LECTURE 1

TSUNAMIS: GENERAL

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

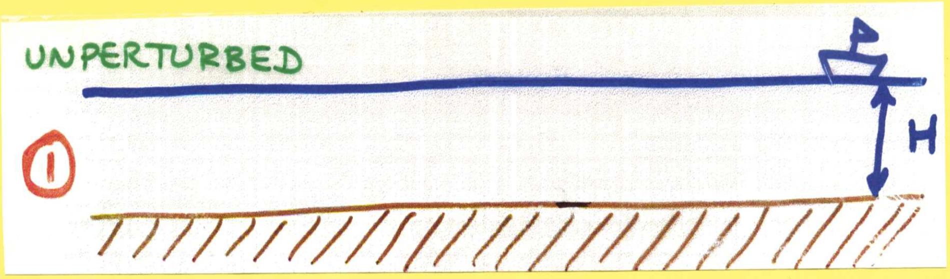
→ Maremoto [Spanish, Italian]

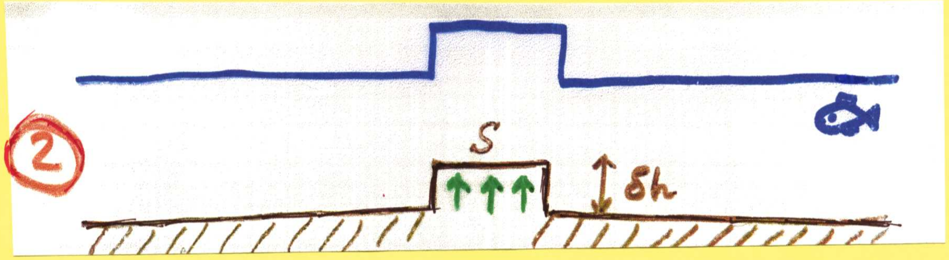
→ Taitoko [Marquesan]

→ Tsu Nami (Harbor wave) [Japanese]

TSUNAMI GENERATION

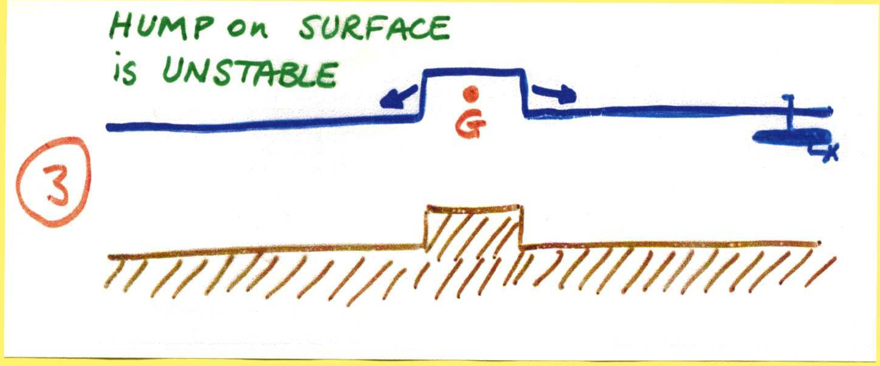
The Earthquake

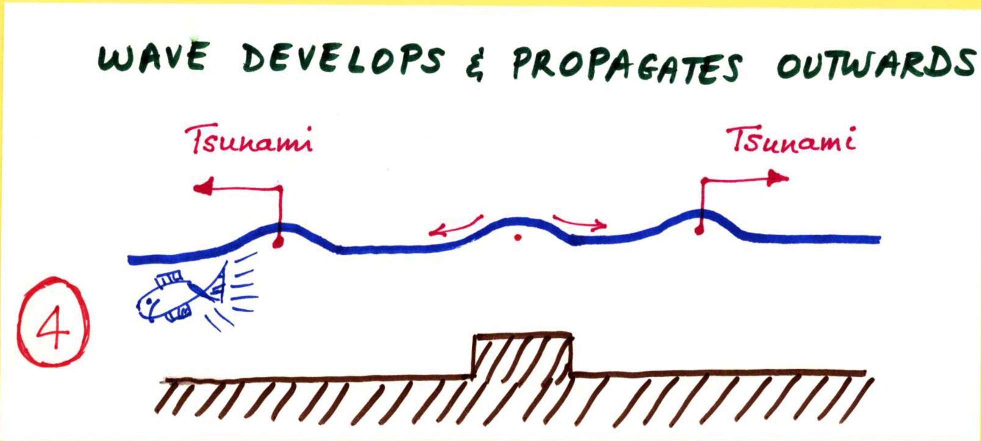


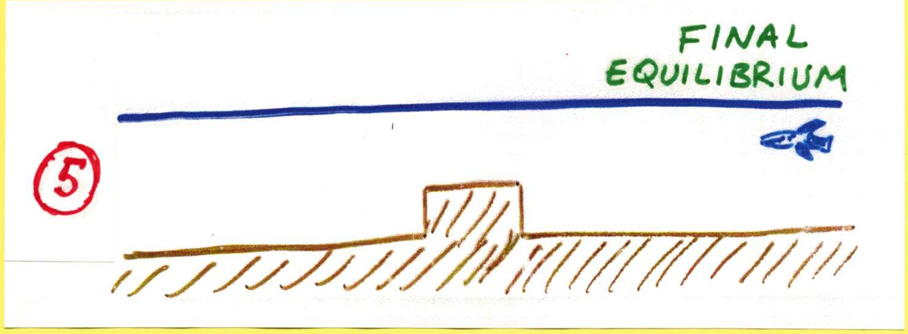


Earthquake deforms ocean floor and displaces it vertically into water mass.

HUMP SHOULD APPEAR ON SURFACE MIRRORING BOTTOM DEFORMATION

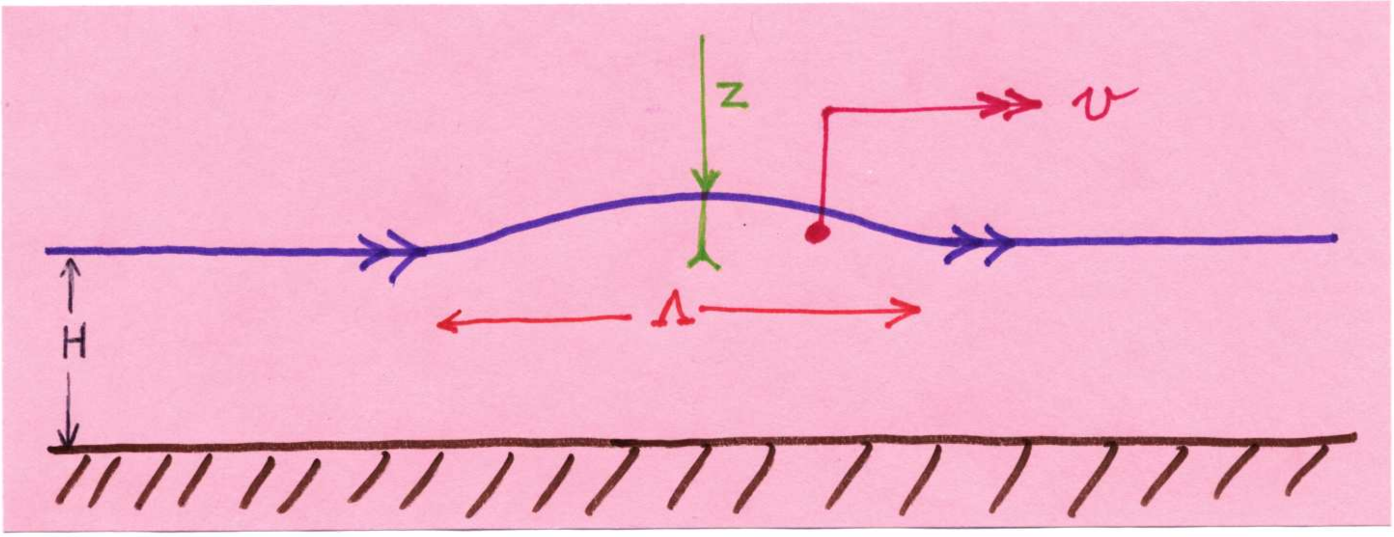






TSUNAMI WAVE CHARACTERISTICS

- *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

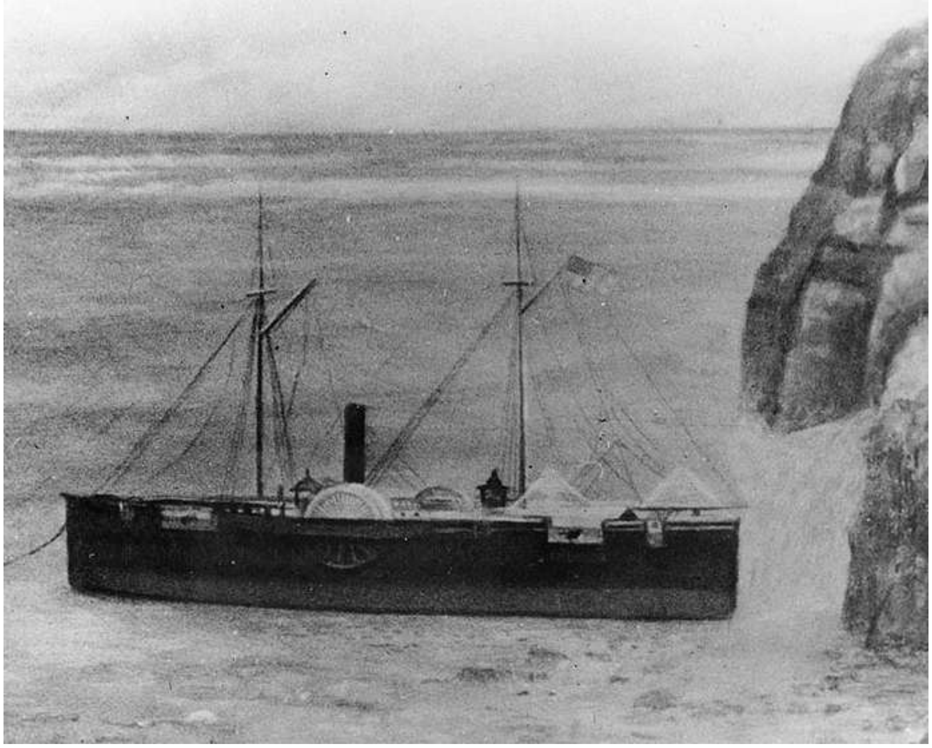
(PERIODS: 600 to 3000 s)

- *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.



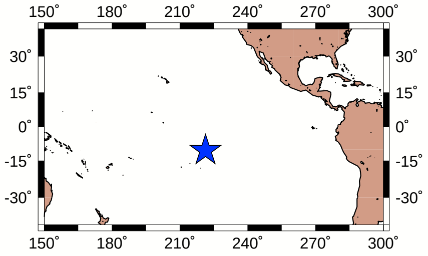
[U.S. Navy]

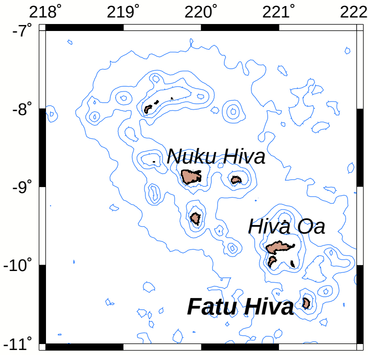
On 13 August 1868, during the Arica, Peru earthquake and tsunami, the *USS Wateree* was moved 3 km inland, and stopped only by the presence of cliffs. On 09 May 1877, a new tsunami moved its remains back to the shoreline, where the boilers where left to rust for more than 100 years.

TSUNAMI GENERATION (ctd.)

Landslides

Fatu Hiva, Marquesas Islands, 13 September 1999



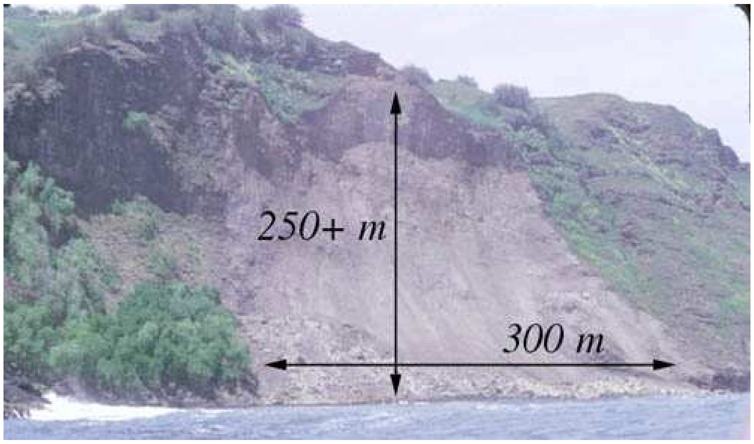


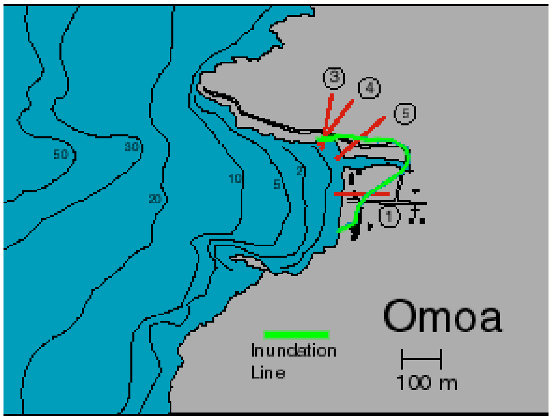
The beachfront school house at Omoa was severely flooded by two "rogue" waves which also destroyed the ice-making plant and several canoe shacks and copra-drying stands.

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

1999 FATU−HIVA TSUNAMI: *The SOURCE*

Estimated Volume of Rock Slide: 4 million m^3





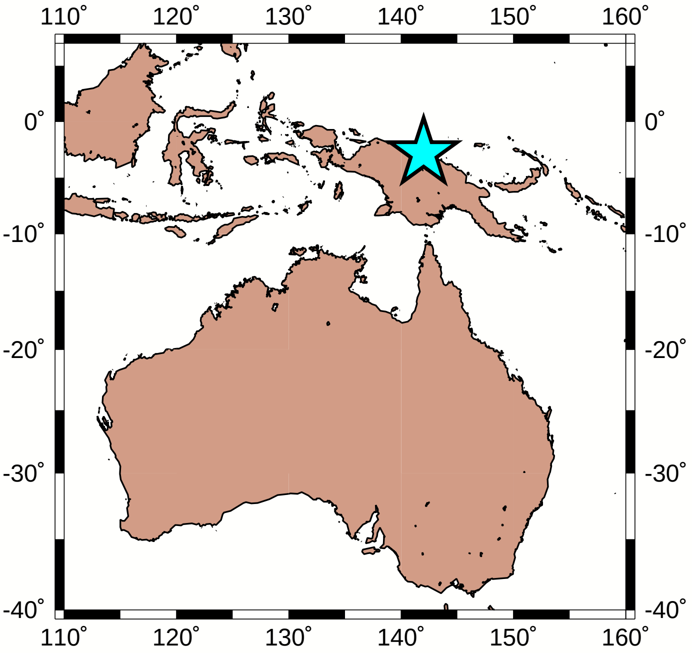
THE PAPUA NEW GUINEA (PNG) TSUNAMI

17 JULY 1998

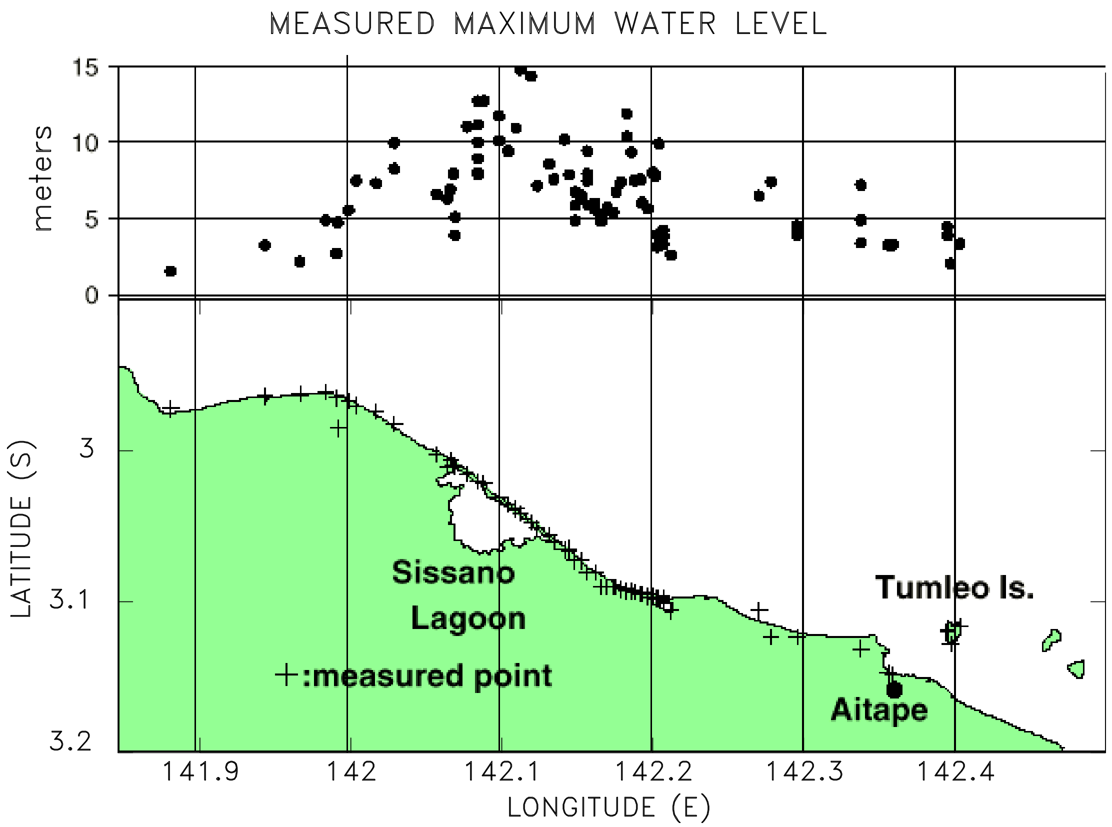
- 2200 people killed
- Ten villages eradicated

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

- No far-field tsunami



- Run-up (up to 15 m) too large for Seismic Slip
- Large run-up and devastation concentrated on short segment of coast



- Tsunami late by approximately 10 mn.

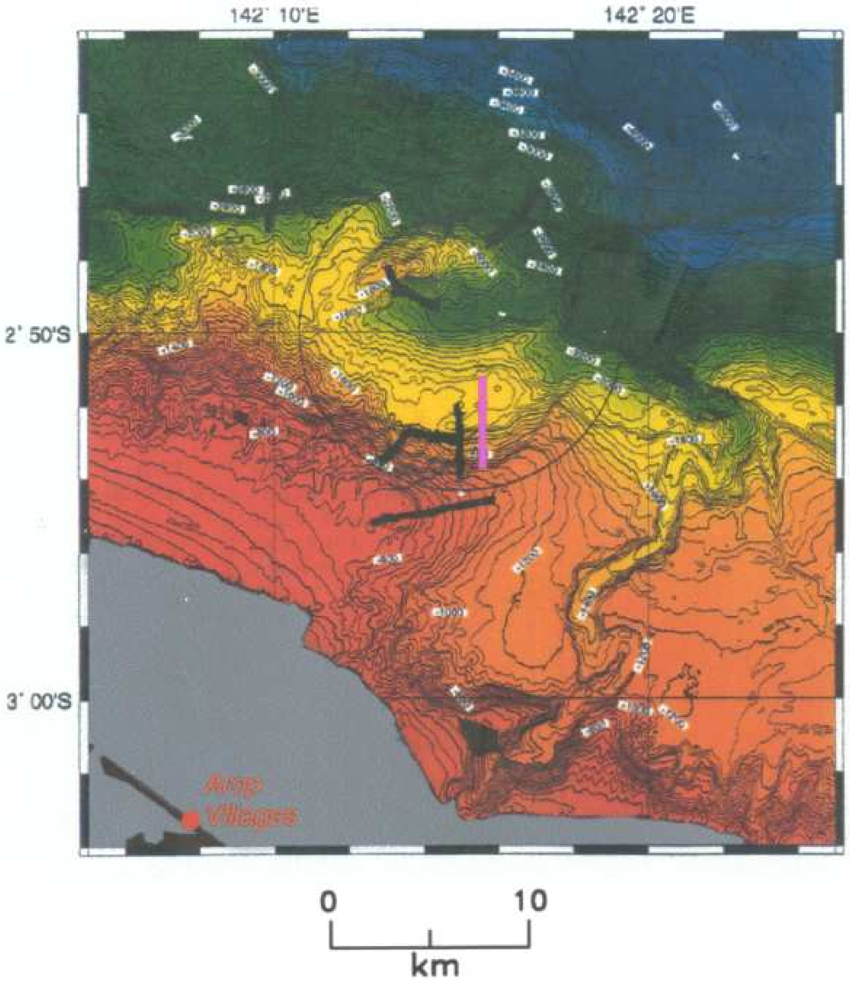
THE SLUMP MODEL

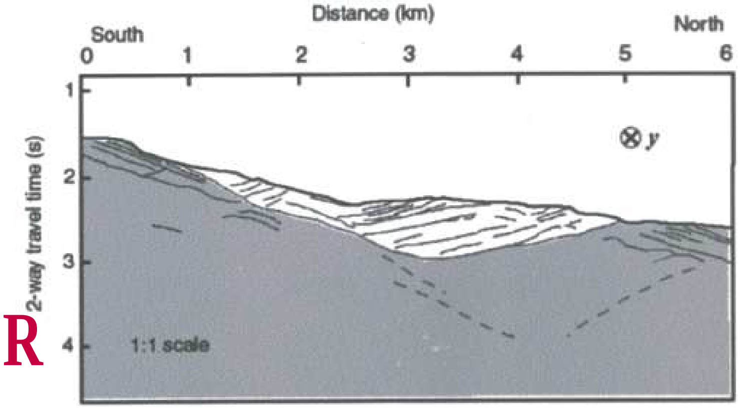
We propose that the near-field PNG tsunami was generated by a massive, 4–km^3 underwater slump, triggered at 09:02 GMT, 13 minutes after the mainshock, inside a bowl-shaped amphitheater located approximately 25 km off shore from Sissano Lagoon.

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.

IT IS THERE !!!



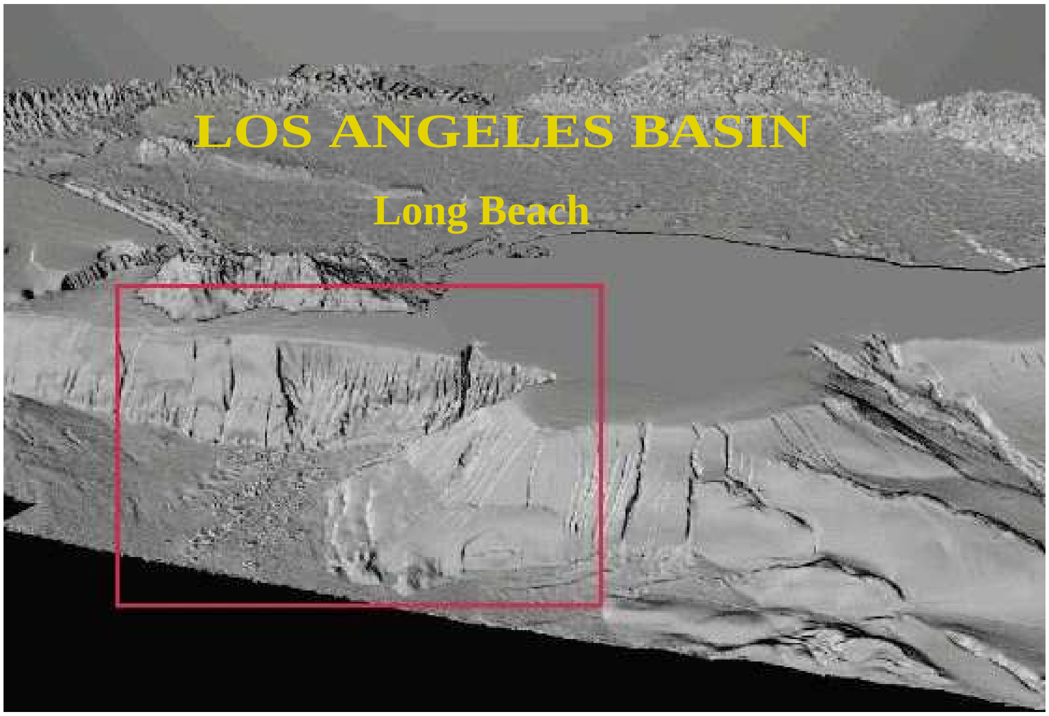


PNG TSUNAMI GENERATED BY UNDERWATER LANDSLIDE TRIGGERED (with DELAY) by EARTHQUAKE

LESSONS FROM 1998 PNG TSUNAMI

→ Underwater landslides (or slumps) can contribute significant tsunami hazard in coastal areas.

- Trigger can be even moderate earthquake.

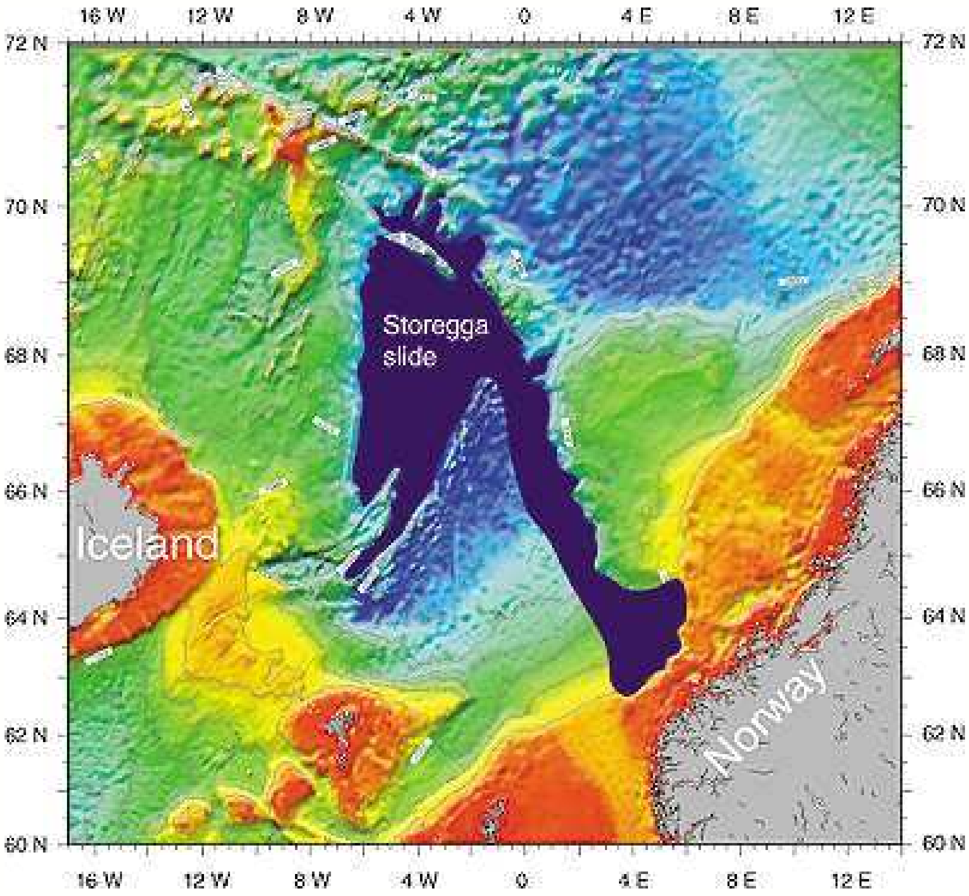


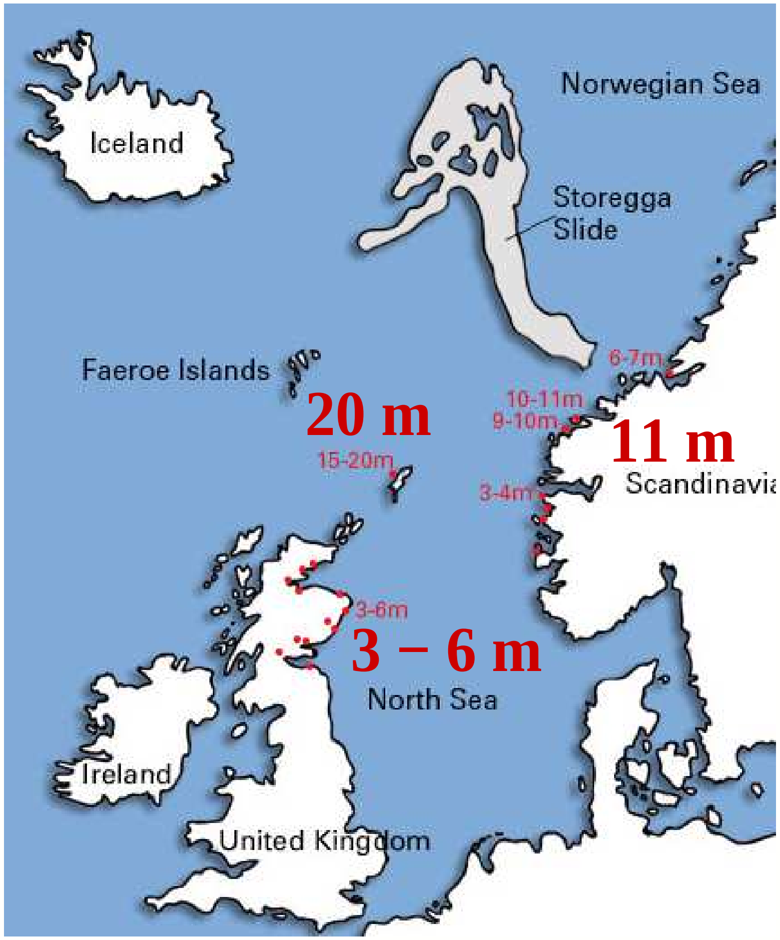
[G. Greene, 2000]

Catastrophic Landslides are known to occur *RARELY, but REGULARLY* over Geological Time.

A recent one, dated 6000 BC, and possibly triggered by the failure of gas hydrates following deglaciation of the Fennoscandian Ice cap, is documented off the coast of Norway.

Tsunami Deposits from the Storrega Event have been identified in Scotland, and Scandinavia.

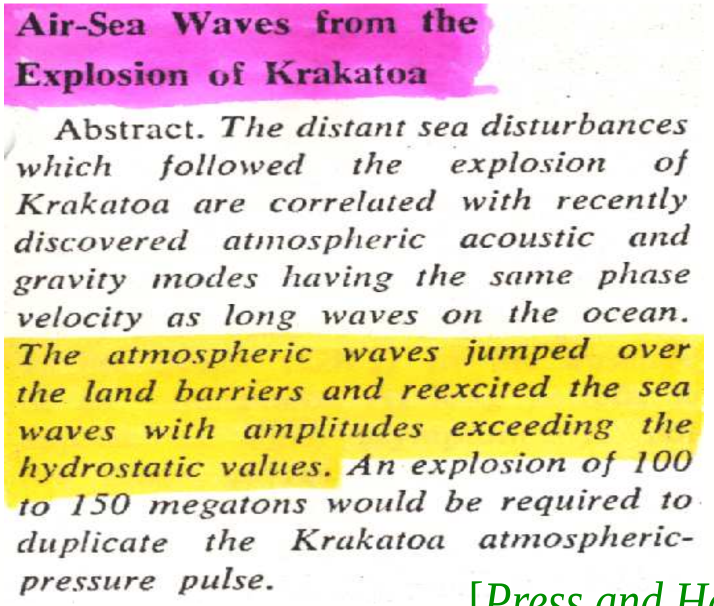




TSUNAMI GENERATION (ctd.): *Volcanic Explosions at Sea*

Krakatoa [Sunda Straits], 27 August 1883

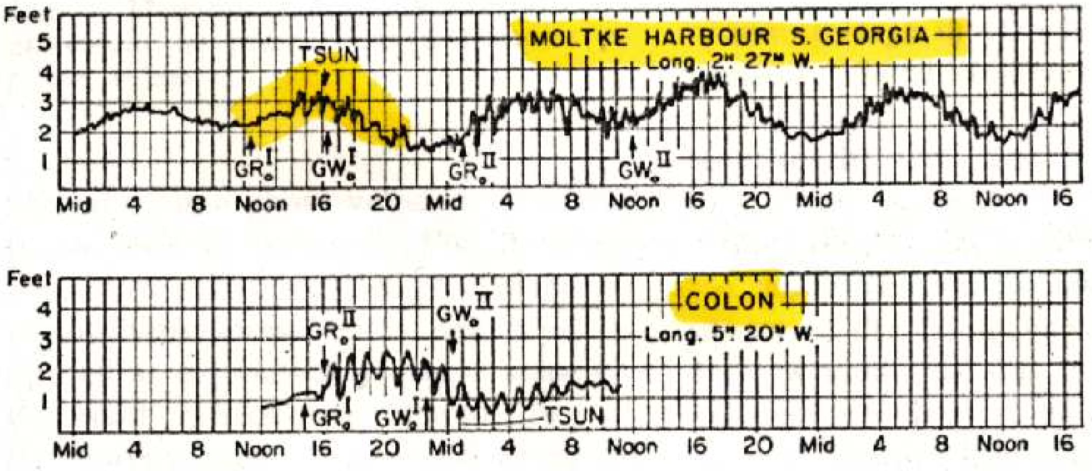
Santorini (Θηρα), 1630 ± 20 B.C.

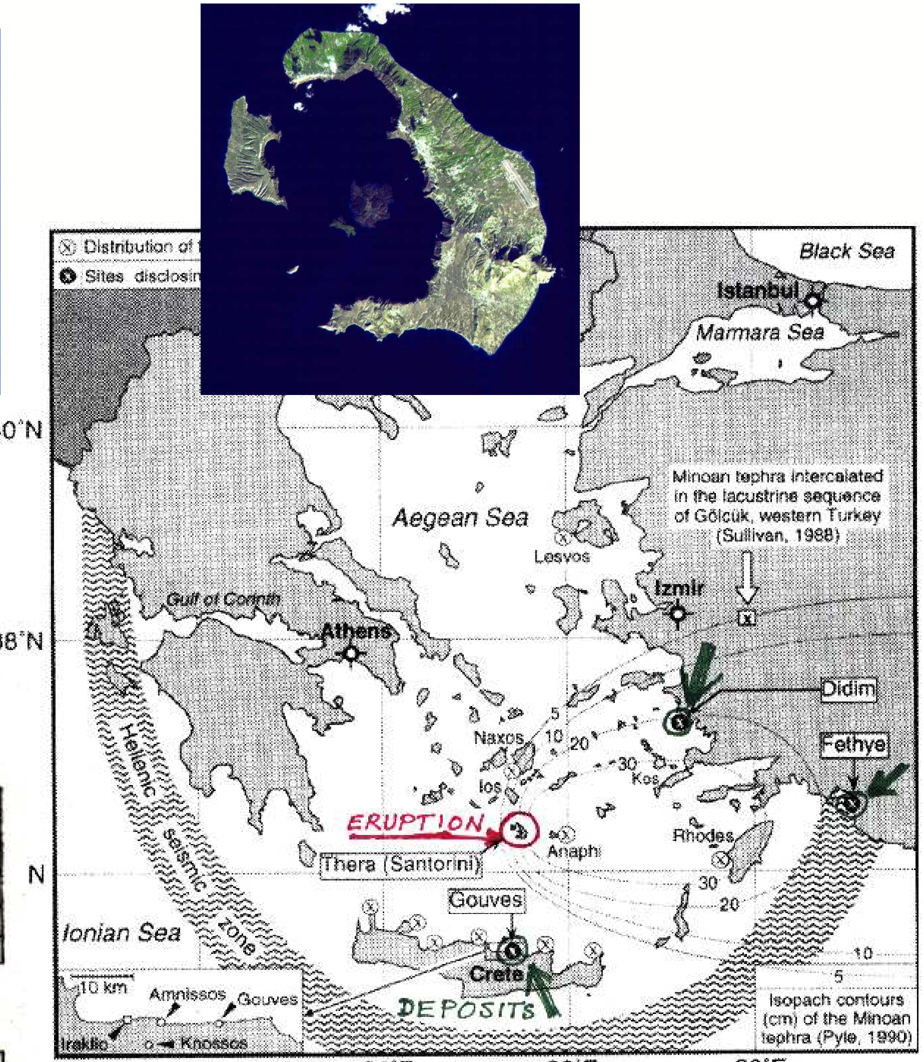


Air-Sea Waves from the Explosion of Krakatoa

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**

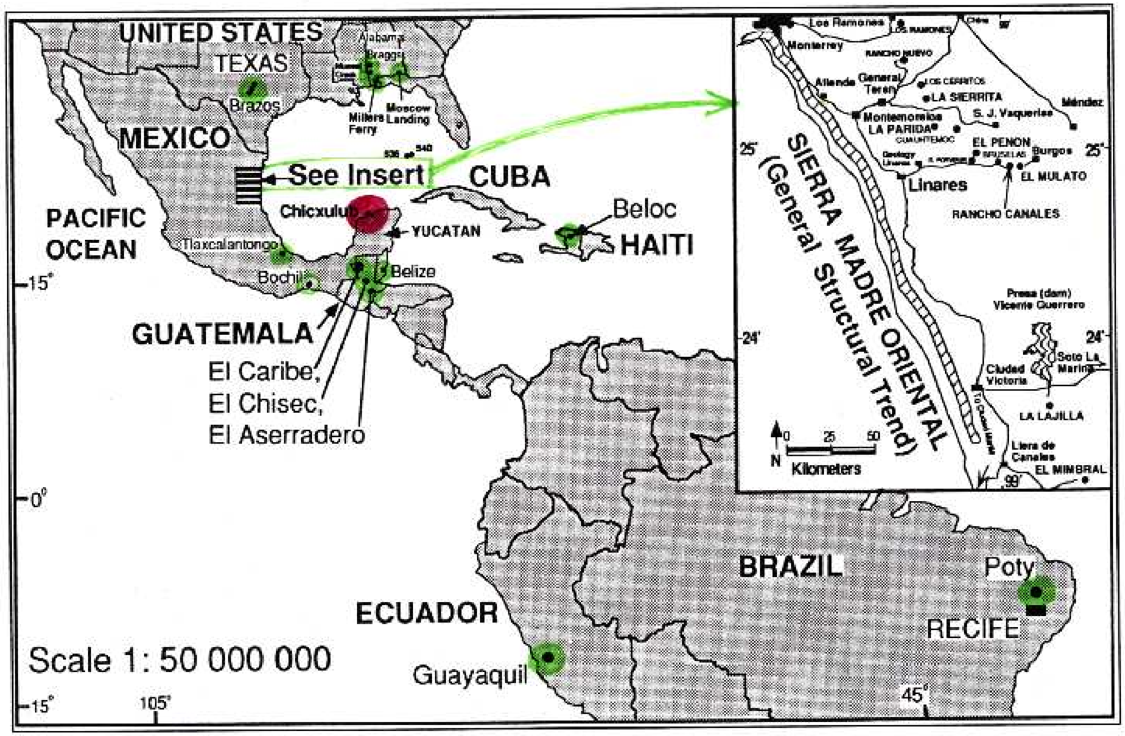


Figure 1. Location of Cretaceous-Tertiary boundary sections with near-K/T clastic deposits from Texas to Brazil. Insert shows area of location of northeastern Mexico sections.

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

TSUNAMI CAN: *FLOOD*

Port-Mathurin,
Rodrigues [Mauritius]

26 DEC 2004

D = 4300 **km**

Run−up = 1.8 meter

TSUNAMI CAN: *DESTROY STRUCTURES*

Camana, Peru, 2001

Mosque, Banda Aceh, 2004

House stilts and Bucket **(→)**
Sissano, Papua New Guinea, 1998

House stilts and Sand Deposit,
Arnold River, P.N.G., 1998

TSUNAMI CAN: *MOVE ANYTHING*

and Transform it into a PROJECTILE

Locomotive, *Sri Lanka*, 2004

Locomotive moved 1 km, *Seward, Alaska*, 1964

Boats, *Sri Lanka*, 2004

CAUSE FIRES

Boats and port debris, *Okushiri, Japan*, 1993

Death Toll in perspective (Earthquakes)

Year	Region	Death Toll	
		Absolute	Scaled to Global Population
1556	Shansi	800,000	1/625
1780	Iran	280,000	1/3000
1976	Tangshan	250,000	
2004	**Sumatra**	**250,000**	**1/24,000**
1920	Kansu	200,000	
1923	Tokyo	200,000	
1927	Tsinghai	200,000	
1755	Lisbon	70,000	1/10,000
1908	Messina	70,000	
1970	Peru	66,000	
2005	**Pakistan**	**50,000**	
1999	Turkey	40,000	
2003	Iran	40,000	
1896	Sanriku	30,000	
1989	Armenia	30,000	
1939	Chile	25,000	
1906	Valparaiso	20,000	
2001	India	20,000	
.....			
1906	San Francisco	3,000	
1989	Loma Prieta	68	

For reference: Hiroshima: 200,000

Death Toll in perspective (Tsunamis only)

Year	Region	Death Toll	
		Absolute	Scaled to Global Population
2004	**Sumatra**	**250,000**	**1/24,000**
1755	Lisbon	70,000	1/10,000
1896	Sanriku	30,000	1/53,000
1952	Kamchatka	5,000	
1960	Chile	5,000	
1933	Sanriku	3,000	
1998	Papua New Guinea	2,200	
1994	Flores	2,000	
2006	**Java**	**700**	
1946	Aleutian	170	
1992	Nicaragua	170	
1964	Alaska	122	
1929	Newfoundland	18	
1883	Krakatau (Volcanic)	30,000	1/50,000

For Reference

Middle Ages	Great Plague		1/30 ?
20th century	WWI +Influenza	30,000,000	1/60

TSUNAMI CAN: *DEPOSIT SEDIMENT*

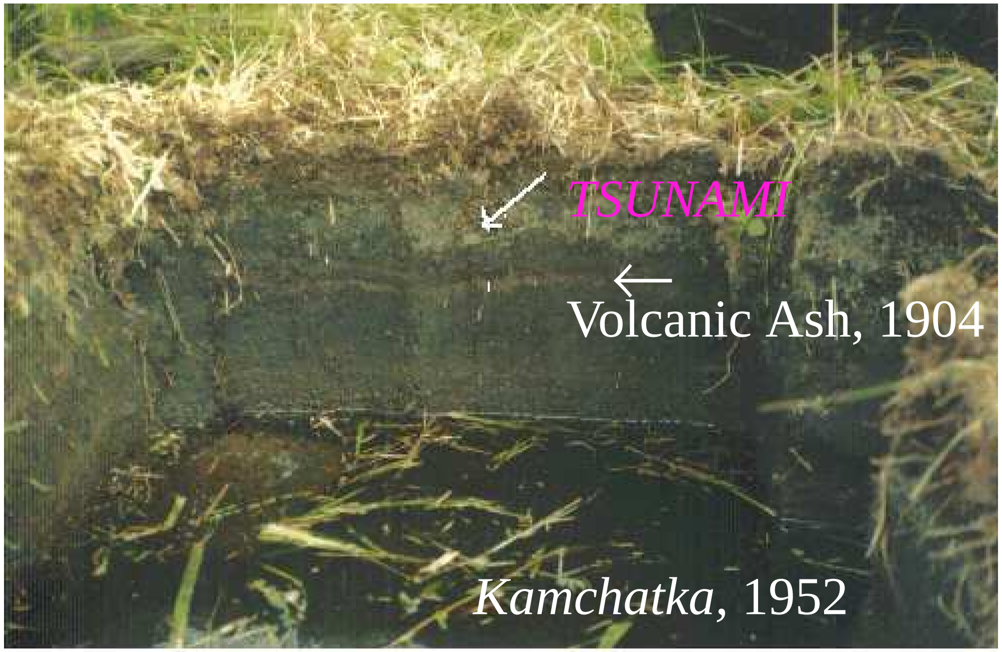
Camana Beach, Peru, 2001

Tofino, B.C., Canada, 1700

TRENCHES CAN REVEAL HISTORICAL

or PALEO- TSUNAMIS

→



Kamchatka, 1952

TSUNAMI CAN: *ERODE* (*SCOUR*)

[*during Down-Draw*]

Road bed destroyed at
Panadura, Sri Lanka, 26 Dec. 2004

Tsunami wave ebbing and Scouring away river bed
Port Mathurin, Rodrigues, 26 Dec. 2004.

LOCAL EFFECTS, SUMATRA 2004

[*R. Davis*, AusAID]

Run-up reaching 32 m

Inundation reaching: **Several km**

WHAT CAN THE SCIENTIST DO ?

- Theoretical Studies

  Explore Physical Nature and Properties of Wave; Propagation
  ** Excitation by Various Sources*

- Research and Development for Real−Time Warning

  Explore Relationship with Seismic Source
  Develop Algorithms to Identify in Real Time
  Tsunamigenic Character of Earthquakes
  ** Implement*

- Numerical Simulation

  Develop Codes to Simulate Numerically Propagation of
  Tsunami and Especially Interaction with Shores
  ** Develop and Deliver Inundation Maps in Realistic Scenarios*

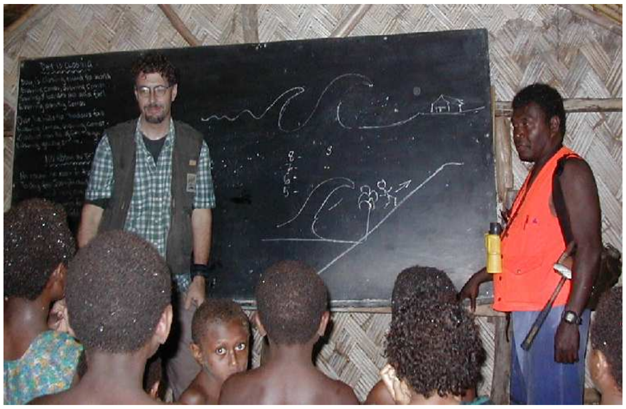
- Laboratory Experiments

  Investigate Influence of Crucial
  Parameters on Wave Generation
  ** Validate Simulation Codes*

- Post-Tsunami Surveys

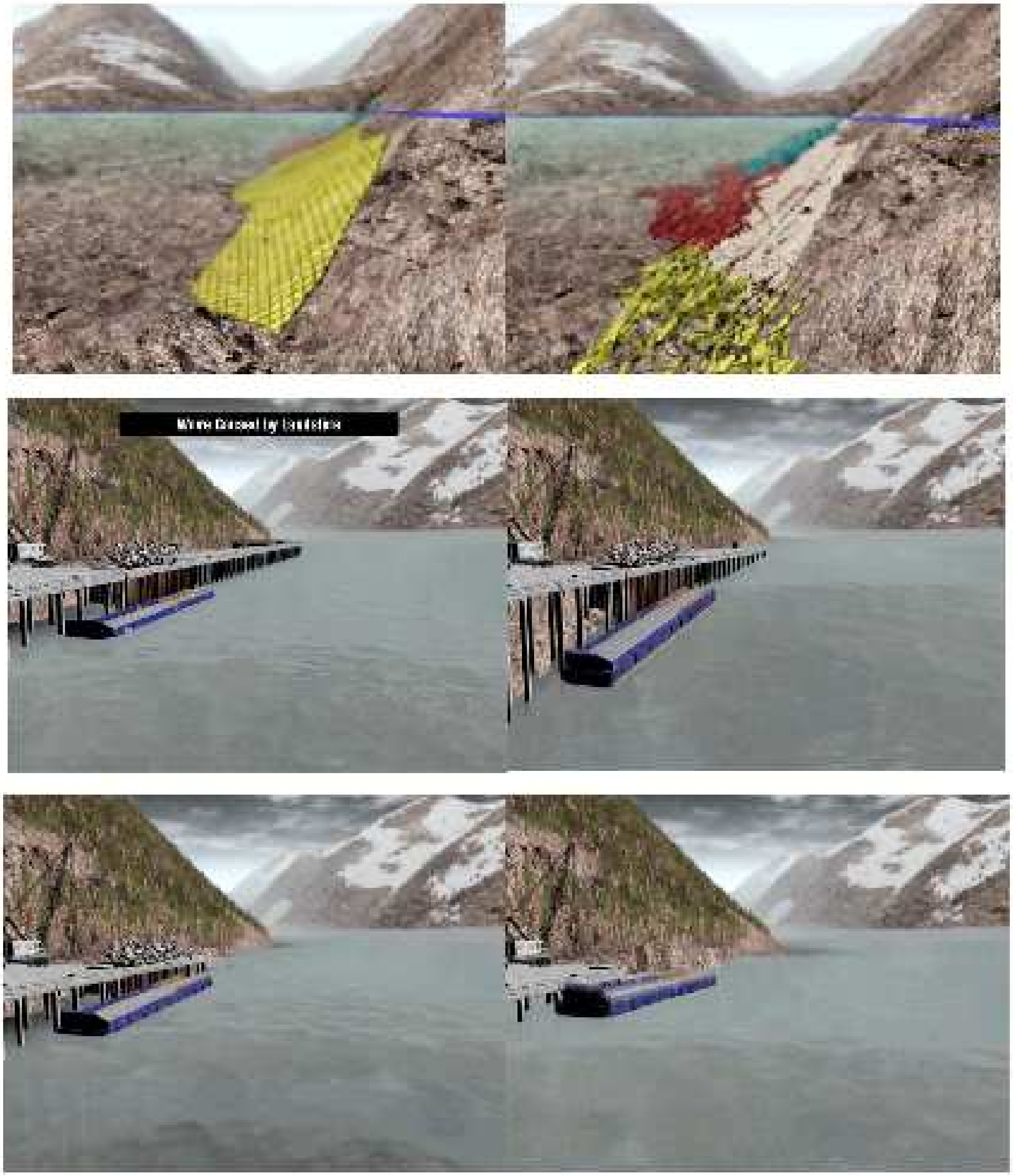
  Map Extent of Tsunami Inundation and Damage
  Produce Datasets to be used as Targets of
  Hydrodynamic Simulations
  ** Reconstruct Physical Model of Phenomenon*

- Education and Outreach



MODELING OF LANDSLIDE TSUNAMI

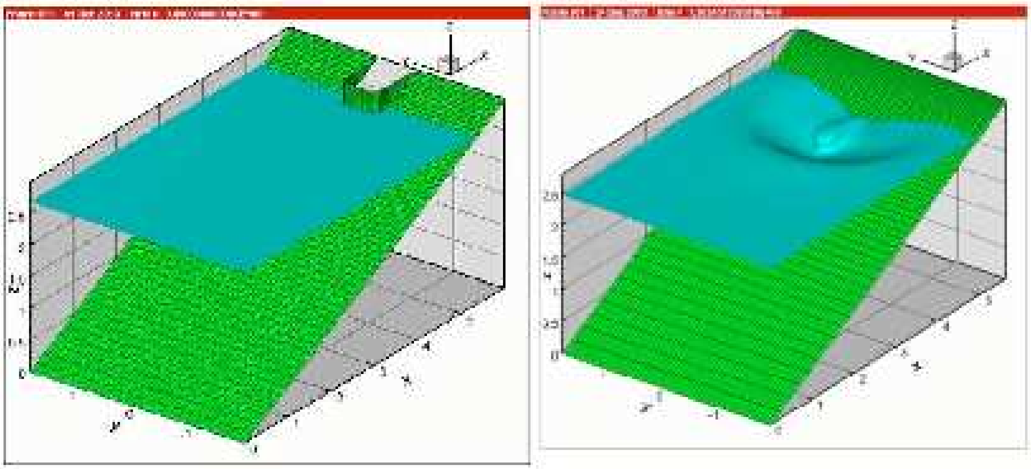
SKAGWAY, ALASKA; 04 NOV 1994

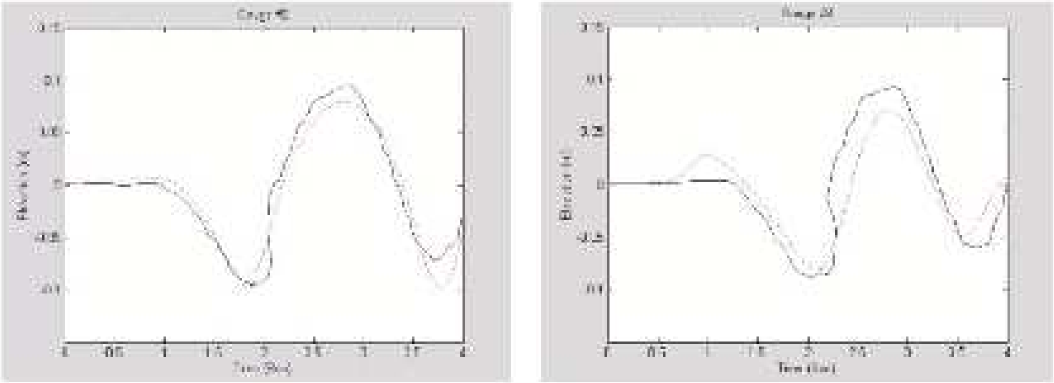


[*Synolakis and Bernard*, 2006]

LANDSLIDE SIMULATIONS

- *In the Laboratory (Top)*
- *Numerical Computation (Center)*
- *Comparison (Bottom)*





[*Liu et al.*, 2005; *C.E. Synolakis;* pers. comm., 2005]

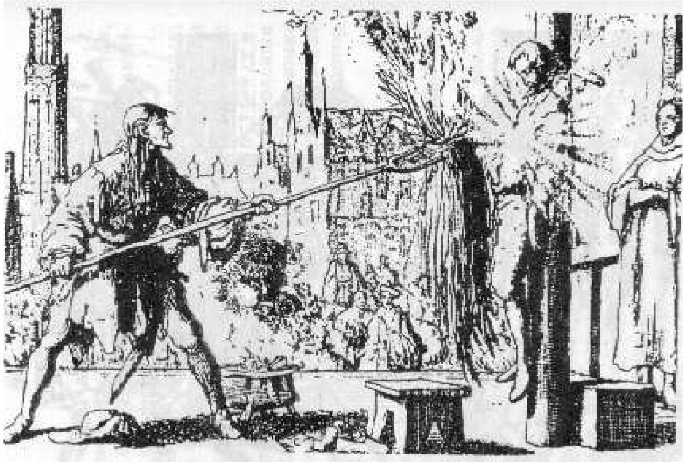
TSUNAMI MITIGATION — *Early Attempts*

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.

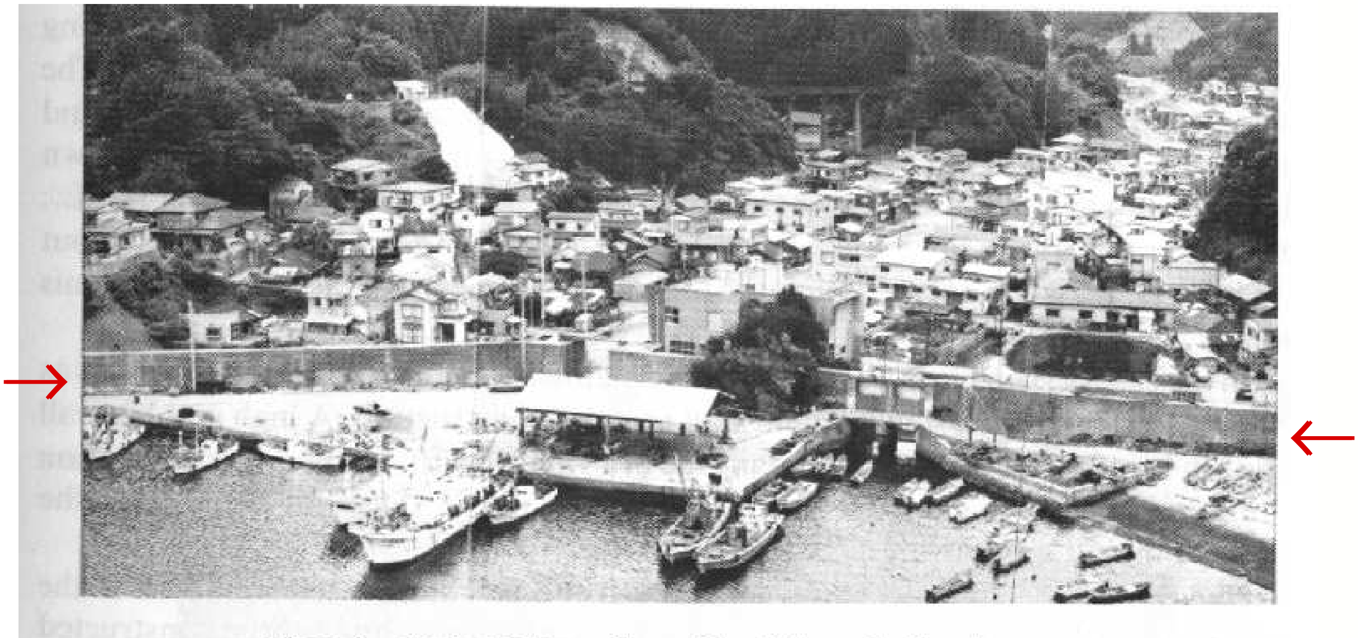


Photo 2. Typical fishing village, (Ryoishi), on the Sanriku coast.

[*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.)

TSUNAMI WALLS: ENGINEERING ASPECTS

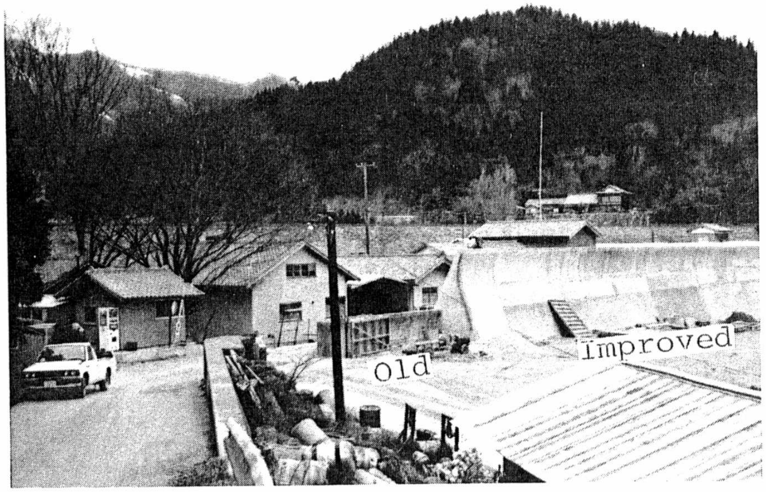


Photo 4. Contrast of old part and improved part of a tsunami wall.

T. Fukuchi and K. Mitsuhashi

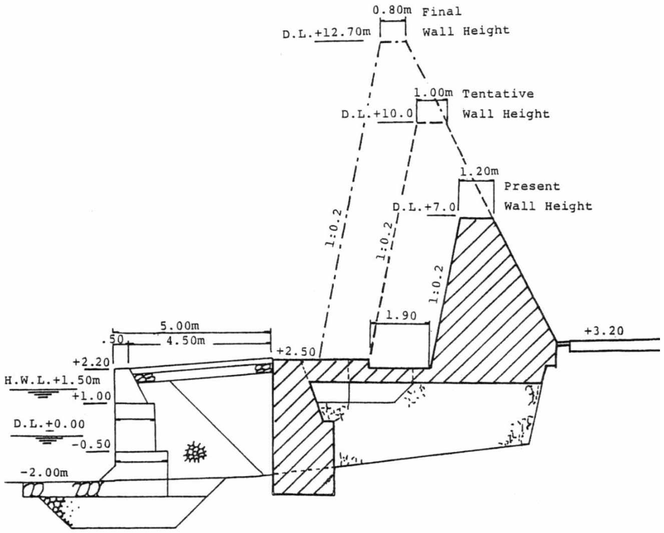


Fig. 3. Stage improvement plan of a tsunami wall.

[*Fukuchi and Mitsuhashi*, 1981]

Okushiri, Japan (2003)

Note Built-in Stairways

FROM SIMULATIONS TO PLANNING & MITIGATION

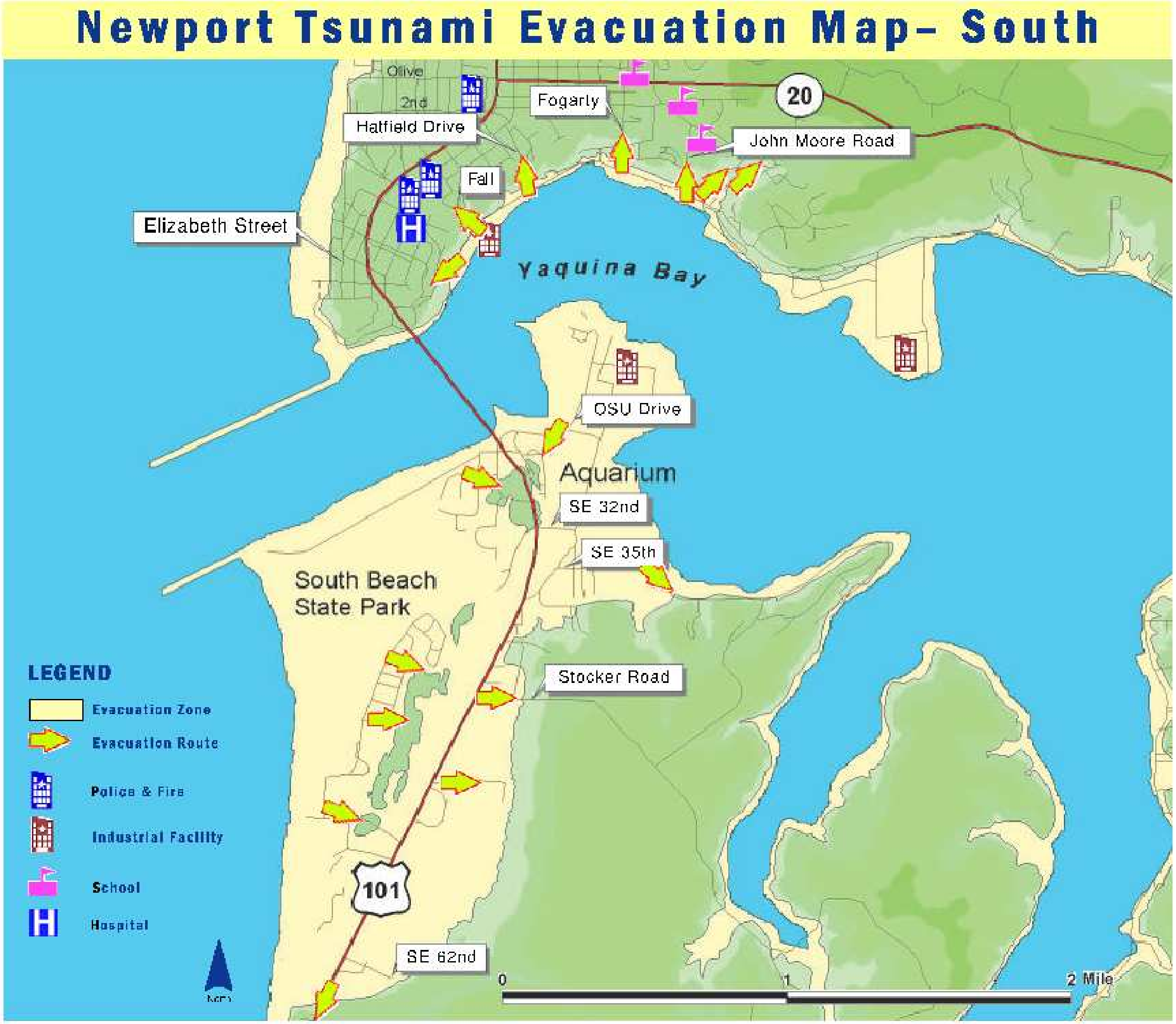
Example of Newport, Oregon

**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.



EDUCATION

GOAL: Raise awareness of tsunami hazard in coastal populations to

- Improve Response to Future Warnings
- Motivate Self-evacuation in Absence of Warning

FORMS of Education:

Formal -- School, Civil Defense

Casual -- Survey Teams

Ancestral

Tsunami Drill, *Sendai, Japan*

Chala, Peru, 2001. Salvador Salsedo (center) noticed the withdrawal of the sea after the earthquake, and warned villagers to get to high ground. His self-described "knowledge of the sea" stems from an ancestral heritage among fishermen of the coast of Southern Peru.

OUTREACH and EDUCATION DURING SURVEYS

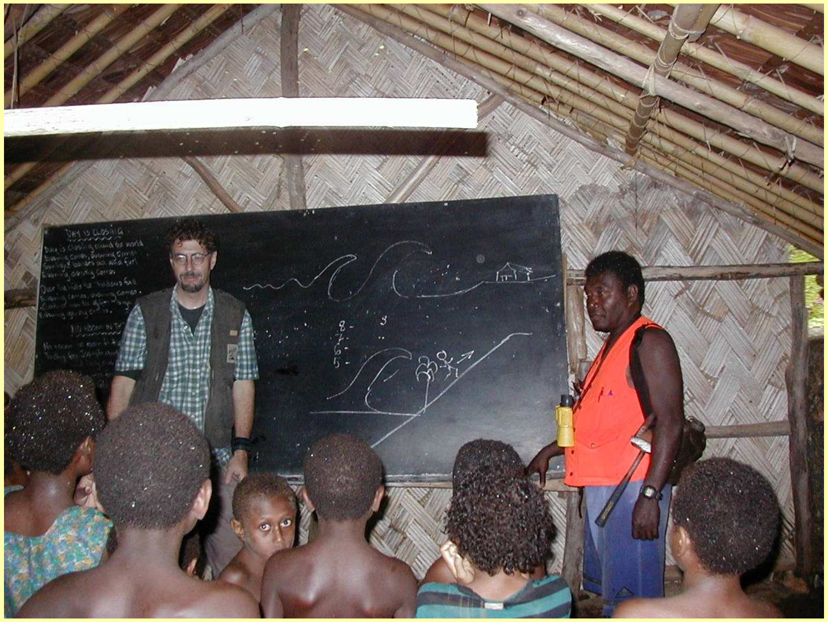
Talk in Schools

E.A. Okal and J.C. Borrero,

Isla Juan Fernandez (Chile), 2000

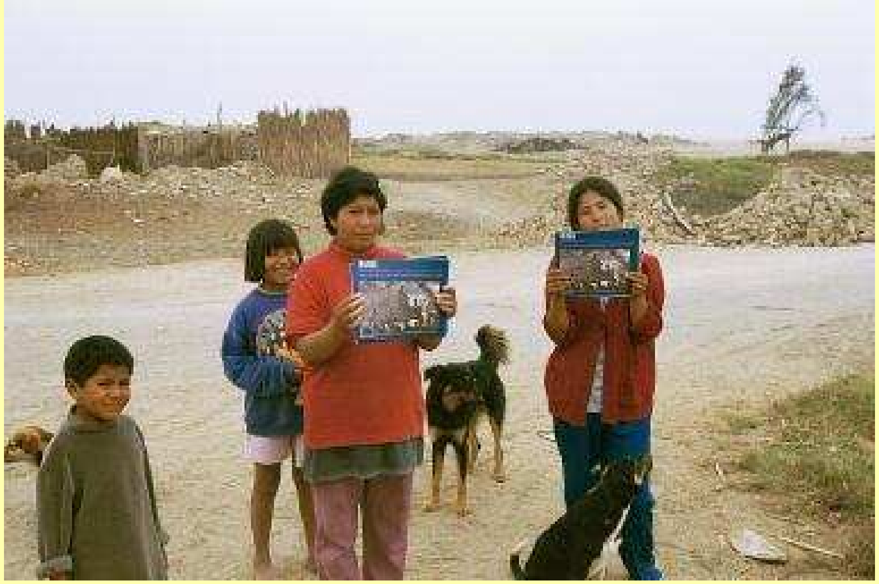
Hold "beachfront meeting"

C. Ruscher, Vanuatu, 1999



C.E. Synolakis, Vanuatu, 1999

Hand out [translated] USGS leaflets



Peru, 2001

THE MESSAGE

- If you feel ANY earthquake and are close to the water,

RUN for the HILLS !!

- If you observe the sea retreat, DO NOT WAIT, but rather

RUN for the HILLS !!

- RUN (or WALK); *DO NOT DRIVE*
- Stay at 15 m altitude
- Remain until sea has calmed down, then wait at least TWO HOURS.

EDUCATION is NEEDED !

DO NOT EXPLORE

EXPOSED BEACHES !!

Sumatra Tsunami, Madagascar, 26 Dec. 2004

RUN TO SAFETY ON HIGHER GROUND !!