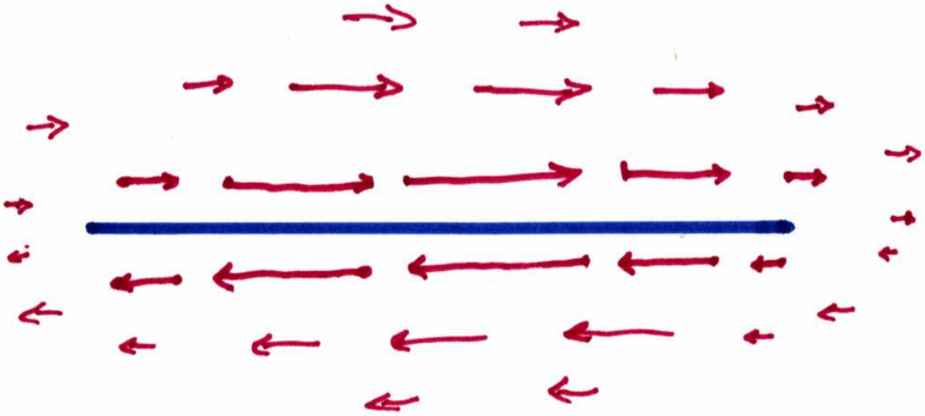
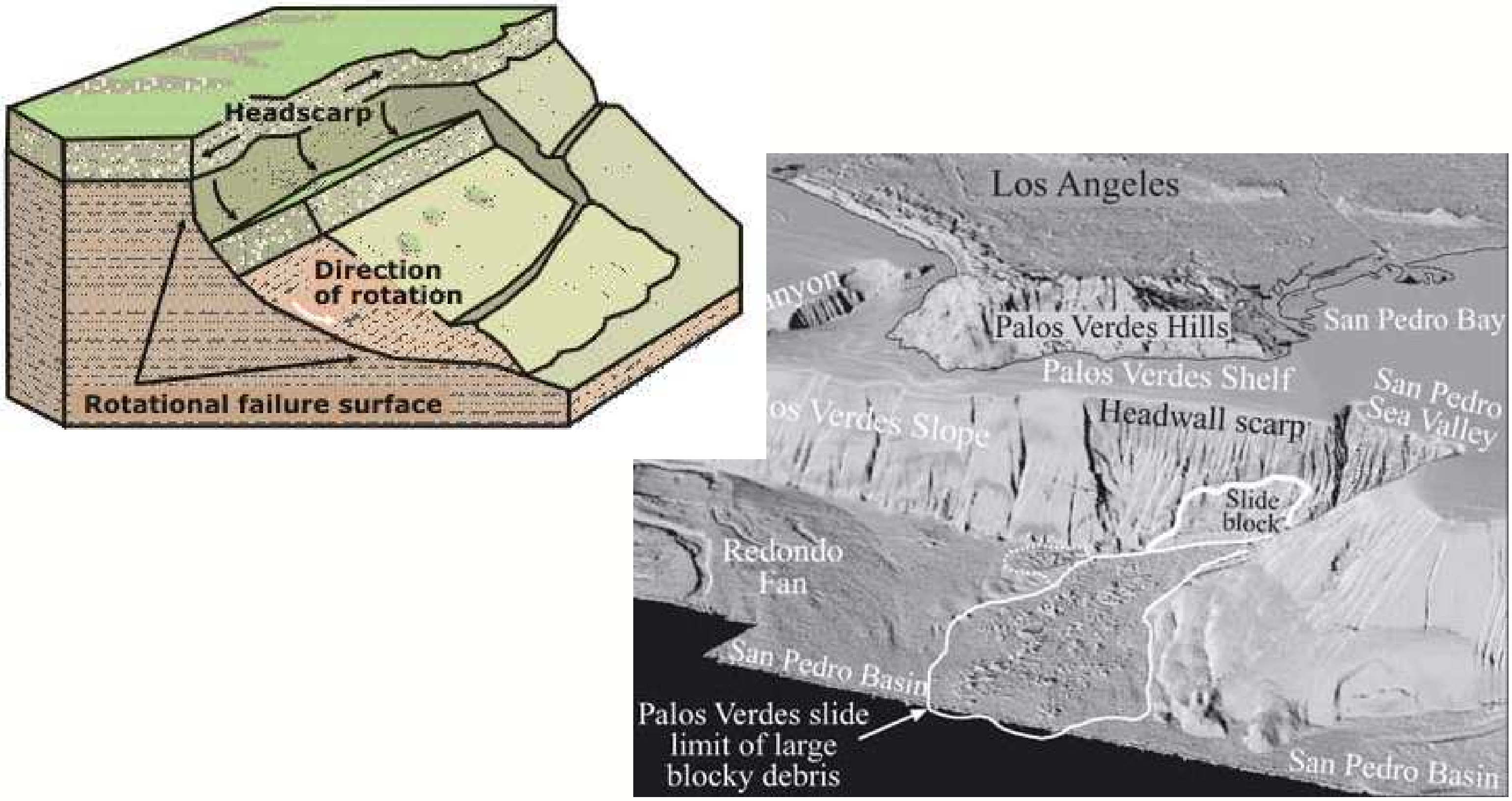
LECTURE 7

LANDSLIDE TSUNAMIS

- 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*.

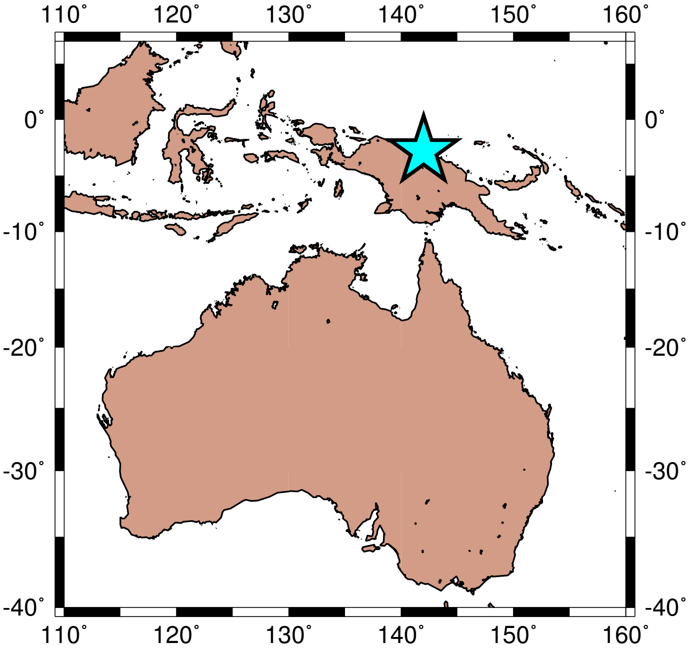


[Mathematically, this is expressed through different *boundary conditions* for the analytical representations of the source].

THE PAPUA NEW GUINEA (PNG) TSUNAMI

17 JULY 1998

- 2200 people killed
- Ten villages eradicated



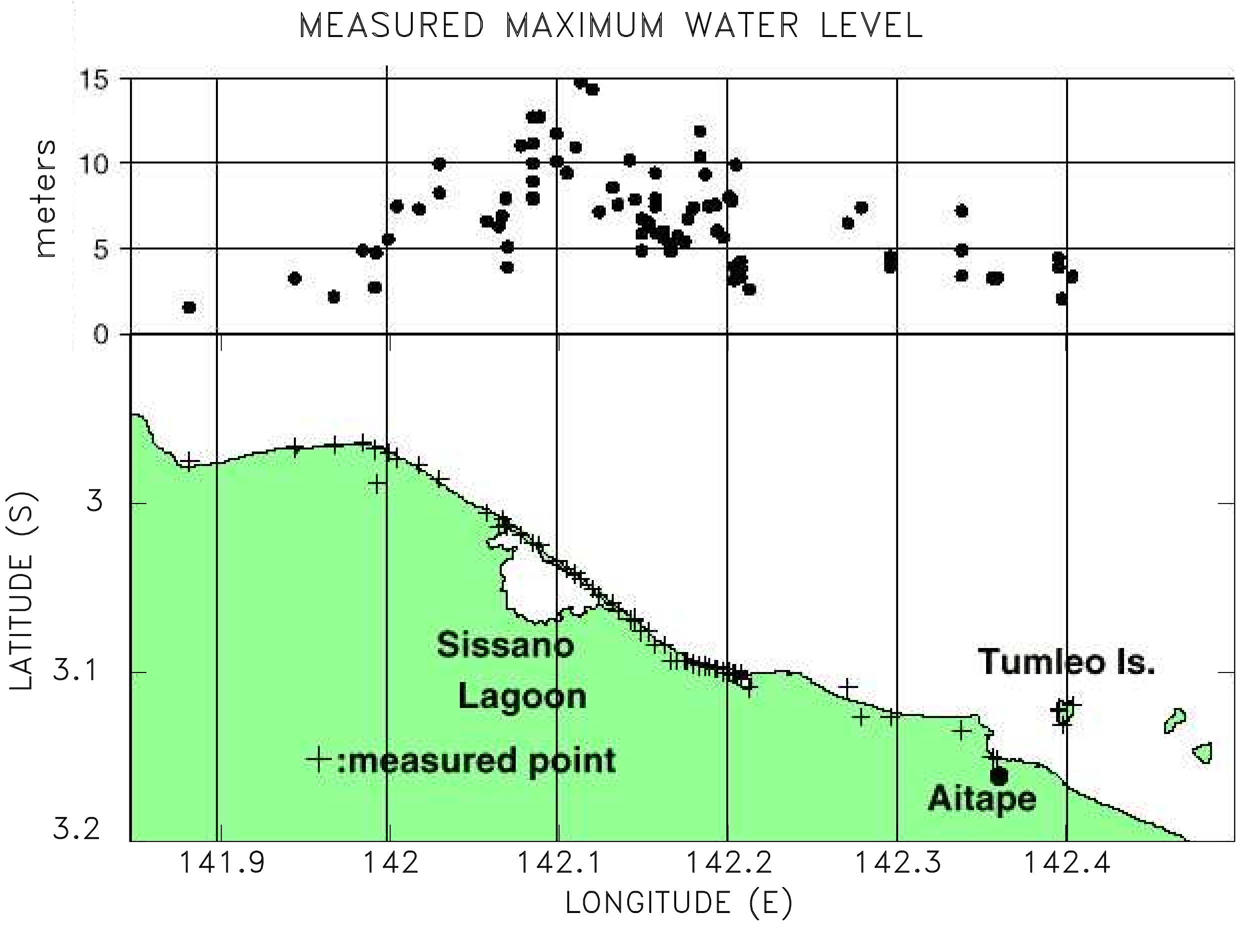
YET, The Earthquake was relatively small ($M_m = 6.8$)

THE PNG PUZZLE

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

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

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

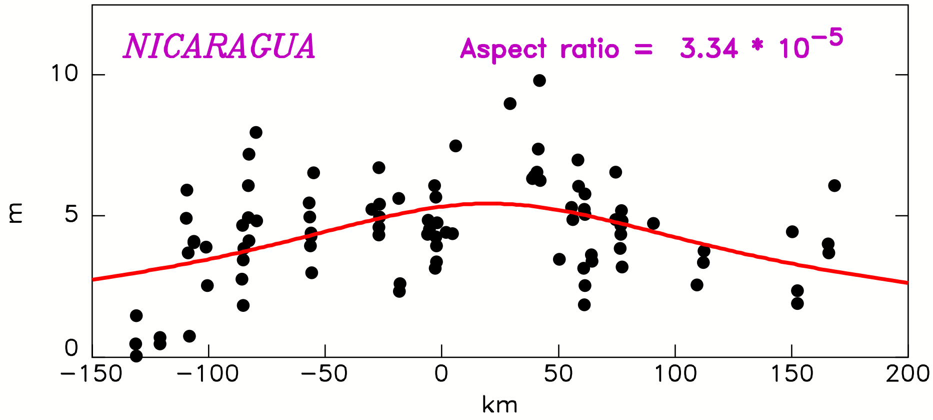


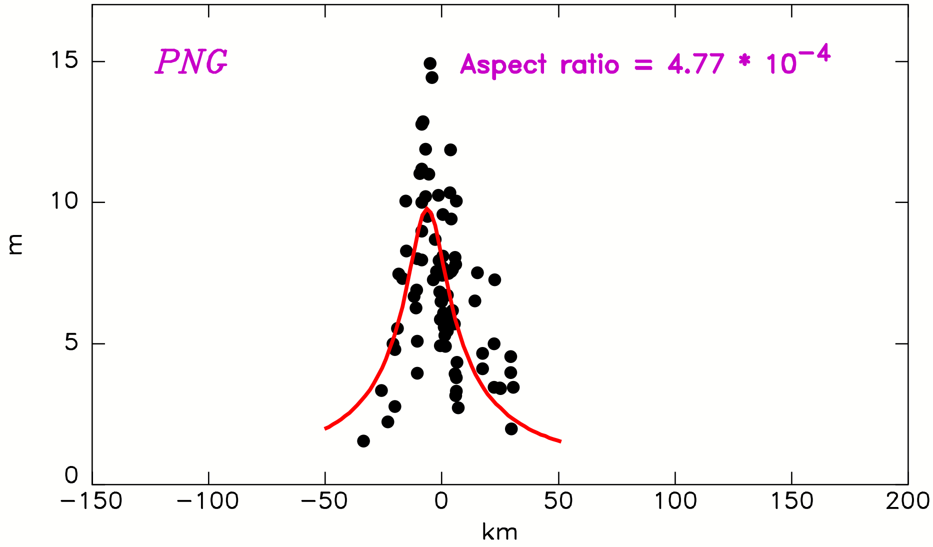
[*Synolakis et al.*, 2002]

THE PNG PUZZLE (continued)

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

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





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

THE PNG PUZZLE (continued)

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

Even though the tsunami was 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.

UPDATE AS OF: 30/7/98/ AITAPE TIDAL WAVE DISASTER STATUS.

CARE CENTRE	CAMP ADM	1990 POPULATION CENSUS	CENTRE POPULATION	INJURED HOSPITALISED	MISSING	DEATHS
RAMO	P. KONAE	1340	1574	344		1082
POU	M. SELMATAN	1644	1404			863
ROWOI/ (AINSOR)	T. NEKEAU	826	1153	49	35	61
OLBRUM	M. KALIT	468	1032	24		25
RAINBRUM	E. HARRY	293	89	5	1	
MALOL	R. MIROI	2268	3816			95
TOWN	N. JALMAN	627	415			1
PALUP				6		7
OTHERS						
		7521	9483	428	35	2134

THE PNG PUZZLE (continued)

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

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

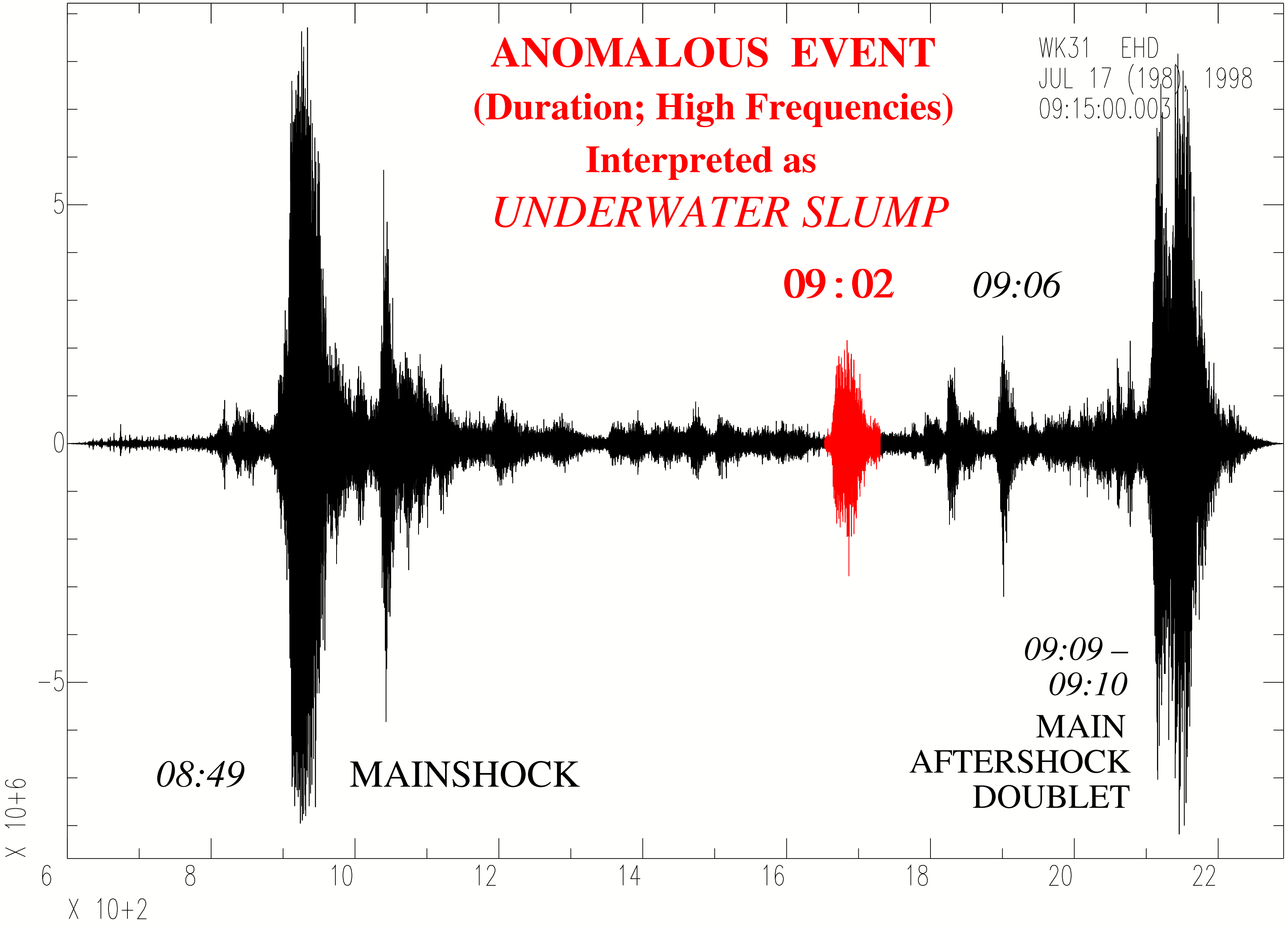
- In some areas (Malol), the tsunami *did not arrive until after the "second felt shock"* (main aftershock at 09:09 GMT);
- In other areas (Arop, Warapu), the tsunami arrived before the population had a chance to feel the main aftershock.

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

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

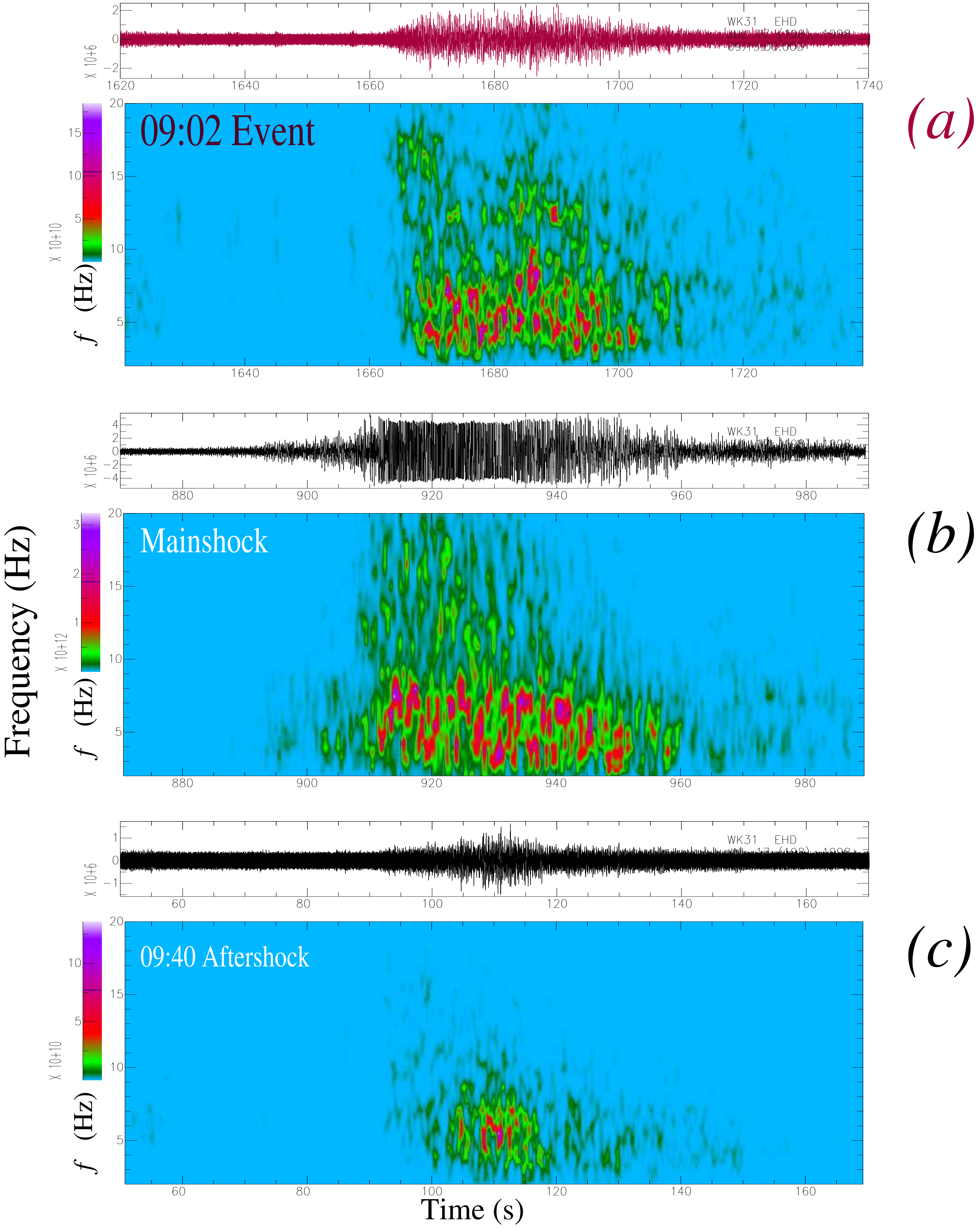
WAKE ISLAND HYDROACOUSTIC RECORD -- 17 JULY 1998

09:25 GMT 09:53:11 GMT



Time after 09:15 GMT (hundreds of seconds)

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.

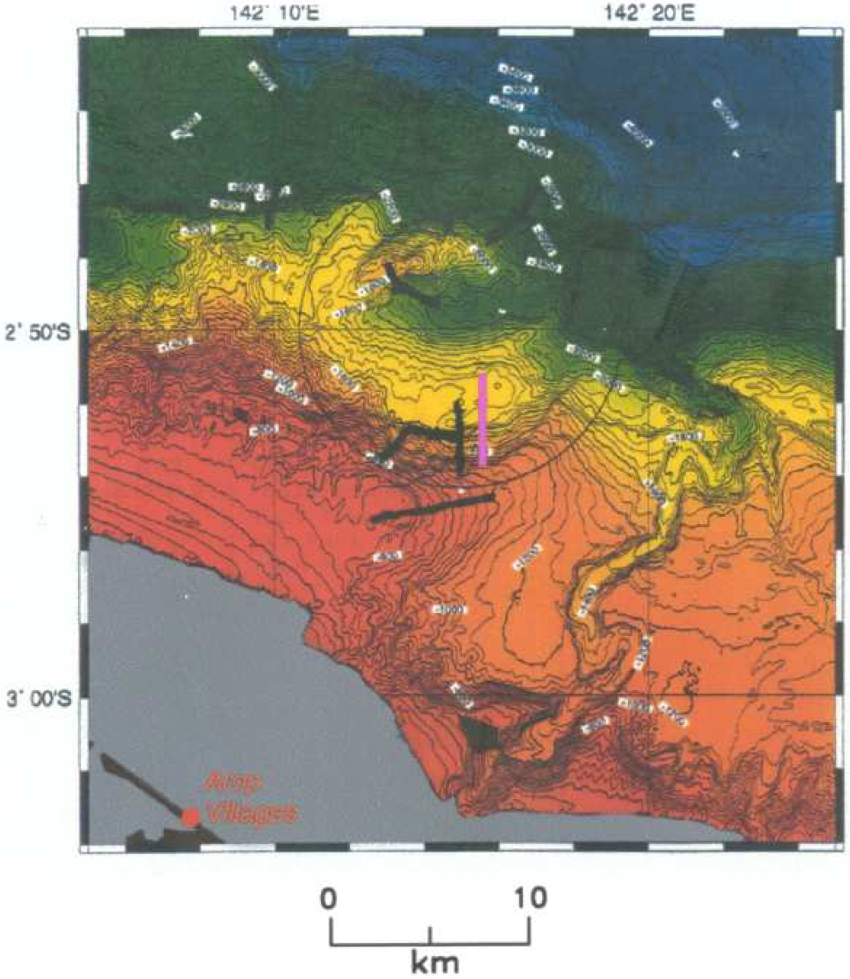
THE SLUMP MODEL

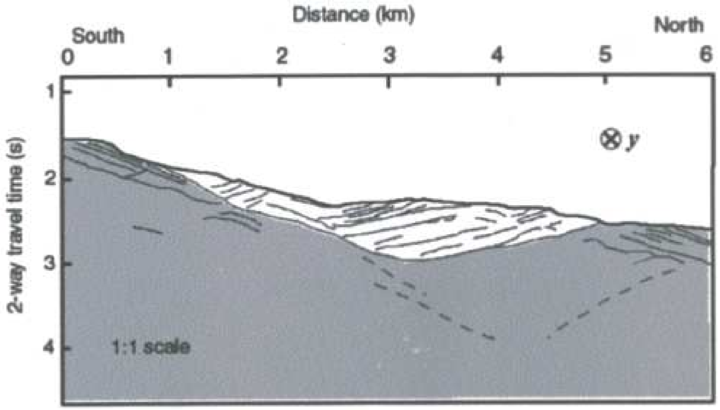
We propose that the near-field PNG tsunami was generated by a massive, 4–km^3 underwater slump, triggered at 09:02 GMT, 13 minutes after the mainshock, inside a bowl-shaped amphitheater located approximately 25 km off shore from Sissano Lagoon.

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.

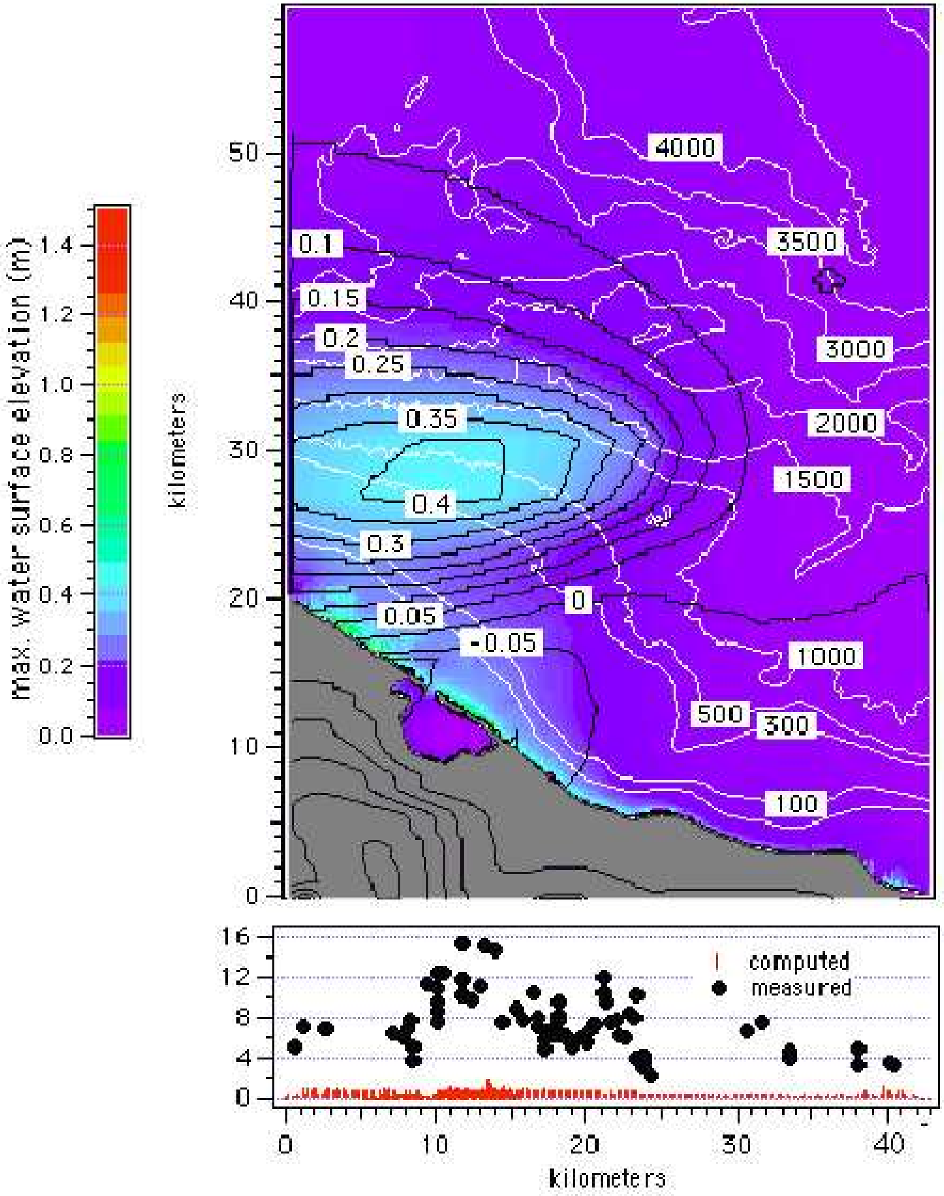
IT IS THERE !!!



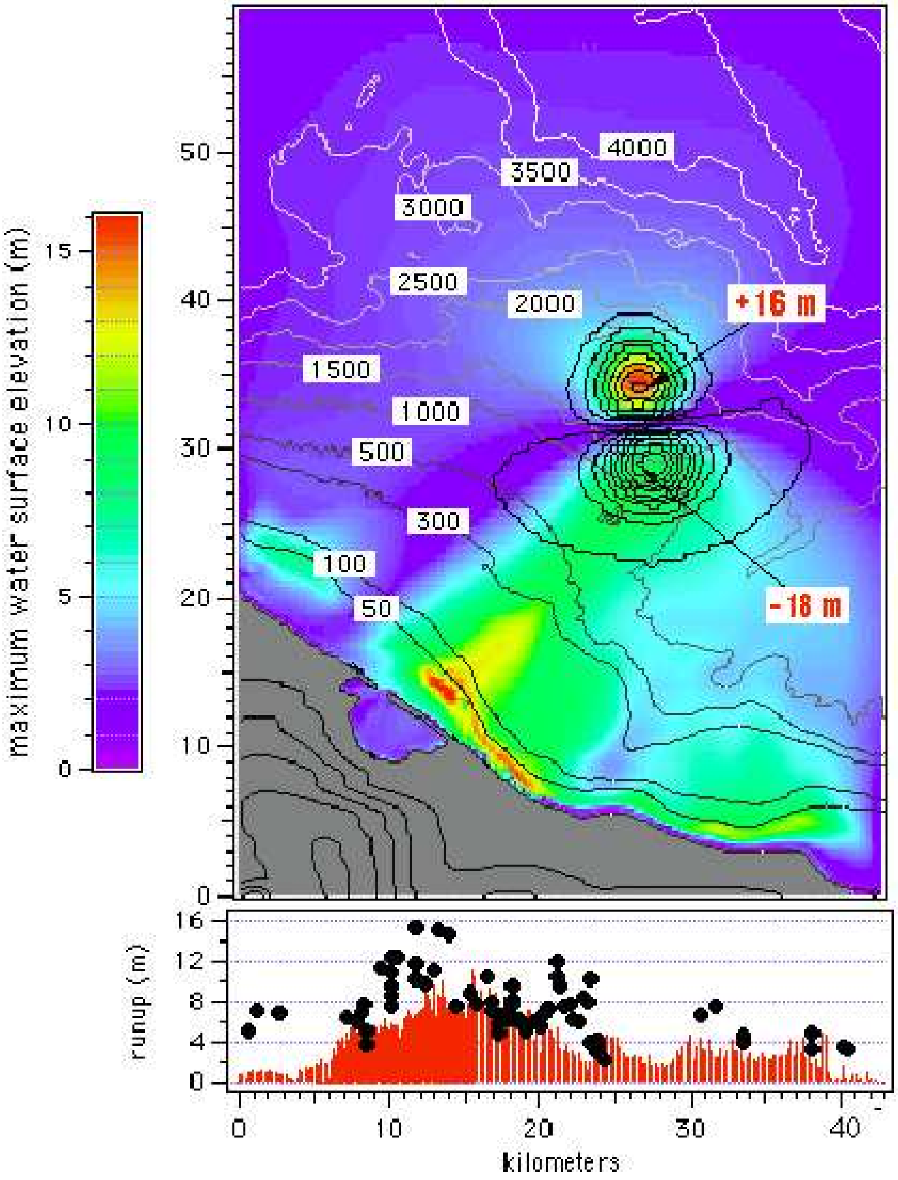


TSUNAMI SIMULATIONS

[*Synolakis et al.*, 2002]



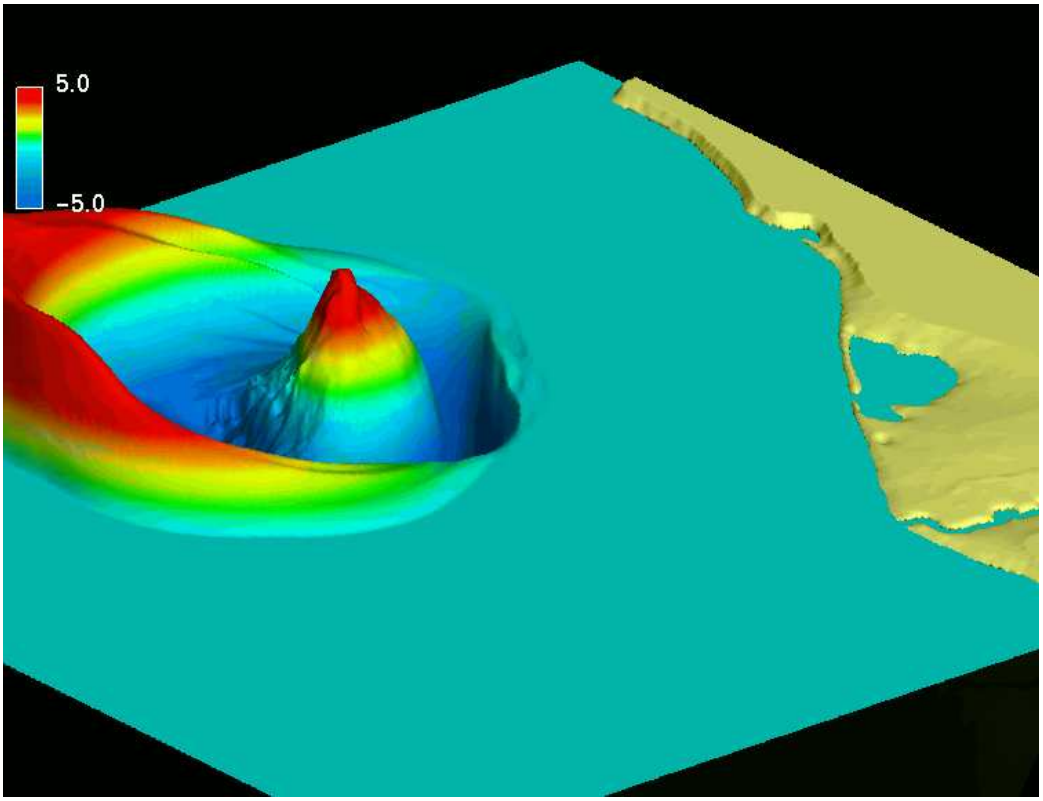
EARTHQUAKE SOURCE



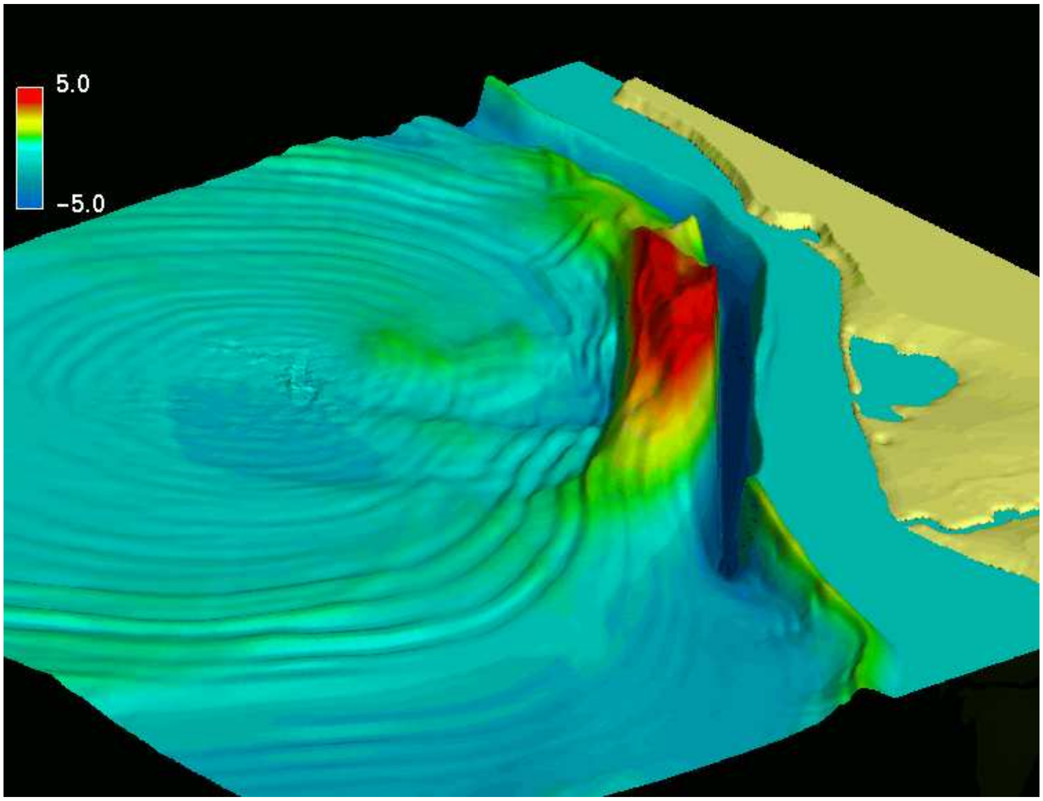
SLUMP SOURCE

TSUNAMI SIMULATIONS — SLUMP SOURCE

[*Heinrich et al.*, 2000] Vertical exaggeration: 750



t = *90* s



t = *360* s

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

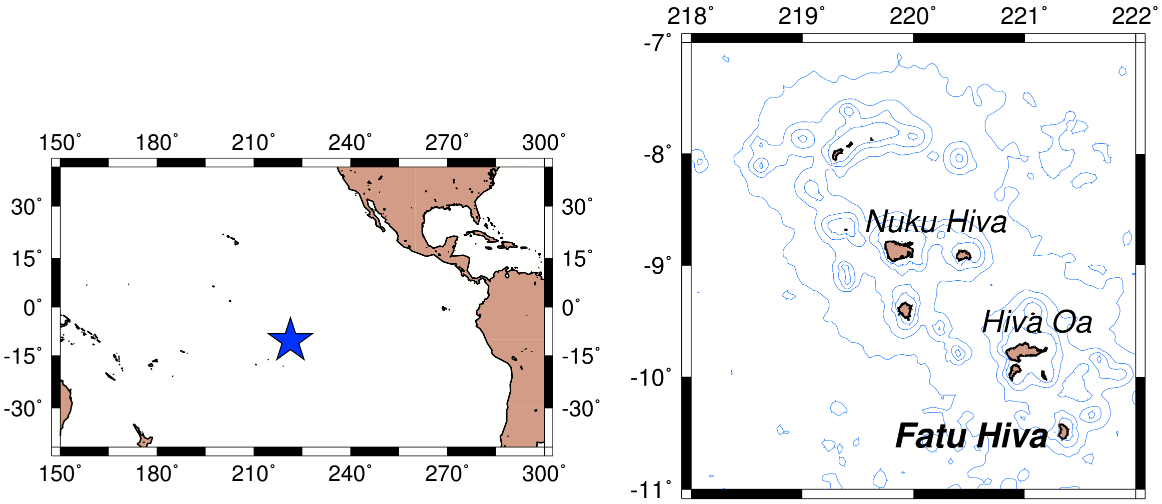
DEVASTATING locally, but pose

LITTLE HAZARD in the FAR FIELD.

TSUNAMI GENERATION (ctd.)

Landslides

Fatu Hiva, Marquesas Islands, 13 September 1999

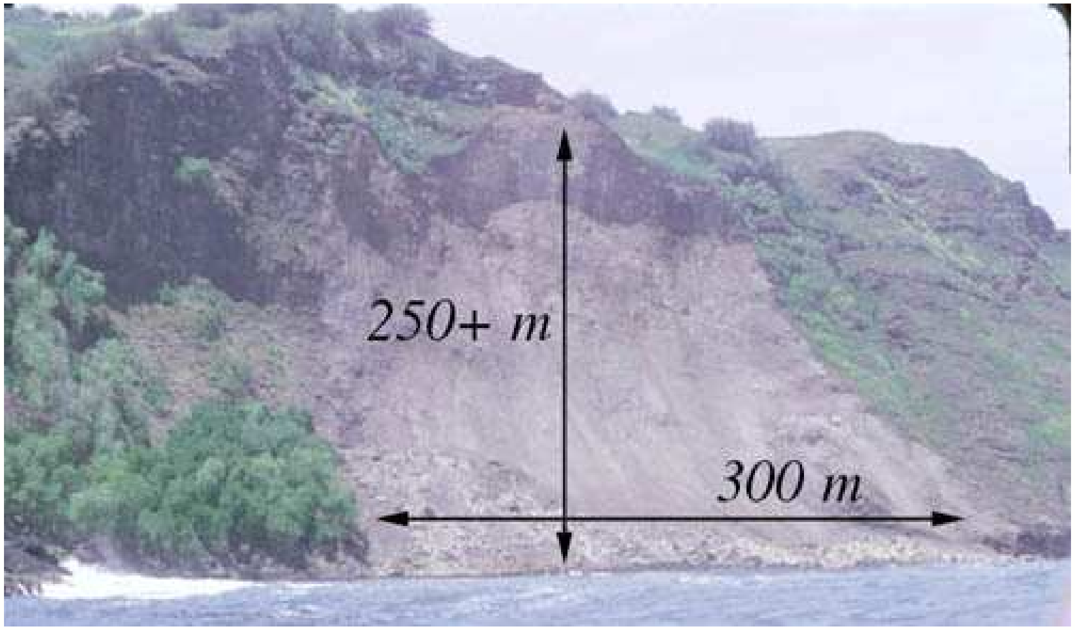


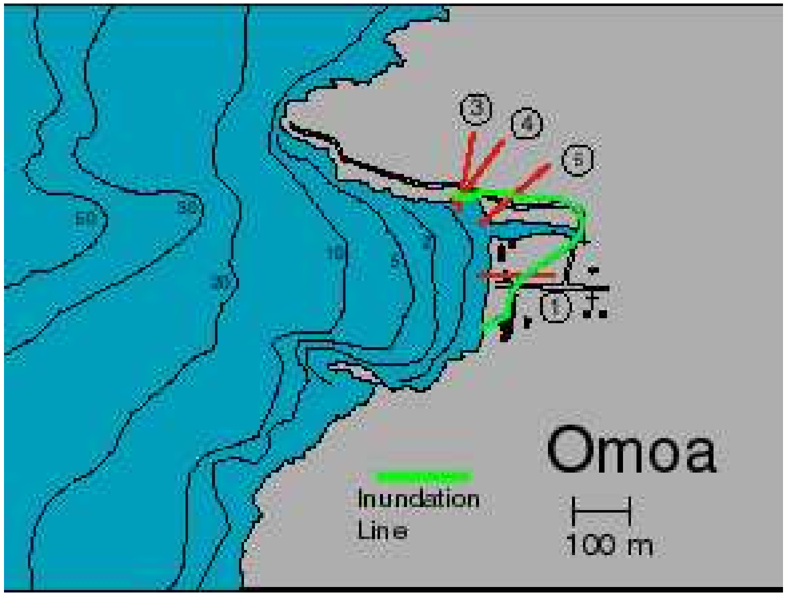
The beachfront school house at Omoa was severely flooded by two "rogue" waves which also destroyed the ice-making plant and several canoe shacks and copra-drying stands.

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

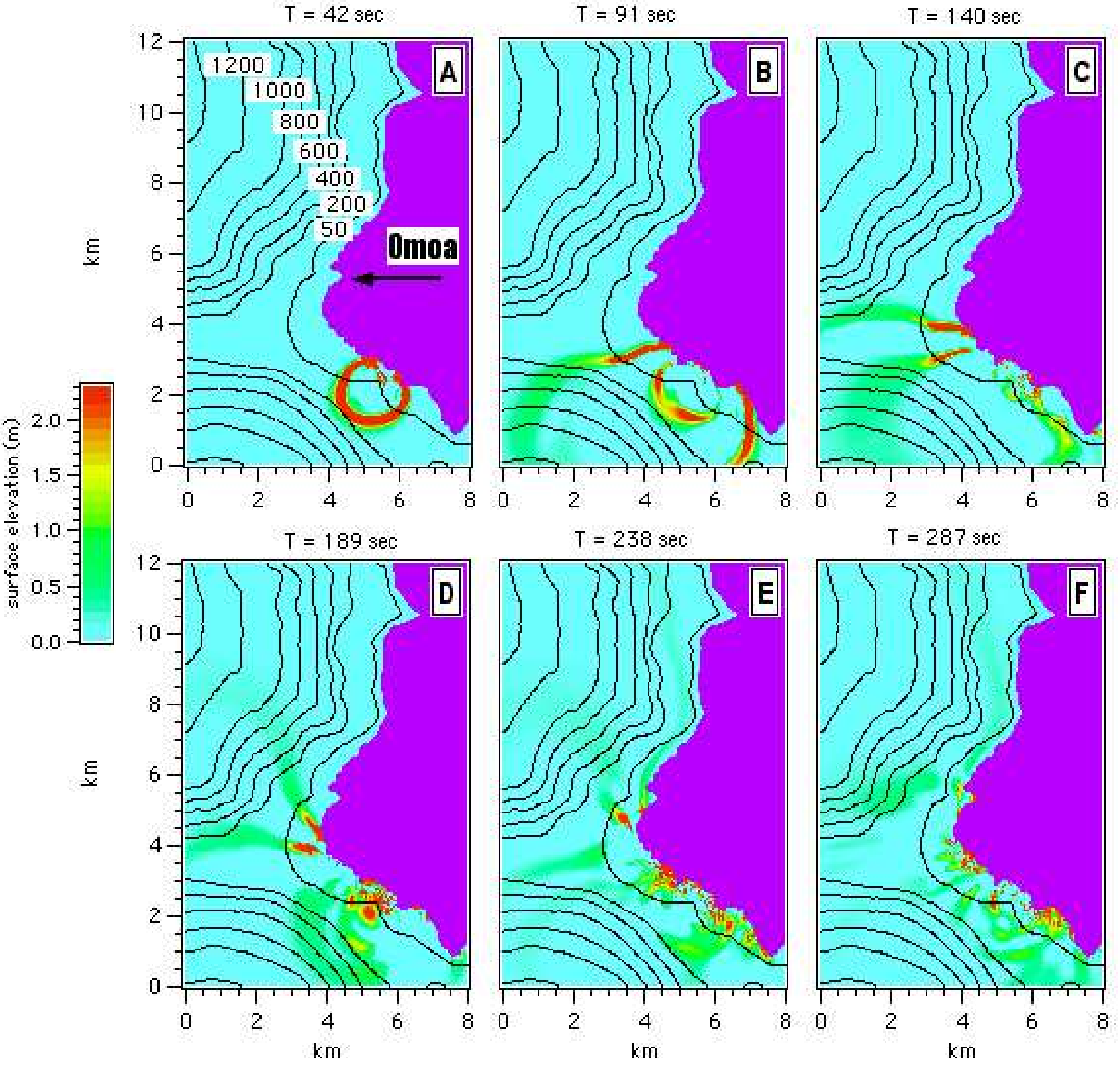
1999 FATU–HIVA TSUNAMI: *The SOURCE*

Estimated Volume of Rock Slide: 4 million m^3





MODELING the 1999 FATU-HIVA LANDSLIDE



Note the refraction of the wave around the promontory and into Omoa Bay (Plates D, E, F).

Note also the arrival of two principal waves.

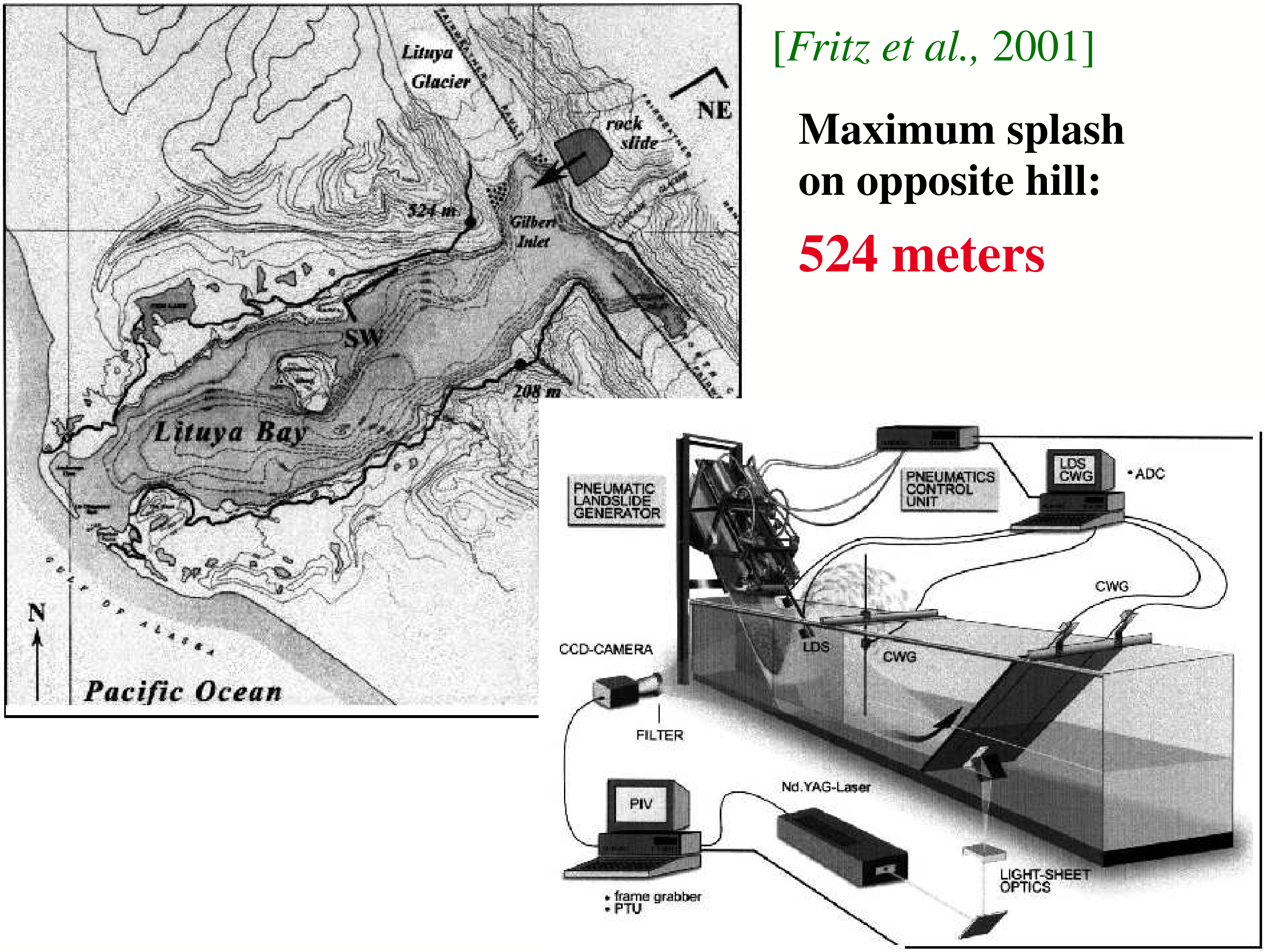
[*Okal et al.*, 2002]

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

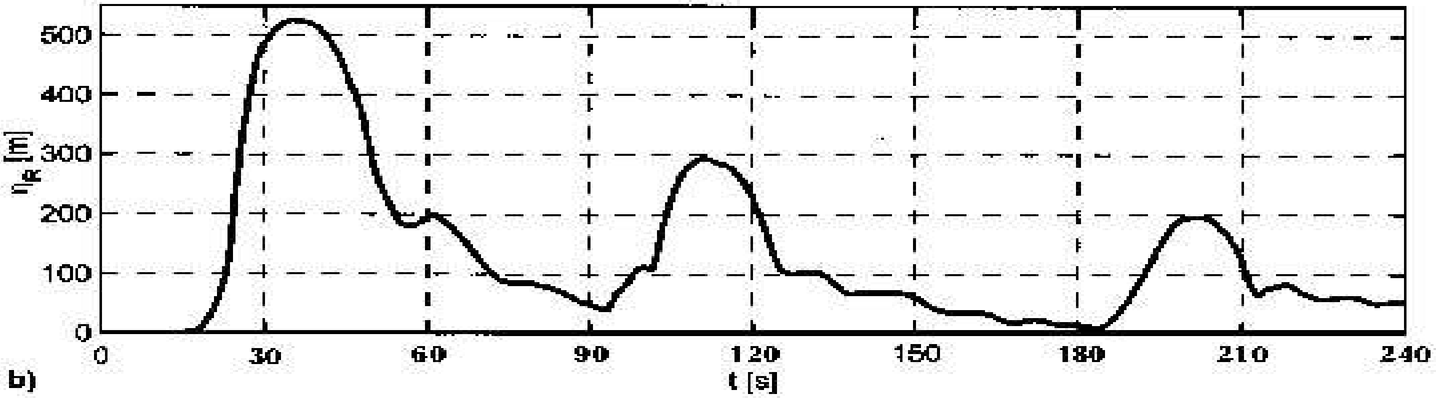
LABORATORY MODELING of LITUYA BAY LANDSLIDE & TSUNAMI



[*Fritz et al.*, 2001]

Maximum splash on opposite hill:

524 meters



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

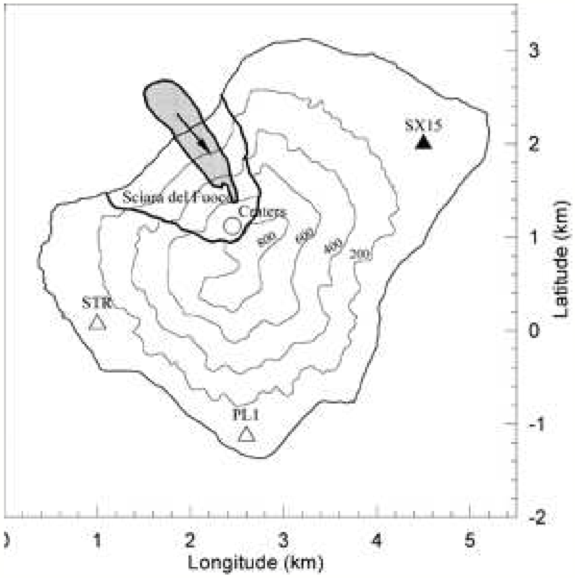
Importance of large air cavity developing during impact of landslide.

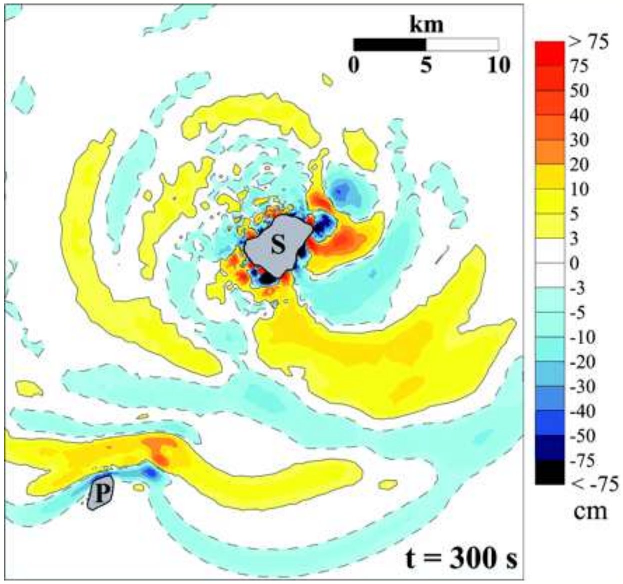
VOLCANIC LANDSLIDES at La Sciara, STROMBOLI (Italy) — 30 DECEMBER 2002

Run-up reached 10 m in nearby village

Miraculously, no victims

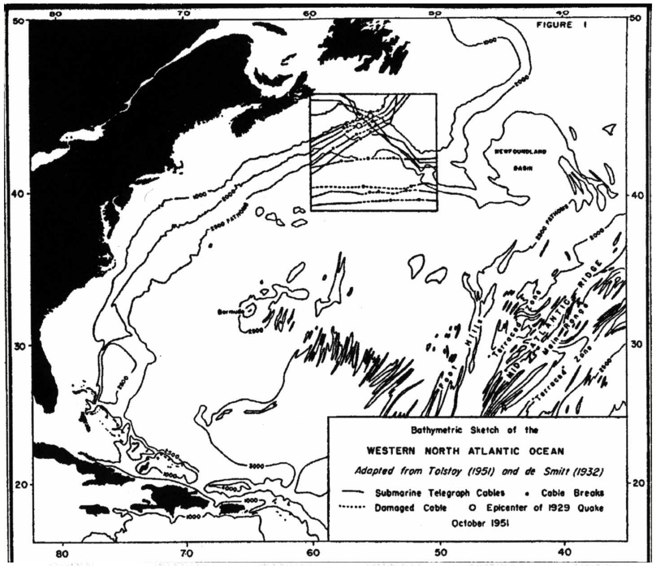
[*La Rocca et al.*, 2004]

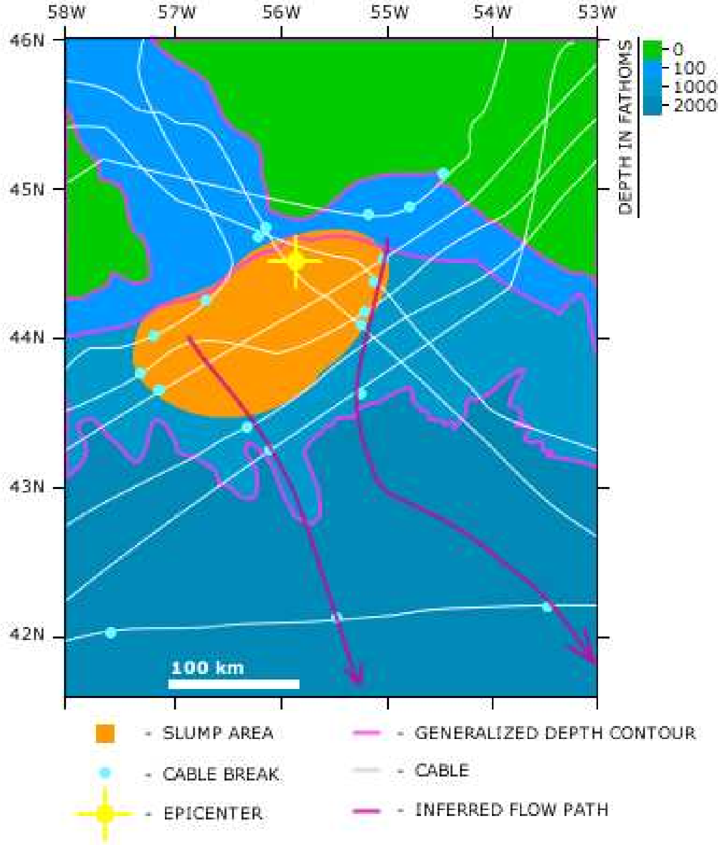


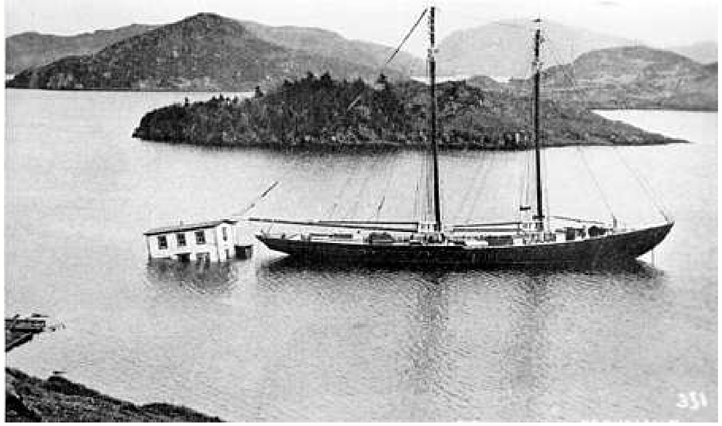


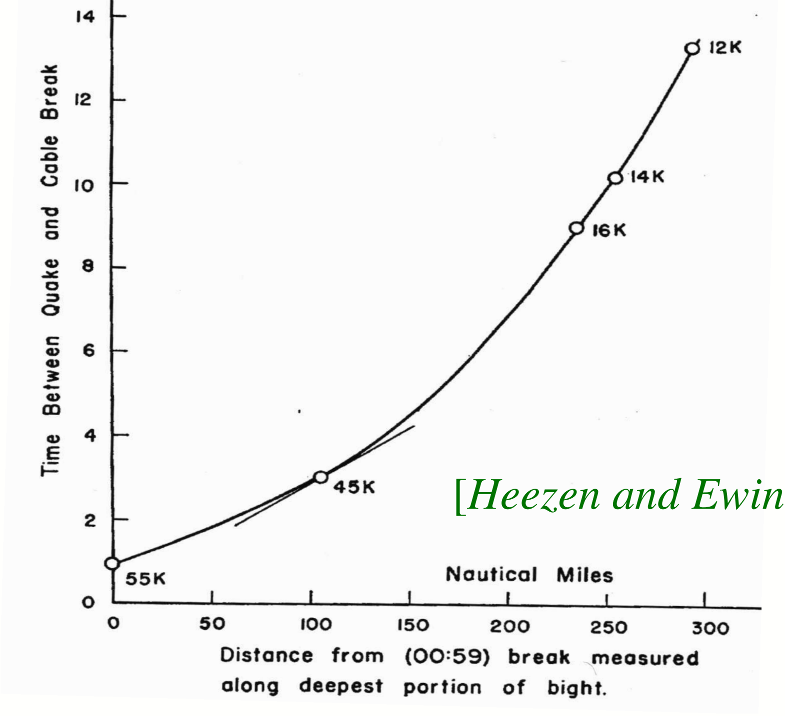
NEWFOUNDLAND — 18 NOVEMBER 1929

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.

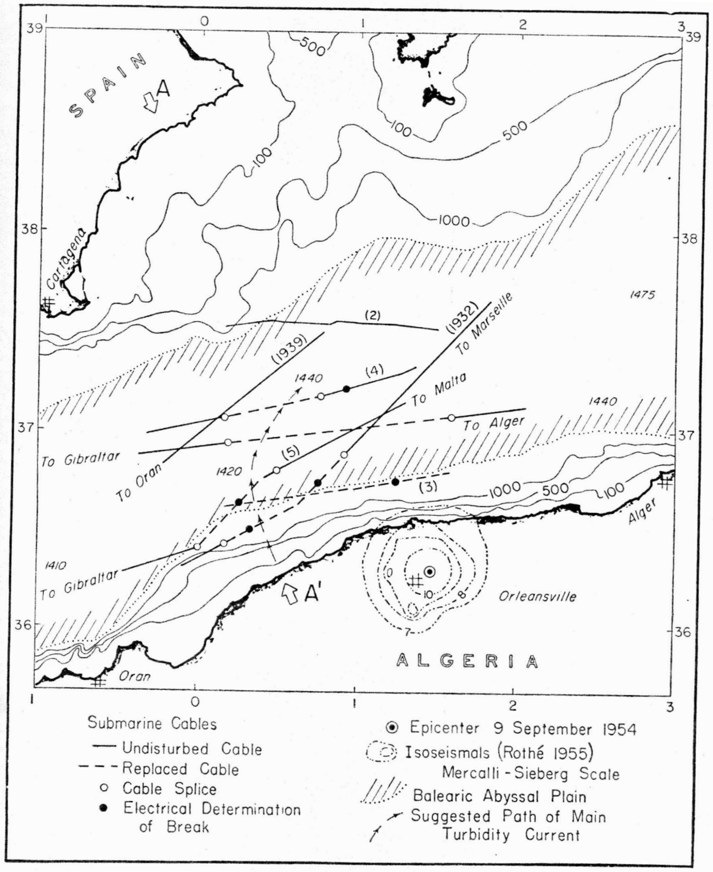


FIG. 2.—Map showing locations of Orléansville earthquake, path of main turbidity current, and submarine cables. Depths in fathoms.

2512 BRUCE C. HEEZEN AND MAURICE EWING

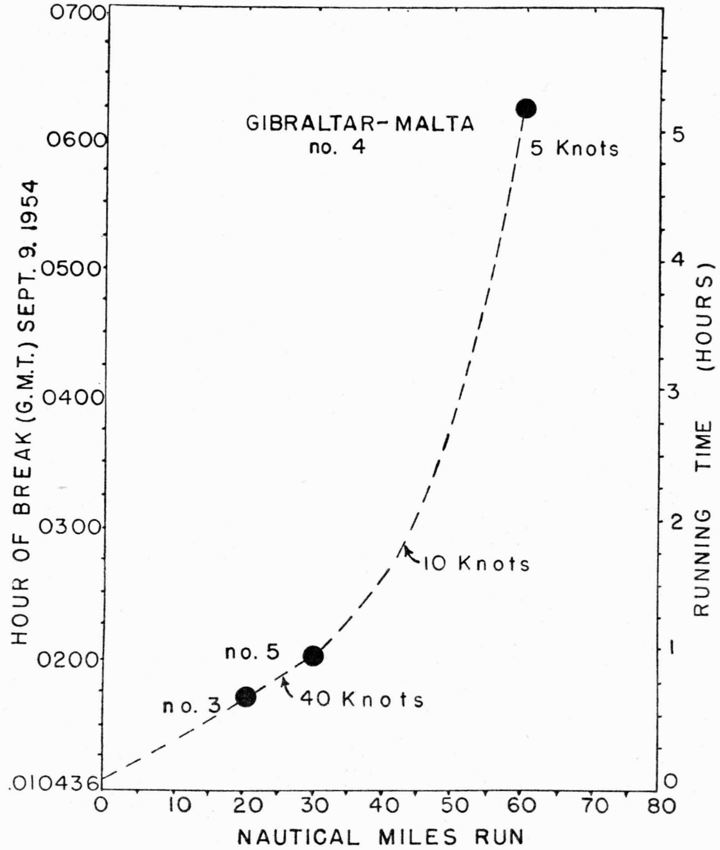


FIG. 4.—Curve showing velocities of Orléansville earthquake.

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]

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)

SUBSEQUENT TSUNAMIS (ctd.)

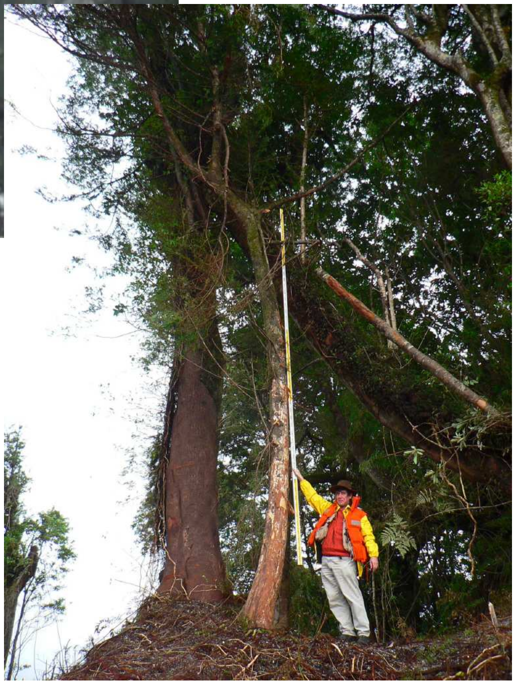
Fjord Aysen, Chile **3 dead**
21 April 2007 **10 missing**

A crossover between
Fatu-Hiva and Lituya Bay

Isla Mendirosa

Punta Tortuga

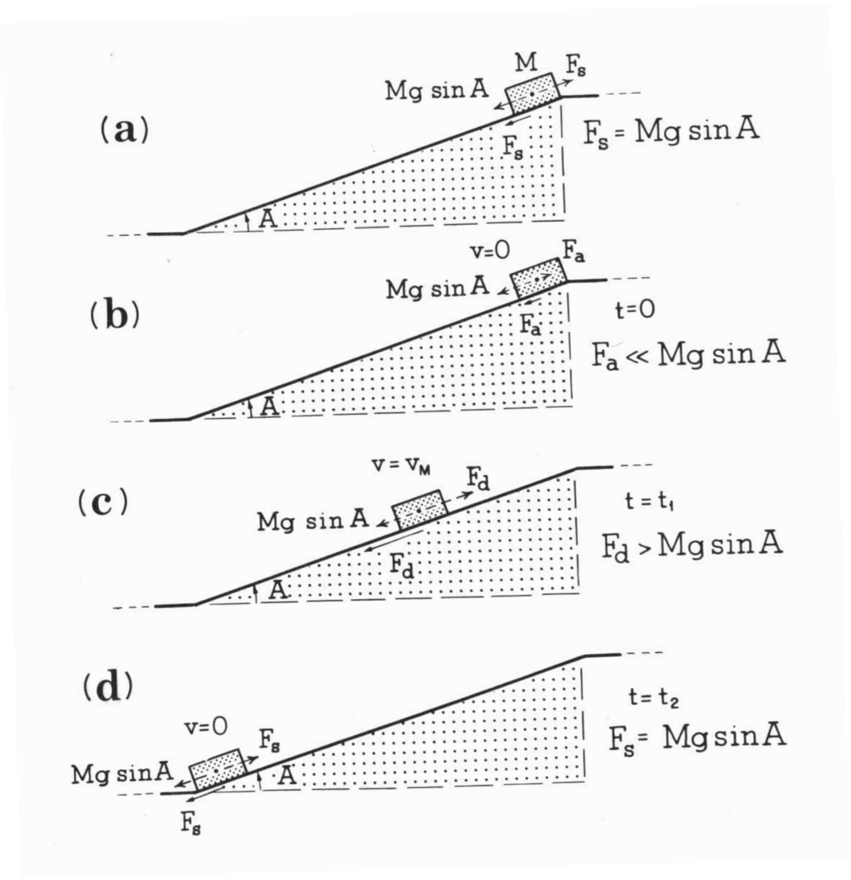
Islote Umbral:
Washed over by tsunami;
Flow depth = 14 m



PHYSICAL REPRESENTATION of LANDSLIDE

- Landslide modeled as *SINGLE FORCE* representing reaction by Earth to acceleration of sliding body.

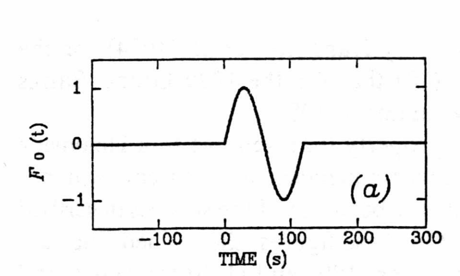
  [*Hasegawa and Kanamori,* 1987]

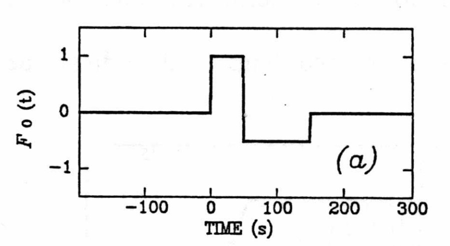


* Always nearly horizontal

* Zero impulse condition on Earth requires

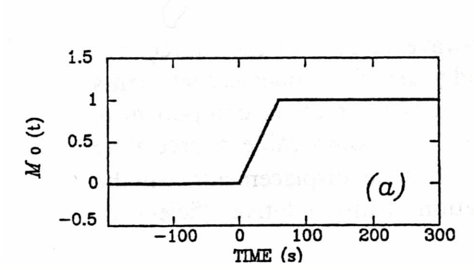
$$\int_{-\infty}^{+\infty} F(t) \cdot dt \;=\; 0$$





* Contrast with Seismic Moment for earthquake source

$$M(t) \;=\; \mu\, S\, \Delta u(t) \;\underset{t\to\infty}{\approx}\; M_0 \cdot H(t)$$



COMPARISON OF SPECTRAL AMPLITUDES

(Rayleigh and Tsunami)

Landslide excitation, [$\mathbf{f} \cdot \mathbf{u}$], proportional to *displacement,*
should be *INTEGRAL* of
Earthquake excitation, [$\boldsymbol{M} : \boldsymbol{\varepsilon}$], proportional to *strain.*

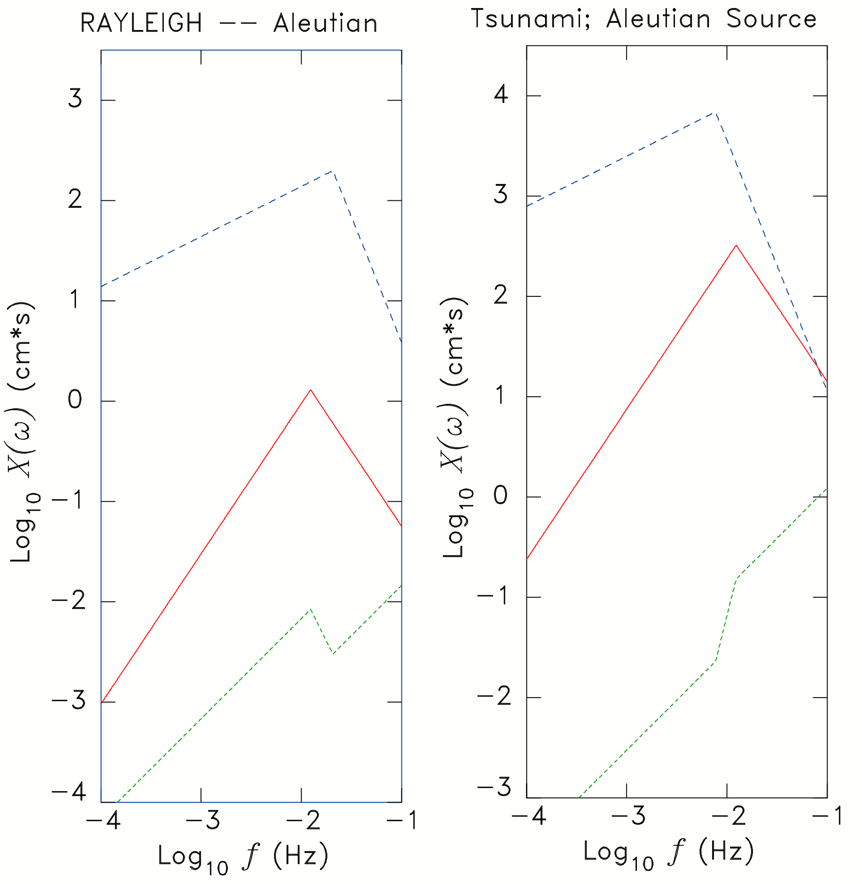
→ **BUT,** Source Time Function of Landslide is

SECOND DERIVATIVE of Earthquake Counterpart.

→ **Excitation by LANDSLIDE (SINGLE -FORCE)**
is DERIVATIVE of that by
EARTHQUAKE (DOUBLE-COUPLE).

EARTHQUAKE **LANDSLIDE**

RATIO



Note:

- Landslide Excitation Deficient by 1.5 orders of magnitude
- Landslide tsunami is Higher-Frequency,

HENCE DISPERSIVE

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.

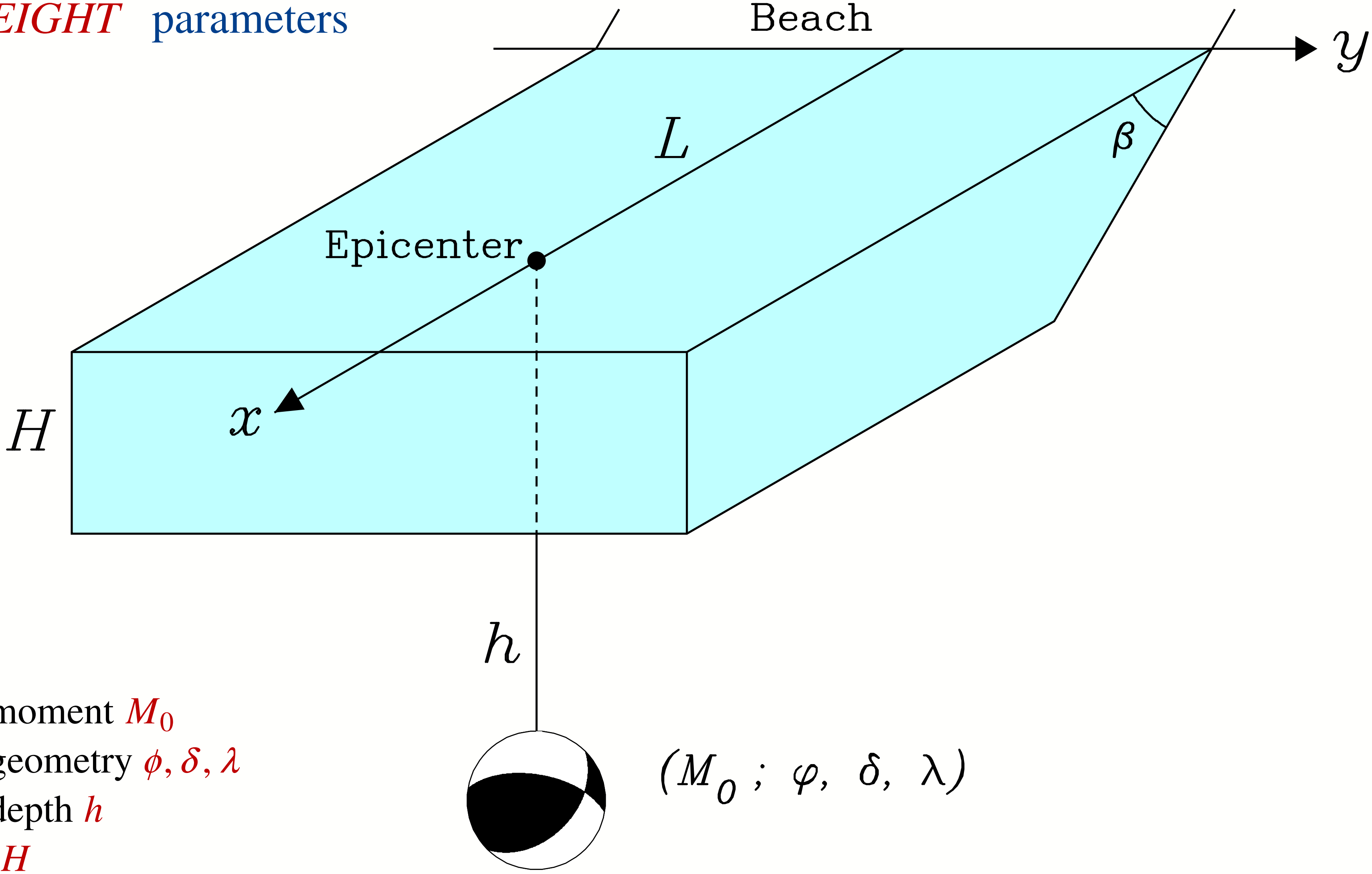
- For dislocations, the latter should be expected to be constant, as it reflects the strength of the rock.

But for landslides, it could be much larger.

We hint that b/a should be an *INVARIANT* for seismic dislocations, 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

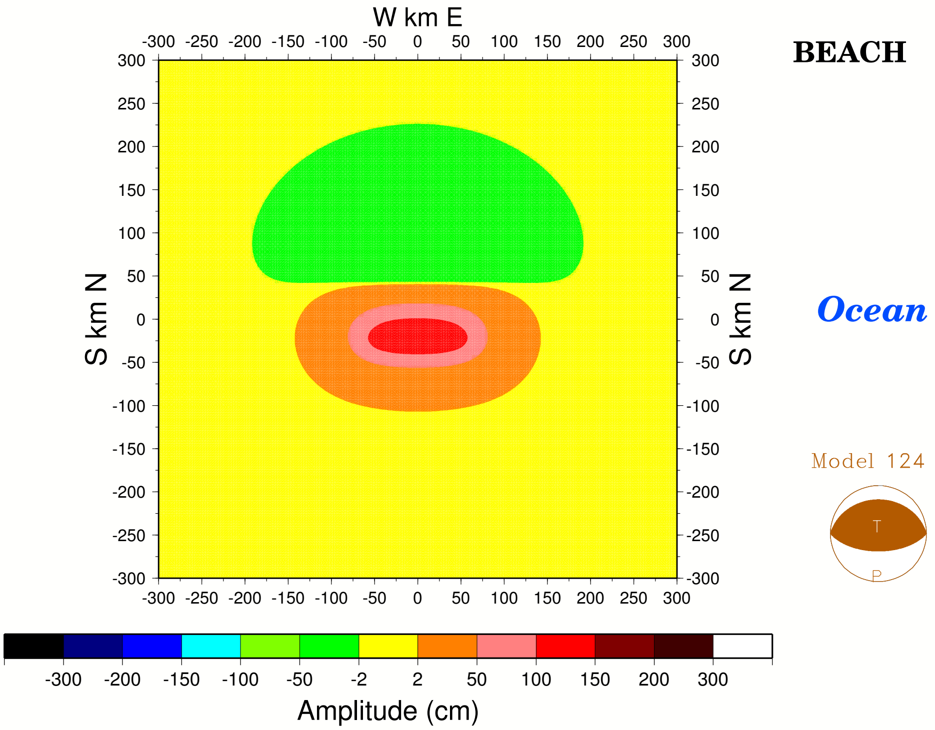
Water depth H

Epicentral distance to shore L

Beach slope β

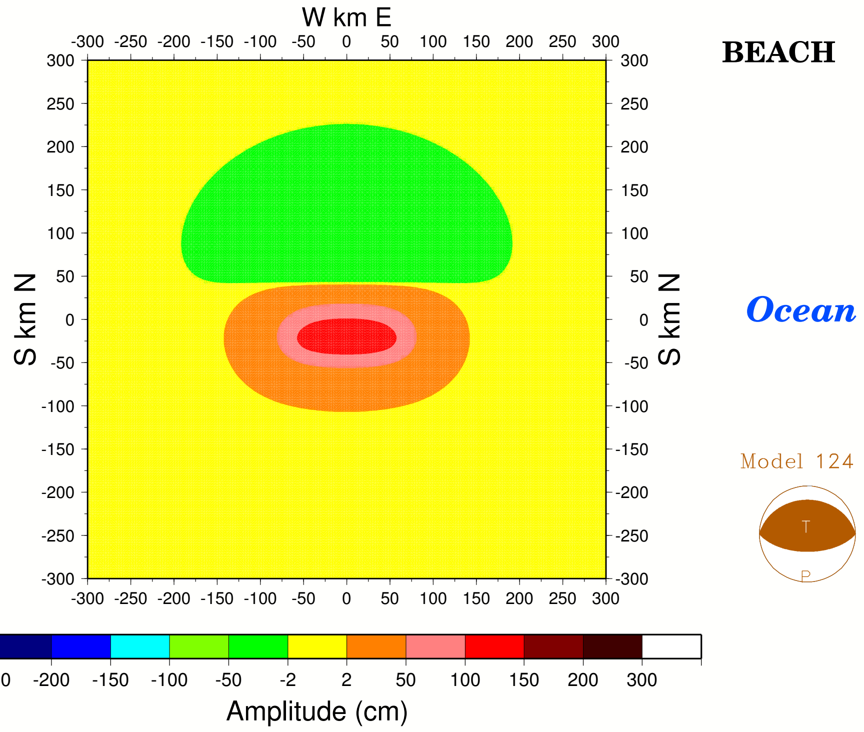
NEAR-FIELD: *The Earthquake Dislocation*

- Compute Ocean-Bottom Deformation due to Dislocation

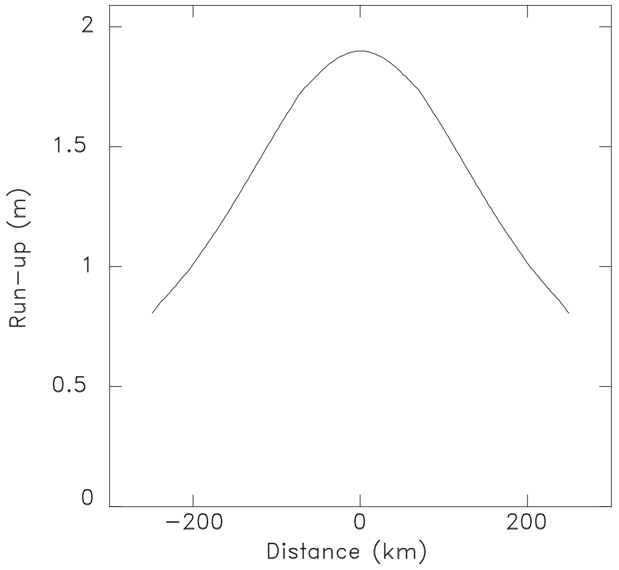


NEAR-FIELD: *The Earthquake Dislocation*

- Compute Ocean-Bottom Deformation due to Dislocation

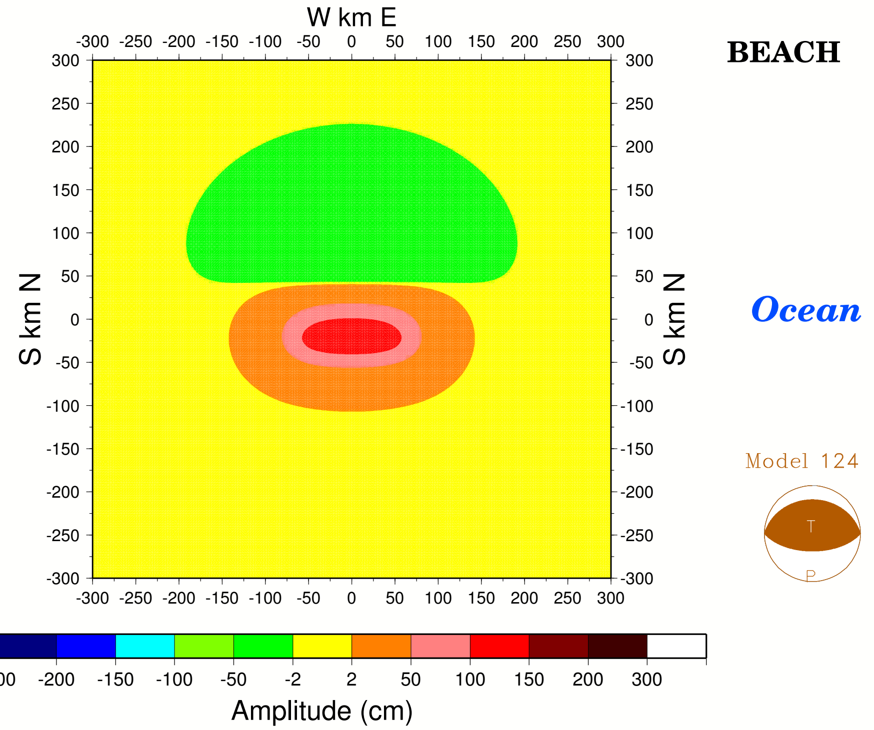


- Simulate Tsunami Propagation to Beach and Run-up



NEAR-FIELD: *The Earthquake Dislocation*

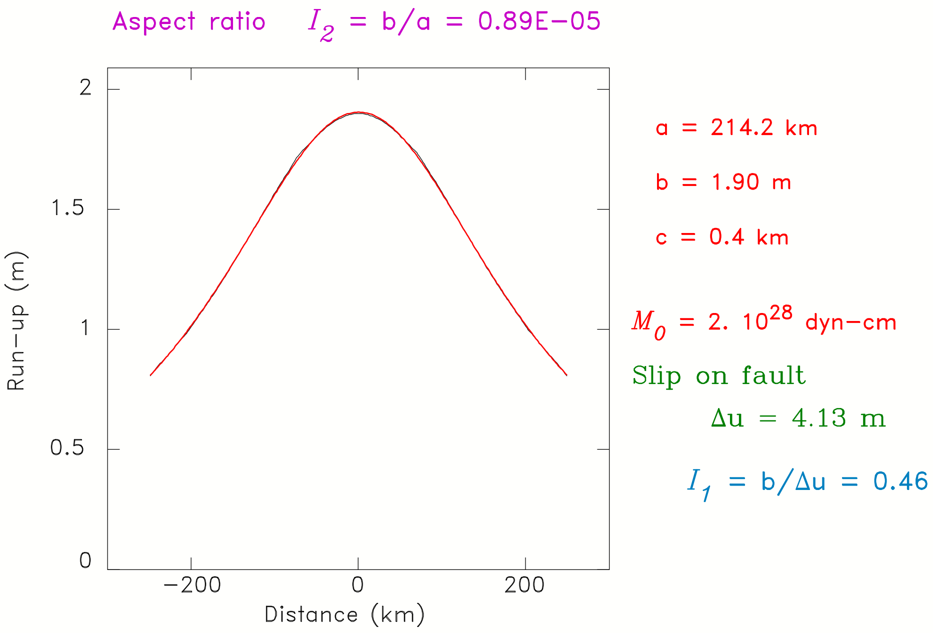
- Compute Ocean-Bottom Deformation due to Dislocation



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

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

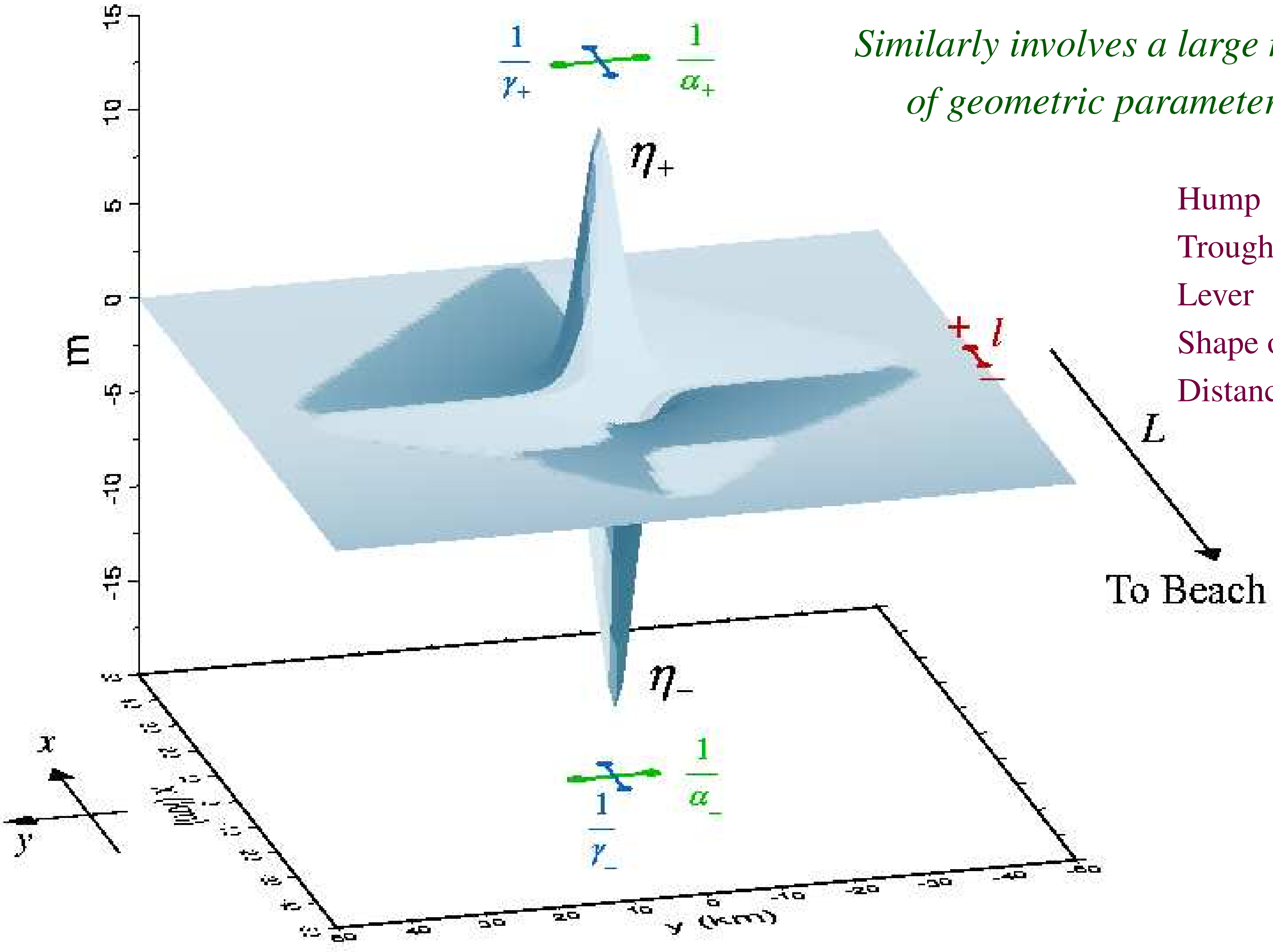


- Retain aspect ratio $I = b/a$

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

THE DIPOLAR SOURCE

Similarly involves a large number
of geometric parameters

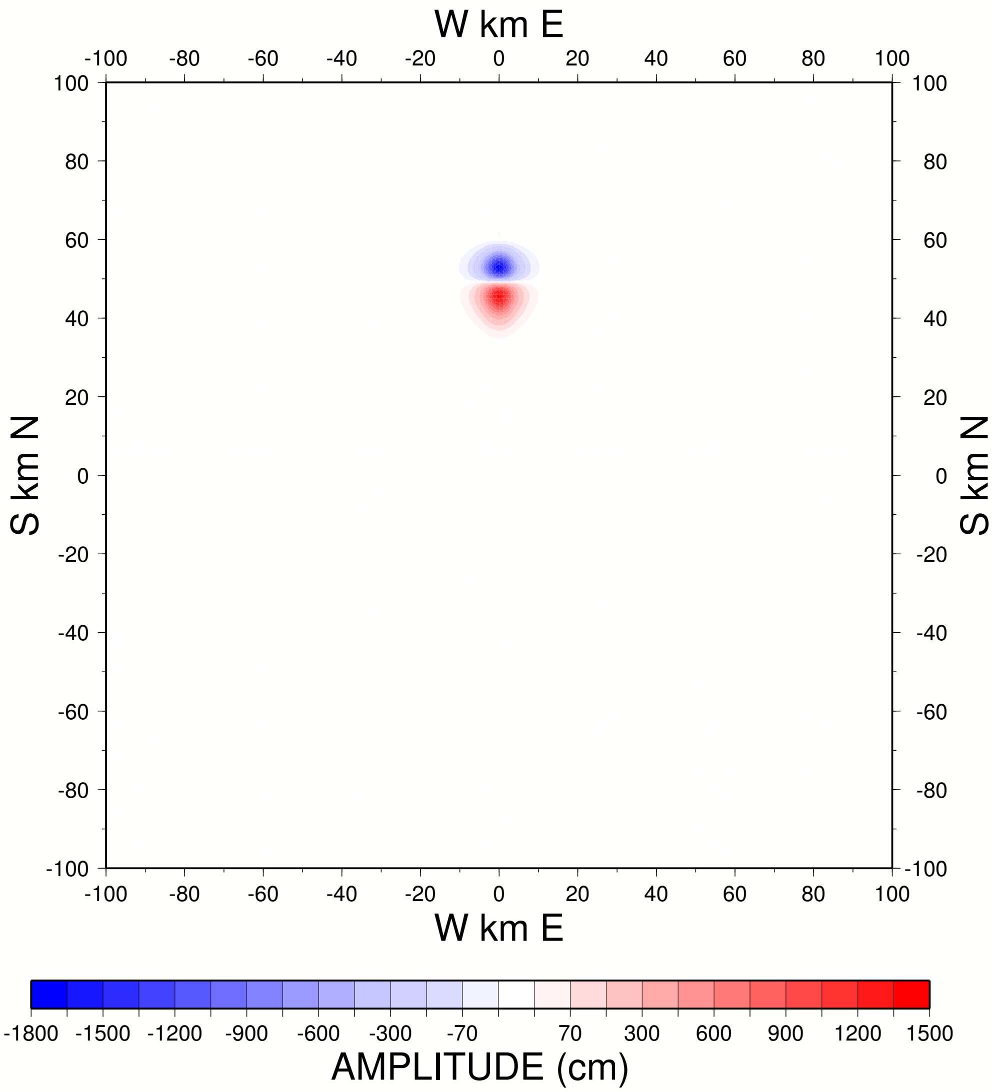


Hump
Trough
Lever
Shape of poles
Distance to Beach...

[*Okal and Synolakis*, 2004]

NEAR-FIELD: *The Landslide Source*

- Compute Ocean-Surface Deformation due to Landslide



BEACH

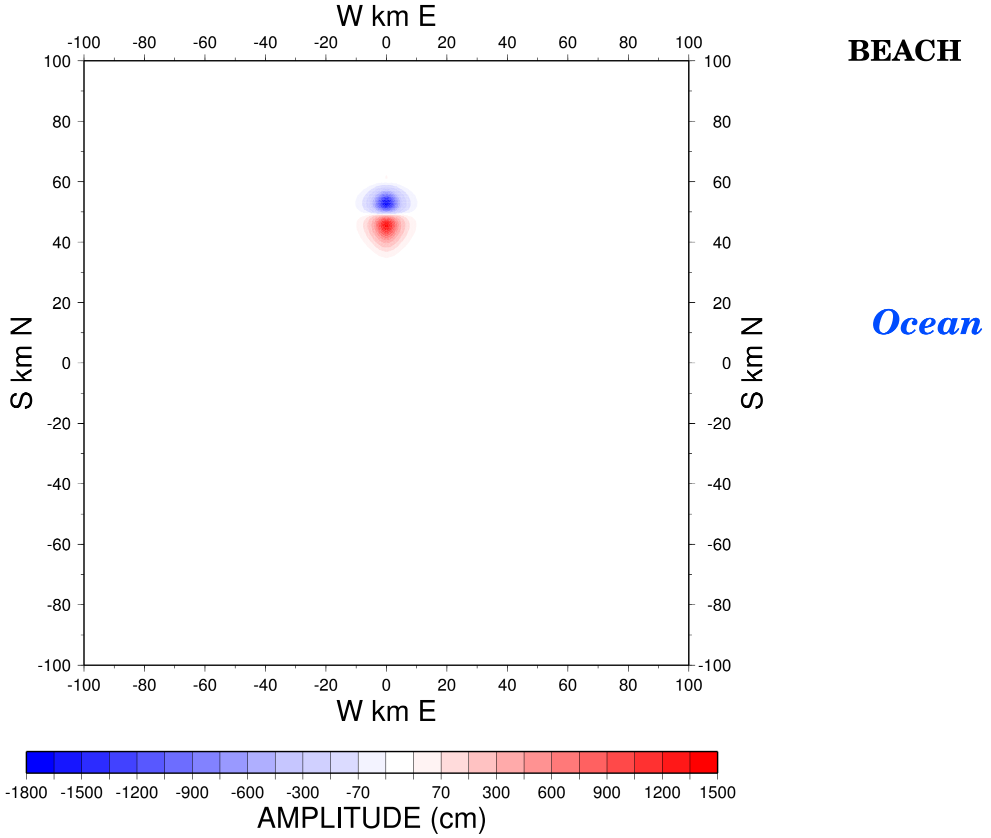
Ocean

NOTE: *Much LARGER Displacements*

Much SMALLER Source Size

NEAR-FIELD: *The Landslide Source*

- Compute Ocean-Surface Deformation due to Landslide

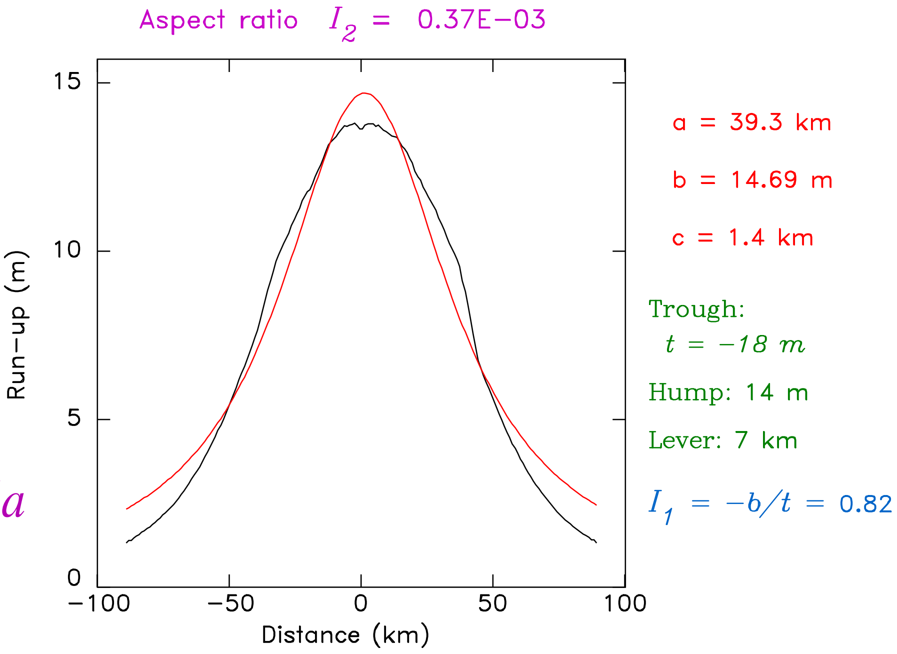


- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

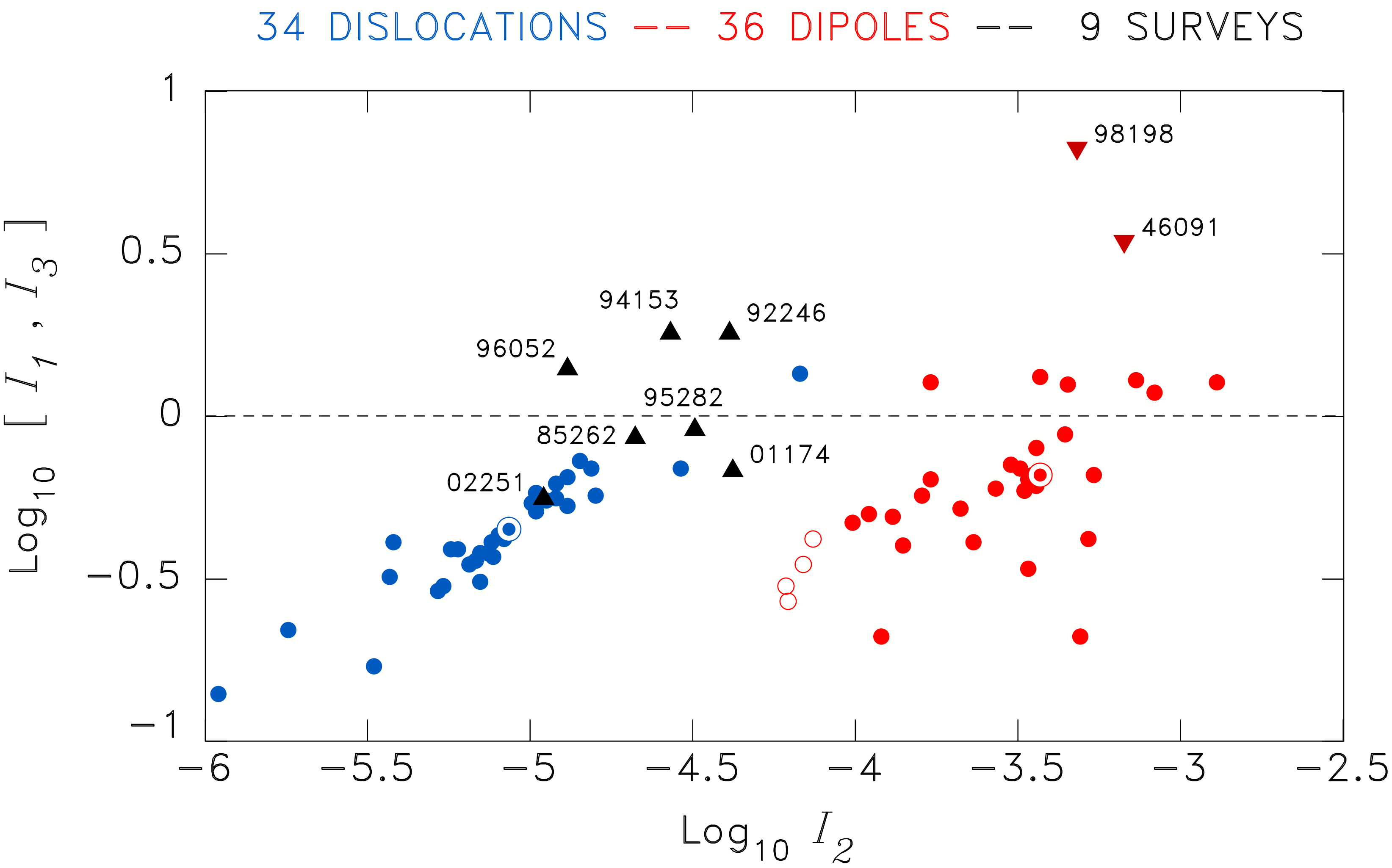
$$\zeta = \frac{b}{\left(\frac{x-c}{a}\right)^2 + 1}$$

- Retain aspect ratio $I = b/a$



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

$I = b/a$ CAN SERVE AS DISCRIMINANT



MAX. RUN-UP SCALED TO FAULT SLIP

MAX. RUN-UP SCALED TO INITIAL TROUGH

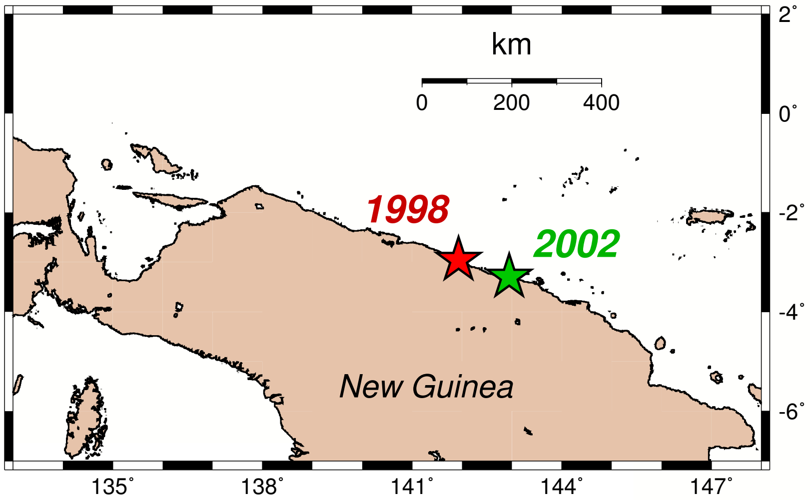
ASPECT RATIO OF RUN-UP DISTRIBUTION ALONG BEACH

[*Okal and Synolakis*, 2004]

PAPUA NEW GUINEA: A TALE of TWO EARTHQUAKES

- 08 SEP 2002: Regular Earthquake, A.R. = 2.6×10^{-5}

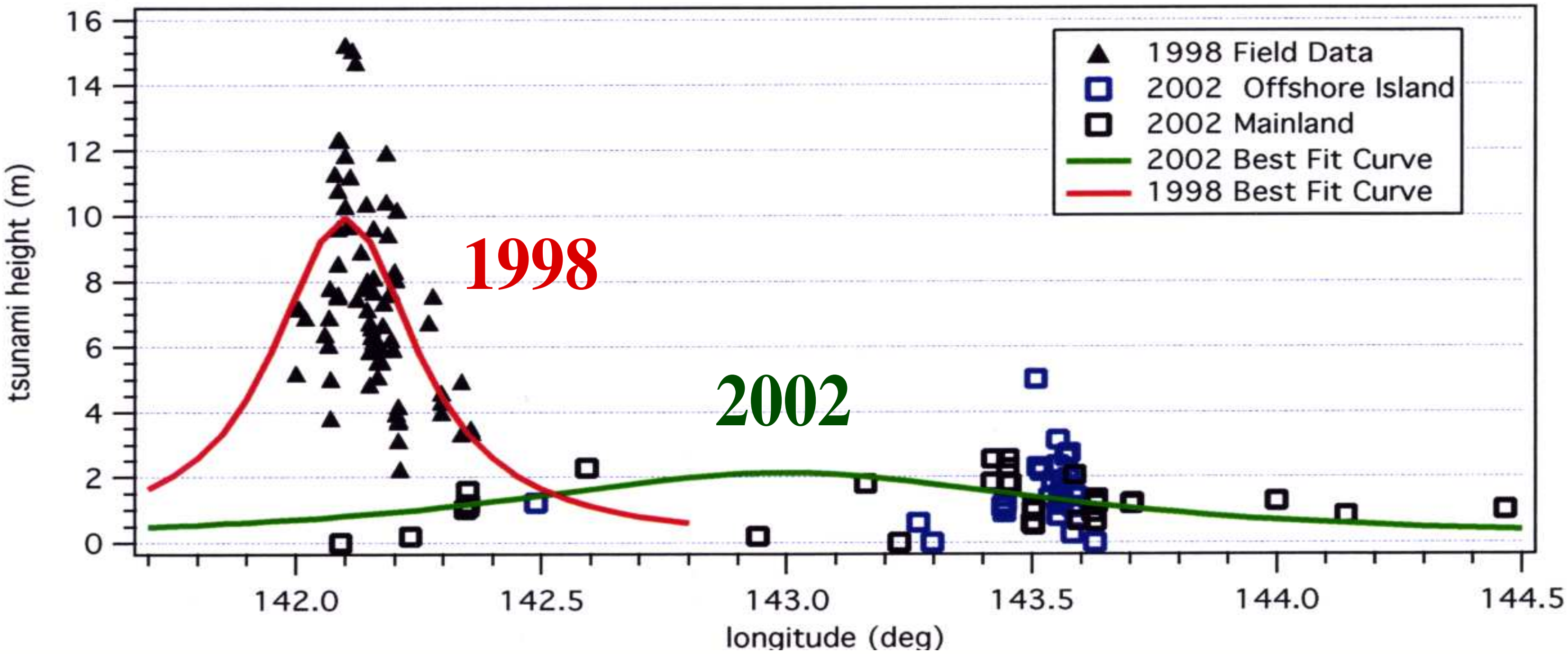
  No tsunami deaths.



- 17 JUL 1998: Landslide Tsunami,

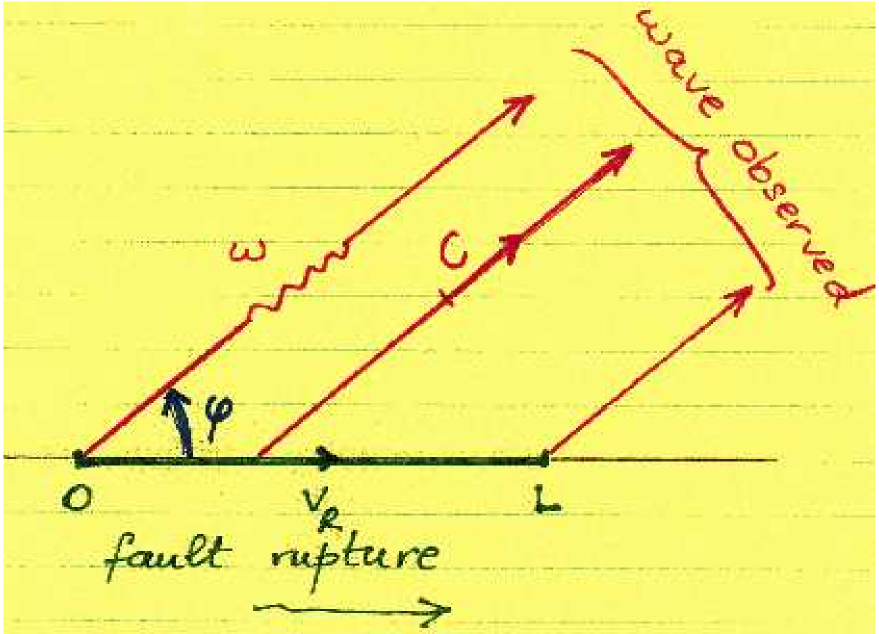
  A.R. = 4.8×10^{-4}

  2200 Tsunami Deaths



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*

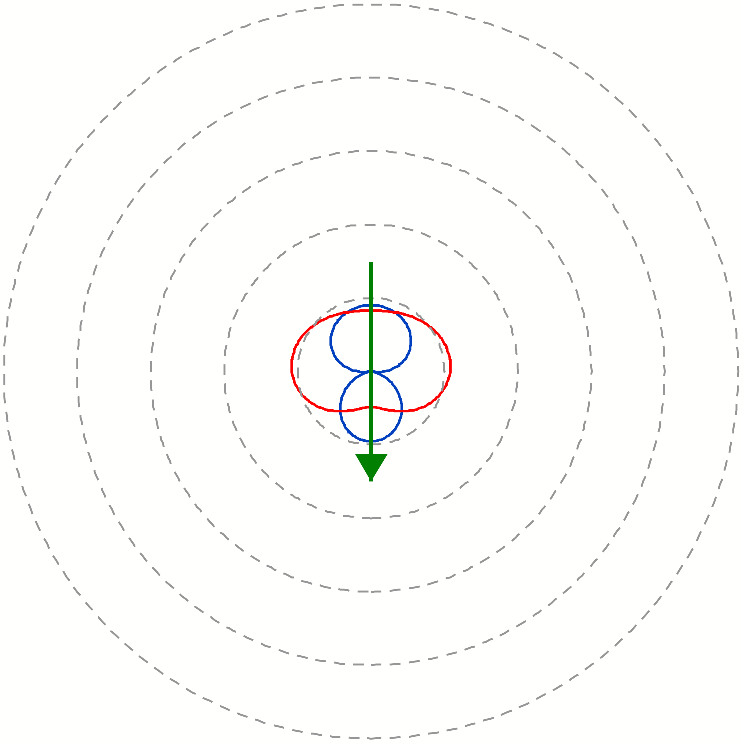
($\sin Y / Y$ maximum requires $Y = 0$.)

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

- *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

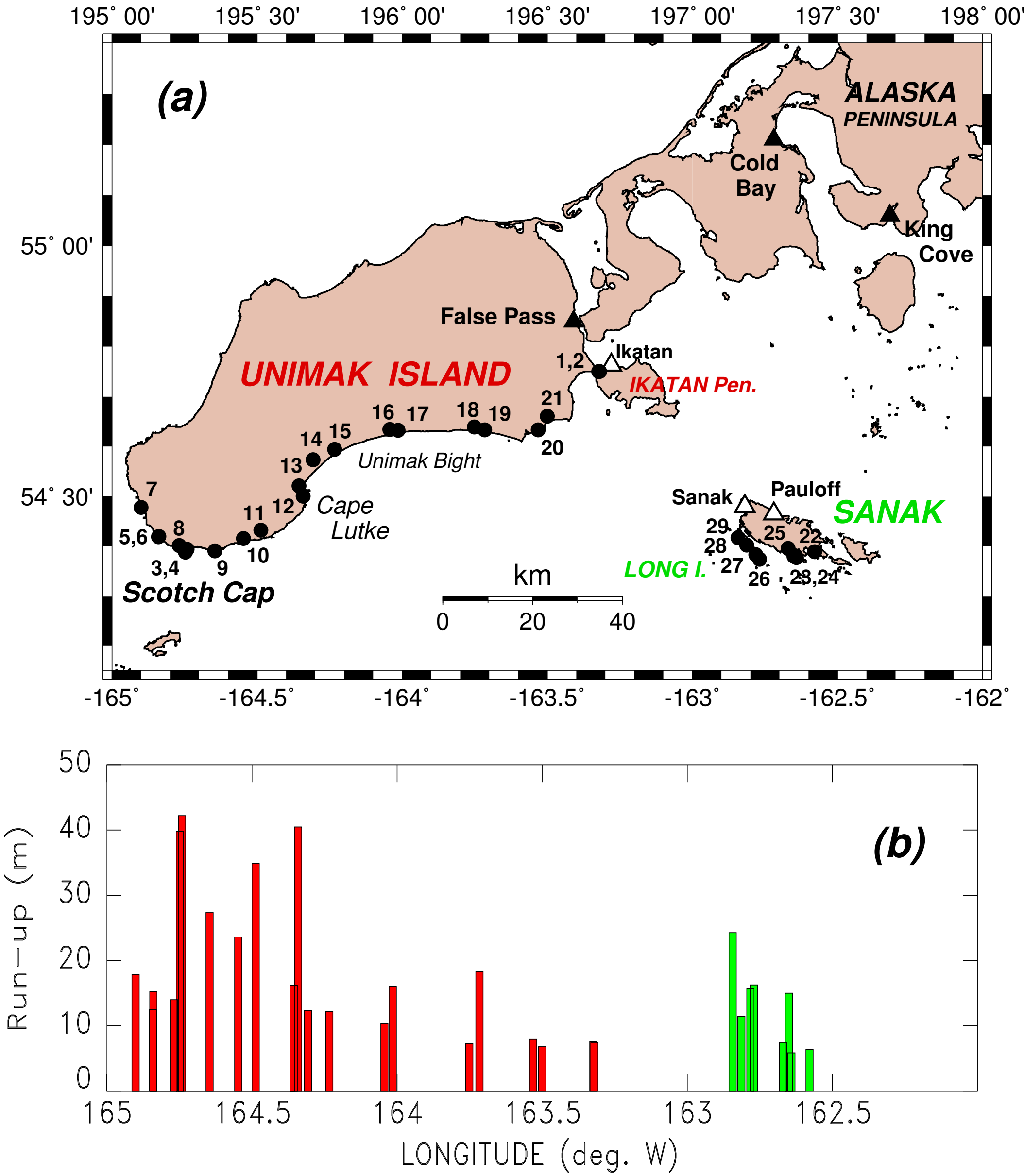


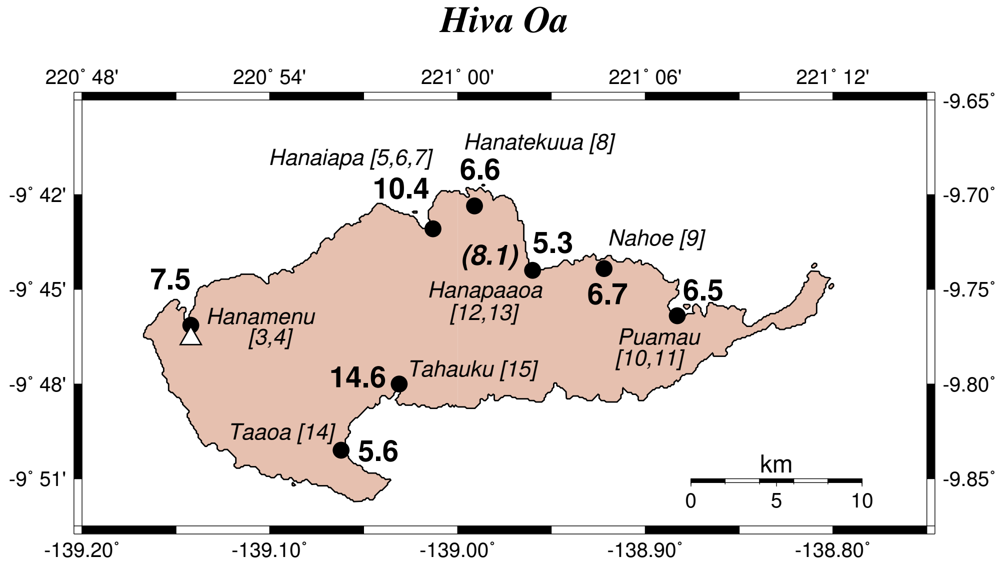
The rupture is so slow (w/r respect to the wave) that there are no directions in which it can be compensated by the variations of phase due to propagation.

LANDSLIDES CANNOT GENERATE FAR-FIELD DIRECTIVITY

7. RESULTS: The PRODUCTS

- *1946 Aleutian tsunami:* In the far field, we interviewed close to 100 witnesses (aged 59 to 89 at the time of the interview) and have compiled a dataset of more than 60 locations in the Marquesas Islands, Easter, Juan Fernández, the Austral Islands and Pitcairn. For each island, we have produced standard maps of run-up values.
- In the near field, we interviewed five witnesses on the islands of Unimak and Sanak and compiled a 29–location database.

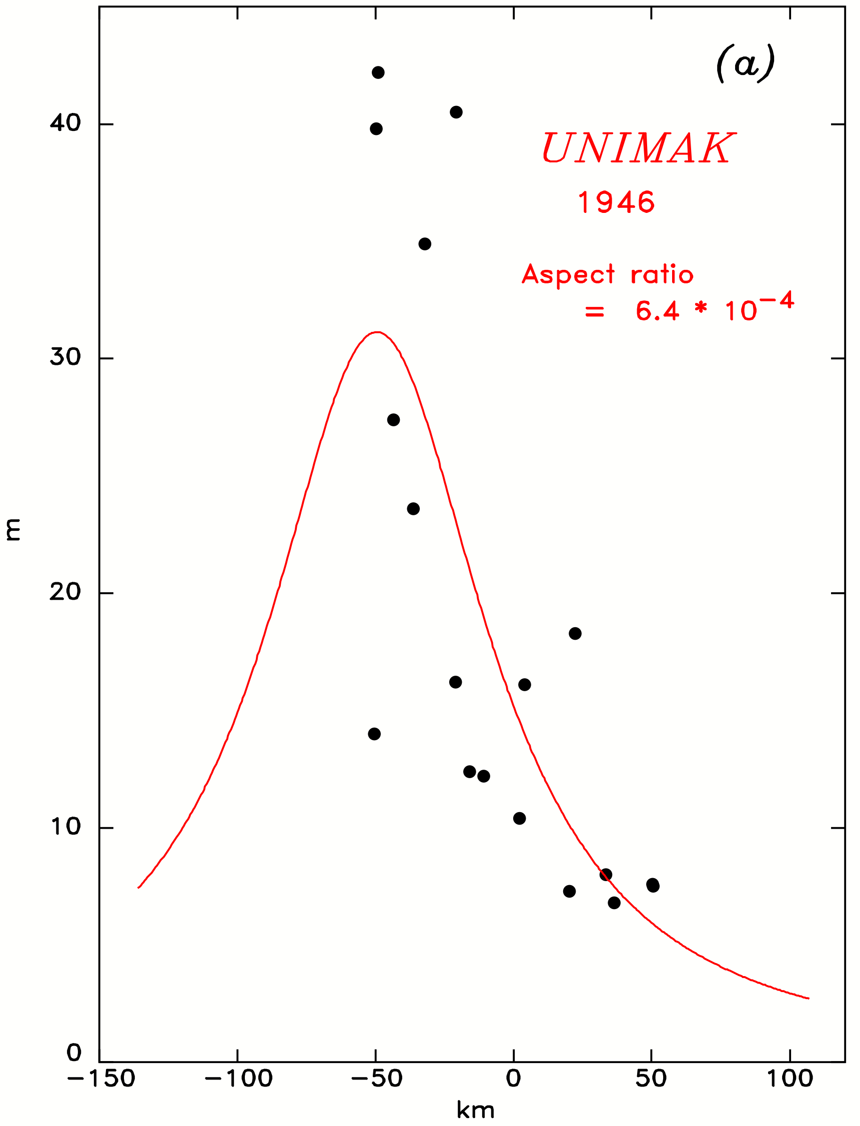


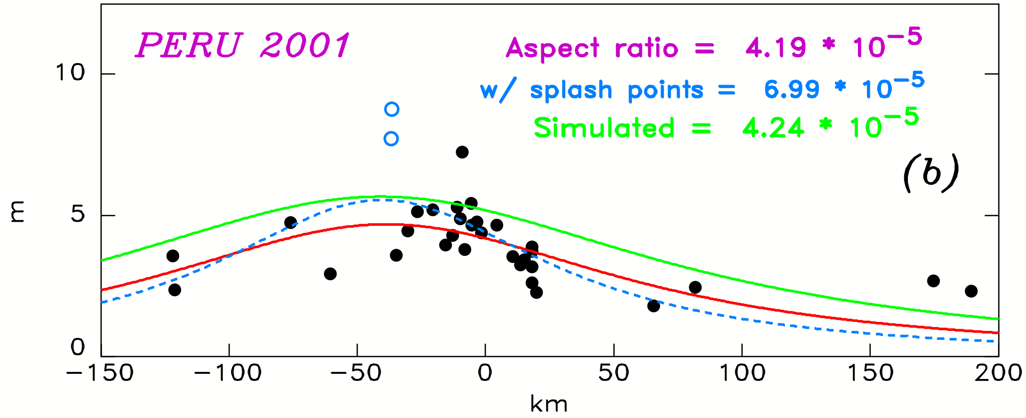


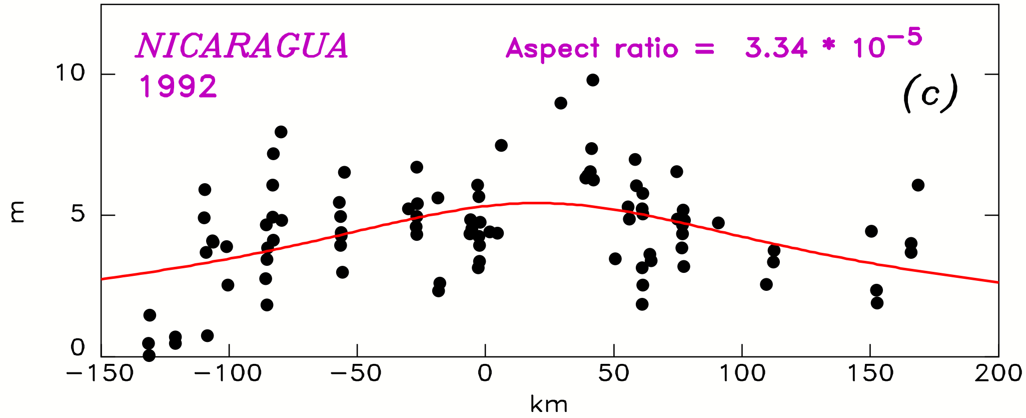
1946 NEAR FIELD

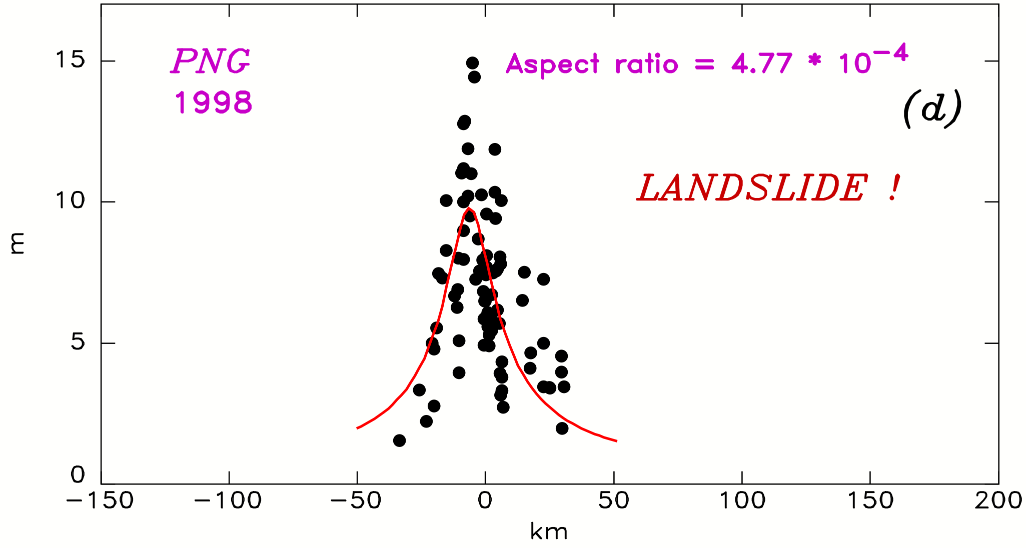
Near-field *Aspect Ratio* of Run-up Distribution at Unimak (6.4×10^{-4}) even larger than for PNG-1998, thus

REQUIRING LANDSLIDE SOURCE

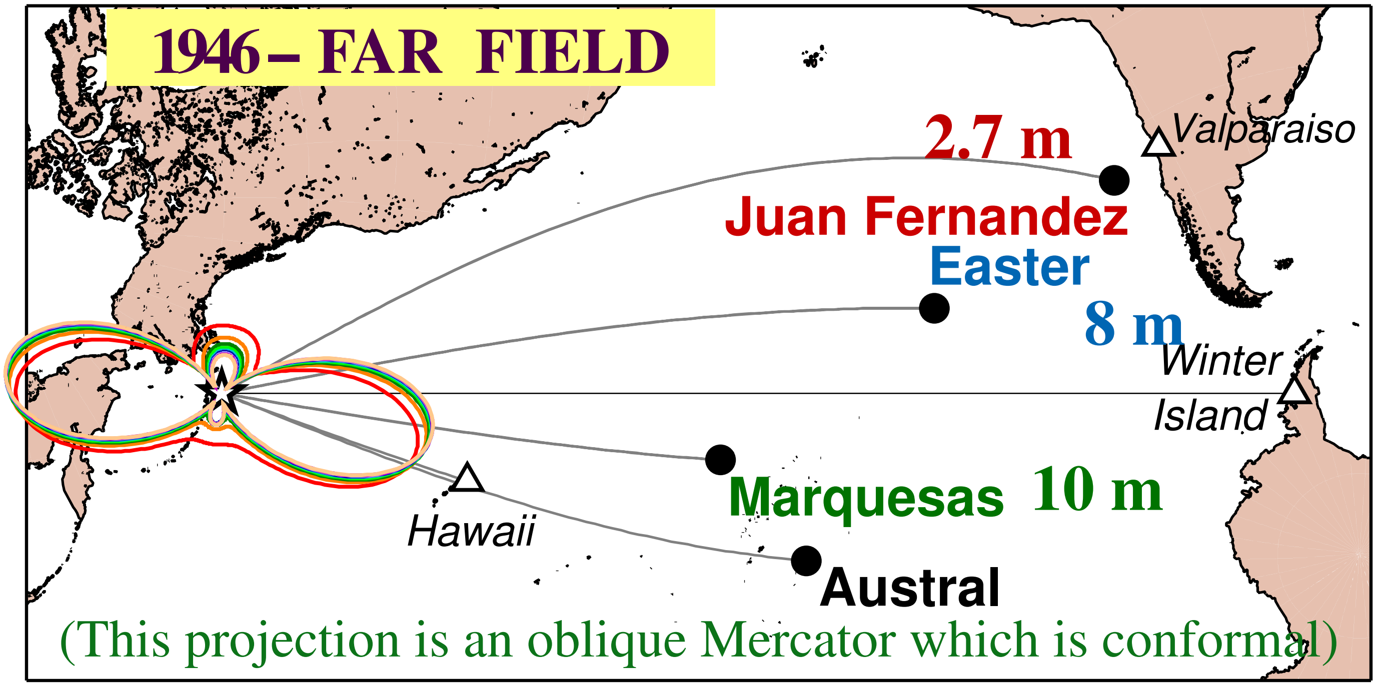








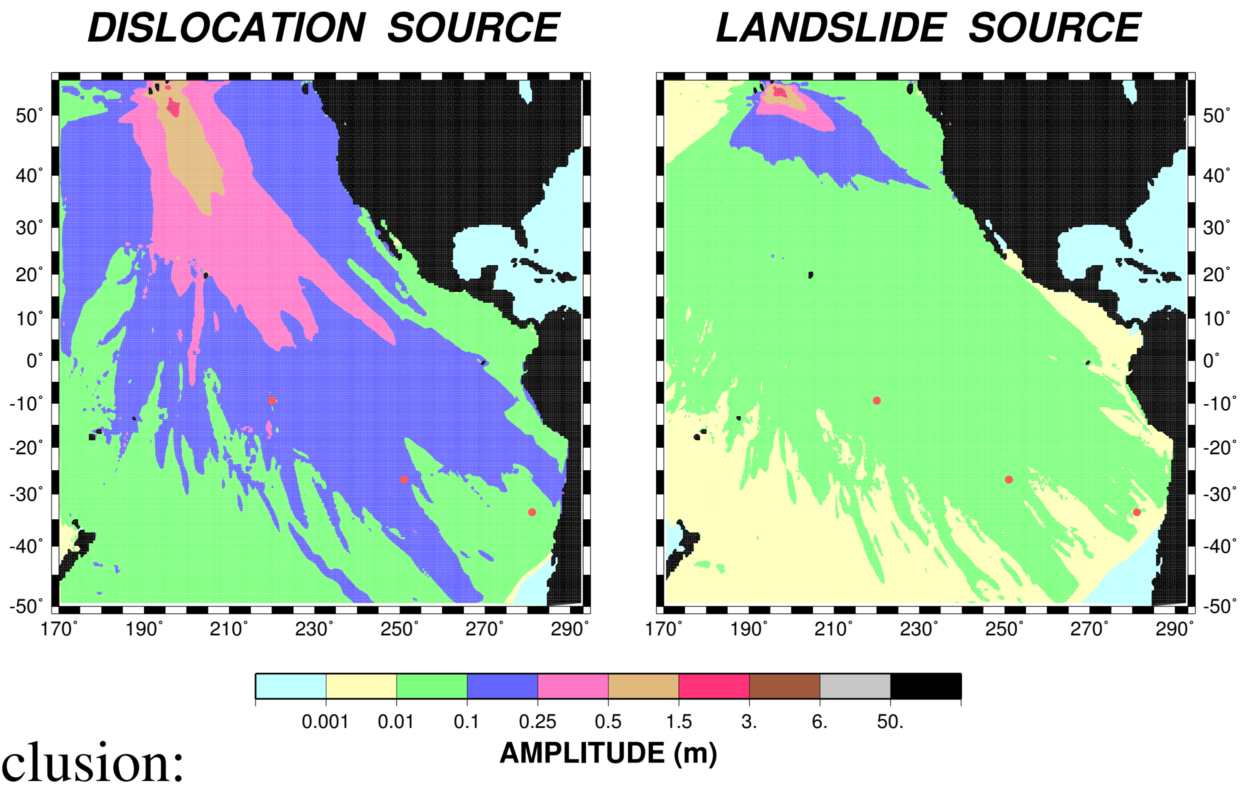
1946 – FAR FIELD



(This projection is an oblique Mercator which is conformal)

The directivity pattern is consistent with the theoretical radiation pattern expected from an earthquake source extending along the Aleutian Trench, in the geometry suggested by an independent reassessment of the earthquake's source extent.

LANDSLIDE SOURCES CANNOT REPLICATE THIS STRONG DIRECTIVITY



Conclusion:

The far-field results require a strong earthquake source.

PRELIMINARY CONCLUSION of 1946 SURVEYS

- The exceptional amplitudes in the near field (42 m) require generation by an underwater landslide.
- The far-field dataset features both amplitude and directivity requiring generation by a large seismic dislocation.

→ Numerical simulations adequately predict most observables using acceptable parameters for both sources.

U.S. COAST GUARD
MEMORIAL

NEAR THIS SITE SCOTCH
CAP LIGHT STATION WAS
DESTROYED BY A SEISMIC
SEA WAVE ON 1 APRIL 1946

THIS TABLET IS IN MEMORY OF:
ANTHONY LAURENCE PETIT
JACK COLVIN
PAUL JAMES NESS
DEWEY DYKSTRA
LEONARD PICKERING
WHO LOST THEIR LIVES IN THIS
DISASTER WHILE SERVING THEIR
COUNTRY.