LECTURE 8

SCIENTIFIC MILESTONES

from HISTORICAL TSUNAMIS

in the PACIFIC OCEAN

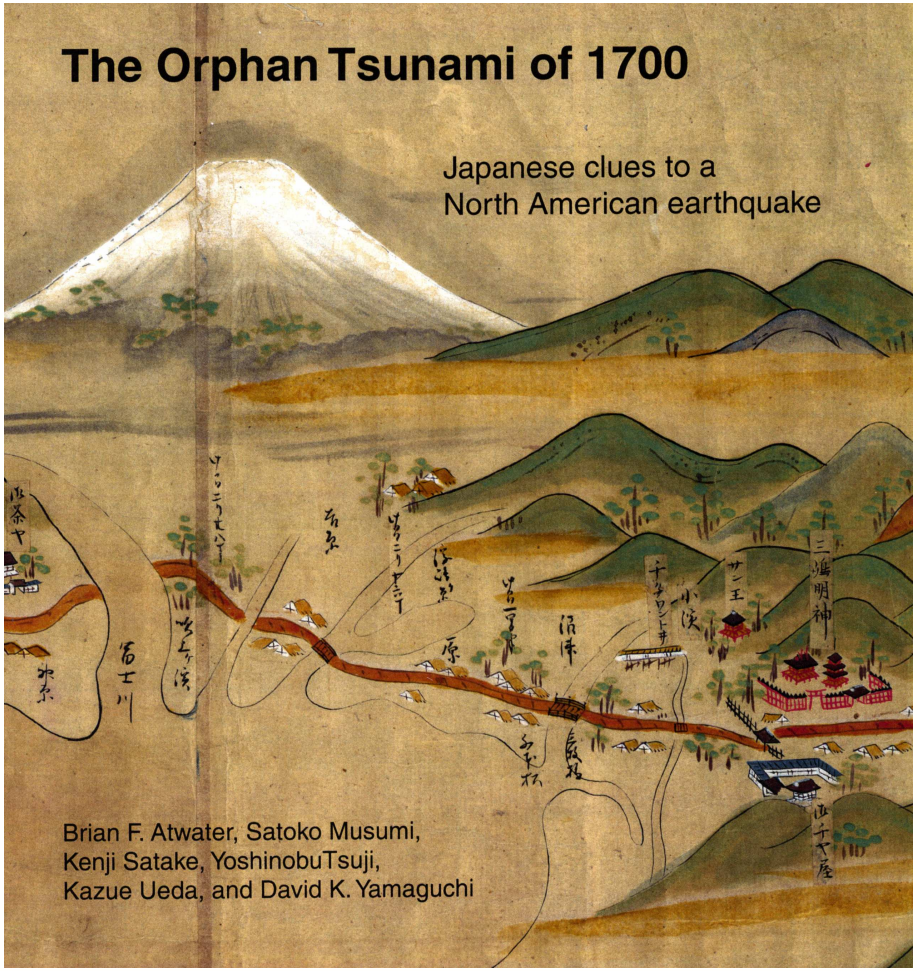
THE CASCADIA EARTHQUAKE of 26 JANUARY 1700

Over the past 25 years...

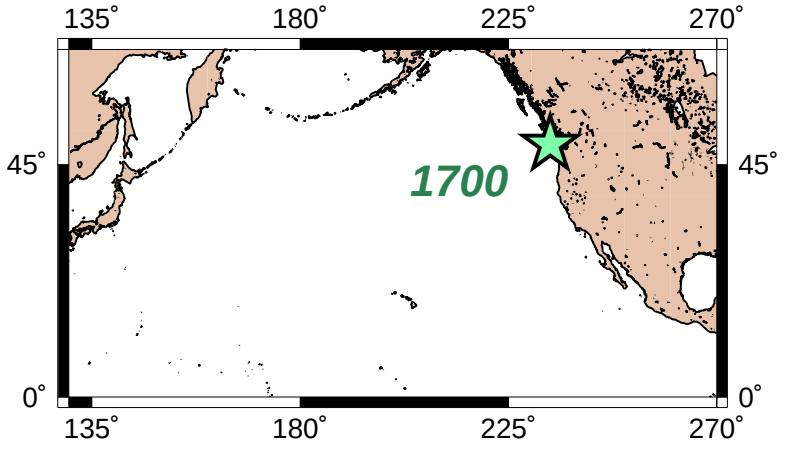
→ **We have** *"discovered" new earthquakes*

Example: **Cascadia, 1700**

- Reconstructed from tsunami records in Japan.
- Confirmed by analysis of paleotsunami data (dead trees; terraces).
- Prior to *Satake et al.*'s work, Cascadia could have fit the model of a decoupling, permanently creeping, subduction zone.



→ **We now understand that this subduction zone is the site of relativley rare (400 yr ?) but gigantic interplate thrust earthquakes.**



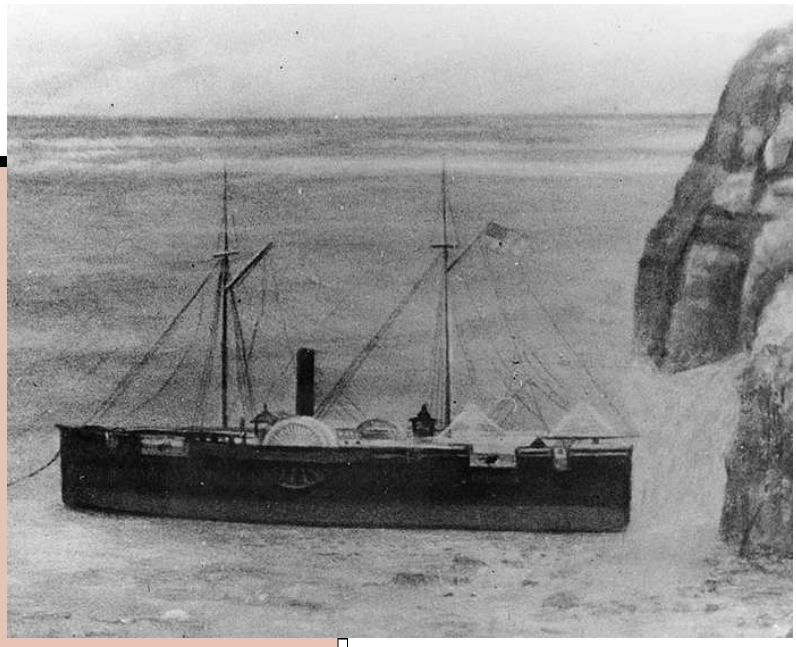
SOUTHERN PERU — 13 AUGUST 1868

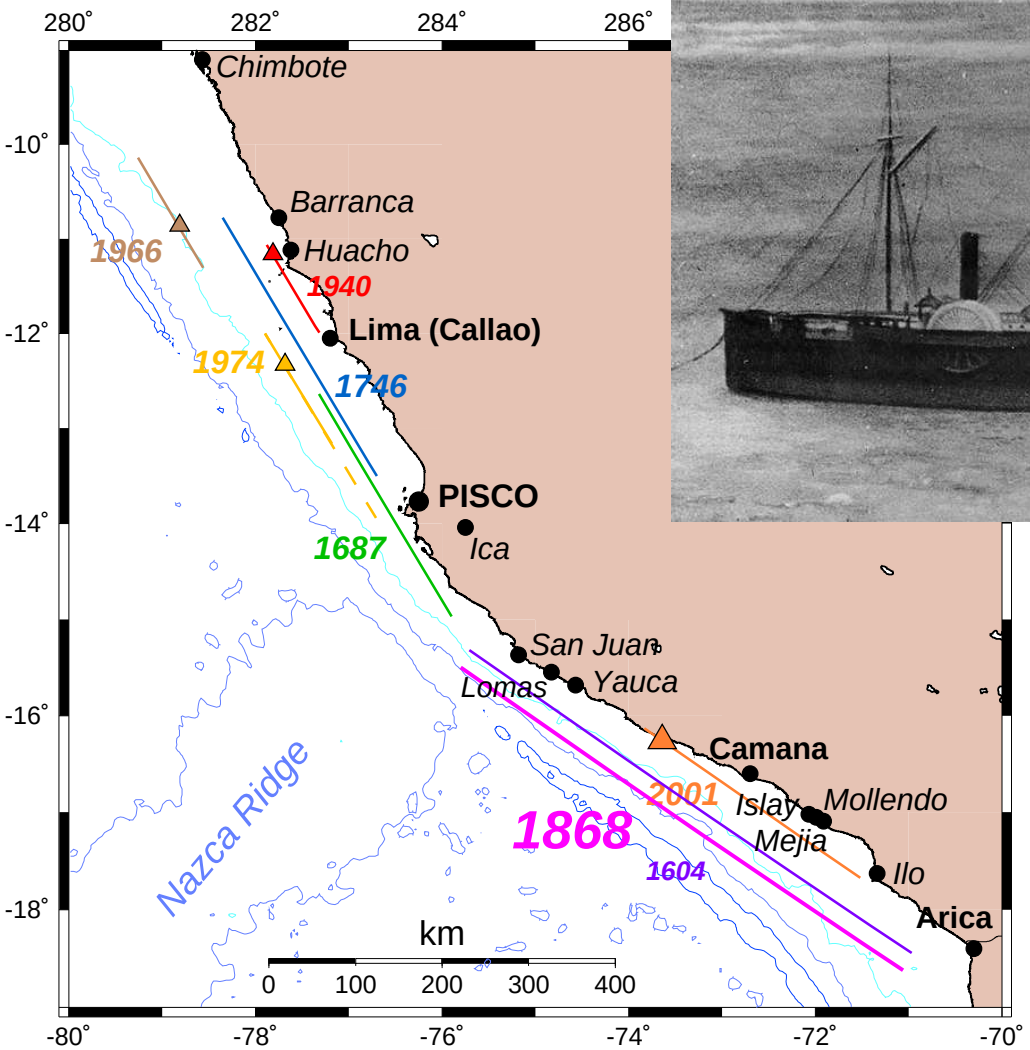
Catastrophic Earthquake and Tsunami

Destroyed Arica, Peru [now Chile].

[Tsunami moved *USS Wateree* 3 km inland at Arica.]

Tsunami destroyed cities along the Southern Shore of Peru, **including Pisco, more than 1000 km from Arica.**





USING TSUNAMI SIMULATIONS to EVALUATE HISTORICAL EVENTS

Example: **1868 South Peru** *"Arica"* Earthquake

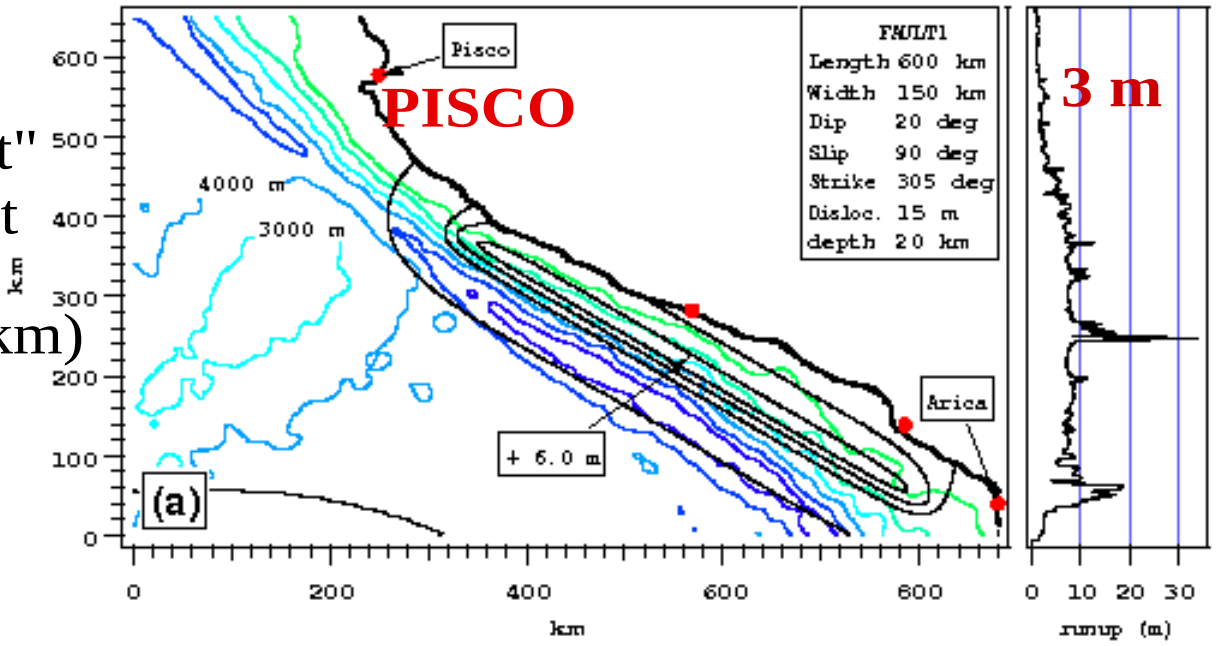
Catastrophic destruction by tsunami at **Pisco, Peru**

Modeling requires **900 km** fault rupture extending past Nazca Ridge, and thus

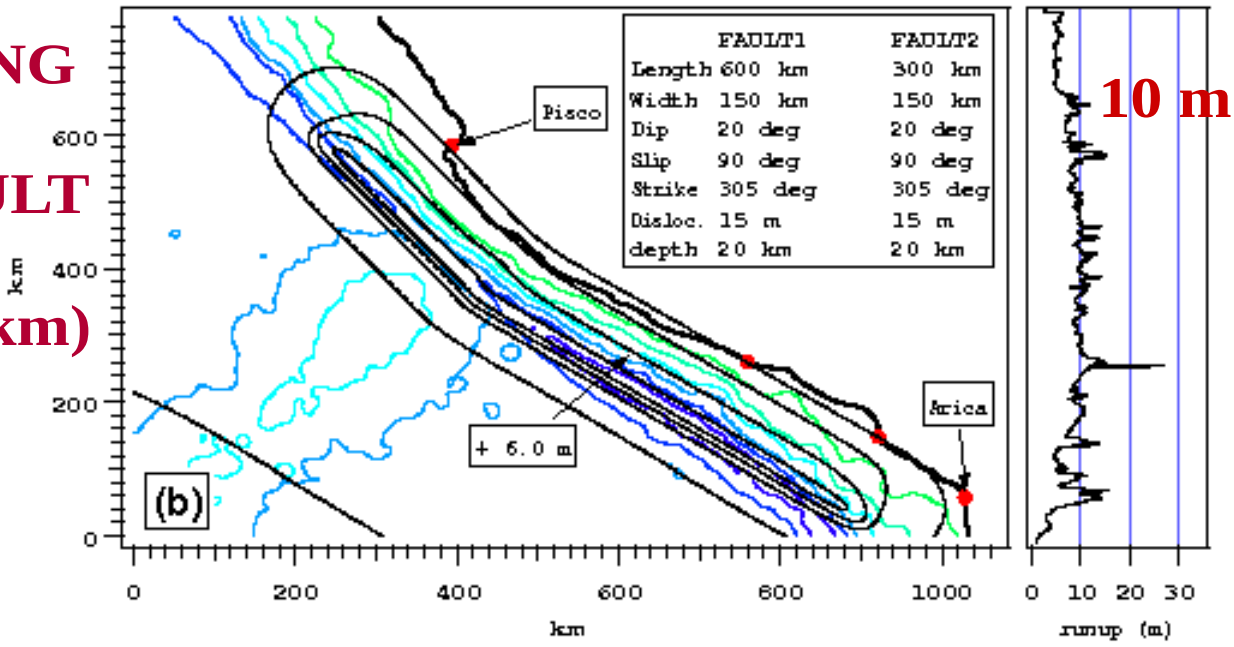
$$M_0 \approx 1 \times 10^{30} \text{ dyn-cm}$$

(*in the league of Sumatra 2004...*)

"Short" Fault (600 km)

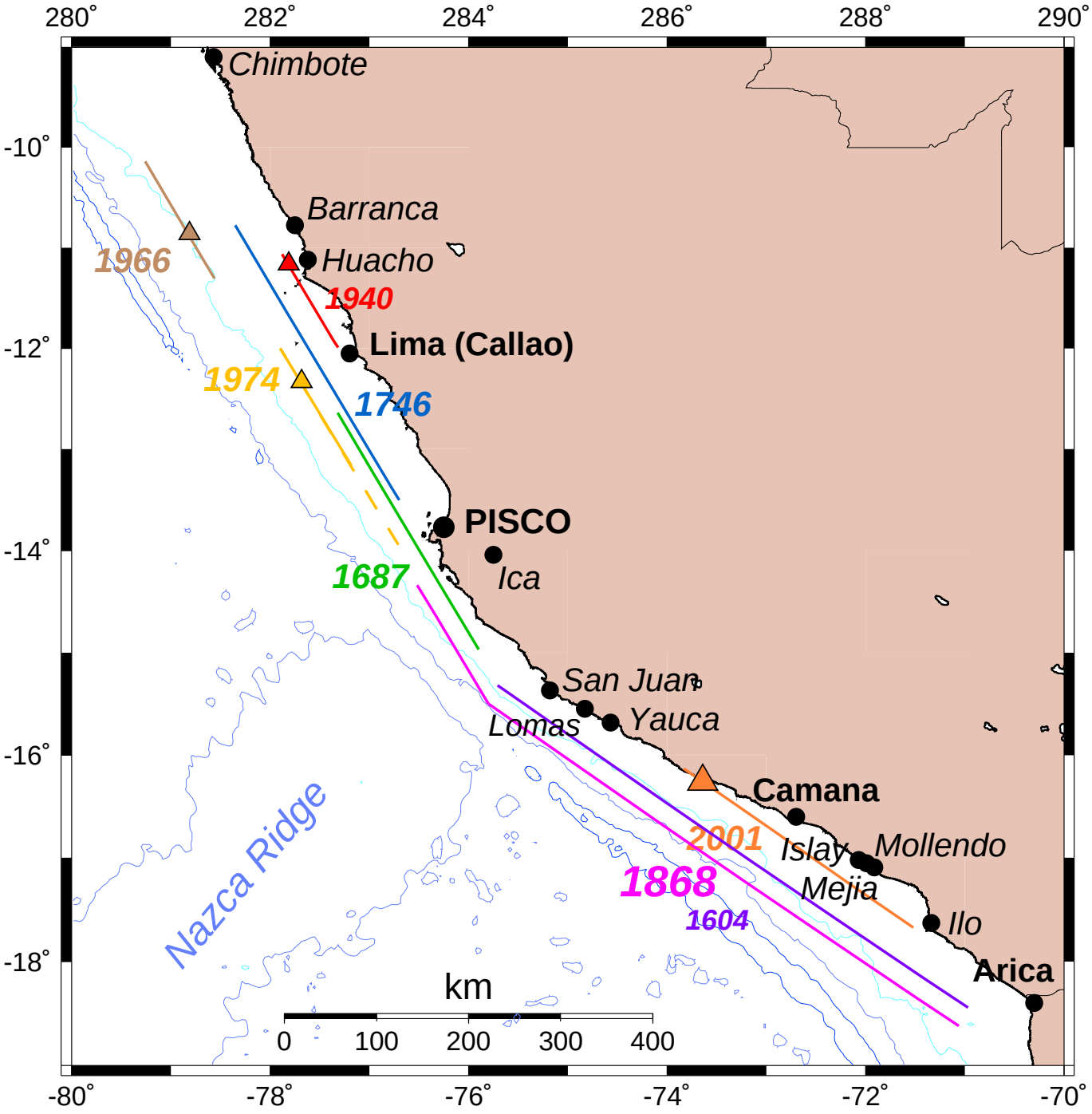


LONG FAULT (900 km)



IMPLICATIONS of 1868 ARICA EVENT

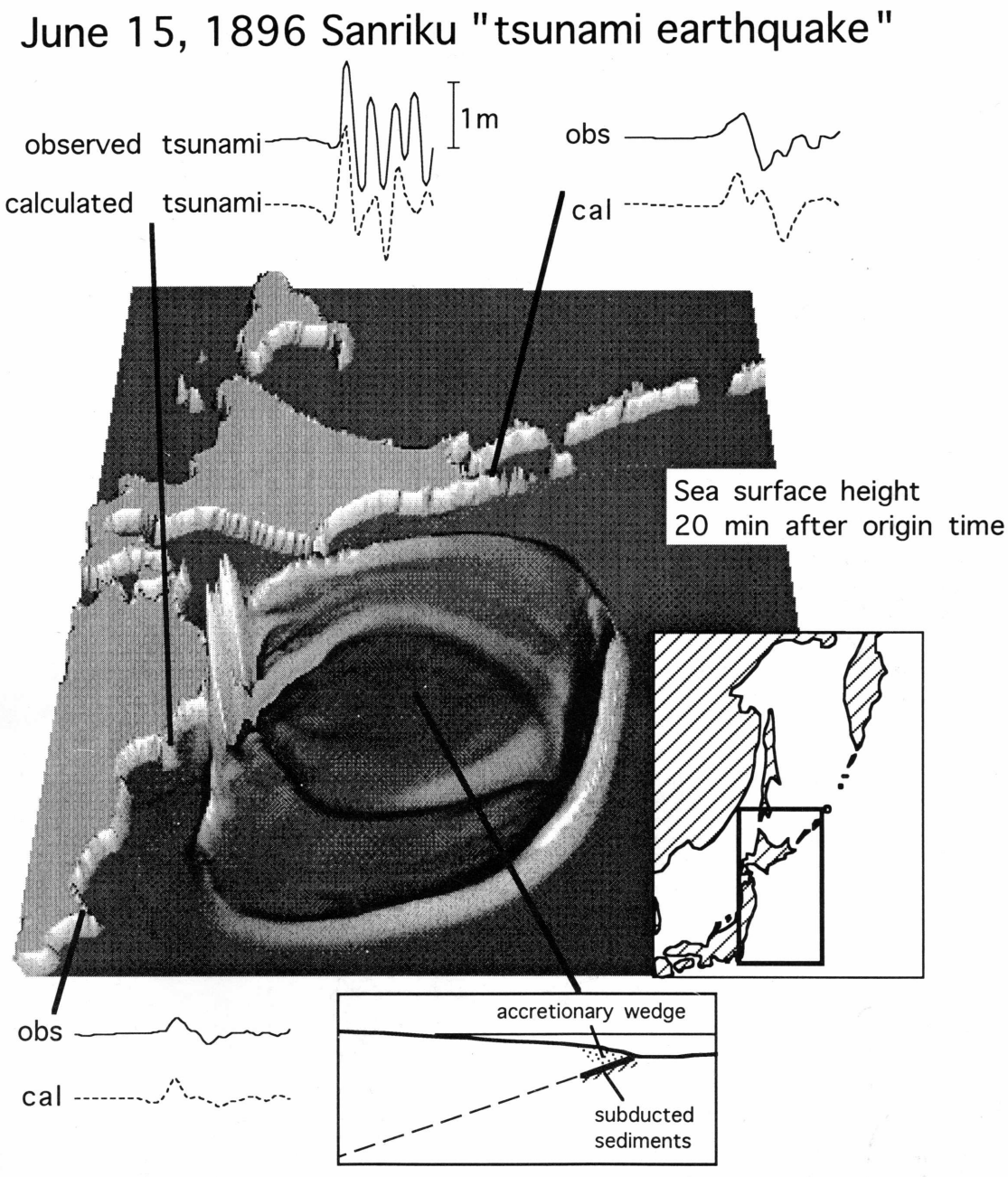
1. Earthquake is *HUGE*
2. Rupture "jumped" the Nazca Ridge
   * What constitutes a "barrier"?
3. Note variability of rupture in Large [Peruvian] earthquakes



SANRIKU, JAPAN — 15 JUNE 1896

First documented "tsunami earthquake"

- Run-up to 25 m on Sanriku coast
- Yet, [tentative] instrumental magnitude only $M = 7.2$
- Rupture must be very slow and may involve accretionary prism

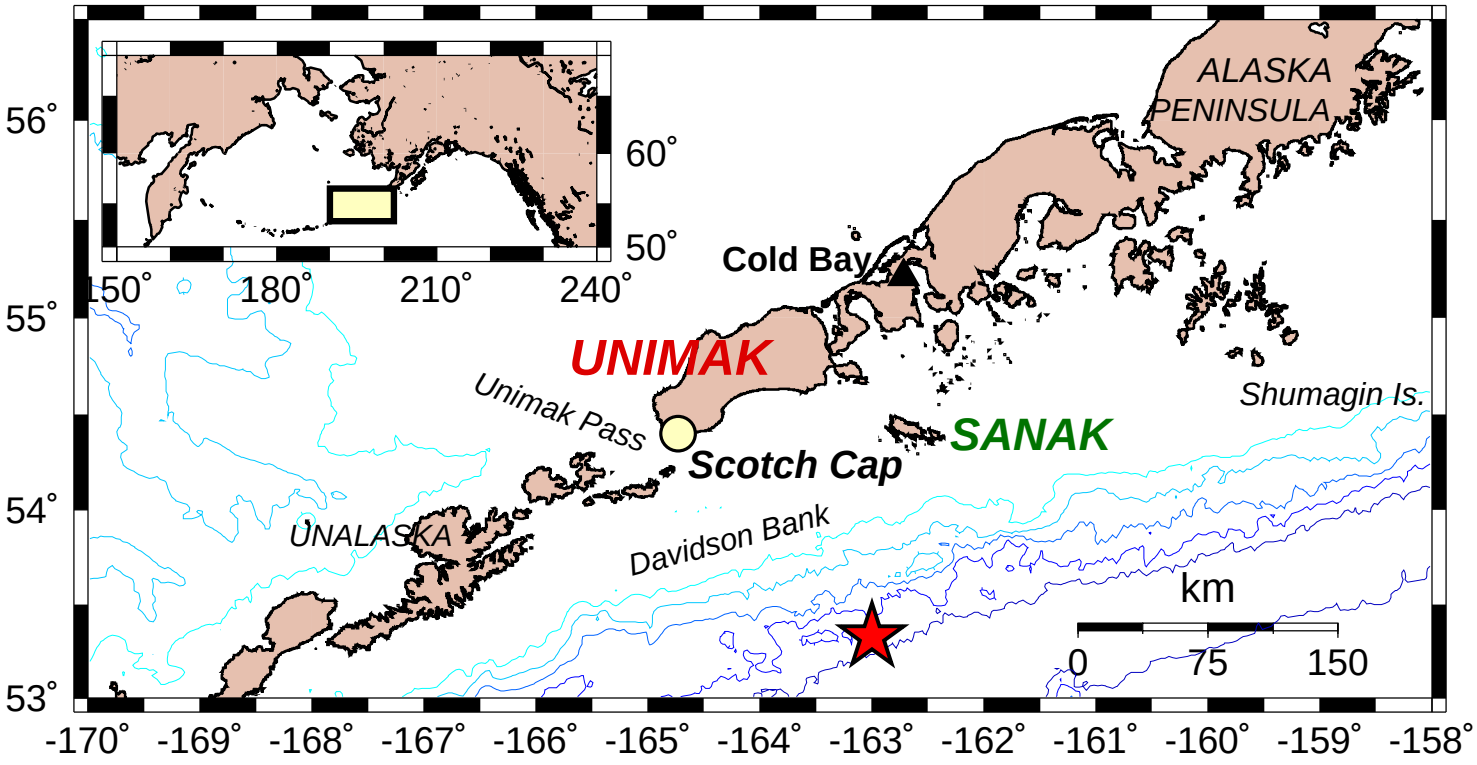


[*Tanioka and Satake*, 1996]

THE ALEUTIAN TSUNAMI of 01 APRIL 1946: 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?

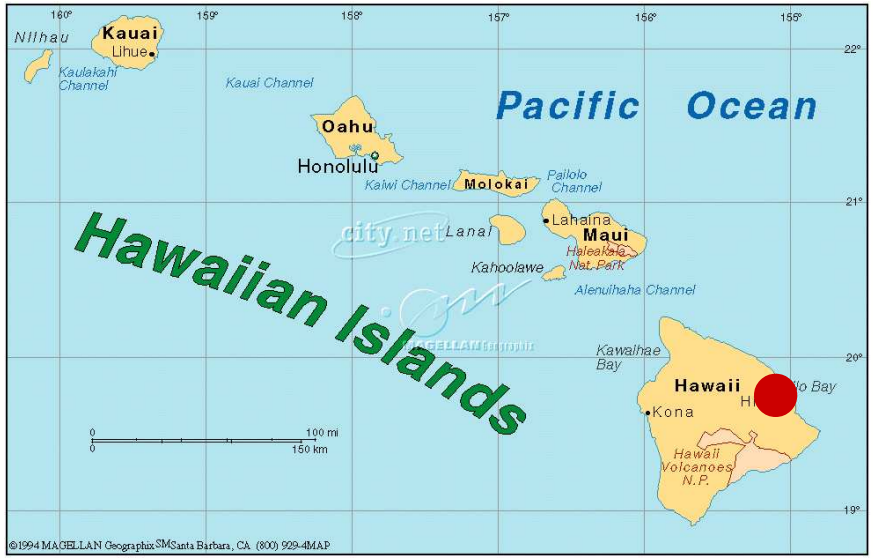
DESTRUCTION OF THE LIGHTHOUSE AT SCOTCH CAP, UNIMAK Is.

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

Before (1945)

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

01 APRIL 1946 TSUNAMI in HILO, Hawaii

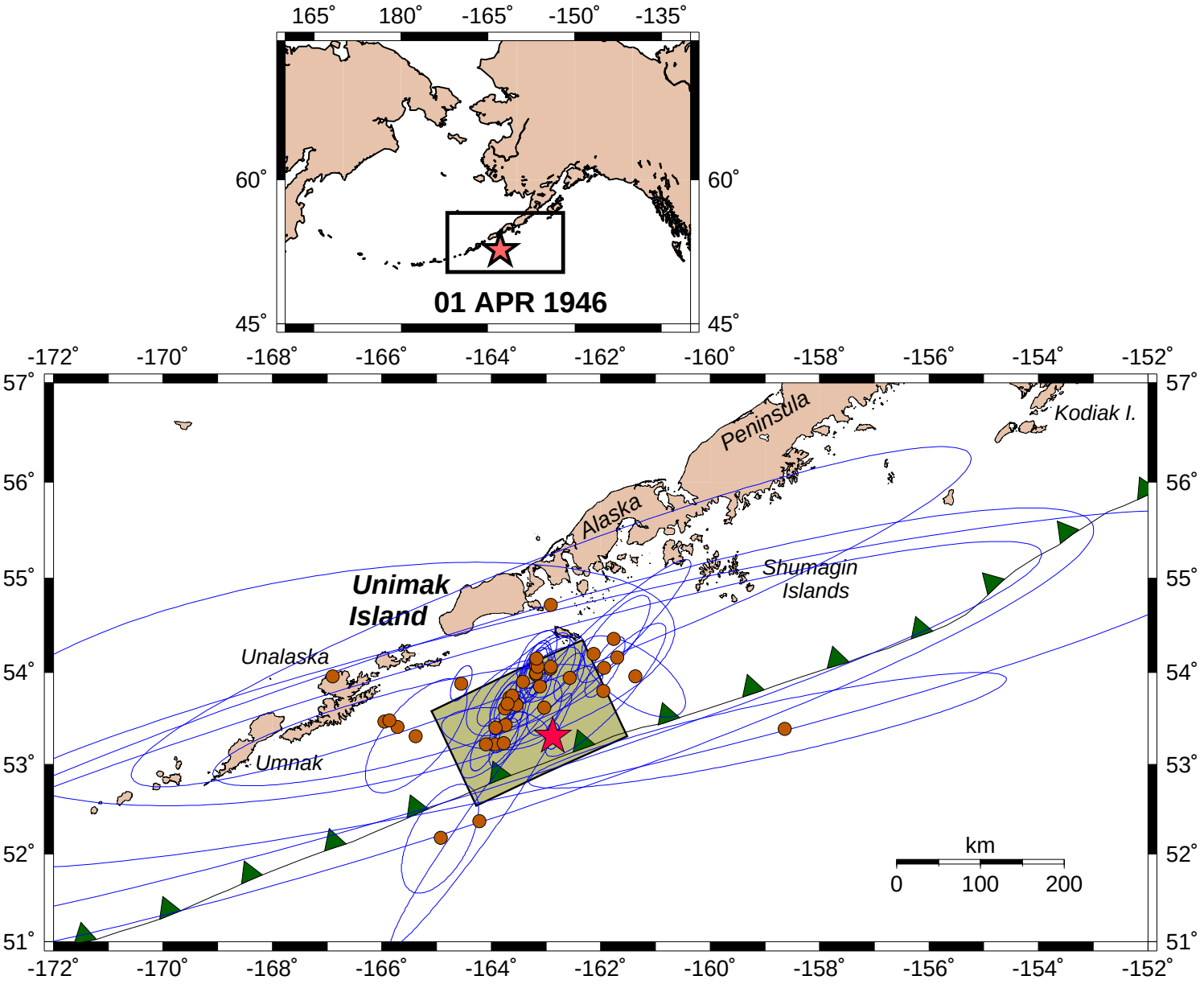


FIRST DEVASTATING TSUNAMI IN U.S. HISTORY

1946 ALEUTIAN EARTHQUAKE & TSUNAMI

- Recent study [*López and Okal*, 2006] shows very large seismic moment ($M_0 = 8.5 \times 10^{28}$ dyn-cm), but very slow, bilateral rupture ($V_R = 1.12$ km/s).

- This makes it the slowest earthquake ever studied, with $\Theta = -7.03$.



ALEUTIAN TSUNAMI, 1946

First event for which field work was conducted on the basis of interviews of elderly residents.

[*Okal*, 1999−2001].

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.

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.

KAMCHATKA — 4 NOV 1952

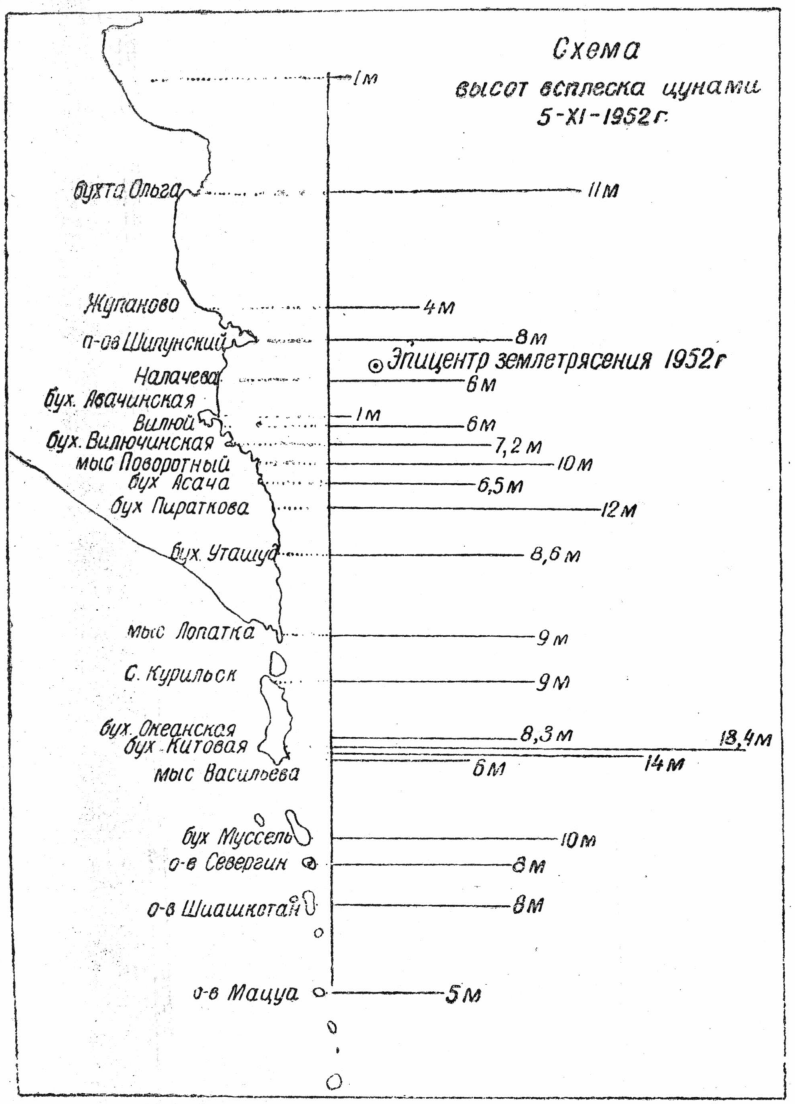


Рис. 3. Схема высот всплеска цунами 5 ноября 1952 г. в разных пунктах Курило-Камчатского побережья.

- This very large earthquake ($M_0 = 3.5 \times 10^{29}$ dyn-cm) allowed the first ever observation of the Earth's free oscillations [*Benioff*, 1954].

- It generated a devastating tsunami in the near field, killing upwards of 5000 persons (which would make it the most devastating tsunami in the 20th century), and eradicating the Naval Base at Severo-Kuril'sk.

- This evidence, long kept a State secret, has slowly emerged in the past 15 years.

Severo-Kuril'sk : 9 m.

Bay of Kitovaya : 18.4 m

CHILE — 22 MAY 1960

- Largest earthquake ever recorded and measured ($M_0 = (2 \text{ to } 5) \times 10^{30}$ dyn-cm)
- Last devastating Transoceanic tsunami in the Pacific.

Hilo, Hawaii, 23 May 1960

Hilo was again devastated by the Chilean tsunami of 22 May 1960. Sixty-one residents lost their lives.

Yet, in this case, a warning had been given, but residents failed to heed it.

RATHER, "CURIOUS" RESIDENTS CONGREGATED ON THE WATER LINE !!!

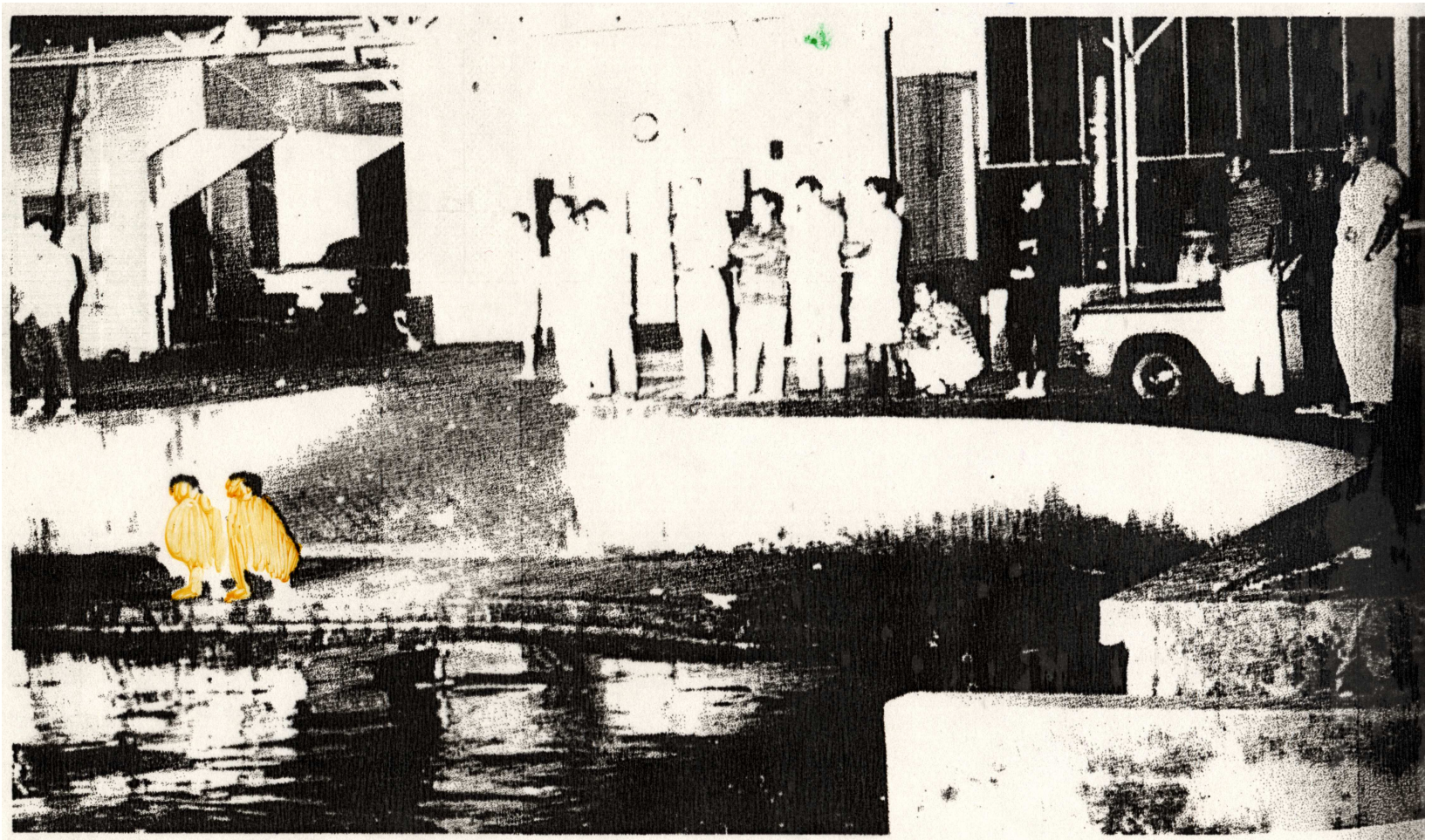


Figure 5.1 Curious Hilo residents await the first waves of the 1960 Chilean tsunami.

Nominees for "1960 DARWIN AWARD WINNER"

The Darwin Award is presented every year to an individual (or the remains thereof) who has done the most to remove undesirable elements from the human gene pool.

The 1960 Chilean tsunami went on to hit the coast of Japan where it killed about 200 people.

04:40 JST (+24:29)

04:50 JST (+24:34)

04:45 JST (+24:39)

07:30 JST (+27:19)

Arrival of the tsunami at Onagawa (Sendai Coast), 24.5 hours after origin time

ALASKA — 28 MARCH 1964

- Second largest earthquake ever recorded ($M_0 = 1.0 \times 10^{30}$ dyn-cm) [*Tsai et al.*, 2005].

- Last major tsunami to affect the U.S. (Seward, Alaska and Crescent City, California).

Locomotive moved 1 km inland by 1964 tsunami at Seward, Alaska.

- Motivated creation of Alaska Tsunami Warning Center.

ALASKA — 28 MARCH 1964

Singular geometry of subduction zone along Alaska Peninsula results in directivity pattern sparing Hawaii (for once), but focused towards California.

→ Explains exceptional level of destruction at Crescent City (12 deaths; 4 at Newport Beach, Oregon) and generally benign character in Central Pacific (Hawaii, Tahiti).

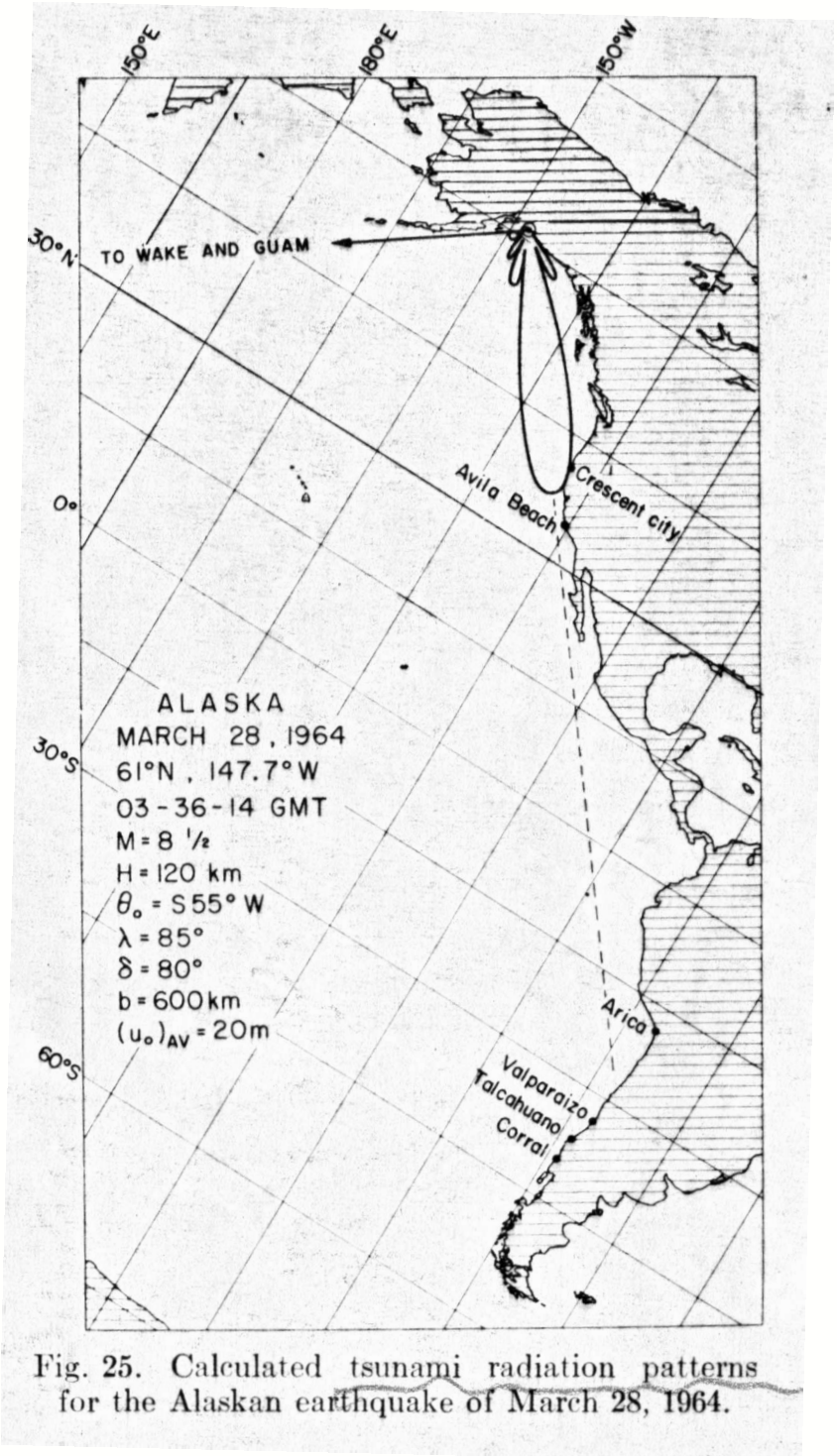


Fig. 25. Calculated tsunami radiation patterns for the Alaskan earthquake of March 28, 1964.

[*Ben-Menahem and Rosenman*, 1972]

Note also that many residents of Crescent City were drowned by **second, larger wave**, afer they had returned to clean up their damaged houses.

KURILES — 10 JUNE 1975

- "Tsunami Earthquake" following larger event in 1973.

  → [Local] tsunamis for the two events comparable, despite much smaller seismic moment in 1975 (see relevant surface waves).

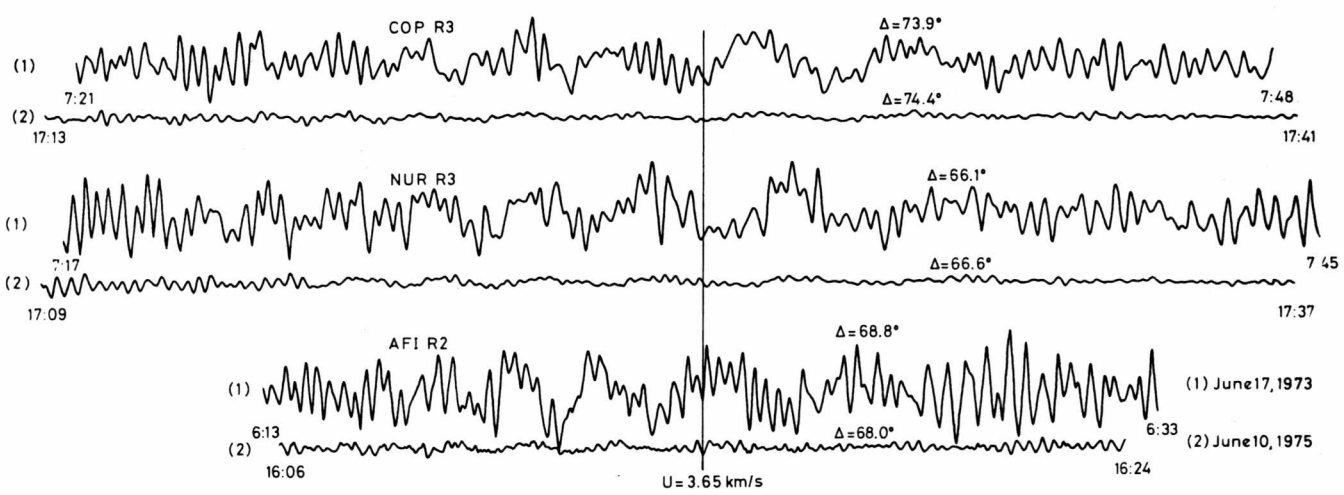
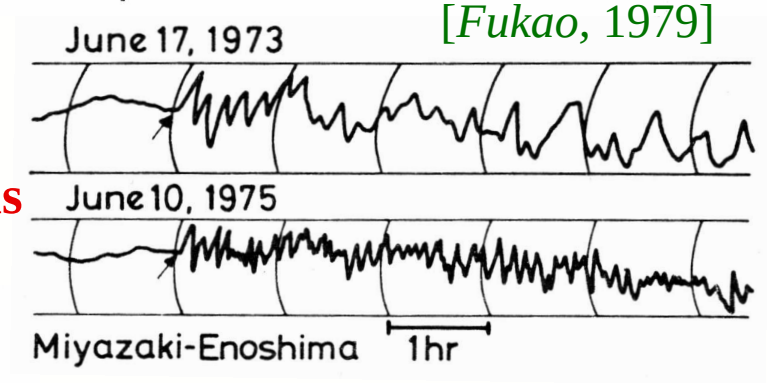


Fig. 8. Long-period *R*3 seismograms at COP, Sweden, and NUR, Finland, and *R*2 seismograms at AFI, Samoa, for the Nemuro-Oki earthquakes of 1973 and 1975.

Seismic waves

[*Fukao*, 1979]

Tsunamis



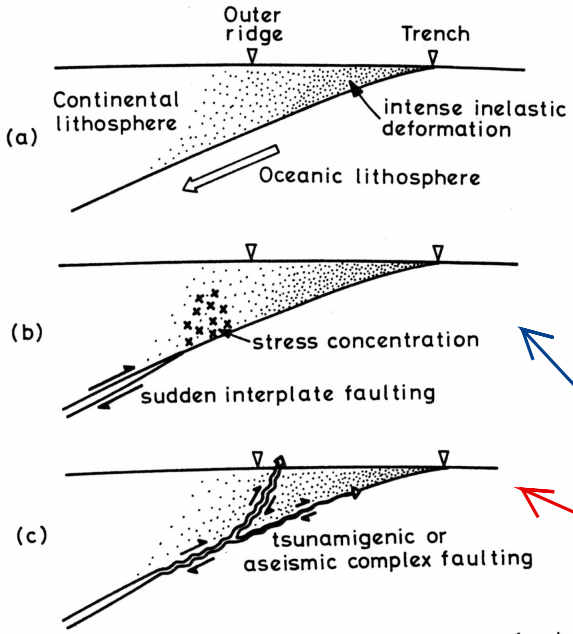


Fig. 19. A model for a great earthquake sequence showing (*a*) interseismic stage, (*b*) coseismic stage, and (*c*) postseismic stage. See the text for details.

- This type of event could correspond to the release of stress induced into the sedimentary wedge (hence rupturing slowly) by stress transfer from the earlier main shock.

Regular Earthquake (1973)

Tsunami Earthquake (1975)

NICARAGUA — 02 SEP 1992

- First major "Tsunami Earthquake" during modern instrumental era.

Playa Popoyo

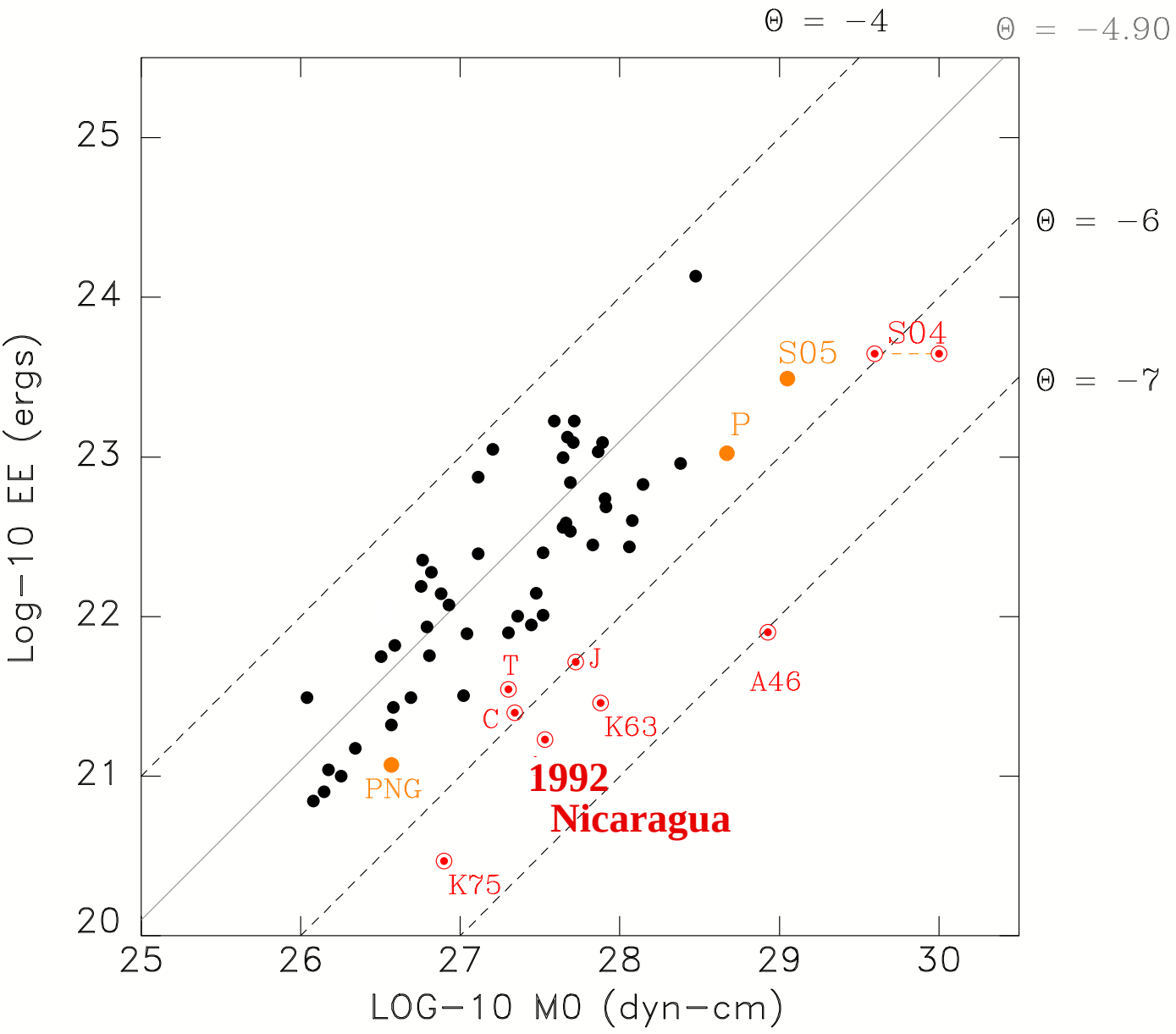
Slow, "tsunami" earthquake, locally not felt on the beaches.

More than 160 dead.

Numerical simulations of event revealed factor of 10 difference with threshold-type models.

NICARAGUA — 02 SEP 1992

- Motivated introduction of slowness parameter Θ [*Newman and Okal*, 1998].



RED Events are SLOW ($\Theta \leq -5.8$)

NICARAGUA — 02 SEP 1992

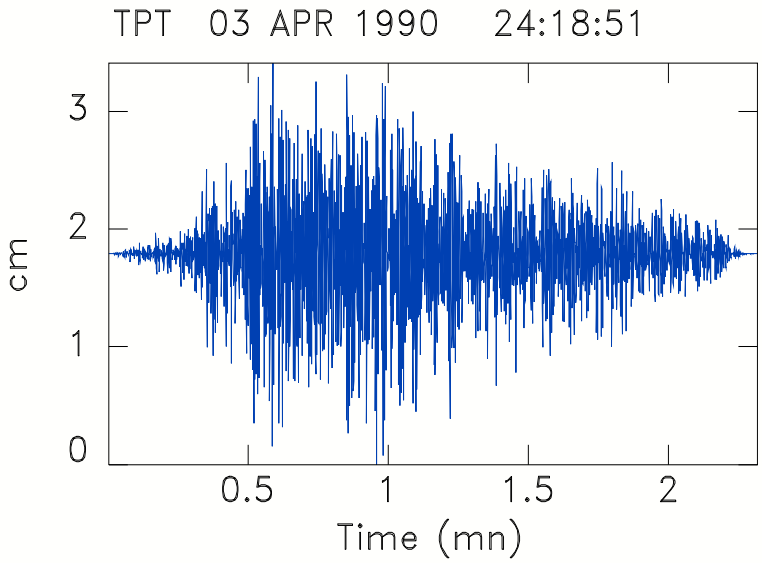
- The earthquake is found to be deficient in T waves, as expressed by the parameter

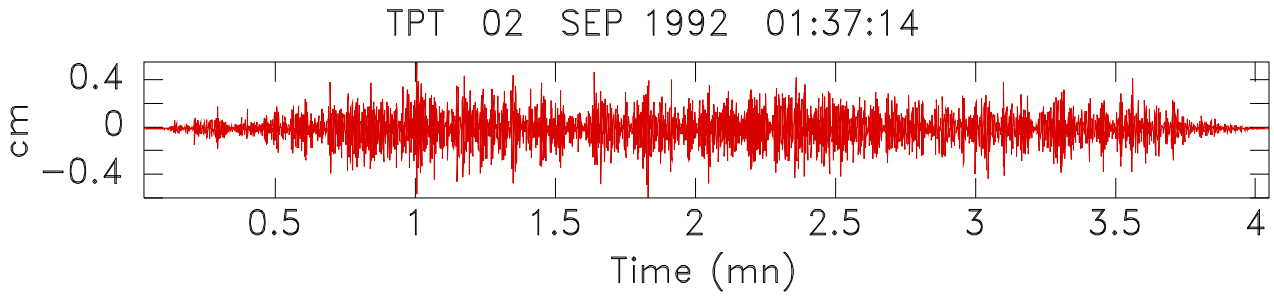
$$\gamma = \log_{10} \frac{TPEF}{M_0}$$

[*Okal et al.*, 2003].

Compare T waves at the same Polynesian station (TPT) from *a regular earthquake (Costa Rica; 1990)* and the **1992 Nicaragua earthquake** of similar moment:

$$\gamma_{1992} - \gamma_{1990} = -2.06$$





1992 *Deficient by TWO ORDERS of MAGNITUDE*

Milestones: Manzanillo 1995

First physical evidence of leading depression N-wave, analytical results.

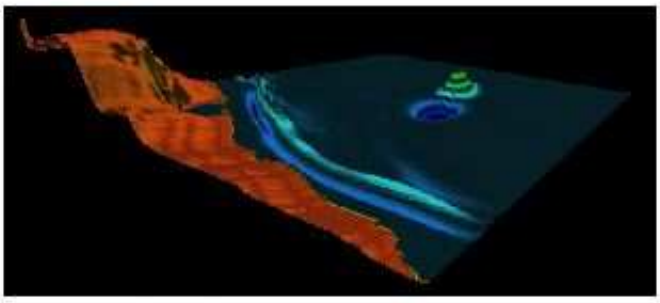
On a usual day.

October 9, 1995

PAPUA NEW GUINEA — 17 JULY 1998

- ***RECALL***

First evidence of *seismically* generated landslide tsunami; validation of overland flow into lagoons.



Initial and final wave, animation of Borrero (2001)

Sissano Spit

VANUATU — 26 NOV 1999

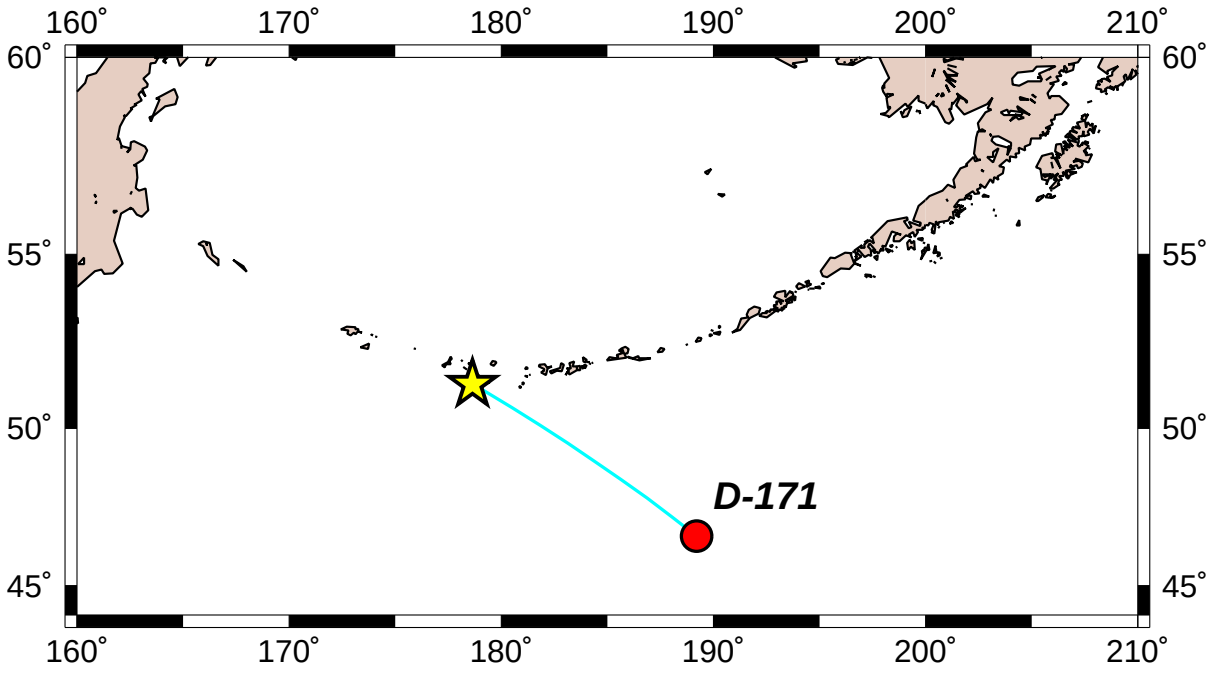
- *Spontaneous night-time self-evacuation following post-PNG Video*

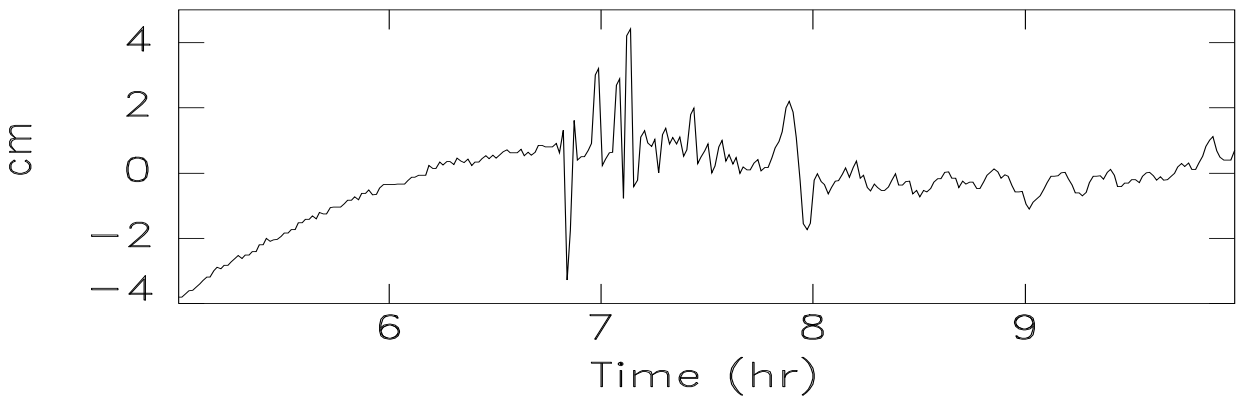
EDUCATION WORKS !!

ALEUTIAN — 17 NOV 2003

- **First successful operational use of DART sensors to call off an alert.**
- The tsunami from this small earthquake was not recorded at the distant Alaska and West Coast DART sites.

  However, a new station, only 900 km from the epicenter, clearly recorded the tsunami, at an amplitude of 3 cm peak-to-peak.





This signal was interpreted by V.V. Titov in terms of source size and a real-time simulation performed to predict the run-up in Hawaii. As a result, the pending alert was called off by PTWC.

SUBSEQUENT TSUNAMIS (ctd.)

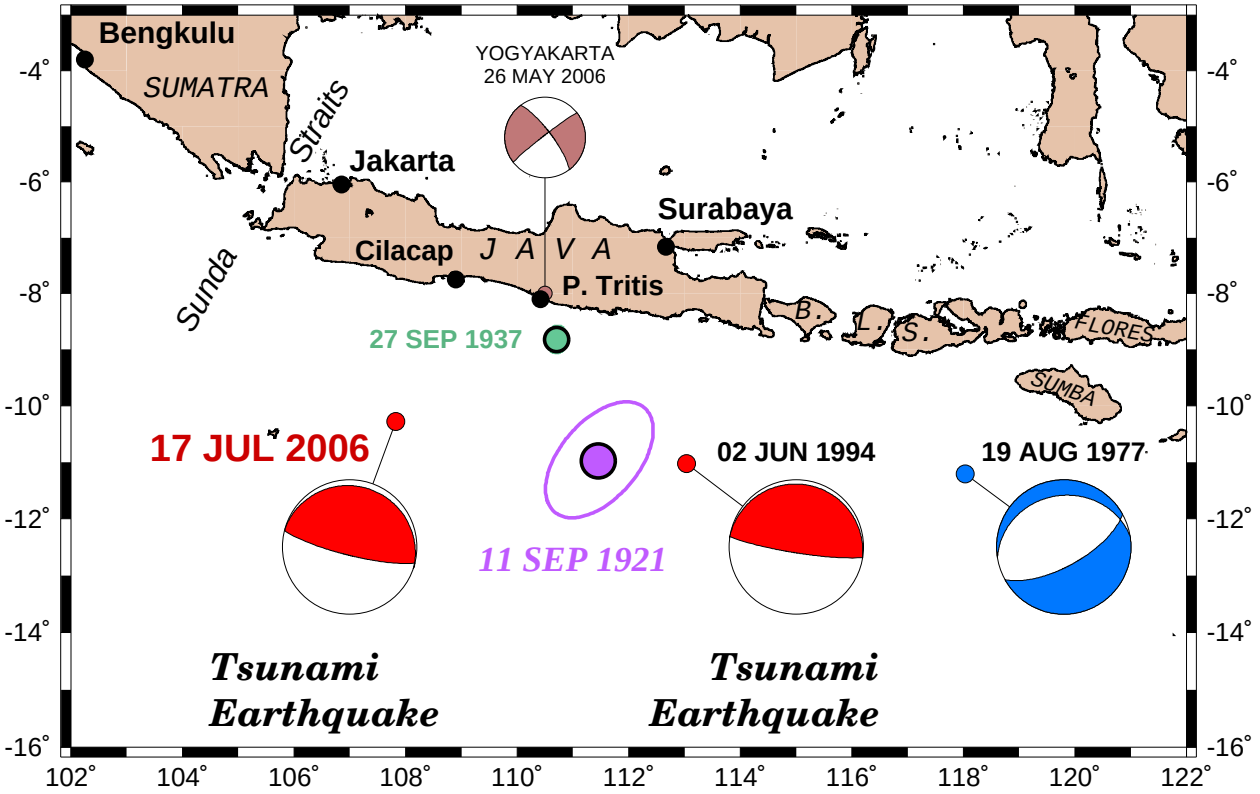
3. *Java, 17 July 2006*

$M_0 = 4.6 \times 10^{27}$ dyn*cm *Slow event*, $\Theta = -6.13$

Typical "Tsunami Earthquake"; — 700 killed by tsunami

Carbon copy of 1994 event, 600 km to the East

T.E. : Event whose tsunami is stronger than suggested by its seismic magnitudes [*Kanamori*, 1972].



This event suggests that *"tsunami earthquakes"* could feature a regional character.

Question: **Does this exclude the danger of a subduction mega-thrust earthquake in Java ???**

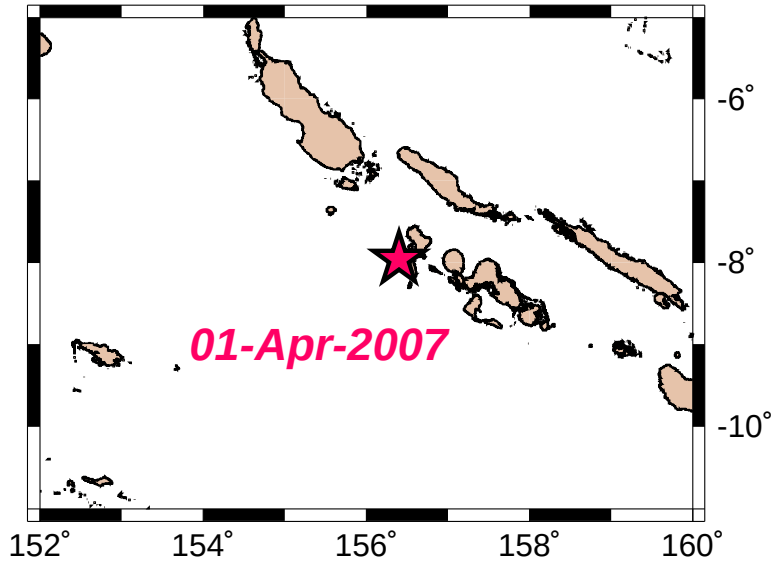
* **What is the role of the 1921 shock (contrary to the T.E.s, strongly felt, but with benign tsunami) ?**

• *Lesson:* Total Failure

(i) of the new, allegedly operational, systems;

(ii) of the response of the Governement officials involved.

SUBSEQUENT TSUNAMIS (ctd.)



5. *Solomon Is., 01 April 2007* [The Miracle ?]

$$M_0 = 1.6 \times 10^{28} \text{ dyn*cm}$$

Preliminary Results:

[H. Fritz, pers. comm., April 2007]

Local Tsunami, resulting in significant damage on several islands

More than 500 houses destroyed; **35 dead or missing**

The community apparently had the reflex of *Self-Evacuation*

(probably conditioned by the memory of strong waves during a volcano-seismic swarm in the 1950s ?)