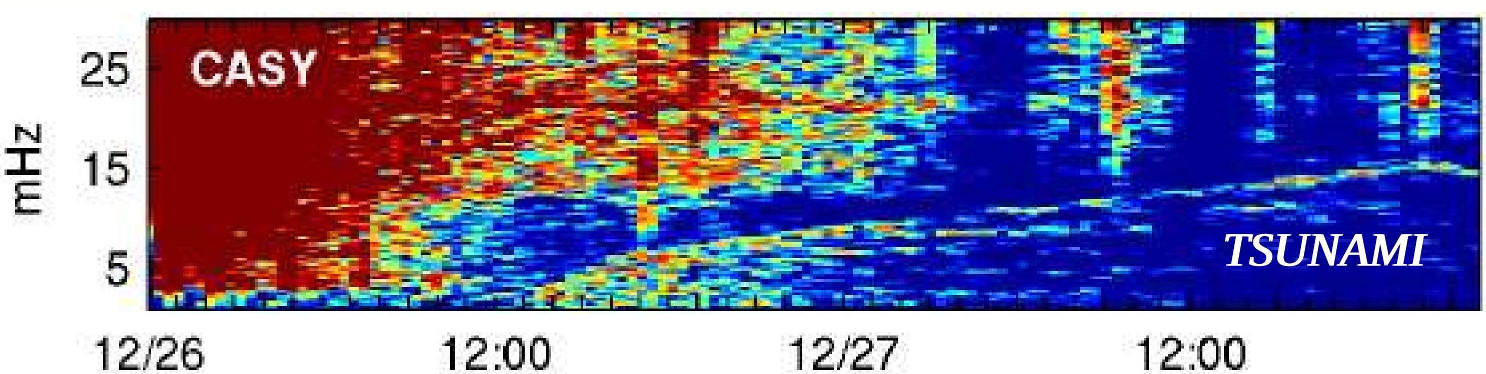
LINEAR, DISPERSIVE technique.

TSUNAMI RECORDED ON SEISMOMETERS

- Horizontal long-period seismometers (GEOSCOPE, IRIS...) record ultra-long period oscillations following arrival of 2004 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]

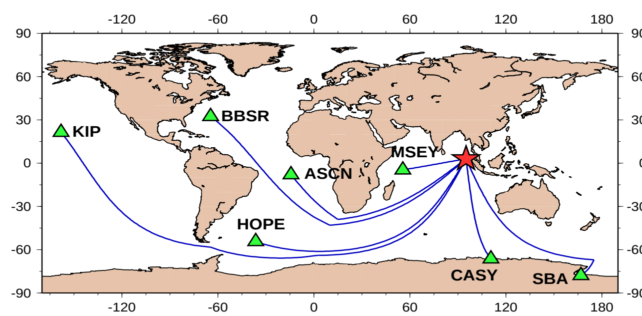
TSUNAMI RECORDED ON SEISMOMETERS (ctd.)

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

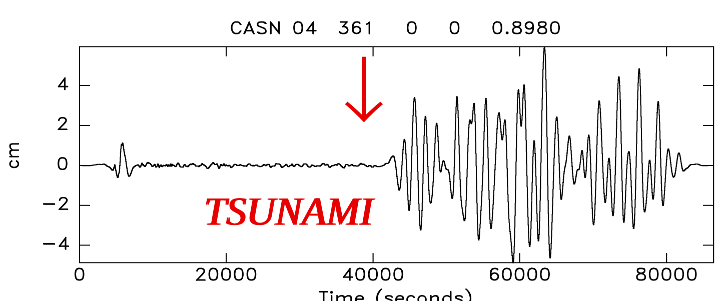
- *RECORDED* **WORLDWIDE** (On Oceanic shores)
- ***HIGHER FREQUENCIES*** (up to 0.01 Hz) *PRESENT* (in regional field)
- Tsunami detectable during **SMALLER EVENTS**
- *CAN BE* **QUANTIFIED**

SUMATRA 2004: TSUNAMI RECORDED ON SEISMOMETERS

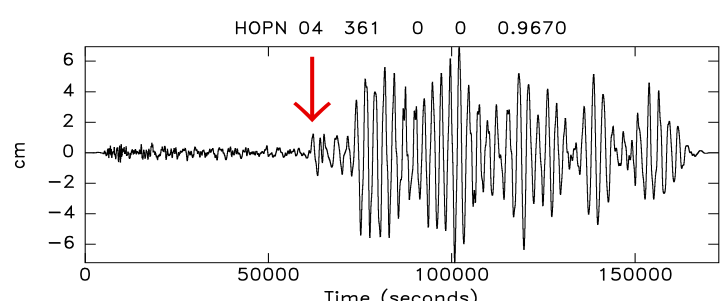
- Recording by shoreline stations is **WORLDWIDE** including in regions requiring strong refraction around continents (Bermuda, Scott Base).



Casey, Antarctica, 8300 km

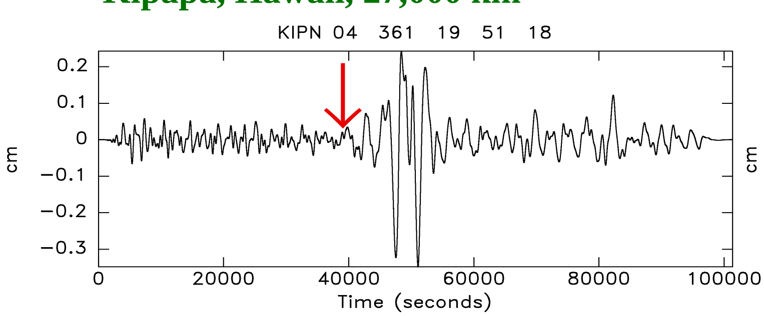


Hope, South Georgia, 13100 km

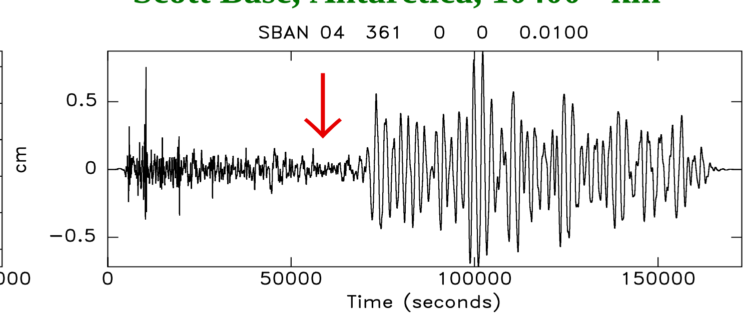


Filtered 100 < T < 10000 s.

Kipapa, Hawaii, 27,000 km

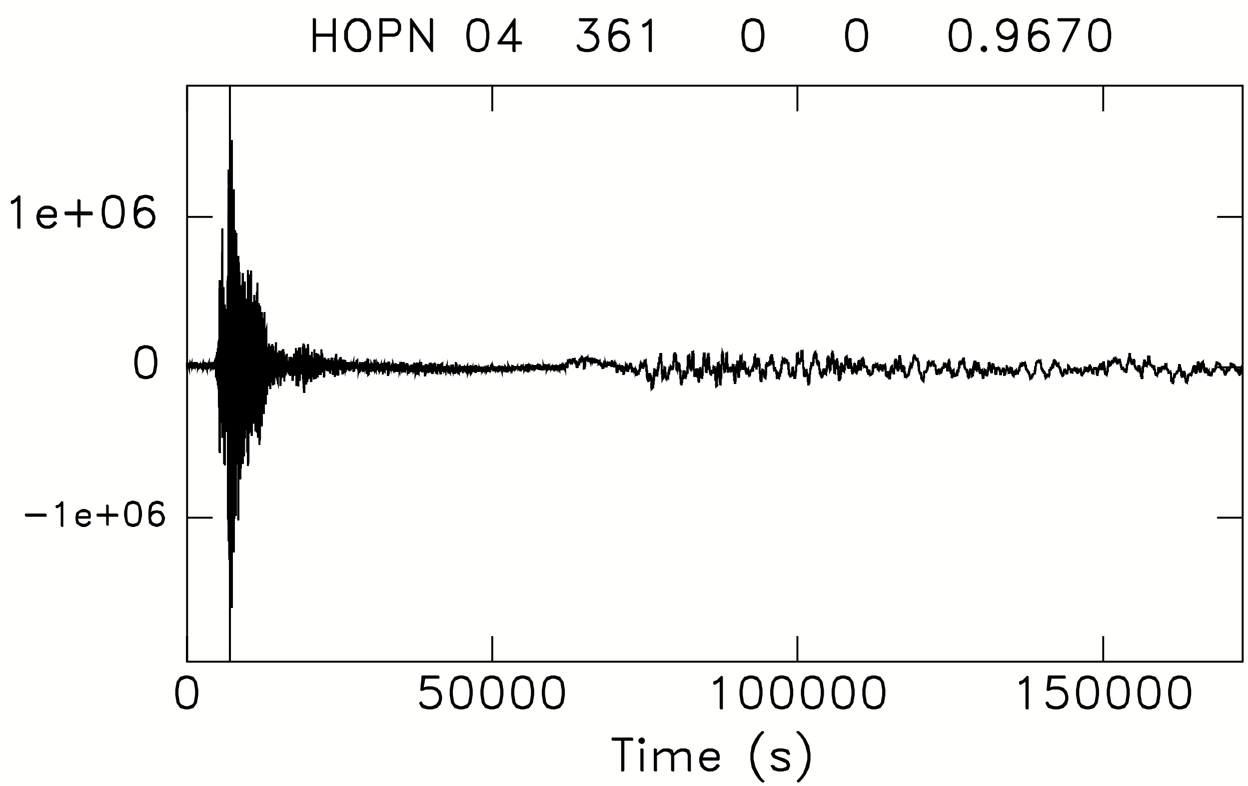


Scott Base, Antarctica, 10400+ km

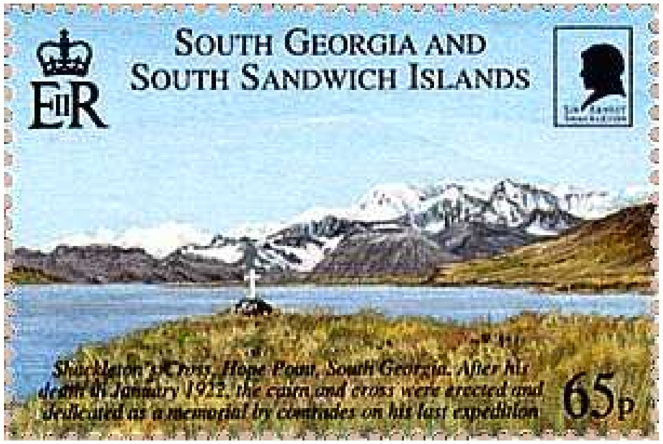


- *On some of the best records, (e.g., HOPE, South Georgia), the tsunami is actually visible* ***on the raw seismogram!!***

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

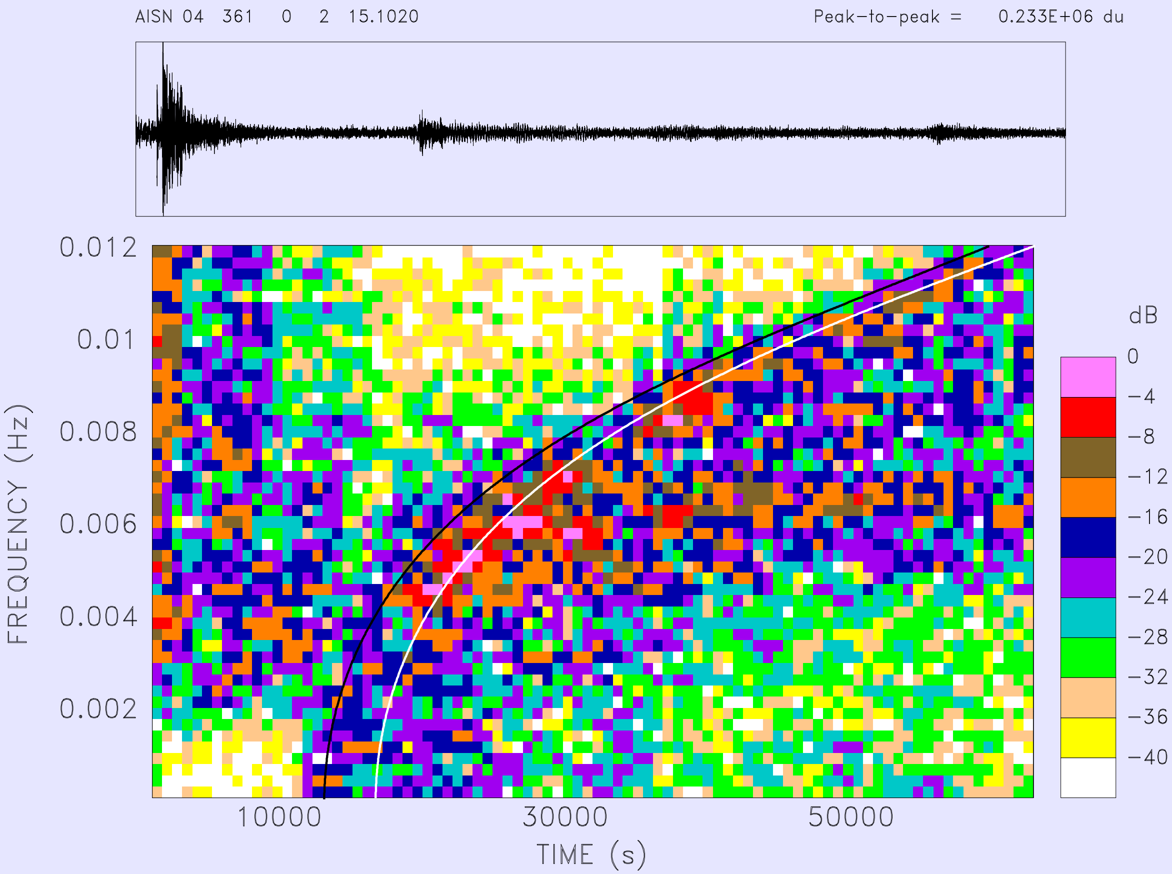


Sir Ernest H Shackleton CVO OBE FRGS



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

Ile Amsterdam, 26 Dec. 2004



NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS

CAN WE QUANTIFY SUCH RECORDS ?

CAN WE QUANTIFY SUCH RECORDS ?

1. *USE NORMAL MODE THEORY*

2. *MAKE SOME RATHER DRASTIC ASSUMPTIONS*

CAN WE QUANTIFY SUCH RECORDS ?

2. MAKE SOME RATHER DRASTIC ASSUMPTIONS

FORGET THE ISLAND *(or continent)* **!!**

QUANTIFYING the SEISMIC RECORD at CASY

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

FORGET THE ISLAND (or continent) !

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

Published: 1.15×10^{30} dyn*cm [*Stein and Okal*, 2005; *Tsai et al.*, 2005]

Acceptable, given the extreme nature of the approximations.

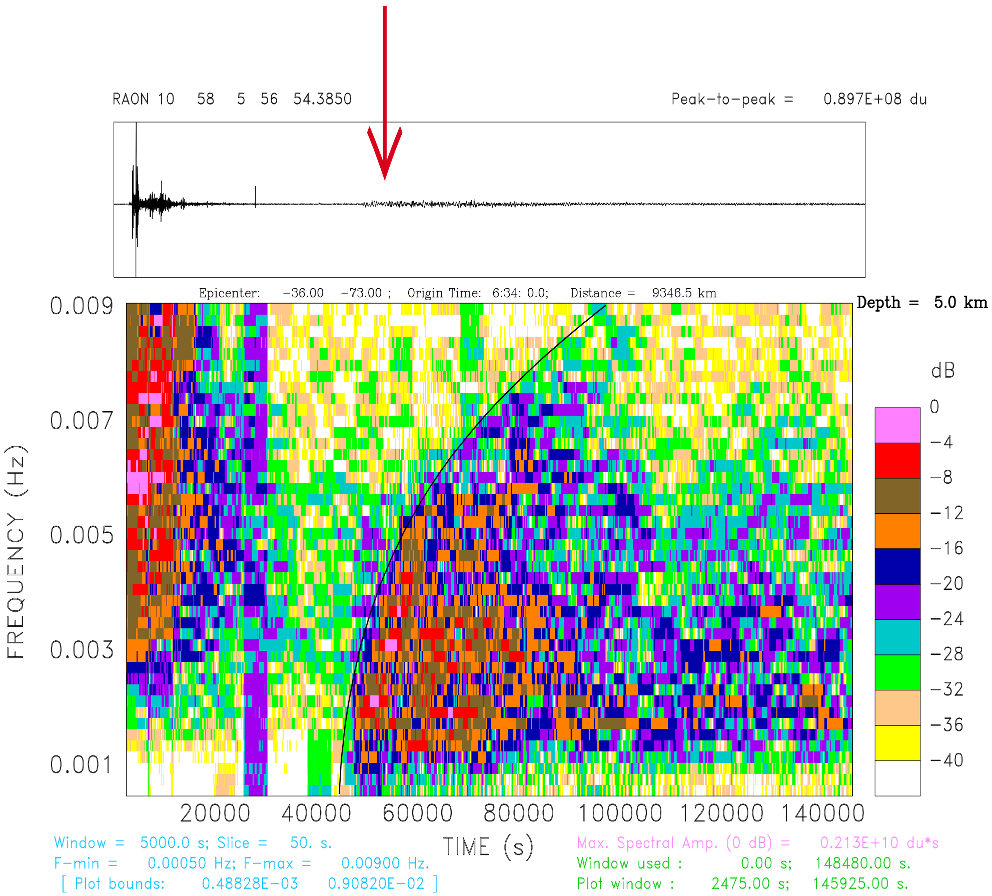
→ Suggests that the signal is just the expression of the horizontal deformation of the ocean floor, and that

CASY functions in a sense like an OBS !!

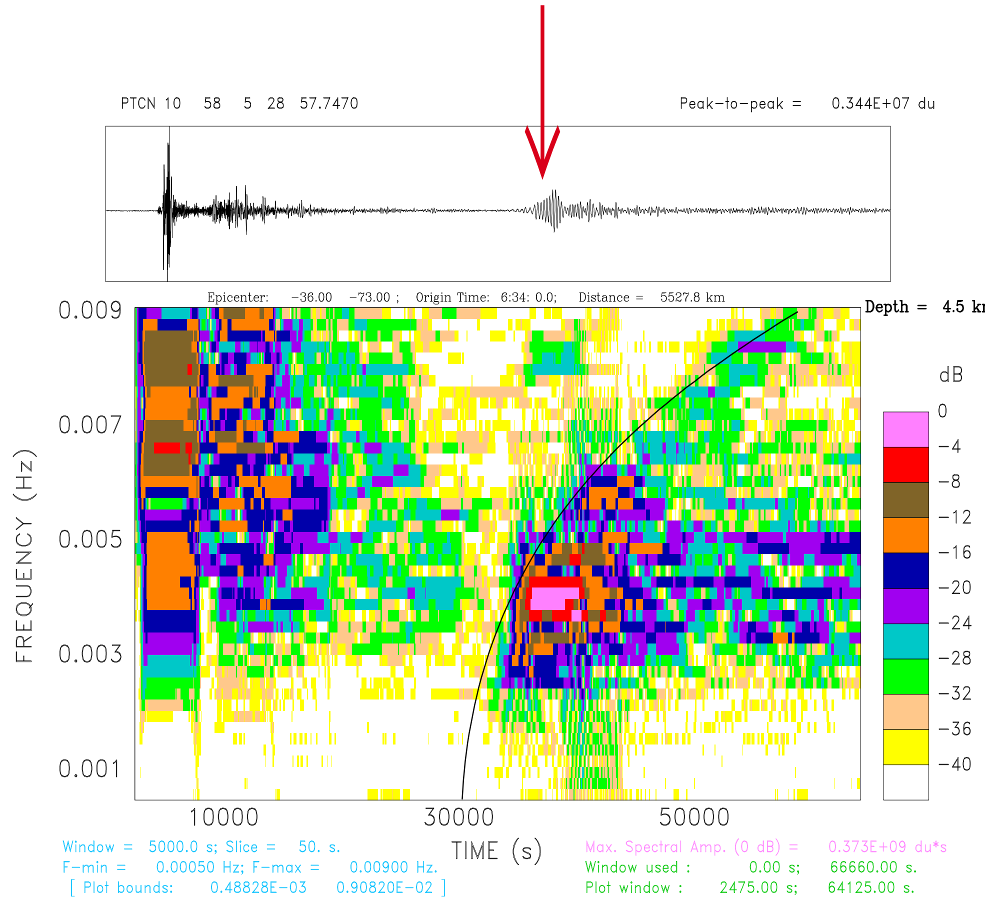
MAULE, CHILE, 27-FEB-2010

The spectacular records at Raoul Island and Pitcairn Island are clearly visible in the raw seismograms, without any processing.

RAO *Raoul Island, Kermadec Islands*



PTCN *Pitcairn Island, B.C.C.*

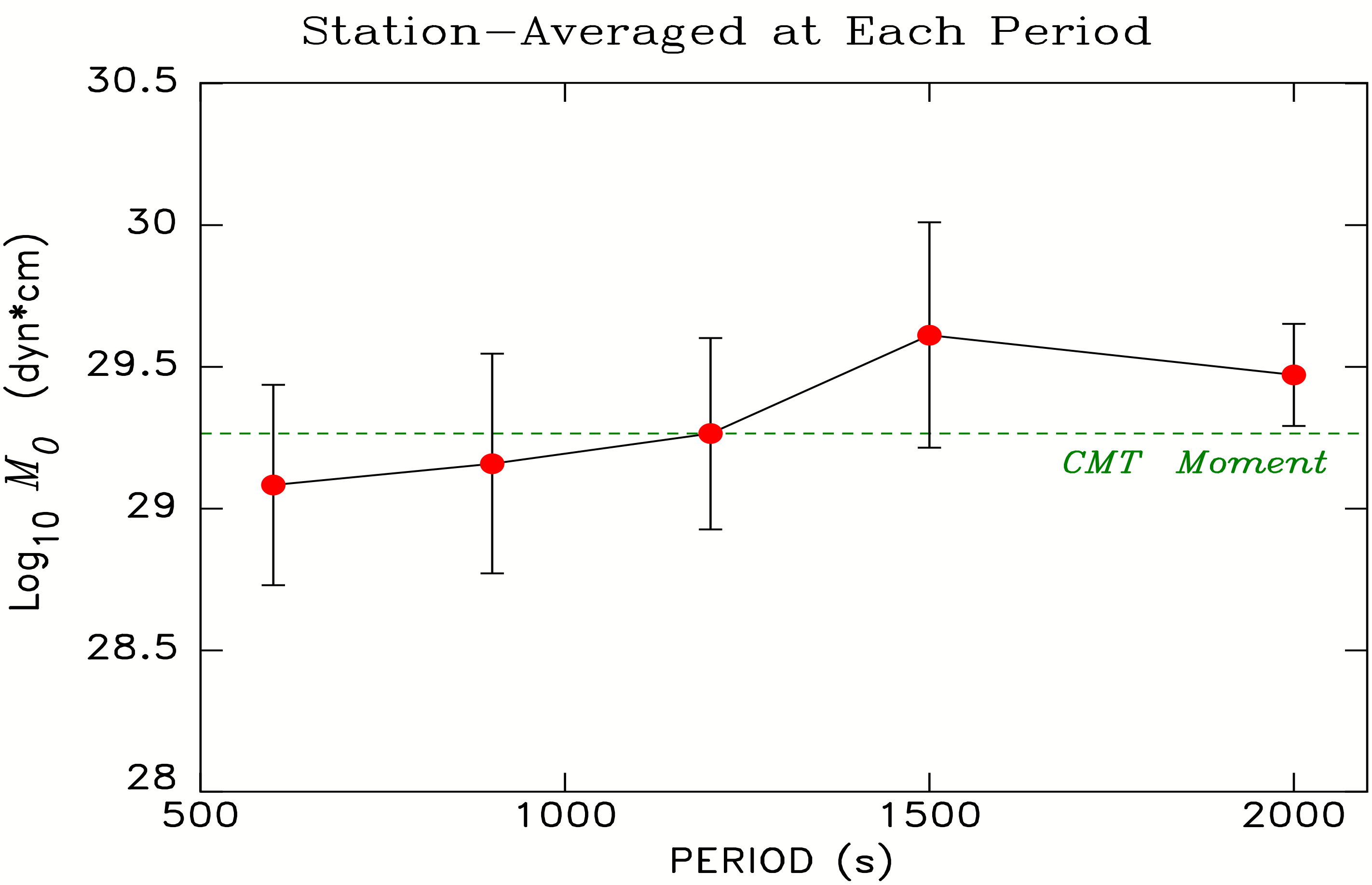


In this case, note the prominent high frequencies, which probably express a non-linear response of the structure of that small island (4.6 km^2).

MAULE, Chile, 2010

8 Seismic Stations — 12 Components

→ *In the 500−2000 s period range, the results are generally in agreement with the CMT scalar moment.*



This supports the finding [*Okal et al.*, 2010] *that the Maule earthquake is* **not a slow event**.

→ At higher frequencies (not shown), the results would depend on the response of the individual island structure.

FROM GROUND UP ...

or

Tsunamis Reaching the Ionosphere

→ *Because the atmosphere is not a vacuum, a tsunami eigenfunction is CONTINUED UPWARDS in the atmosphere...*, an idea originally proposed by *Hines* [1972].

> But a tsunami must displace the atmosphere as it propagates and the displaced atmosphere must respond by generating a gravity wave. The parameters are such that these waves will be of the internal type, and so will grow exponentially with height. A rise of a few metres at the surface of the water might well amplify to a few km at ionospheric heights, and that sort of amplitude could hardly escape detection if it were sought. We arrive, then, at this speculative question: If we wish to keep track of the progress of a tsunami, and so predict with some assurance the onslaught of its destructive force, might we not serve our interests best by keeping watch on the ionosphere?

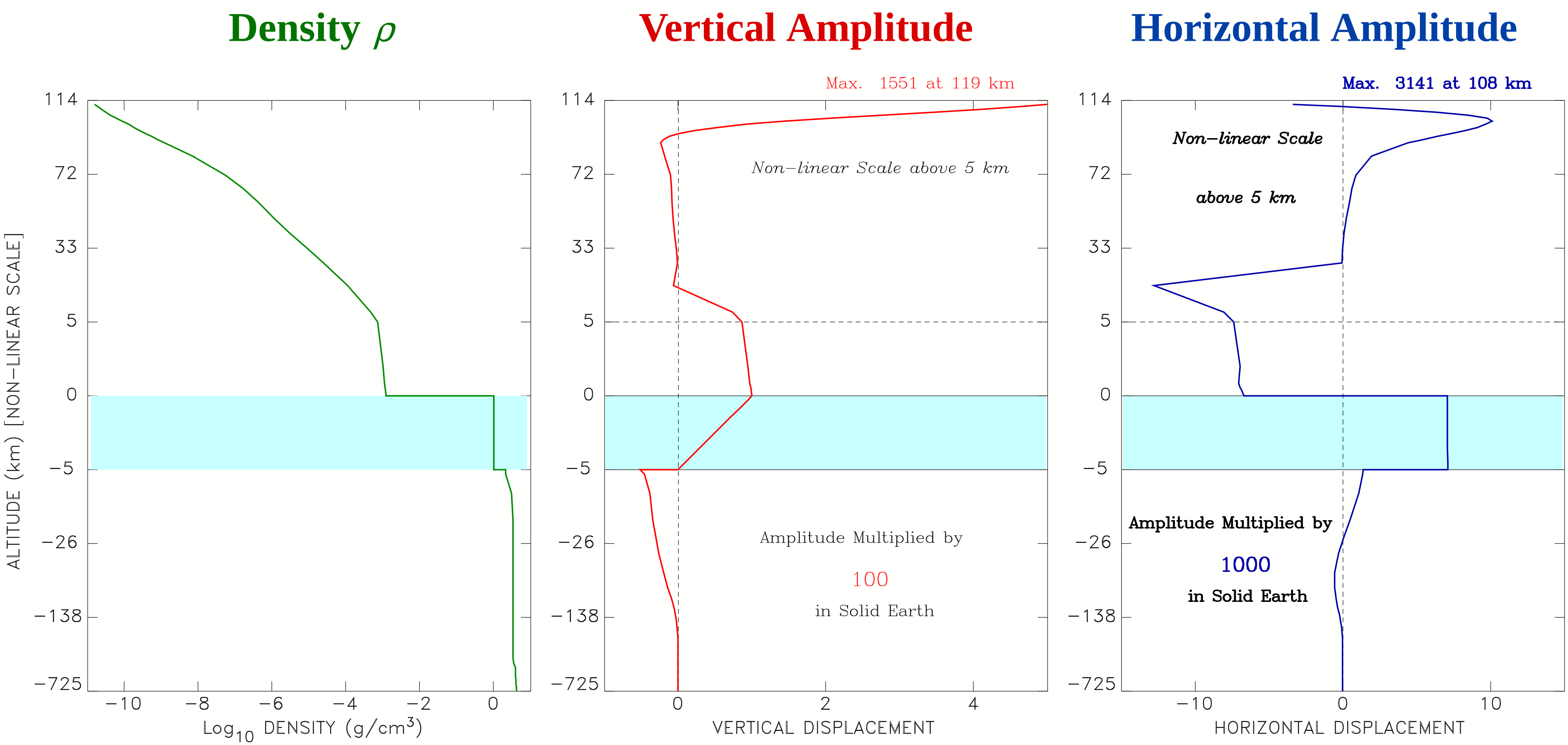
Peltier and Hines [1976] elaborated on the subject, but

IT TOOK CLOSE TO 30 YEARS TO OBSERVE...

STRUCTURE of the TSUNAMI WAVE in the ATMOSPHERE

→ We compute the continuation of the tsunami wave both in the solid Earth and in the atmosphere using the generalized code "***HASH***" by *Harkrider et al.* [1974].

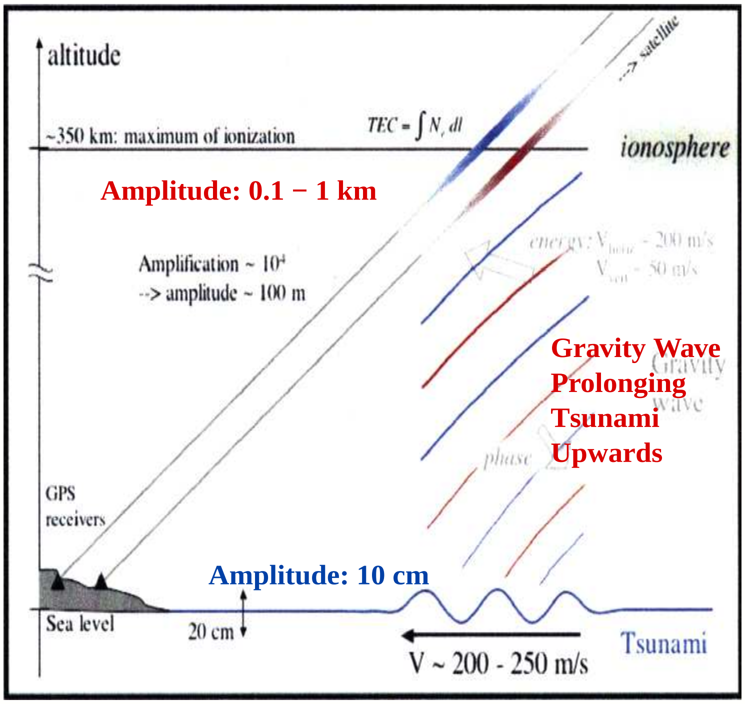
- Flat-layered model
- 5−km deep ocean
- Period ≈ 1000 seconds



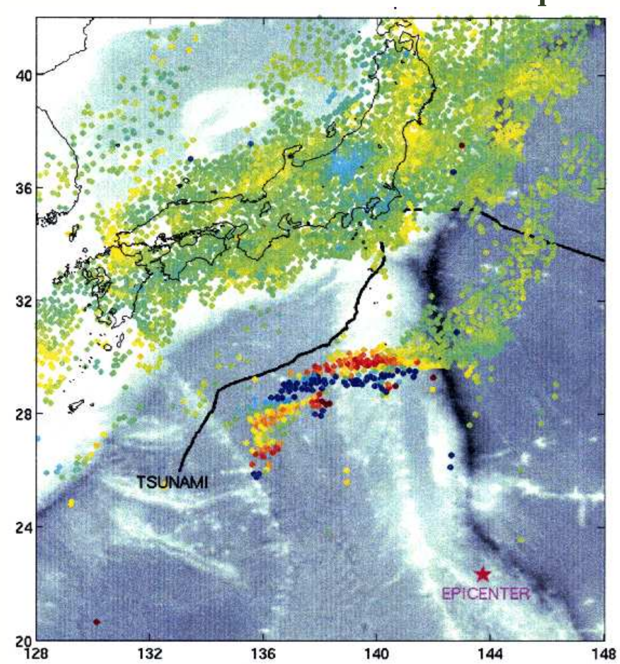
TSUNAMI DETECTION by GPS IONOSPHERIC MONITORING

J. Artru, H. Kanamori (Caltech); M. Murakami (Tsukuba); P. Lognonné, V. Dučić (IPG Paris) -- (2002)

- Ocean surface is not free boundary — Atmosphere has finite density
- Tsunami wave *prolonged* into atmosphere; *amplitude increases* with height.
- Perturbation in ionosphere (h = 150−350 km) detectable by GPS.



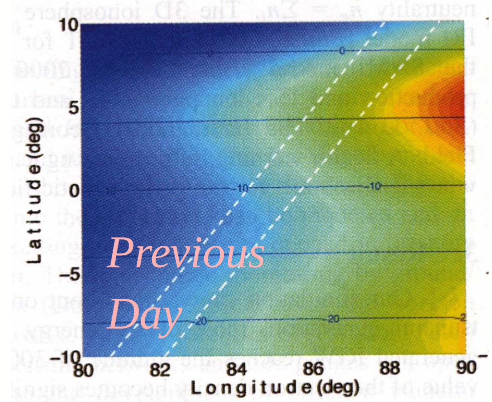
28 MAR 2000 -- 90 mn after earthquake

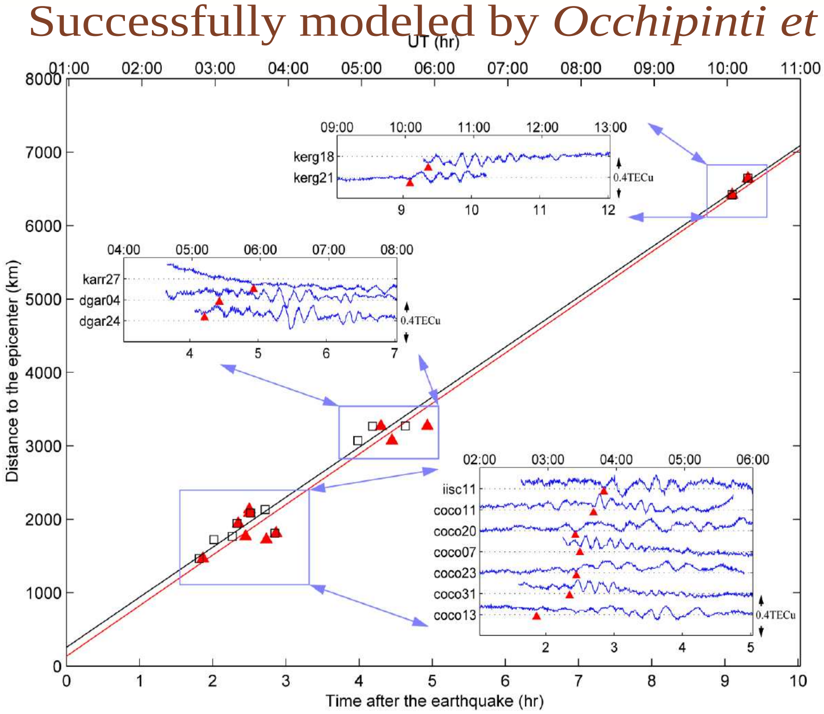


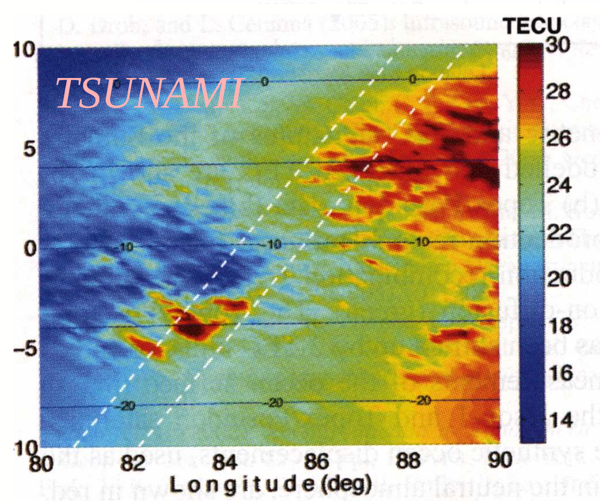
SUMATRA 2004

Perturbations detected in ionospheric
Total **E**lectron **C**ontent [*Liu et al.*, 2006]

Successfully modeled by *Occhipinti et al.* [2006].







Upon passage of the tsunami, the ionosphere may **glow in the visible...**

A map of this phenomenon was obtained by photography during night-time hours at Mauna Kea Observatory, Hawaii as the 2011 Tohoku tsunami was propagating across the Pacific Ocean [*Makela et al.*, 2011; *Rakoto et al.*, 2017].

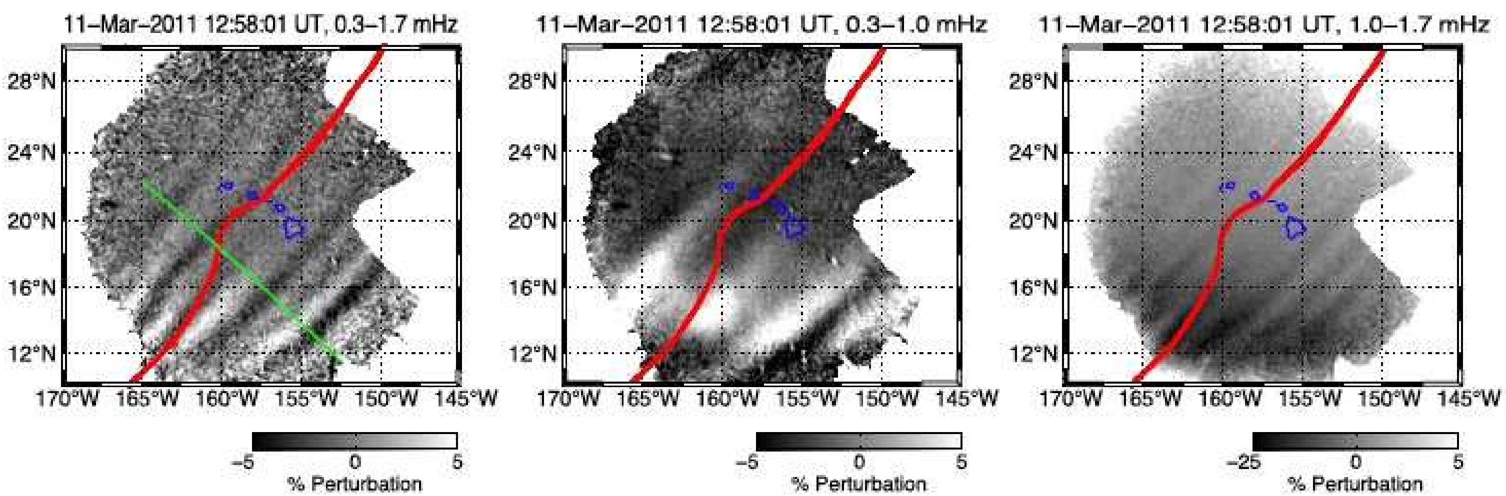


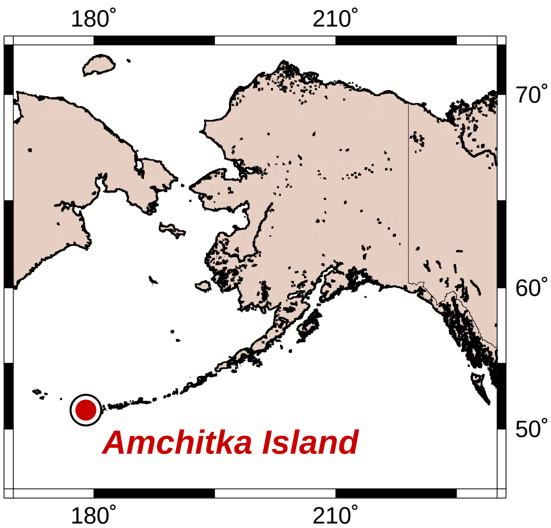
Figure 1. Example of 630.0-nm images processed using length-8 FIR filters with passbands of (left) 0.3–1.7 mHz, (middle) 0.3–1.0 mHz to highlight the 26.2-min period waves, and (right) 1.0–1.7 mHz to highlight the 14.2-min period waves. The red line in each image indicates the tsunami location at the time of the image. The green line in Figure 1 (left) indicates the line from which intensities were taken to construct Figure 2.

Detection of such visible perturbations may in the future be incorporated in tsunami warning procedures.

FROM GROUND TO WATER

Tsunami from Big Bomb !

Operation "MILROW"



Amchitka Island

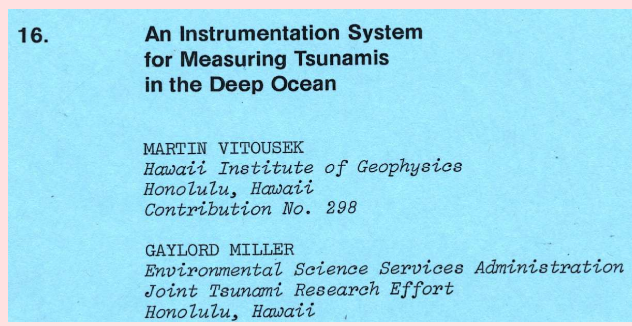
02 OCT 1969

1 Megaton

VISIONARY RESEARCH PROGRAMS (1969)

- Attempt to **Detect Tsunami on the High Seas**

A **" Concept−DART "?**



16. **An Instrumentation System for Measuring Tsunamis in the Deep Ocean**

MARTIN VITOUSEK
Hawaii Institute of Geophysics
Honolulu, Hawaii
Contribution No. 298

GAYLORD MILLER
Environmental Science Services Administration
Joint Tsunami Research Effort
Honolulu, Hawaii

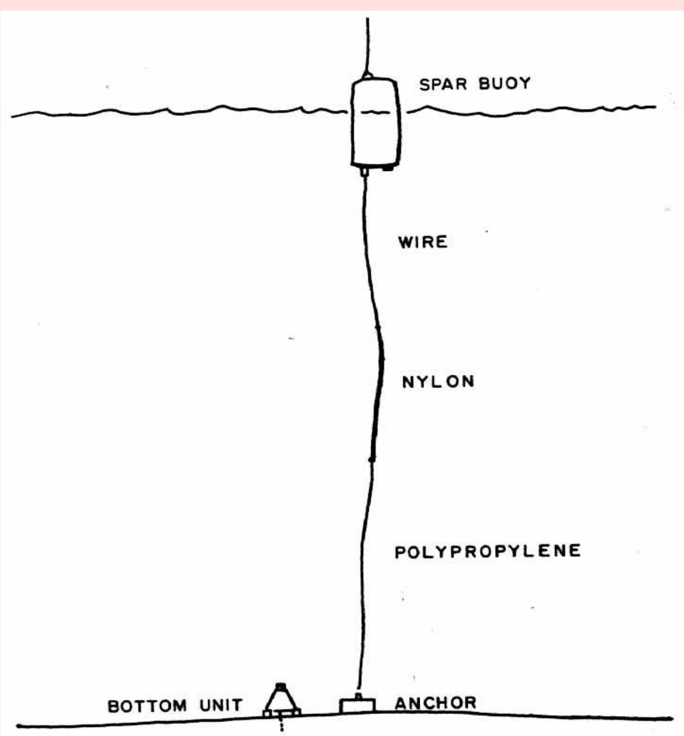


Fig. 5: Buoy system.

Tsunami Signal from the Milrow Nuclear Test (1 Megaton; 02 OCT 1969) !

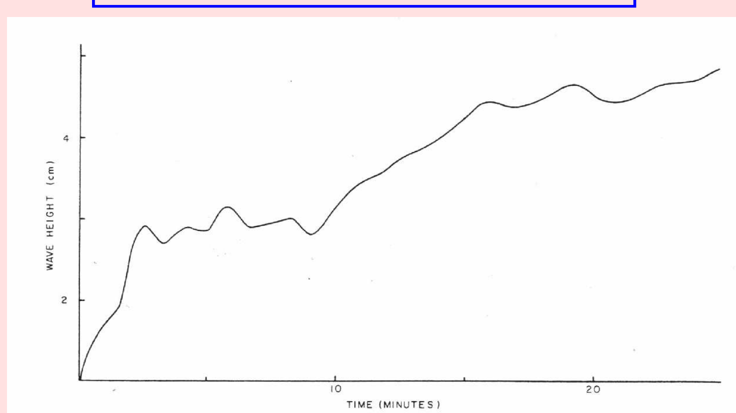
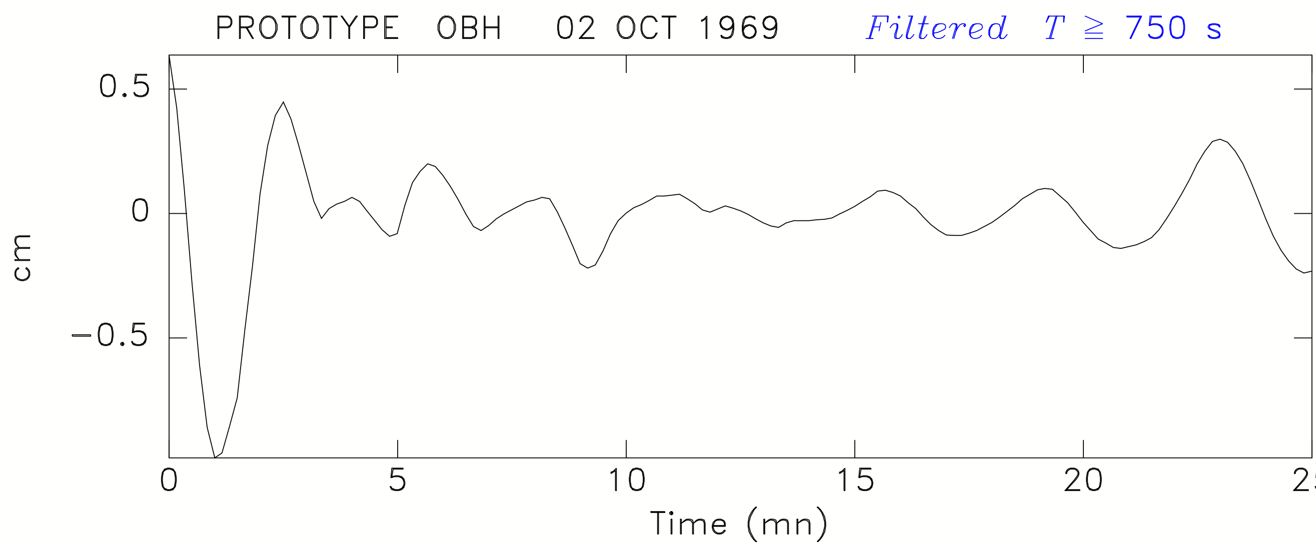


Fig. 8: Waves generated by Amchitka tests.

Tsunami Signal from the Milrow Nuclear Test (1 Megaton; 02 OCT 1969)!

CAN IT BE QUANTIFIED ?

- Once filtered this signal suggests a peak-to-peak amplitude of 1.2 cm



- Use the [outrageously simplistic] model of an explosive source 1.2 km below an ocean of depth 1800 m [as per *Vitousek and Miller*, 1970];

- Use normal mode formalism [*Ward*, 1980] to compute a synthetic maregram at distance of 0.5°; infer an isotropic moment for Milrow: $M_0 \approx 5 \times 10^{24}$ dyn*cm;

- Use *Haskell* [1967] to derive a static *reduced displacement potential*

$$\psi(\infty) = \frac{M_0}{4\pi \rho \alpha^2} = 400,000 \text{ m}^3$$

which in turn scales to a yield

$$\mathbf{W = 800 \text{ kt}}$$

which is only 20% smaller than the estimated yield of 1 Mt.

Given the approximations used, the agreement of the order of magnitude is

nothing short of staggering!

TSUNAMI

by

NEXT-DAY AIR ?

TSUNAMI GENERATION by *Volcanic Explosions at Sea*

Krakatau [Sunda Straits], 27 August 1883

ANAK KRAKATAU, Sept. 2016

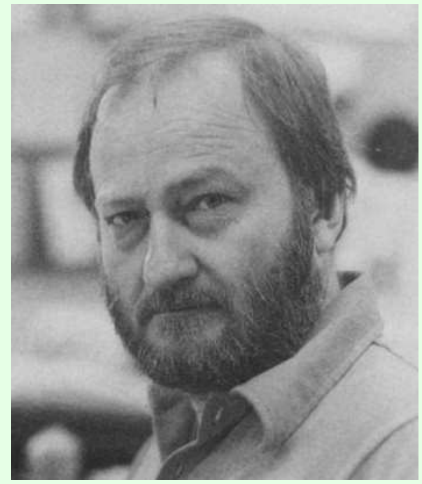
Born 1927... and Still Growing !

← 12 km →

A catastrophic tsunami killed 35,000 people in Batavia (Jakarta). *Nomambhoy and Satake* [1995] showed that it can be well modeled by an underwater explosion.

The tsunami was reported recorded world-wide (on tidal gauges), which would seem to contradict the dispersive nature of the short wavelengths associated with sources of small dimensions...

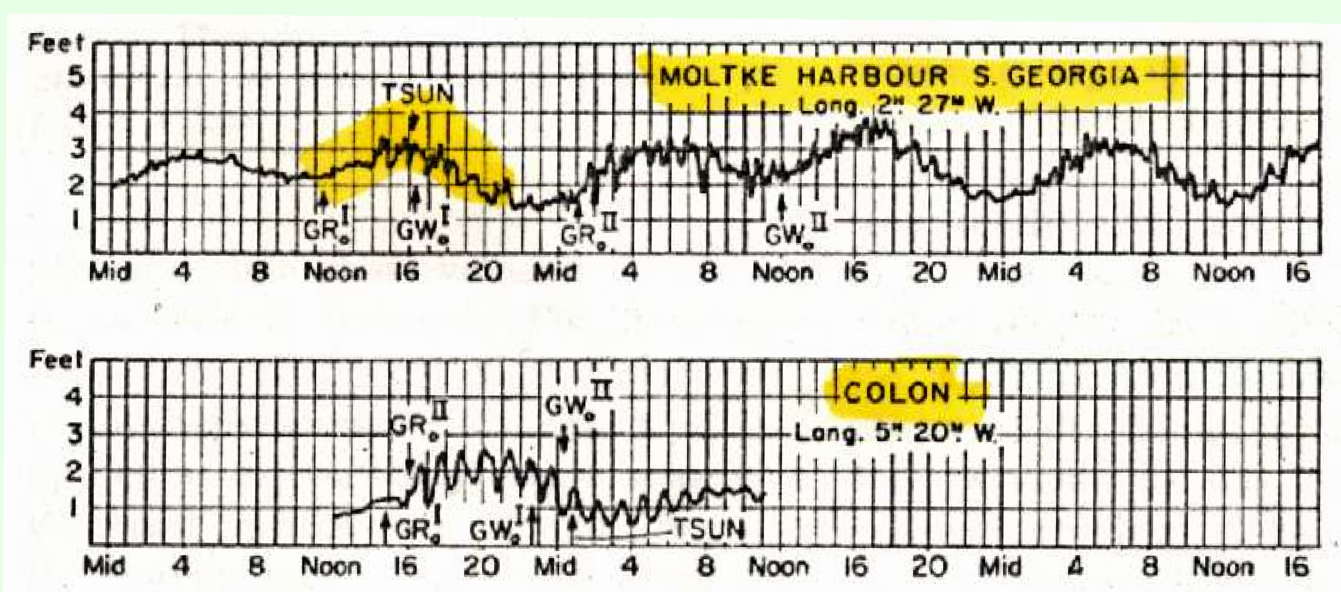
HOWEVER ...



Press and Harkrider [1962, 1964] had shown that the tsunami is actually triggered by an **air wave** generated by an atmospheric explosion, and re-exciting the ocean as it propagates.

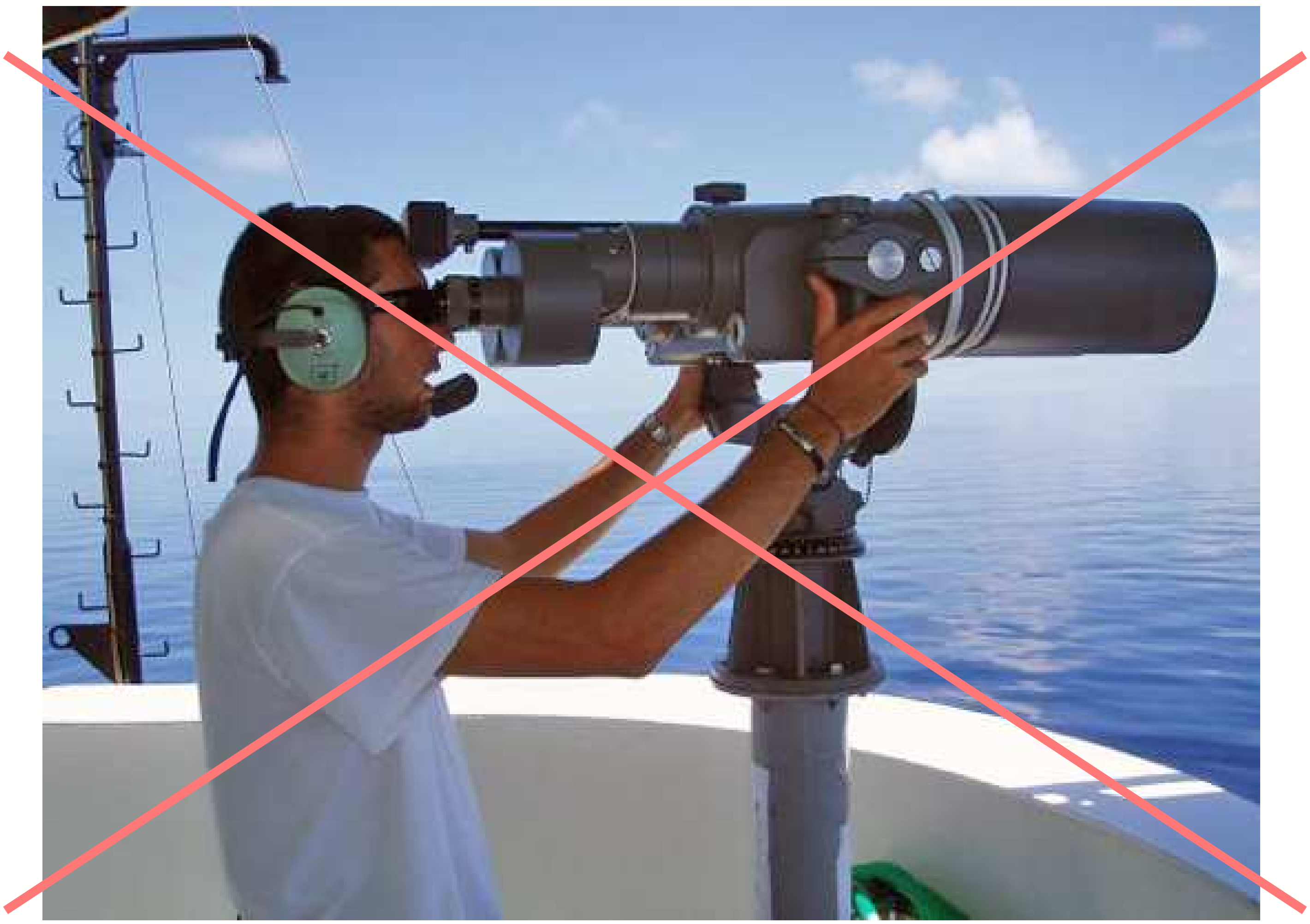
This explains

- the propagation of the *"tsunami"* along great circle paths occasionally crossing... a continent!
- the occasional early arrival of the tsunami at distant tidal stations **(350 m/s** as opposed to **200 m/s).**
- and allows an estimate of the power of the explosion (100 to 150 Mt).



DIRECT "VISUAL" DETECTION of TSUNAMI on HIGH SEAS ??

- *In principle, should be impossible*



(Amplitudes too small; wavelengths too large)

YET **· · ·   ?**

TSUNAMI SHADOWS — *Can we "SEE" Tsunamis, after all ?*

There exist a number of somewhat anecdotal reports of tsunamis accompanied by a *"shadow"* on the ocean surface.

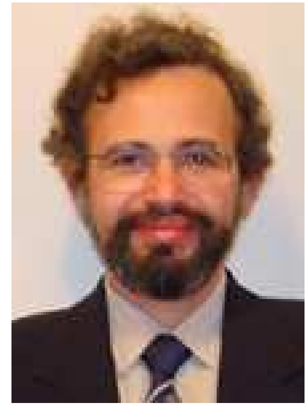
- *Walker* [1996] has published a shot from a video lending support to this idea.

11

Figure 1. The tsunami "shadow" can be seen just below the horizon and extends across the entire field of view of the camera. Approximately 12 minutes has to be added to the time indicated based on simultaneously recorded audio of a local radio station. The video was taken at an elevation of about 50 meters above sea-level.

Godin [2003] explains this phenomenon theoretically as follows:

- Tsunami wave creates steep *gradient* in sea surface.
- This gradient affects boundary condition of lower atmosphere **wind** near surface, making it ***turbulent***.
- In turn, this turbulence creates *roughness* in Sea Surface, perceived as *Tsunami Shadow*.



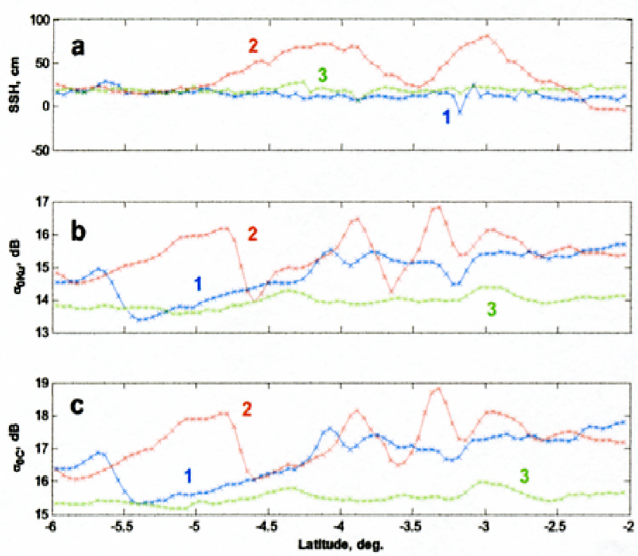


Fig. 3. Jason-1 data for pass 129 from 6° S to 2° S obtained days before (Cycle 108) (1), coincident with (Cycle 109) (2), and 10 days after (Cycle 110) (3) the Sumatra-Andaman tsunami.**(a)** Sea surface height. **(b)** Ku-band radar backscattering strength. **(c)** C-band radar backscattering strength.

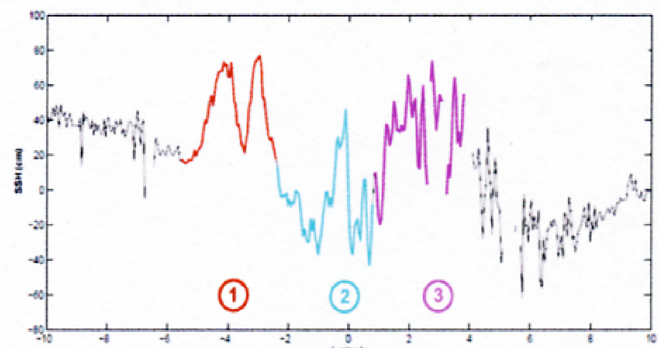


Fig. 4. Sea surface height data from Jason-1 ascending path 129 for cycle 109. Data segments 1, 2, and 3 chosen for detailed analysis of tsunami manifestations are shown in color. Breaks in the graph reflect gaps in the available SSH data.

At present, there is no universally accepted model of air flow over fast, as compared to the background wind, sea waves. Under assumptions made in (Godin, 2005), in the presence of a monochromatic tsunami wave, the wind speed relative to the ocean surface retains a logarithmic profile up

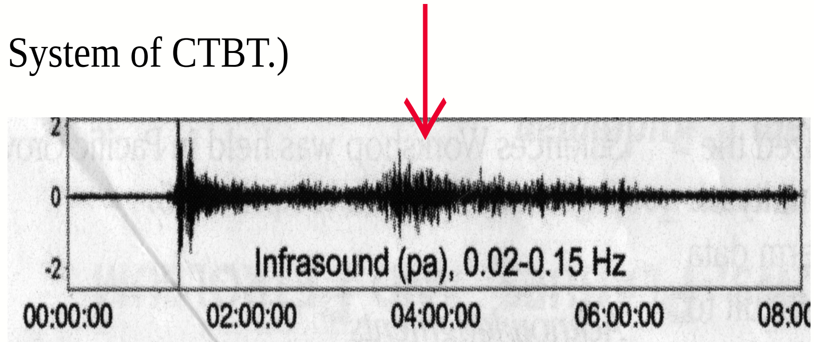
Godin et al. [2009] detect roughness in JASON altimeter records of 2004 Sumatra tsunami.

LOUD TSUNAMI ??

TSUNAMI DETECTED by INFRA SOUND ARRAYS (CTBT)

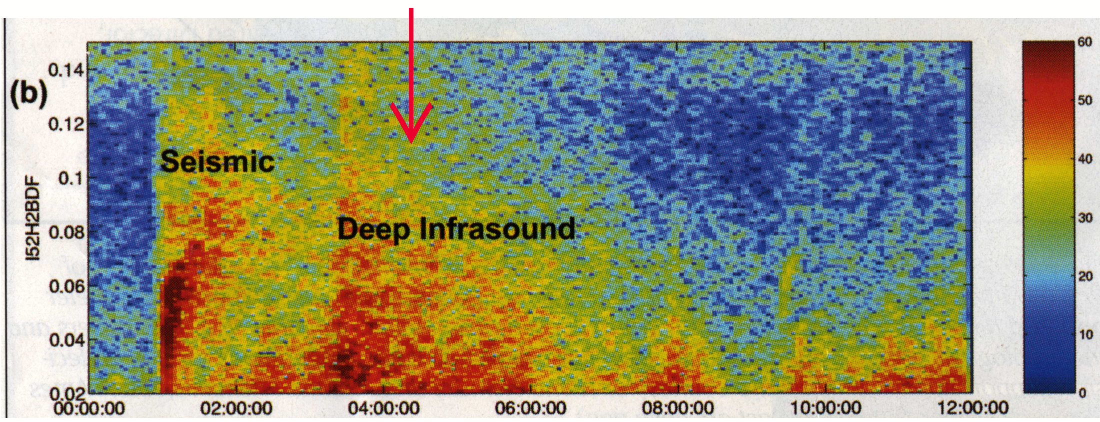
Arrays of barographs monitoring pressure disturbances carried by atmosphere.

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



Diego Garcia, BIOT, 26 Dec. 2004

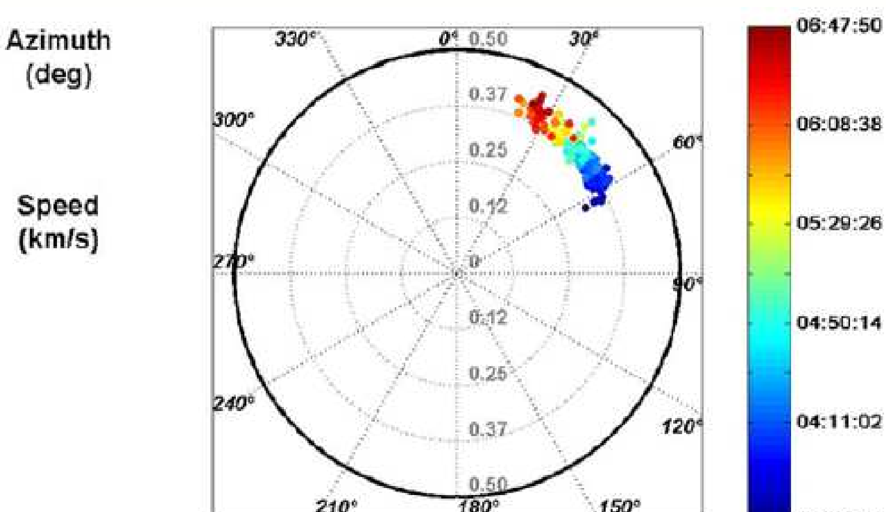
[*Le Pichon et al.*, 2005]



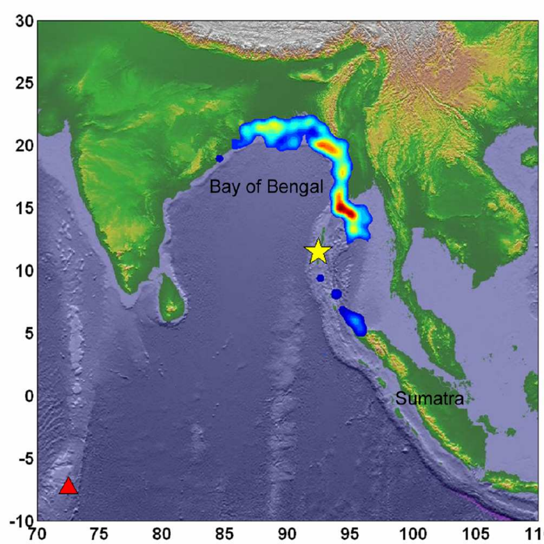
Detects signal in DEEP INFRASOUND about 3 hours after source time

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 INFRASOUND SOURCE: A PARADOX ?

- Infrasound waves come *from Burma, where tsunami was relatively benign (2.9 m run-up; 100−400 deaths (?))*
- rather than *from Thailand (16 m run-up; ~10,000 deaths)*

WHY ?

TSUNAMI INFRASOUND SOURCE: A PARADOX ?

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- rather than *from Thailand (16 m run-up; ~10,000 deaths)*

WHY ?

→ *Remember how waves BREAK at the beach*

... and then do not propagate very far inland

BUT MAKE LOTS OF NOISE IN THE PROCESS !

TSUNAMI INFRASOUND SOURCE: A PARADOX ?

- Infrasound waves come *from Burma, where tsunami was relatively benign (2.9 m run-up; 100−400 deaths (?))*
- rather than *from Thailand (16 m run-up; ~10,000 deaths)*

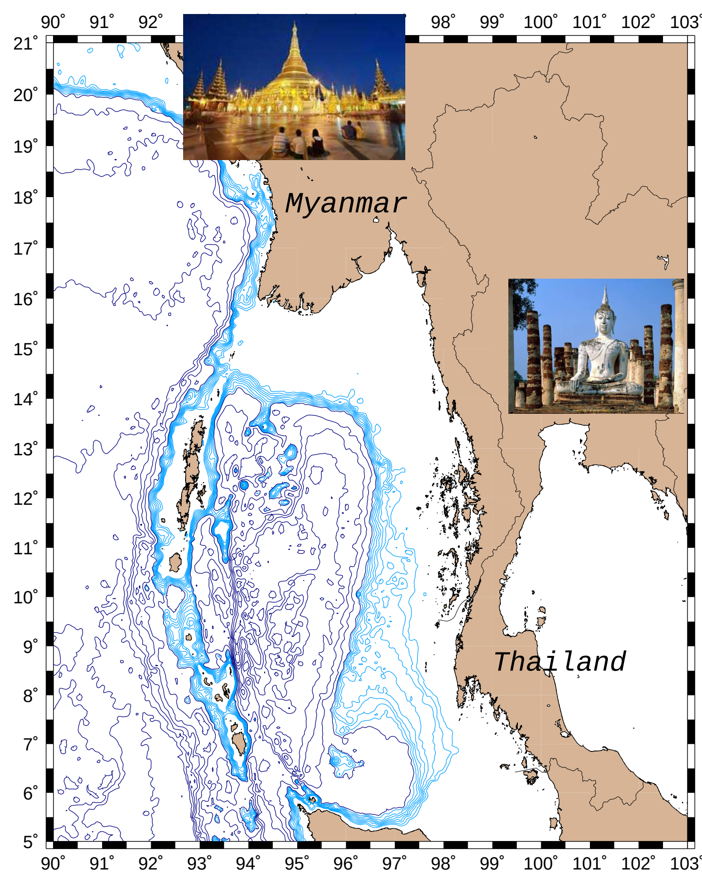
WHY ?

→ *Remember how waves BREAK at the beach*

... and then do not propagate very far inland

BUT MAKE LOTS OF NOISE IN THE PROCESS !

→ *2004 Sumatra tsunami may have* **BROKEN** *on the extensive continental shelf present off Myanmar, but largely absent from the Thai coast in the Andaman Sea.*



TSUNAMI DETECTED IN GEOMAGNETIC FIELD

A SENSIBLE IDEA...

- Tsunami moves water, a conducting fluid, inside the magnetic field of the Earth.
- Should create a current, which in turn, perturbs the Earth's magnetic field **B**.
- Indeed, tidal signals have been detected in daily fluctuations of **B** [*e.g., McKnight,* 1995].

→ *Tyler* [2005] showed that the perturbation b_z of the vertical component of **B** should be linked to the tsunami's amplitude η through

$$\frac{b_z}{\eta} = \frac{F_z\, c}{h\, c_s} \cdot e^{-\kappa z}$$

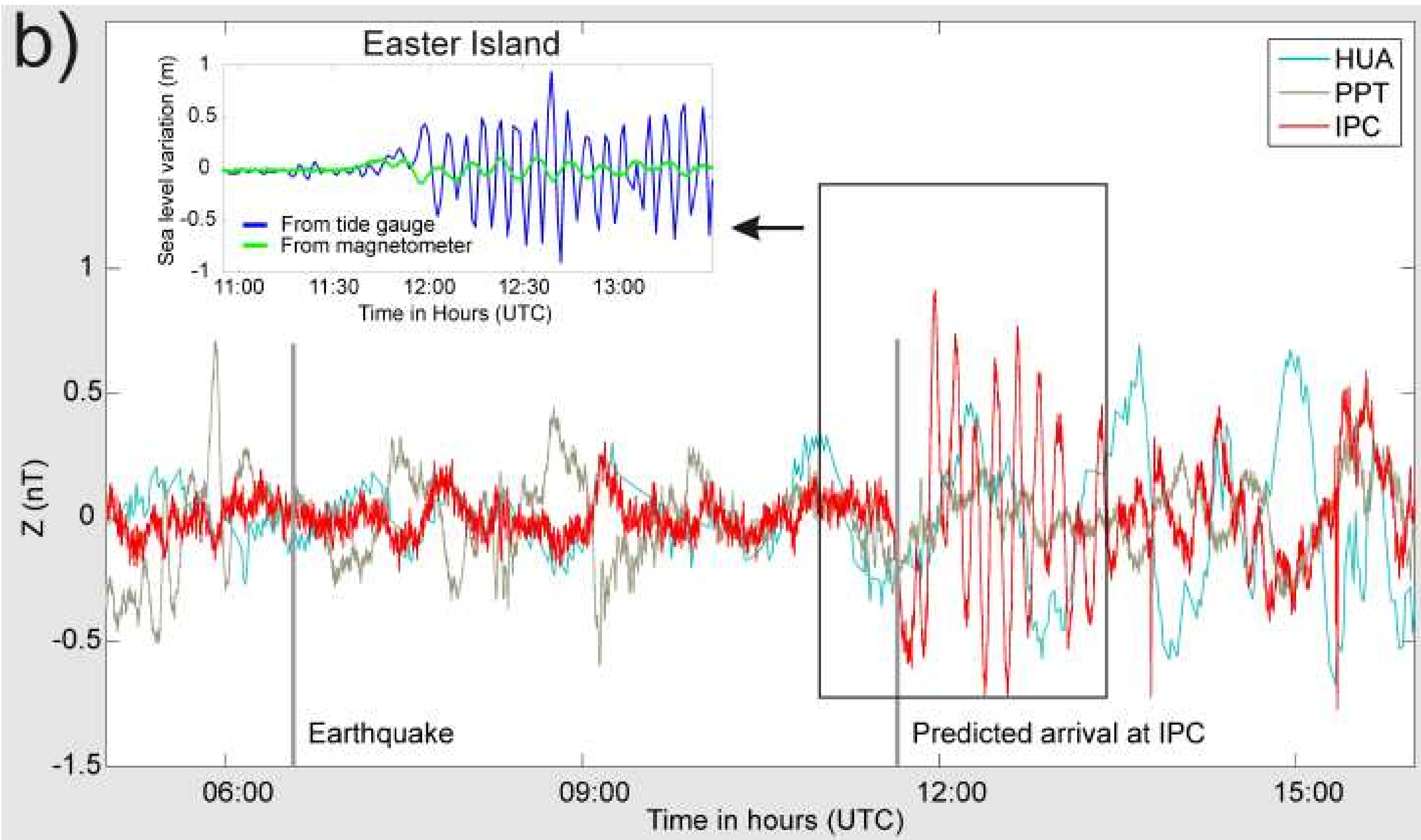
where F_z is the unperturbed vertical field, $c = \sqrt{g\,h}$ the tsunami's phase velocity, $c_s = c + i\, c_d$ with $c_d = 2\,K\,/\,h$ and K the magnetic diffusivity ($K = 1/\mu\sigma$).

- Unfortunately, in the case of the 2004 Sumatra tsunami, the areas with maximum η are at the magnetic Equator, and no signal was detected...

→ Otherwise, one would expect about **10 to 20 nT per meter** of vertical sea surface displacement...

DETECTION DURING THE 2010 CHILEAN TSUNAMI

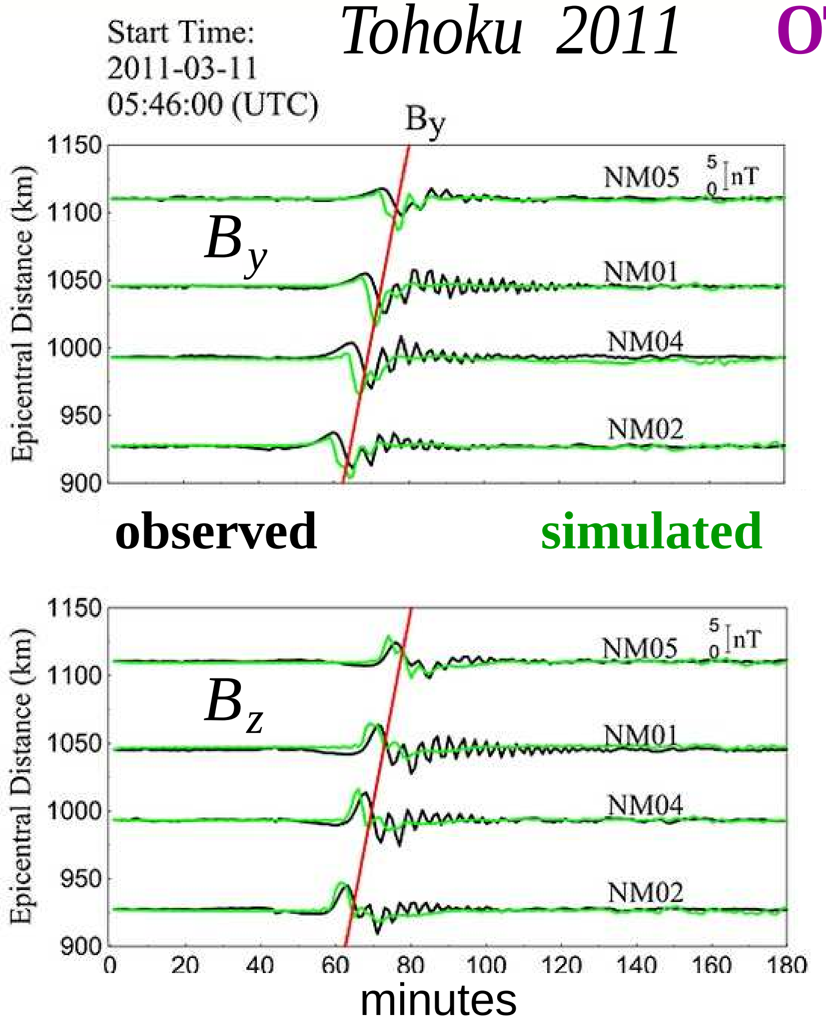
- *Manoj et al.* [2011] detected this effect during the 2010 Chilean tsunami using the geomagnetic station at Easter Island (IPC -- below, **red**)

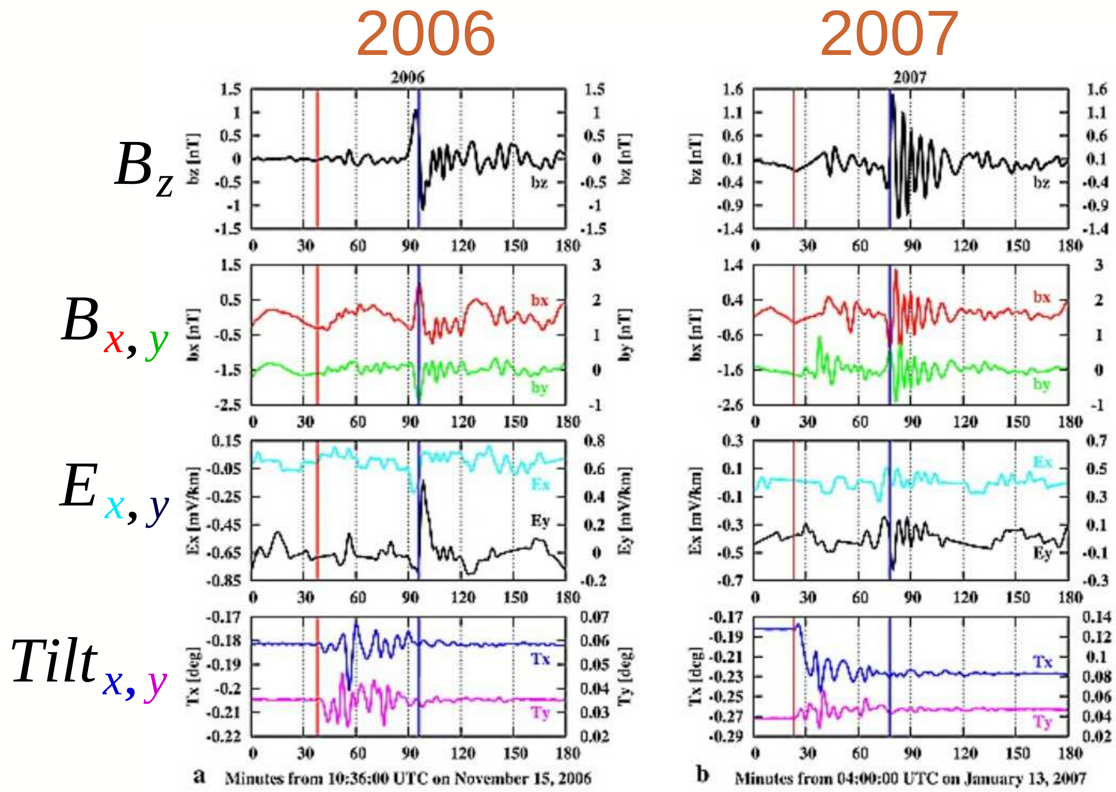


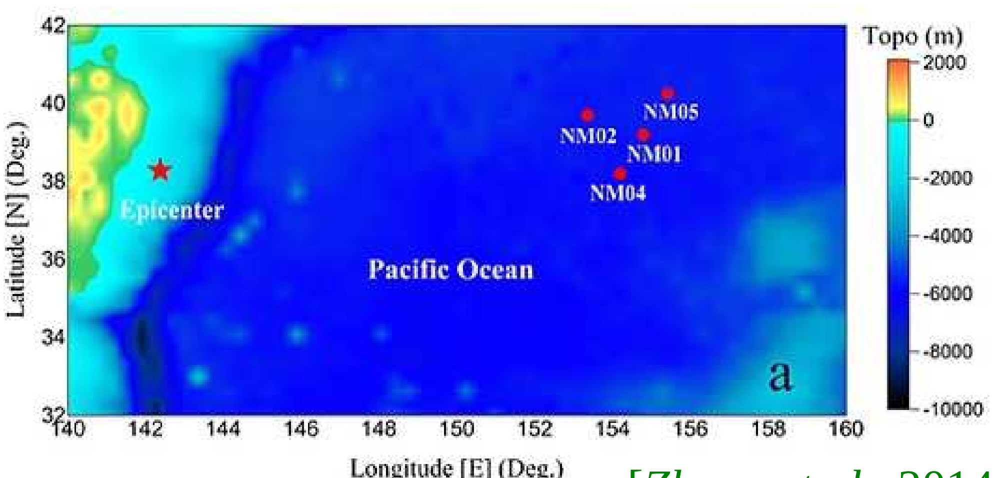
→ *The amplitude detected, ≈ 1 nT, is in good agreement with that of the tsunami on the high seas (15 to 20 cm),* **as recorded on DART buoys.**

- They should **NOT** be comparing to a tide gauge record, which is strongly affected by harbor response.

Tohoku 2011 **OTHER EVENTS** *Kuril Is., 2006−2007*

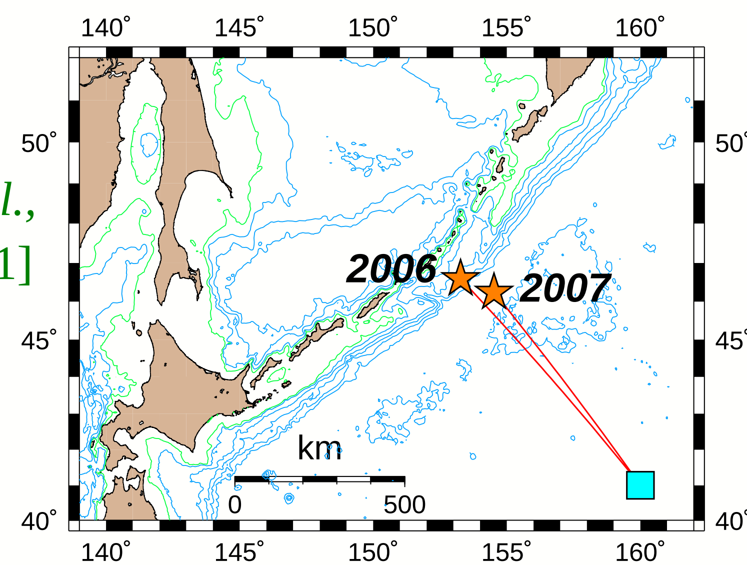






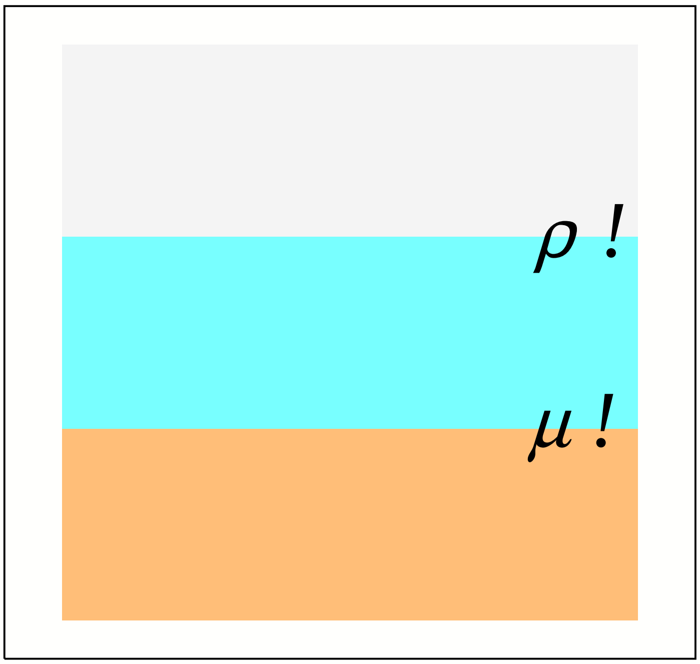
[*Zhang et al.*, 2014]

[*Toh et al.*, 2011]



CONCLUSION

- A tsunami is an oscillation of the ocean, a critical layer weakly, but unescapably, coupled to the other two components of the Earth system (the atmosphere and the solid Earth), through boundaries which are neither free ("only" 3 orders of magnitude in ρ at the surface, nor rigid (μ large but finite in the solid Earth).



Largest recorded sources

- *Krakatau, 1883* **(100−150 Mt)**
  Царь Бомба, 1961 **(57 Mt)**
- *WIGWAM, 1955* **(20 kt)**
- *Chile, 1960*
  (2×10^{30} dyn*cm)

→ The full understanding of many tsunami properties mandates the modeling of subtle coupling effects at these boundaries.

* The weak nature of these effects requires gigantic sources in the "other" media (Large earthquakes; Catastrophic explosions)

- *Incidentally, we have few examples of large tsunami sources directly exciting the oceanic column.*