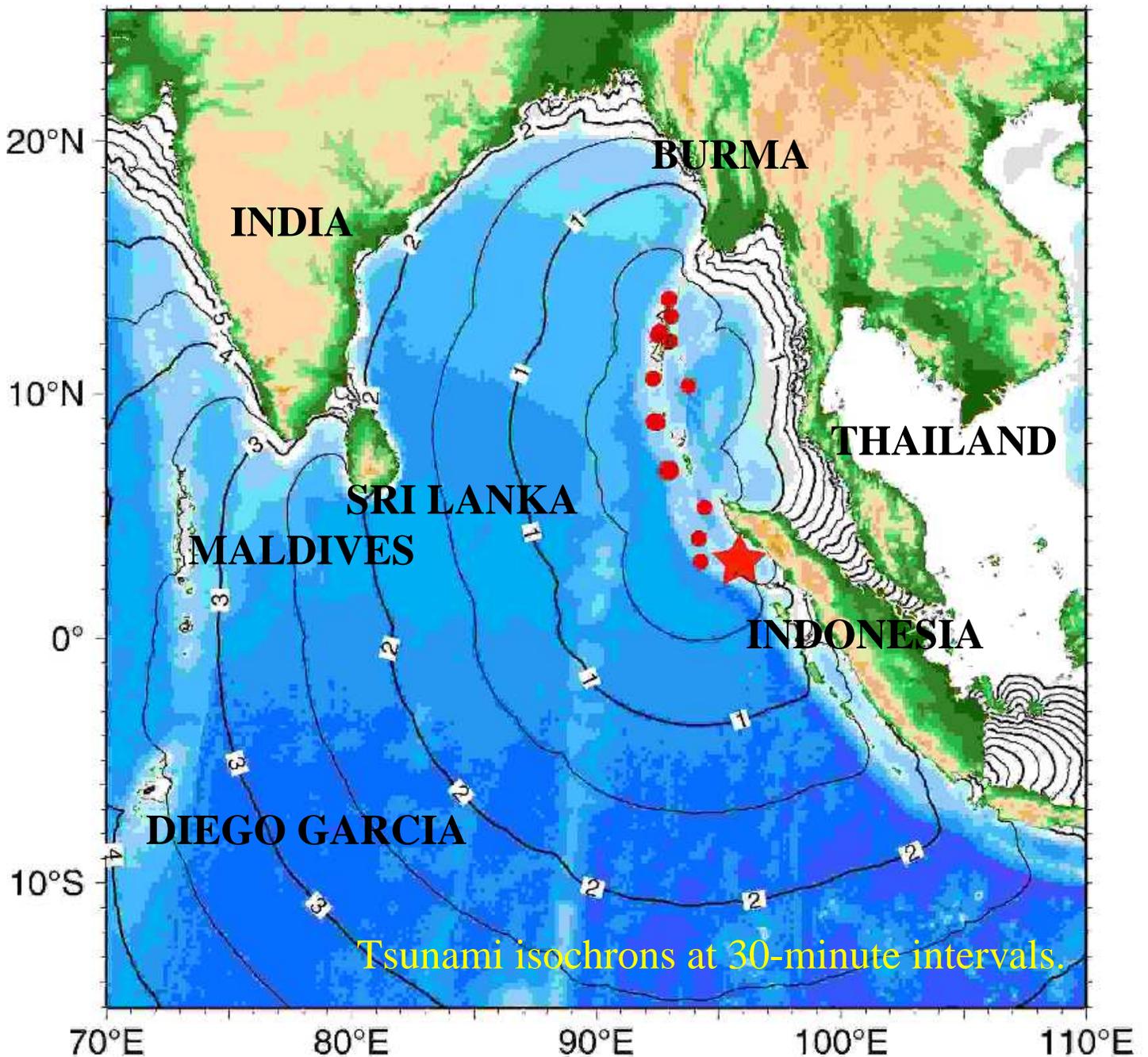


SUMATRA EARTHQUAKE AND TSUNAMI

26 DEC (361) 2004 -- 00:58:53 GMT -- 3.32°N; 95.85°E

$m_b = 7.1$; $M_s = 8.2$; $M_m = 9.3$; $M_w = 9.0$ (9.3 ?)

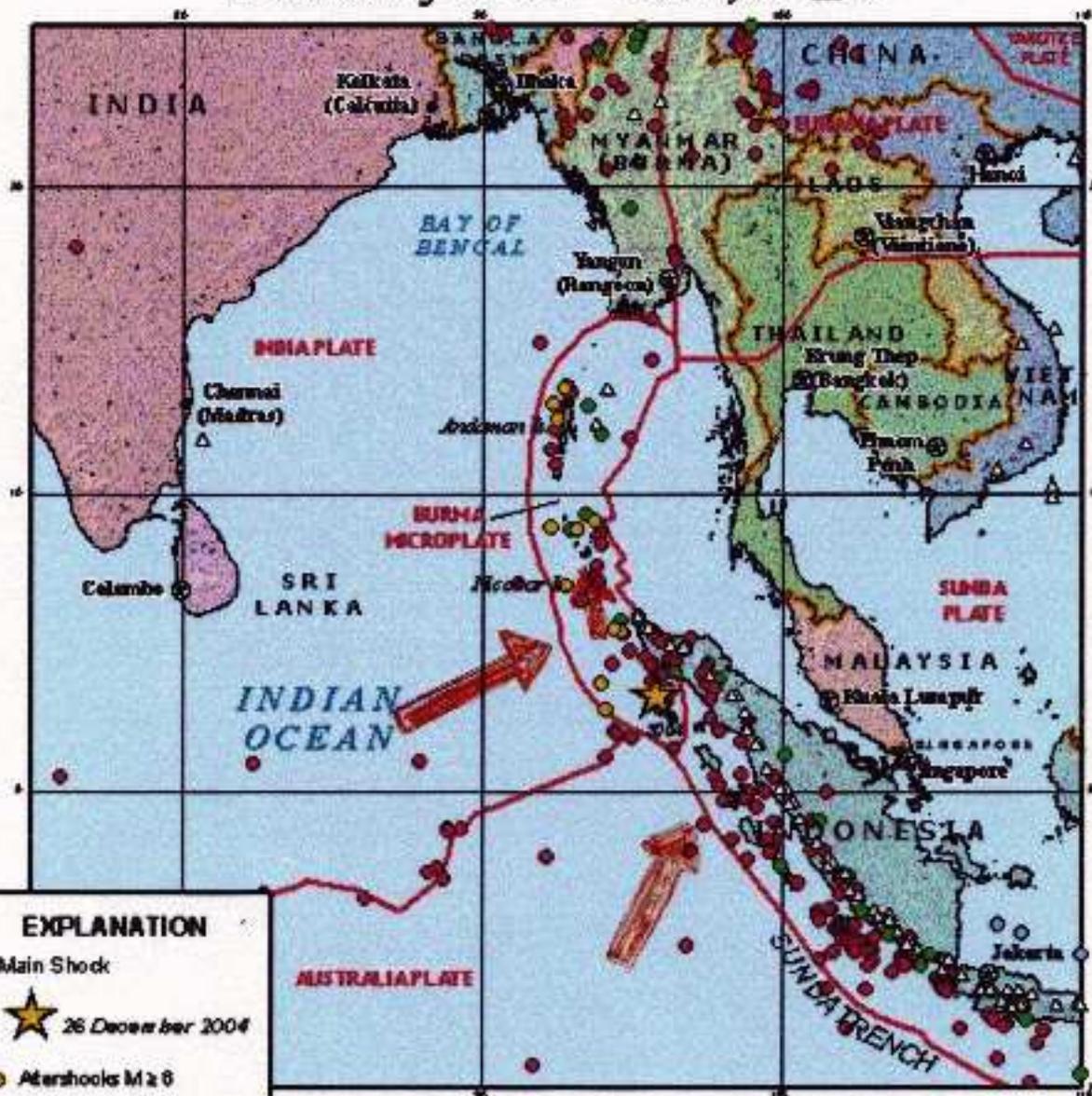


● Main aftershocks

Energy: 8×10^{25} erg = 200 million tons TNT
(est. 1% into tsunami)

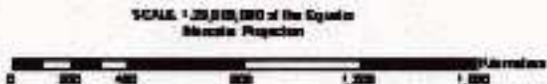
~ 2000 km³ of water displaced 5–10 m.

Northeast Indian Ocean Region Seismicity 1900 - 2002, $M \geq 6$



EXPLANATION

- Main Shock
 - ★ 26 December 2004
- Aftershocks $M \geq 6$
- Earthquakes $M \geq 6$
 - 0 - 60 km
 - 70 - 200
 - 300 - 600
- Plate Boundaries
- △ Volcanoes



[Handwritten signature]

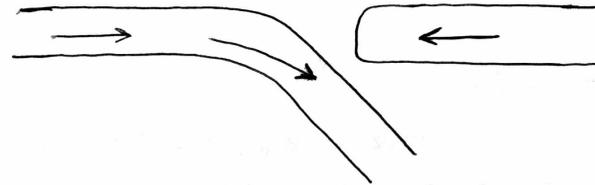
NORTHERN SUMATRA TECTONIC CONTEXT

- The Indian plate moves with respect to the Burma sliver at ~ 5 cm/yr.
 - The 2004 earthquake involved a slip of 15 to 20 meters.
 - This suggests a recurrence time of 300 to 400 years.
- This would contribute significantly to lowering the awareness of the population to tsunami hazard.

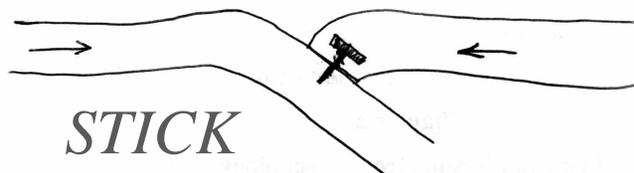
→ Tectonic plates move, at the surface of the Earth, at an average of a few cm/yr.

This motion can be

- *Aseismic* (without earthquakes), *i.e.*, a smooth gliding between decoupled plates **(i)**; or



- A *Stick-and-Slip* process in which the plates remain coupled for a long time, until stress builds up to a critical level, and the plates slip during an *earthquake*.



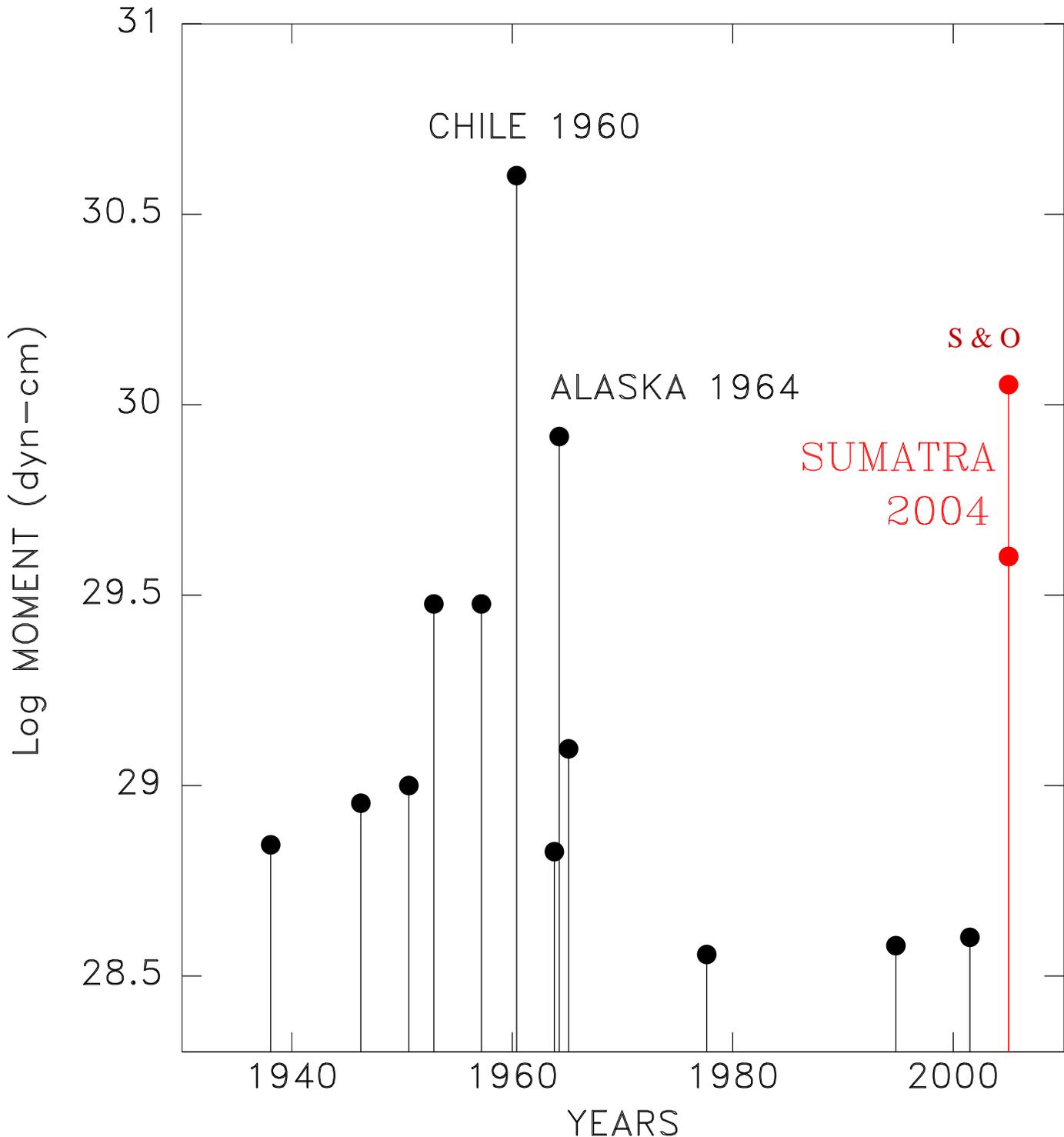
The characteristic time of this process depends in principle on the level of coupling and can vary widely.

- If it is short (100 years), the region experiences frequent, but moderate, earthquakes **(ii)**.
- If it is long, the region will experience very large, but also very rare, earthquakes **(iii)**.

In the absence of historical or geological records of large events, Northern Sumatra could have fit either of scenarios (i) or (iii).

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

[Stein and Okal, 2005]



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]
- *Flutwellen* [German]

Properly called

- *Maremoto* [Spanish, Italian]
- *Taitoko* [Marquesan]
- *Tsu Nami* (Harbor wave) [Japanese]

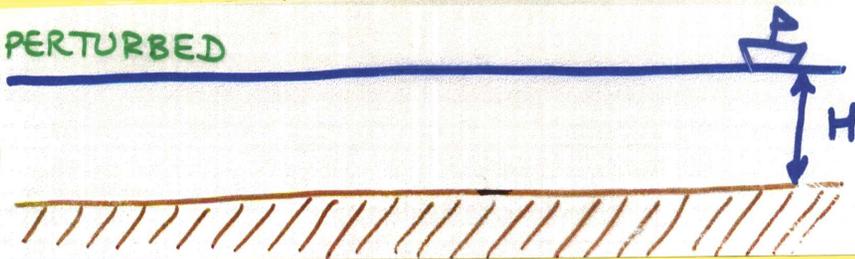


TSUNAMI GENERATION

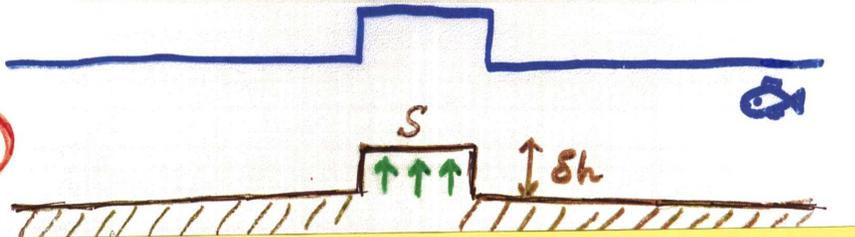
The Earthquake

UNPERTURBED

①



②

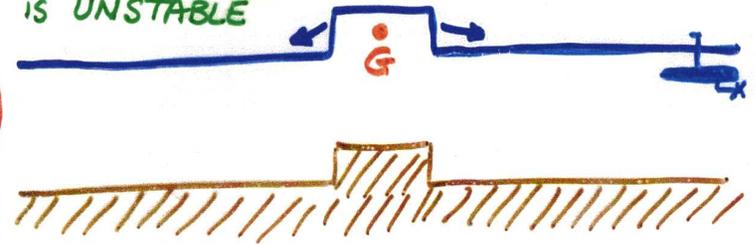


Earthquake deforms ocean floor and displaces it vertically into water mass.

HUMP SHOULD APPEAR ON SURFACE MIRRORING BOTTOM DEFORMATION

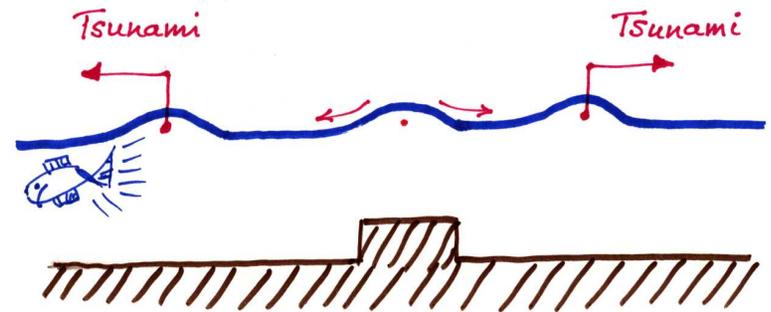
HUMP ON SURFACE IS UNSTABLE

③



WAVE DEVELOPS & PROPAGATES OUTWARDS

④



FINAL EQUILIBRIUM

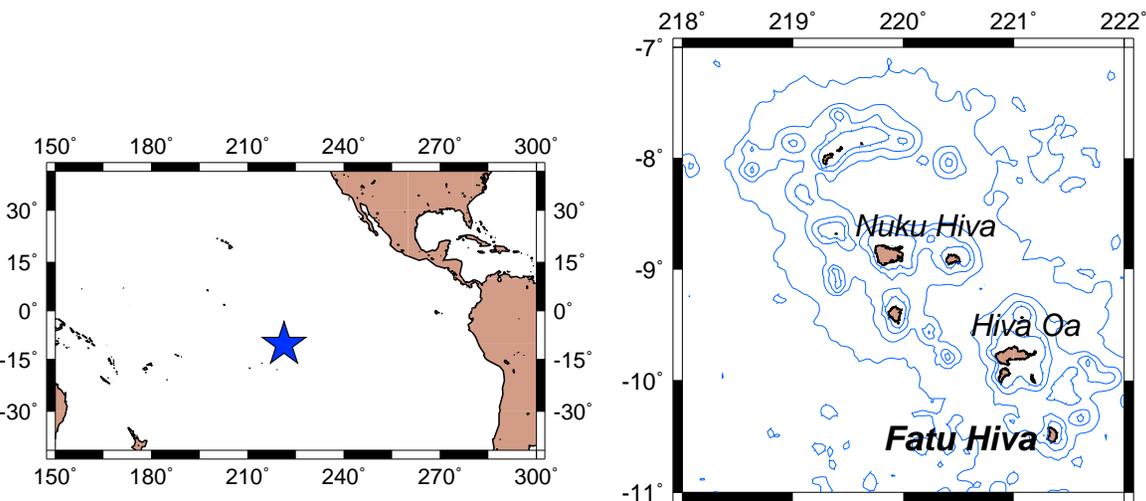
⑤



TSUNAMI GENERATION (ctd.)

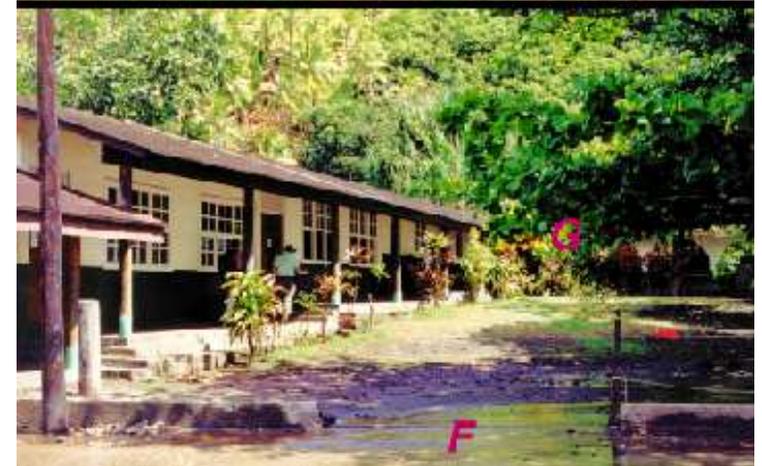
Landslides

Fatu Hiva, Marquesas Islands, 13 September 1999



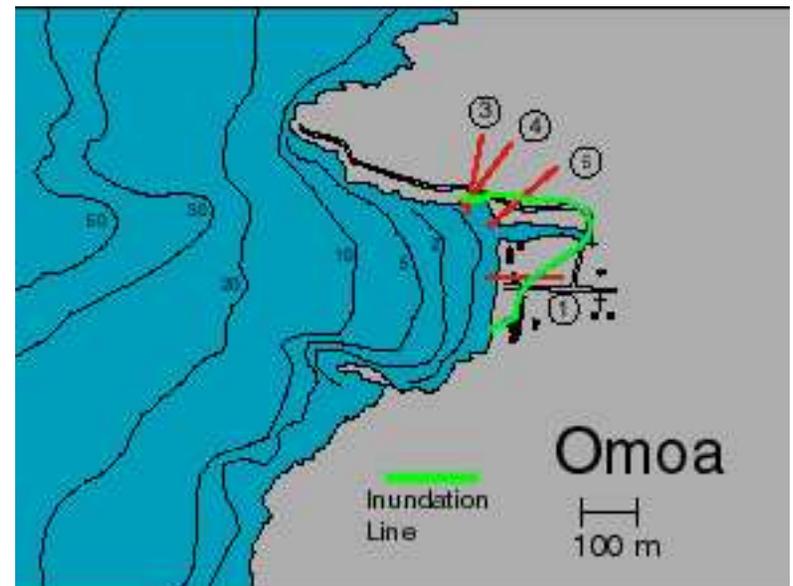
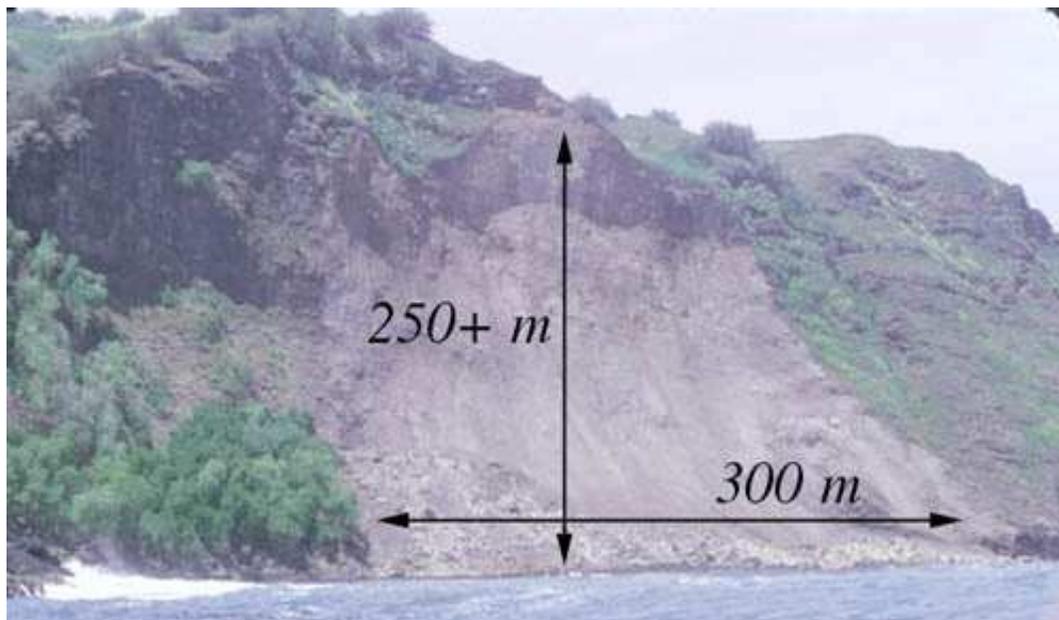
The beachfront school house at Omoa was severely flooded by two "rogue" waves which also destroyed the ice-making plant and several canoe shacks and copra-drying stands.

Miraculously, there were no victims, even though 85 children were attending school.





Estimated Volume of Rock Slide: 4 million m³



TSUNAMI GENERATION (ctd.): *Volcanic Explosions at Sea*

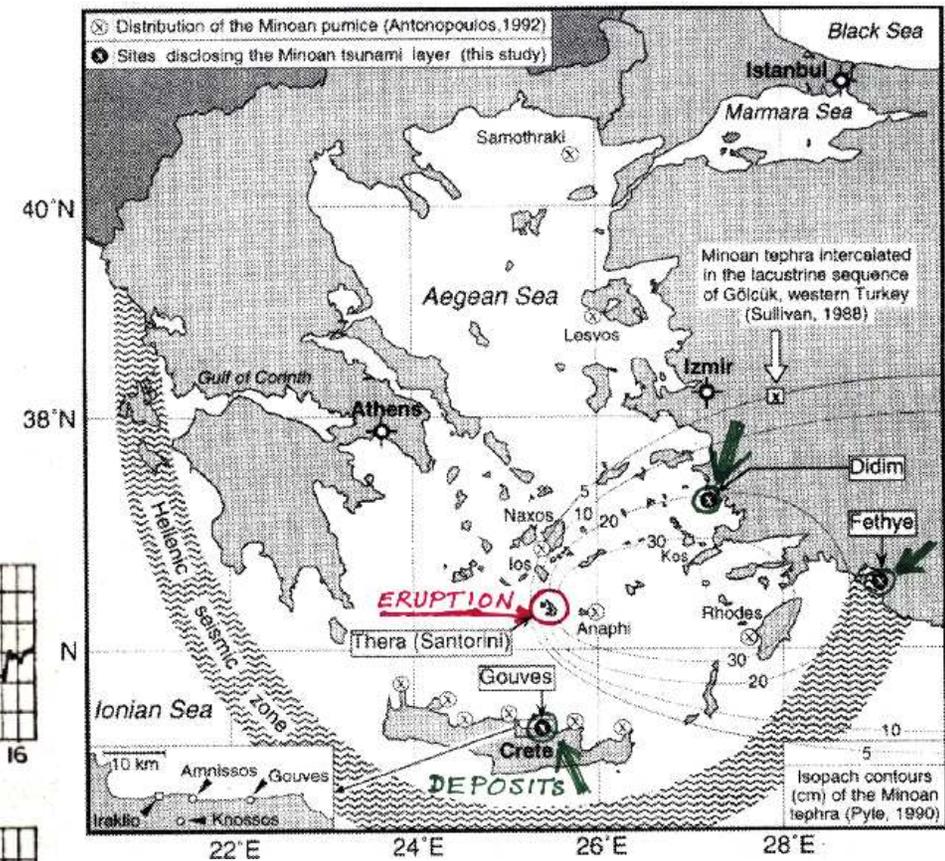
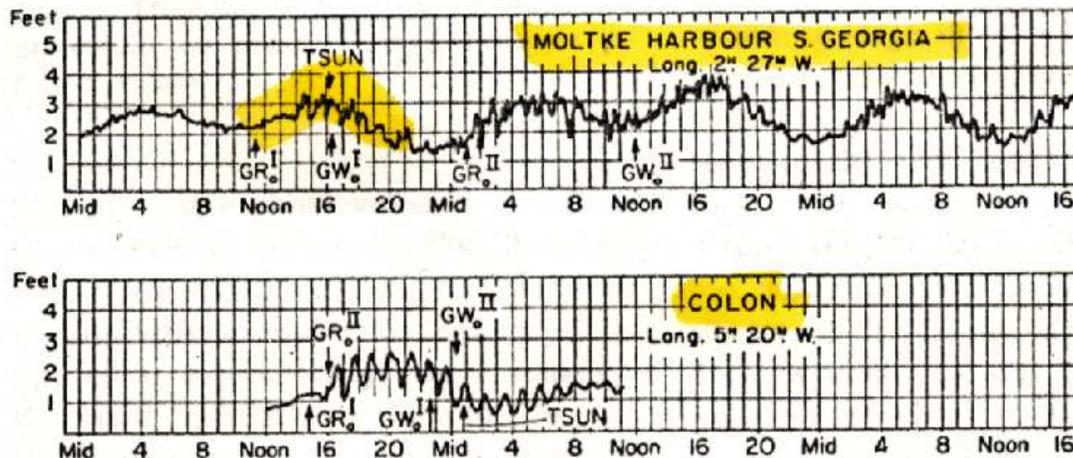
Krakatoa [Sunda Straits], 27 August 1883

Santorini (Θηρα), 1630 ± 20 B.C.

Air-Sea Waves from the Explosion of Krakatoa

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

[Press and Harkrider, 1966]



[Minoura et al., 2000]

TSUNAMI GENERATION (ctd.)

Catastrophic Bolide Impact

- *Chicxulub, Yucatan* ["K/T boundary event"], *65 million years b.p.*
10-km (?) size impactor; ~100-million-megaton explosion;
Extinction of dinosaurs (??).

● **IMPACT**

● **CLASTIC DEPOSITS**

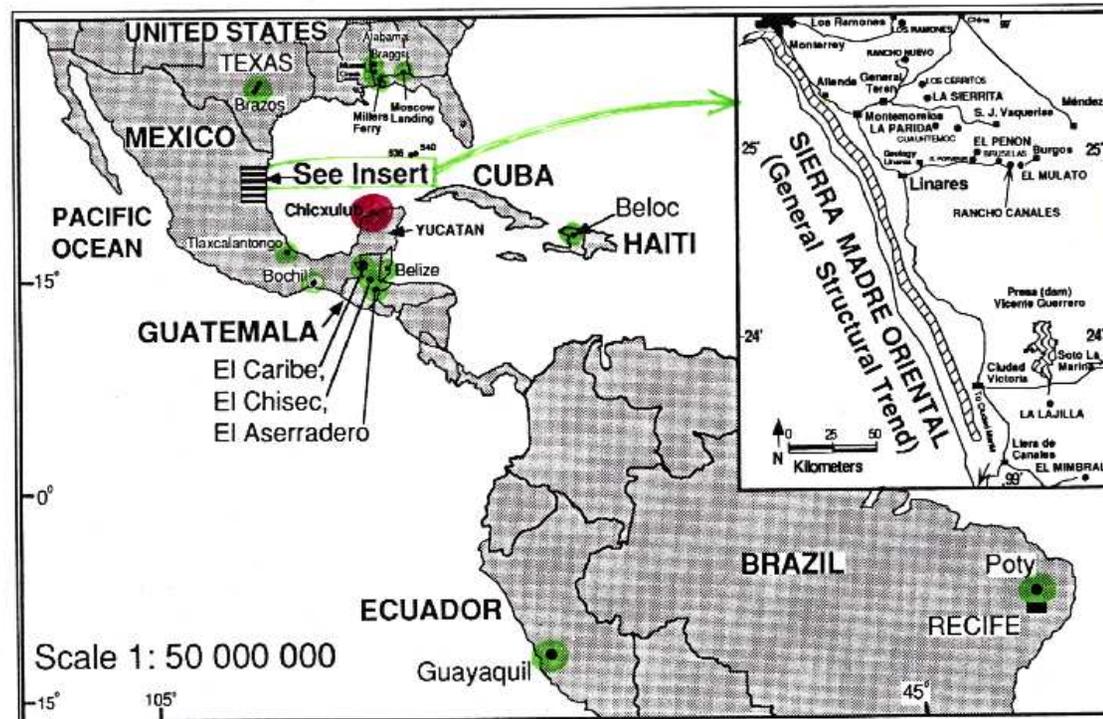
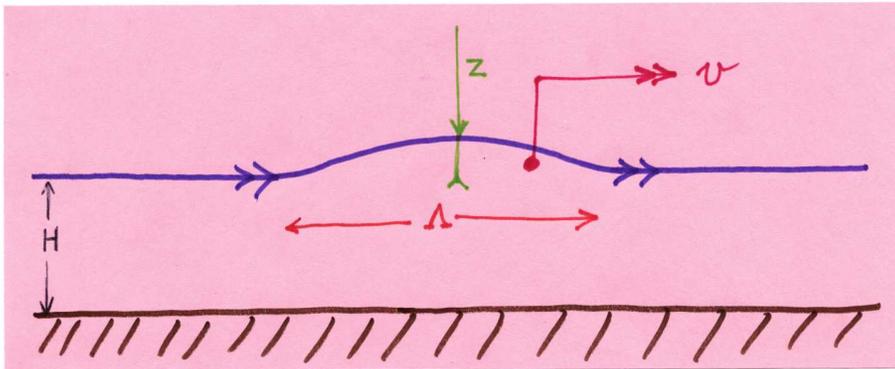


Figure 1. Location of Cretaceous-Tertiary boundary sections with near-K/T clastic deposits from Texas to Brazil. Insert shows area of location of northeastern Mexico sections.

[*Bourgeois et al., 1988; Stinnesbeck and Keller, 1996*]

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.*

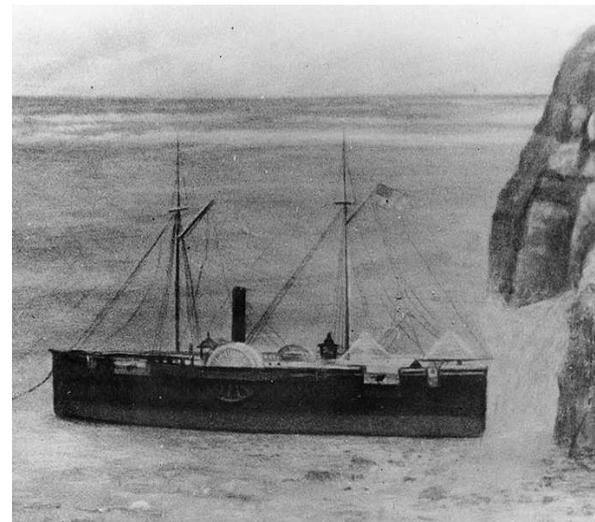
- * *WAVELENGTH, Λ , is typically 300 km*

- *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.



[U.S. Navy]

On 13 August 1868, during the Arica, Peru earthquake and tsunami, the *USS Wateree* was moved 3 km inland, and stopped only by the presence of cliffs. On 09 May 1877, a new tsunami moved its remains back to the shoreline, where the boilers can still be seen [but Arica is now part of Chile].

TSUNAMI CAN:

- Flood low-lying areas
- Destroy wave-facing structures
- Carry debris at speeds of ~ 20 m/s
- Deposit sediment scoured from sea bed
- Erode soils during down-draw



Phuket, Thailand, 2004



Camana, Peru, 2001



Seward, Alaska, 1964



Camana, Peru, 2001



Camana, Peru, 2001

TSUNAMI MITIGATION — *Early Attempts*

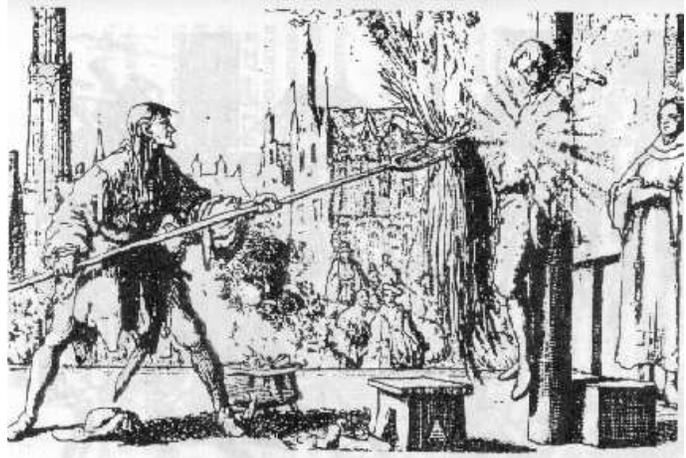
Medieval Japan



Kashima restrains Namazu

The Enlightenment

(**Lisbon Tsunami — 01 November 1755**)



Committee of Experts from Coimbra University recommends Auto-da-fe

[Voltaire, *Candide ou l'Optimisme*, 1759]

More Modern Approach

- *Protection:* The walls of the Japanese coastline.

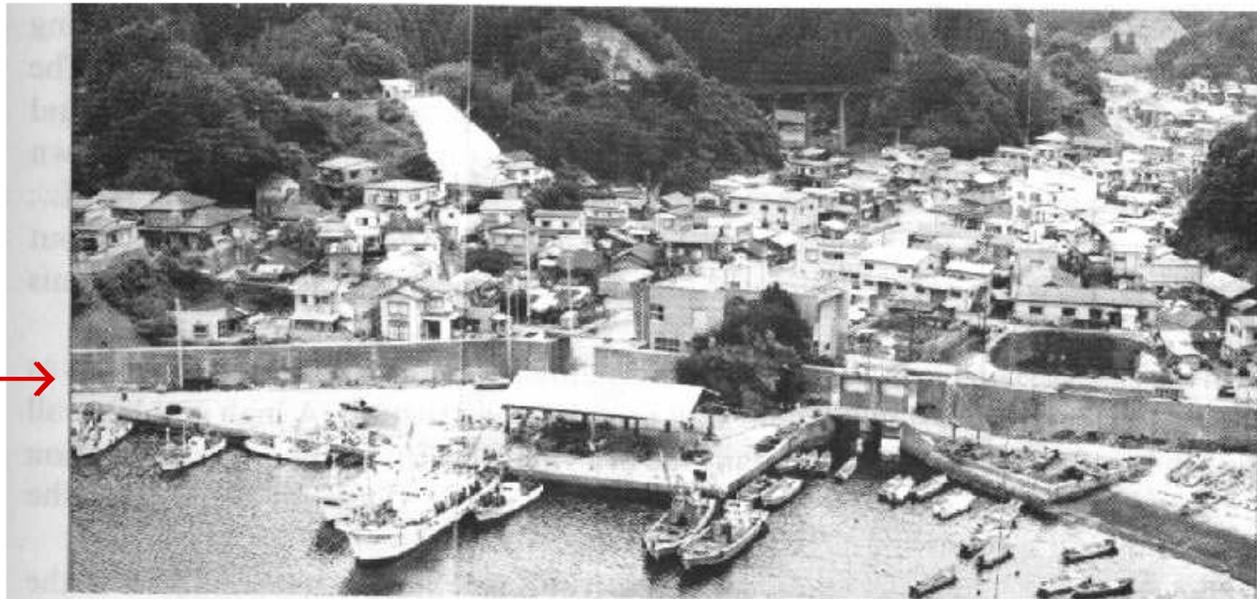


Photo 2. Typical fishing village, (Ryoishi), on the Sanriku coast.

[Fukuchi and Mitsuhashi, 1983]

TSUNAMI MITIGATION (ctd.)

- *Walls... What height ?* Okushiri Island, Japan, 13 July 1993



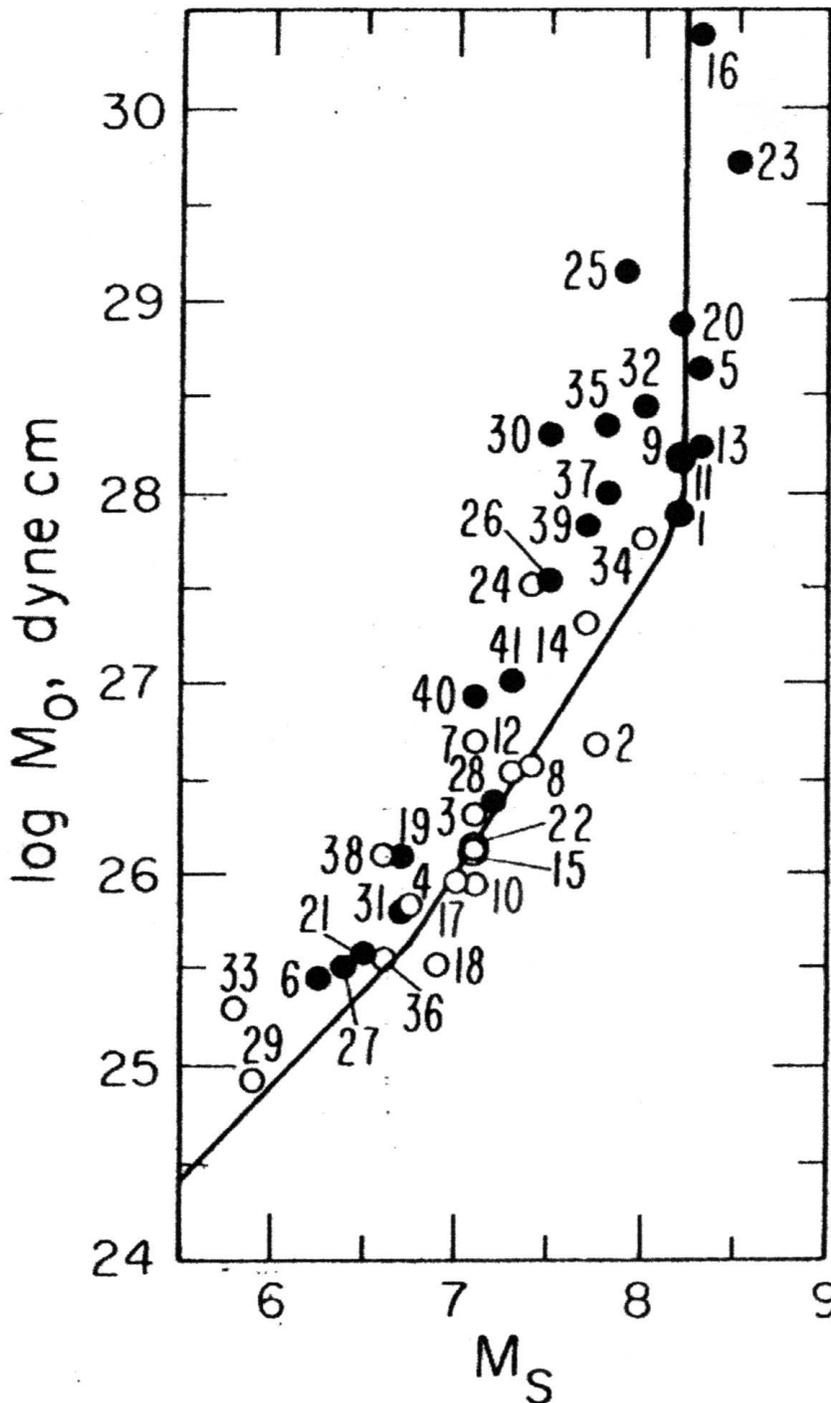
Figure 1 View of the small town of Aonae, on the island of Okushiri, Japan, in the aftermath of the Japan Sea tsunami of 12 July 1993. Note the devastation wrought on the island by the tsunami wave; all housing in the left part of the photograph has been destroyed and the rubble washed out in the harbour; note also the fishing boats carried inland and the fires, still burning in this next-day photograph. (Courtesy of Y. Tsuji.)

WHAT CAN THE SCIENTIST DO ?

- Research and Development for Real-Time Warning
- Post-Tsunami Surveys
- Numerical Simulation and Mitigation Efforts
- Education
- Pushing the Frontier: High-Tech Developments

TSUNAMI WARNING: THE CHALLENGE

- Upon detection of a teleseismic earthquake, assess in real-time its tsunami potential.
- **HINT:** Tsunami being low frequency is generated by longest periods in seismic source ("static moment M_0 ").
- **PROBLEM:** Most popular measure of seismic source size, surface wave magnitude M_s , saturates for large earthquakes.



FAR-FIELD TSUNAMI DANGER

EXTREME

PROBABLE

LOW

NIL



[Geller, 1976]

TREMORS: [Okal and Talandier, 1989; 1991; 1992]

Kurile Is. Earthquake, 04 OCT 1994,
Station: TKK (Chuuk, Micronesia)

- Detection: Analyse signal level compared to previous minute.
- Location : $S - P$ gives distance (36° or 4000 km).
Geometry of P wave gives azimuth.
- Estimate seismic moment

→ Fourier-transform Rayleigh wave (highlighted)

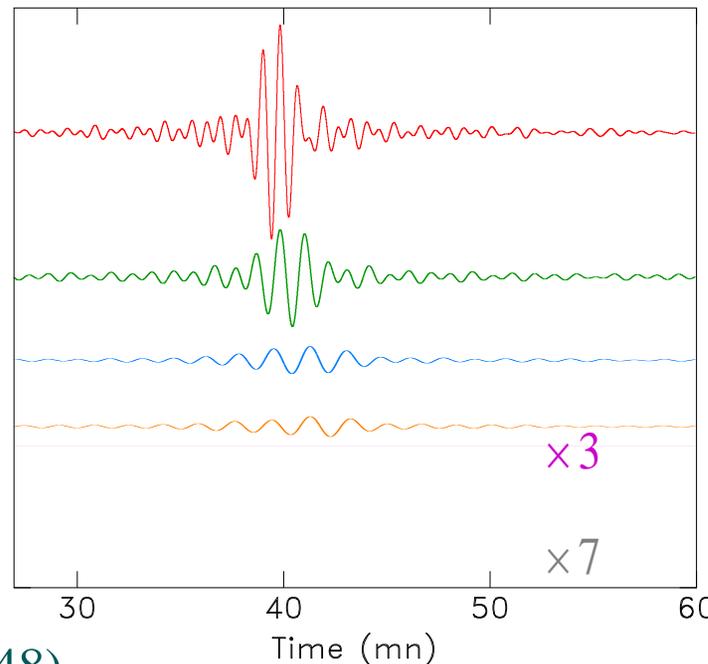
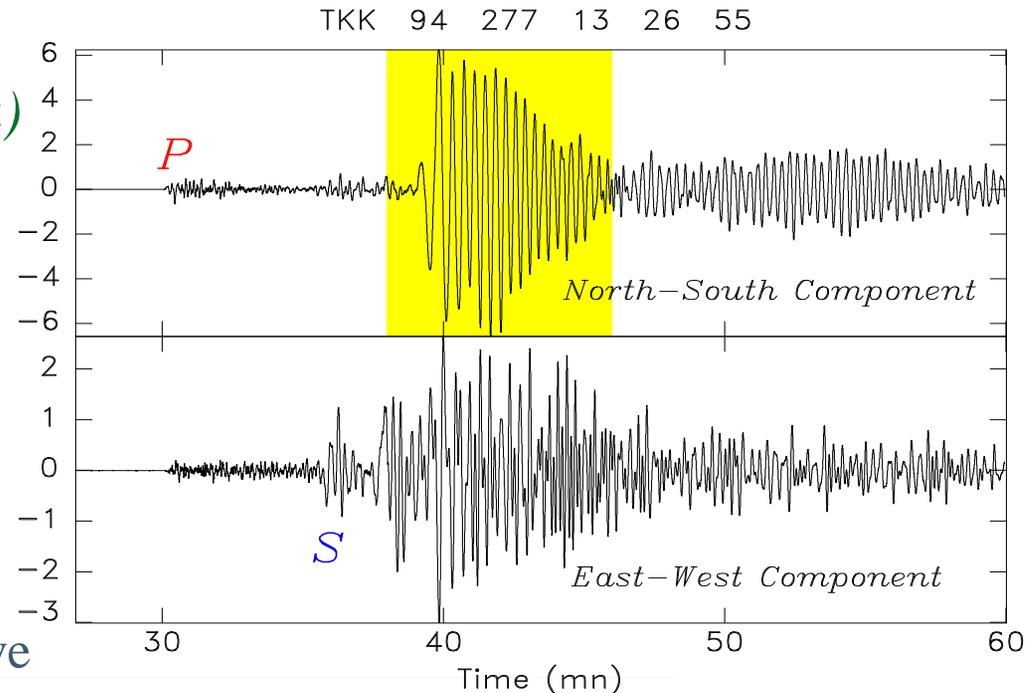
→ At each period, compute

$$M_m = \log_{10} X(\omega) + C_D + C_S - 0.90$$

→ Conclusion: Average $M_m = 8.60$
($M_0 = 4 \times 10^{28}$ dyn-cm).

Harvard solution:

$$M_0 = 3 \times 10^{28} \text{ dyn-cm } (M_m = 8.48)$$



$T = 55 \text{ s}; M_m = 8.78$

$T = 80 \text{ s}; M_m = 8.71$

$T = 120 \text{ s}; M_m = 8.60$

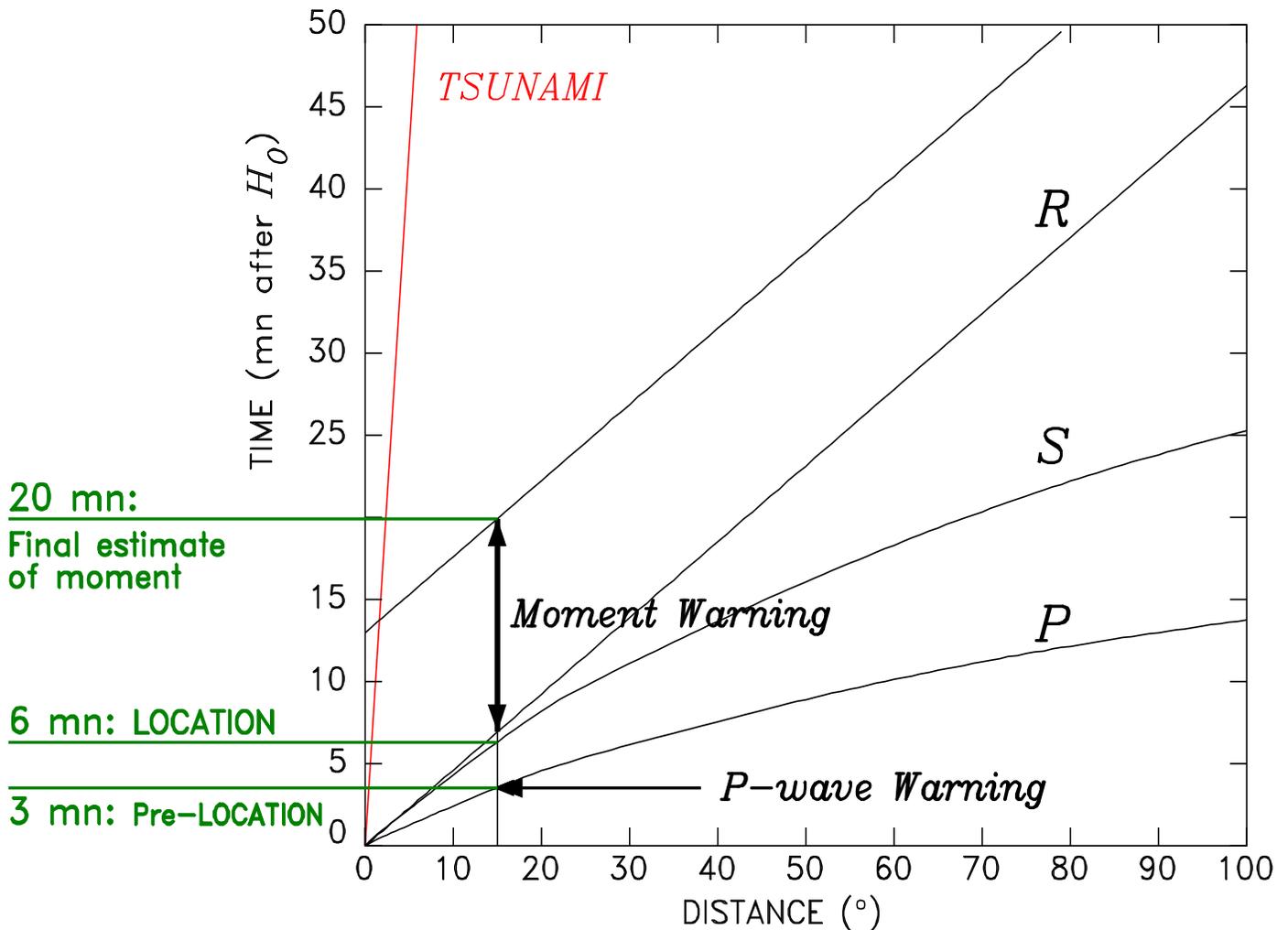
$T = 150 \text{ s}; M_m = 8.55$

$T = 200 \text{ s}; M_m = 8.49$

$T = 250 \text{ s}; M_m = 8.40$

TREMORS -- Operational Aspects

- Response Time of TREMORS algorithm



A TREMORS station at an epicentral distance of 15° can issue a useful warning for a shore located 400 km from the event.

THE INFAMOUS "TSUNAMI EARTHQUAKES"

- A particular class of earthquakes defying seismic source scaling laws. Their tsunamis are much larger than expected from their seismic magnitudes (even M_m).
- Example: Nicaragua, 02 September 1992.

*THE EARTHQUAKE WAS NOT FELT AT SOME BEACH COMMUNITIES,
WHICH WERE DESTROYED BY THE WAVE 40 MINUTES LATER*

170 killed, all by the tsunami, none by the earthquake



El Popoyo, Nicaragua



El Transito, Nicaragua

"TSUNAMI EARTHQUAKES"

- *The Cause:* Earthquake has exceedingly slow rupture process releasing very little energy into high frequencies felt by humans and contributing to damage [Tanioka, 1997; Polet and Kanamori, 2000].
 - *The Challenge:* Can we recognize them from their seismic waves in [quasi-]real time?
 - *The Solution:* The Θ parameter [Newman and Okal, 1998] compares the "size" of the earthquake in two different frequency bands.
- Use generalized- P wavetrain (P , pP , sP).
- Compute Energy Flux at station [Boatwright and Choy, 1986]
- *IGNORE Focal mechanism and exact depth to effect source and distance corrections (keep the "quick and dirty "magnitude" philosophy).*
- Add representative contribution of S waves.

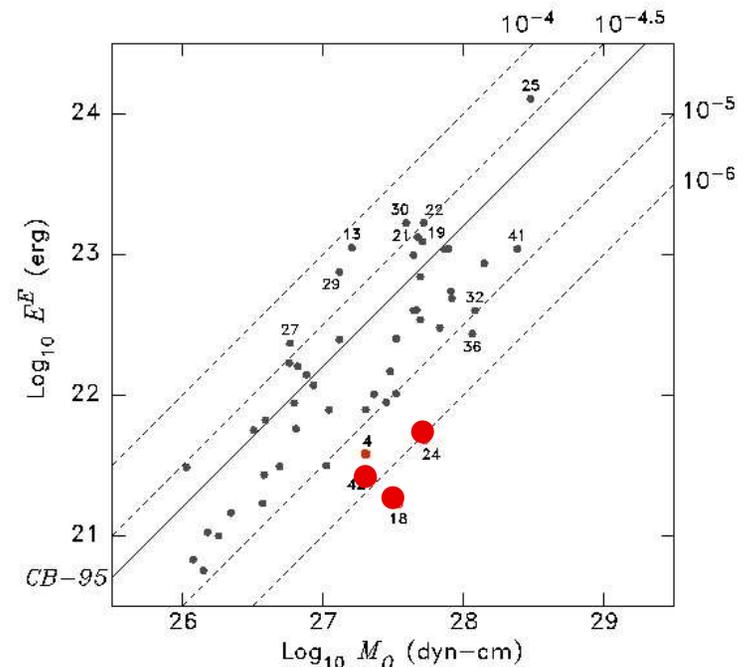
→ Define *Estimated Energy*, E^E

$$E^E = (1 + q) \frac{16}{5} \frac{[a/g(15; \Delta)]^2}{(F^{est})^2} \rho \alpha \int_{\omega_{min}}^{\omega_{max}} \omega^2 |u(\omega)|^2 e^{\omega t^*(\omega)} \cdot d\omega$$

→ Scale to Moment through $\Theta = \log_{10} \frac{E^E}{M_0}$

→ Scaling laws predict $\Theta = -4.92$.

- **Tsunami earthquakes characterized by Deficient Θ (as much as 1.5 units).**



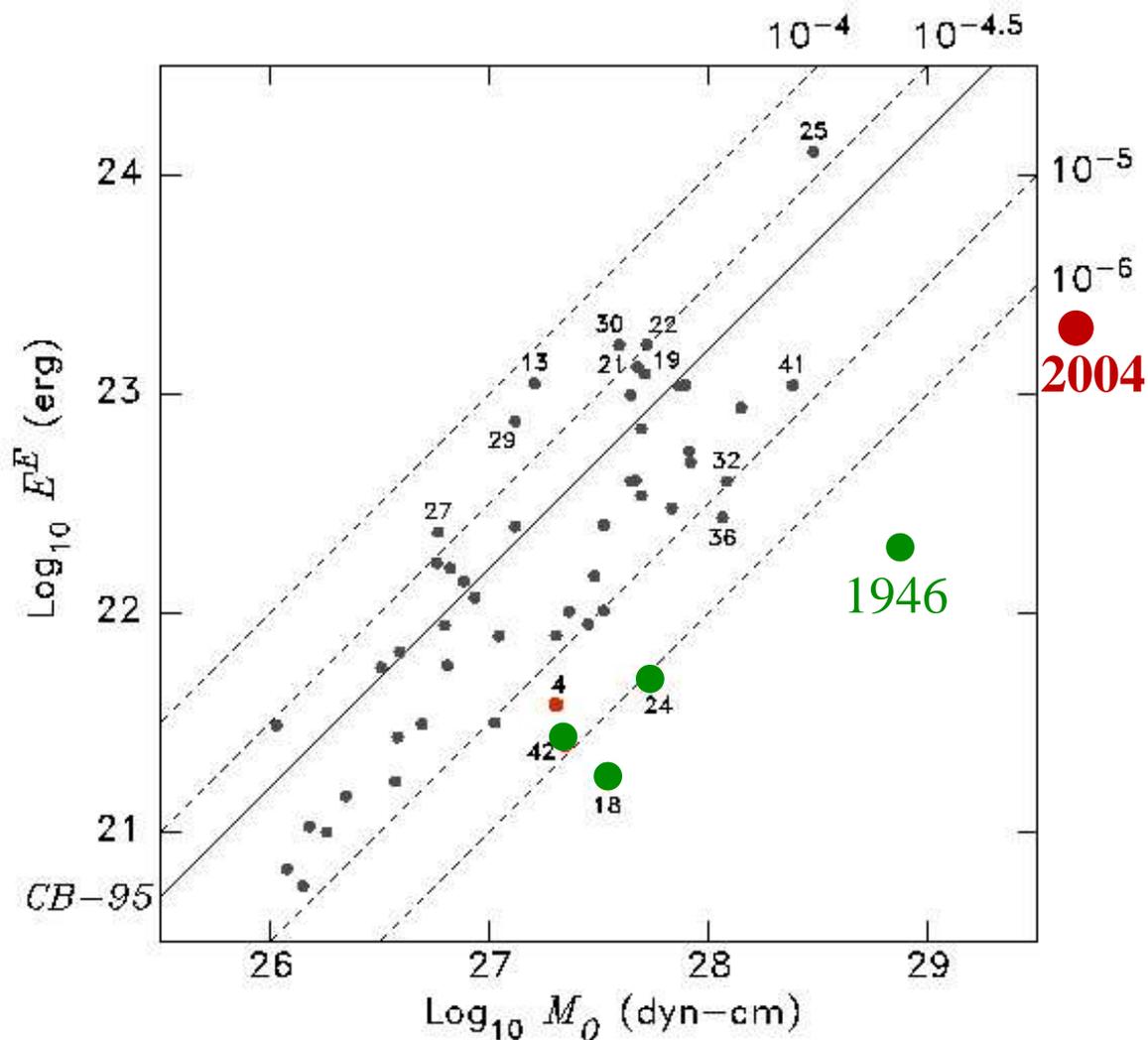
Now being implemented at Papeete and PTWC

"TSUNAMI EARTHQUAKES"

Newman and Okal [1998] have designed a test ("Parameter Θ ") comparing the energy released by the seismic source at high and low frequencies.

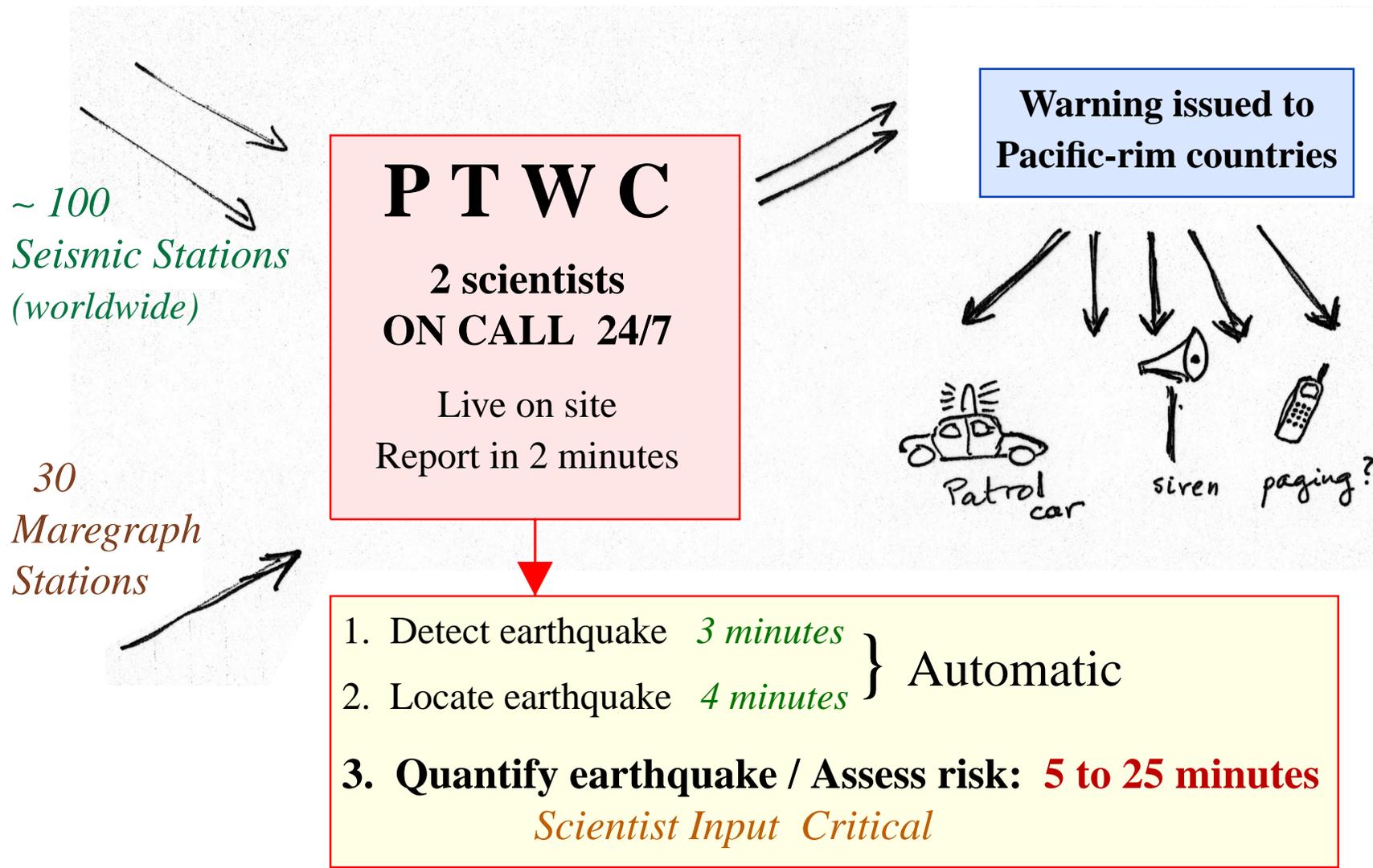
- Identifies in real time anomalous behavior of the source and enhanced tsunami danger.
- Examples: 1992 Nicaragua
1994, Java
1996 Chimbote, Peru
1946, Aleutian

2004 Sumatra : also probably anomalously slow



TSUNAMI WARNING PROCEDURES at

Pacific Tsunami Warning Center, *Ewa Beach, Hawaii*



NOTE: Evacuation of Waikiki before tsunami would require 2.5 hours (HPD).

POST-TSUNAMI SURVEYS

Why?

Survey runup and inundation along coastlines to create quantitative database in order to document scientifically water penetration and understand parameters controlling it.

How?

Identify watermarks and record testimonies from eyewitnesses. Use surveying techniques (GPS, etc.) to build database.

When?

Ideally a few weeks after event.

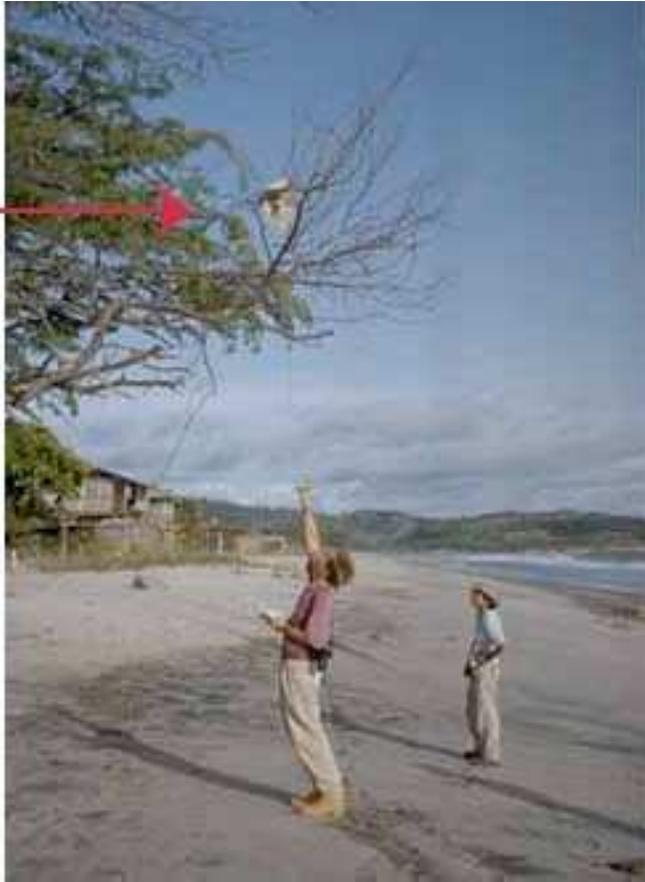
Occasionally (1946 Aleutian; 1956 Amorgos) as much as 55 years later...



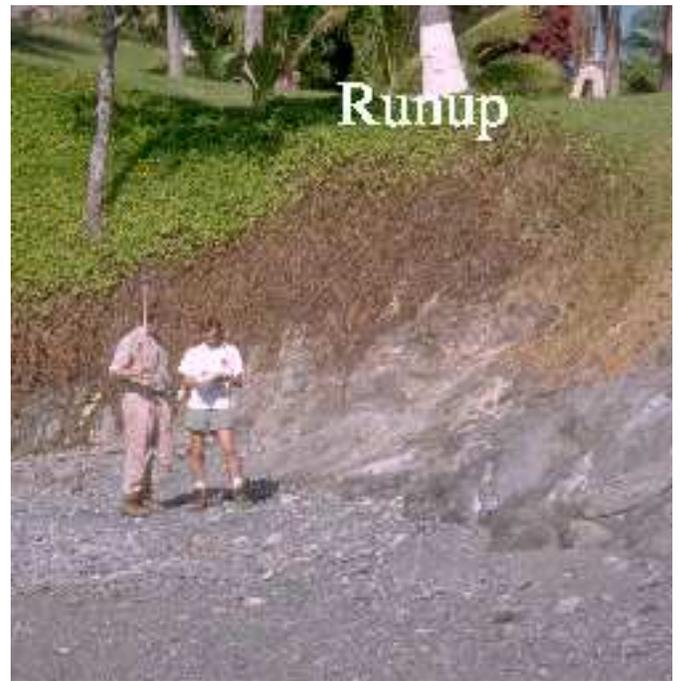
Papua New Guinea, 1998. Note the bucket in the tree.

Nicaragua, 1992

5 m



Mexico, 1995



Peru, 2001

HISTORICAL TSUNAMIS: Preserving the Eyewitness Record

1946 Aleutian tsunami
Unimak, Alaska, 2001

1946 Aleutian tsunami
Marquesas Islands, 2000



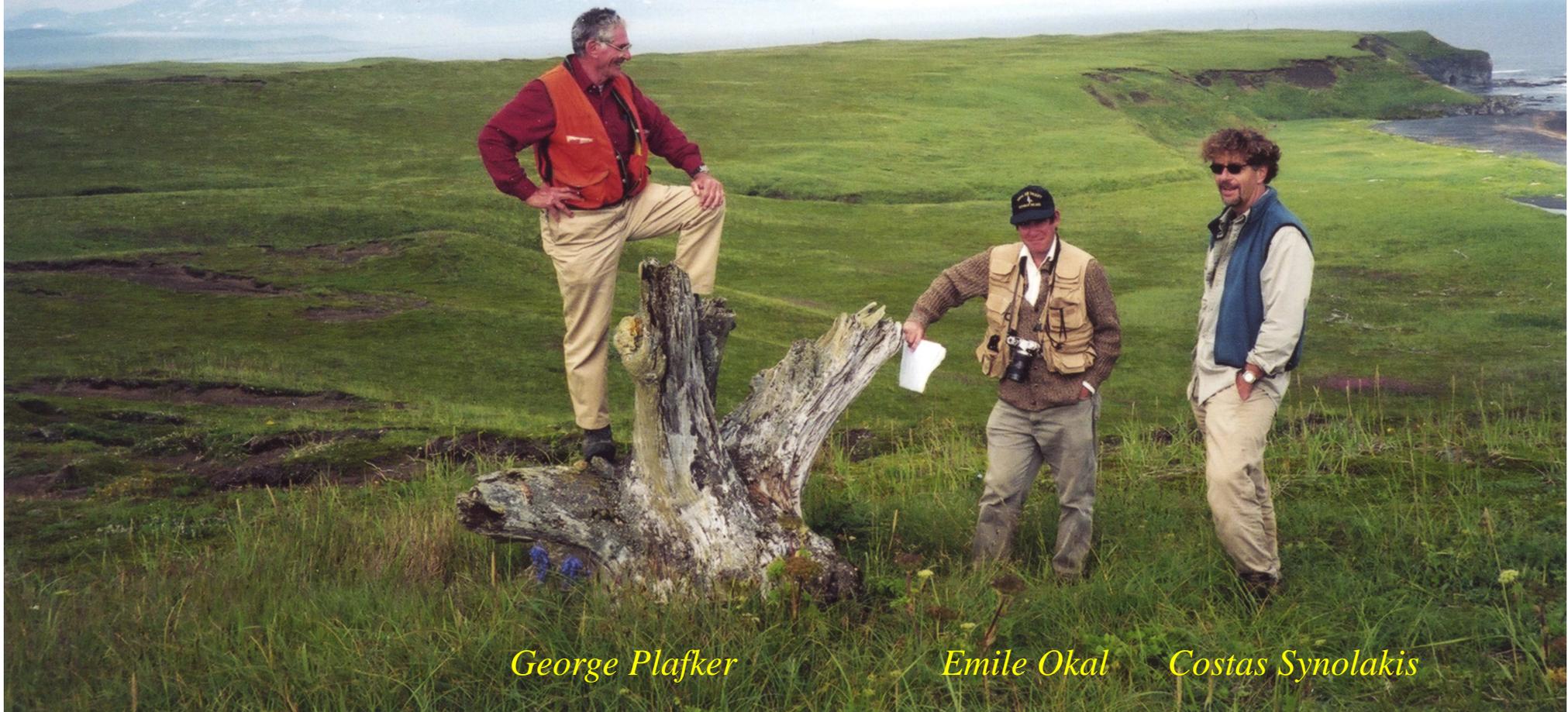
1956 Amorgos, Greece tsunami
Anafi, Greece, 2004



No trees grow on the Eastern Aleutian Islands...

Thus, large logs lying several hundred meters inland at altitudes of 10 to 30 m constitute watermarks of inundation by a tsunami, since they are way beyond the limit of even the most powerful storm surges.

In recent decades, only the 1946 tsunami is a viable candidate as the agent of their deposition.



George Plafker

Emile Okal

Costas Synolakis

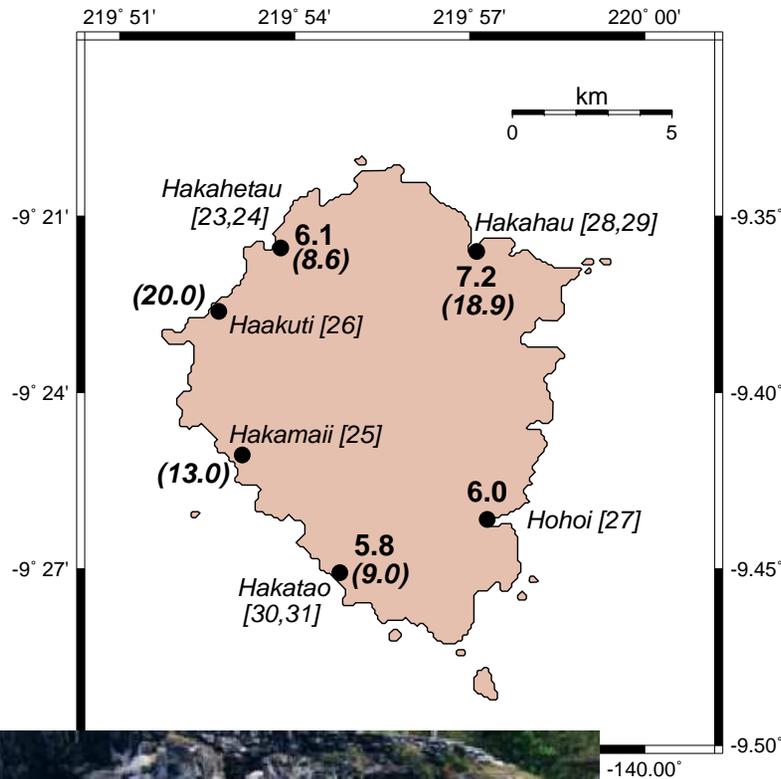
Cape Lutke, UNIMAK ISLAND, August 2001

TSUNAMI SURVEYS: The Products

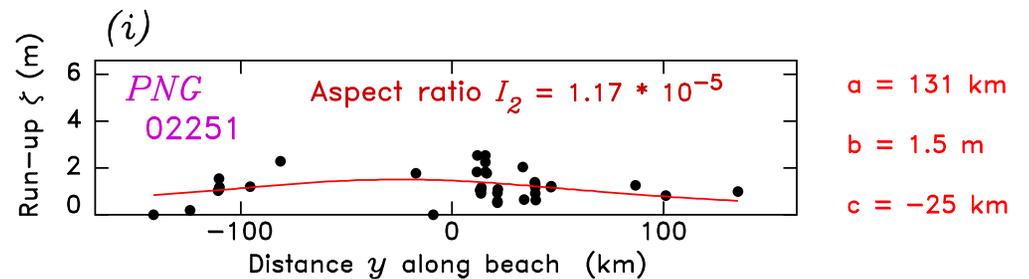
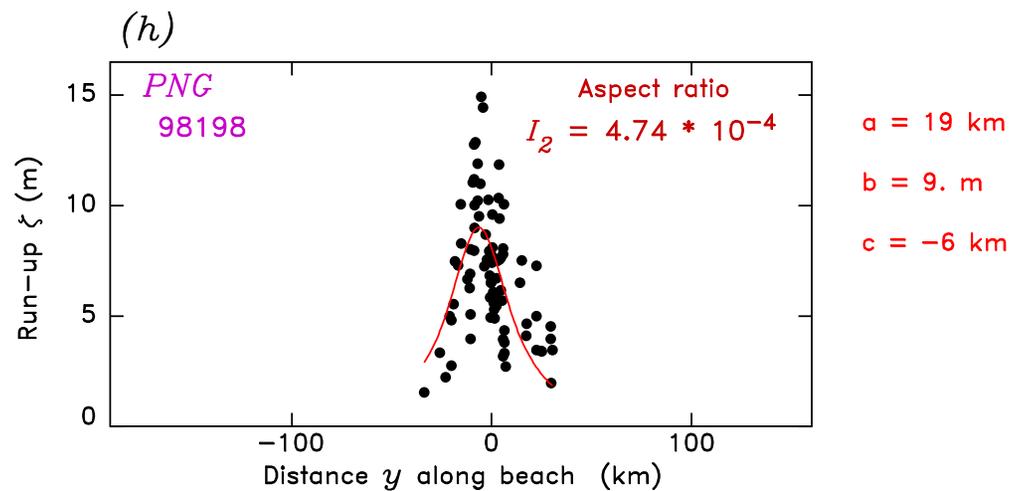
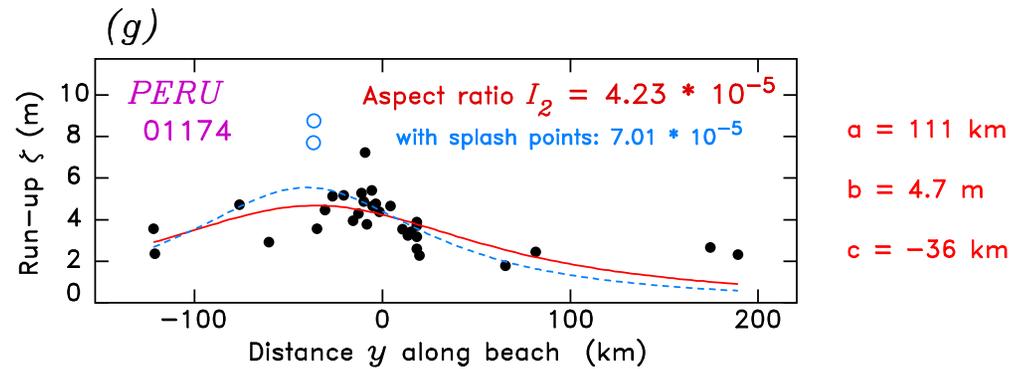
MAPS quantify penetration of the wave.

Ua Pou, Marquesas Is.

1946 Aleutian Tsunami



PROFILES define distribution of run-up along the beach and identify non-seismic (landslide) sources (PNG, 1998; Aleutian, 1946).



NUMERICAL SIMULATIONS & APPLICATION TO MITIGATION

- Compute numerically model of tsunami: generation by earthquake, propagation on high seas, interaction with beach.

GOALS:

- Understand parameters controlling inundation;
- Provide civil defense and planning authorities with guidelines for development and evacuation of communities.

CHALLENGE:

- Extreme complexity of mathematical formalism:
 - Non-linear equations;
 - Variations in bathymetry;
 - Variations in domains of validity of approximations;
 - Necessary rescaling of grids for finite difference codes.
- Full computation for large ocean basin is presently slower than wave itself (need 36 hours of computer to simulate 24 hours of wave propagation in the entire Pacific Basin).

SIMULATIONS: EQUATIONS and APPROXIMATIONS

- Start with Full Navier-Stokes system
- Usually assume:

No viscosity

Incompressible medium

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

(\mathbf{u} velocity field; p pressure, \mathbf{f} external gravity force)

Note Full Derivative $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \mathbf{grad}$

(source of non-linearity...).

- Many possible approximations, controlled by ratios between three essential ***LENGTHS***:
 - * Depth of Water
 - * Amplitude of Wave
 - * 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,

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

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

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

Then, SOLVE BY FINITE DIFFERENCE ALGORITHM
(MOST Code ; [Synolakis and Titov, 1997]).

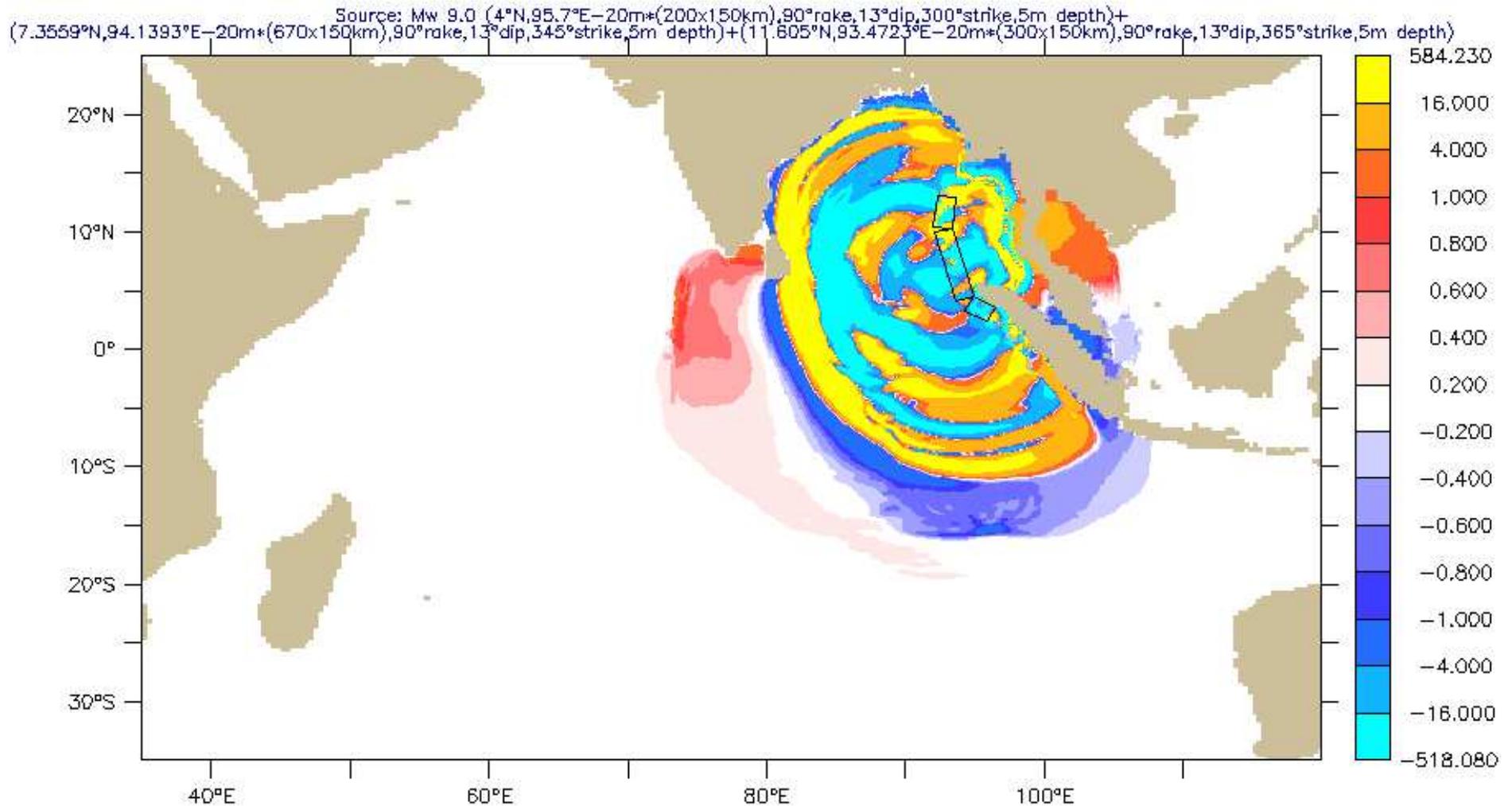
SIMULATION of 2004 SUMATRA TSUNAMI:

Snapshot at T = 02:45:53 GMT (1 hr 52 minutes after origin time)

Facility for the Analysis and Comparison of Tsunami Simulations (FACTS)

Tsunami Wave Height(cm) – 2004.12.26 Indonesian Tsunami

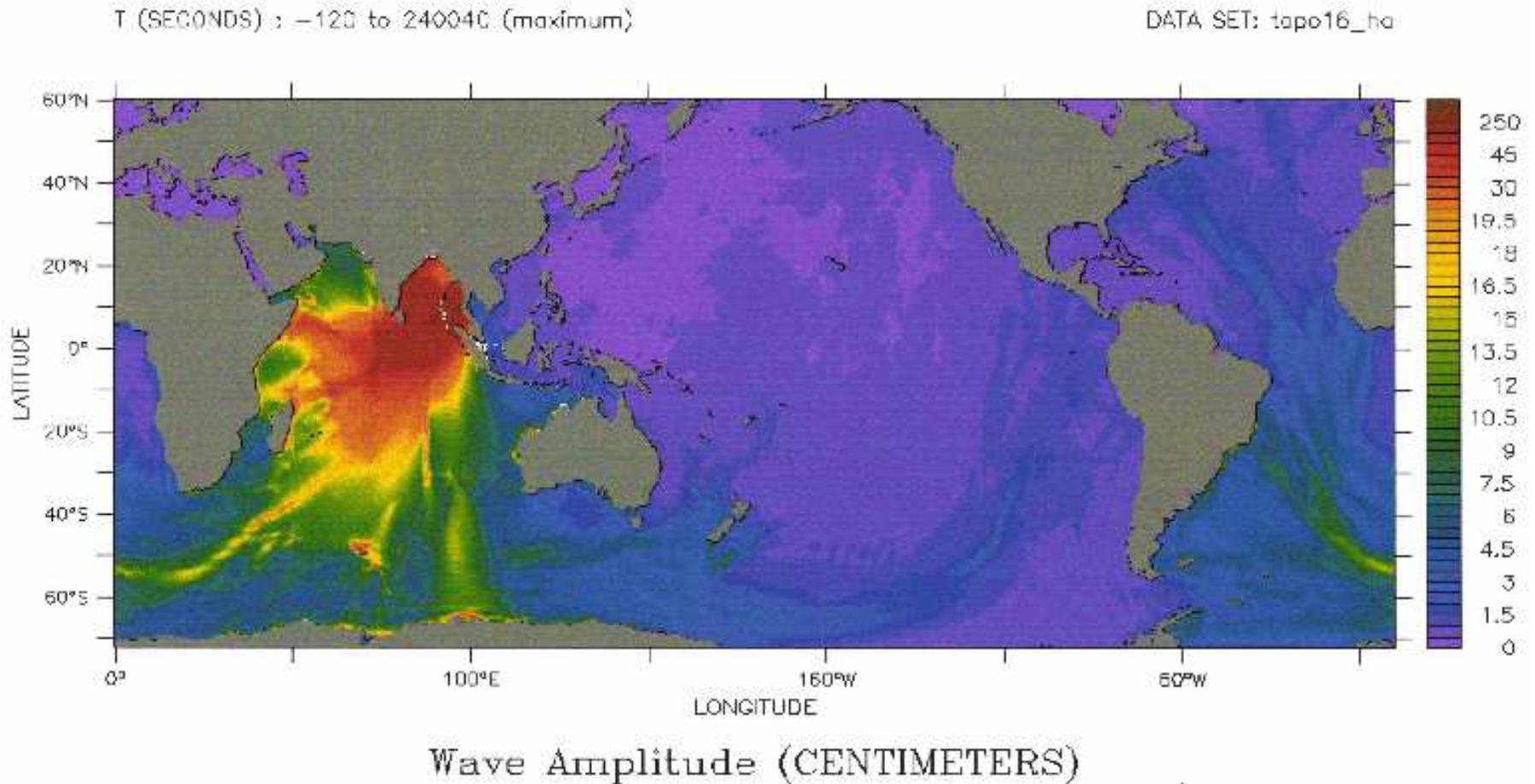
T (SECONDS) : 6720



[V.V. Titov, NOAA, pers. comm., 2005].

SIMULATION of 2004 SUMATRA TSUNAMI (35 hours):

Global model of Maximum Wave Height
(before interaction with coastlines)



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

EXAMPLE of SIMULATION

1946 Aleutian Tsunami

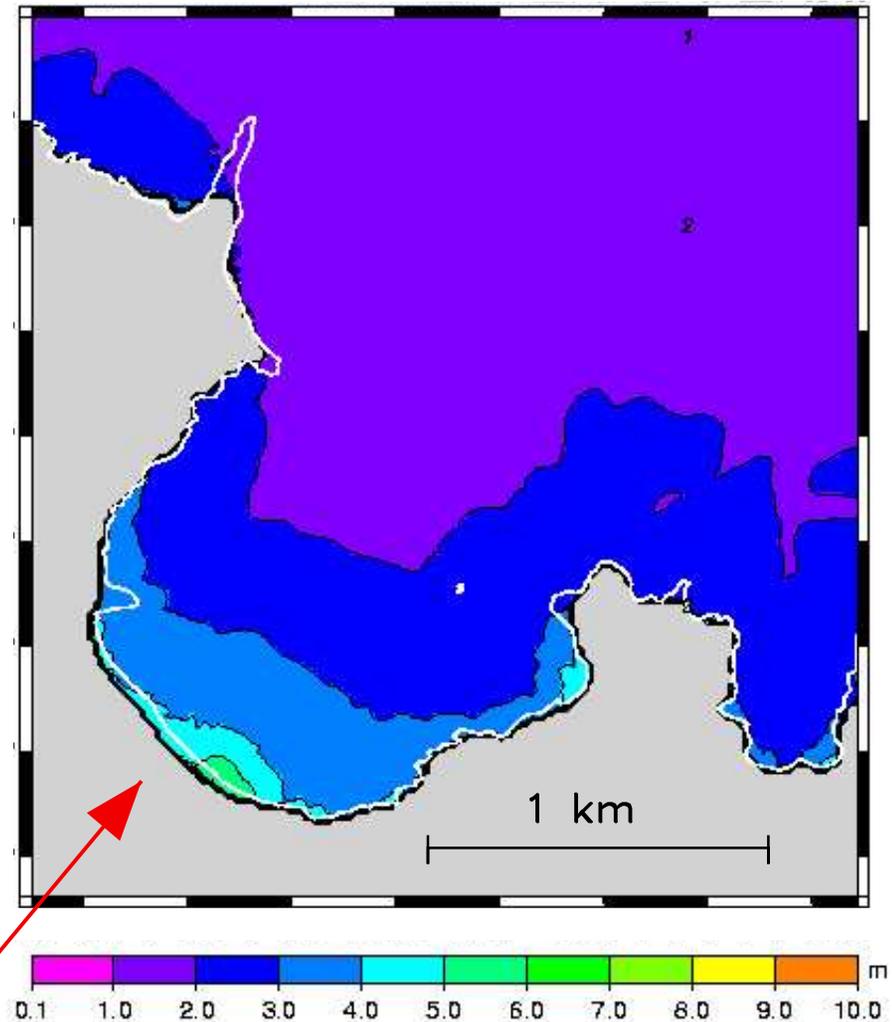
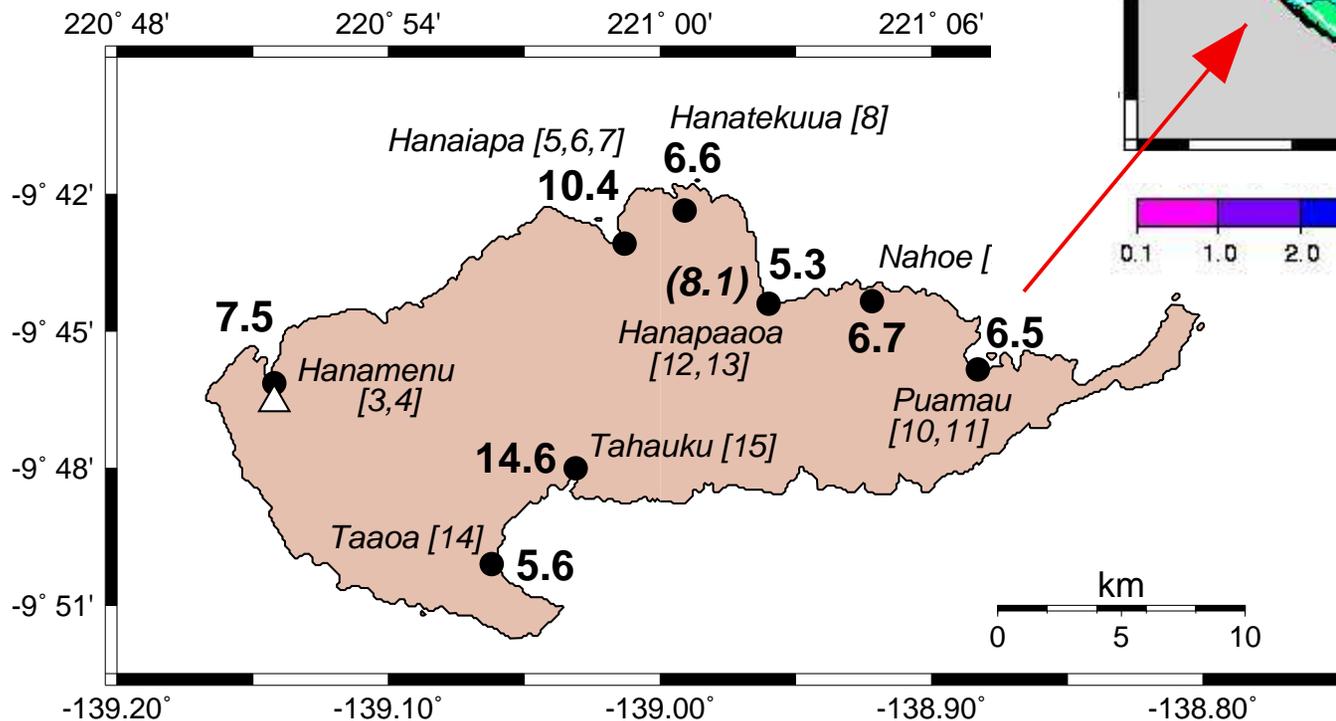
Puamau, Island of Hiva Oa, Marquesas

(7400 km from source; 09:20 propagation time)

- Observed: 6.5 m (overland)
- Modeled: 5.5 m

Ratio = 0.85; $r = \log_{10} \text{Ratio} = -0.07$

Hiva Oa



Run-up (m)



FROM SIMULATIONS TO PLANNING & MITIGATION

Example of Newport, Oregon

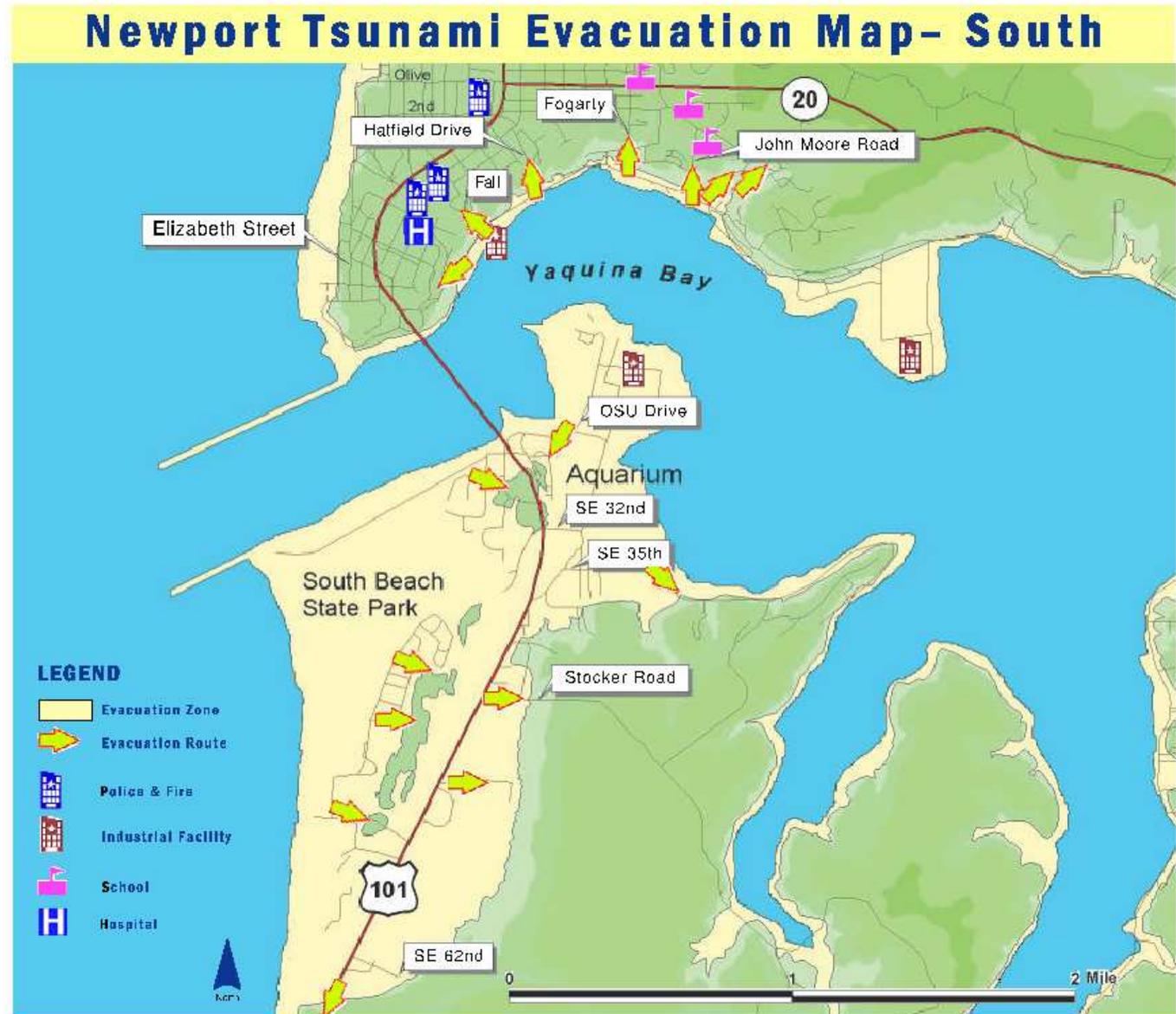
**IF YOU FEEL THE GROUND SHAKE,
MOVE QUICKLY TO HIGHER GROUND
AND SAFETY!
DO NOT WAIT FOR AN OFFICIAL WARNING!**



NOTICE

The evacuation zone on this map was developed by the Oregon Department of Geology and Mineral Industries in consultation with local officials. It is intended to represent a worst-case scenario for a tsunami caused by an undersea earthquake near the Oregon coast. Evacuation routes were developed by local officials and reviewed by the Oregon Department of Emergency Management.

The Oregon Department of Geology and Mineral Industries is publishing this brochure because the information furthers the mission of the Department. The map is intended for emergency response and should not be used for site-specific planning.

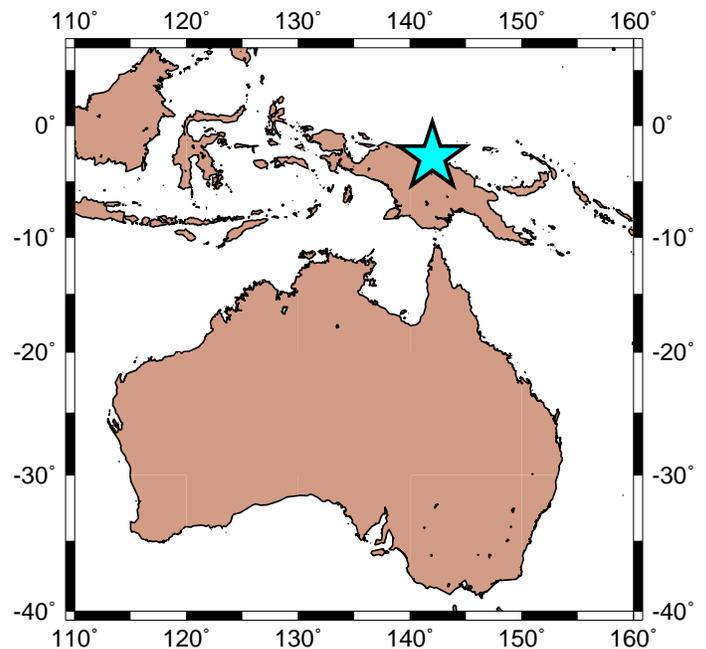


THE PAPUA NEW GUINEA (PNG) TSUNAMI

A very intriguing tsunami

17 JULY 1998

- 2200 people killed
- Ten villages eradicated



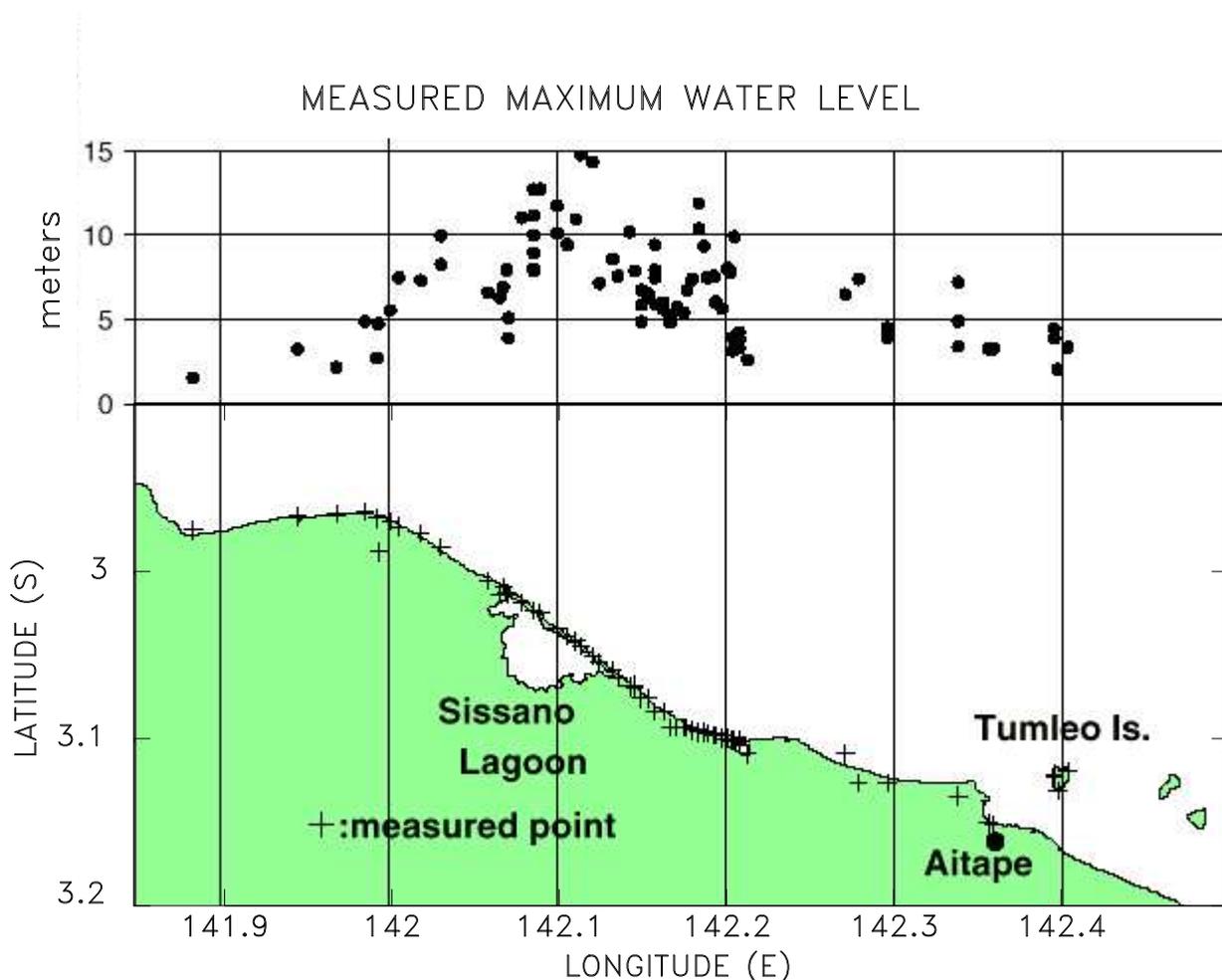
YET, The Earthquake was relatively small ($M_m = 6.8$)

THE PNG PUZZLE

1. LOCAL RUN-UP AMPLITUDE TOO LARGE RELATIVE TO EARTHQUAKE SIZE

Local run-up amplitude is consistently 10 m, with a peak at 15 m.

It cannot be reconciled with the size of the earthquake, and in particular with its fault length, without leading to strains in excess of the strength of crustal rocks.

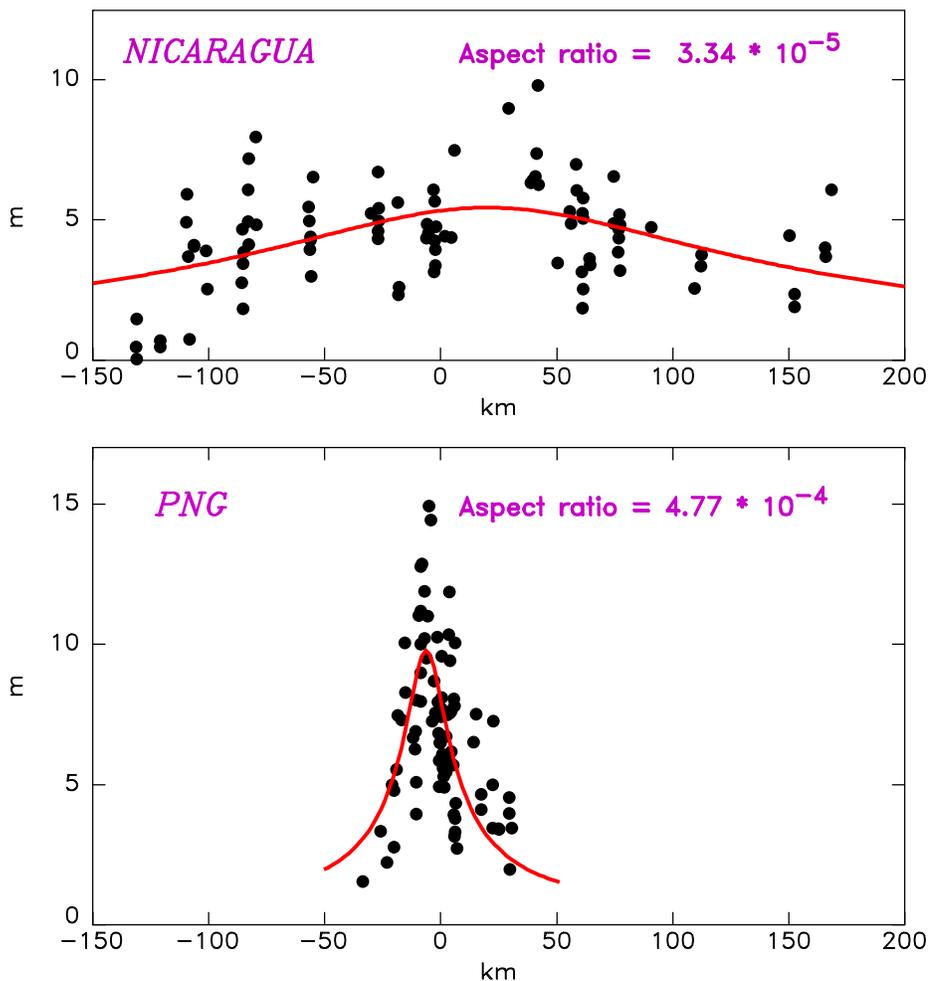


[Synolakis et al., 2002]

THE PNG PUZZLE (continued)

2. THE LARGE LOCAL RUN-UP AMPLITUDES ARE CONCENTRATED ALONG TOO SHORT A SECTION OF COAST (at most 30 km).

- Contrast with the run-up distribution for the 1992 Nicaragua tsunami



The aspect ratio of the run-up distribution cannot be predicted by dislocation models based on continuum mechanics — they would require a *strain release* greater than the yield strain of rock.

THE PNG PUZZLE (continued)

3. THERE IS A STRONG DISCREPANCY IN TSUNAMI AMPLITUDES BETWEEN THE NEAR- AND FAR-FIELDS

Even though the tsunami was monstrous in the vicinity of the source, it was recorded only marginally in Japan (10 to 25 cm), and was not detected at other Pacific locations (e.g., Hawaii).

Contrast this situation with transpacific tsunamis (1946, 1960) capable of inflicting heavy damage both in the far and near fields.

UPDATE AS OF: 20/11/95

CAMP CENTRE	CAMP NAME	1990 POPULATION (CENSUS)	1990 POPULATION (CENTRE POPULATION)	DEATHS	MISSING	OTHERS
RAMO	P. KONGI	1340	1574	344		1082
POU	M. SIKUMIN	1644	1404			863
ROWO (ANSOR)	TNEKAU	826	1153	49	35	61
OLBRIM	M. KALIT	468	1032	24		25
RANBRIM	E. HARRY	293	89	5	1	
MALOL	R. MIROI	2268	3816			95
TOWN	N. JUMAN	629	415			1
PAUP				6		7
OTHERS		7521	10483	429	35	2139

THE PNG PUZZLE (continued)



4. THE TSUNAMI IS *ABOUT 10 minutes* LATE !!

Comprehensive interviews by *Davies* [1998] indicate that:

- In some areas (Malol), the tsunami *did not arrive until after the "second felt shock"* (main aftershock at 09:09 GMT);
- In other areas (Arop, Warapu), the tsunami arrived before the population had a chance to feel the main aftershock.

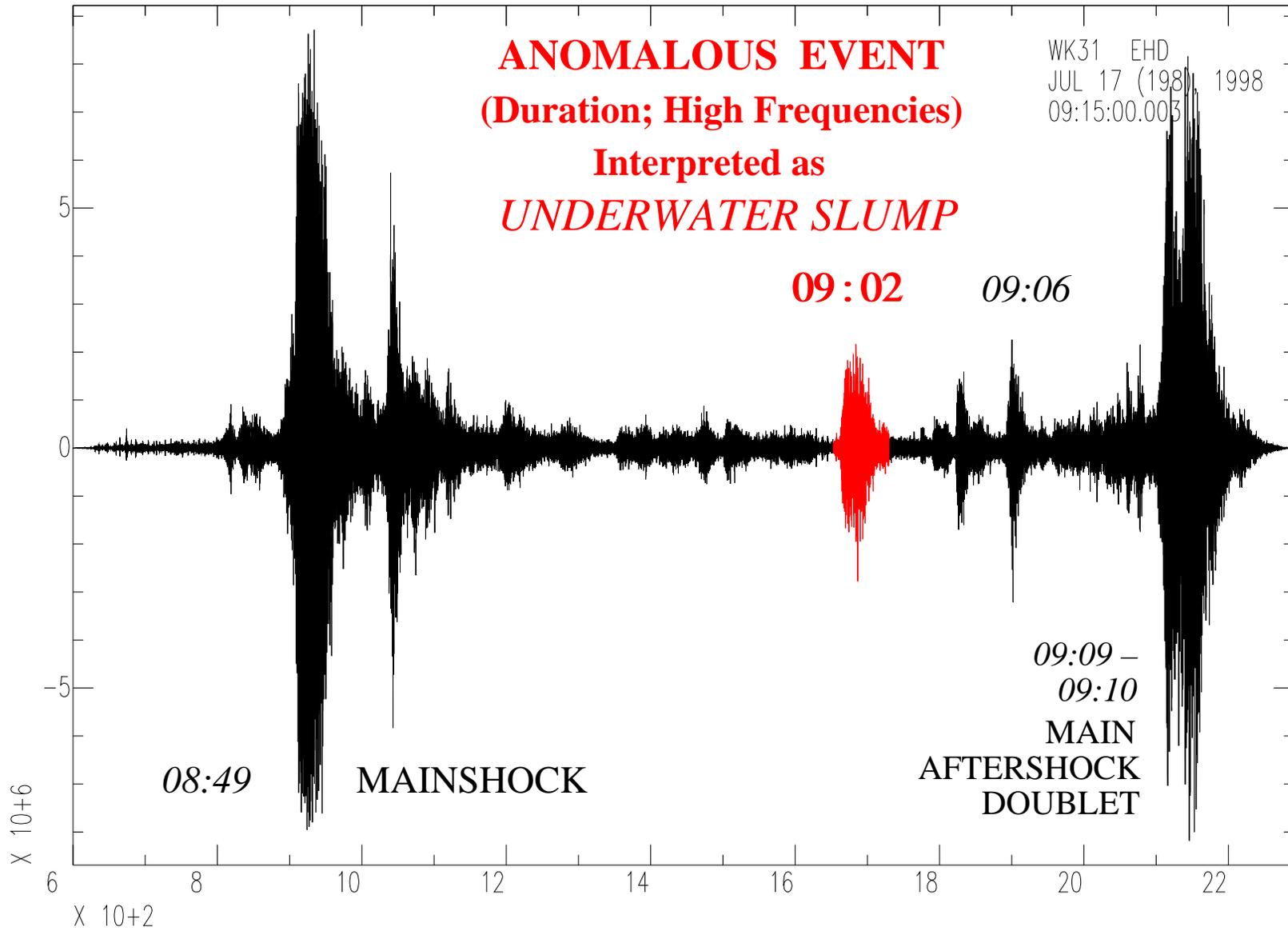
This essentially rules out the mainshock as a plausible source of the tsunami, and requires that its source take place

Some time between the mainshock (08:49) and the main aftershock (09:09).

WAKE ISLAND HYDROACOUSTIC RECORD -- 17 JULY 1998

09:25 GMT

09:53:11 GMT



Time after 09:15 GMT (hundreds of seconds)

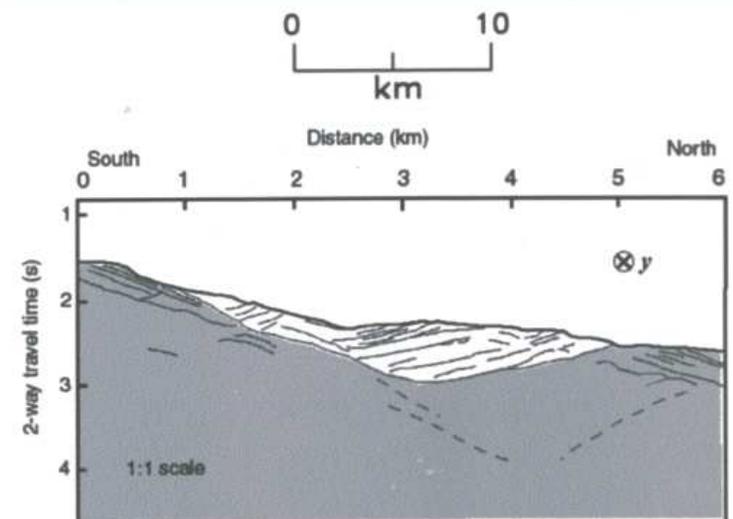
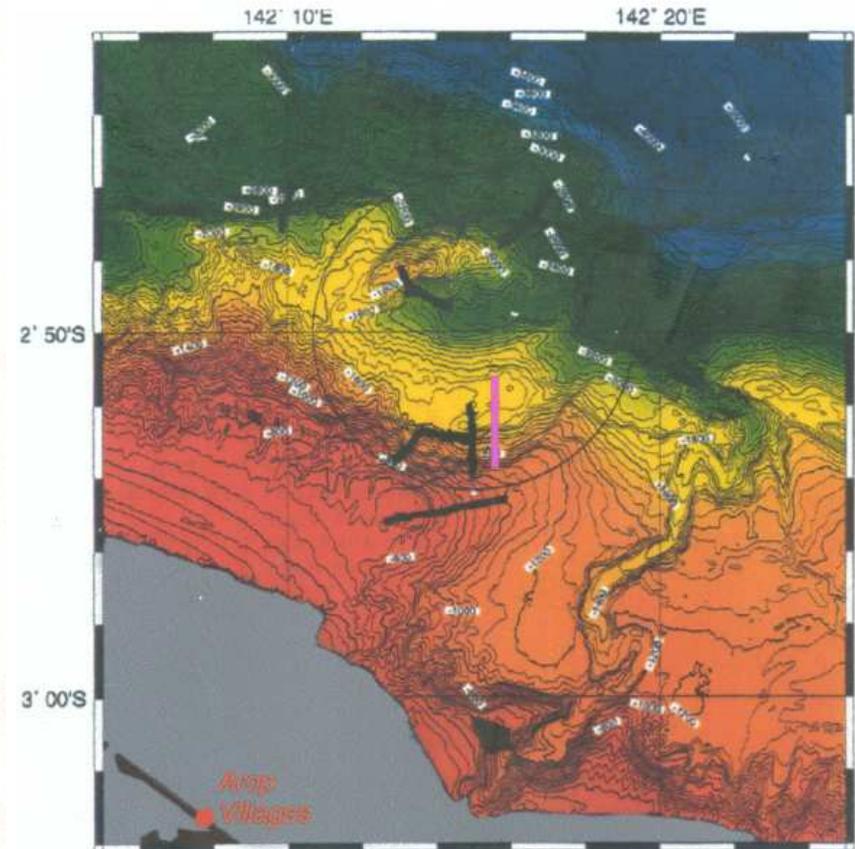
IT IS THERE !!!

THE SLUMP MODEL

We propose that the near-field PNG tsunami was generated by a massive, 4-km^3 underwater slump, triggered at 09:02 GMT, 13 minutes after the mainshock, inside a bowl-shaped amphitheater located approximately 25 km off shore from Sissano Lagoon.

This Slump....

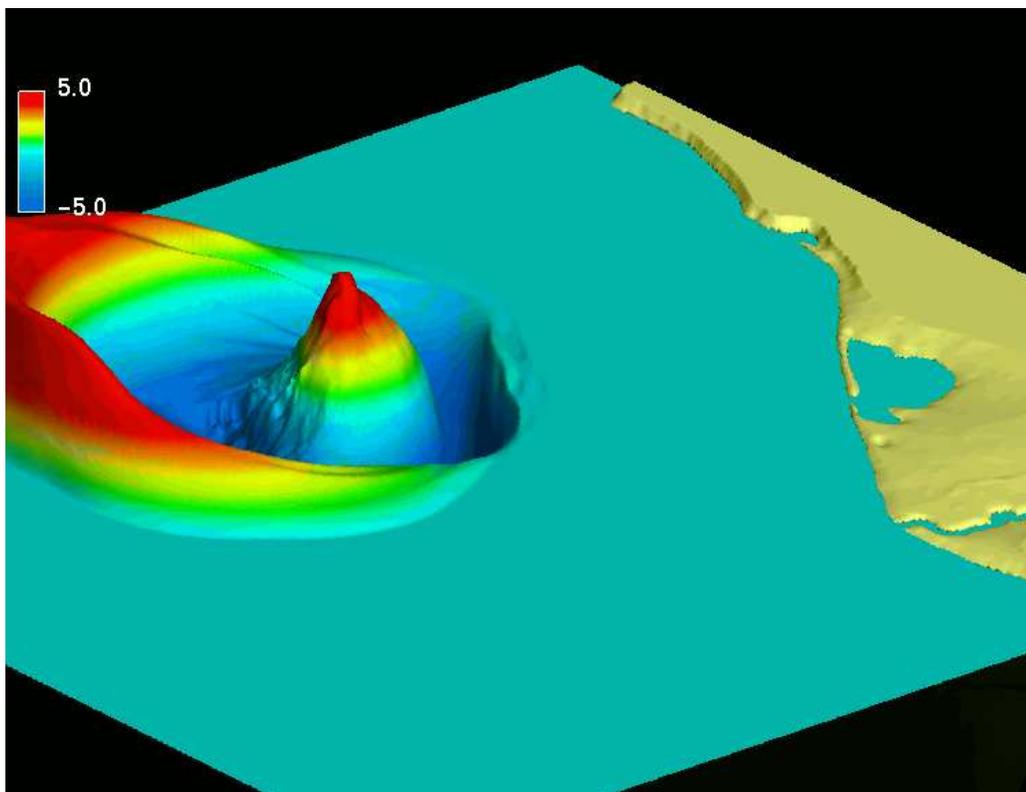
- is well documented in the bathymetry
- can be timed from its T waves recorded throughout the Pacific Basin
- gives the right arrival times of the tsunami at the shore
- predicts acceptable simulated models of run-up along the shore, including lateral distribution.



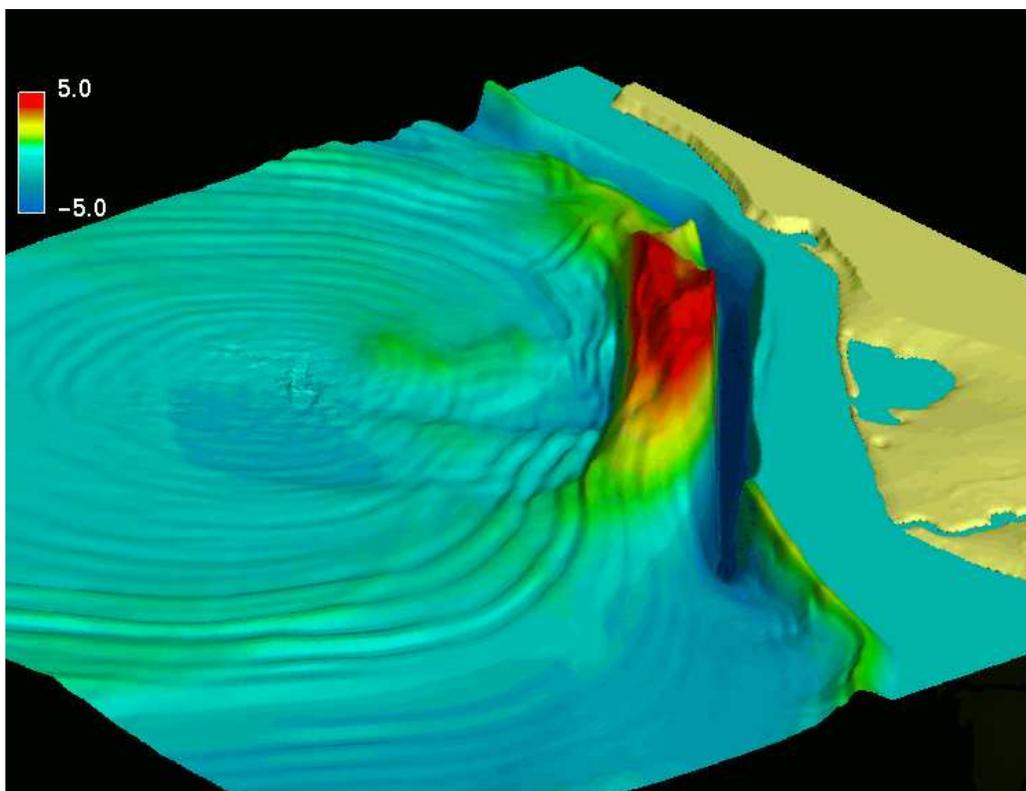
TSUNAMI SIMULATIONS — SLUMP SOURCE

[Heinrich et al., 2000]

Vertical exaggeration: 750



$t = 90$ s



$t = 360$ s

SIMULATION OF TSUNAMI ATTACK FROM UNDERWATER LANDSLIDE OFF L.A.-L.B. HARBOR

[Borrero et al., 2003]

320

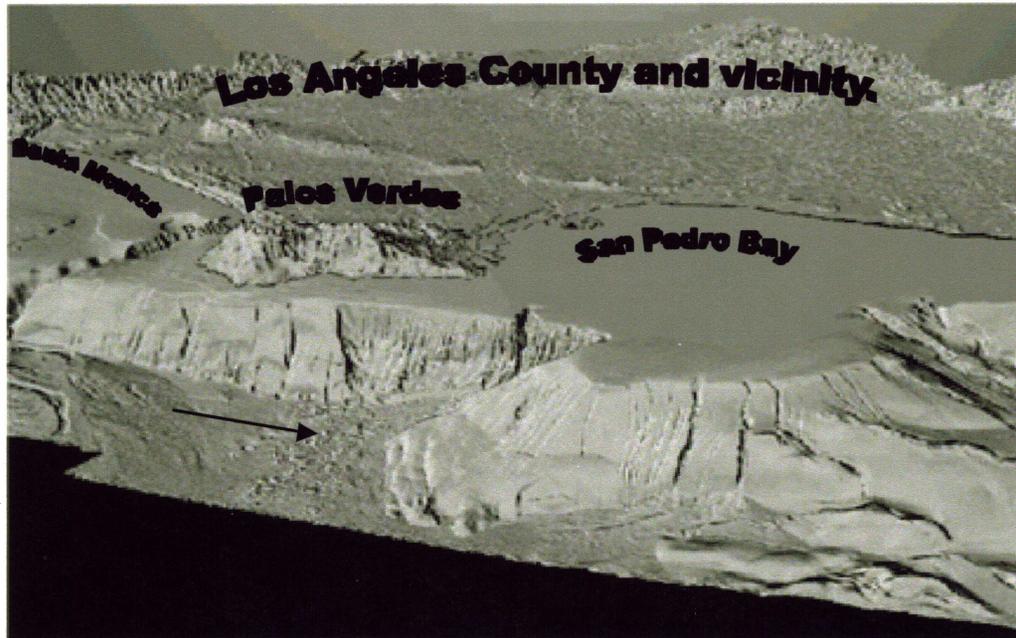


Figure 3. The bathymetry off Los Angeles, California. The Palos Verdes peninsula is seen on the left separating Santa Monica (left) and San Pedro bays (right). Various scarps suggestive of paleotsunami slides are shown including the PV debris avalanche.

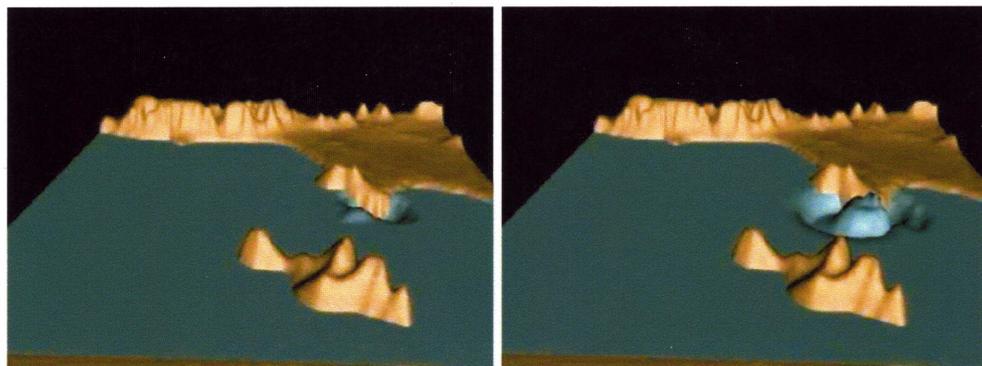


Figure 4. Two instances of the wave evolution off Palos Verdes to simulate the PV debris avalanche. Calculations of [13], animation images by Salim Pamukcu.

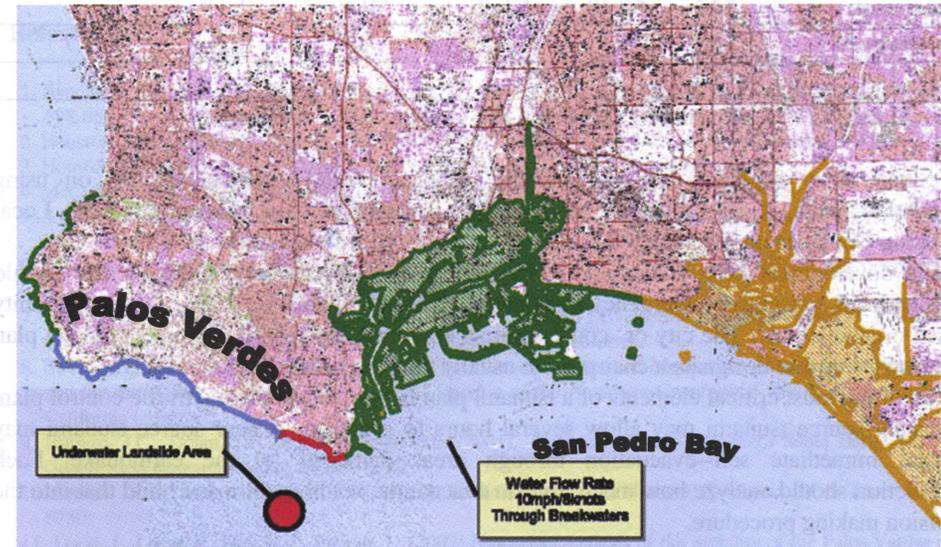
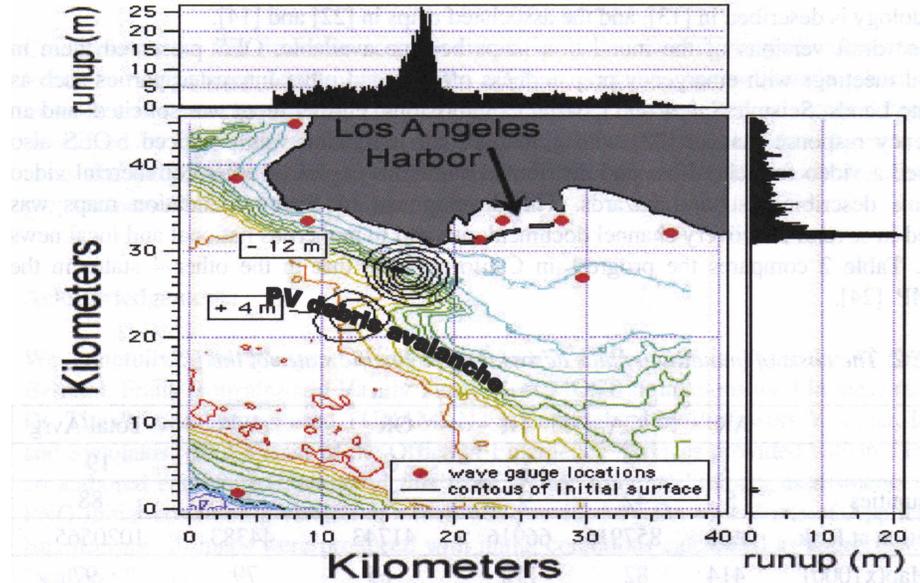
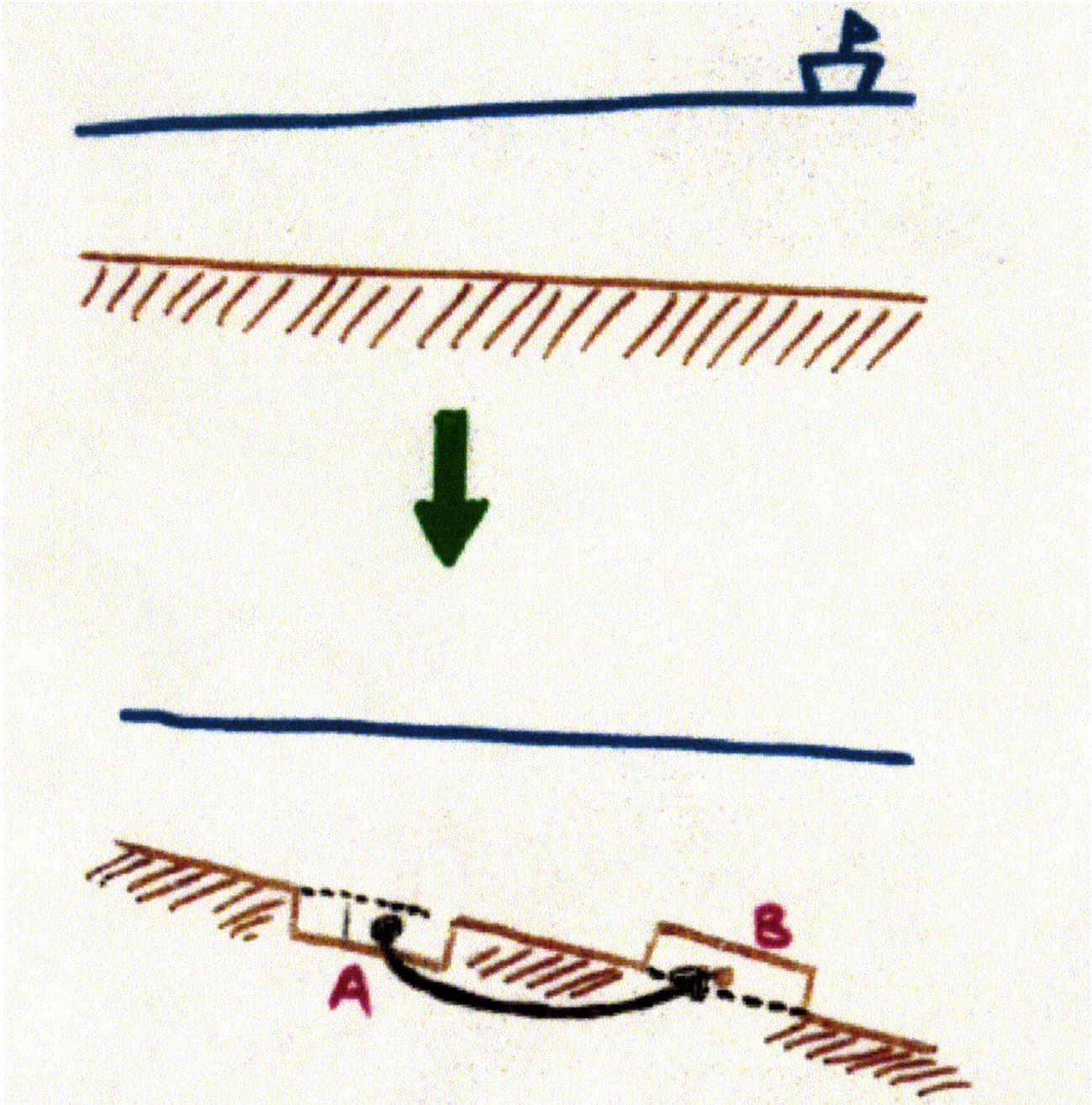


Figure 6. Predicted inundation from the PV debris avalanche. OES Estimates of the affected region comparing the impact of a tsunami attack (green) and of a scenario dam break (yellow).

THE CASE OF A SLUMP SOURCE



THE SLUMP SOURCE IS ESSENTIALLY

DIPOLAR

and it follows *DIFFERENT SCALING LAWS*

Remember, in all fields of Physics, a DIPOLE source is

- High frequency (space and time domain)
- Near field

In the case of tsunami waves, the landslide source will

- Allow larger values of the deformation δh relative to the extent L of deformation, hence, larger aspect ratios of the distribution of run-up along a local beach;
- Generate large wave numbers in the far field, hence higher frequencies, which suffer dispersion, and hence reduced amplitudes ("*No far field...*").

Source discriminants will consist

- In the near field, of the *Aspect Ratio* of runup along the beach;

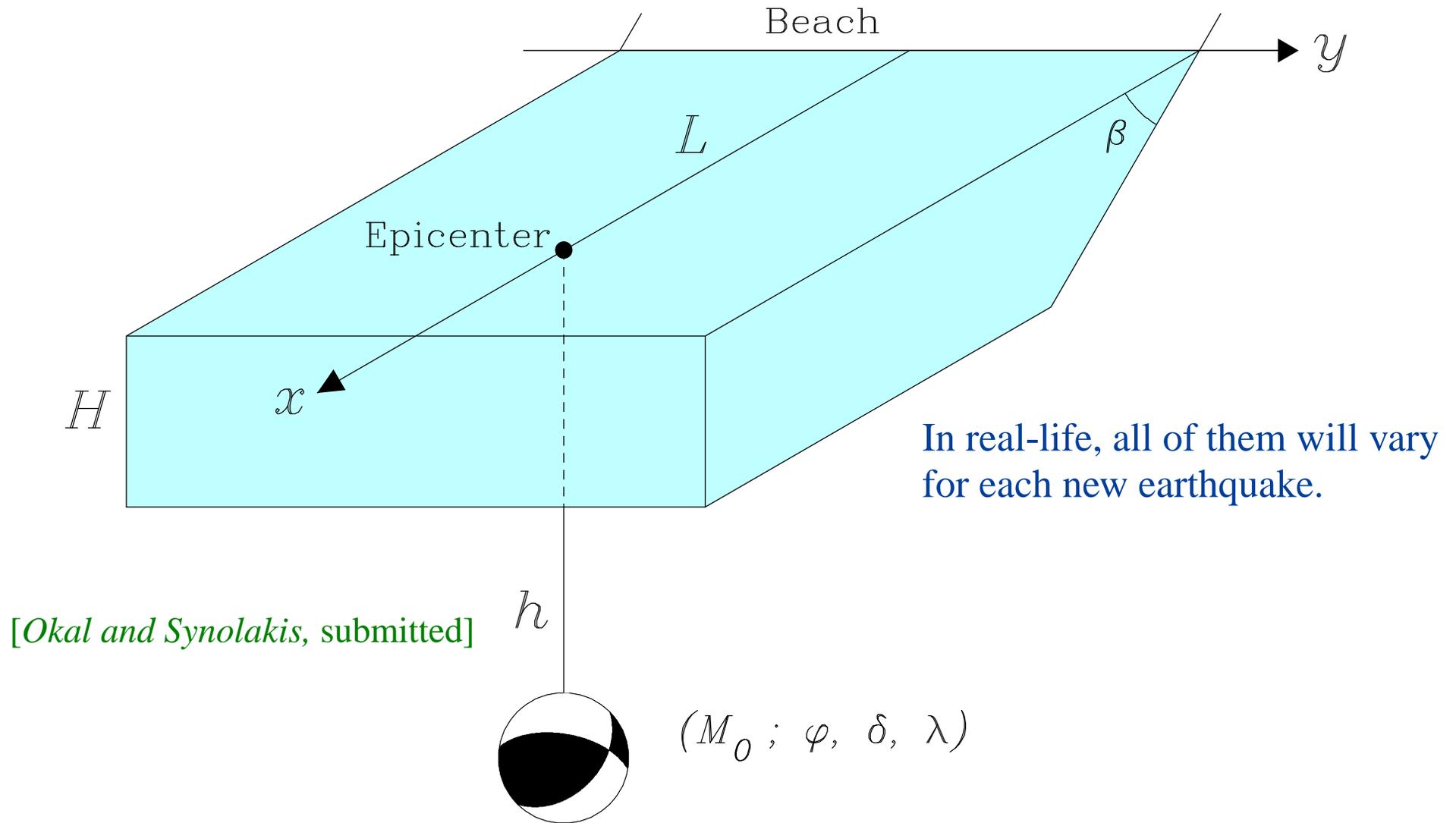
Any value greater than 10^{-4} precludes a dislocative source

- In the far field, of the *Azimuthal Directivity* of the wave field, expressing the variable interference due to finiteness of the source [*Ben-Menahem, 1962*].

Strong directivity requires a dislocation

THE DISLOCATION SOURCE in the NEAR FIELD

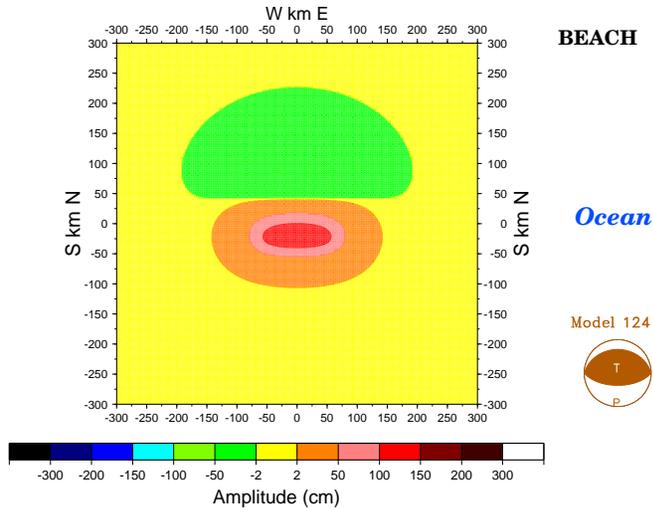
A full description requires at least 8 parameters.



We explore systematically their influence on run-up and seek to define INVARIANTS

NEAR-FIELD: *The Earthquake Dislocation*

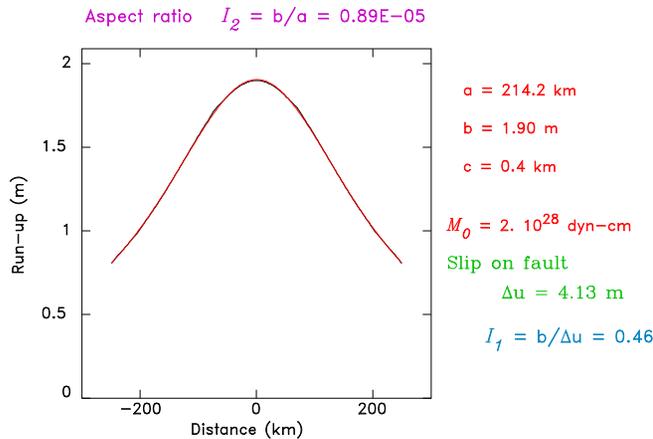
- Compute Ocean-Bottom Deformation due to Dislocation



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

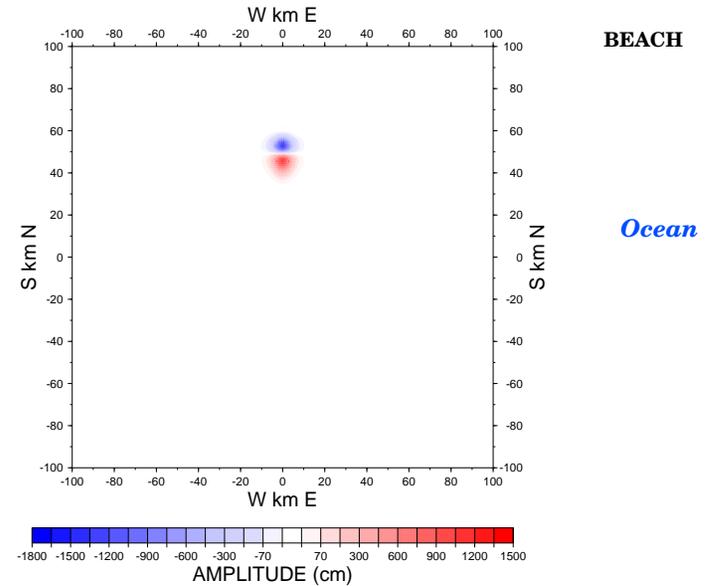
$$\zeta = \frac{b}{\left(\frac{x-c}{a}\right)^2 + 1}$$



- Retain aspect ratio $I = b/a$
- Vary source parameters: I no greater than 2.3×10^{-5} .

NEAR-FIELD: *The Landslide Source*

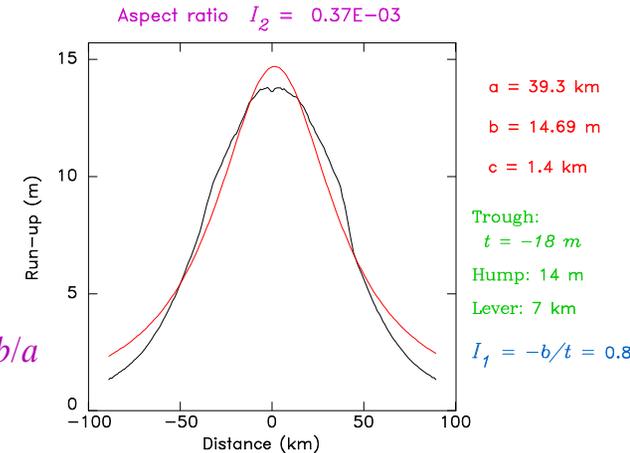
- Compute Ocean-Surface Deformation due to Landslide



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

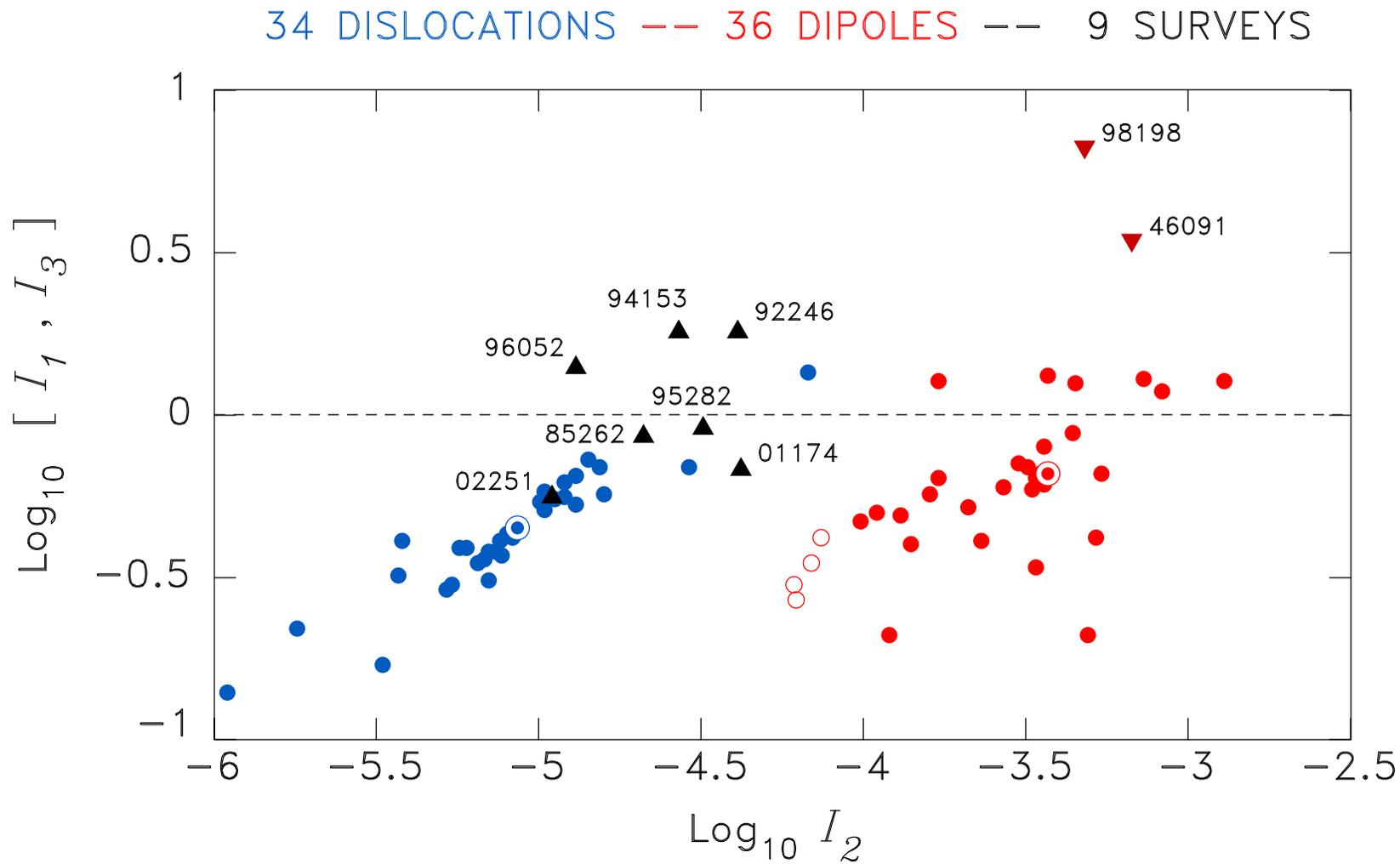
$$\zeta = \frac{b}{\left(\frac{x-c}{a}\right)^2 + 1}$$



- Retain aspect ratio $I = b/a$
- Vary source parameters: I greater than 10^{-4} .

$I = b/a$ CAN SERVE AS DISCRIMINANT

MAX. RUN-UP SCALED TO FAULT SLIP
MAX. RUN-UP SCALED TO INITIAL TROUGH



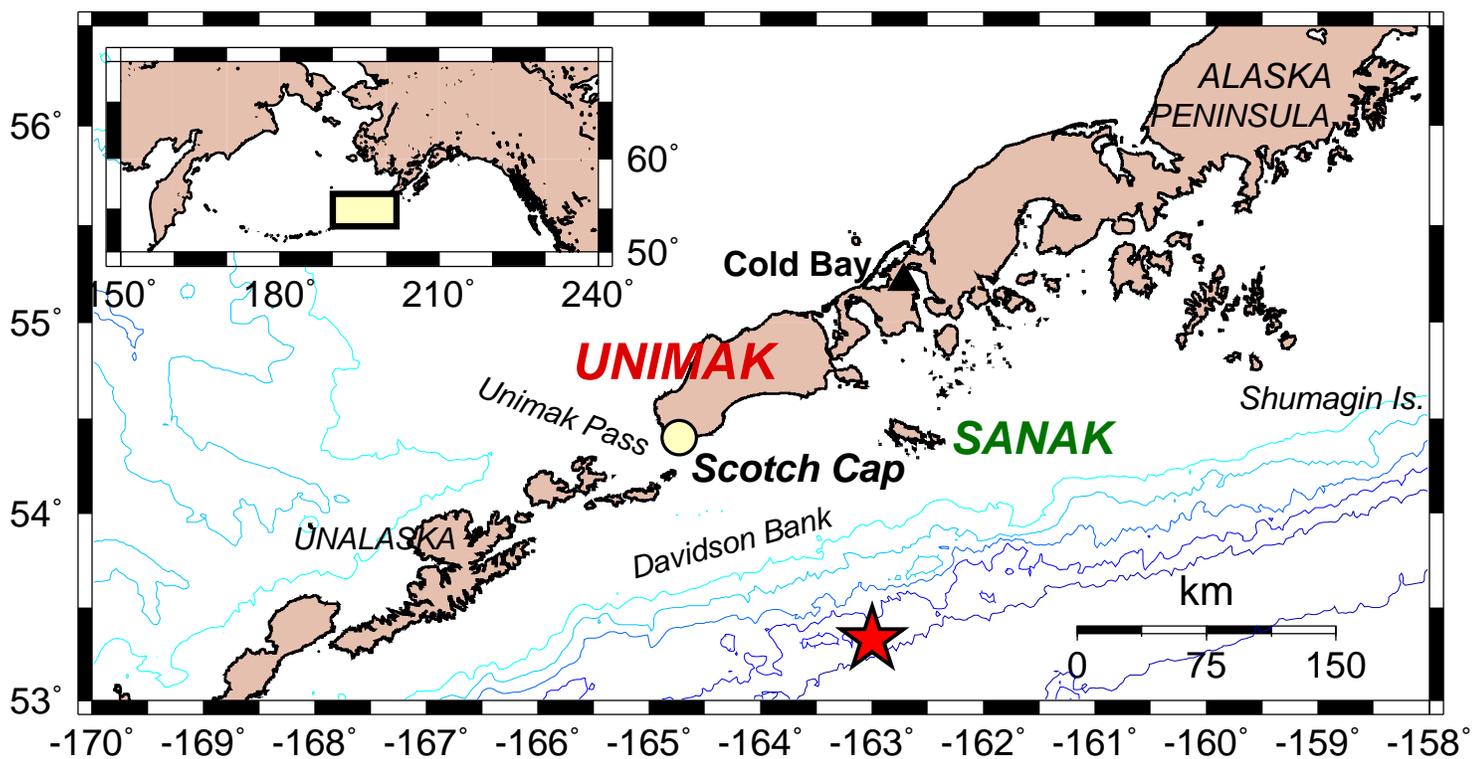
ASPECT RATIO OF RUN-UP DISTRIBUTION ALONG BEACH

[Okal and Synolakis, submitted]

THE 1946 ALEUTIAN TSUNAMI: A PERSISTING CHALLENGE

- A rather moderate earthquake ($M_{PAS} = 7.4$)
- A devastating transpacific tsunami
- A catastrophic local tsunami

Scotch Cap lighthouse eradicated.



THE QUESTION REMAINS

How to model the source of the tsunami: A gigantic earthquake source, or a large underwater landslide, triggered by the seismic event?

DESTRUCTION OF THE LIGHTHOUSE AT SCOTCH CAP, UNIMAK Is.

[Photog. *H. Hartman*; Courtesy G. Fryer]

Before (1945)



After (est. 03-04 (?) Apr. 1946)



1946 ALEUTIAN TSUNAMI FIELD WORK

Emile A. Okal, 1999–2001

- In order to test adequate hydrodynamic models of the source, it is necessary to gather more inundation and run-up data, both in the near and far fields.
- The challenge is do this more than 50 years after the event...
- In the far field, we examine unreefed "high" (volcanic) islands, principally the Marquesas, with a record of high run-up amplitudes.

We found out that [elderly] *witnesses* of the tsunami keep sharp memories of the disaster, allowing us to measure 54 new data points on six Marquesan Islands, Easter and Juan Fernández.
- In the near field, we take a pilgrimage to Scotch Cap, to conduct an *in situ* survey, based on available 1946 Coast Guard reports from the Radio Station.

We obtained 29 new data points.

THE FAR FIELD (Marquesas Islands)

GETTING THERE...

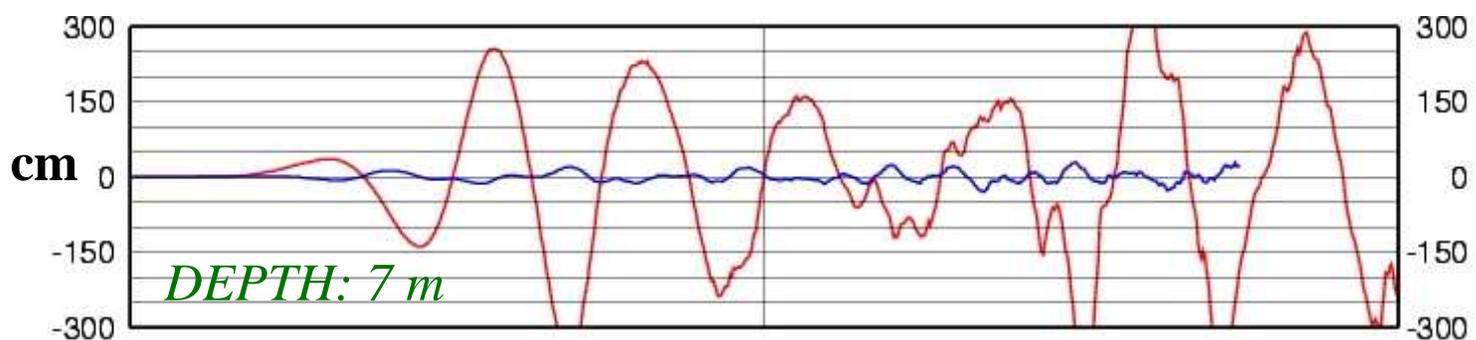
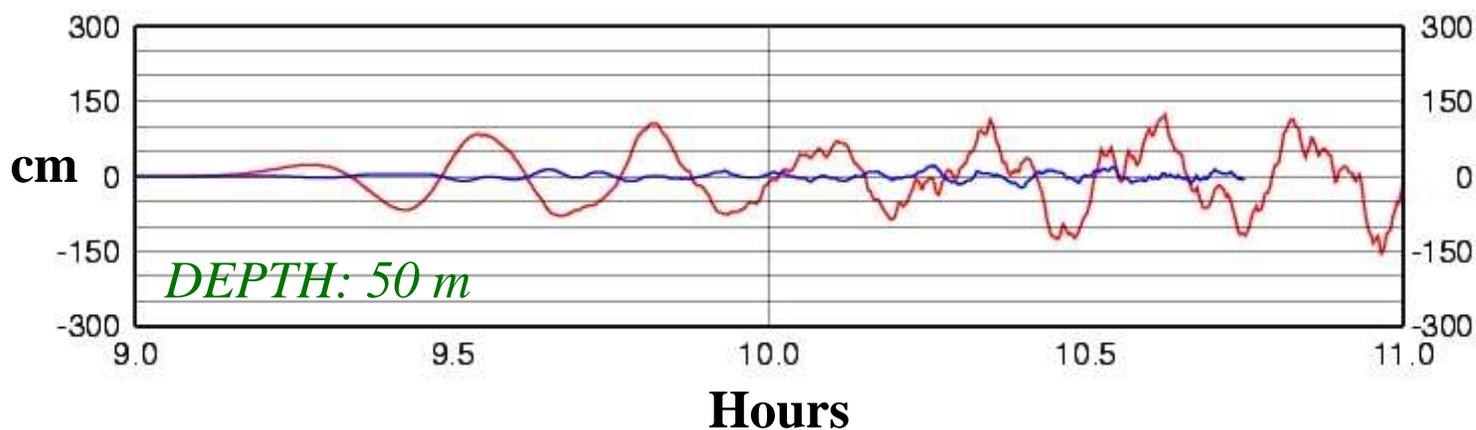


EXAMPLES OF SYNTHETIC MAREGRAMS

These plots compare synthetic maregrams for the dislocation (earthquake) and dipolar (landslide) sources at virtual gauges located at in Taiohae Bay, Nuku Hiva (Marquesas), over water depths of 7 and 50 meters, respectively.

**DISLOCATION
(EARTHQUAKE)**

**DIPOLE
(LANDSLIDE)**



Note

- (i) the much lower amplitude of the dipolar wave;
- (ii) the lack of response of this [large] bay to the shorter wavelengths of the dipolar wave.

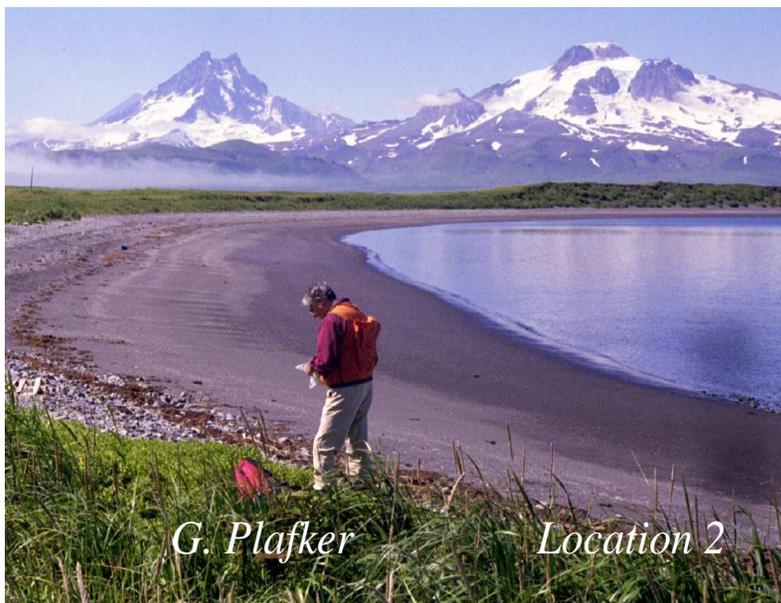
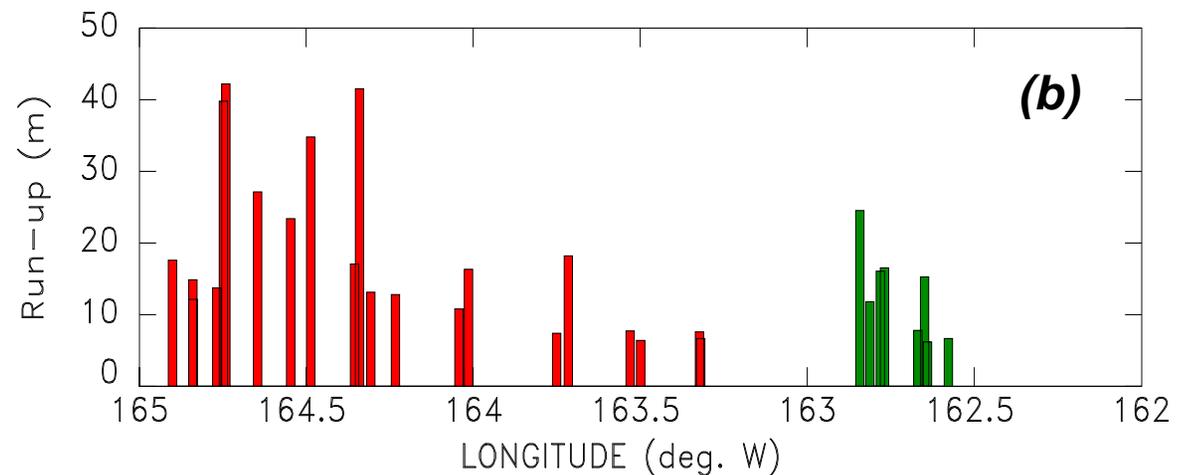
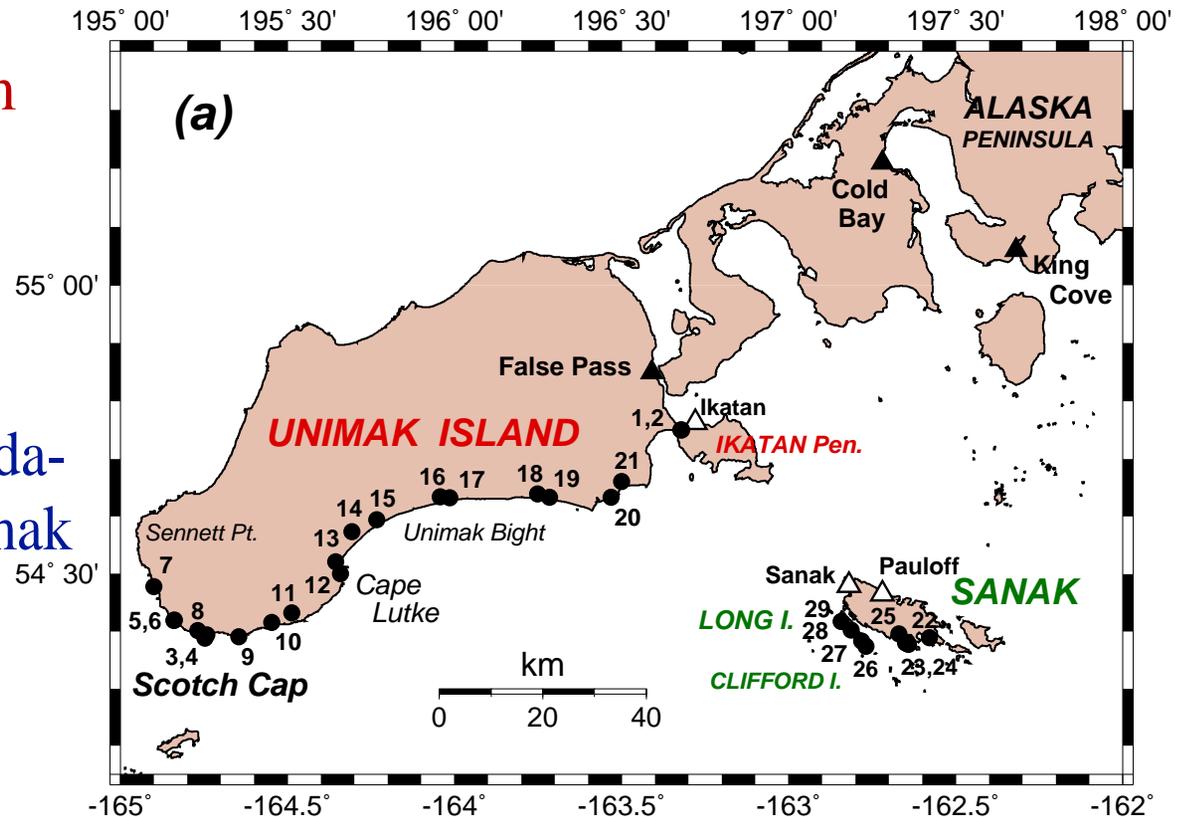
The Near Field (UNIMAK Is.)

GETTING THERE



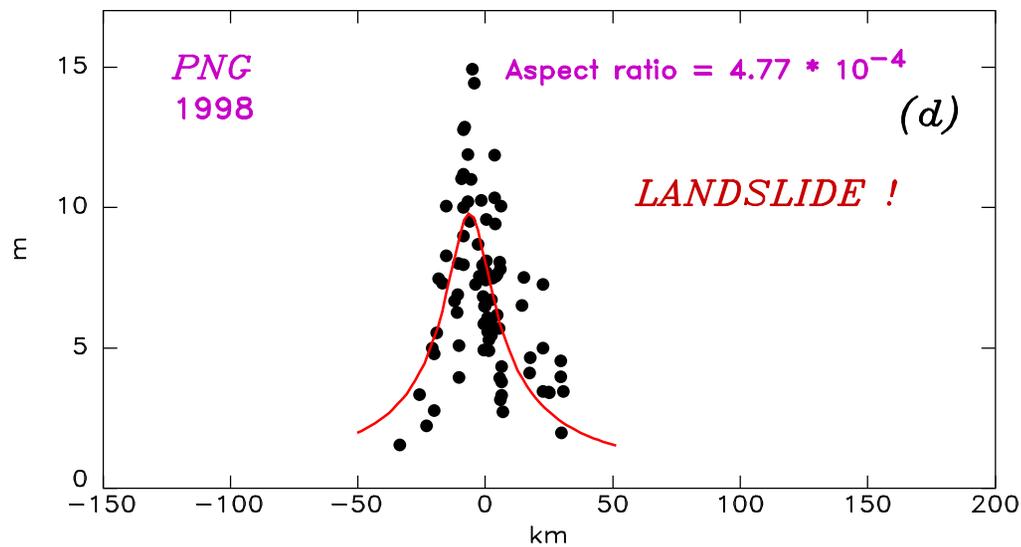
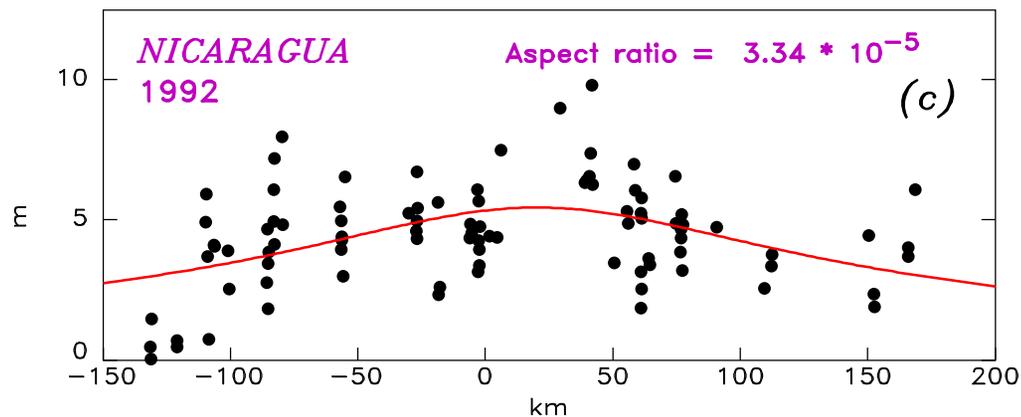
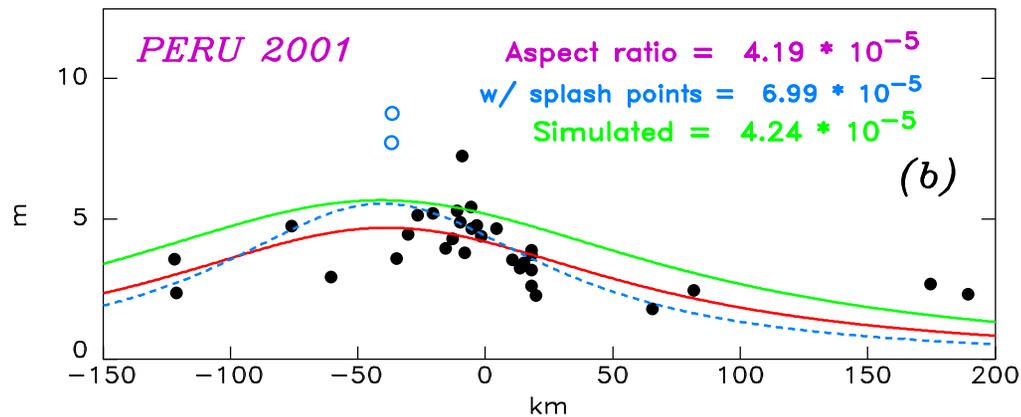
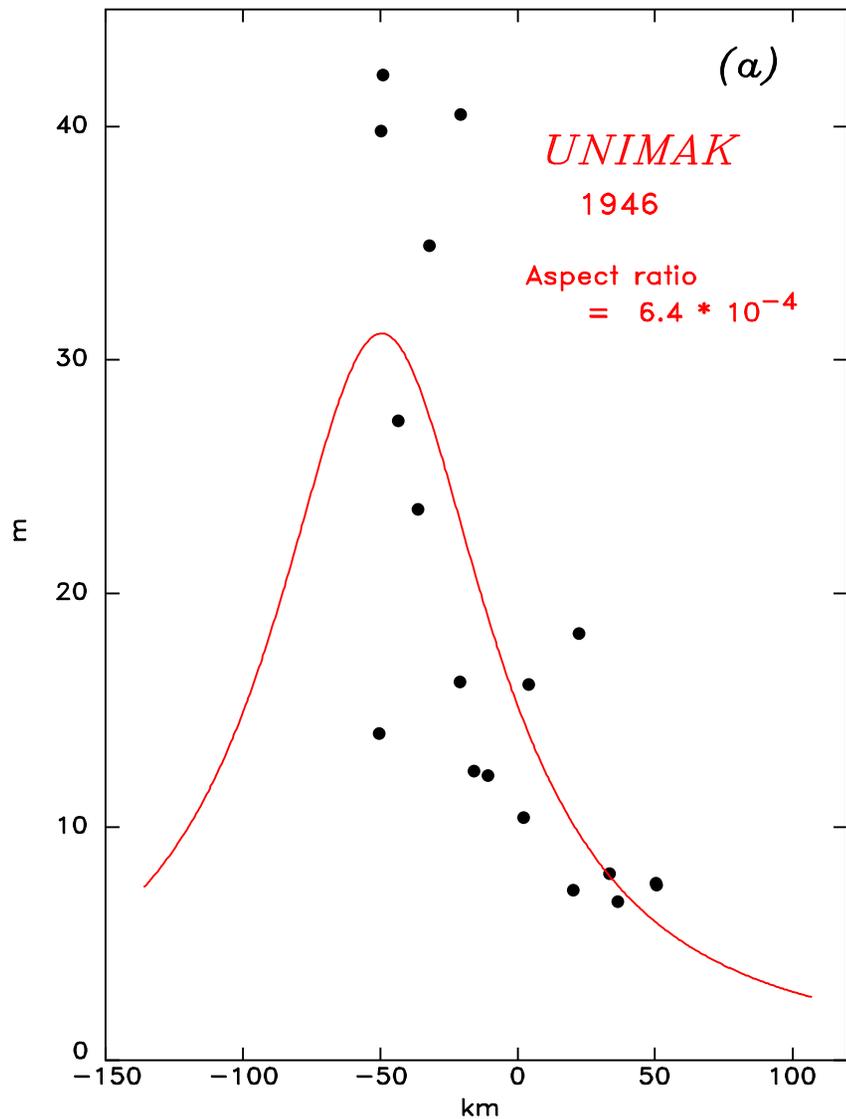
1946 RESULTS IN NEAR FIELD

- Run-up at Scotch Cap: 42 m (Ruins of Radio Station)
- Extreme run-up concentrated along 40 km of coast line.
- Run-up "only" 15 m, but inundation up to 2 km along Unimak Bight
- Run-up up to 24 m on Sanak



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

REQUIRING LANDSLIDE SOURCE



PRELIMINARY CONCLUSION of 1946 SURVEYS

- The exceptional amplitudes in the near field (42 m) require generation by an underwater landslide.
 - The far-field dataset features both amplitude and directivity requiring generation by a large seismic dislocation.
- Numerical simulations adequately predict most observables using acceptable parameters for both sources.

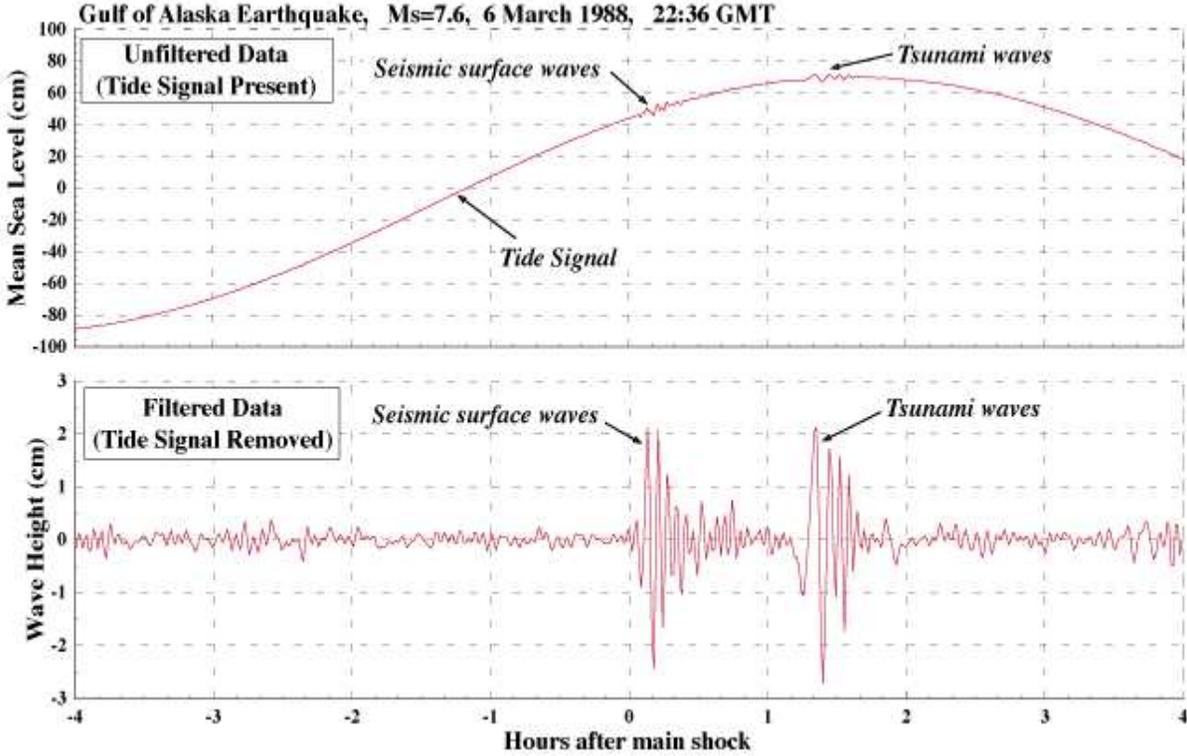
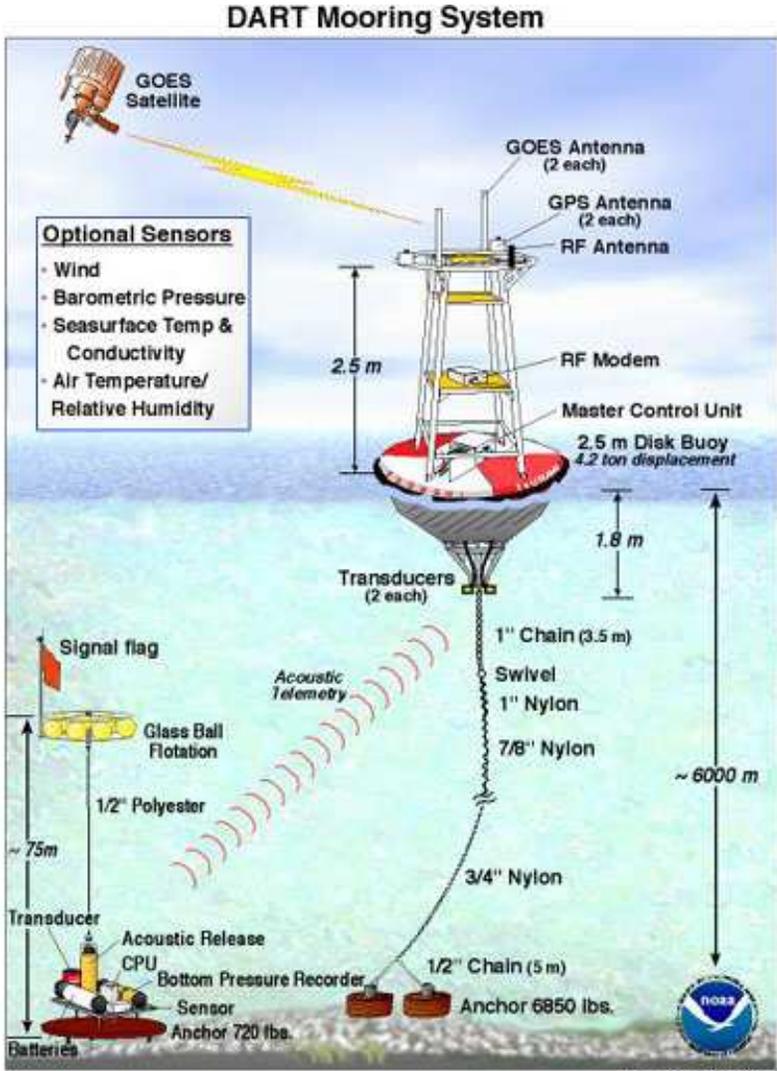


TOWARDS DIRECT DETECTION of a TSUNAMI on the HIGH SEAS

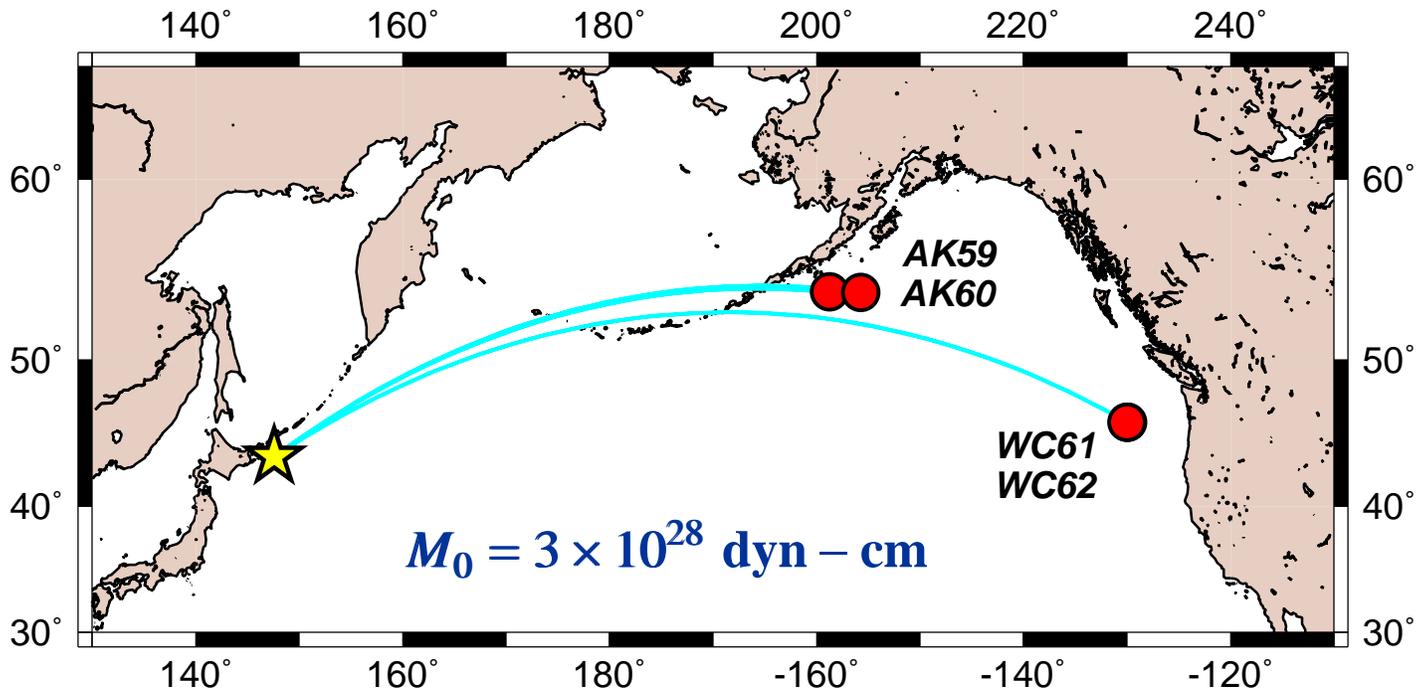
1. DEEP-OCEAN ASSESSMENT & REPORTING of TSUNAMIS

PMEL - NOAA, Seattle (E.N. Bernard; F.I. Gonzalez; H.B. Milburn)

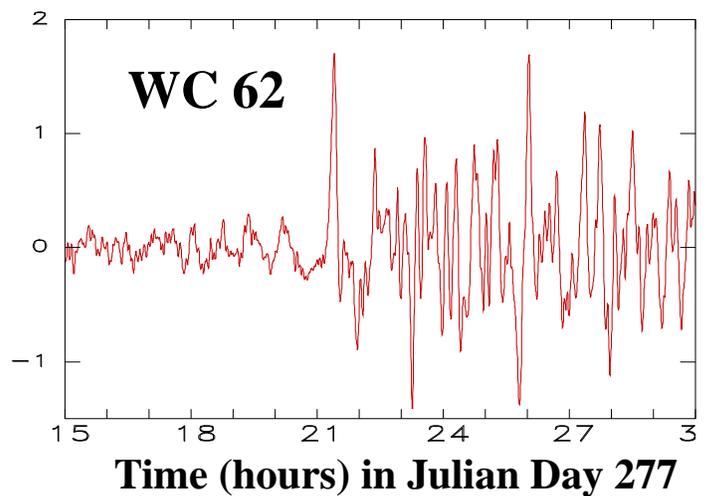
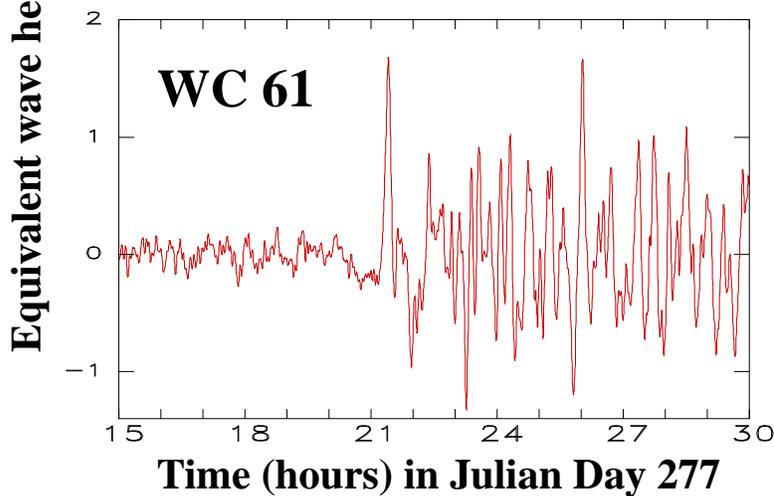
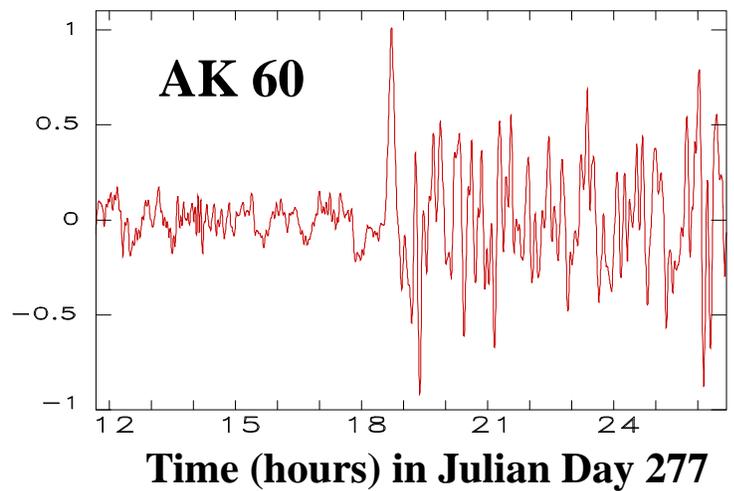
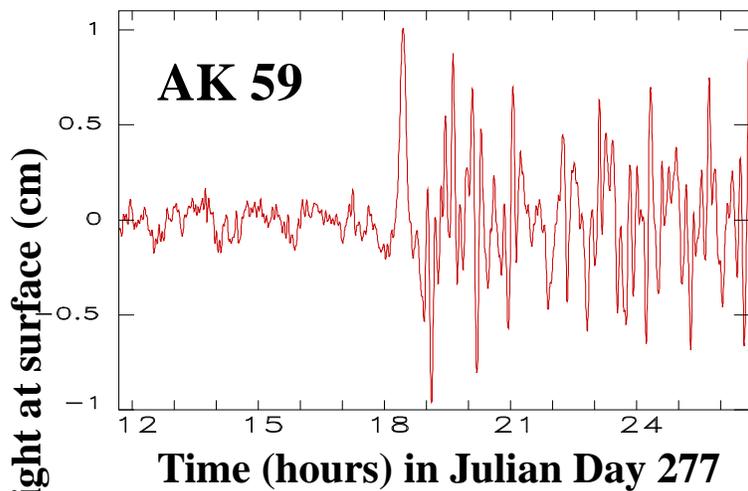
- Use pressure sensor at the bottom of the ocean to detect the overpressure caused by the passage of the tsunami.
- Relay information by satellite through buoy.



Case Study: KURIL ISLANDS, 04-OCT-1994



To date, Largest Event Recorded by DART

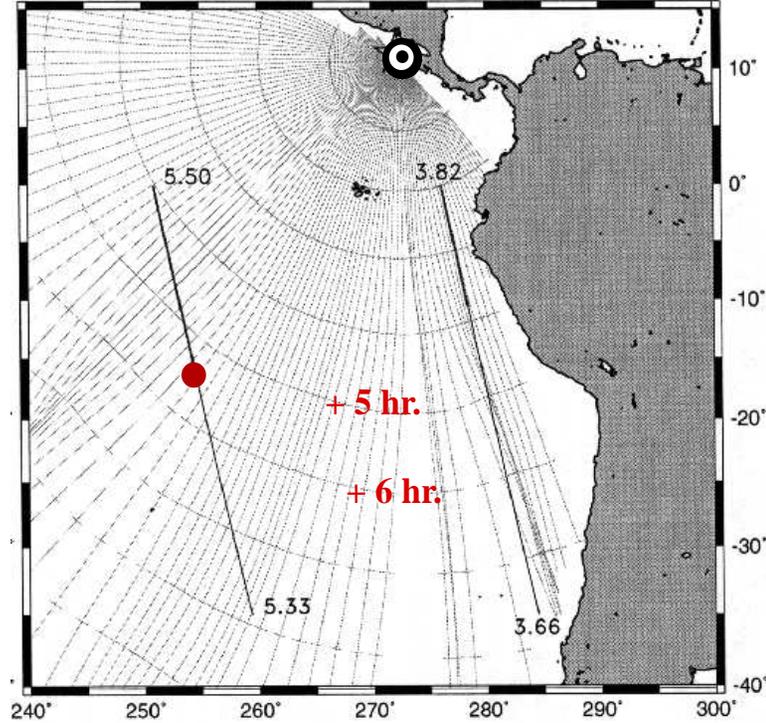


TOWARDS DIRECT DETECTION of a TSUNAMI on the HIGH SEAS

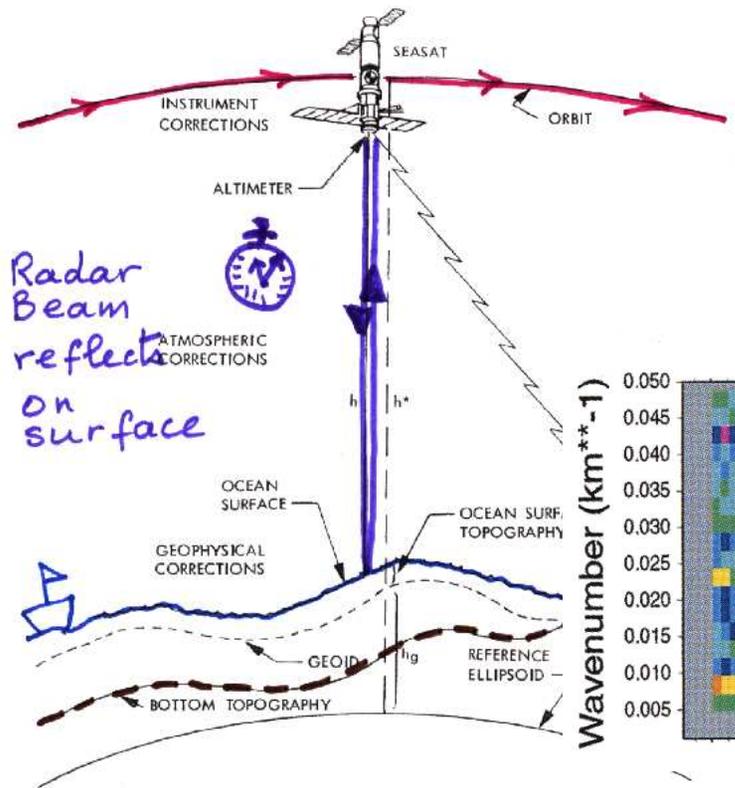
2. TSUNAMI DETECTION by SATELLITE ALTIMETRY

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

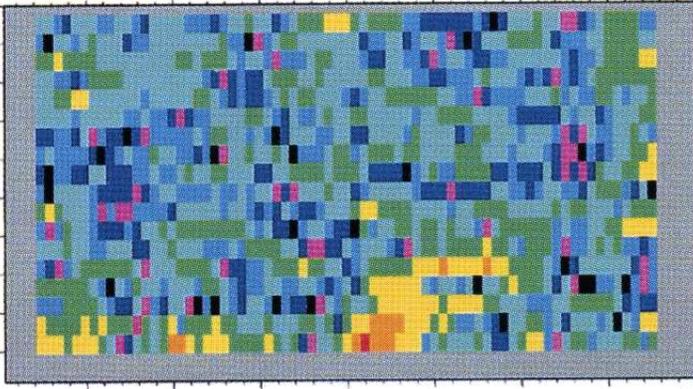
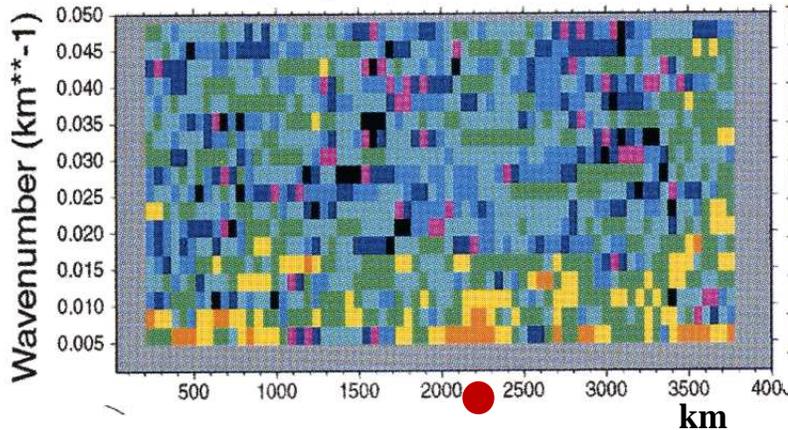
- Altimetric satellites constantly map sea-surface height variability
 - Tsunami wave may be detected if satellite flies over it.
 - 8-cm signal confirmed for 1992 Nicaragua tsunami.
- *Problem: Satellite must be at right place at right time...*



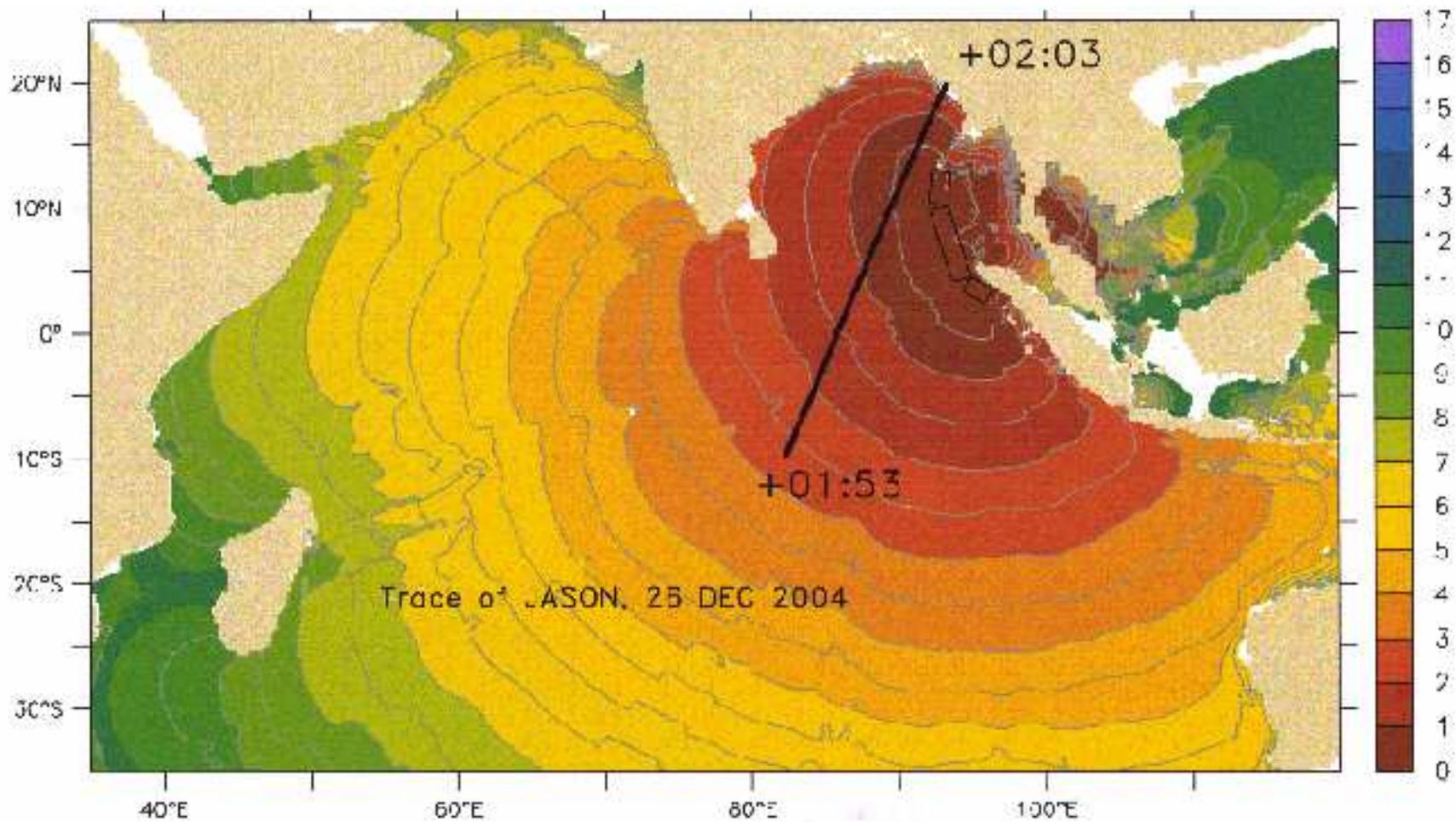
Track Number 525 Track Number 523
SYNTHETIC (8 cm)



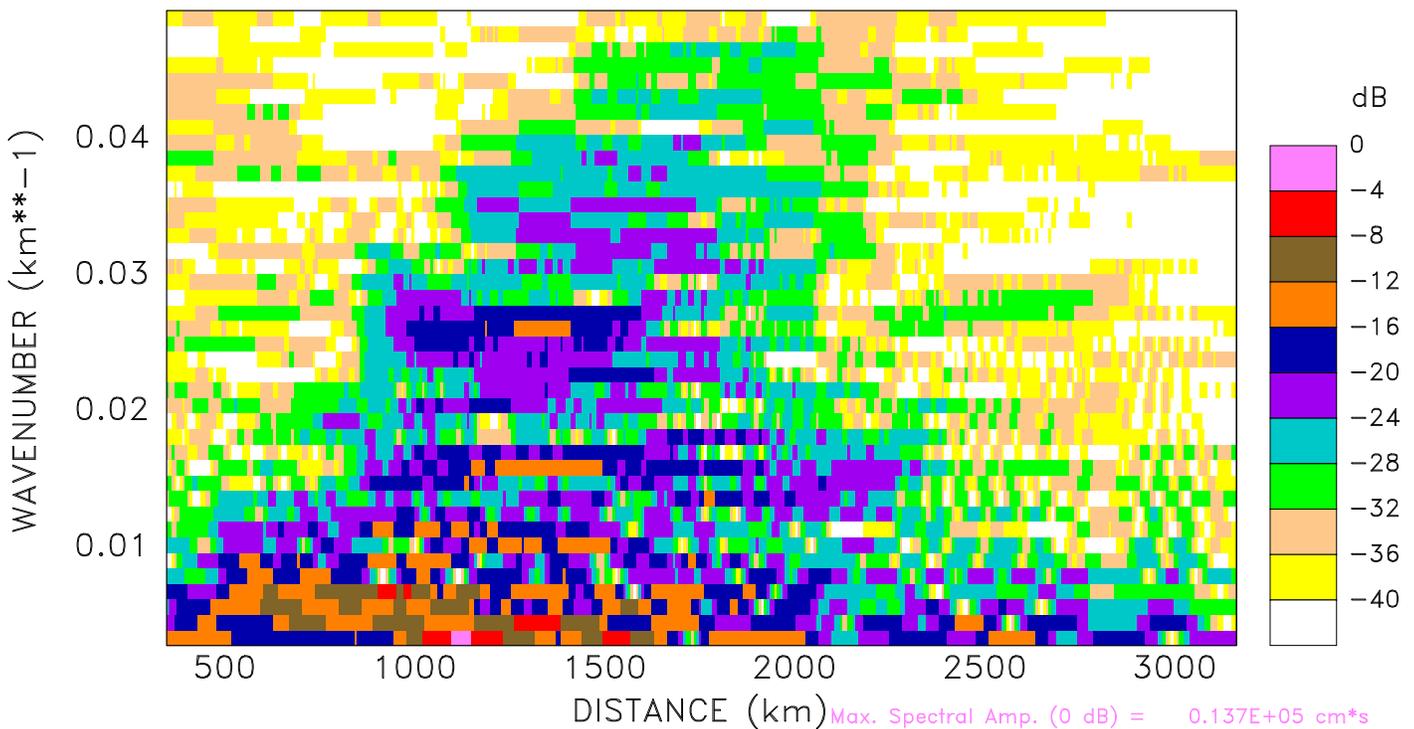
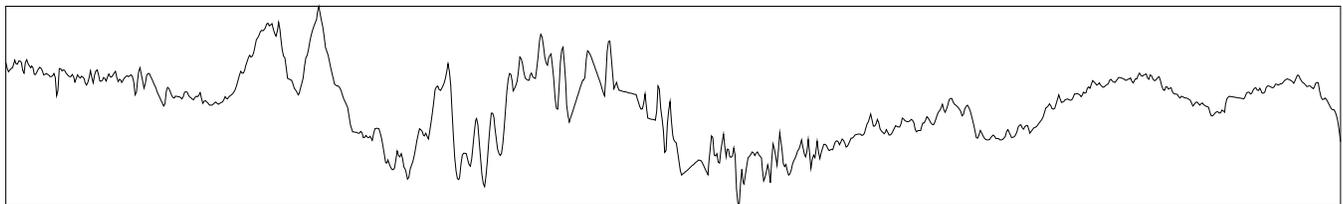
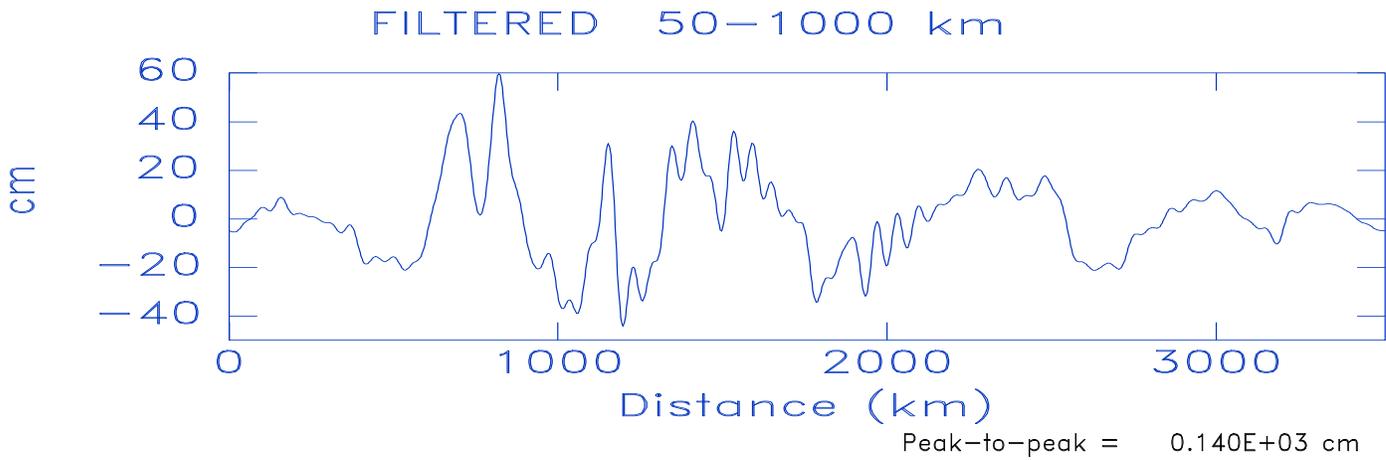
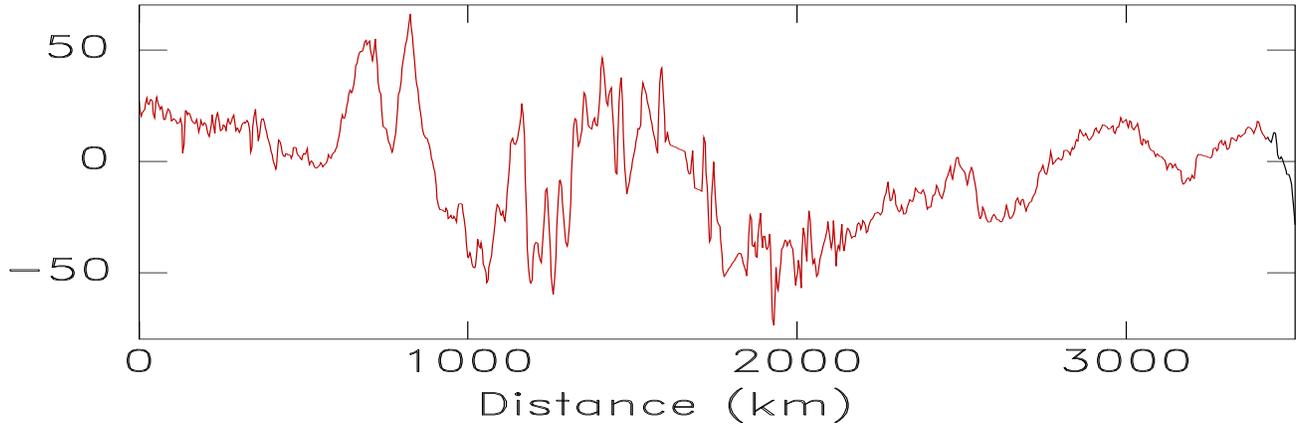
(a): Cycle 005 -- 02 SEP 1992



TRACE of ALTIMETRY SATELLITE OVER INDIAN OCEAN



DETECTION of TSUNAMI by JASON, 26 DEC 2004



NUMERICAL SIMULATION FITS JASON PROFILE REMARKABLY

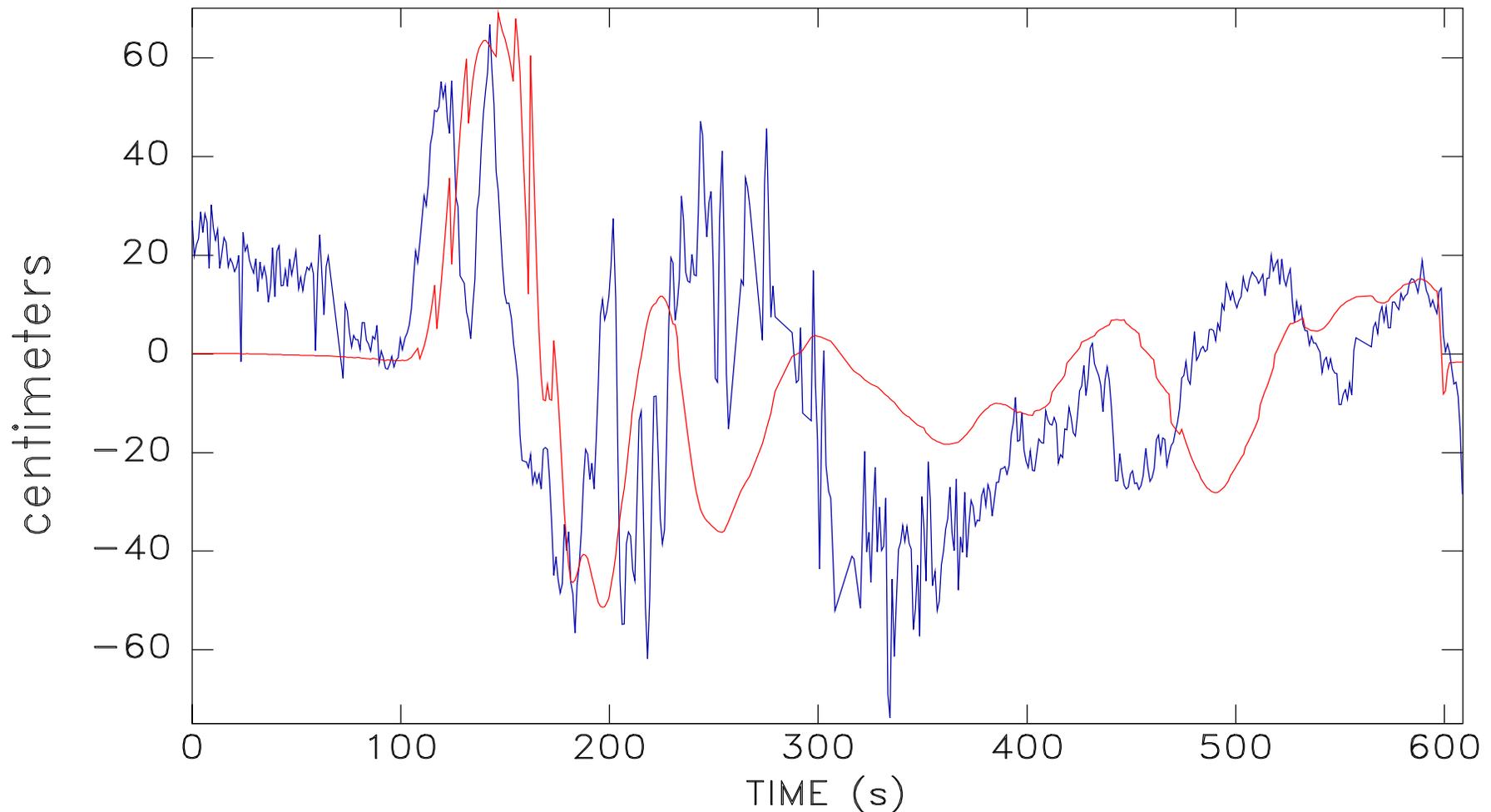
... Using "LONG" (1000 km +) Rupture Fault

OBSERVED (Jason)

[*M. Ablain*, pers. comm., 2005]

SIMULATED (NOAA)

[*V.V. Titov*, pers. comm., 2005]

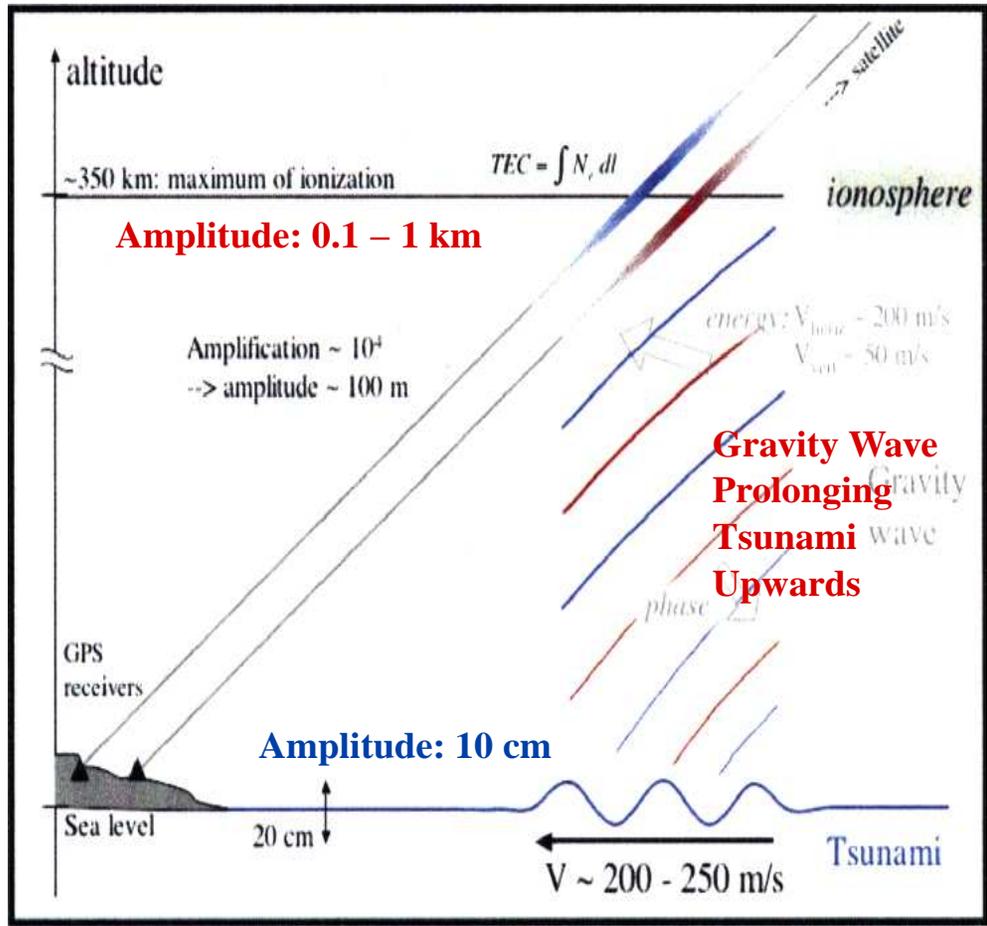


TOWARDS DIRECT DETECTION of a TSUNAMI on the HIGH SEAS

3. 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 ($h = 150\text{--}350$ km) detectable by GPS.



28 MAR 2000 -- 90 mn after earthquake

