HISTORICAL PERSPECTIVE on NON-SEISMIC TSUNAMIS

In the Warning Context

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TSUNAMIS GENERATED BY

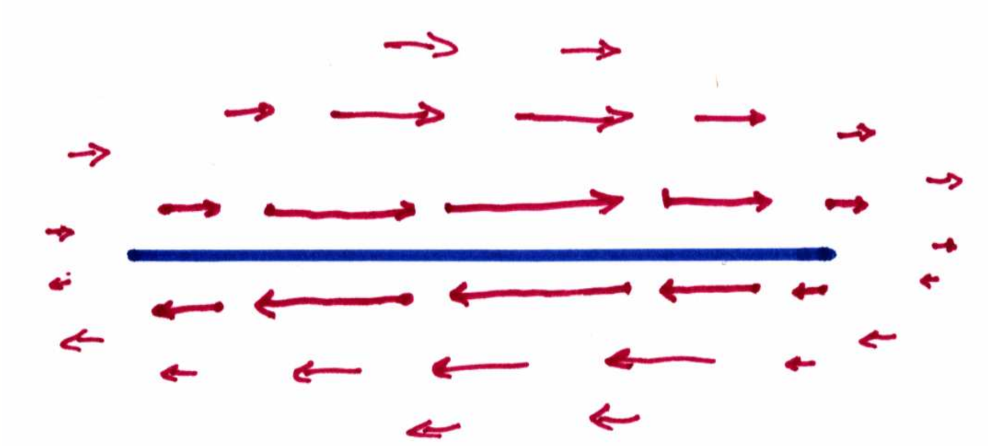
- **Earthquakes**
- **Landslides** ←
- **Volcanic Eruptions** ←
- **Bolide Impacts** ←

→ ***Meteo – Tsunamis***

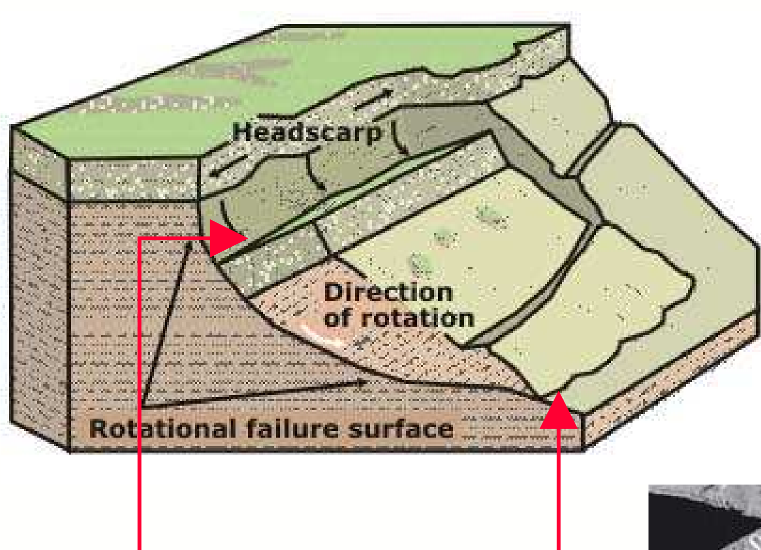
LANDSLIDE TSUNAMIS

RECALL DIFFERENCE BETWEEN EARTHQUAKE and LANDSLIDE

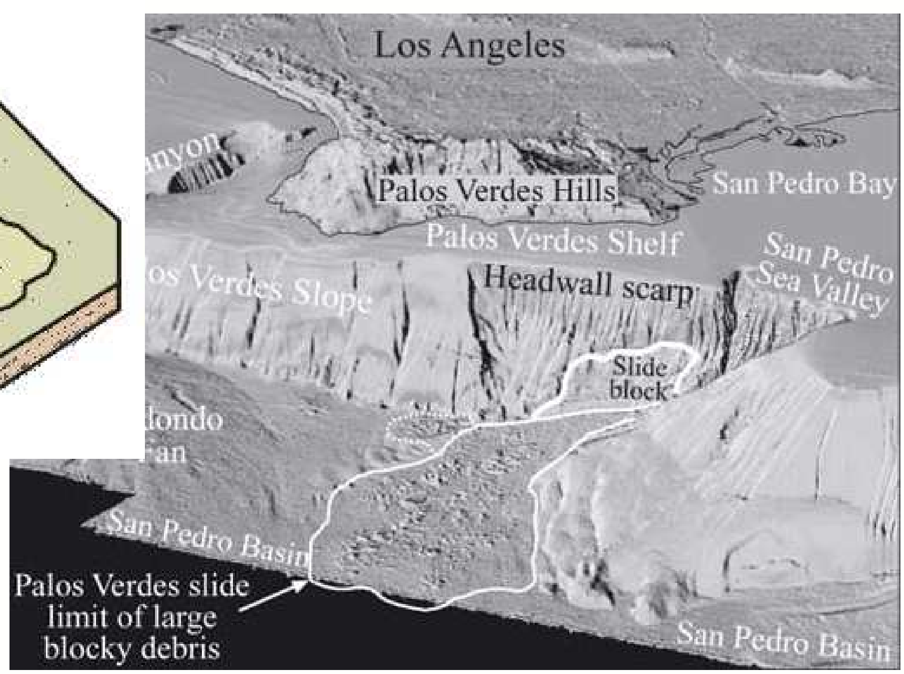
- An important aspect of an *Earthquake Rupture* is that the walls of the fault remain *cohesive continuous media* outside of the dislocation surface. In particular, the continuity of the structure is preserved near the ends (tips) of the fault.



Contrast this with the case of a *Slump* or *Landslide*.

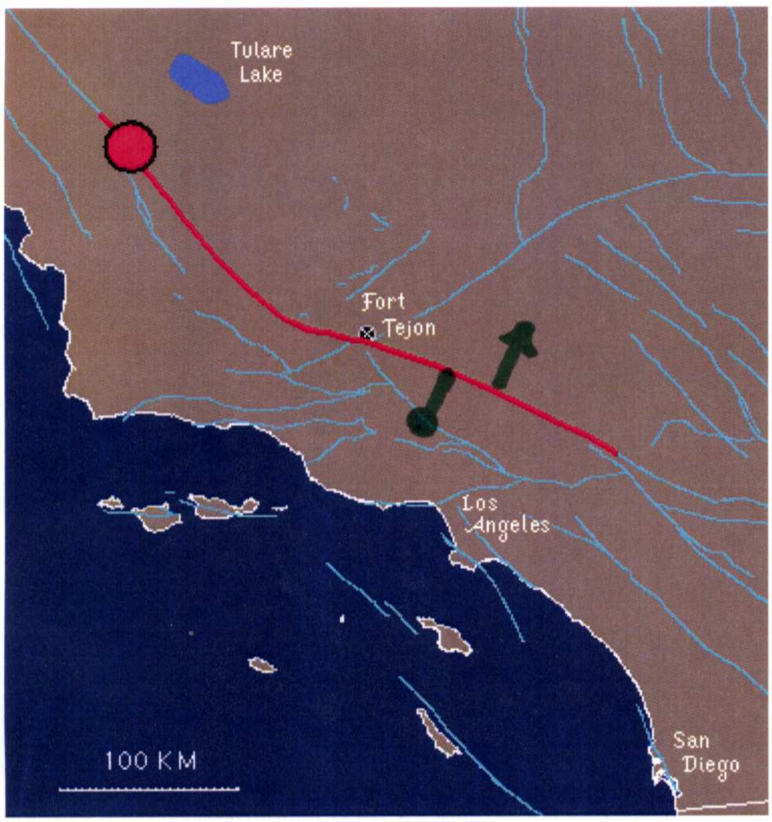


DISCONTINUITIES at ENDS of BLOCK



[Mathematically, this is expressed through different *boundary conditions* for the analytical representations of the source].

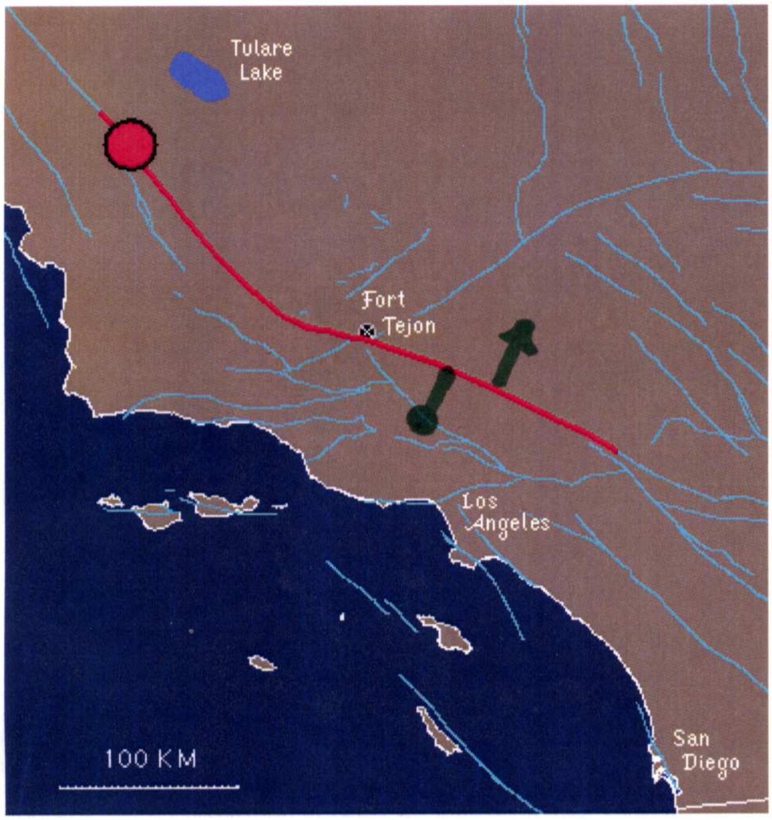
EARTHQUAKE (inspired from Fort Tejon, 1857)



ROAD cut !

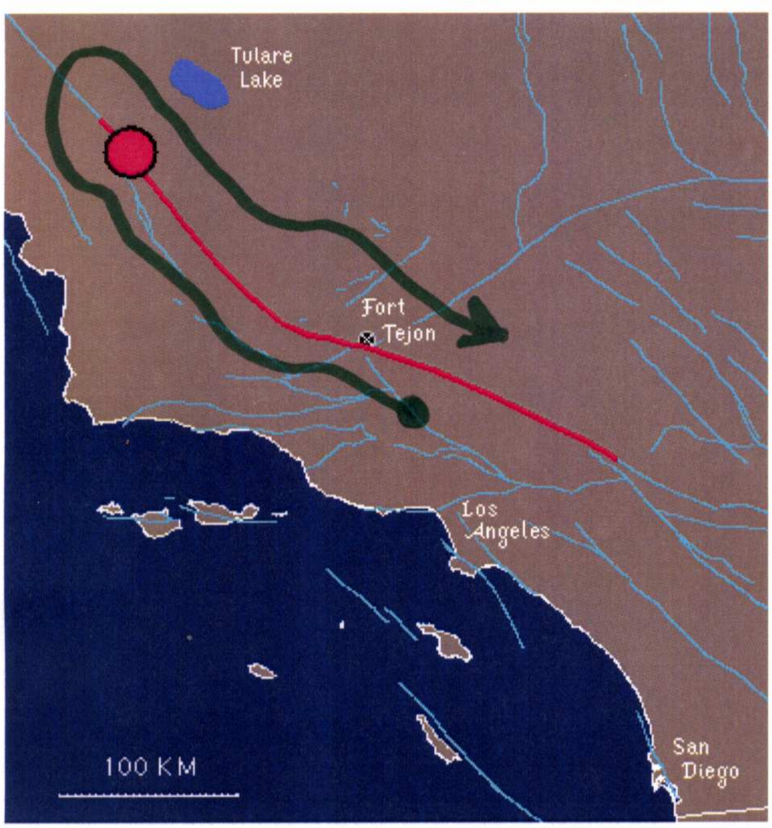
Cannot Drive Across ...

EARTHQUAKE (inspired from Fort Tejon, 1857)



ROAD cut !

Cannot Drive Across ...



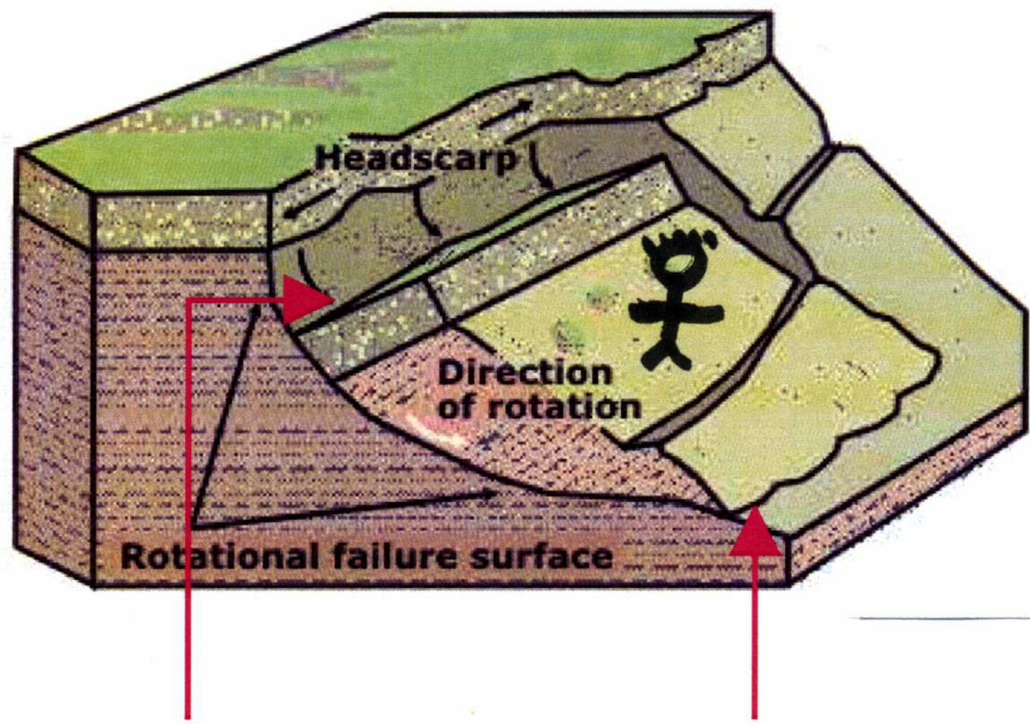
But You Still

CAN

DRIVE AROUND !!

Contrast this with the Case of a

LANDSLIDE or SLUMP



Because of DISCONTINUITIES at ENDS of BLOCK

YOU ***CANNOT***

GO CONTINUOUSLY from

ONE WALL of the CUT

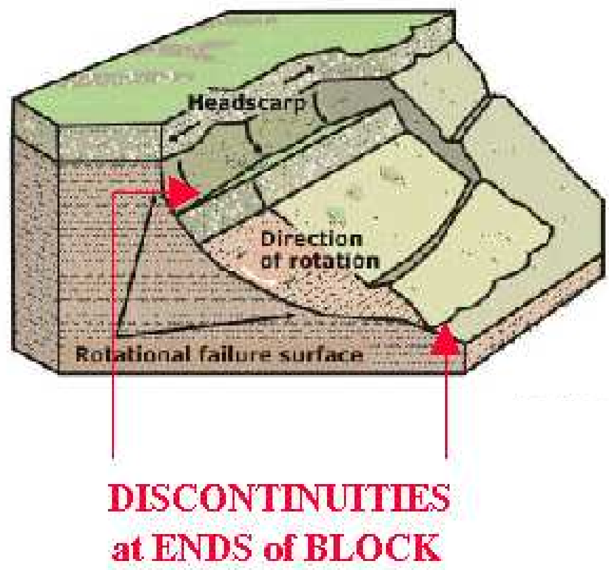
to the OTHER

LANDSLIDES — The DAHLEN TERMS

F.A. Dahlen
(1942−2007)

Dahlen [1993] has shown that, in addition to the "Kanamori" force used above to model the landslide, a set of three higher-order moment terms are required to properly describe the excitation of seismic and tsunami waves.

They represent the contribution of the fully integrated terms in the integration by parts used by the representation theorem, which, in the case of a landslide, *cannot be moved to infinity because of the discontinuity of the material around the tips of the slide.*



These terms multiply the excitation of seismic and tsunami waves by a *Dahlen Factor*

$$f_D = \left(1 - \frac{8}{3}\,\frac{\beta_0^2}{C^2}\right)$$

where C is the phase velocity of the relevant wave and β_0 the shear velocity of the sliding material. This effect is generally negligible for seismic waves, but becomes *VERY SIGNIFICANT* for tsunamis, typically on the order of a factor of **50**) for [expectedly] brecciated material (*included in the following discussion)*, and as much as **500** for a slumping block keeping its cohesion (*e.g.*, PNG slide). On the other hand, the effect becomes negligible in the case of a turbidity current, where $\beta_0 \to 0$ with time.

For details, see *Okal* [2003].

INCIDENTALLY

→ This different behavior at the fault tips is of course what controls the *total slip* released during the faulting:

- *DURING an EARTHQUAKE,* the tips are constrained.

  Δu is *limited* by a fixed strain ε, generally on the order of 10^{-4}.

AN EARTHQUAKE MOVES ENORMOUS AMOUNTS OF ROCK
(Sumatra: 1200 km)
BUT OVER VERY SMALL DISTANCES
(Sumatra, maximum: 20 m)

- *DURING a LANDSLIDE,* the tips are free to move;

  Δu is essentially unlimited.

A LANDSLIDE MOVES RELATIVELY SMALL AMOUNTS OF ROCK
(Maximum 30 km or so)
BUT OVER HUGE DISTANCES
(Storrega: 500 km)

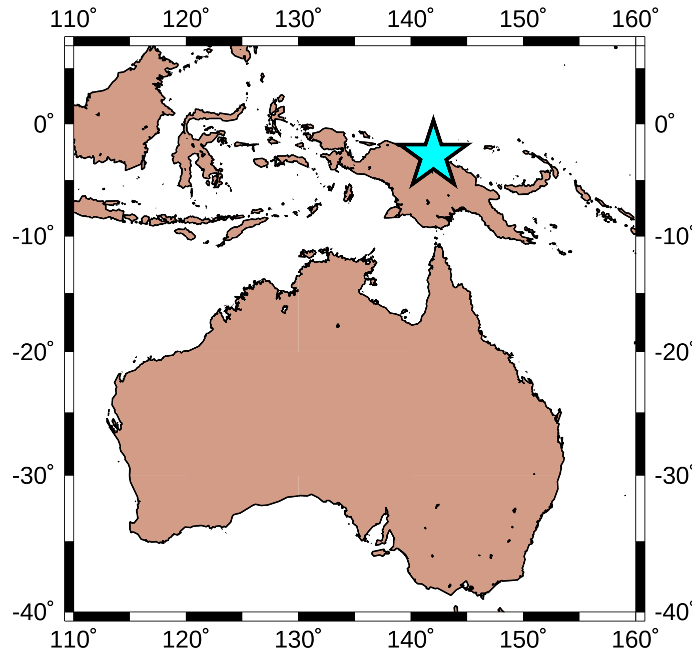
Would-be "strain" $\varepsilon = 17$...

They are DIFFERENT CLASSES of PHENOMENA
because they involve
DIFFERENT [DIMENSIONLESS] INVARIANTS
$\Delta u / L$ **("Strains")**

THE PAPUA NEW GUINEA (PNG) TSUNAMI

17 JULY 1998

- 2200 people killed
- Ten villages eradicated

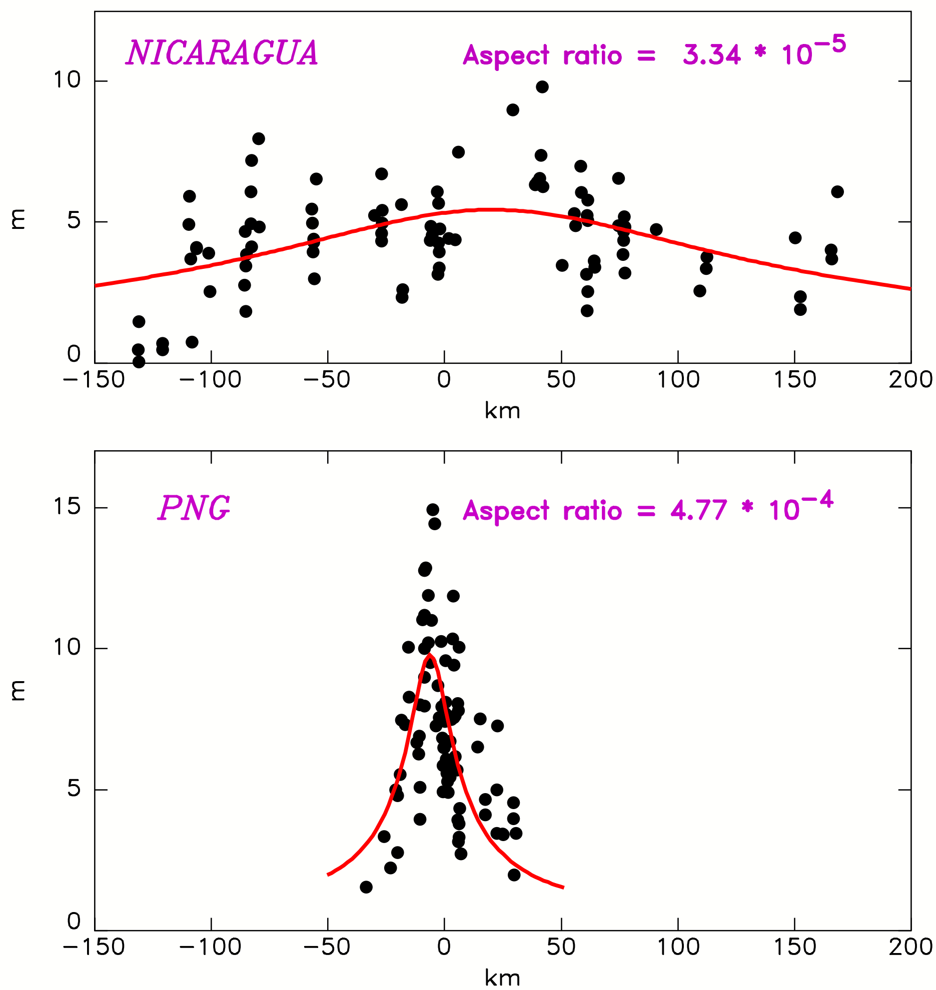


YET, The Earthquake was relatively small $(M_m = 6.8)$

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**



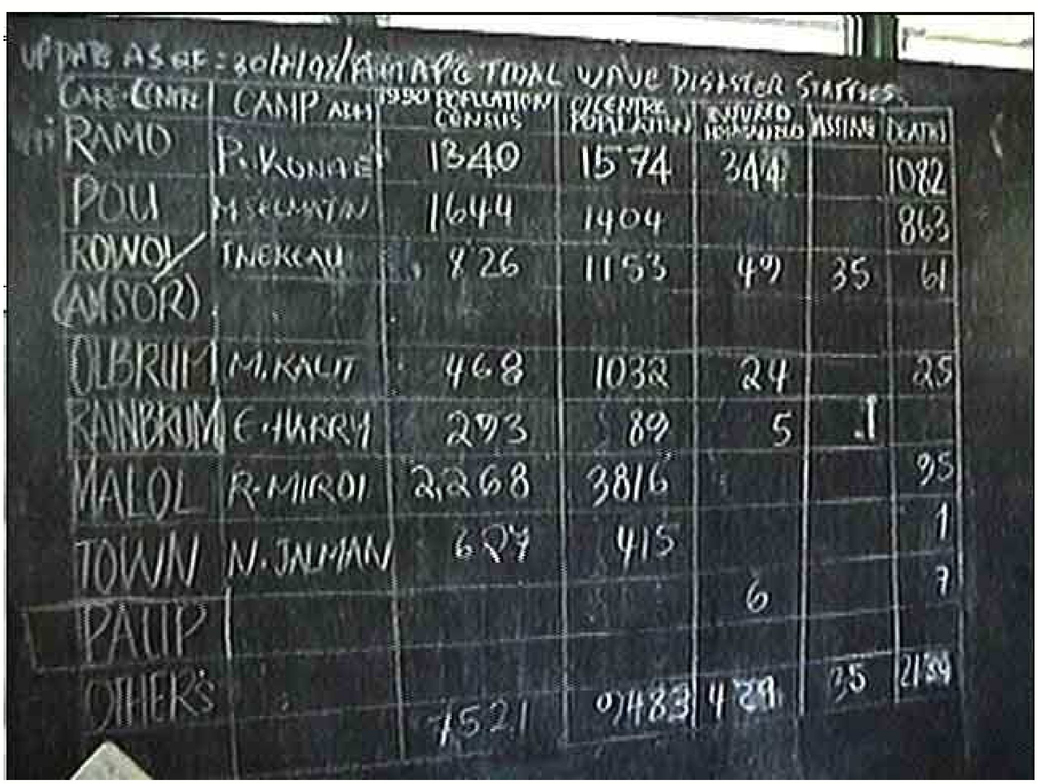
The aspect ratio of the run-up distribution cannot be predicted by dislocation models based on continuum mechanics — they would require a *strain release* greater than the yield strain of rock.

THE PNG PUZZLE (continued)

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

Even though the tsunami was monstruous 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.



THE PNG PUZZLE (continued)

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

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

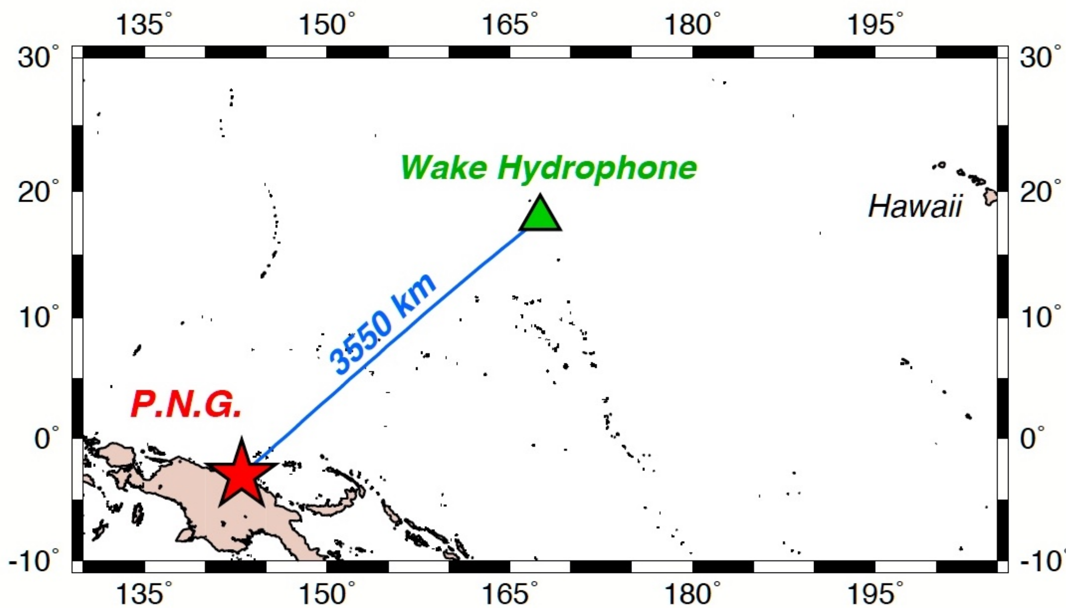
- In some areas (Malol), the tsunami *did not arrive until after the "second felt shock"* (main aftershock at 09:09 GMT);

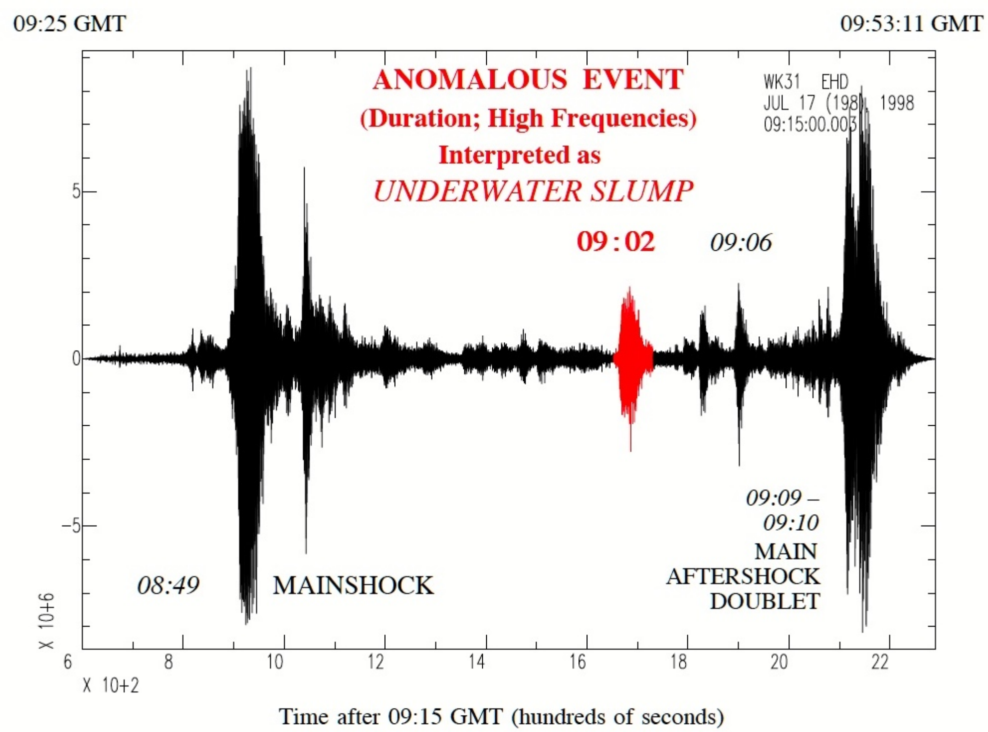
- In other areas (Arop, Warapu), the tsunami arrived before the population had a chance to feel the main aftershock.

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

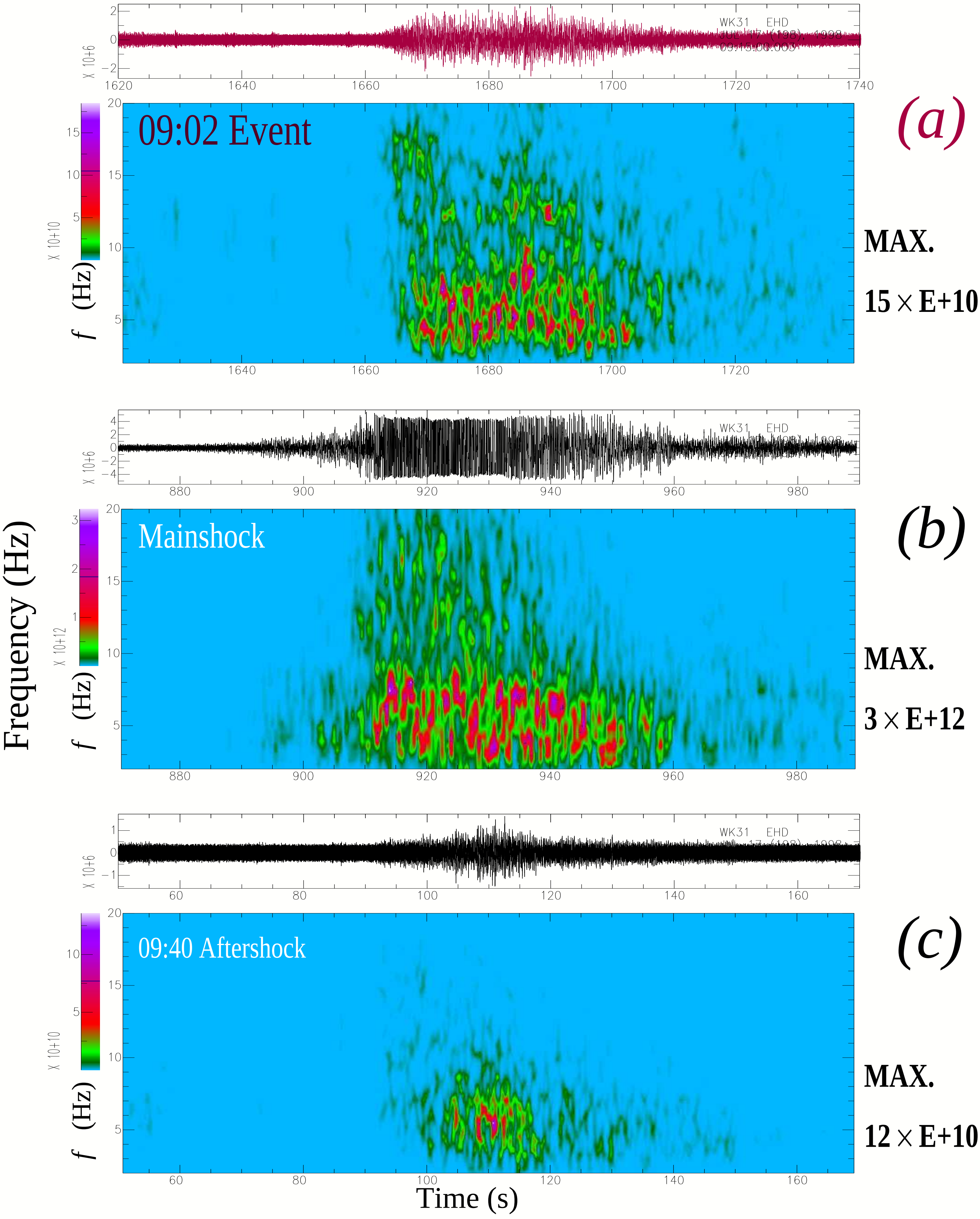
Some time between the mainshock (08:49) and the main aftershock (09:09).

WAKE ISLAND HYDROACOUSTIC RECORD -- 17 JULY 1998





09:02 HYDROACOUSTIC SIGNAL SMALL and LONG



- In short, the event at 09:02 is

  TOO WEAK FOR ITS DURATION

  or

  TOO LONG FOR ITS AMPLITUDE

→ *In other words, it*

VIOLATES SCALING LAWS

which suggests that it must represent a different physical phenomenon.

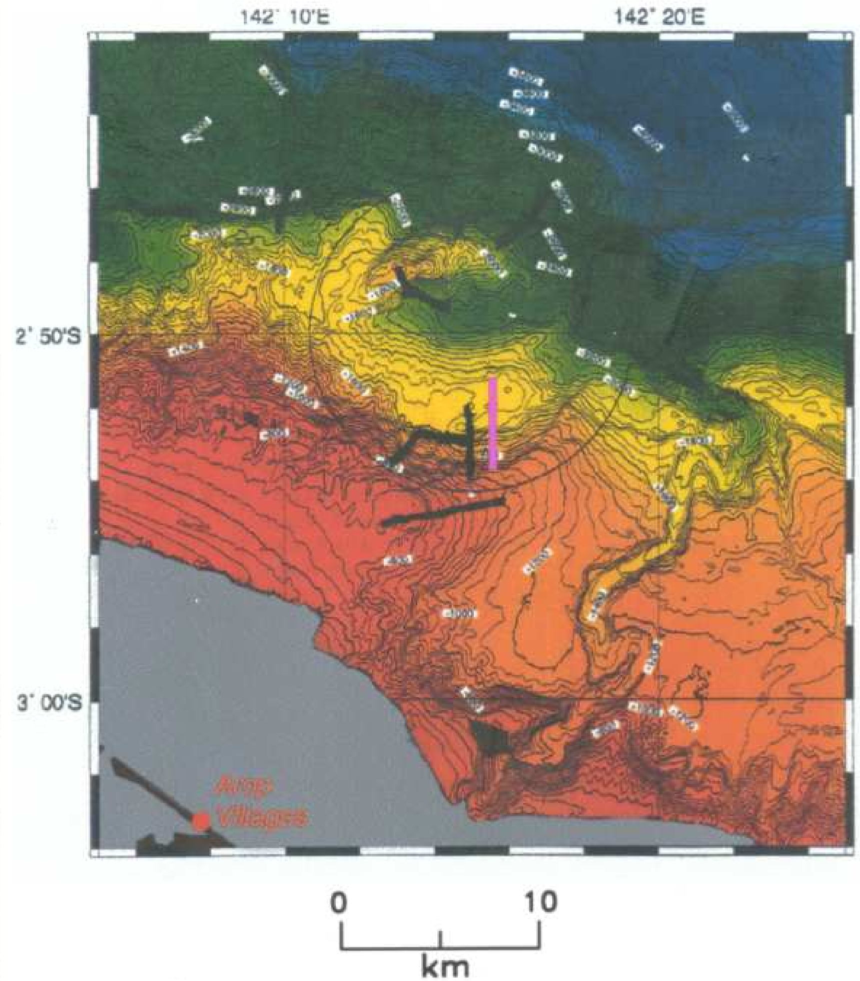
IT IS THERE !!!

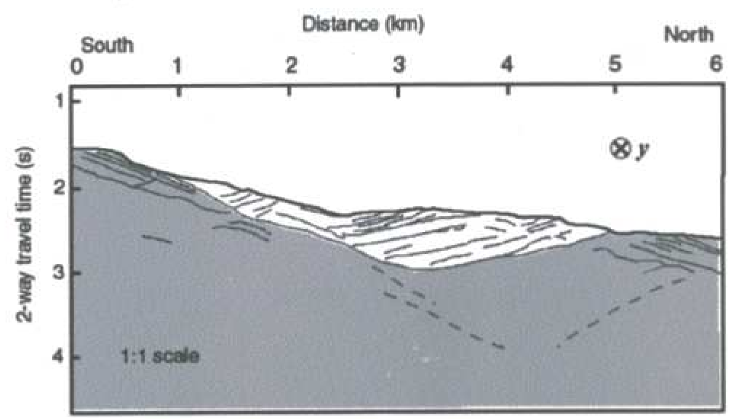
THE SLUMP MODEL

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.

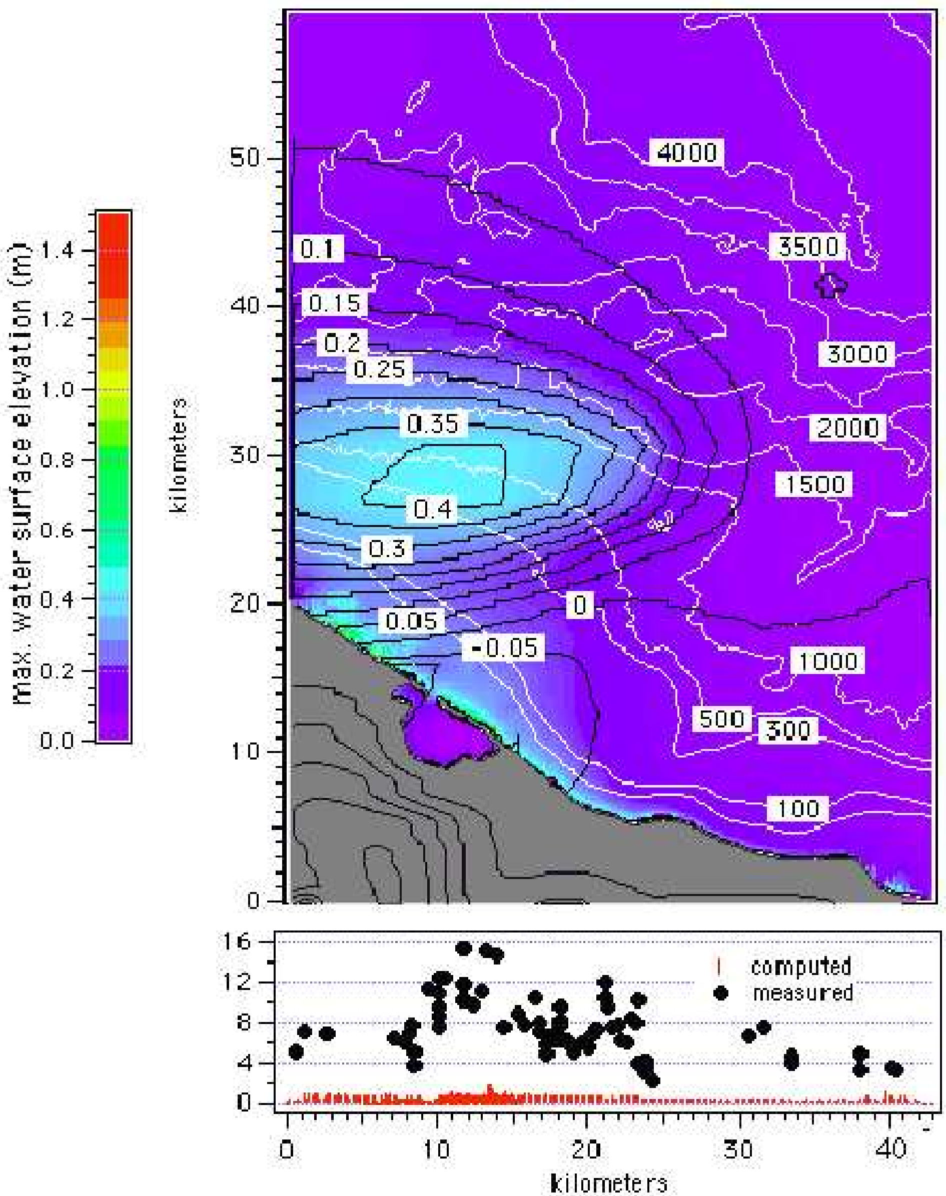
This Slump....

- 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.

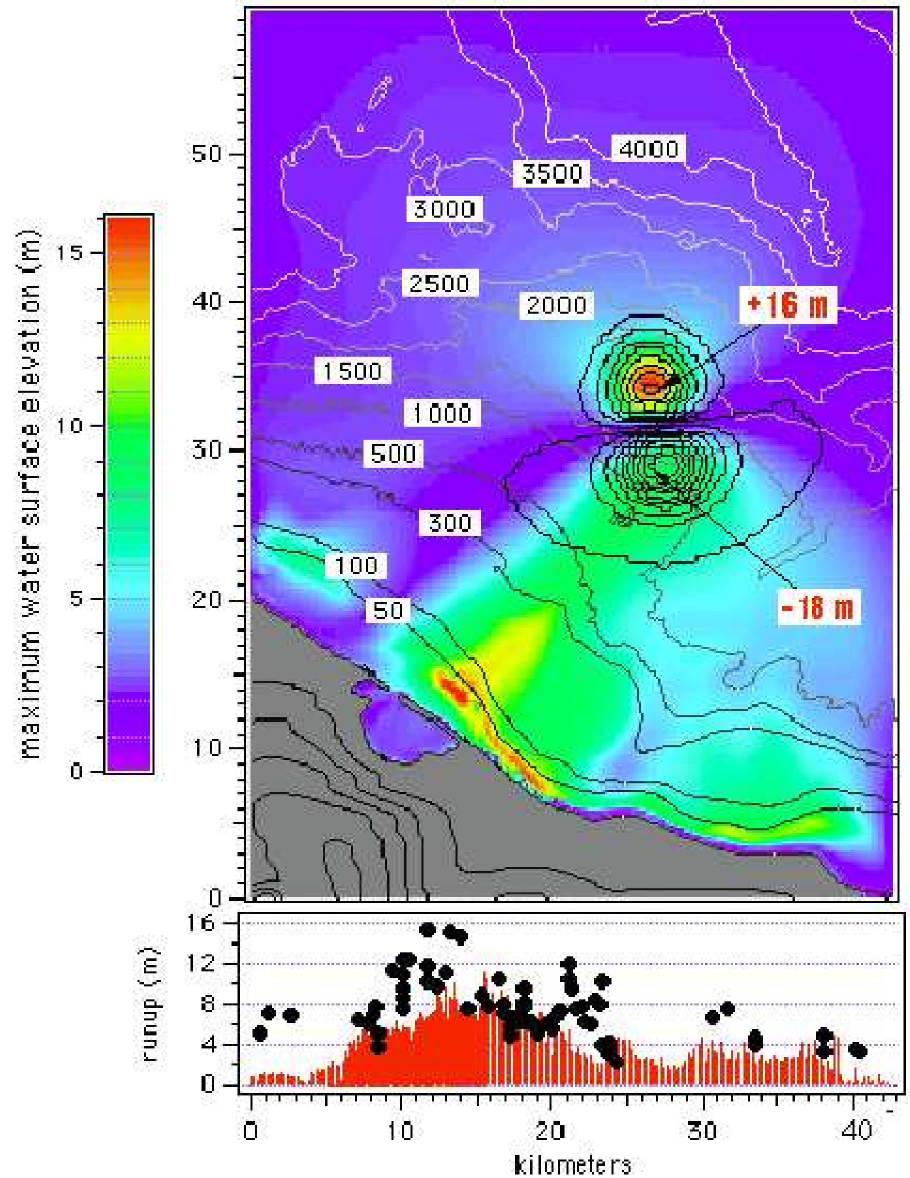




TSUNAMI SIMULATIONS [*Synolakis et al.*, 2002]



EARTHQUAKE SOURCE



SLUMP SOURCE

PERSPECTIVE on LANDSLIDE TSUNAMIS

- As compared to earthquakes,

  Landslides move *SMALLER AMOUNTS* of material over *MUCH LARGER DISTANCES.*

- Therefore, their tsunamis have

  MUCH LARGER AMPLITUDES

  MUCH SHORTER WAVELENGTHS

→ Hence, they will be *MORE EFFICIENTLY DISPERSED* during propagation.

- They may also become intrinsically unstable and *BREAK* (like surf) rather than propagate.

As a result, LANDSLIDE tsunamis are

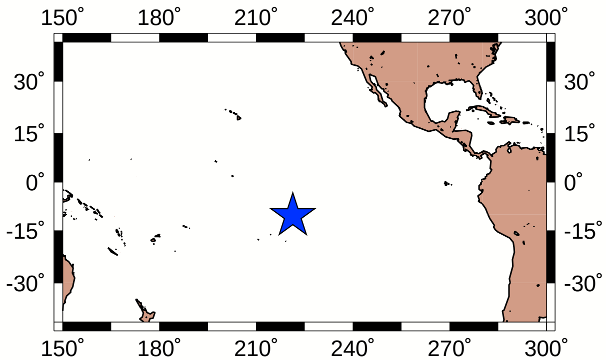
DEVASTATING locally, but pose

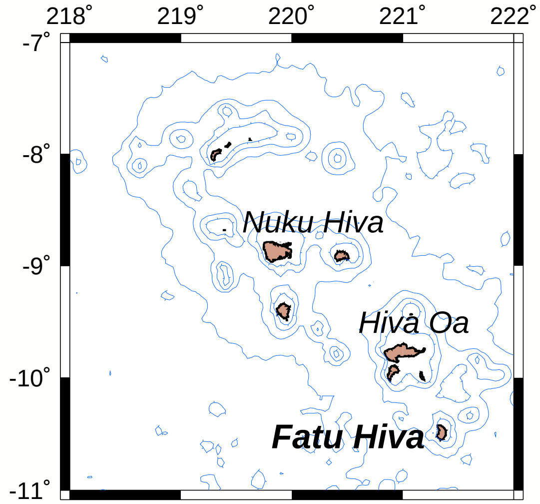
LITTLE HAZARD in the FAR FIELD.

MORE LANDSLIDE TSUNAMIS

Fatu Hiva, Marquesas Islands

13 September 1999



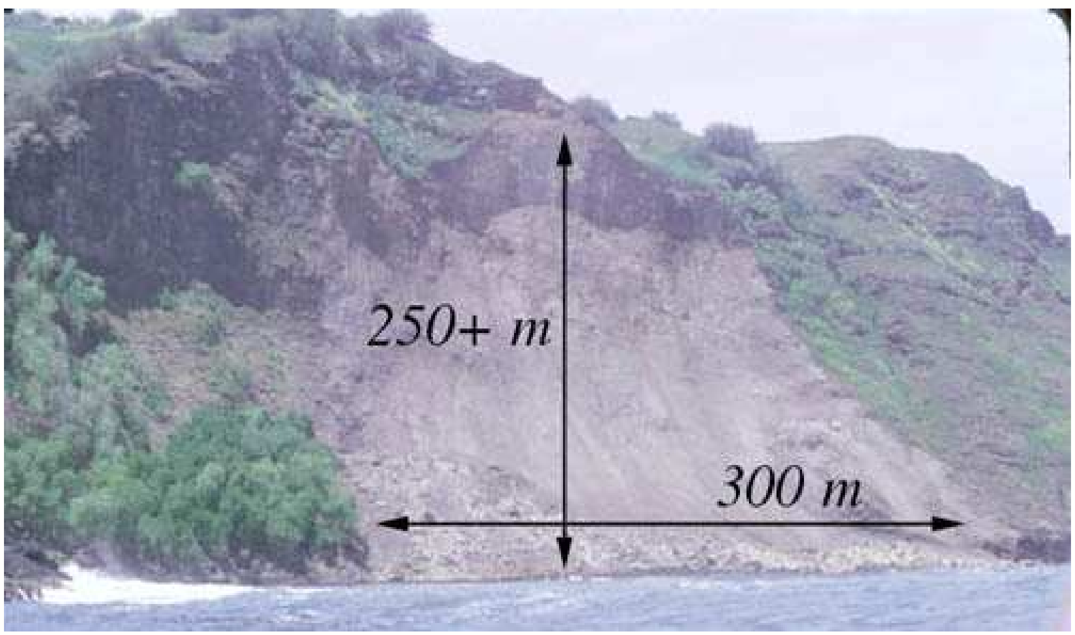


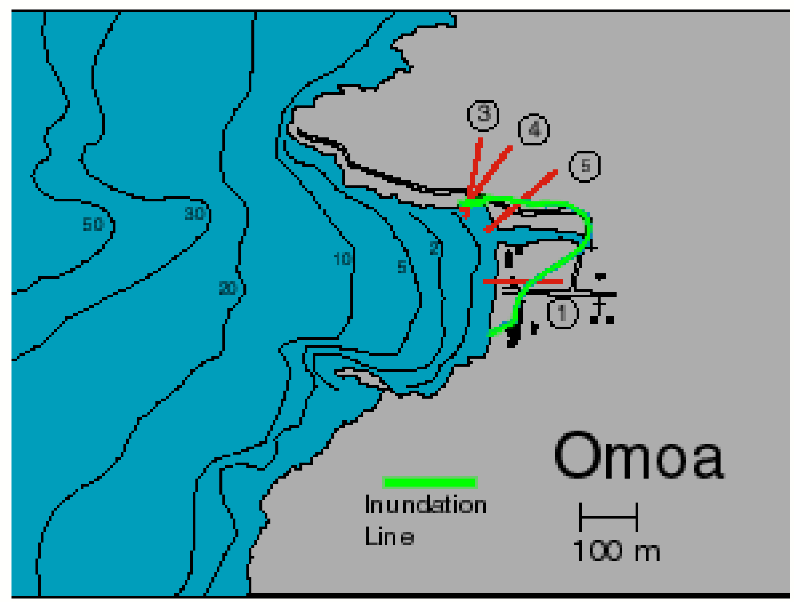
The beachfront school house at Omoa was severely flooded by two "rogue" waves which also destroyed the ice-making plant and several canoe shacks and copra-drying stands.

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



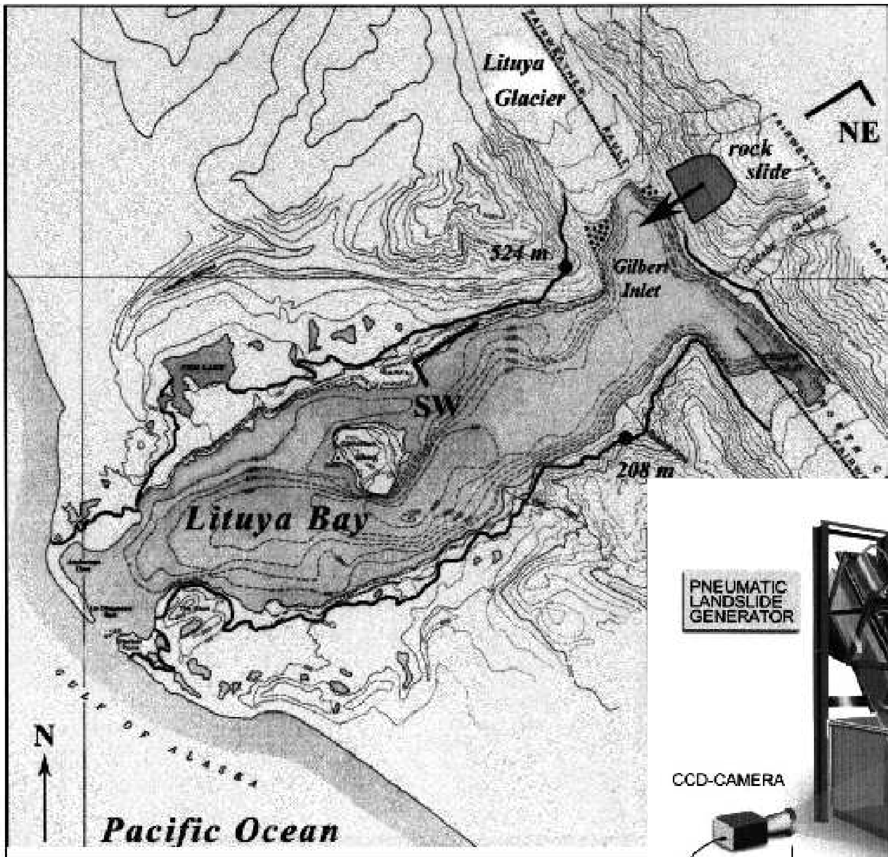


LITUYA BAY, Alaska, 10 JULY 1958

Strike-slip earthquake on Fairweather Fault triggered massive aerial rock slide into local Bay, creating 525−m high splash on oppposite mountain range.

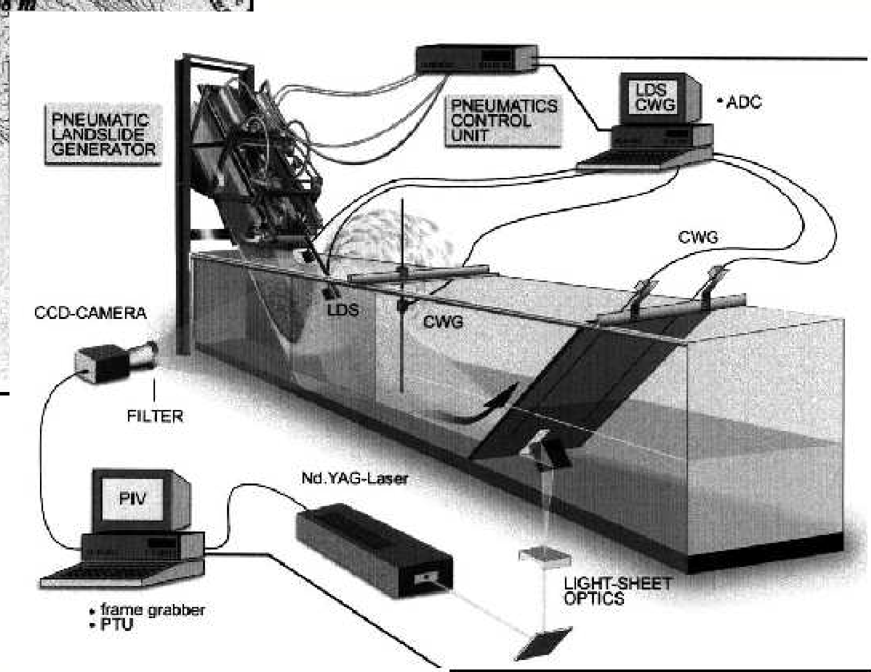
ONE DEATH -- Did Not Penetrate Into Ocean

LABORATORY MODELING of LITUYA BAY LANDSLIDE & TSUNAMI

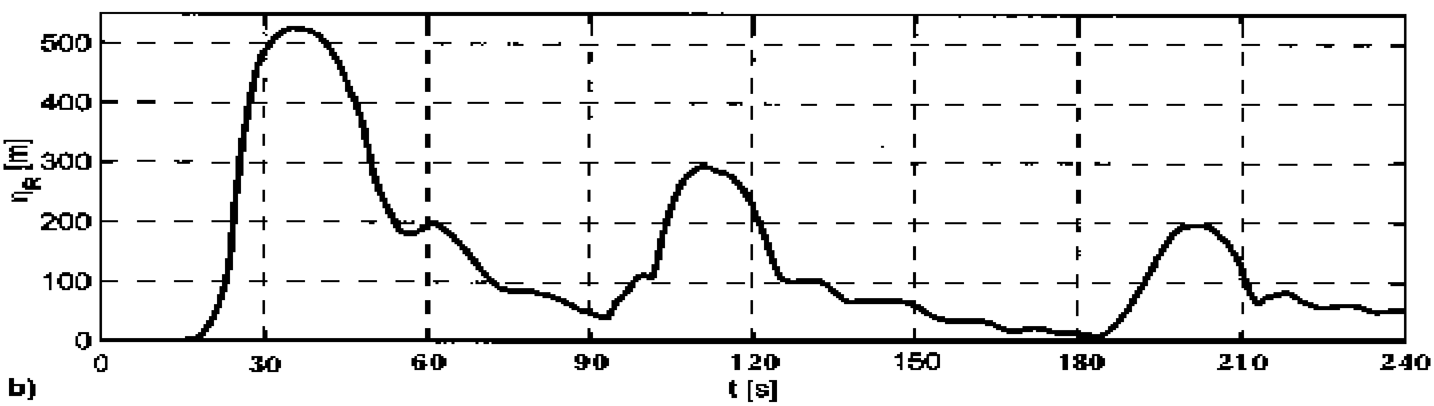


Maximum splash on opposite hill:

524 meters



[*Fritz et al.*, 2001]

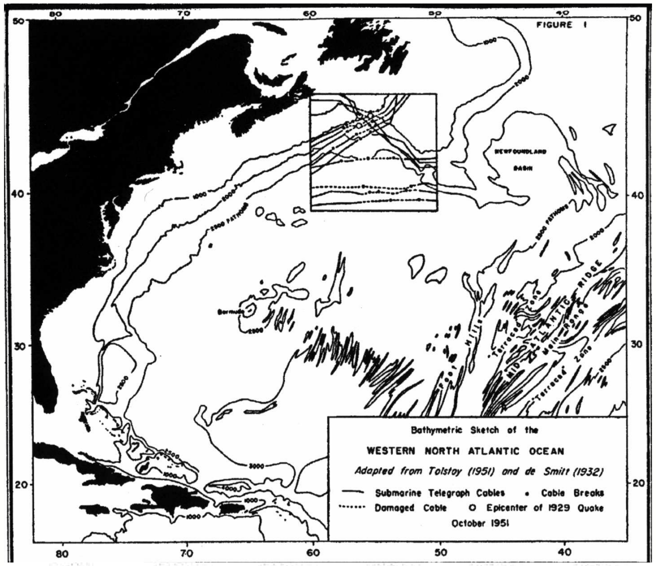


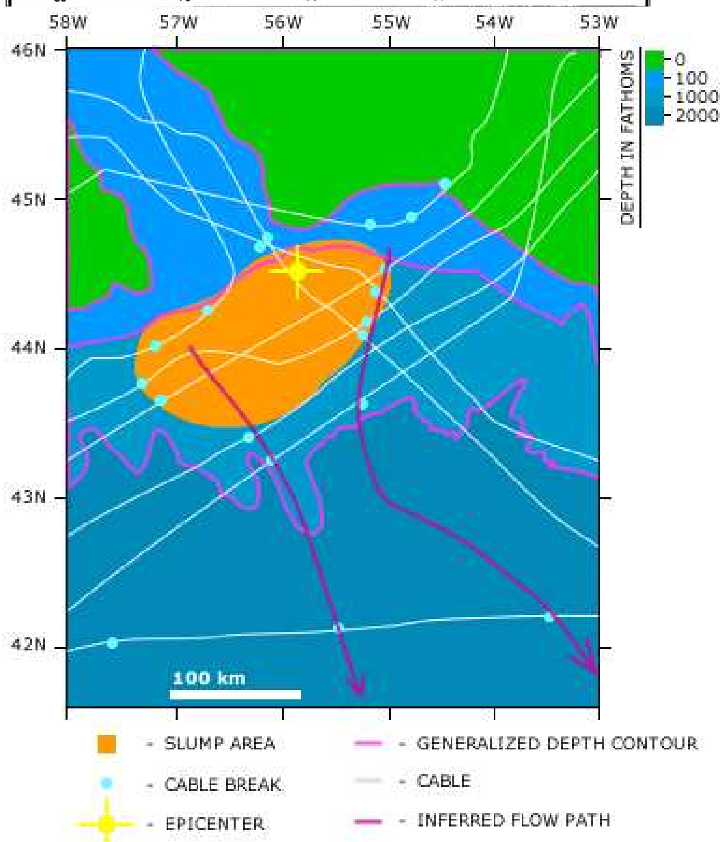
Conclusion: Exceptional run-up well reproduced in laboratory experiment.

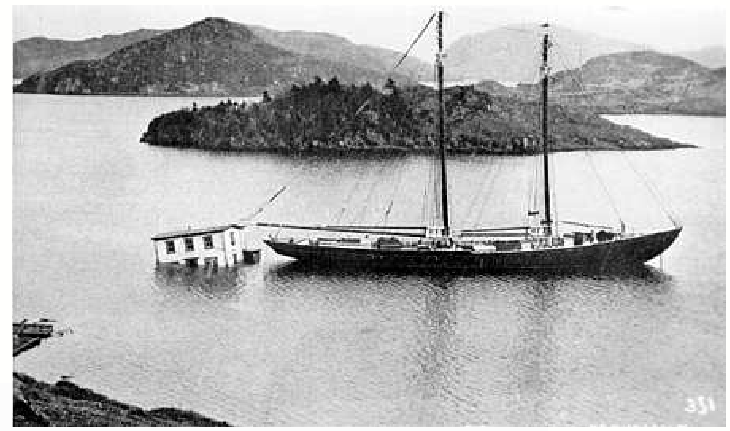
Importance of large air cavity developing during impact of landslide.

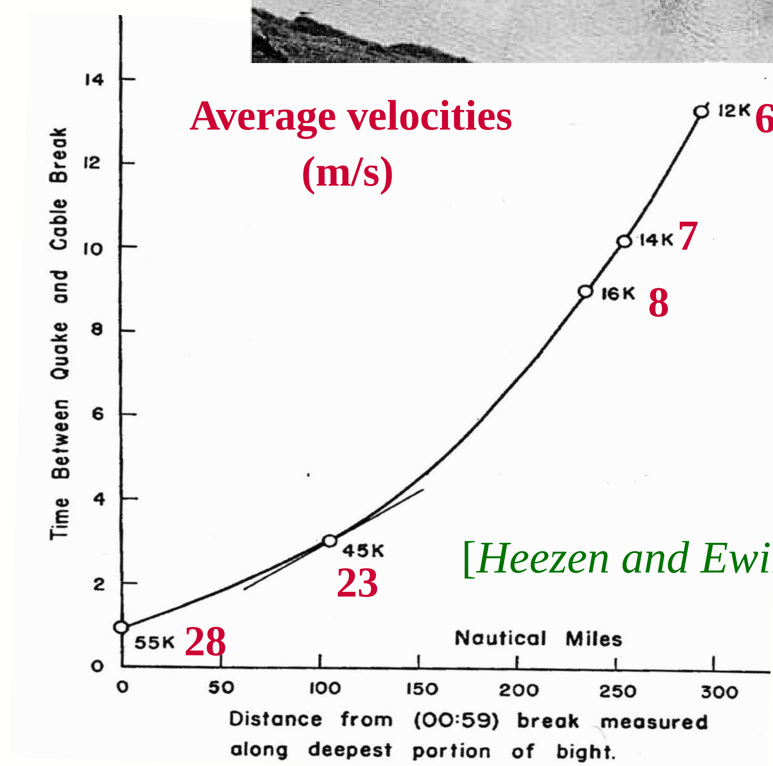
NEWFOUNDLAND — 18 NOVEMBER 1929

Earthquake ($M = 7.2$) triggered tsunami through large underwater slumps giving rise to
TURBIDITY CURRENTS detected through
TELEGRAPHIC CABLE BREAKS









[*Heezen and Ewing*, 1952]

ORLEANSVILLE, Algeria, 09 SEPTEMBER 1954

A continental earthquake (M = 7) in Algeria generated a turbidity current in the Mediterranean and a small tsunami observed locally, in the Balearic Islands and in Spain.

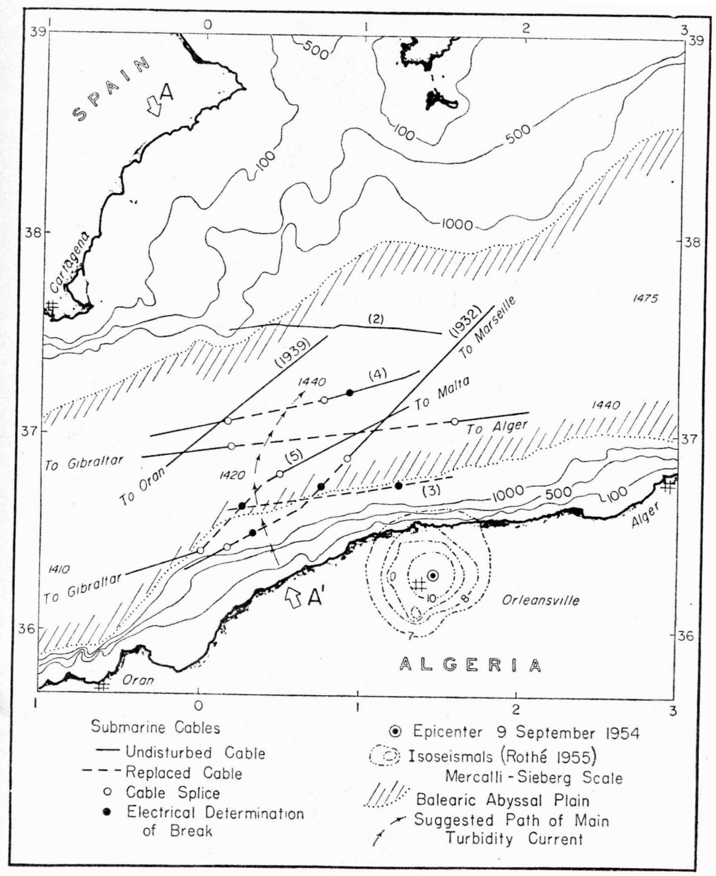


FIG. 2.—Map showing locations of Orléansville earthquake, path of main turbidity current, and submarine cables. Depths in fathoms.

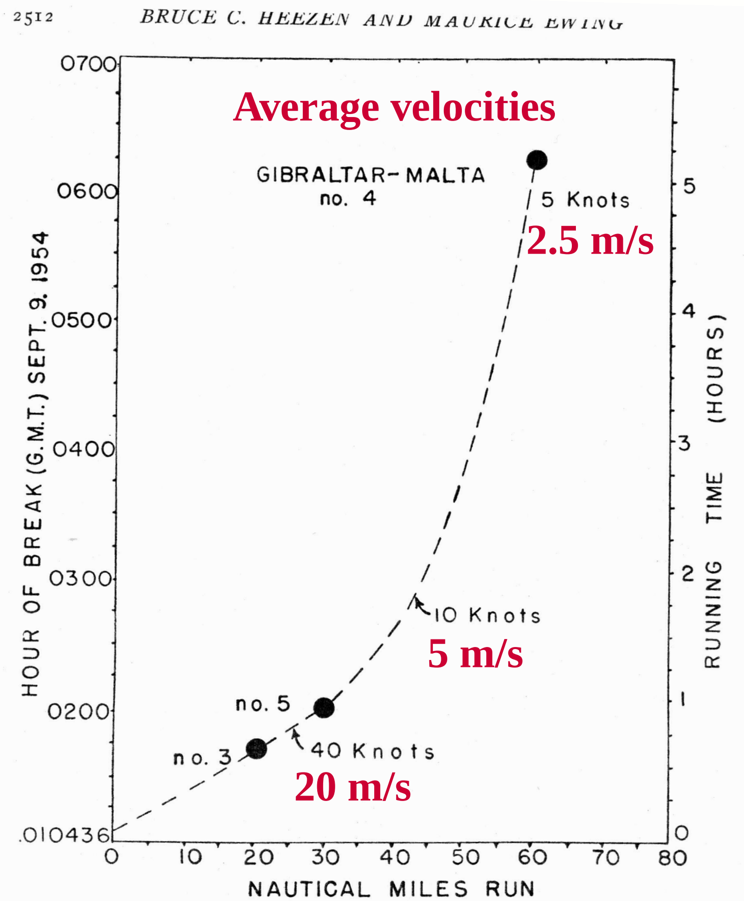


FIG. 4.—Curve showing velocities of Orléansville earthquake.

This scenario was repeated during the El Asnam earthquake of 1980, and, 250 km to the East during the 2003 Boumerdes earthquake.

[*Heezen et al.*, 1955]

CABLE BREAKS:

A VERY STRONG PROXY FOR UNDERWATER SLUMPING

→ Whenever marine telegraphic (nowadays, fiber optics) cables have broken (mainly following large earthquakes), their repair operations have documented the presence of turbidity currents documenting underwater slumping, generally triggered by the seismic source.

- Examples include:

* **1910** Rukwa

* **1929** Newfoundland

* **1934** North Luzon

* **1945** Makran

* **1953** Suva, Fiji

* **1954, 1980** Orléansville / El Asnam

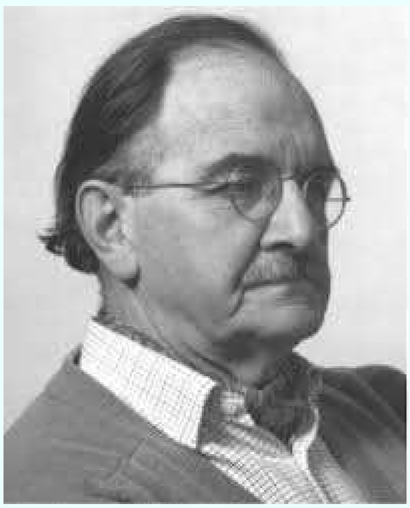
* **2003** Boummedes, Algeria

* **2006** Hengchun, Taiwan

A record for distant triggering ?

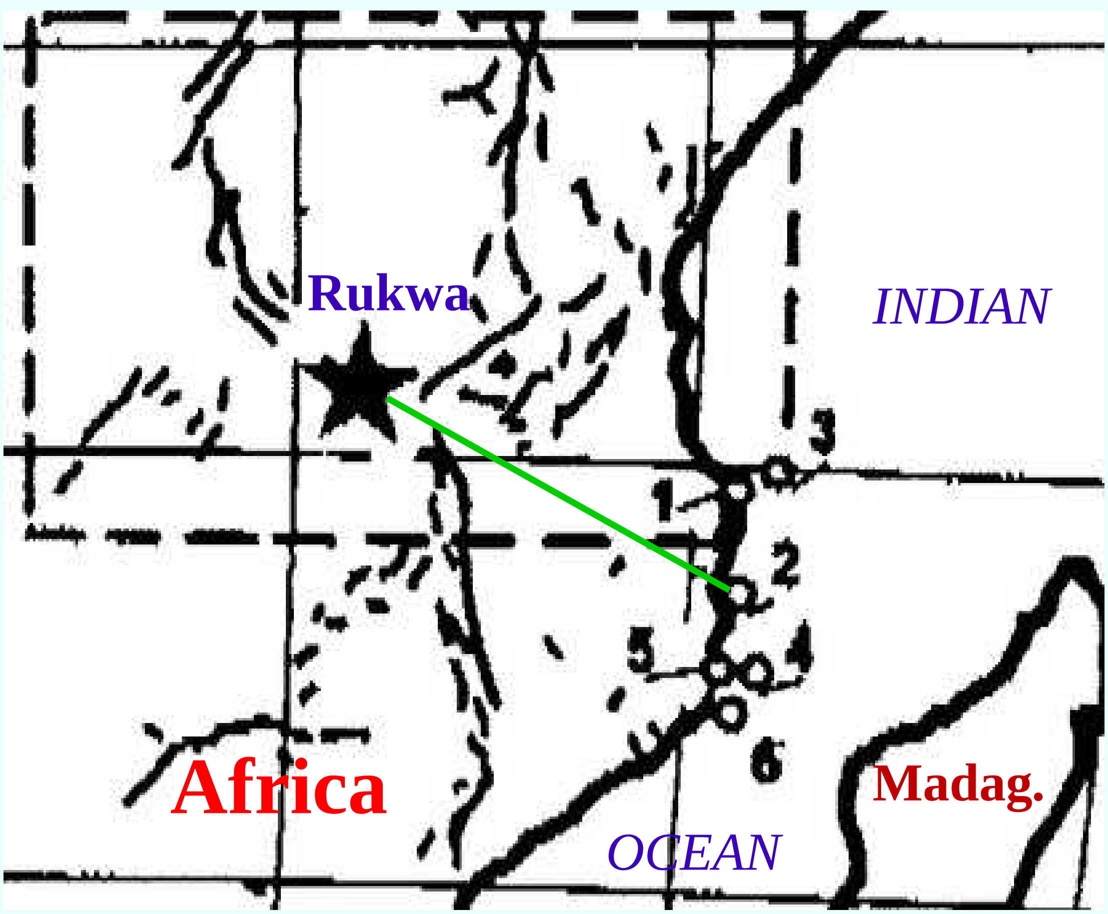
The Rukwa earthquake of 13 December 1910 in East Africa

N.N. Ambraseys
Department of Civil Engineering, Imperial College of Science, Technology and Medicine, London SW7 2BU, UK



Also the offshore telegraph cables between Zanzibar and Mozambique, as well as between Durban and Beira were broken by the earthquake so that the news about the location of this event never made the headlines in the World press.

900 km



OTHER EARTHQUAKE-INDUCED TSUNAMIGENIC LANDSLIDES

Many similar cases of anomalous tsunamis in the wake of earthquakes have been reported, notably in the Makran (1945), the Philippines (1934) and Fiji (1953).

Characteristic proxies for landslides are:

- Anamolous delay in the tsunami (*e.g.*, Makran, 1945; Amorgos, 1956)
- Extreme concentration of run-up along the shore (*e.g.*, Aleutian, 1946)
- Extreme variability of run-up along a given coast (*e.g.*, Amorgos, 1956)
- Cable breaks (*e.g.*, Philippines, 1934; Makran, 1945)

OTHER CASES of LANDSLIDE TSUNAMIS

Not directly associable with known earthquakes

- 04 November 1994 **Skagway, Alaska**
  One dead, $20 million damage
- 27 April 1975, **Kitimak, B.C., Canada**
  Waves reached 8 m; no casualties.
  Note: Many other smaller occurrences in the area.
- 16 October 1979, **Nice, France**
  10 [11?] dead, 1 [2?] from tsunami.

And, in geological past

- **Storrega Slide**
  Norwegian Sea
  3500 km^3; 8,000 years B.P.
- **Brunei Slide**
  South China Sea
  1400 km^3; *Holocene ?*

RECOGNIZING TSUNAMI SOURCES

or How to devise Source Discriminants

- **NEAR FIELD :** *Distribution Aspect Ratios*
- **FAR FIELD:** Directivity Patterns

APPLY TO 1946 ALEUTIAN TSUNAMI

- Far field tsunami devastated Hilo, Hawaii, and Marquesas Islands
- Catastrophic tsunami featured local run-up of **42 m**
- Field work conducted in 1999-2001.

BUILDING A DISCRIMINANT in the NEAR FIELD

GENERAL IDEA

- The maximum run-up, b, along the beach should be controlled by the maximum initial deformation of the ocean surface, η_0 .

  Which in turn should be controlled by the maximum *seismic slip* on the fault, Δu.

- The width of the run-up distribution, a, should be controlled by the *size* (length) of the fault, L.

→ Thus, the aspect ratio, b/a of the run-up distribution, should be controlled by the ratio $\Delta u / L$, which is related to the *STRAIN RELEASE* in the dislocation.

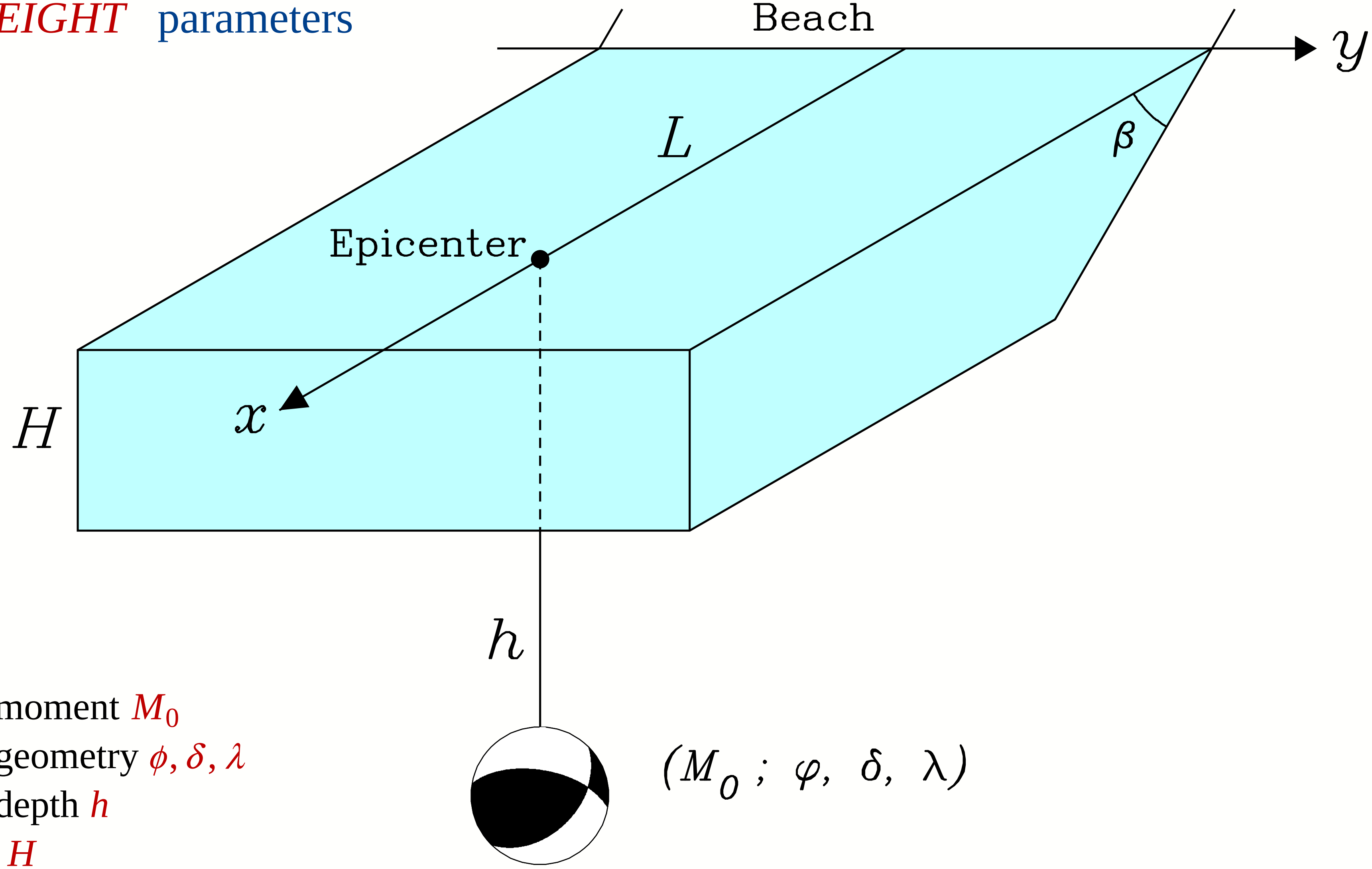
- For dislocations, the latter should be expected to be constant, as it reflects the strength of the rock.

But for landslides, it could be much larger.

We hint that b/a should be an *INVARIANT* for seismic dislocat-ions, and serve as a *DISCRIMINANT* of landslides.

GENERIC DISLOCATION in the NEAR FIELD

Involves *EIGHT* parameters



Earthquake moment M_0

Earthquake geometry ϕ, δ, λ

Earthquake depth h

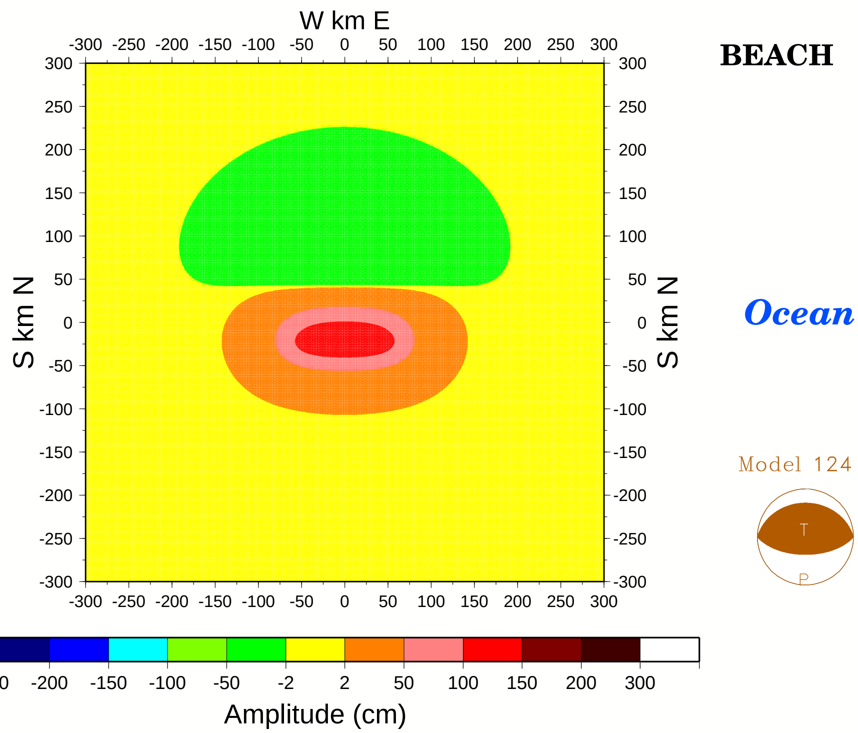
Water depth H

Epicentral distance to shore L

Beach slope β

NEAR-FIELD: *The Earthquake Dislocation*

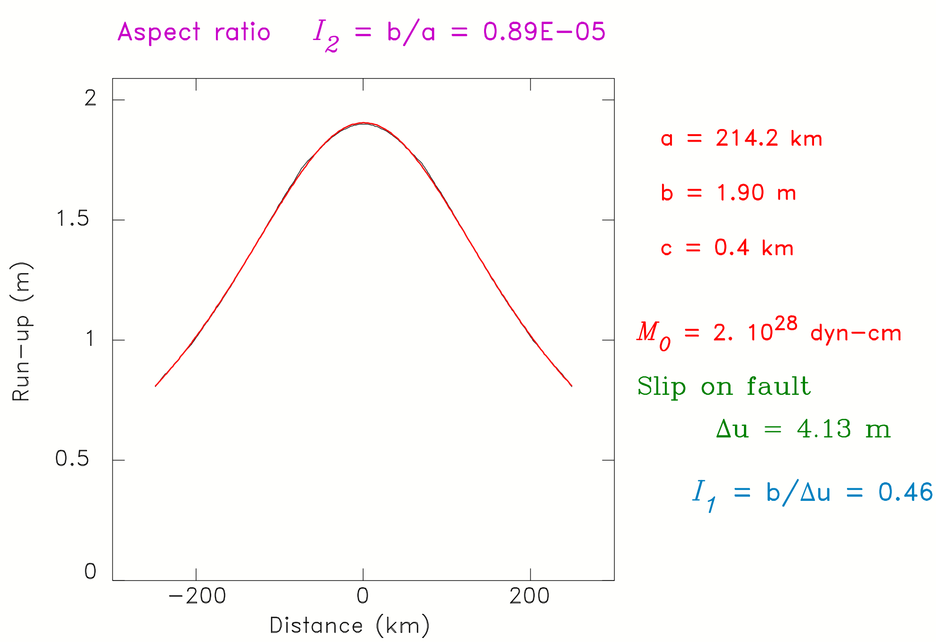
- Compute Ocean-Bottom Deformation due to Dislocation



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

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



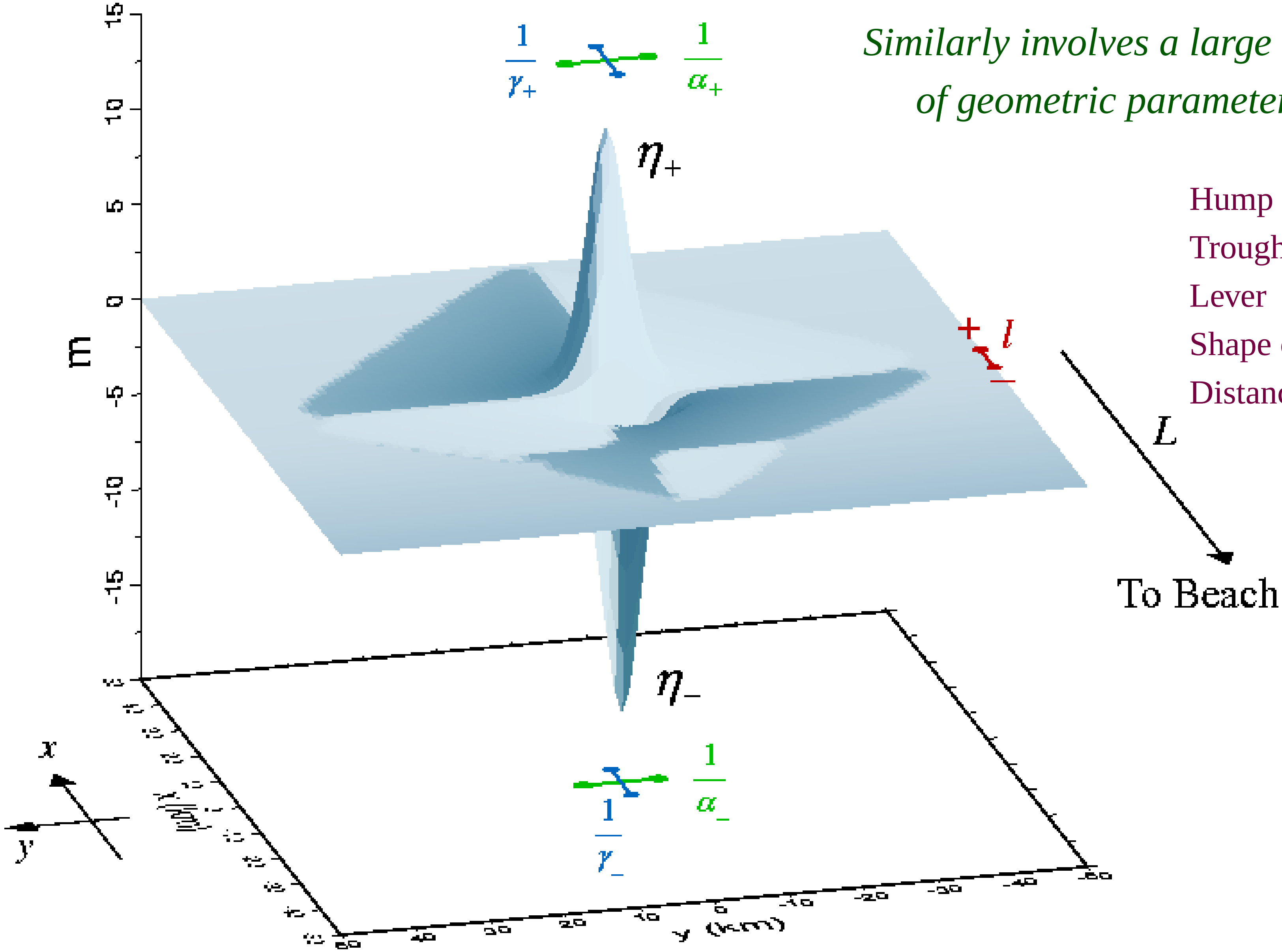
- Retain aspect ratio $I = b/a$

- Vary source parameters: I no greater than 2.3×10^{-5}.

THE DIPOLAR SOURCE

Similarly involves a large number of geometric parameters

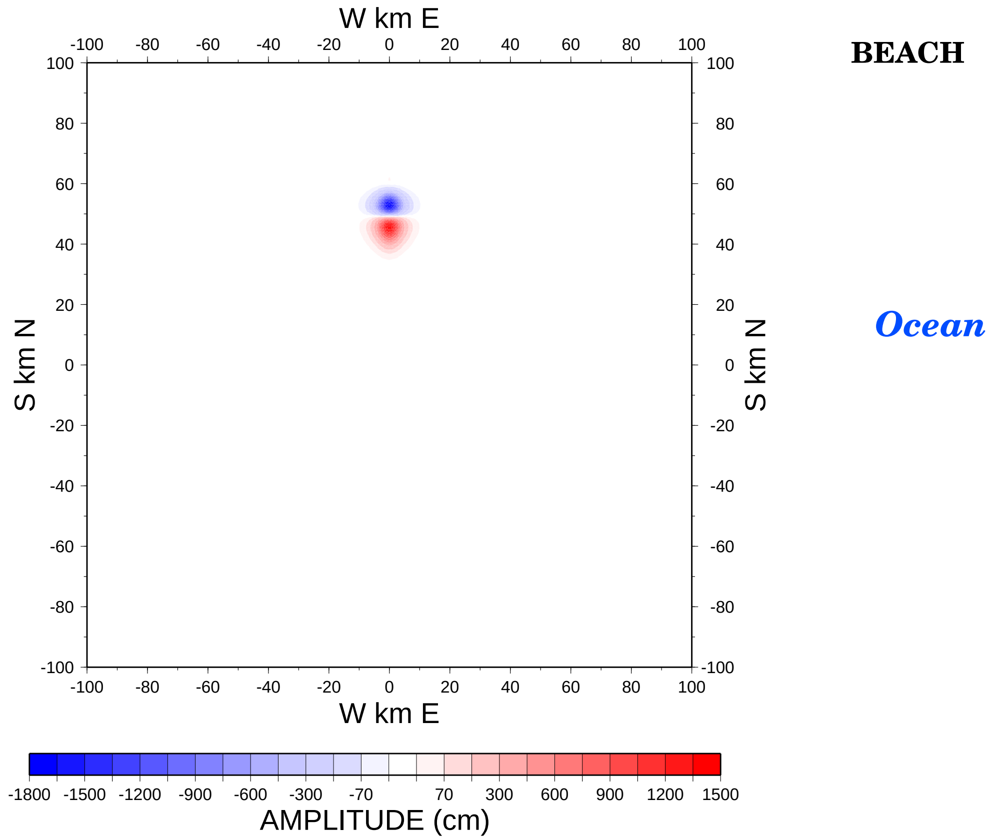
Hump
Trough
Lever
Shape of poles
Distance to Beach...



[*Okal and Synolakis*, 2004]

NEAR-FIELD: *The Landslide Source*

- Compute Ocean-Surface Deformation due to Landslide



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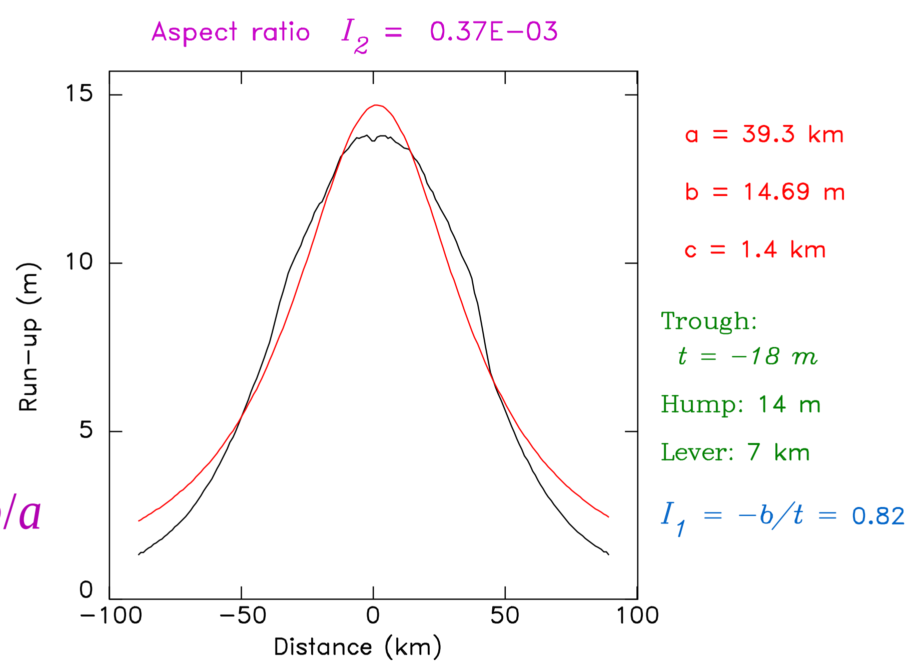
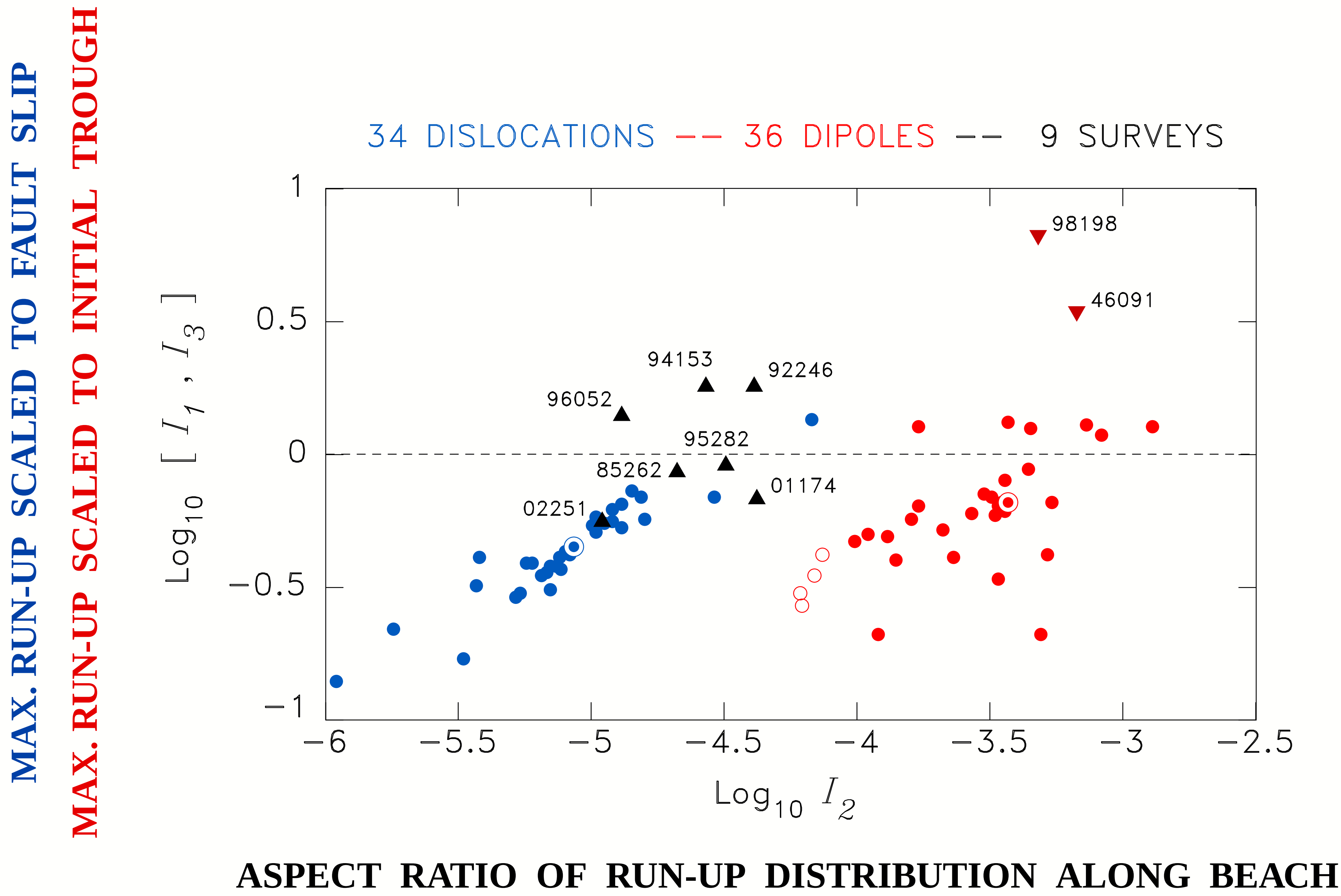


- Vary source parameters: I greater than 10^{-4}.

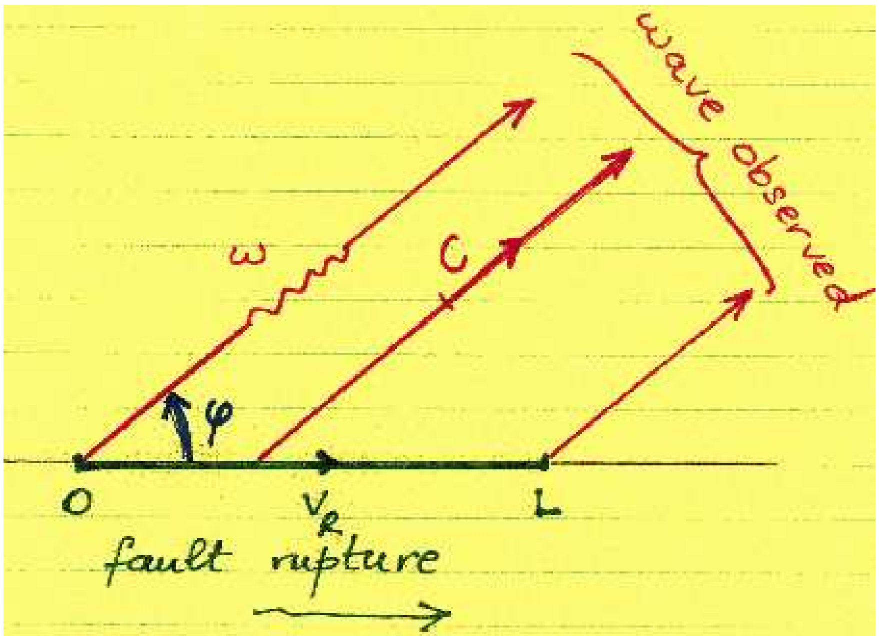
$I = b/a$ CAN SERVE AS DISCRIMINANT



[*Okal and Synolakis*, 2004]

FAR FIELD: THE BASICS of DIRECTIVITY

[*Ben Menahem*, 1962]



If a source propagating a length L at velocity V_R in the direction x generates a wave traveling at phase velocity C observed at an angle ϕ from x, then the amplitude of the wave is affected by a *DIRECTIVITY* function D

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega\, L}{2\, C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

This formula simply expresses that the various elements of the source always interact destructively at high enough frequencies, *except when the wave propagation compensates exactly the offset of source time*

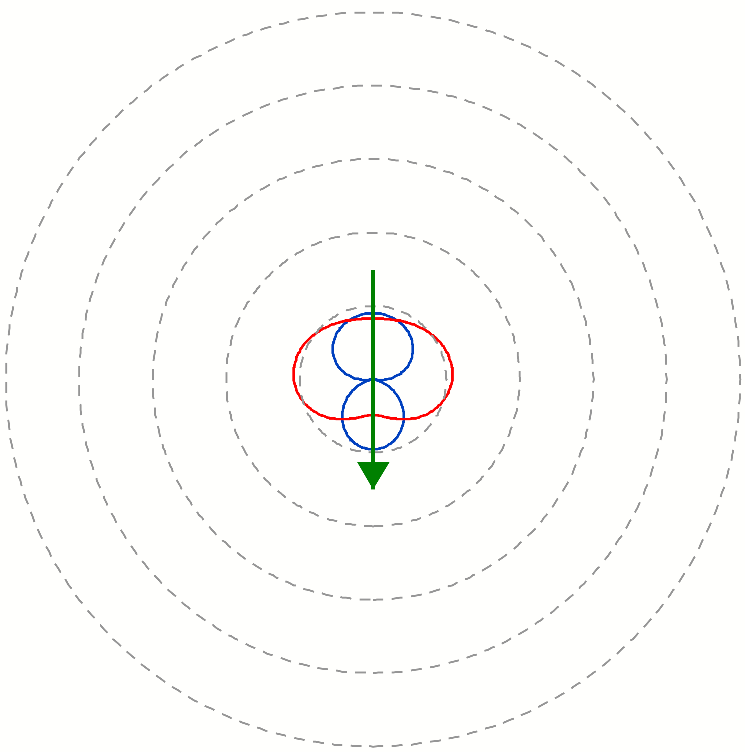
($\sin Y / Y$ maximum requires $Y = 0$.)

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega L}{2C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

• *Tsunami generated by a landslide*

Then, V_R is always much *SMALLER* than C, and the interference is always destructive (for long enough sources).

600 s; 25 km; VR =0.04 km/s; C = 0.2 km/s
900 s; 50 km; VR =0.04 km/s; C = 0.2 km/s



The rupture is so slow (w/r respect to the wave) that there are no directions in which it can be compensated by the variations of phase due to propagation.

LANDSLIDES CANNOT GENERATE FAR-FIELD DIRECTIVITY

Wrapping Up : **LANDSLIDES** *in the Warning Context*

GOOD NEWS

1. *Wavelengths are short... so,* **Large waves are dispersed and/or break fast** *during propagation;*

   Little hazard in far field

2. *Landslides are often the* **cataclysmic culmination** *of a* **slow deformation process,** *finally triggerred, e.g., by an earthquake*

   We may have time to prepare

3. *We have analytic tools to* **model landslides**, *including for forecasting*

4. **Subaerial landslides** *can be recognized and monitored,*

   or even triggered *in a controlled fashion.*

Wrapping Up : **LANDSLIDES** *in the Warning Context*

BAD NEWS

1. **Amplitudes** *of displacement are* **HUGE**.

   LARGE, LETHAL *waves in* **NEAR FIELD**

2. *Fundamentally* **NON-LINEAR process**

   Difficult to forecast, in particular **TIMING**
   of [triggered] Landslide

3. **Undersea Landslides** *by definition* **poorly known** *(Hidden…)*

   Very difficult to monitor evolution of deformation
   of potentially hazardous sites

4. *Long duration of whole cycle can result in* **Loss of awareness**
   of populations at risk.

VOLCANIC TSUNAMIS

VOLCANIC TSUNAMIS

Mechanisms of Generation

- **Landslide reaching the sea**
  * *Flank Collapse*
  * *Pyroclastic flow reaching the sea*

- **Explosion in an immerged seamount**

- **Atmospheric explosion**

  generating

  * *Genuine tsunami*
  * *Ocean-Coupled Airwaves* [*Lamb, Pekeris*]

→ *MOST LIKELY:* **A combination of all above**

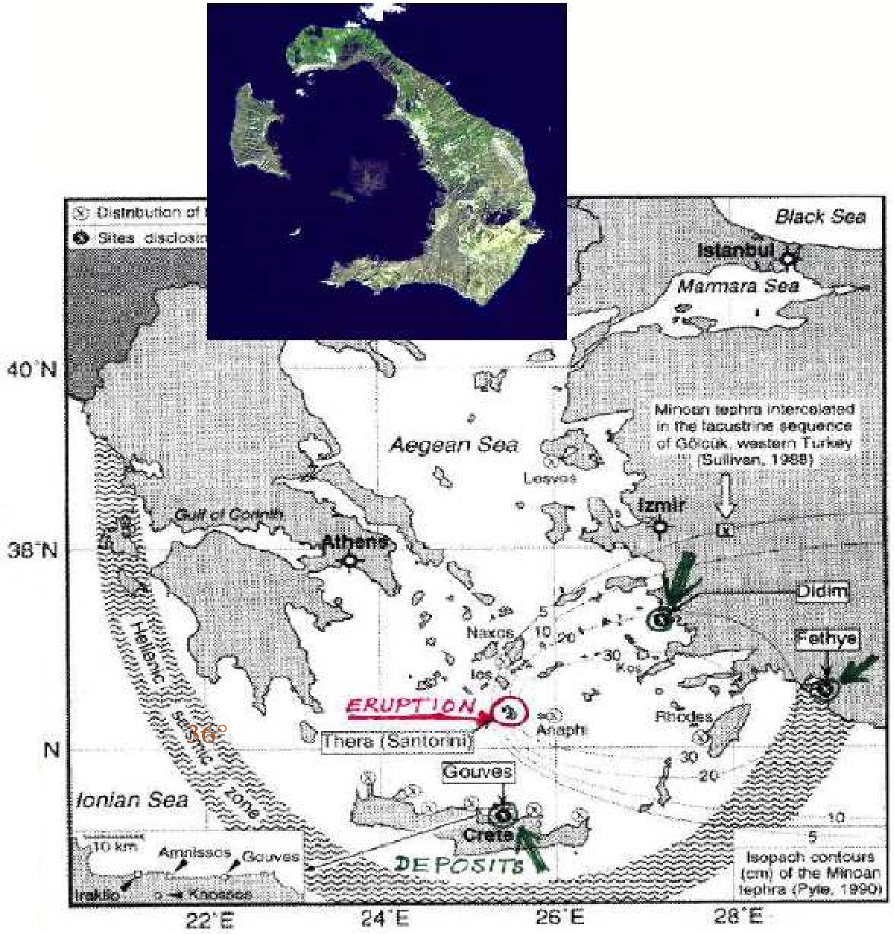
A Ray of Hope

As in the case of landslides, volcanic eruptions are

LONG **on-going episodes**

Volcanic Explosions at Sea

Santorini (Θηρα), 1630 ± 20 B.C.



[*Minoura et al.*, 2000]

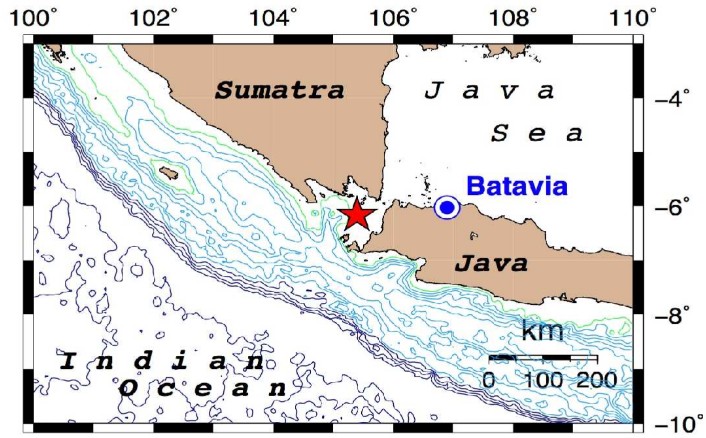
- Improvements in dating now suggest that the demise of the Minoan civilisation [*Marinatos,* 1939] was *NOT COEVAL* with the eruption, but rather followed it within ~75 years
  Note in particular that Knossos is 7 km inland at an altitude > 100 m.

- *A probable scenario is an economic demise of the whole region due to the devastation of its coastal plain, which made it vulnerable to a later war or epidemic.*

- Note the necessity to differentiate between volcanic deposits (ash) and tsunami ones (marine sedimentary material).

KRAKATAU

27 AUG 1883



- *A ~1−yr long volcanic episode culminates in a* **catastrophic explosion**
- *Local tsunami due to eradication of island kills 30,000 in Batavia* (Jakarta) [*Nomambhoy and Satake*, 1995].

→ Perturbations in sea level recorded

WORLDWIDE

TIDE-GAGE DISTURBANCES FROM THE GREAT ERUPTION OF KRAKATOA

Maurice Ewing and Frank Press

Discussion--The hypothesis of air coupling can well explain the origin of the tide-gage disturbances recorded at remote stations on August 27-29, 1883, and relates these disturbances to the Krakatoa explosion.

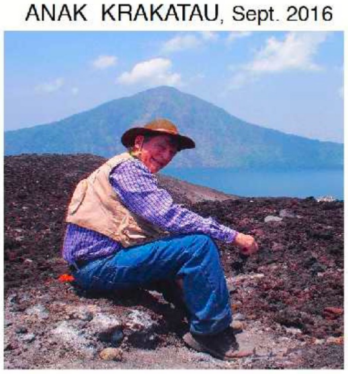
Transactions, American Geophysical Union Volume 36, Number 1 February 1955

AIR-SEA WAVES OBSERVED DURING 1883 KRAKATAU EXPLOSION

TSUNAMI GENERATION by *Volcanic Explosions at Sea*

Krakatau [Sunda Straits], 27 August 1883

ANAK KRAKATAU, Sept. 2016



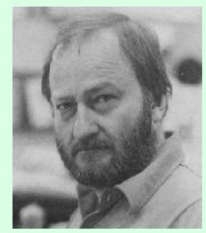
Born 1927... and Still Growing !

← 12 km →

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

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

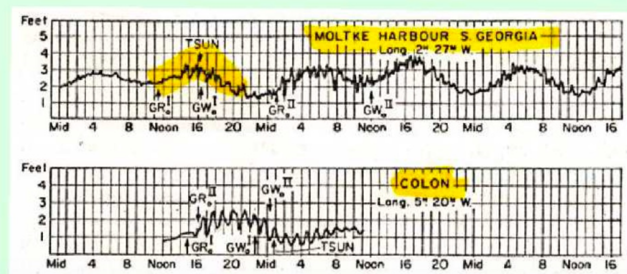
HOWEVER ...



Press and Harkrider [1965, 1967] had shown that the tsunami is actually triggered by an **air wave** generated by an atmospheric explosion, and re-exciting the ocean as it propagates.

This explains

- the propagation of the *"tsunami"* along great circle paths occasionally crossing... a continent!
- the occasional early arrival of the tsunami at distant tidal stations **(315 m/s** as opposed to **200 m/s).**
- and allows an estimate of the power of the explosion (100 to 150 Mt).



MORE VOLCANIC TSUNAMIS

MAY 1902: A remarkable Sequence

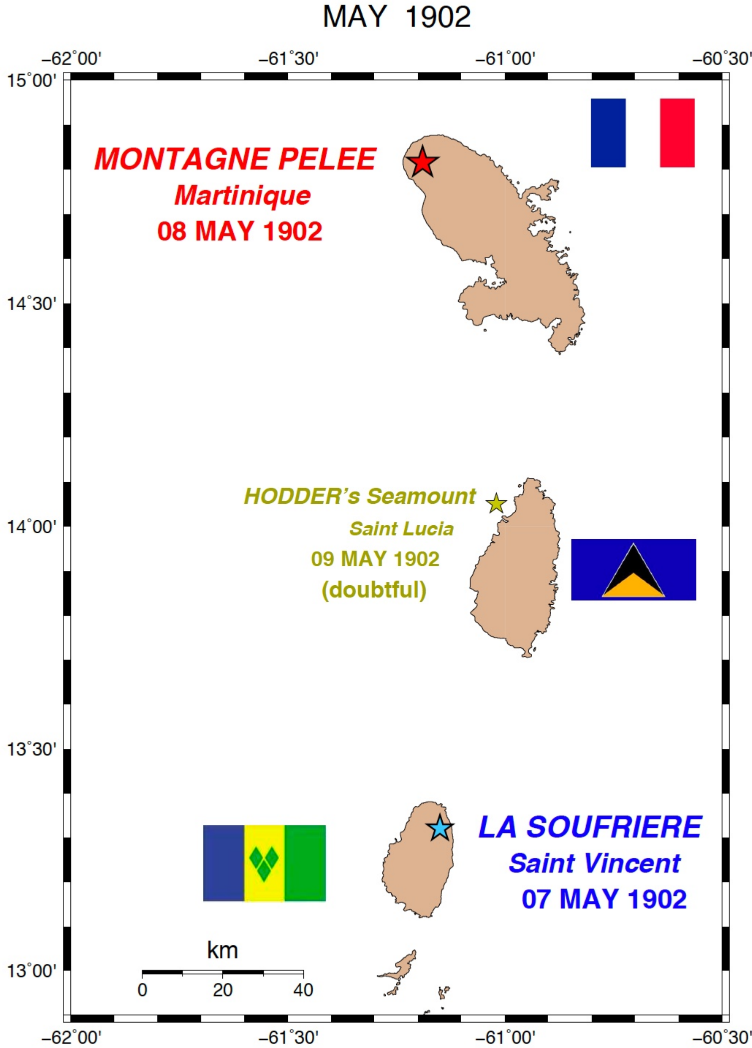
→ Most notorious is the **catastrophic eruption of Montagne Pelée on 08 May 1902,** whose Nuées Ardentes eradicated the (then) capital city of St. Pierre, killing all but one of its ~**30,000** inhabitants.

- *A concurrent tsunami is described, but its exact generation mechanism is obscure.*

- Activity continued, with a *significant wave* reported at Fort-de-France following a large eruption on **30 May 1902.**

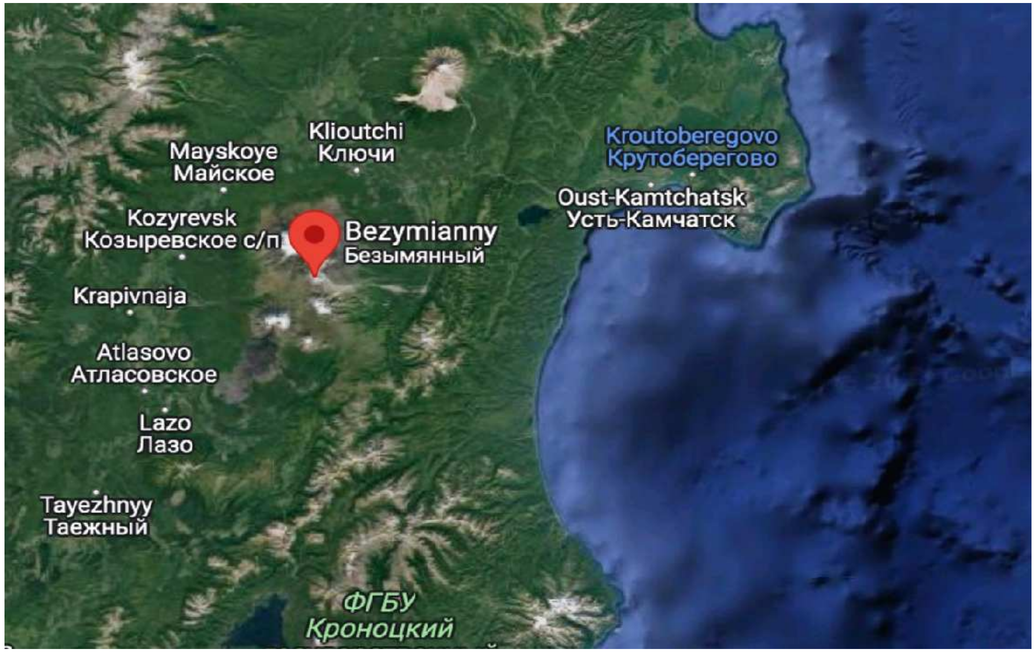
→ On 07 May, *the day before the Mt. Pelée disaster,* a large eruption took place at **la Soufrière de St. Vincent,** with a pyroclastic flow reaching the sea and generating a **tsunami,** probably comparable to the recent ones at Montserrat. The death toll is reported at **1,565.**

→ Unusual sea-surface disturbances near St. Lucia on 09 May, *not accompanied by genuine waves,* cannot be associated with definitive submarine relief, even if they are probably related to the above two eruptions.



BEZYMYANNIY (Kamchatka) — 30 MARCH 1956

The catastrophic explosion of Bezymyanniy on 30 Mar 1956 generated a small tsunami, recorded at Pacific Islands (including Hawaii) with **decimetric** *amplitudes* (max. 30 cm 0-to-pk).



→ **This is quite remarkable since the volcano is located on land, more than 60 km from the nearest coastline, and no pyroclastic invasion of the sea was reported.**

- *It is probable that the waves recorded were* **Ocean-Coupled Airwaves.**

VOLCANIC LANDSLIDES at La Sciara, STROMBOLI (Italy) — 30 DECEMBER 2002

Stromboli is an essentially permanently active volcano of the Calabrian arc in the Tyrhenean Sea. Its unconsolidated flank is the site of continuous [small] pyroclastic rockslides.

During a major eruption, the volcanic flank is rapidly destabilized and a large slide can generate a tsunami.

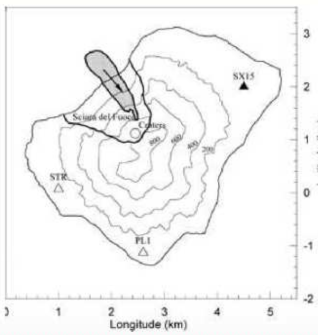
In December 2003, waves of 10 m reached the main village, fortunately deserted of tourists during the Winter season.

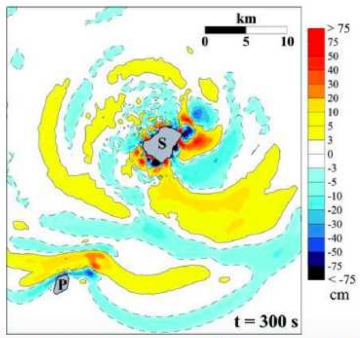
I. Bergman
(1950)

Run-up reached 10 m in nearby village

Miraculously, no victims

[*La Rocca et al.*, 2004]



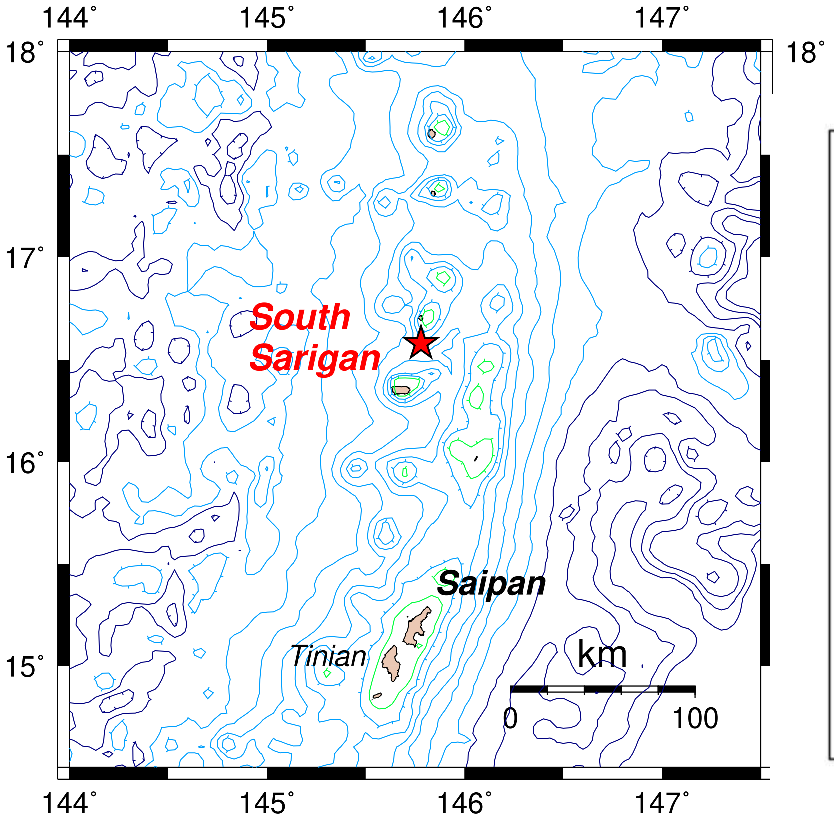


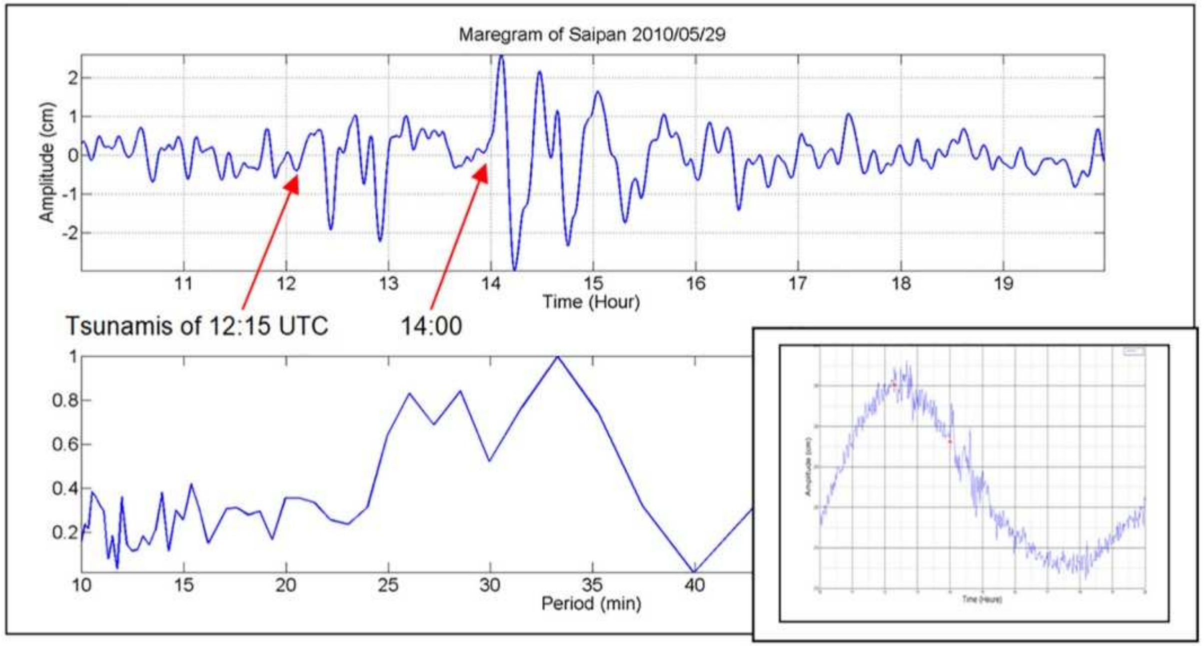
SOUTH SARIGAN (CNMI) — 29 MAY 2010

Explosive eruption at underwater seamount

- **Small tsunamis (TWO events; 6 cm paek-to-peak recorded at Saipan (166 km)**

→ *Exact mechanism of explosion and coupling with ocean column poorly understood*



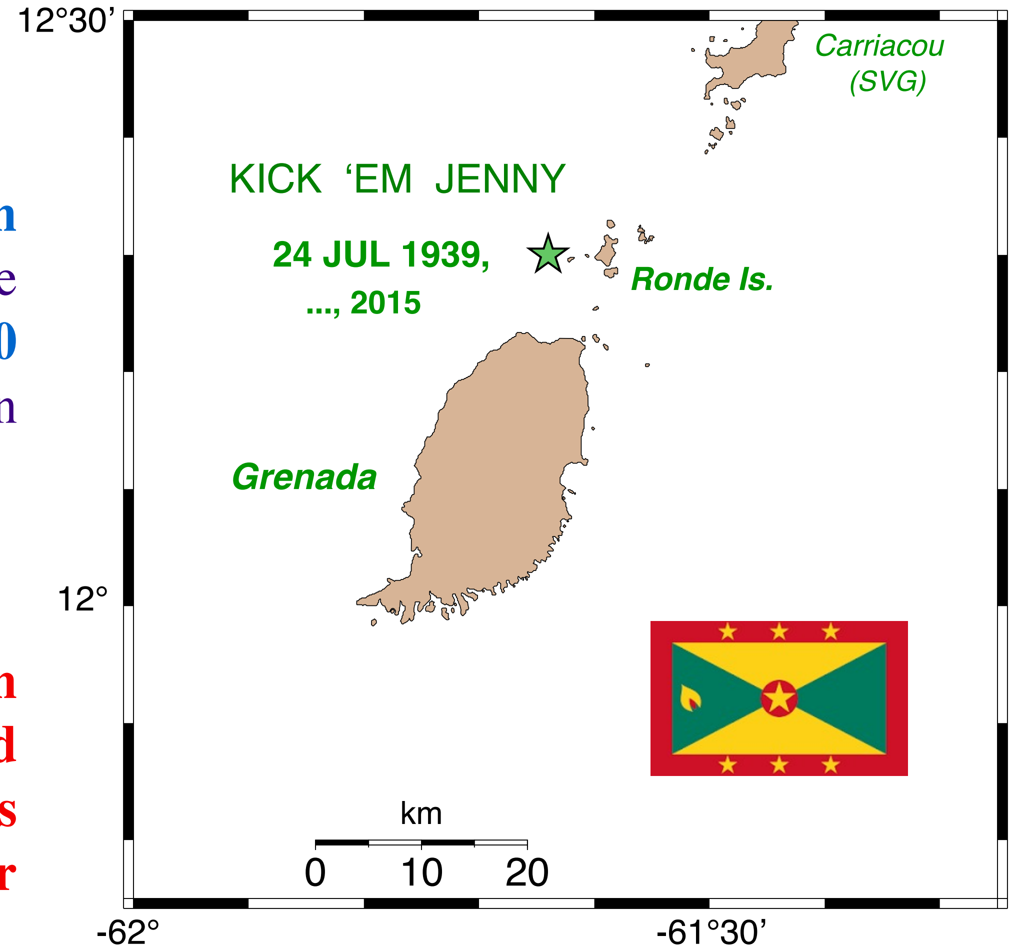


[*Talandier et al.*, 2020]

MORE VOLCANIC TSUNAMI HAZARD: *Kick ’Em Jenny*

- Kick ’Em Jenny, the only known underwater active voclano in the East Caribbean, is only *8 km from the Northern coast of Grenada*. It has been active about every 5 years since its discovery in 1939.

→ On that occasion, the eruption burst through the sea surface, and a **tsunami was reported in Grenada** (measured at 2 m), the Grenadines, and possibly Barbados.



* This situation is reminiscent of **South Sarigan** (Northern Marianas) whose catastrophic eruption on **29 May 2010** generated a tsunami recorded in Saipan, 150 km away.

→ **A major eruption at Kick ‘Em Jenny, larger than in 1939, would generate a significantly hazardous tsunami in the Southern Lesser Antilles.**

VOLCANIC COLLAPSE

Anak Krakatau, Indonesia, 22 December 2018

→ Locally catastrophic tsunami (~ 400 deaths)

West Java, 23 December 2018

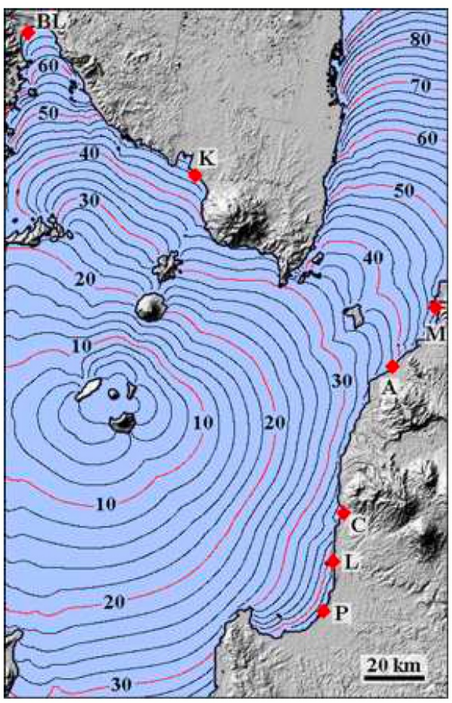
generated by underwater landslide during collapsing episode of subaerial volcanic edifice.

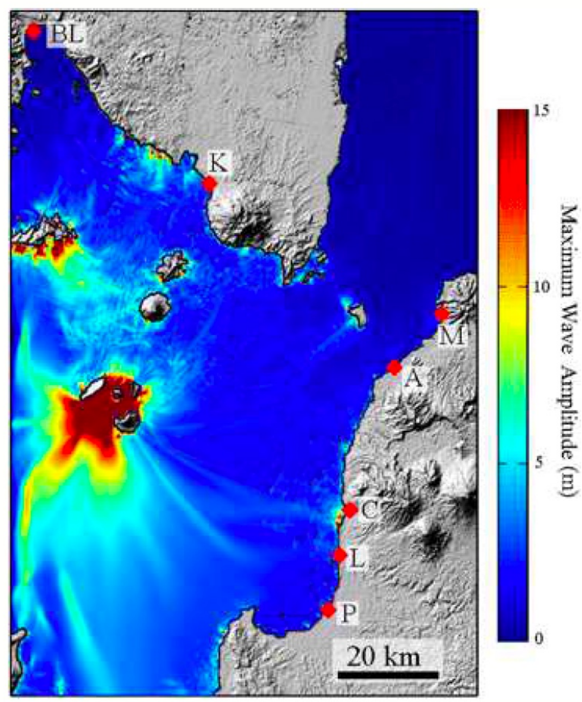
E.A. Okal on Anak Krakatau, September 2016

This part of the island has now disappeared...

Anak Krakatau, Indonesia, 22 December 2018

AND YET.... The event had been modeled [predicted] by Giachetti et al. [2012] *on the basis of a southwestward flank collapse at Anak Krakatau, the* **exact scenario in 2018.**

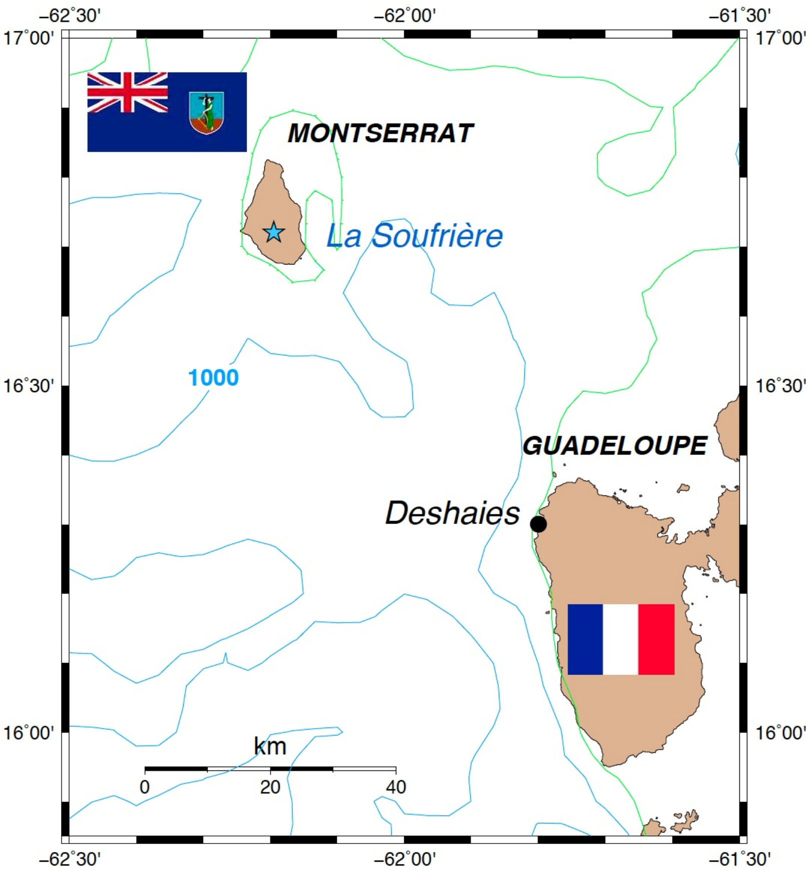




Remarkably, the authors had modeled the volume of the slide (0.28 km^3*) on the same order has estimated for 2018 (0.1* km^3*), leading to comparable runup heights on the island* (40 *vs*. 30 m) *and 5 to 10 m on Western Java and Southern Sumatra*.

MONTSERRAT (→ Guadeloupe)

A comparable (but not equivalent) situation exists in the Caribeean, as documented by the volcanic tsunamis (principally 1997 and 2003) at Montserrat, which can flood the Northeastern shores at Deshaies, Guadeloupe, at a similar distance (~ 50 km).



NOTE, however:

- Montserrat landslides were mostly subaerial, involving pyroclastic flows into the ocean;
- Smaller waves at Deshaies (~ 1 m; moderate damage, no casualties);
- Much deeper water (1000–1500 m), hence shorter propagation times on path to Guadeloupe.

MONTSERRAT (→ Guadeloupe)

The Prediction

→ Remarkably, *Heinrich et al*. [1998] had computed a predictive model for a "***potential debris avalanche***" at La Soufrière, Montserrat, which was outstandingly upheld during the 1997 event a few months later.

GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 19, PAGES 3697-3700, OCTOBER 1, 1998

Simulation of water waves generated by a potential debris avalanche in Montserrat, Lesser Antilles

Philippe Heinrich, Anne Mangeney, Sandrine Guibourg, Roger Roche
Laboratoire de Détection et de Géophysique, Commissariat à l'Energie Atomique, France

Georges Boudon, Jean-Louis Cheminée
Institut de Physique du Globe, Paris, France

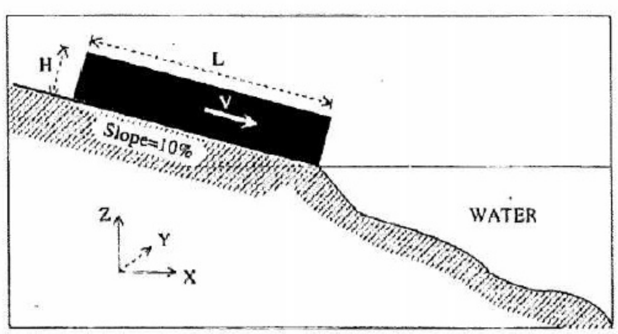
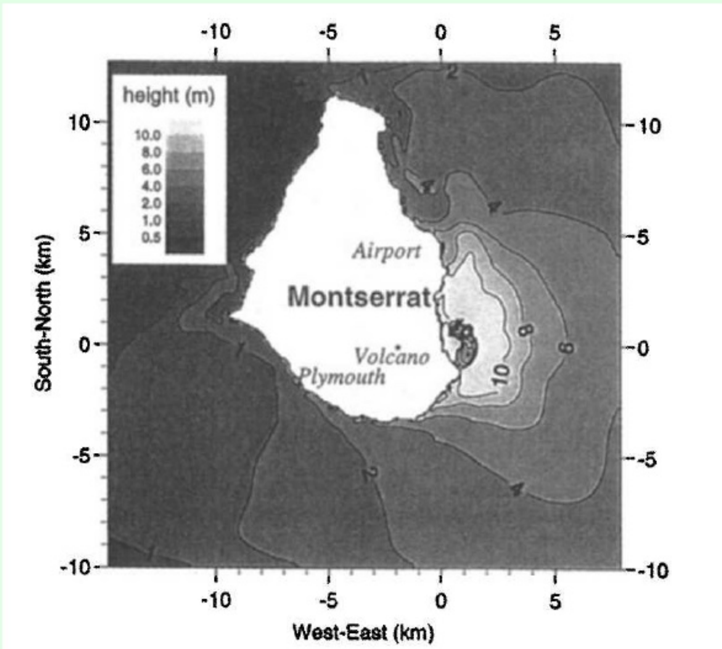


Figure 1. Sketch of the landslide geometry. The landslide contacts the still water surface at the time t=0s.



Note that the paper was submitted **before the eruption of 26 December 1997**, *but published after it*.

(Received November 5, 1997; revised February 12, 1998; accepted April 14, 1998)

Note added in proof → The calculated water heights along the Montserrat coast are in the range of those estimated for a similar event that occurred on the 26th of December, 1997 at Old Town.

The case of

HUNGA TONGA-HUNGA HA'APAI

15 January 2022

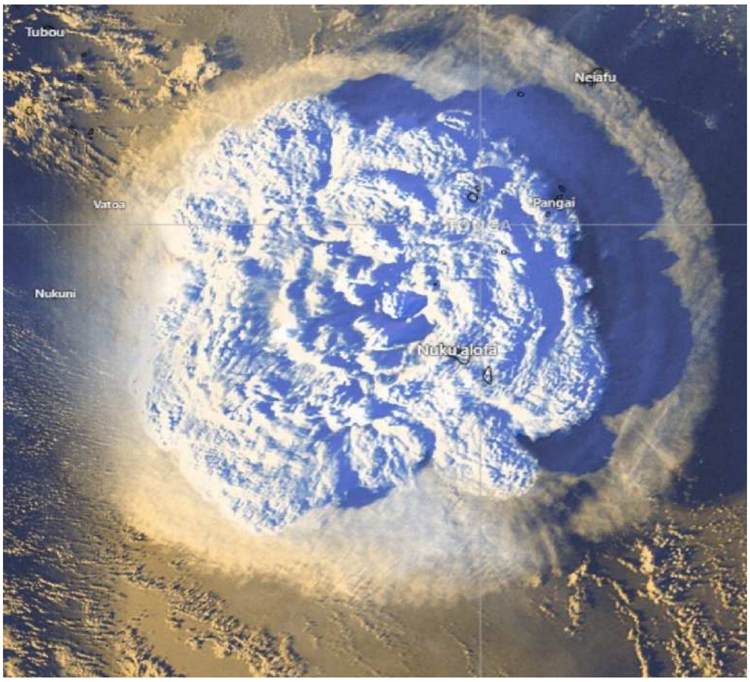
[*The New York Times*]

In addition to a regular tsunami,

the volcanic explosion produced a gigantic atmospheric gravity wave, which coupled with oceanic basins, resulting in surface disturbances observed worldwide.

TONGA 2022

Catastrophic explosion over Hunga Tonga-Hunga Ha'apai



Principal Characteristics

- **Most comparable to 1883 Krakatau**

- *Local tsunami splashed to 15 m on Tongatapu, reported 40 m on Tofua*

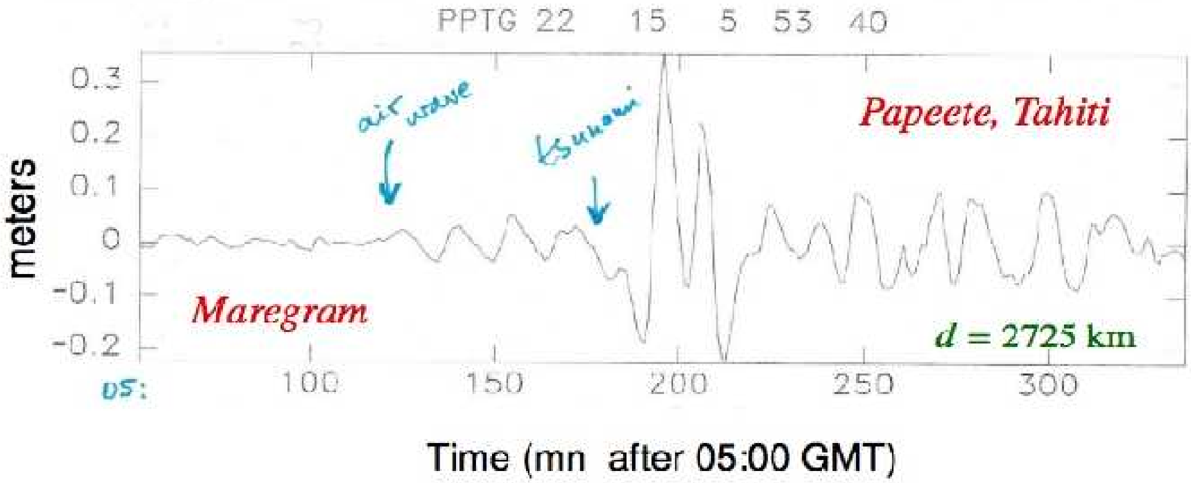
- **In the far field, both genuine tsunami and ocean-coupled airwaves**

ONLY FIVE REPORTED CASUALTIES
(3 in Tonga; 2 in Peru)

THE PRECUSORY TSUNAMI in the FAR FIELD:

AN OCEAN-COUPLED AIR WAVE

- At many locations of the Pacific, wave activity starts **BEFORE** the predicted arrival of the tsunami.



→ *This corresponds to an acoustic wave in the atmosphere, which is coupled to the water column, resulting in a disturbance of the sea surface.*

That wave, propagating at a typical velocity of 313 m/s, is significantly precursory to the tsunami.

- **This is the same wave (*GR_0* or "Lamb" wave) observed after Krakatau 1883, and studied in detail by *Harkrider* and *Press* [1967]**

THE GR_0 ("LAMB") WAVES

Principal properties relevant in the Warning Context

[*Okal*, 2022; 2023]

- *They are* **undispersed** *and travel at* **~313 m/s**, *i.e.*, *faster than tsunamis*

- *Their energy is* **mostly elastic**

- *Like seismic waves, they can go several times around the Earth*

- *Over a marine environment, they couple to the water column and set the water surface in motion. This can take place* **within less than 100 km** *of a continental shore.*

→ *The dynamic response of the surface, on the order* **of a few mm per mbar**, **decreases strongly** *with water depth. As a result, their coupling – and the ensuing hazard –* **falters quickly in shallow waters.**

- *Due to a different structure of the wave inside the water column,* **the overpressure in the water increases faster** *with depth than the hydrostatic ratio of 1 cm/mbar, resulting in the* **DART sensors over-representing the true amplitude** *at the sea surface.*

Wrapping up: **VOLCANIC EVENTS** *in the Warning Context*

GOOD NEWS

1. *Except in the near field during Krakatau 1883,*

   Very few casualties

2. *Most volcanic tsunamis occur during* **cataclysmic culmination** *of a* **slow volcanic cycle,** *often taking weeks or months to mature*

   We should have time to prepare

3. *Most volcanic tsunamis result from sea invasion by* **pyroclastic flows.** *Examples at Montserrat and Krakatau (2018) prove that we can* **model them** *reasonably accurately* **ahead of time**.

4. *Even the largest airwaves in the far field during mega-events of 1883 and 2022 reached* **at most a few hPa (mbar),** *resulting in* **less-than-decimetric** *sea level amplitudes, which additionally,* **falter in shallow waters**

Wrapping up: **VOLCANIC EVENTS** *in the Warning Context*

BAD NEWS

1. The TWCs were clearly caught unprepared

They issued a whole spectrum of warnings, ranging from "No hazard" (Peru)" to "3–m waves expected" (Japan).

→ **The former may have contributed to the two Peruvian casualties** *in Lambayeque (apparently swept away while driving on the beach)*

→ **The latter provoked needless scare** *and would in general be detrimental to building confidence in the TWC among the population involved*

→ **PTWC's response** *("We cannot tell for sure and give numbers, but just do not go the beach!")* **may have been the most sensible** *under the circumstances.*

PTWC

```
TSUNAMI THREAT FORECAST
-----------------------

  * HAZARDOUS TSUNAMI WAVES FROM THIS ERUPTION ARE POSSIBLE
    WITHIN 1000 KM OF THE VOLCANO ALONG THE COASTS OF

      TONGA... NIUE... FIJI... WALLIS AND FUTUNA... AMERICAN
      SAMOA... SAMOA AND KERMADEC ISLANDS

  * DUE TO THE VOLCANO SOURCE WE CANNOT PREDICT TSUNAMI
    AMPLITUDES NOR HOW FAR THE TSUNAMI HAZARD MAY EXTEND
```

Russia

Угроза цунами объявлена на Курилах после извержения подводного вулкана у островов Тонга. Об этом 15 января «РИА Новости» сообщил представитель экстренных служб.

Peru

NOTA DE PRENSA Nº 02 - 2022

CARACTERÍSTICAS DE ERUPCIÓN VOLCANICA A 73 KM AL N DE NUKUALOFA, TONGA

La Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú, organismo responsable del Sistema Nacional de Alerta de Tsunamis, informa a la población lo siguiente:
El día Viernes 14 de Enero 2022, a 23:27 hora local (04:27 UTC), se registró una erupción volcánica con epicentro en el Mar, localizado a 73 KM N de Nukualofa, Tonga con Latitud -20.5 y Longitud 175.4, con una Magnitud de 1.0. Esta información fue recibida por el Centro de Alerta de Tsunamis del Pacífico.
Luego de un análisis y evaluación a través del Centro Nacional de Alerta de Tsunamis de esta Dirección, se comunica que este evento NO GENERA TSUNAMI EN EL LITORAL PERUANO. Se mantendrá en constante vigilancia dicho evento.
Sábado 15 de Enero 2022

Japan's meteorological agency issued tsunami warnings in the early hours on Sunday and said waves as high as three metres (9.84 feet) were expected in the Amami islands in the south. Waves of more than a metre were recorded there earlier.

Japan

15 de enero de 2022

SHOA decreta alerta de tsunami para la región de Los Ríos

[AHORA] Solo las regiones de Coquimbo y Los Ríos deberán asegurar una evacuación total desde la cota 30.

Chile

Wrapping up: **VOLCANIC EVENTS** *in the Warning Context:* **More BAD NEWS**

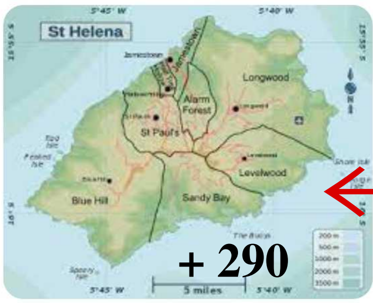
2. *As of Fall, 2023, no consensus available on size of 2022 event*

Estimates range **from 17 to more than 400 Mt**

3. *While the event is reminiscent of Krakatau (1883), significant differences remain with, e.g.,*

* **Tambora (1815)***: no tsunami reported except in near field (Sulawezi, Java), despite explosion generally regarded as larger*

[Granted, the world was busy addressing other matters at the time]



* **"Tsar' Bomba" (57 Mt** *on 30 OCT 1961): no sea waves reported despite air waves with generally comparable amplitude — probably different spectrum*

→ *Which suggests*

All volcanic explosions may not be created equal

and begs the question

Could a Tonga-like event be even bigger ?

... and in turn

OTHER POTENTIAL TSUNAMI HAZARD:

Catastrophic Bolide Impact

Only one definitive case documented:

- *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

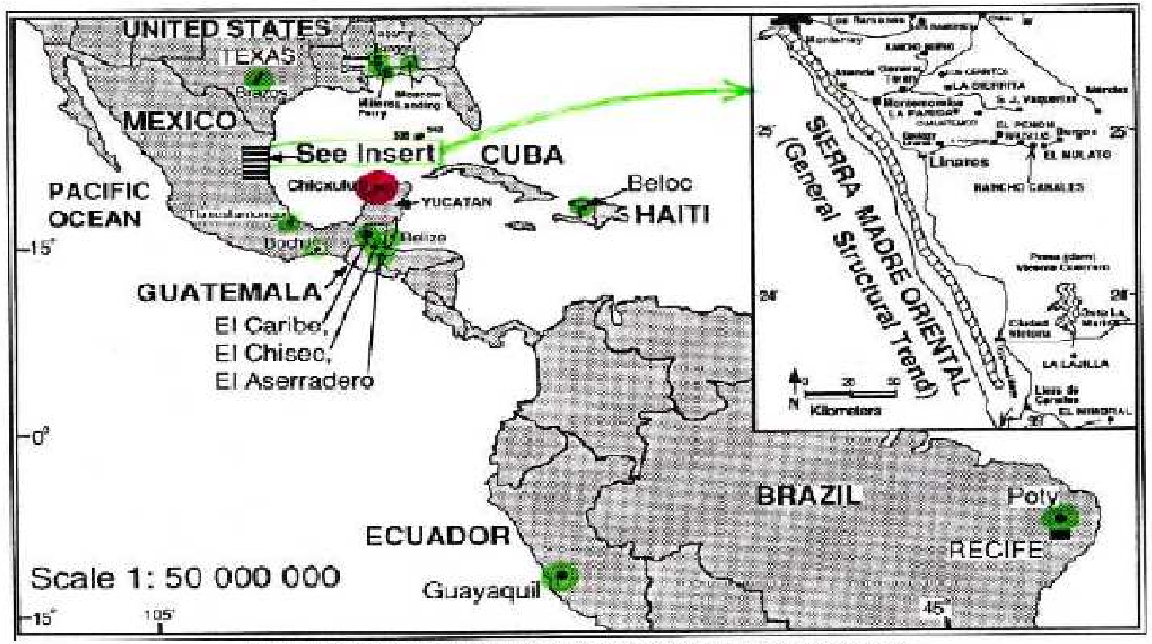


Figure 1. Location of Cretaceous-Tertiary boundary sections with near-K/T clastic deposits from Texas to Brazil. Inset shows area of location of northeastern Mexico sections.

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

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† For reference, the largest man-made explosion had a yield of **57 Megatons**

("Царь Бомба", 1961)