TSUNAMIS:

BRIDGING SCIENCE AND SOCIETY

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Woods Hole Oceanographic Institution
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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]

TSUNAMI GENERATION

EARTHQUAKE

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

LANDSLIDE

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

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

→ *Reproducible in Laboratory*

VOLCANIC EXPLOSION

Documented: Krakatoa, 1883; Santorini, −1650.

BOLIDE IMPACT

Speculated: Chicxulub, (K/T)

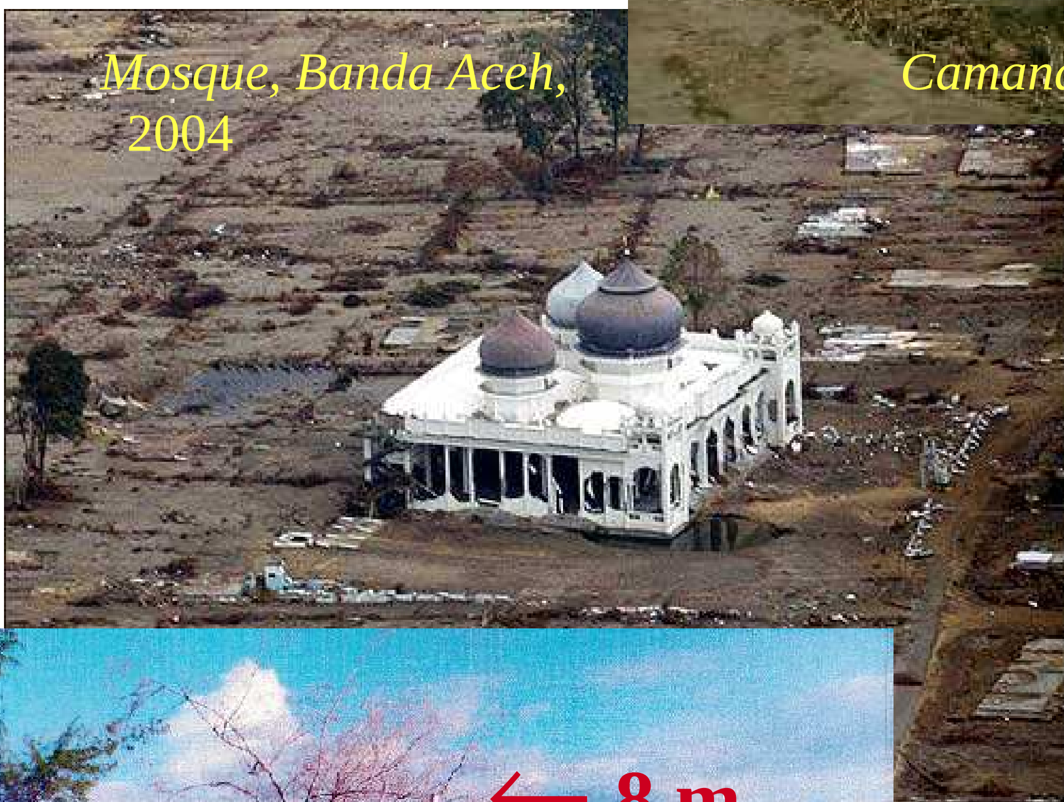
TSUNAMI CAN:

PENETRATE INLAND
and FLOOD CITY

BREAK on BEACH
and INUNDATE

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

Boats, *Sri Lanka*, 2004

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

CAUSE FIRES

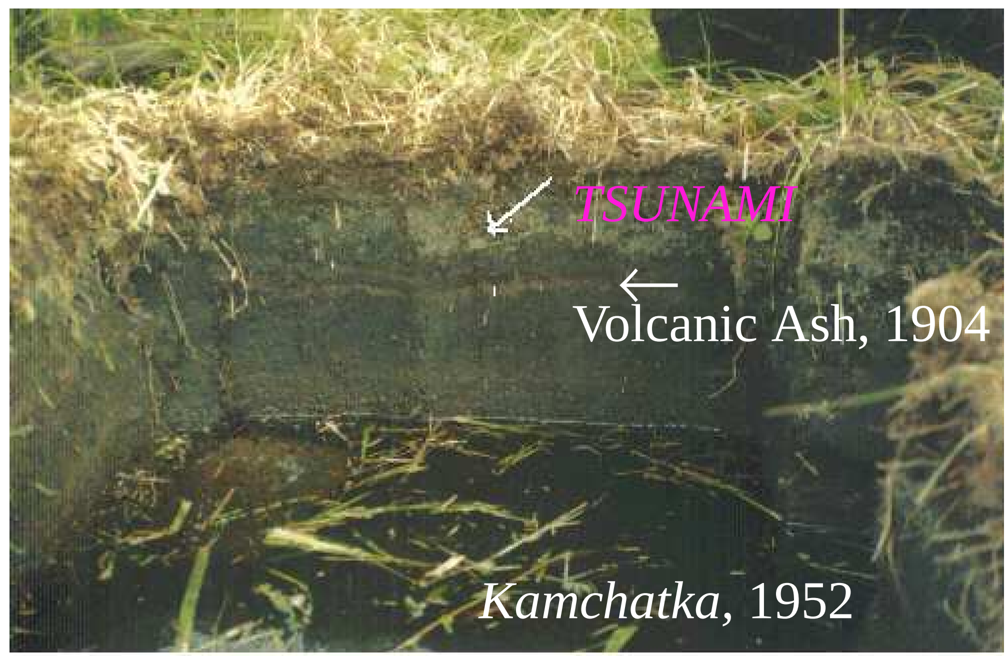
Boats and port debris, *Okushiri, Japan*, 1993

TSUNAMI CAN: *DEPOSIT SEDIMENT*

TRENCHES CAN REVEAL HISTORICAL

or PALEO- TSUNAMIS

→



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.

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*

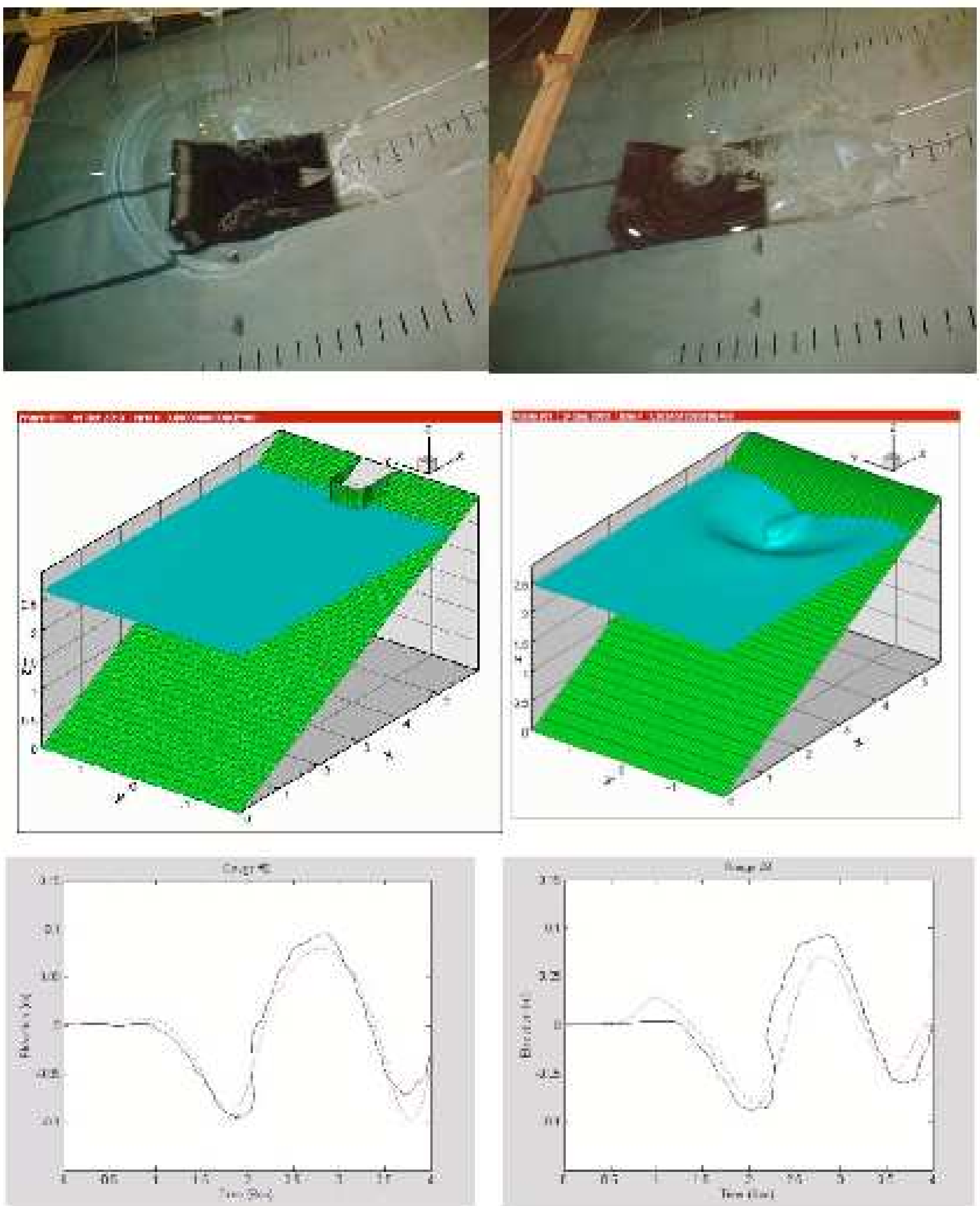
- Post-Tsunami Surveys

  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

LANDSLIDE SIMULATIONS

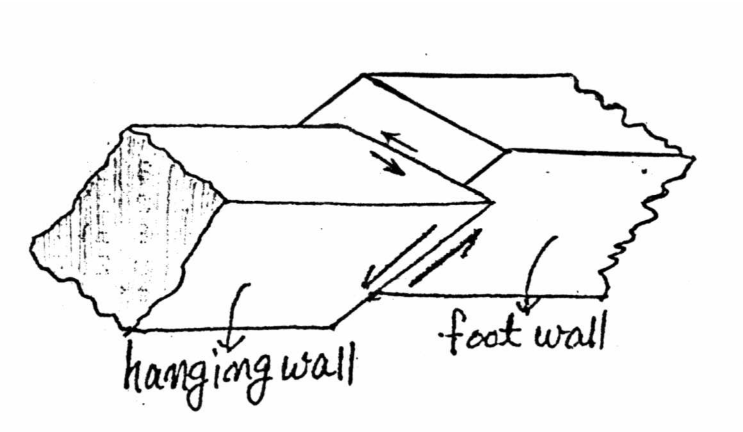
- *In the Laboratory (Top)*
- *Numerical Computation (Center)*
- *Comparison (Bottom)*



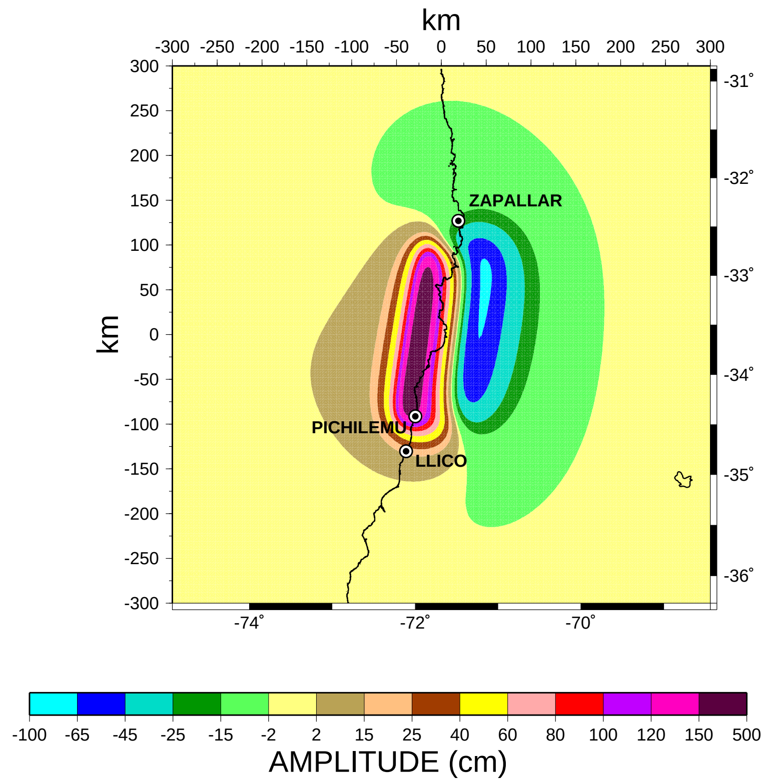
[*Liu et al.*, 2005; *C.E. Synolakis;* pers. comm., 2005]

STEPS to SIMULATION

1. Obtain Earthquake Source Model



2. Compute Static Deformation of Ocean Bottom

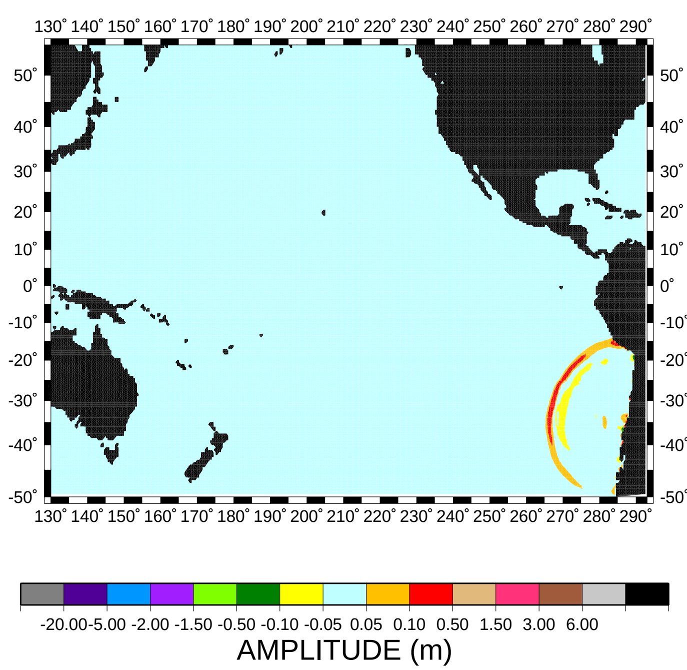


3. Perform Numerical Simulation

Products:

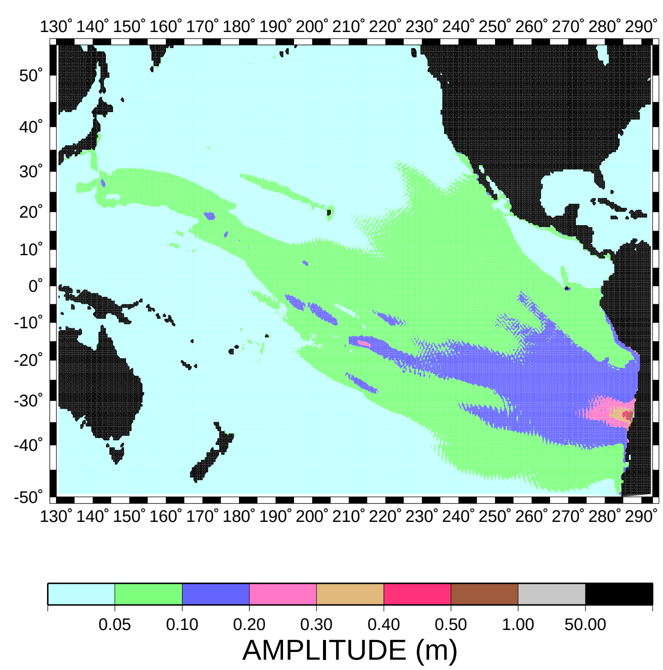
INSTANTANEOUS SURFACE SNAPSHOT

CHILE 1906 +02:52:30



MAXIMUM SEA SURFACE HEIGHT

1906 MAXIMUM AMPLITUDES



FROM SIMULATIONS TO PLANNING & MITIGATION

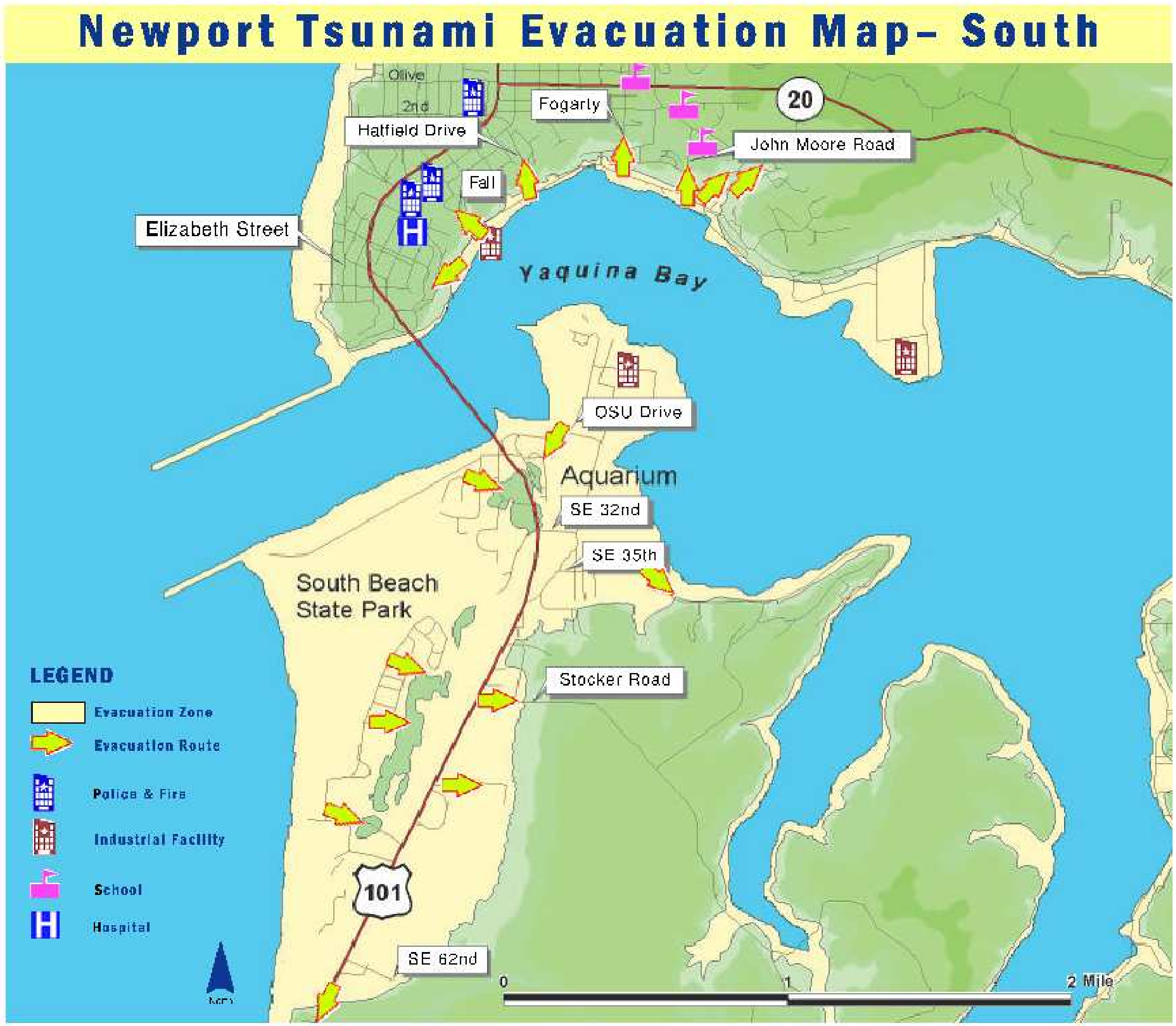
Example of Newport, Oregon

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.



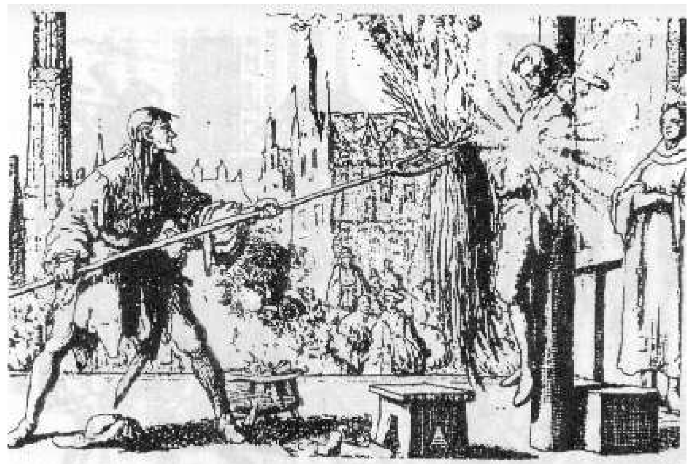
TSUNAMI MITIGATION — *Early Attempts*

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.

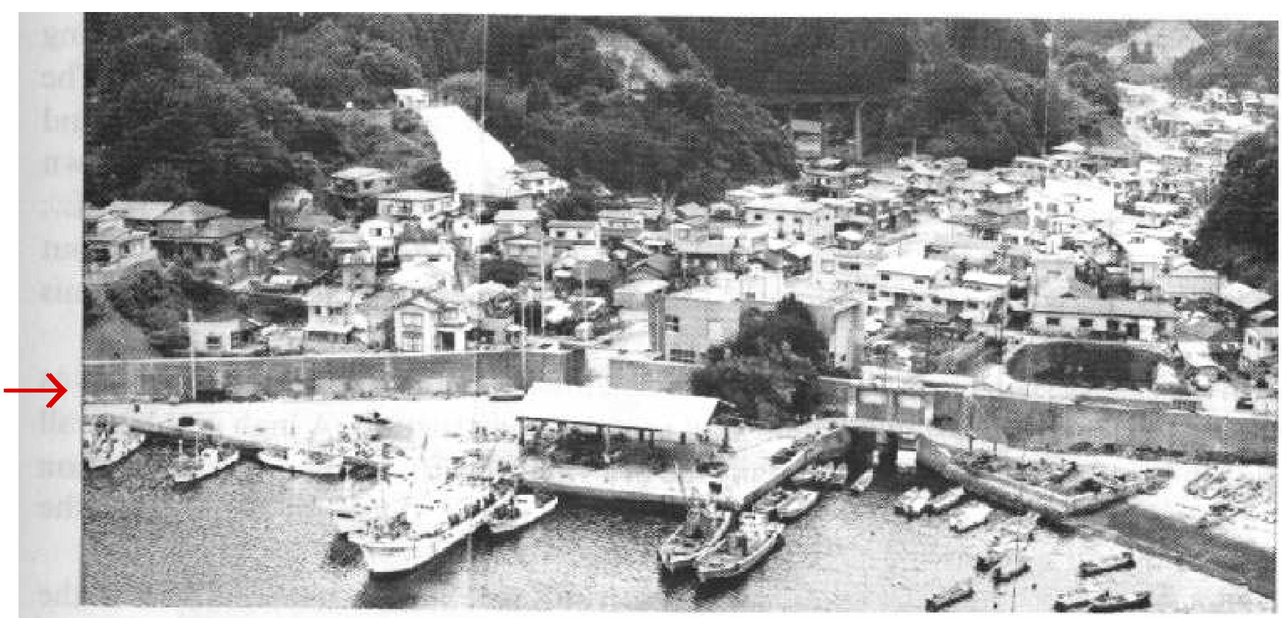
→  ←

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

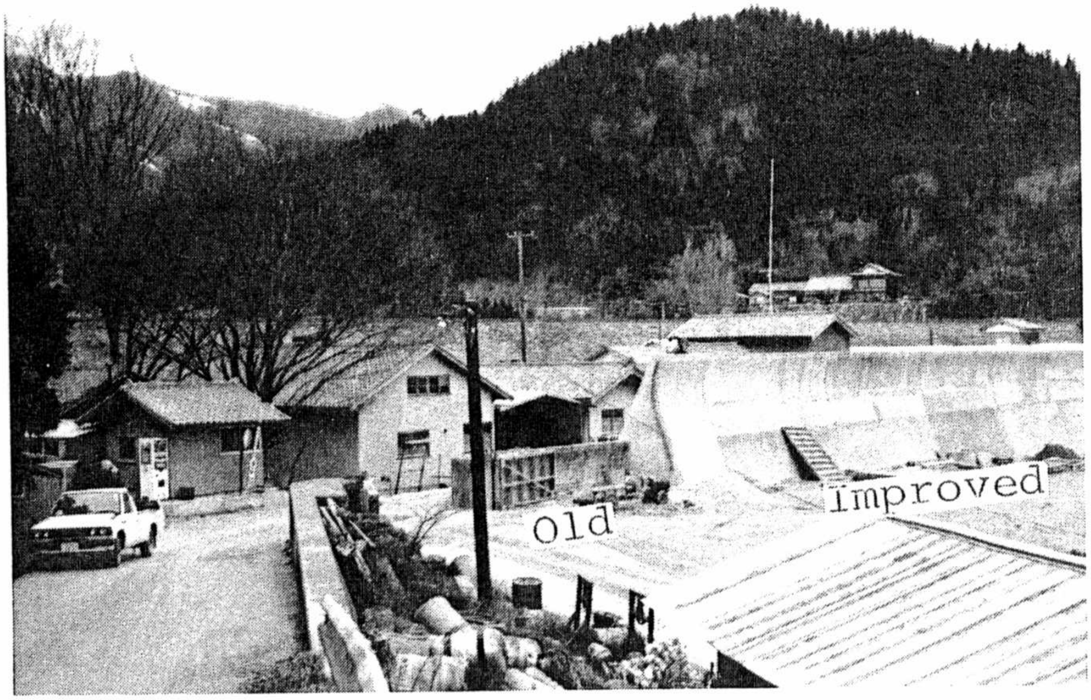


Photo 4. Contrast of old part and improved part of a tsunami wall.

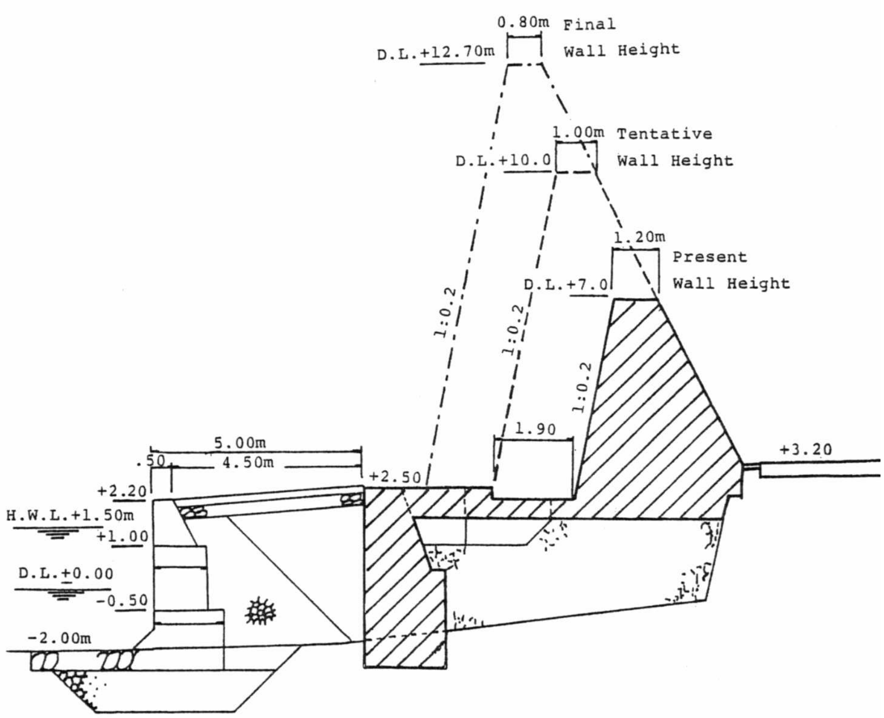
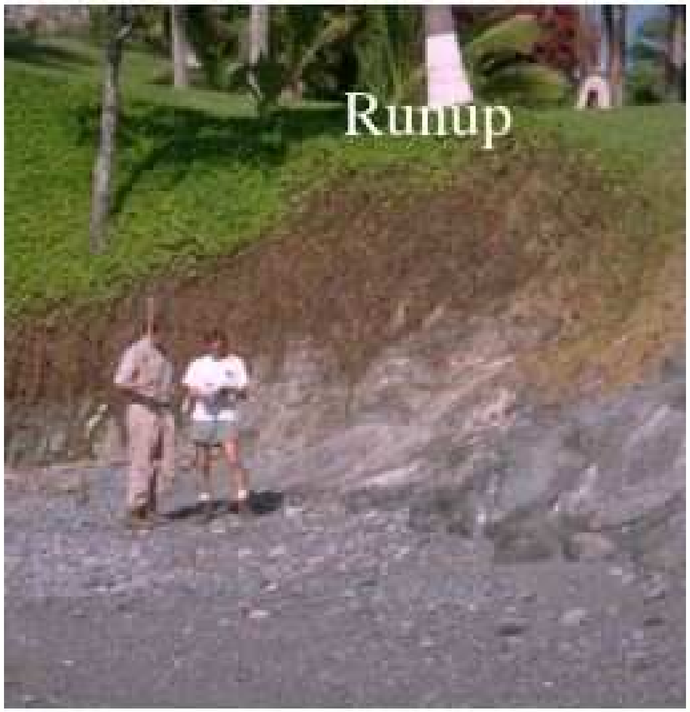


Fig. 3. Stage improvement plan of a tsunami wall.

[*Fukuchi and Mitsuhashi*, 1981]

Goals of Field Surveys - (I)

Collect Runup and Inundation Data



Mexico 1995 **Peru 2001**

Note ephemeral nature of watermark data.

RUN−UP OBTAINED BY STANDARD TOPOGRAPHIC METHODS

Port-Mathurin,
Rodrigues [Mauritius]

26 DEC 2004

D = 4300 **km**

Run−up = 1.8 meter

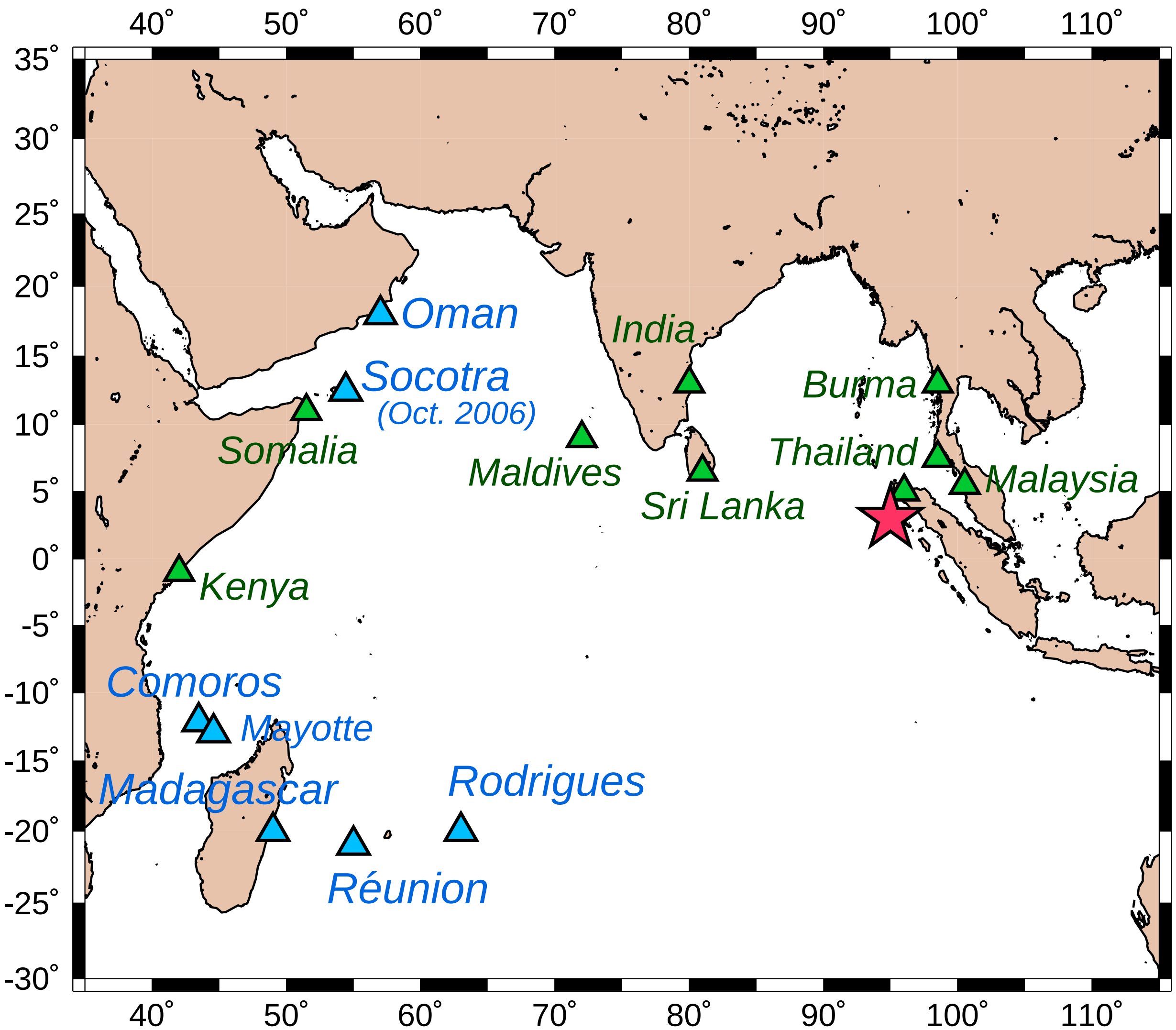
RUN−UP OBTAINED BY LASER SURVEYING

2004 Sumatra Tsunami surveyed at ***Ras-al-Duqm, Oman***

[H.M. Fritz, P.E. Raad; August 2005]

2004 INDONESIAN TSUNAMI

Location of Field Surveys by ITST



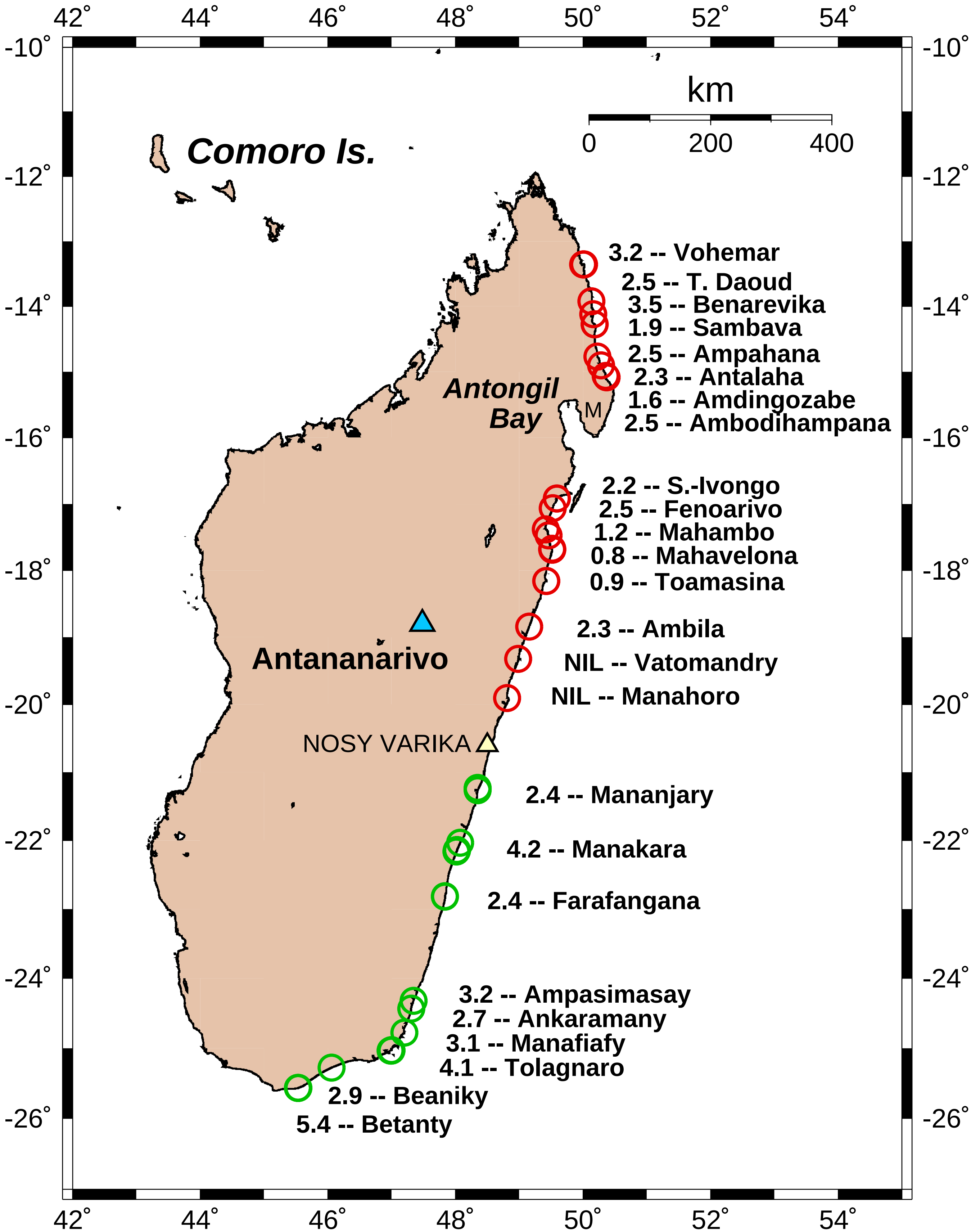
E.A. Okal

Others

Maldives
[*C.E. Synolakis, 2005*]

Madagascar

SURVEY RESULTS in MADAGASCAR

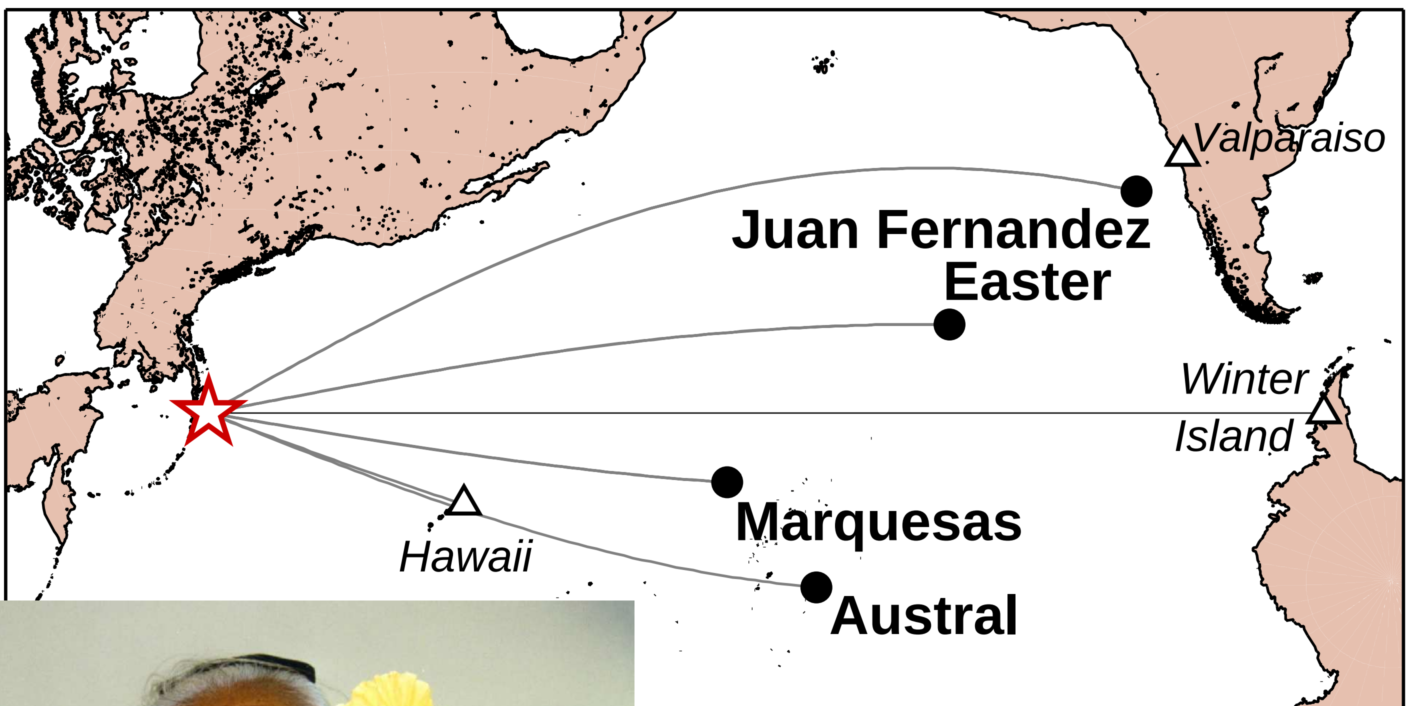


Run-up Very Irregular -- from Zero to 5.4 m
One death by drowning

HISTORICAL TSUNAMIS

For events dating back to 1940, we have found that it is possible to identify and interview elderly witnesses, and to quantitatively transcribe their depositions into a usable geo-physical database

Example: The catastrophic Aleutian tsunami of 01 April 1946



(159 killed in Hawaii)

1. IDENTIFY WITNESS

Hanaiapa, Island of Hiva Oa, 30 July 2000.

Octave Bono was 18 in 1946. He recalls vividly inundation by three waves. The last one reached all the way to the road intersection at the center of the village, defining a run-up of 8.5 m, and a maximum inundation of 490 m from the shoreline.

Three horses were lost, carried away by the downdraw.

2. INTERVIEW SURVIVORS

Isla Juan Fernández, Chile, 23 November 2000.

Diego Arcas (USC) interviews 82-yr. old resident Mr. Reynolds Green, a witness of the 1946 Aleutian tsunami, 12500 km from its source.

3. VISIT RUN-UP SITES with SURVIVORS

Hatiheu, Nuku Hiva, Marquesas, 09 August 2000.

Yvonne Katuai, then Assistant Mayor for Hatiheu, was 8 years old in 1946. She remembers how the tsunami destroyed her father's store, and carried a bag of flour into the cemetery, depositing it on this tomb, 8.2 m above sea level.

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.

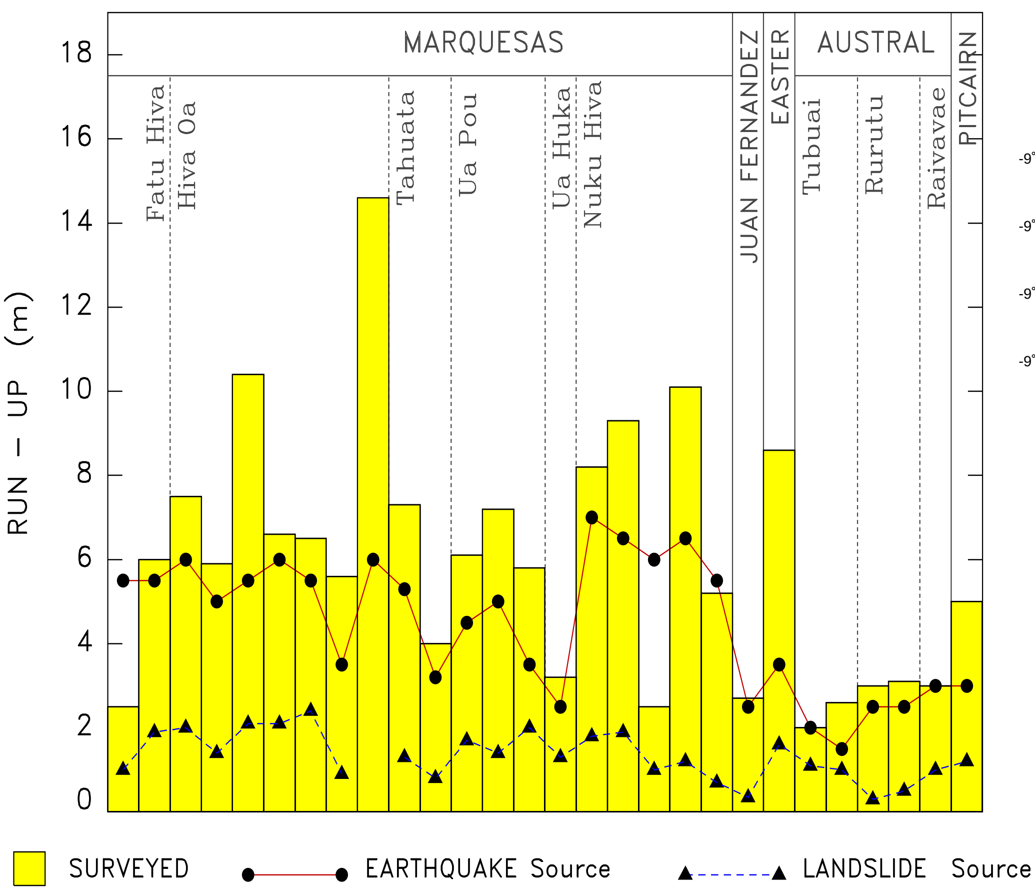
Cape Lutke, UNIMAK ISLAND

4. USING the DATASETS for SIMULATION

The datasets gathered from eyewitness accounts can be used as benchmarks in hydrodynamic simulations aimed at understanding the mechanism of generation of the tsunami.

In this example [*Hébert and Okal*, 2006], we test both a dislocation (classic earthquake) and a dipole (representing a landslide) as the source of the 1946 tsunami, and compare numerical predictions to run-up measured in the Marquesas Islands.

1946 Fits to RUN-UP OBSERVATIONS



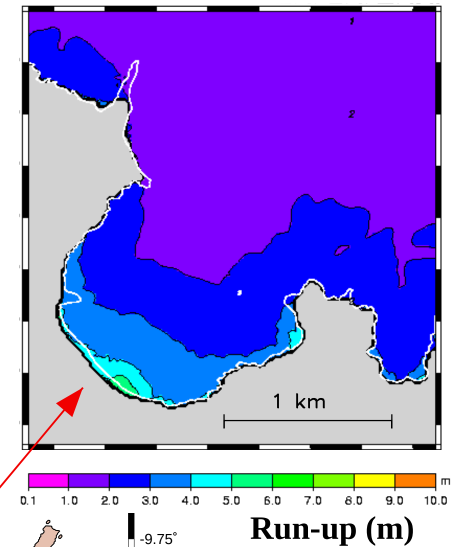
Note the good agreement with the earthquake source, but the deficient simulated values for the landslide.

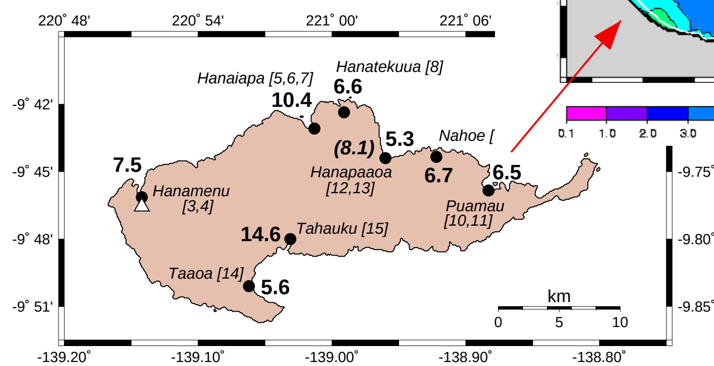
EXAMPLE of SIMULATION

Puamau, Island of Hiva Oa, Marquesas

DISLOCATION (EARTHQUAKE)

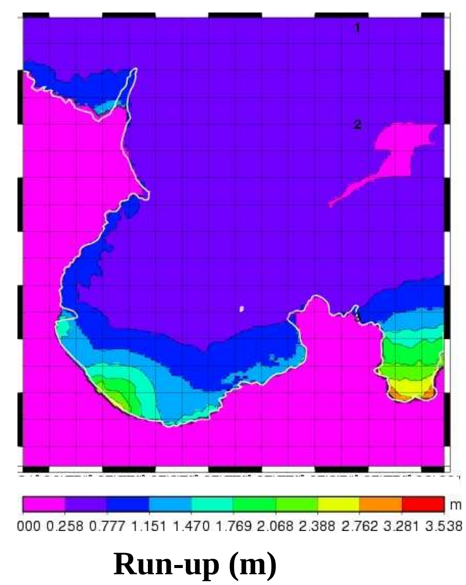
- Observed: 6.5 m (overland)
- Modeled: 5.5 m





LANDSLIDE (DIPOLE)

- Modeled: 2.40 m



TSUNAMI WARNING: IDEA and CHALLENGES

- Tsunamis are much slower (220 m/s) than seismic waves (3 to 10 km/s).

- Hence, it should be possible to provide warning, at least in the far field, based on interpretation of seismic waves.

→ Difficult to measure true size of very large earthquakes.

→ Uncertainties remain as to factors contributing to generation of tsunami.

Other Aspects

* In the near field, essentially no time to issue warning.

  Must rely on *EDUCATION.*

* Research must progress based on extremely small samples.

* Implementation of warning procedures transcends Science.

* Other (newer) technologies may help, but are largely unproven.

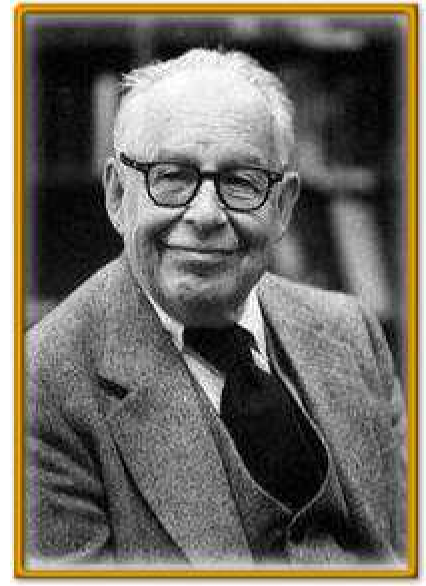
EARTHQUAKE MAGNITUDES

- An essentially empirical concept, intr-oduced by *Richter* [1935], long before any physical understanding of earth-quake sources

→ To this day, measurements have remained largely

ad hoc,

especially at short distances.



Bulletin of the Seismological Society of America

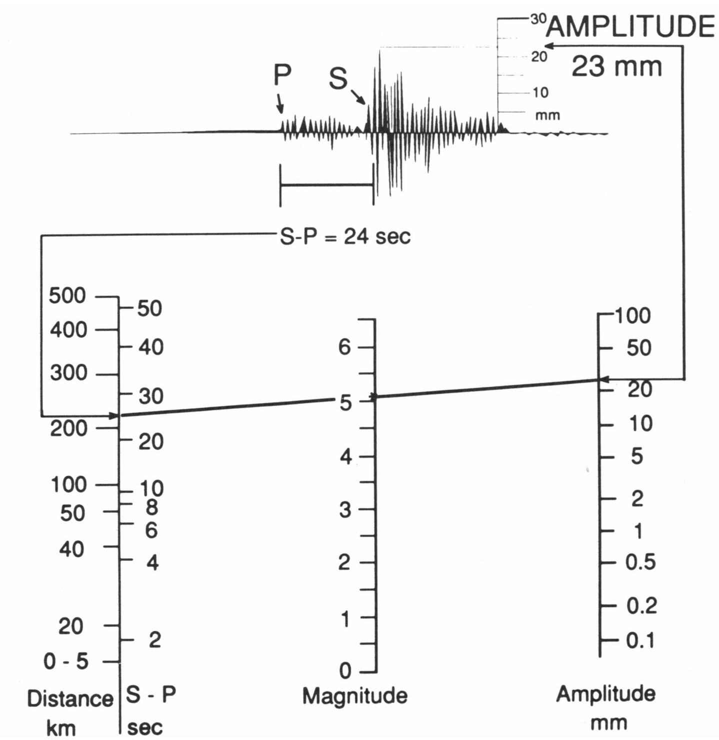
VOL. 25 JANUARY, 1935 No. 1

AN INSTRUMENTAL EARTHQUAKE MAGNITUDE SCALE*

BY CHARLES F. RICHTER

The procedure may be interpreted to give a definition of the magnitude scale number being used, as follows: *The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer ($T_0 = 0.8$ sec., $V = 2800$, $h = 0.8$) would register that shock at an epicentral distance of 100 kilometers.*

This definition is in part arbitrary; an absolute scale, in which the numbers referred directly to shock energy or intensity measured in physical units, would be preferable. At present the data for correlating the arbitrary scale with an absolute scale are so inadequate that it appears better to preserve the arbitrary scale for its practical convenience. Since the scale is logarithmic, any future reduction to an absolute scale can be accomplished by adding a constant to the scale numbers.



[*Bolt*, 1987]

SUMATRA–ANDAMAN, 26 DEC 2004

BODY-WAVE MAGNITUDE m_b

From first-arriving wave trains (" *P* " Waves)

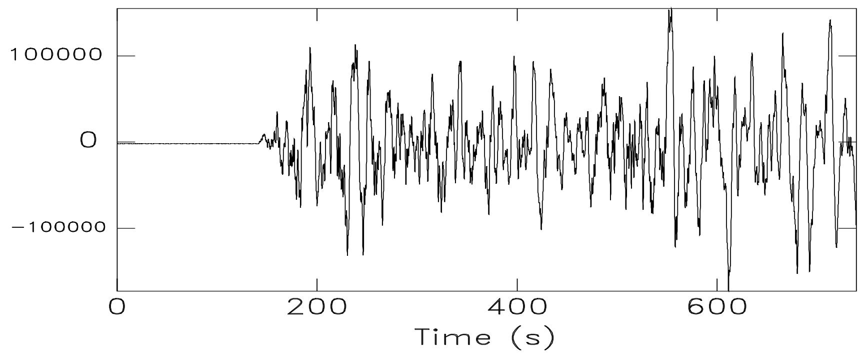
* Should be measured at period close to 1 second

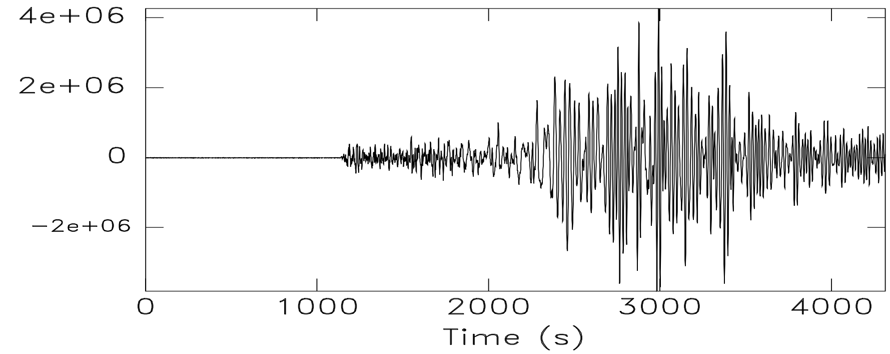
SURFACE-WAVE MAGNITUDE M_s

From later Surface-wave train (" *Rayleigh* " Waves)

* Should be measured at Period of 20 seconds

Station CTA (Charter Towers, Queensland, Australia); $\Delta = 55°$



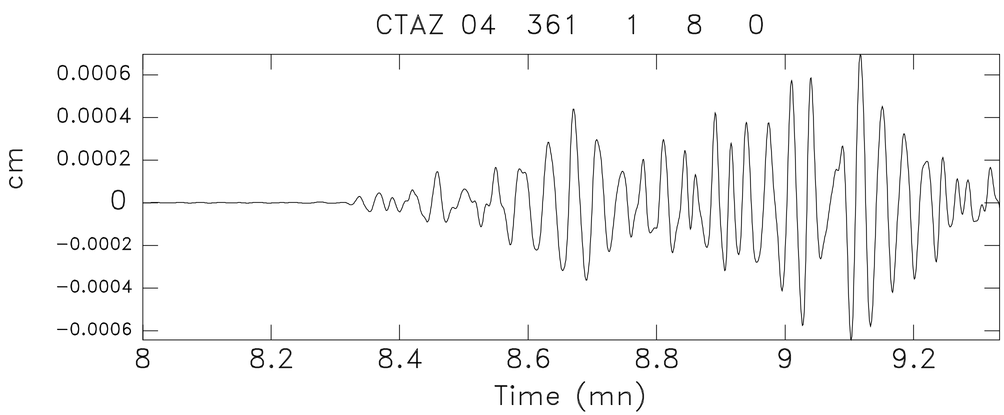


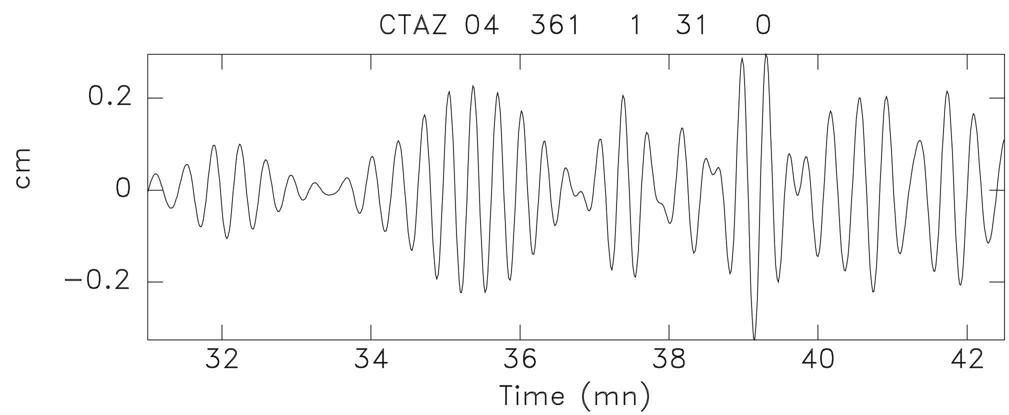
Body waves:

- Remove instrument response
- Band-pass filter between 0.3 and 3 seconds
- Select window of 80 seconds duration around *P* wave

Surface waves:

- Remove instrument response
- Band-pass filter between 15 and 25 seconds
- Select window of 11 minutes duration around Rayleigh wave





Body waves:

- Apply Body-wave Magnitude formula

$$m_b = \log_{10} \frac{A}{T} + Q(\Delta; h) \qquad (A \text{ in } microns)$$

$$\boldsymbol{m_b = 7.2}$$

Surface waves:

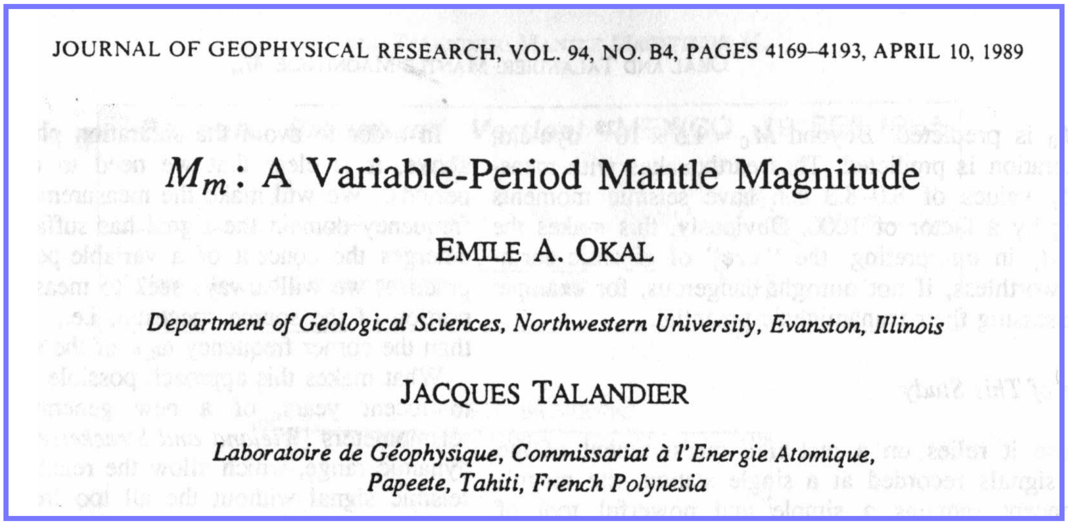
- Apply Surface-wave Magnitude formula

$$M_s = \log_{10} \frac{A}{T} + 1.66 \log_{10} \Delta + 3.3 \qquad (A \text{ in } microns)$$

$$\boldsymbol{M_s = 8.19}$$

M_m and TREMORS

[*Okal and Talandier*, 1989]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B4, PAGES 4169–4193, APRIL 10, 1989

M_m: A Variable-Period Mantle Magnitude

EMILE A. OKAL

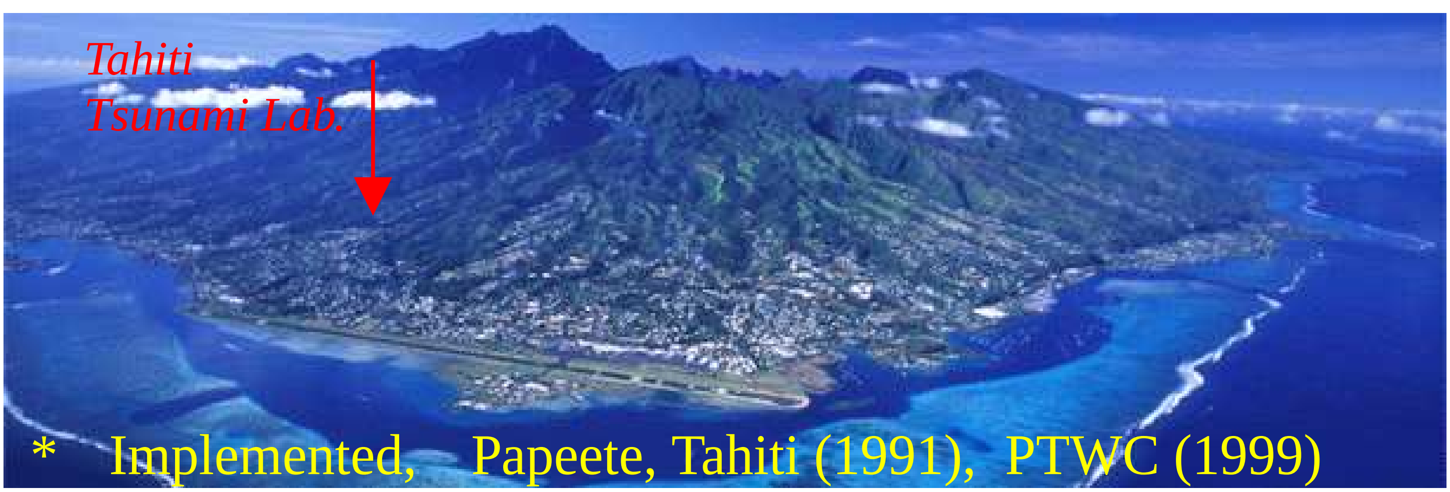
Department of Geological Sciences, Northwestern University, Evanston, Illinois

JACQUES TALANDIER

Laboratoire de Géophysique, Commissariat à l'Energie Atomique, Papeete, Tahiti, French Polynesia

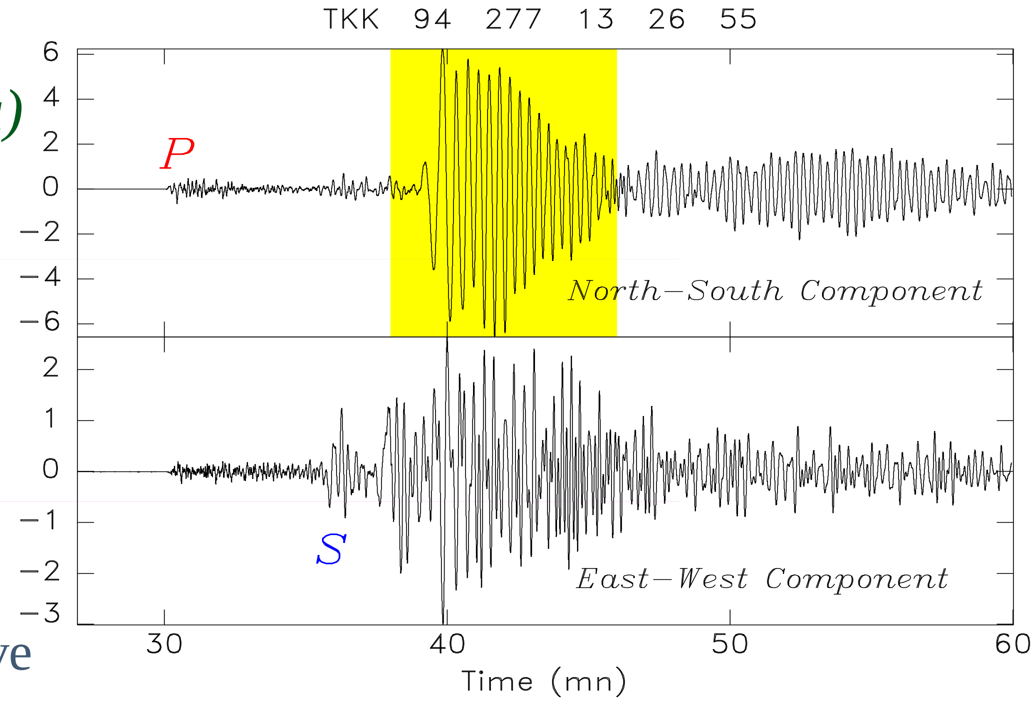
- Design *NEW* Magnitude Scale, M_m ,
  using mantle Rayleigh waves,
  with ***variable*** period
- Directly related to seismic moment M_0
- All constants justified theoretically
- Incorporate into Detection Algorithms to

AUTOMATE PROCESS



TREMORS: EXAMPLE OF APPLICATION

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



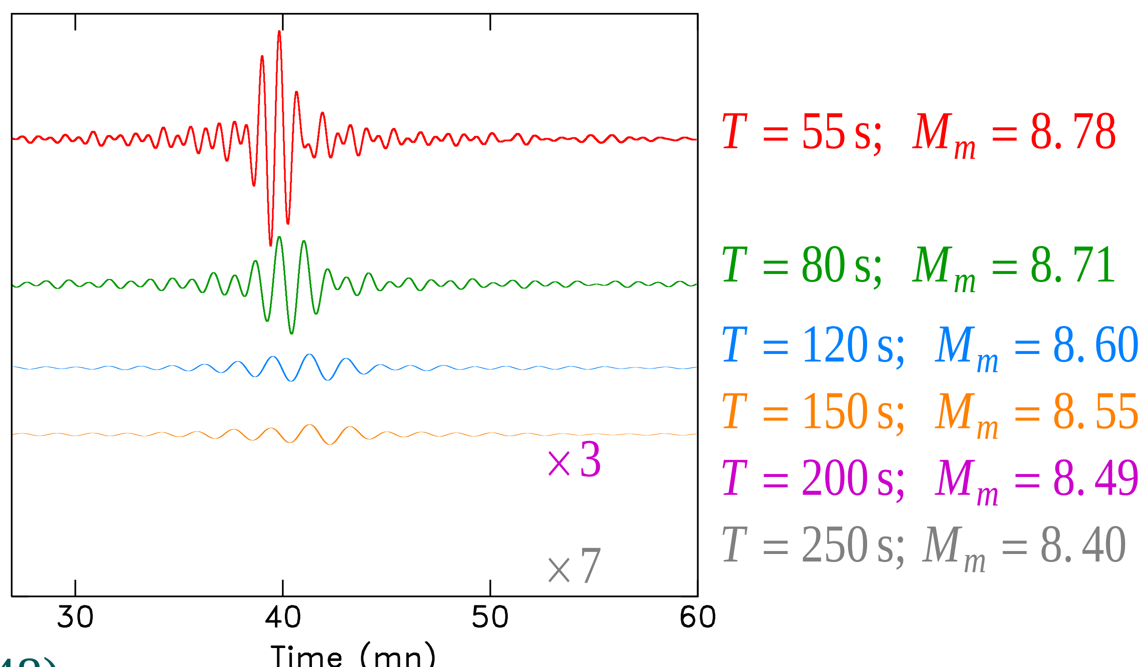
- Detection: Analyse signal level compared to previous minute.
- Location : $S - P$ gives distance (36° or 4000 km).

  Geometry of P wave gives azimuth.
- Estimate seismic moment

→ Fourier-transform Rayleigh wave (highlighted)

→ At each period, compute spectral amplitude, correct for excitation and distance; obtain M_m

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

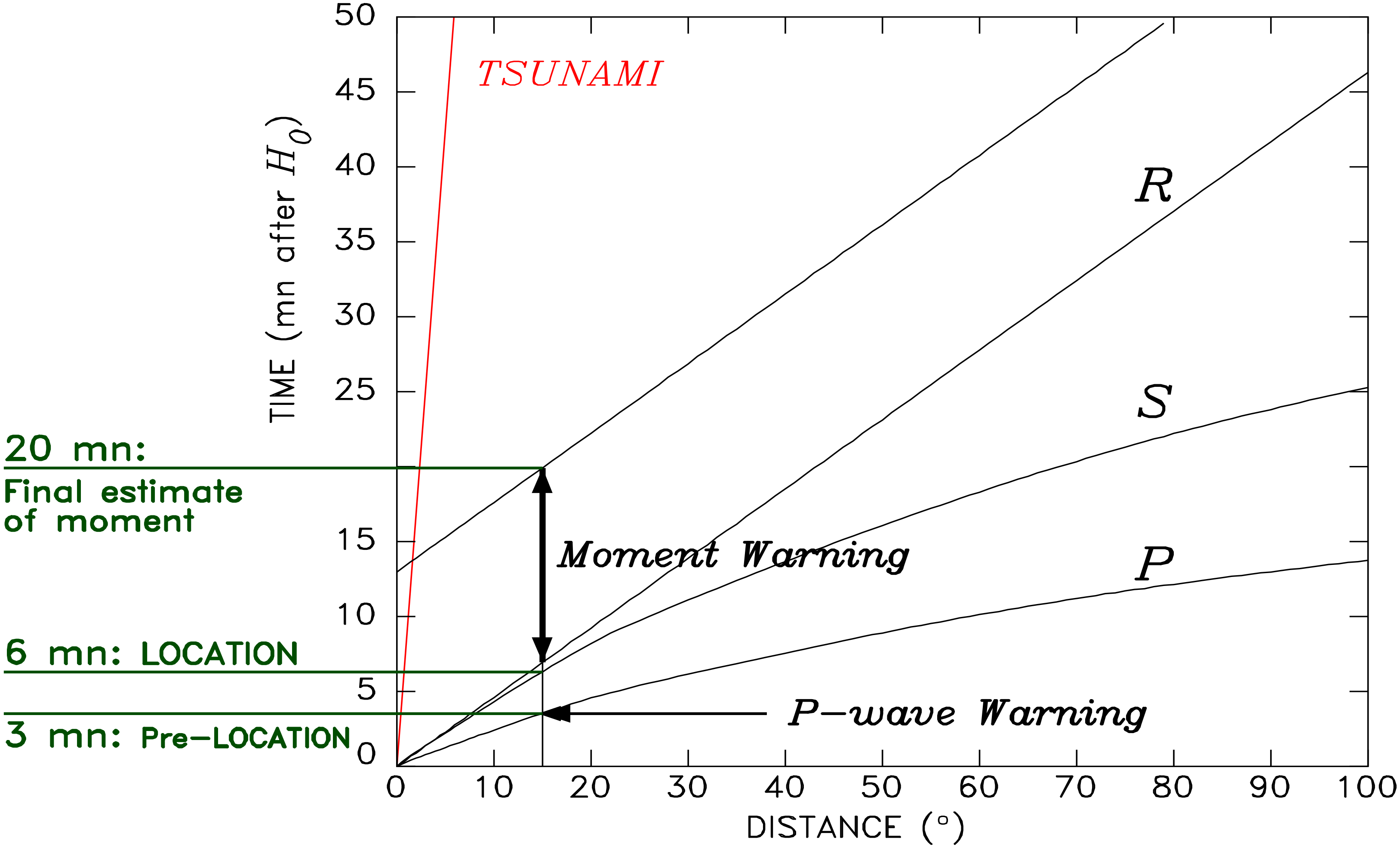


Harvard solution (obtained later):

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

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

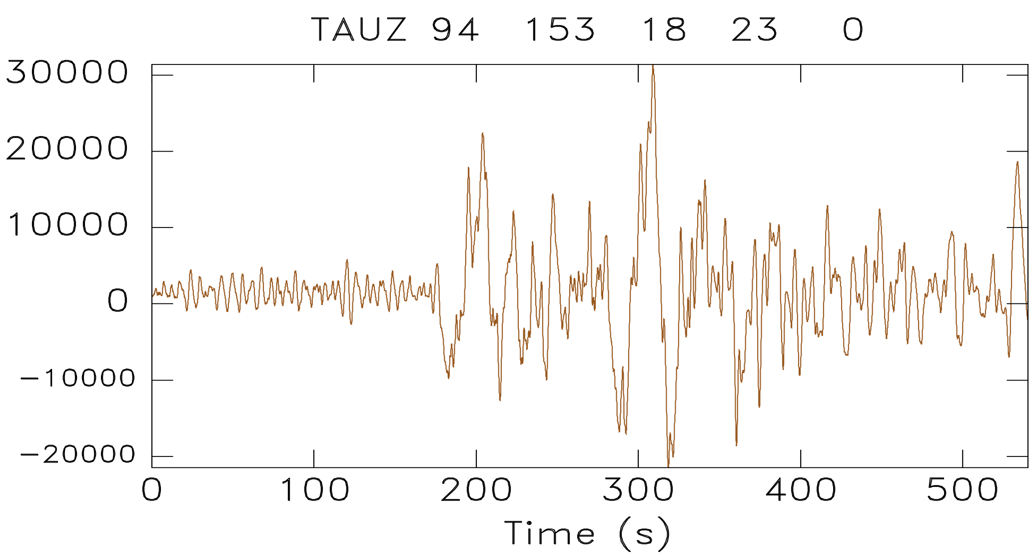
"TSUNAMI EARTHQUAKES"

- *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.

$\longrightarrow$ Use generalized$-P$ wavetrain (P, pP, sP).



1994 Java
"Tsunami Earthquake"

Station: TAU
(Hobart, Tasmania)

$\longrightarrow$ Compute Energy Flux at station [*Boatwright and Choy*, 1986]

$\longrightarrow$ *IGNORE Focal mechanism and exact depth* to effect source and distance corrections (keep the "quick and dirty *"magnitude"* philosophy).

$\longrightarrow$ Add representative contribution of S waves.

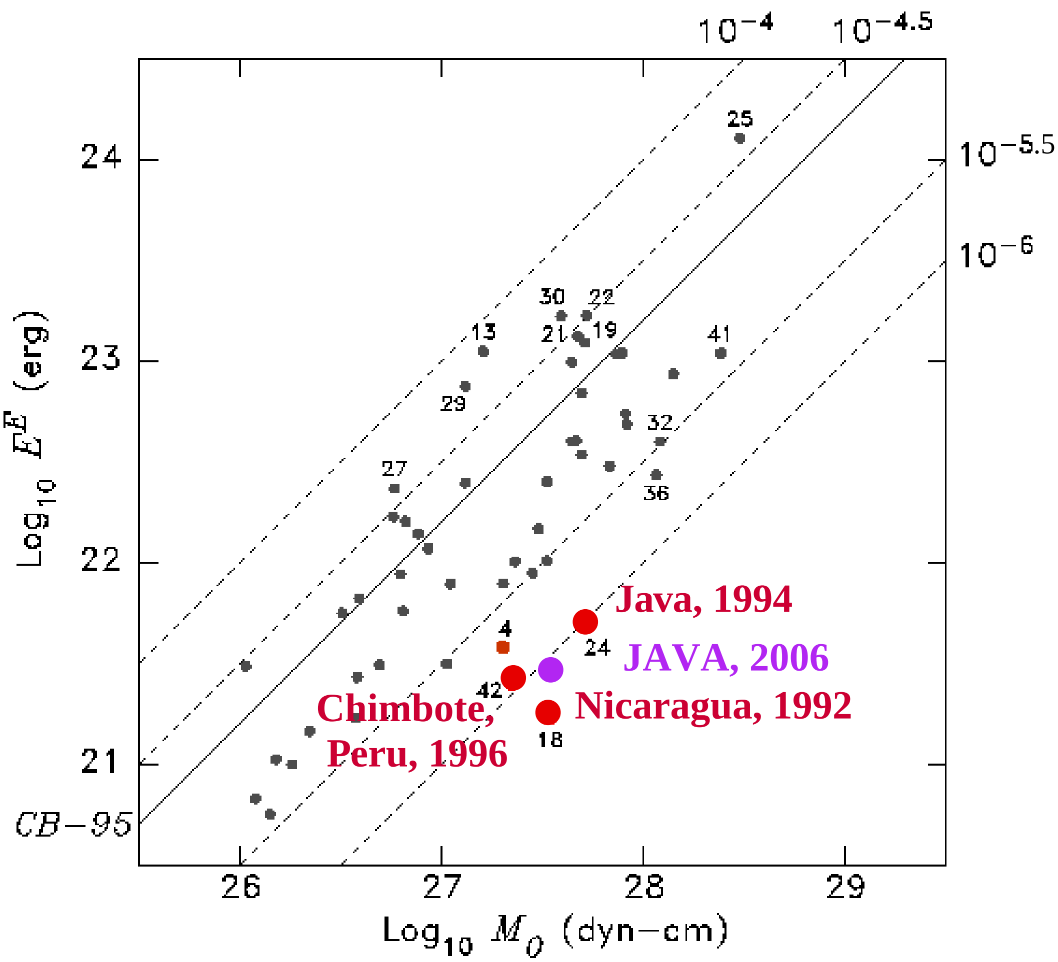
$\longrightarrow$ Define *Estimated Energy*, E^E

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

$\longrightarrow$ Scale to Moment through $\Theta = \log_{10} \dfrac{E^E}{M_0}$

$\longrightarrow$ 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

There are presently two U.S. Tsunami Warning Centers

PTWC in Ewa Beach, Hawaii (founded, 1949)

ATWC in Palmer, Alaska (founded, 1967)

TSUNAMI WARNING PROCEDURES at

Pacific Tsunami Warning Center, *Ewa Beach, Hawaii*

~ 100
Seismic Stations
(worldwide)

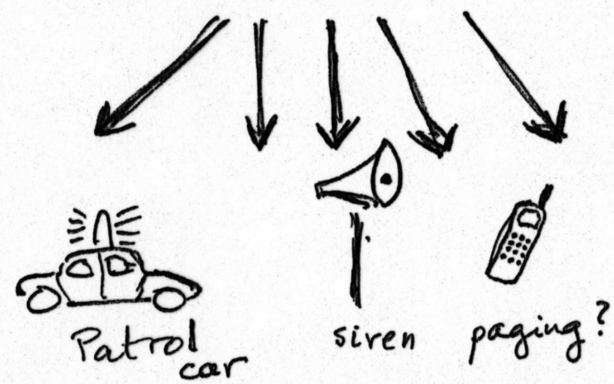
60
Maregraph
Stations

P T W C

2 scientists
ON CALL 24/7

Live on site
Report in 2 minutes

Warning issued to Pacific-rim countries



1. Detect earthquake *3 minutes* } Automatic
2. Locate earthquake *4 minutes* } Automatic

3. Quantify earthquake / Assess risk: 5 to 25 minutes

Scientist Input Critical

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

LESSONS in OPERATIONS

SCIENCE did not FAIL; COMMUNICATIONS DID.

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

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

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

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

  COMMUNICATIONS,

  to a greater extent than on additional seismic sensors.

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

THE SPECIAL CASE of the NEAR FIELD

At short distances (less than 500 km), there may not be enough lead time for the provision — and utilization — of a centralized warning

Hence, the NECESSITY of

SELF-EVACUATION **IN THE NEAR FIELD,**

TRIGGERED BY EVIDENCE OF TSUNAMI DANGER:

** FEELING OF THE EARTHQUAKE BY THE POPULATION*

** ANOMALOUS BEHAVIOR (RETREAT) OF THE SEA*

[[• Warnings may still be useful in the near field to trigger

AUTOMATED RESPONSES, e.g.,
Shut off Gas Lines,
Stop Trains,
Close sluices, etc.]]

→ SELF-EVACUATION REQUIRES

AN EDUCATED POPULATION

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.

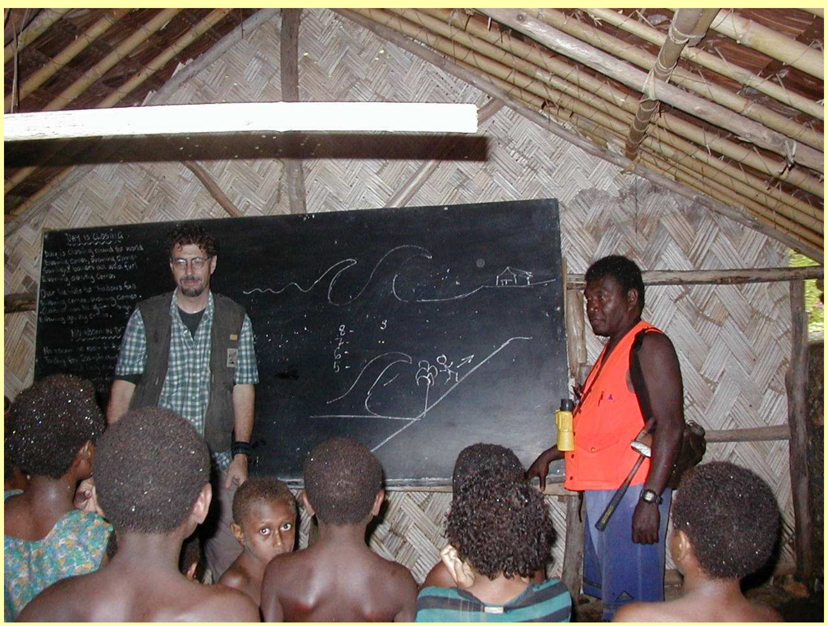
OUTREACH and EDUCATION DURING SURVEYS

Talk in Schools

E.A. Okal and J.C. Borrero,
Isla Juan Fernandez (Chile), 2000

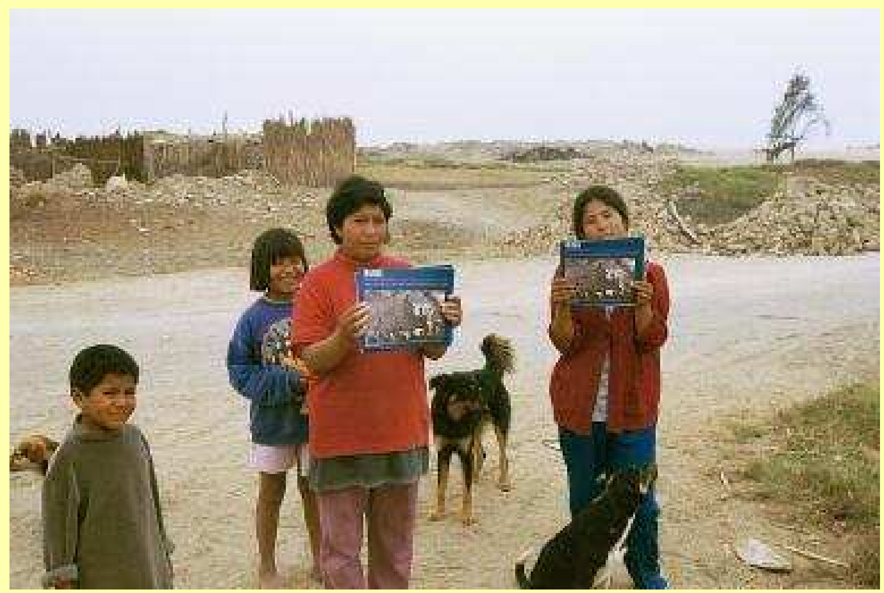
Hold "beachfront meeting"

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 !!