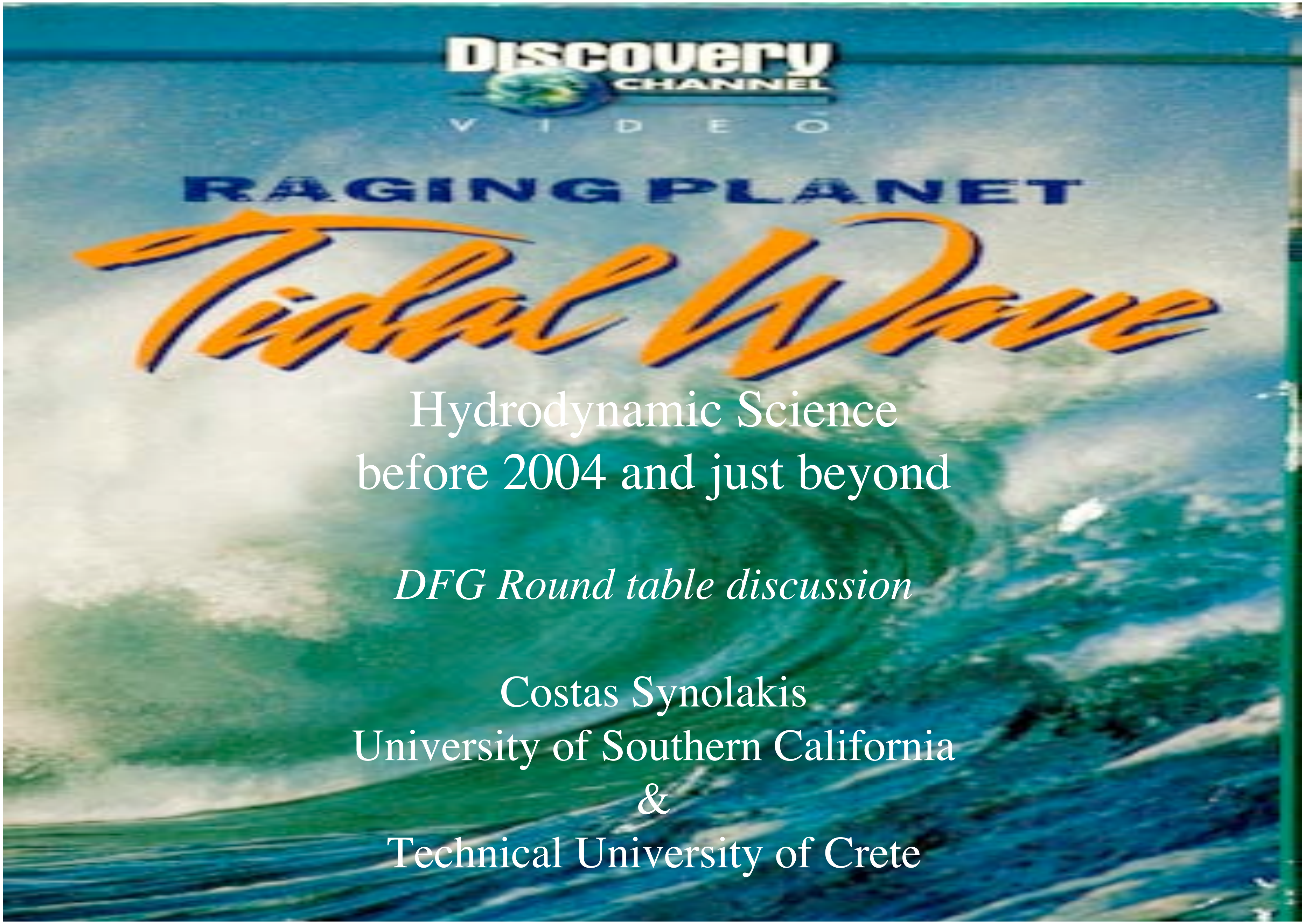


Hydrodynamic Science before 2004 and just beyond

DFG Round table discussion

Costas Synolakis
University of Southern California
&
Technical University of Crete

The challenges in tsunami hydrodynamics are greater (?)

Once the seafloor displacement is known, the tsunami evolution can -in principle- be deterministically calculated and the tsunami inundation forecast. Tsunami forces still present a challenge.

Uncertainty arises in the seafloor-fluid interaction and the lack of statistics - before the 1990s no measuring instruments existed - before 2003 (when the first real time tsunamograph recording was acquired), tsunami science stood where seismology was before Charles Richter.

Despite advances in modeling in the past decade, we still rely on worst case scenario studies for tsunami hazard assessment.

When all is said and done, the rate limiting steps are in small details.

Milestones in tsunami hydrodynamics in the last 30 years

The solitary wave (as model of the initial tsunami wave) paradigm-70s.

The runup algorithm to calculate wave inundation-80s.

Nicaragua 1992 and then one tsunami per year in the Pacific.

The N-wave (new leading wave model) -90s.

First validated 2+1D inundation models - 90s.

The landslide tsunami wave-90s.

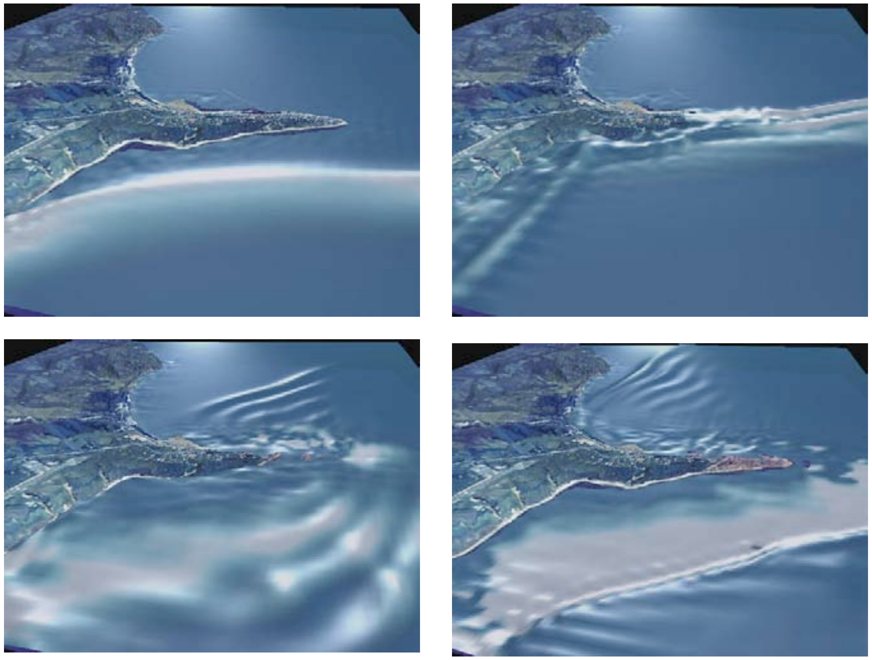
The first real time tsunami forecast based on a tsunamograph-2003

Next generation validated 2+1 & 3+1 inundation models - 21st century.

The effect of "small scale" features, islands, tsunami forces, now.

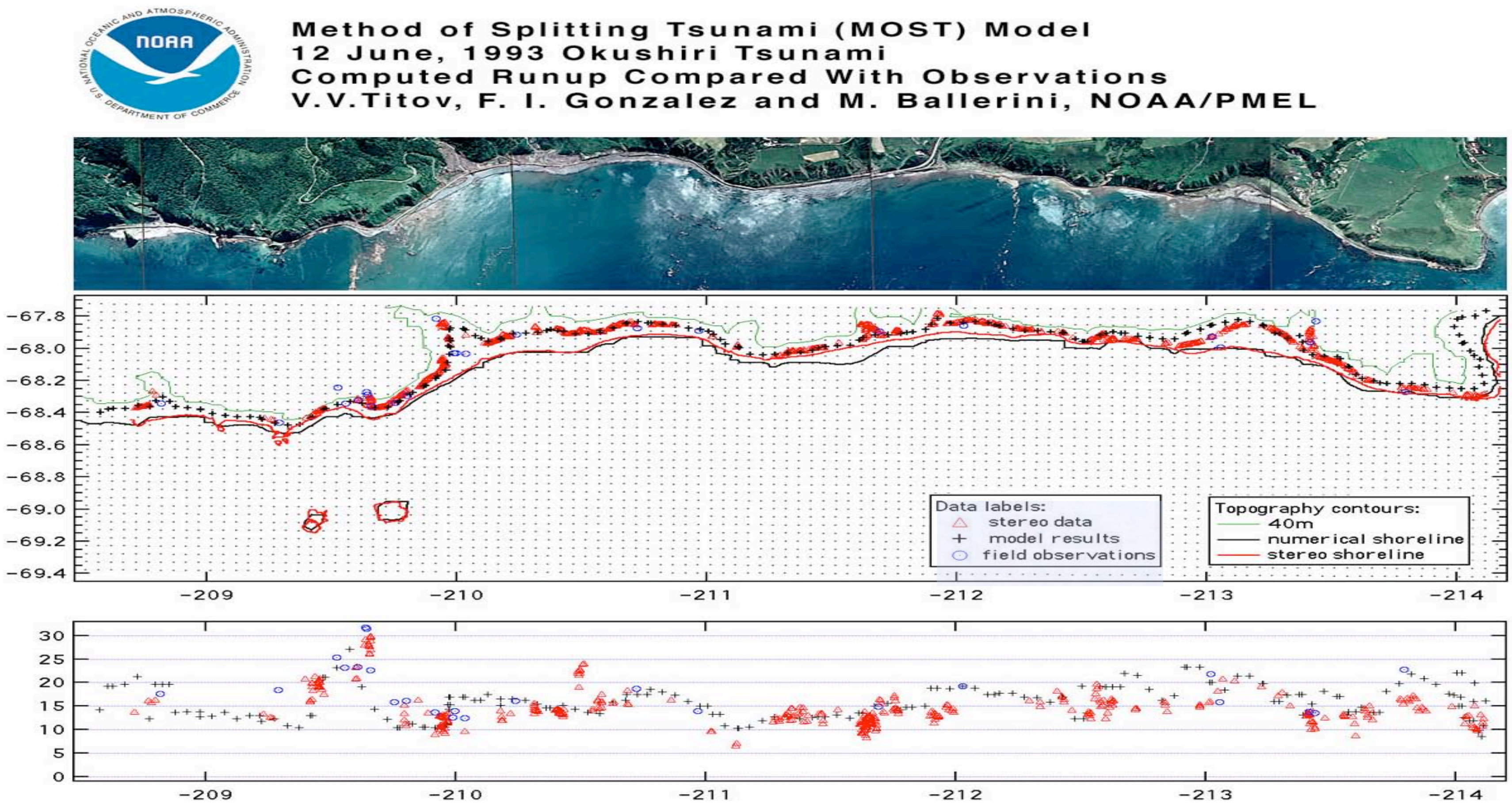
Okushiri, Japan 1993

Damage in Aonae, during the 1993 tsunami. *Notice the overland flow in the animation stills from MOST on the right.*



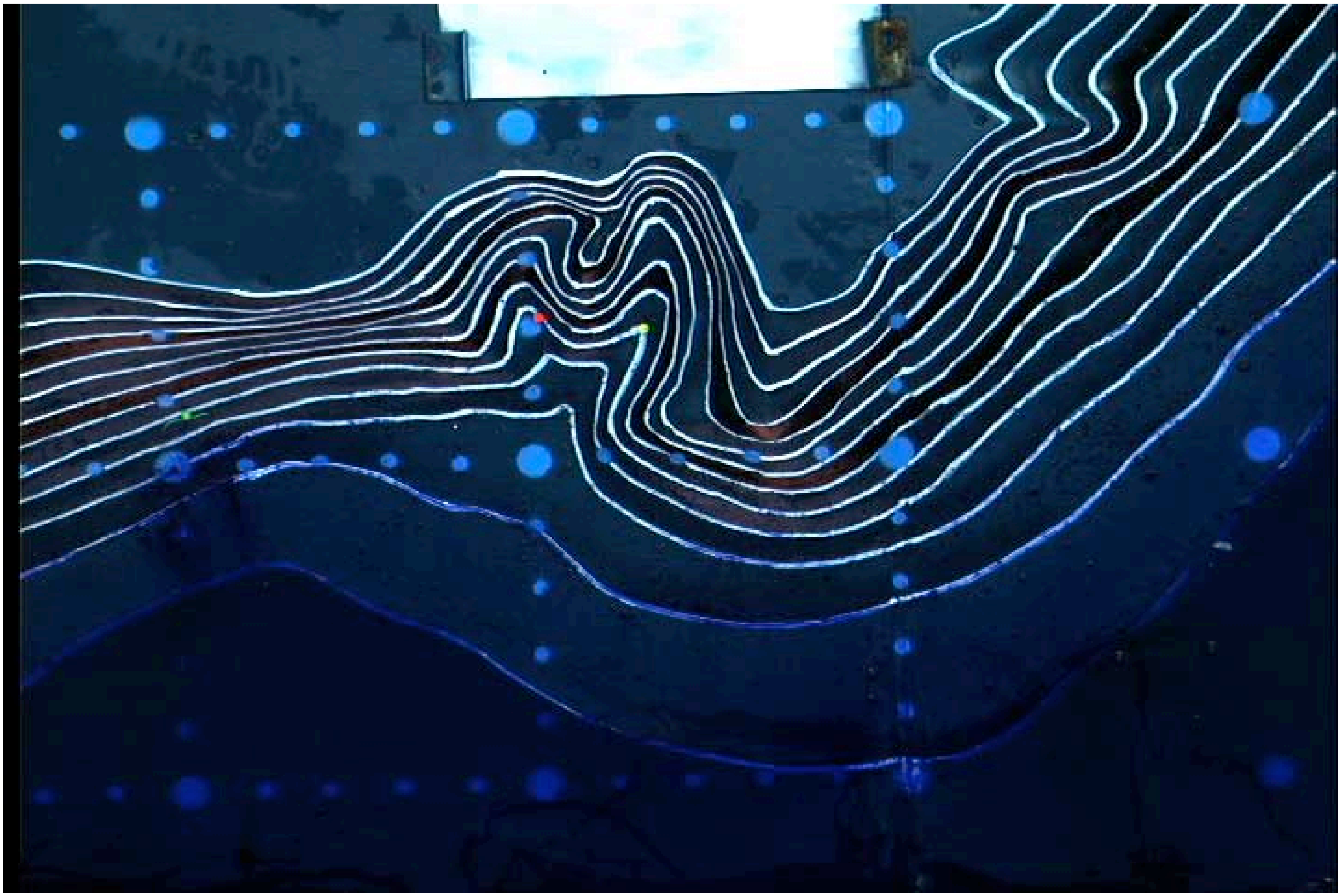
Milestone: Okushiri 1993

Validation of inundation codes (MOST) for extreme runup and overland flows.



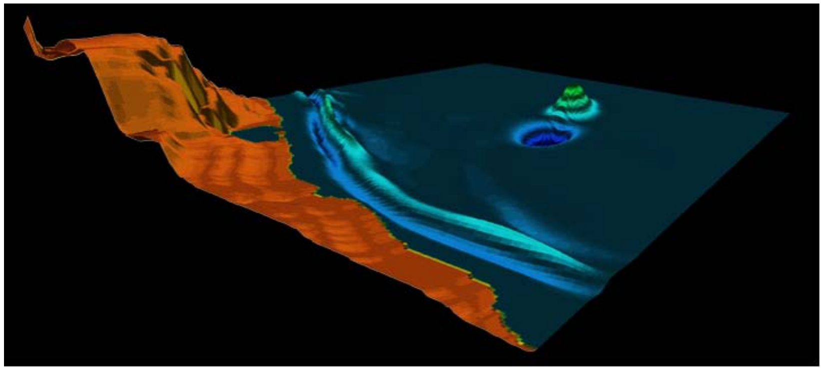
By 1998, tecto-tsunami inundation was fairly well(?) understood, i.e., model results fit on the same plot as field measurements.

Japanese laboratory experiments of the extreme Okushiri runup used for model validation used in the 2004 NSF Catalina workshop.

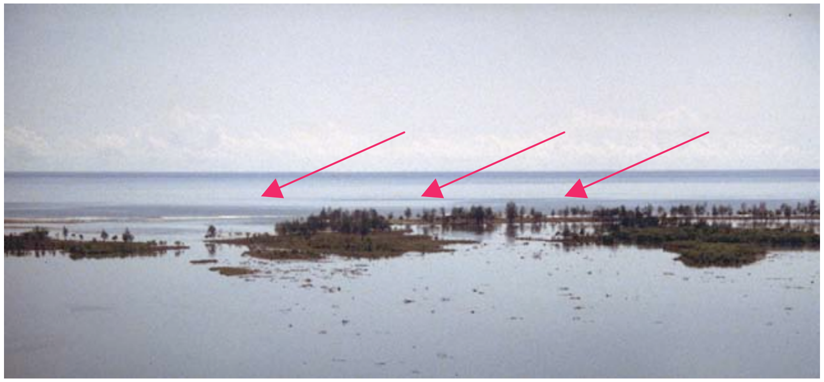


Milestone: Papua New Guinea 1998

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



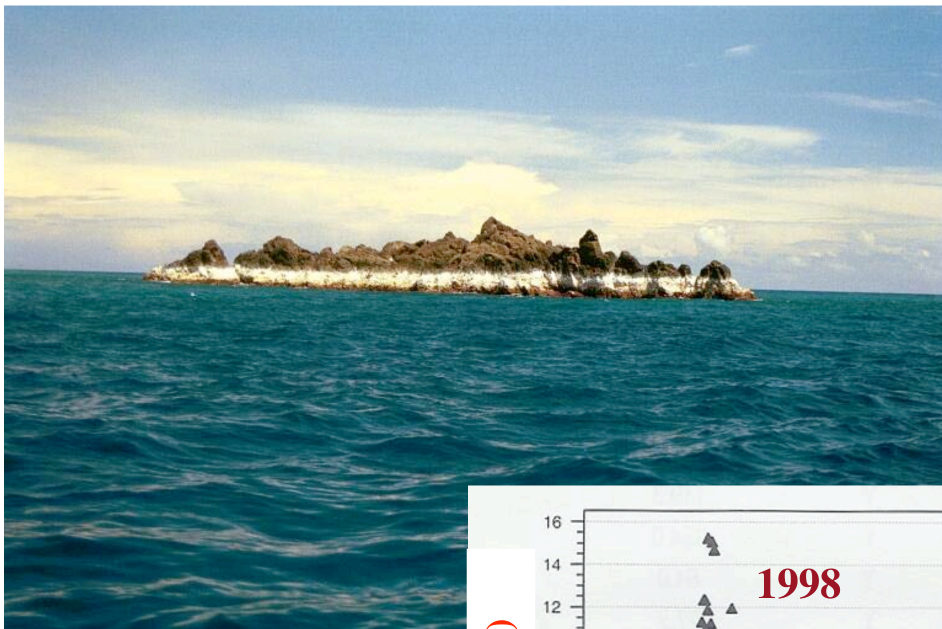
Initial and final wave, animation of Borrero (2001)

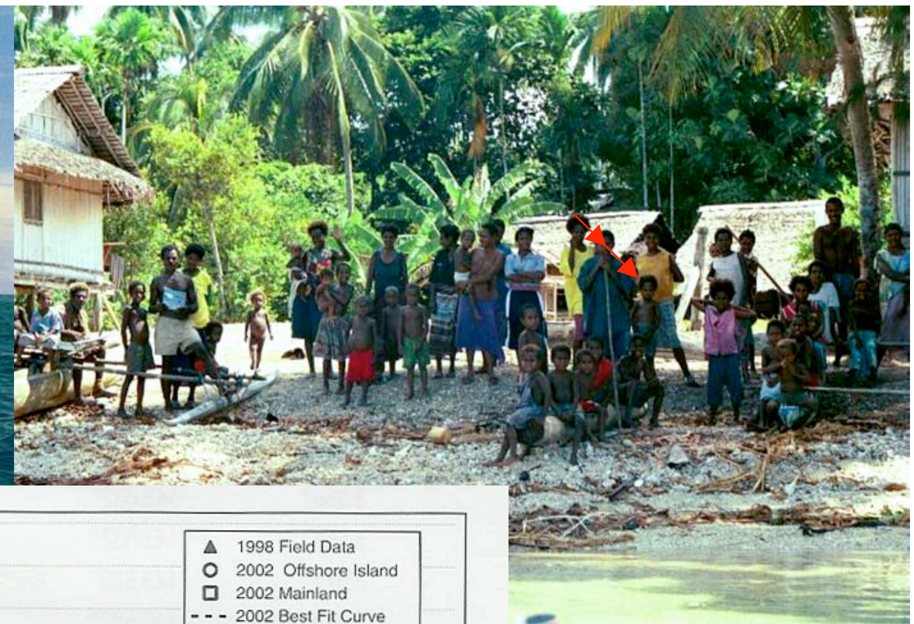


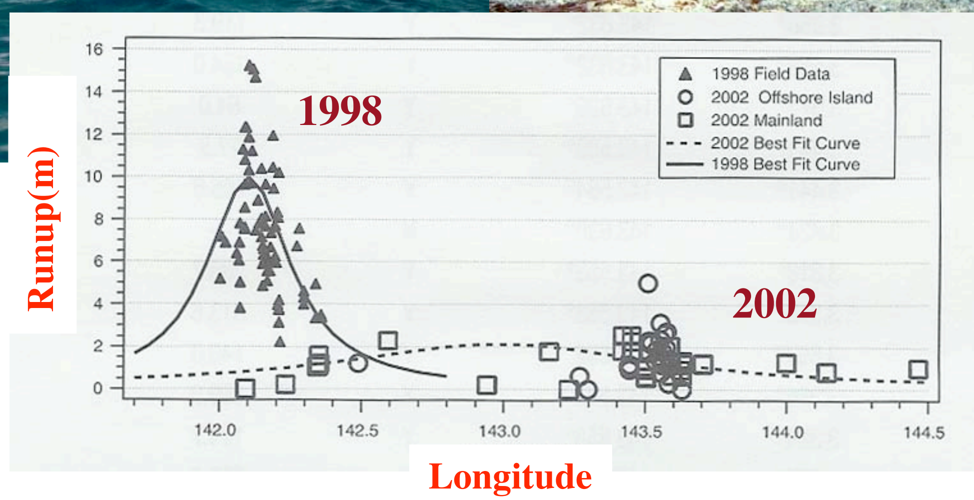
Sissano Spit

Milestones: PNG 2002

Larger earthquake than 1998, significant uplift, smaller tsunami.



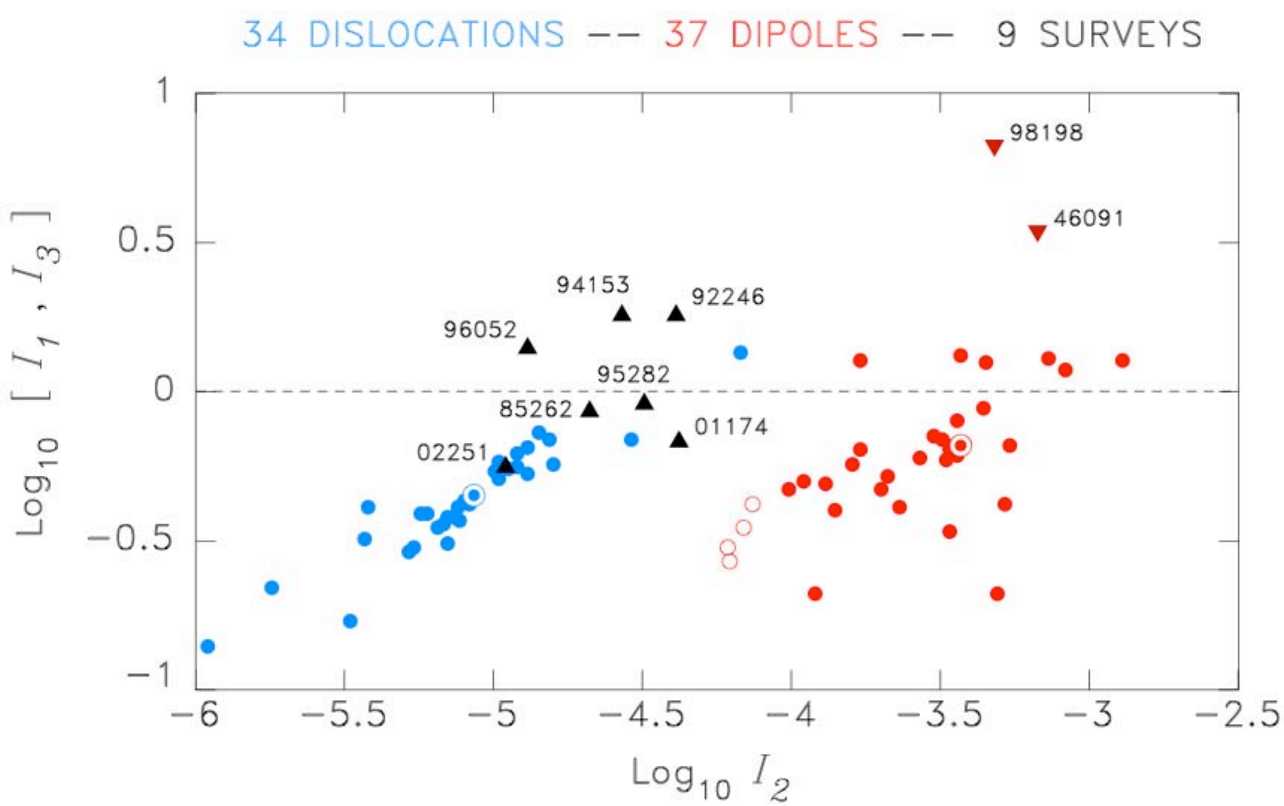




No large slump in 2002. Notice differences in runup distribution.

After 500 simulations of tsunamigenic events, a source discriminant is introduced for nearfield tsunami impact - basically to help determine whether a co-seismic landslide may be involved in any given event.

Maximum run – up



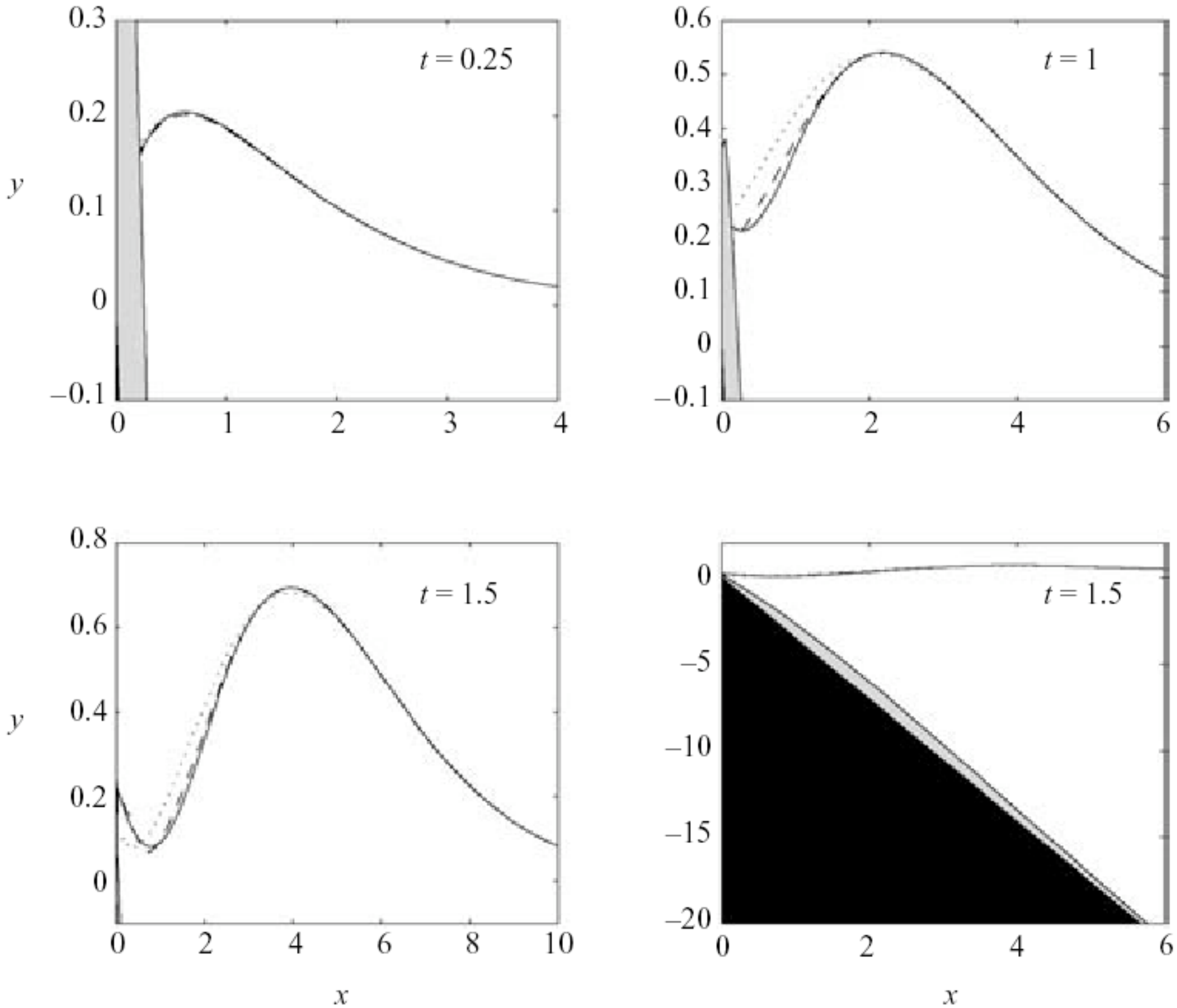
"PLA

$$\textbf{ASPECT RATIO} = \frac{\textbf{Maximum amplitude of run – up}}{\textbf{Extent of run – up along beach}}$$

Okal&Synolakis, GJI, 2004

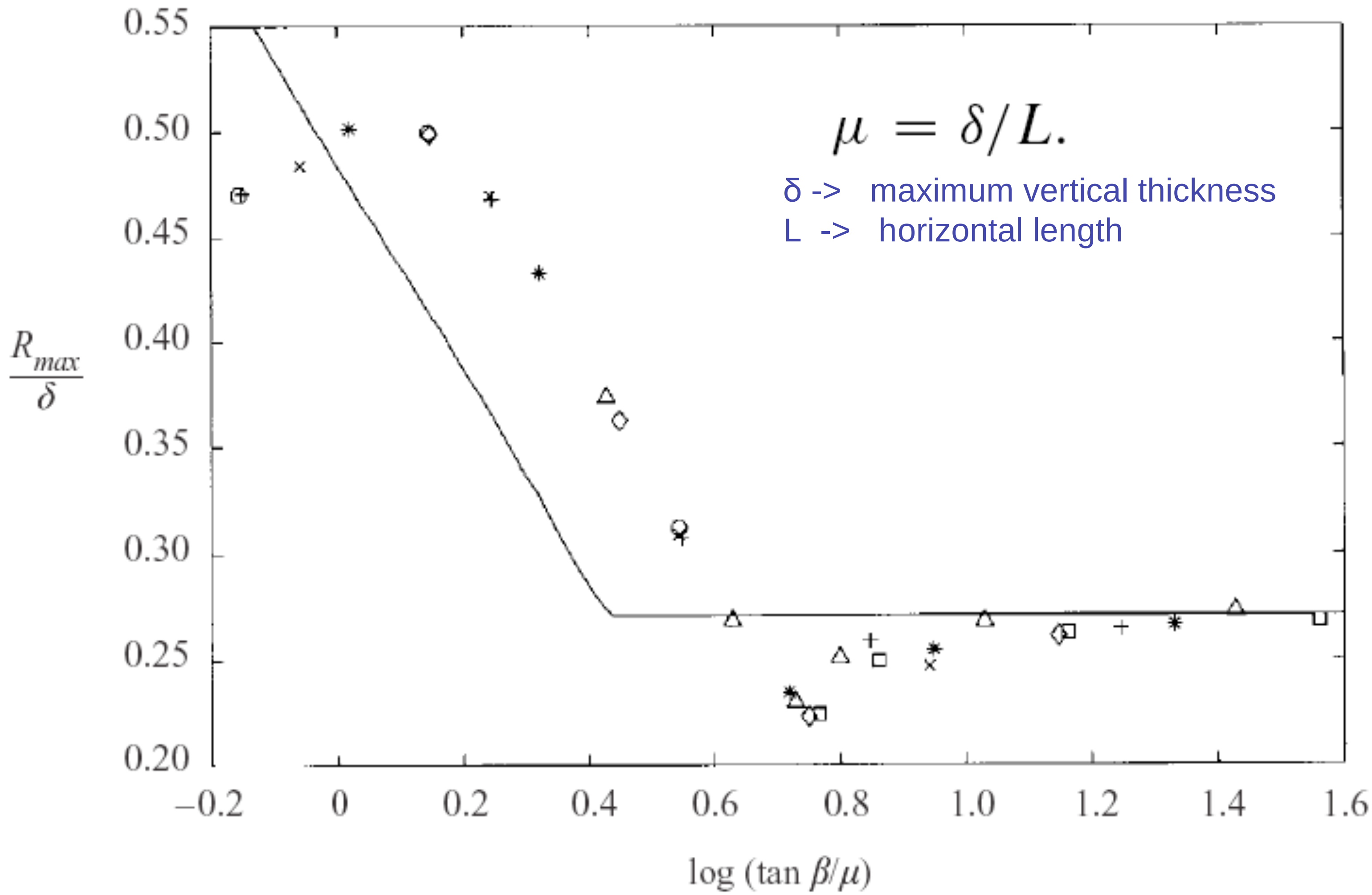
In the aftermath of the Papua New Guinea tsunami, early analytical model of a sliding mass to get an estimate of first order effects in runup.

Exact solution of a forced wave equation.

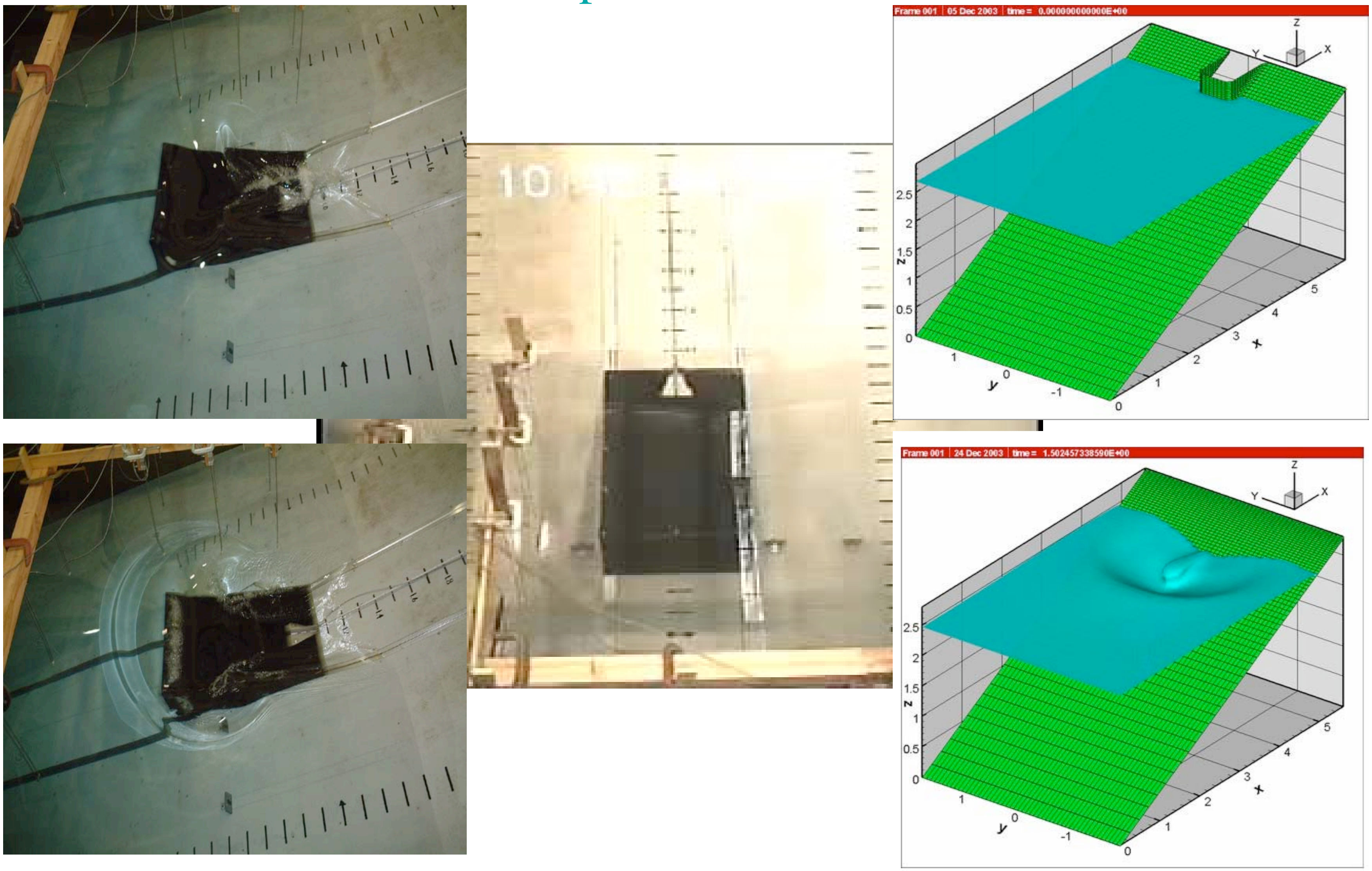


Liu, Lynett, Synolakis, JFM,2003

Comparisons of asymptotic solutions of the FLSW for a moving Gaussian slide with numerical results.



Large scale laboratory experiments on "landslide" tsunami generation motivated development of DNS simulations.



Comparison of experiments with predictions using LES of Navier-Stokes equations.

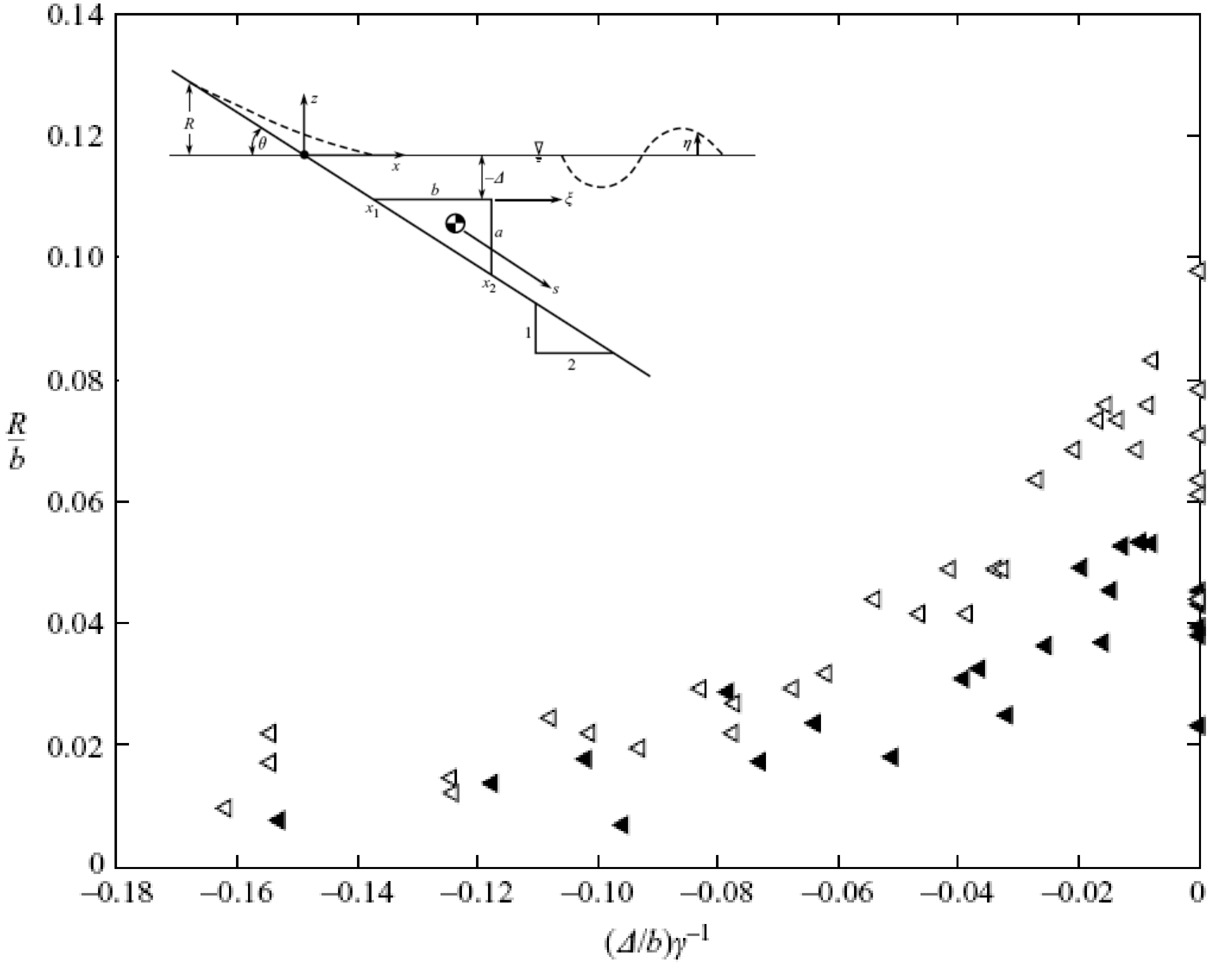


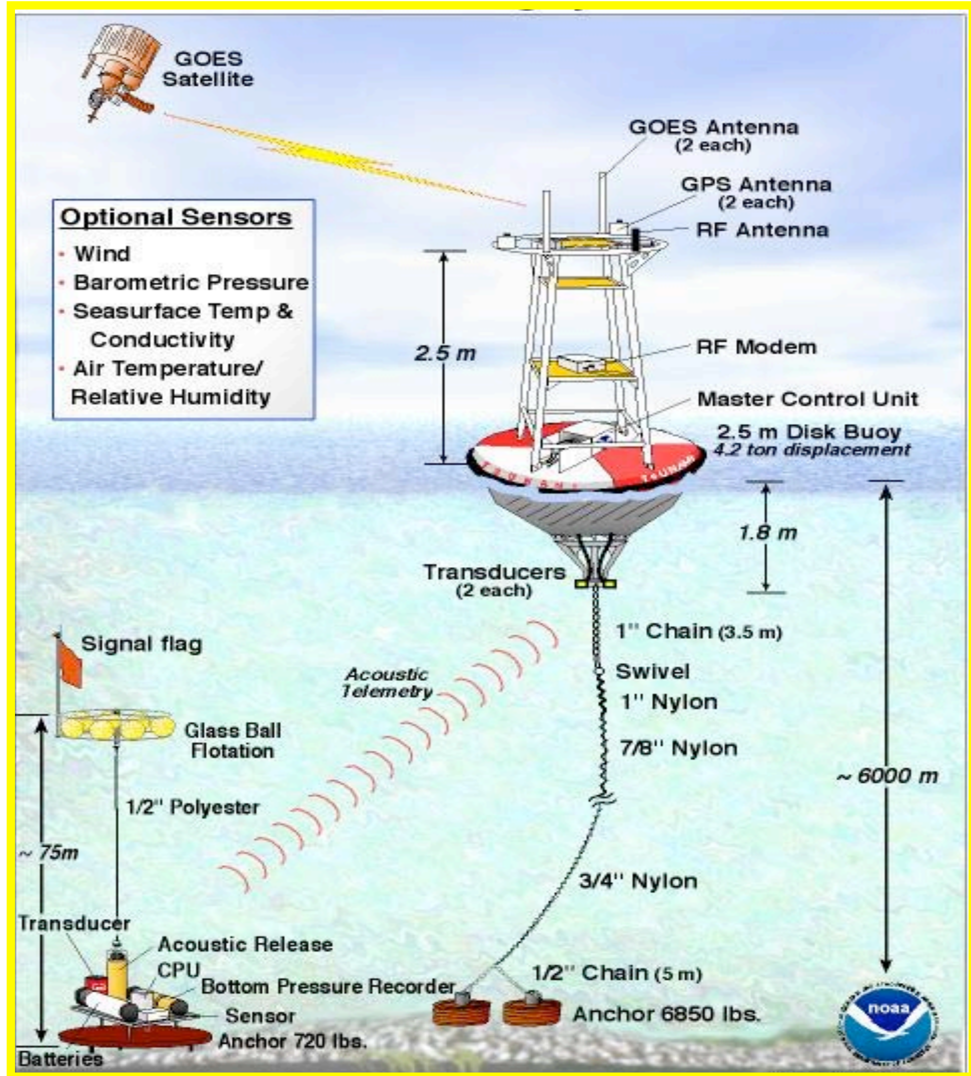
FIGURE 25. The normalized maximum runups obtained from both ◁, experiments and ◀, numerical simulations are plotted against $(\Delta/b)\gamma^{-1}$ for submerged slides.

Liu, Wu, Raichlen and Synolakis, JFM, 2005

Where we were before Boxing Day 2004 - the DART system.

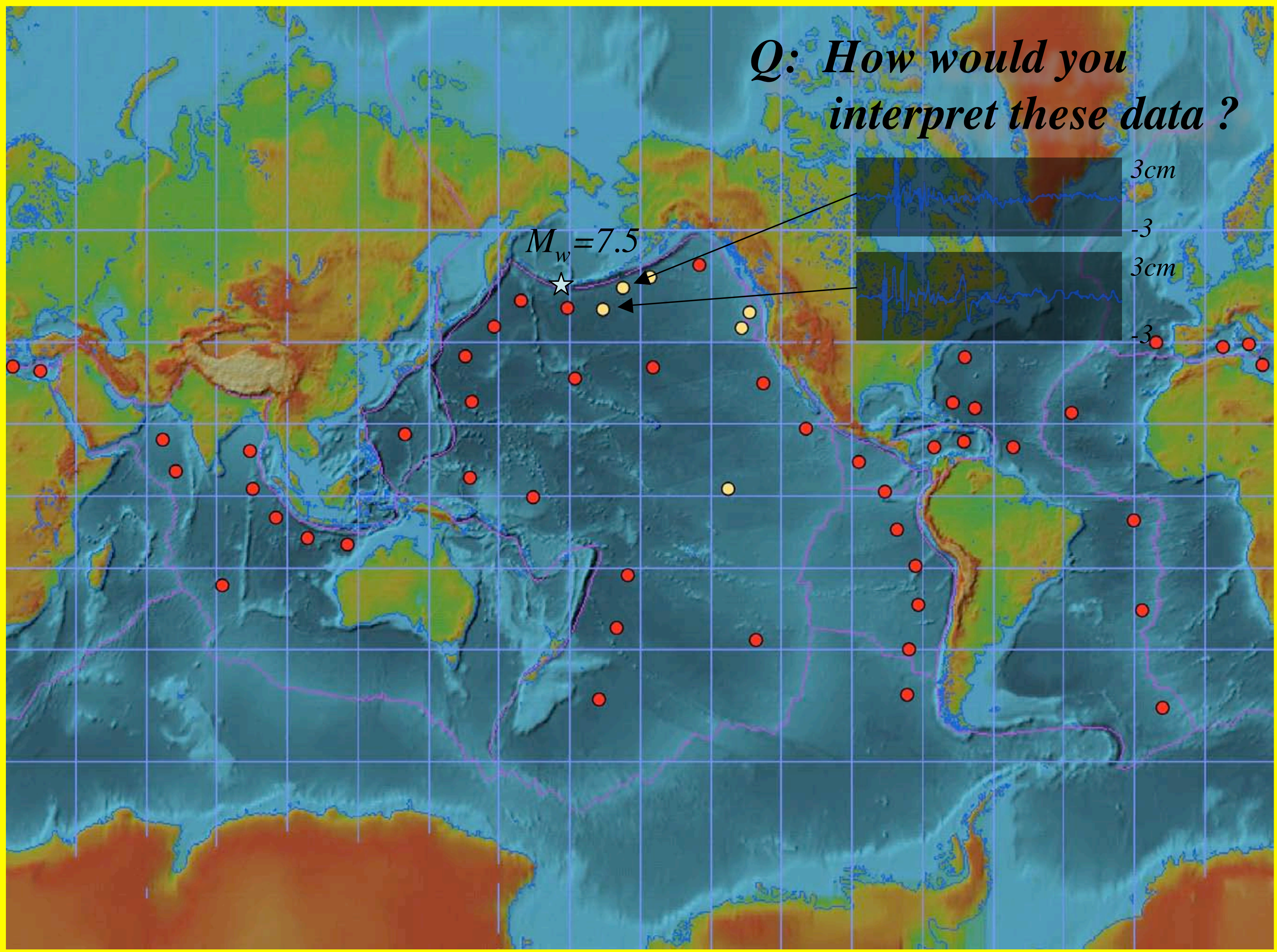
Tsunameter measures small changes in pressure at the seafloor. Data sent acoustically to surface buoy, then via satellite to the Warning Centers. Concept now standard in copycat technologies and reinventions of the tsuwheel.

<u>Normal transmissions</u>: Hourly reporting of 15 minute data to confirm system readiness.

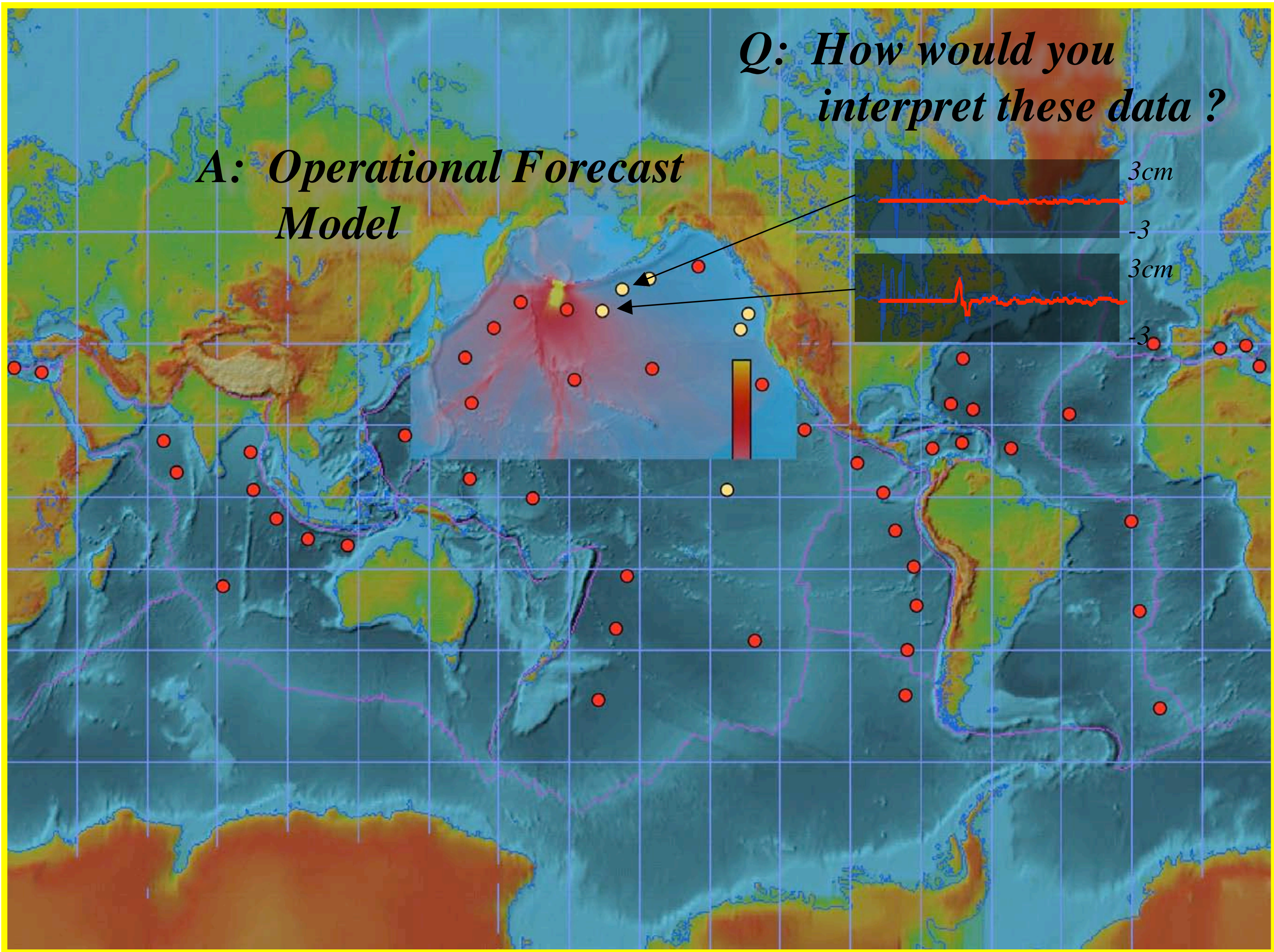


Animation

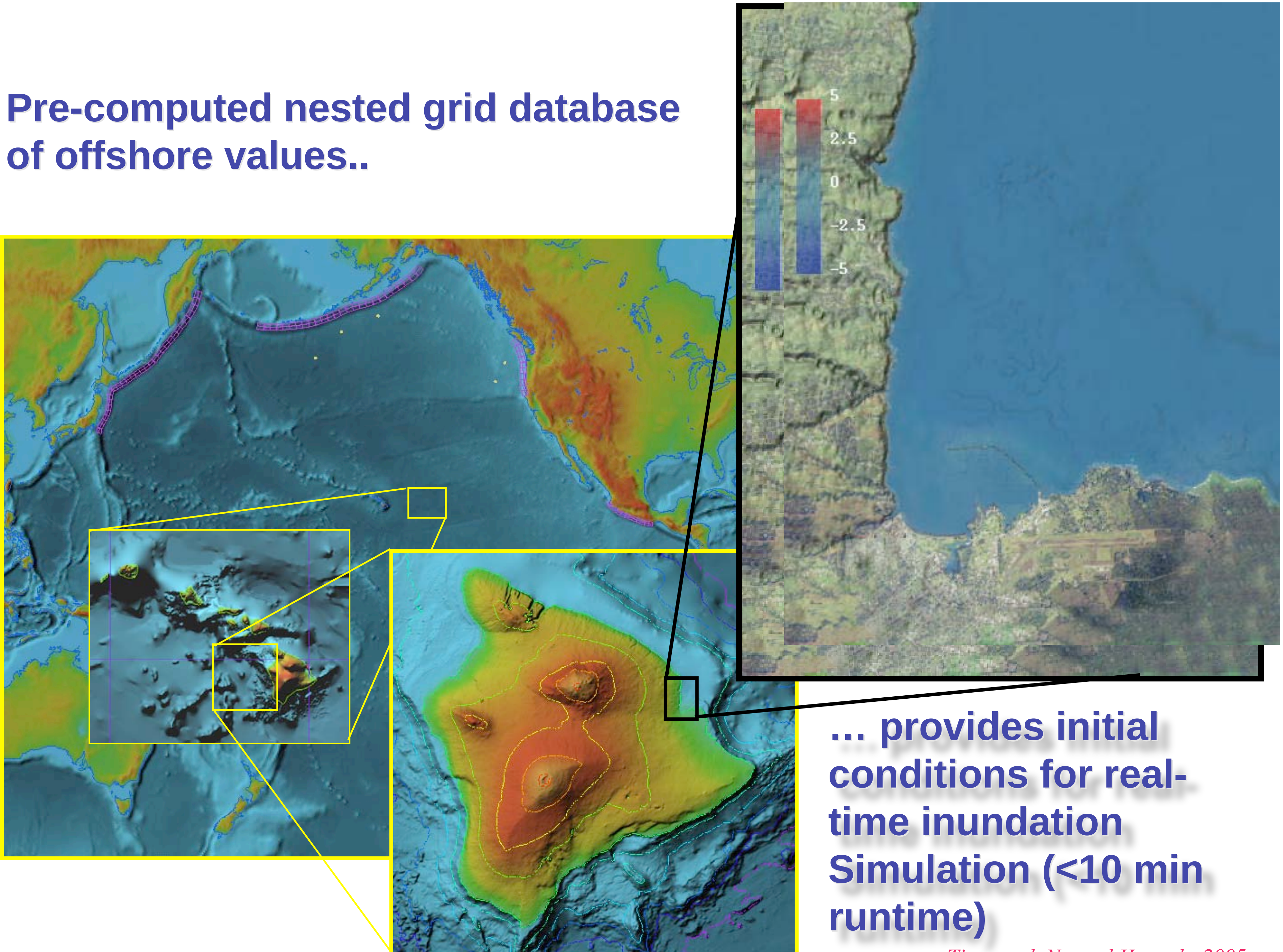
The first and only tsunami forecast: 17 Nov 2003



Titov's operational tsunami forecast for 2003 Adreanoff tsunami.



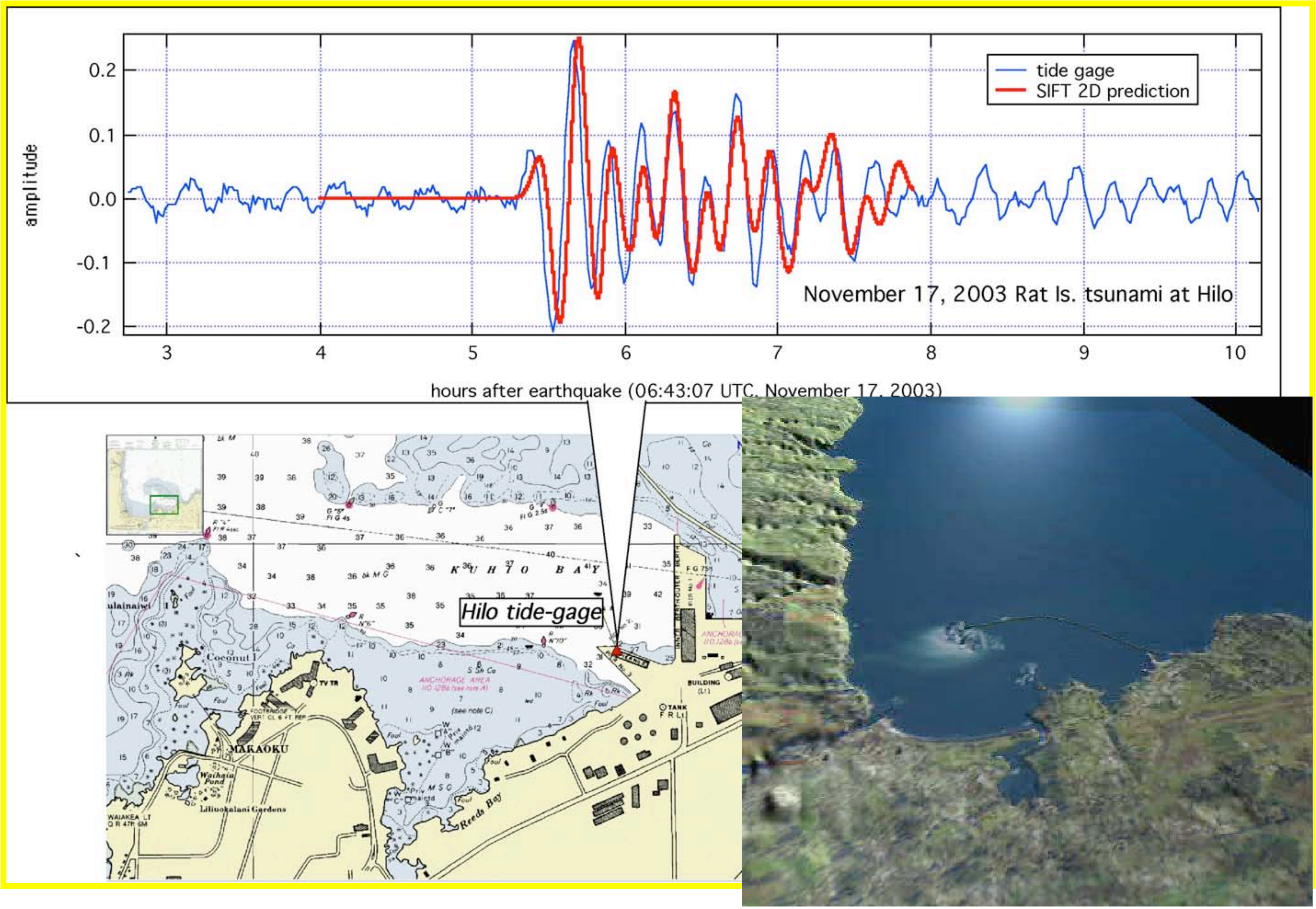
Pre-computed nested grid database of offshore values..



… provides initial conditions for real-time inundation Simulation (<10 min runtime)

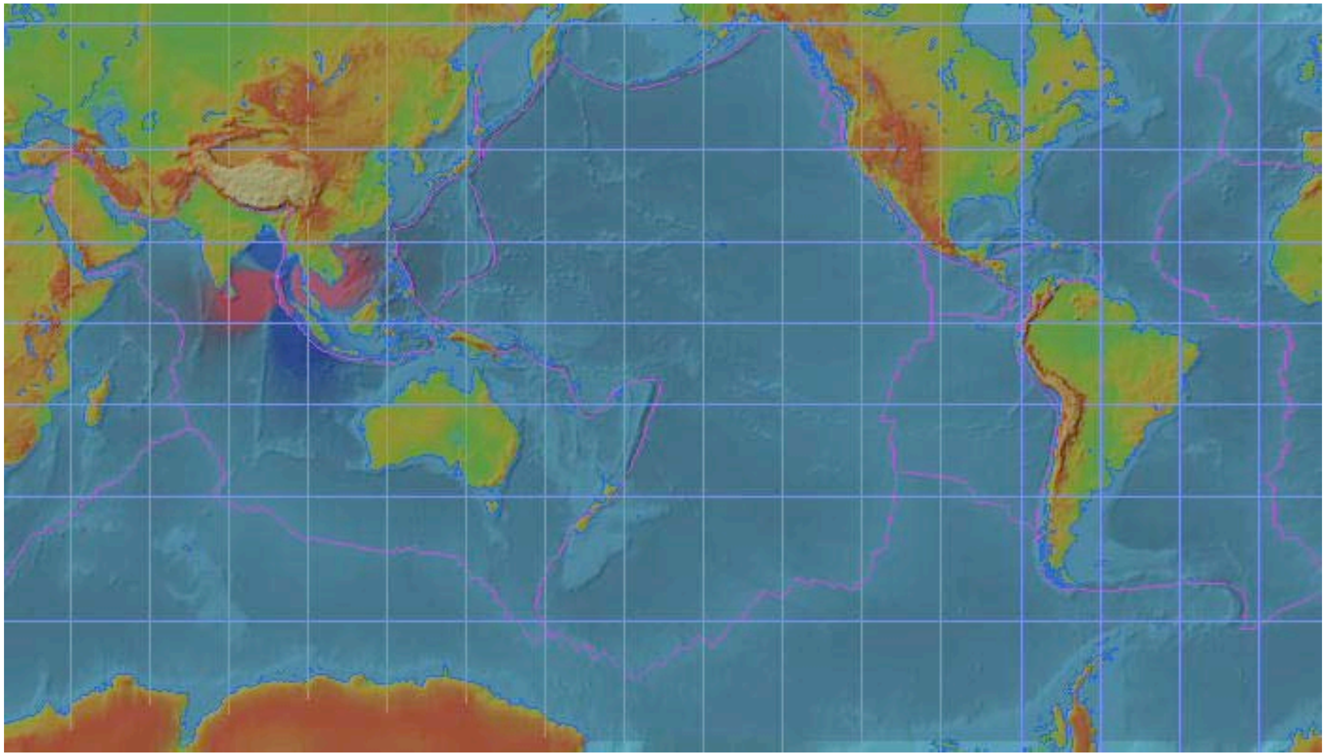
Titov et al, Natural Hazards, 2005

2003 Tsunami forecast at Hilo, Hawaii leads to warning cancellation.



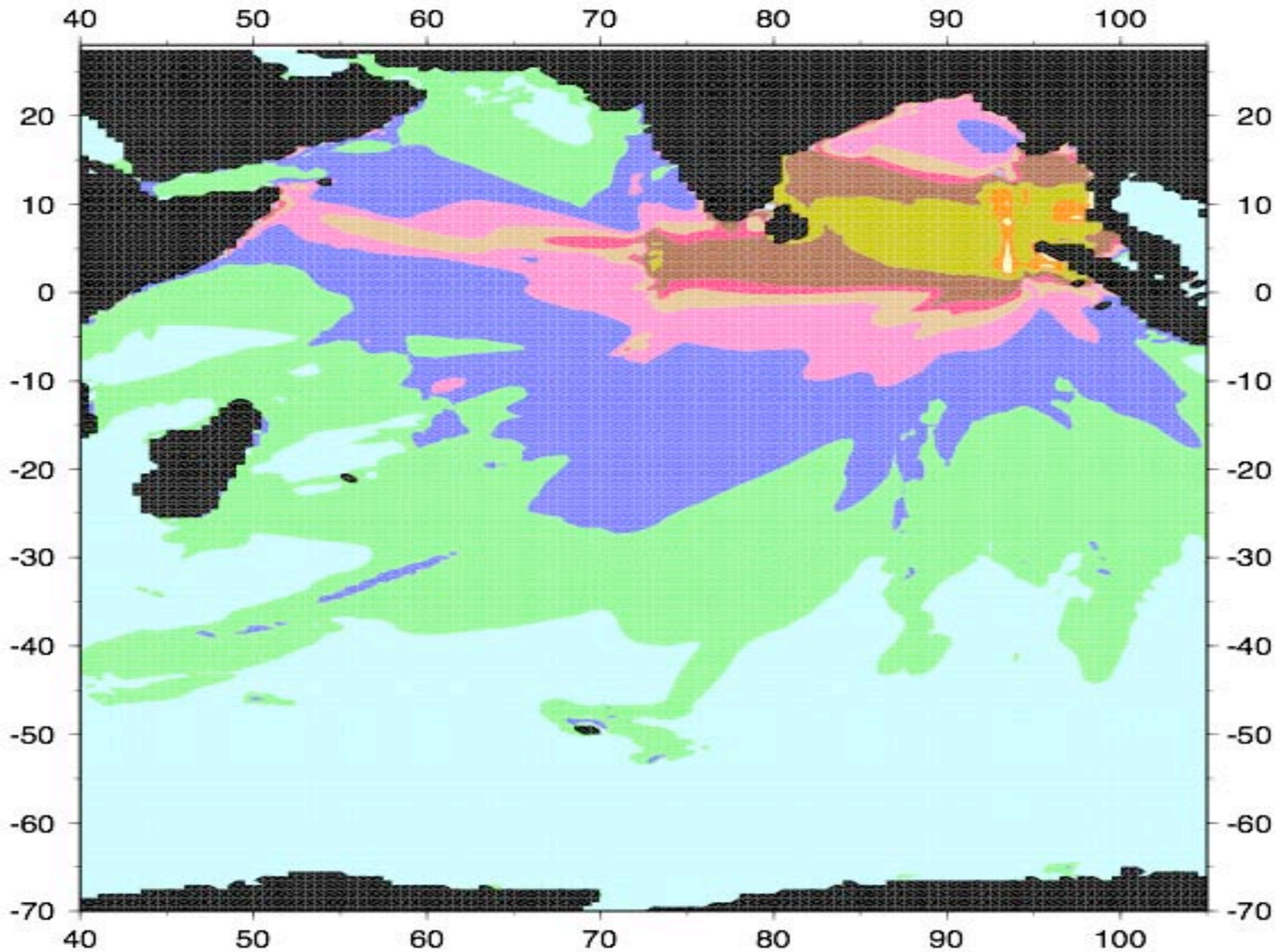
When the lessons
are not
learned and when
hazards are
underestimated…

Titov's calculation of the propagation of the 26-December-2004 tsunami ~ 4 days later.

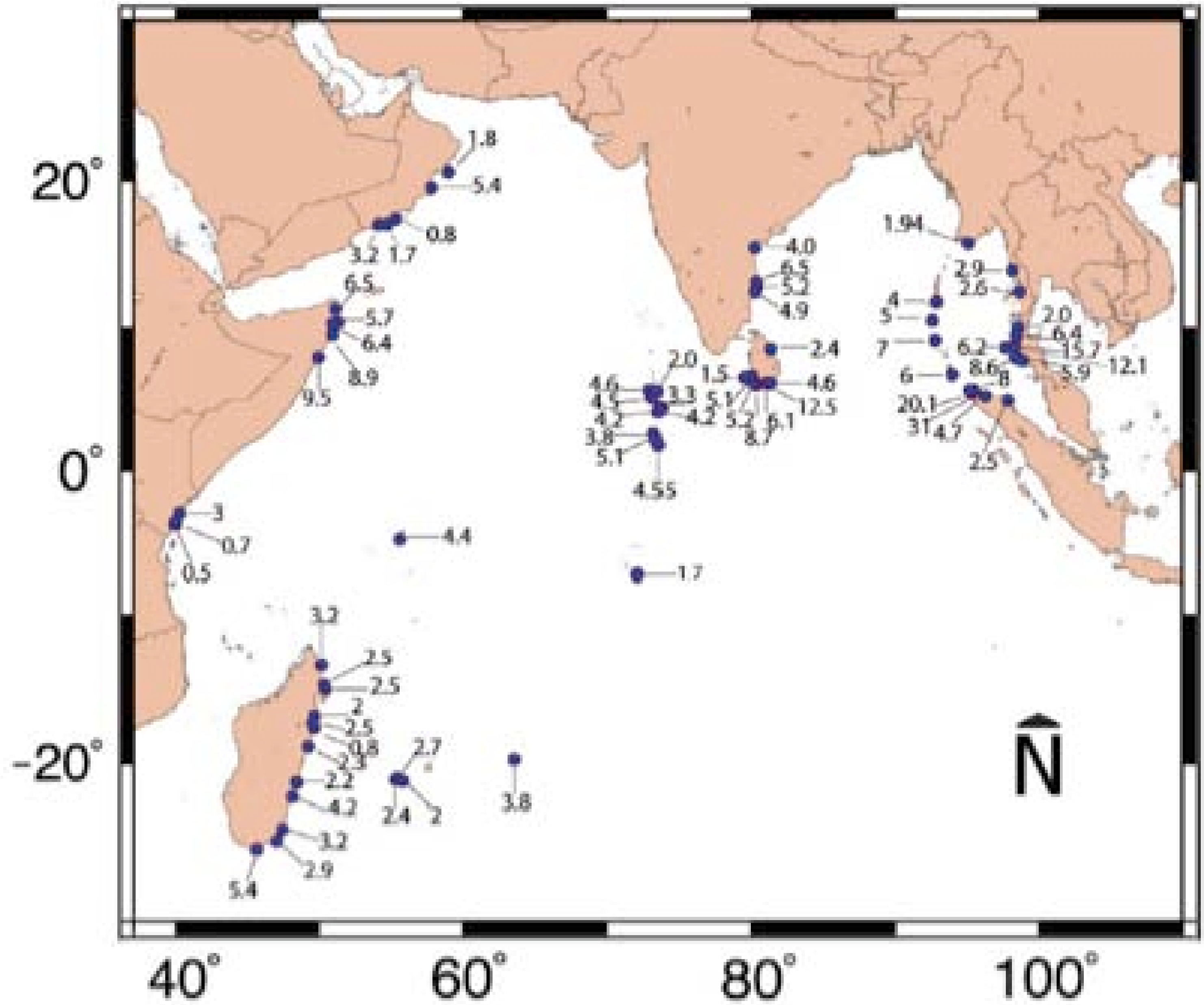


Titov et al, Science, 2005

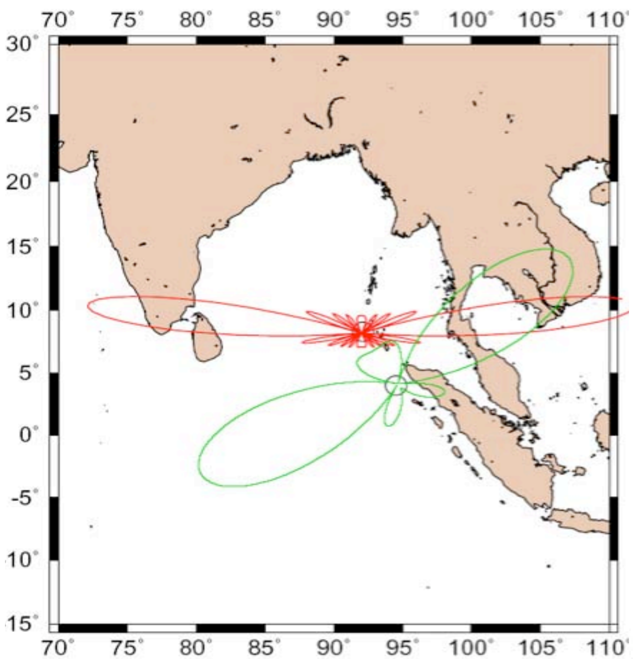
Maximum wave heights over the Indian Ocean a la Okal

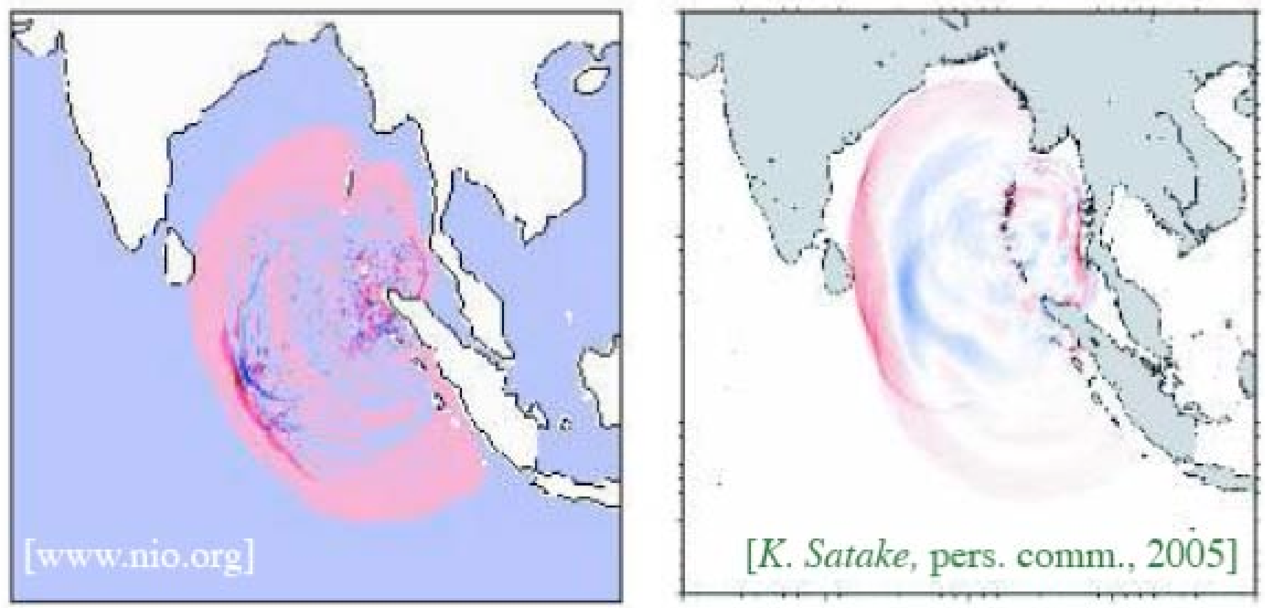


Summary of runup/flow depths of Boxing Day tsunami
from the International Tsunami Survey Team (worldwide).



In the immediate aftermath, a short (400km) source was proposed, as opposed to the long (1200km) source.

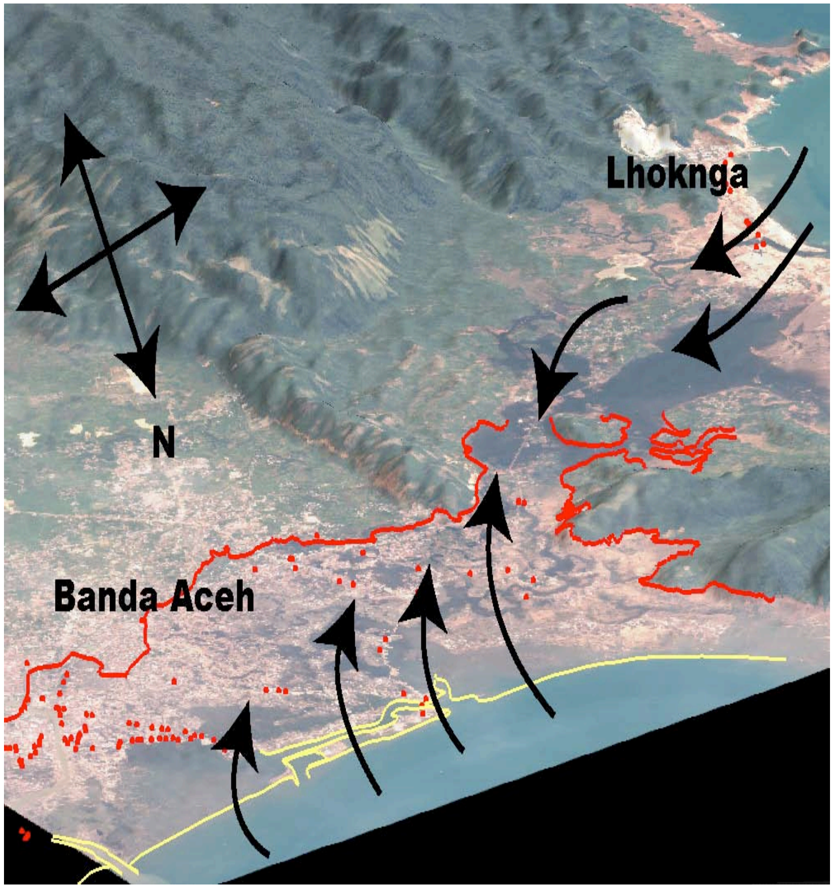




Snapshots from hydrodynamic simulations, 100 minutes after origin time

Simple directivity arguments were quickly able to differentiate the source mechanisms, and eventually the long source was confirmed through seismic and field studies.

Measurements and modeling of tsunami attack on Banda Aceh using MOST

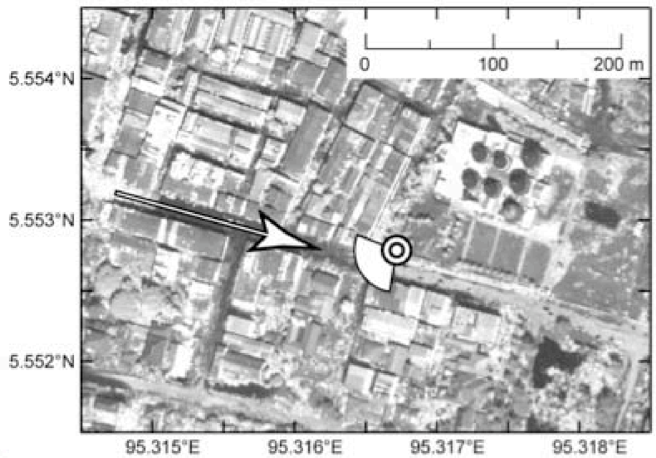


Borrero, Science, 2005

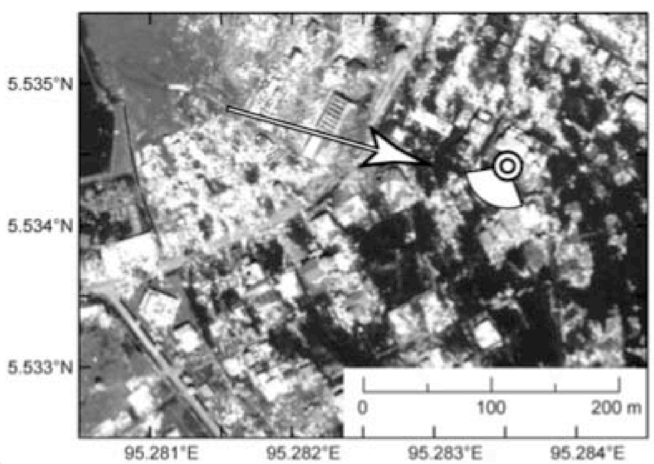
Titov et al, Science, 2005

Measuring velocities in Banda Aceh

(After spending two days finding the locations where from the videos were shot.)



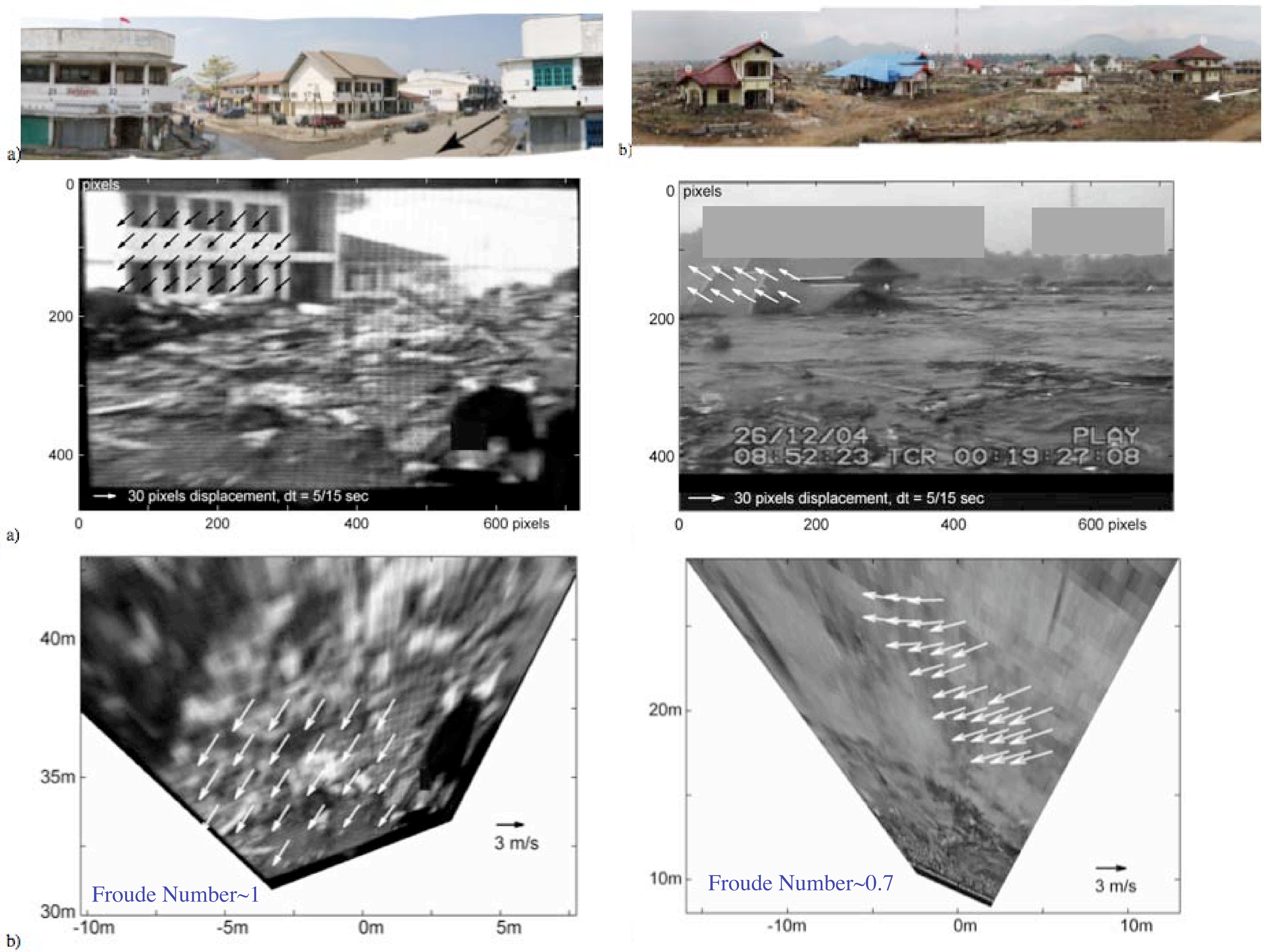
a)



b)

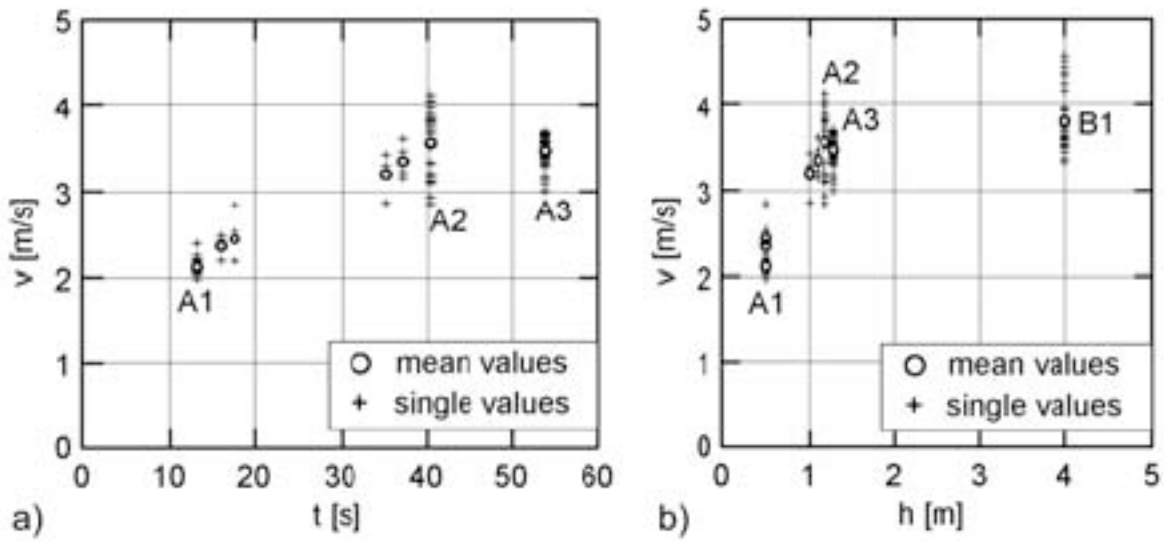
a)

b)



Fritz et al, GRL, 2006

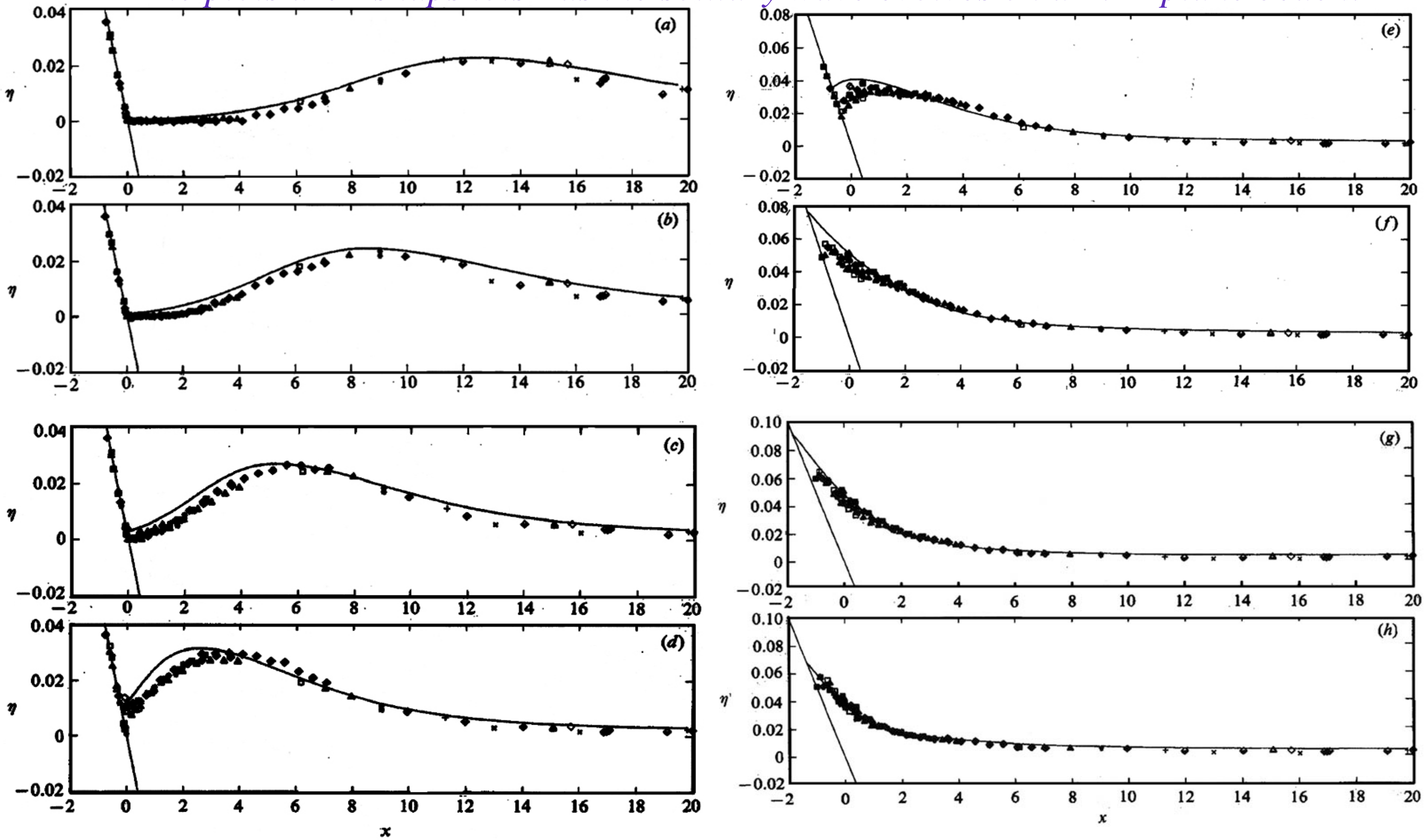
How do velocities at the Grand Mosque (A) an at the police chief's house(B) vary ?



At (A) where video footage exists from the initiation of the flow, the velocity increases with time, and so does the depth.
The velocity almost doubles from 2m/sec to 3.5m/sec, about 40sec after initiation and turns from subcritical to supercritical.

Comparison of analytical NSW solution with laboratory measurements for solitary wave evolution and runup.

The plots are "snapshots" as the solitary wave evolves on a 1:20 plane beach.

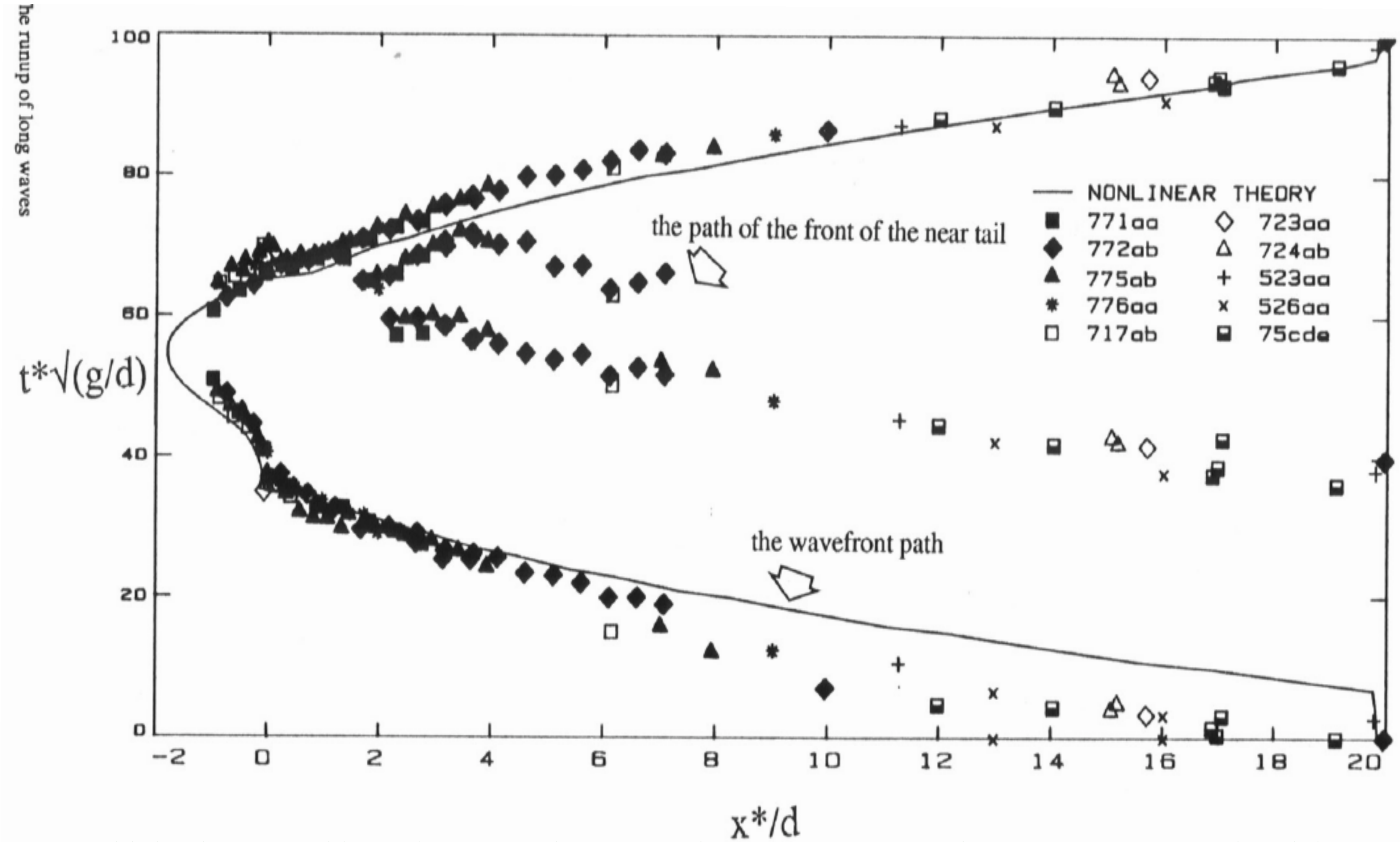


Offshore Height/Depth=0.02. The initial shoreline is at x=0, the continental shelf with constant depth starts at x=20.

Synolakis, 1987

The shoreline path (wavefront path) for a 0.02 solitary wave up a beach.
Shoreline is at x=0.

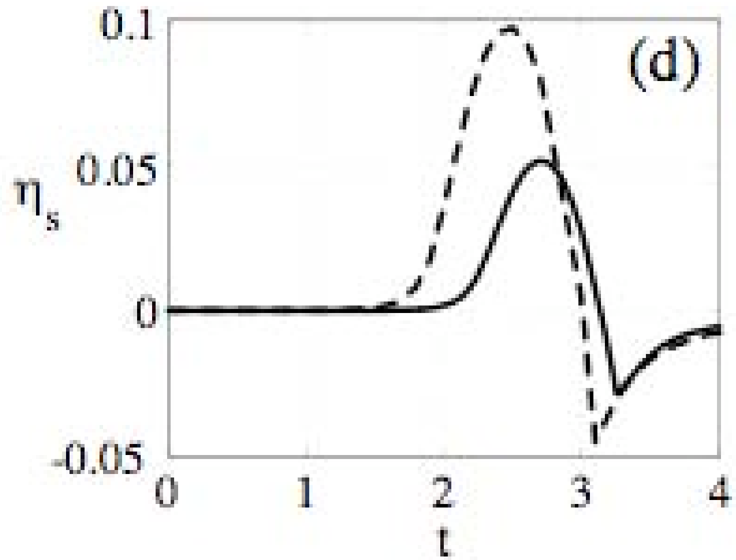
Notice how the front speed dx/dt decreases, then increases suddenly when the wavefront hits the shoreline, then again decreases to maximum runup.



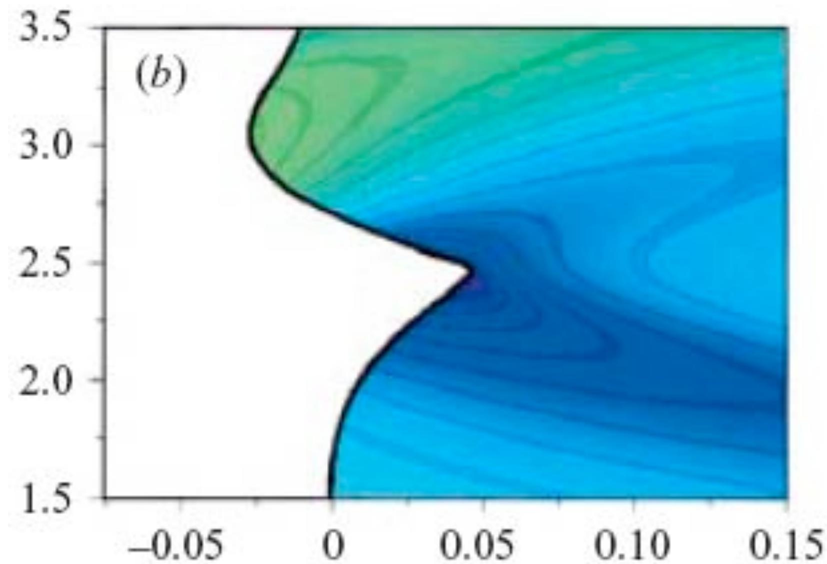
Could this be a possible explanation why victims during tsunami attacks appear mesmerized and do not self-evacuate until too late ? (Synolakis and Bernard, Phil. Trans. Roy. Soc. A, 2006)

Comparison of shoreline motions of an initially negative Gaussian wave - the simplest leading depression wave.

On the left a comparison with and without initial velocity.



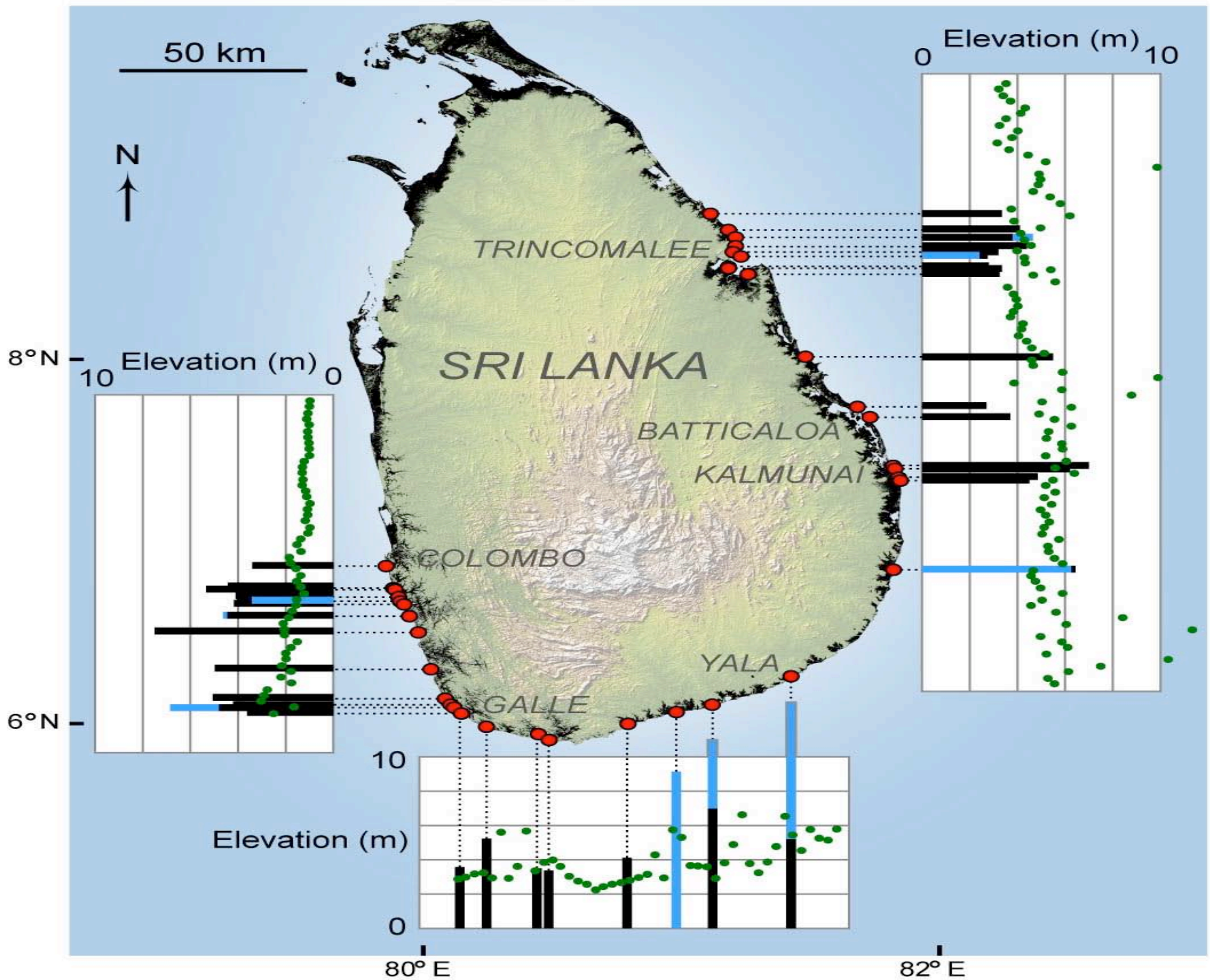
Kanoglu and Synolakis, PRL, 2006



Carrier, Wu and Yeh, JFM, 2003

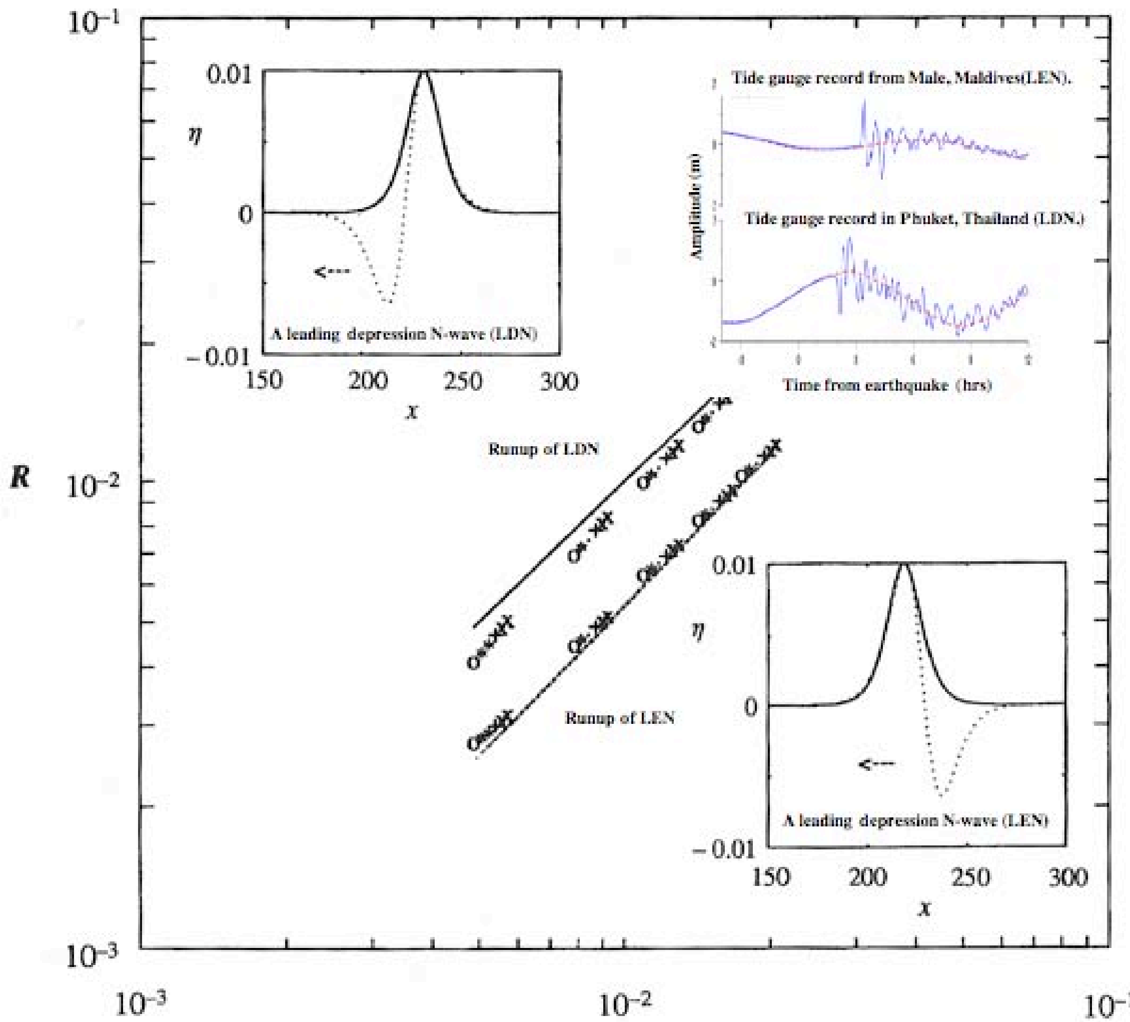
Notice the rapid shoreline accelaration during rundown (LEN) and runup (LDN) once the wave reaches maximum runup (LEN) or minimum rundown (LDN).

Sri Lanka Inundation
Measurements and Lynett - model predictions < 1 month post event



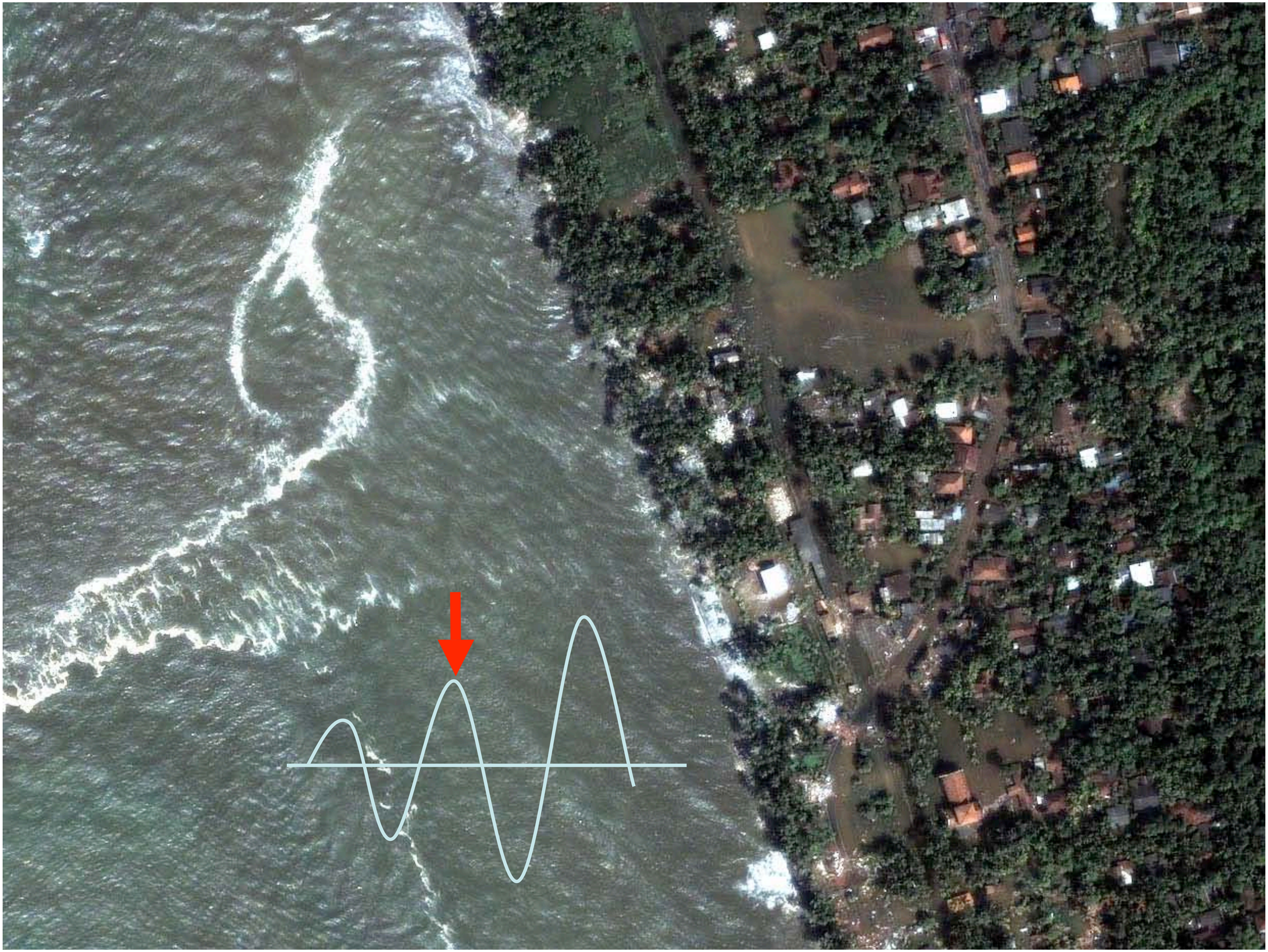
Liu et al, SCIENCE, 2006.

The megatsunami manifested itself as an LDN east of the subduction zone and as an LEN west.



$2.831\mathscr{E}\sqrt{(\cot\beta_0)}\mathscr{H}^{5/4}\ [|\beta - \alpha - 0.366/\gamma| + 0.618/\gamma]$

Tadepalli & Synolakis, PRL 1996



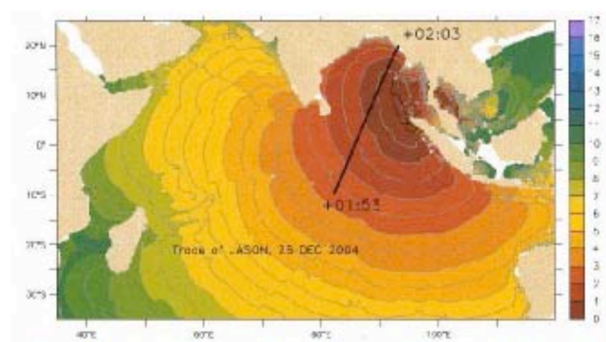
Were there surprizes ?

SCIENTIFIC LESSONS from TSUNAMI

4. DETECTION by SATELLITE ALTIMETRY gives first definitive measurement of *MAJOR* tsunami on *HIGH SEAS*

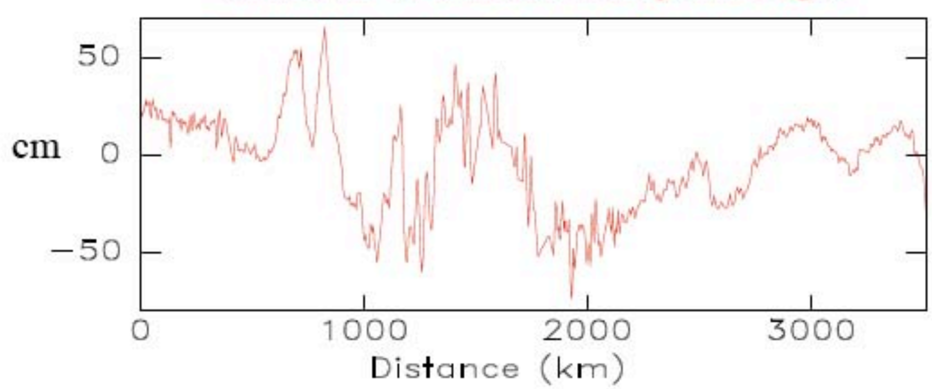
(previous detection by *Okal et al.* [1999] during 1992 Nicaragua tsunami -- 8 cm -- at the limit of noise).

TRACE of ALTIMETRY SATELLITE OVER INDIAN OCEAN



Satellite at the right place at the right time!

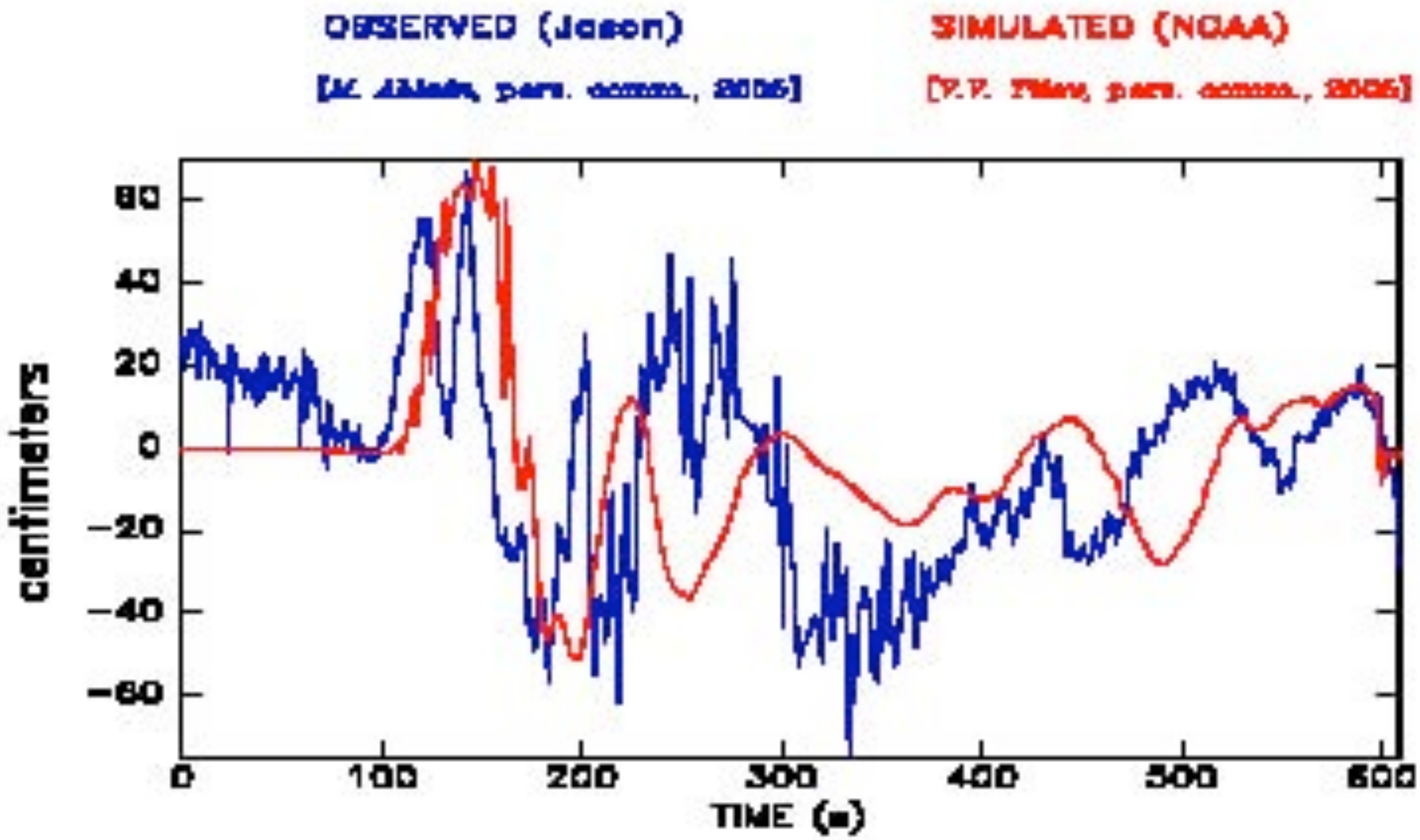
measures 70 cm across Bay of Bengal



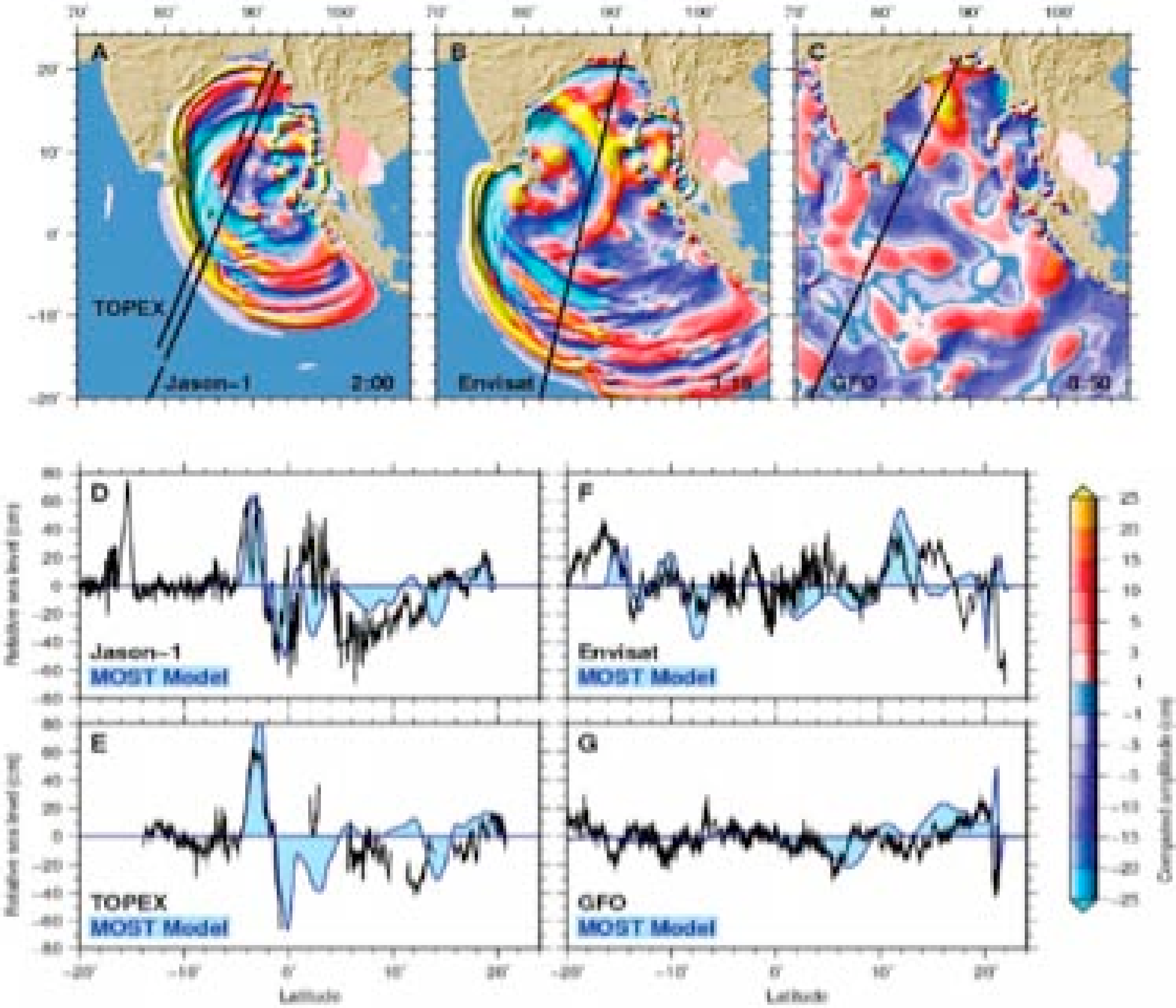
NUMERICAL SIMULATION FITS AMPLITUDE, PERIOD

of INITIAL STAGE of JASON PROFILE REMARKABLY WELL

(Using "LONG" (1000 km) Rupture Fault)



Comparison of MOST predictions with satellite measurements.



Titov et al, 2005

Did seismological paradigms work as expected ?

LESSONS in TECTONICS

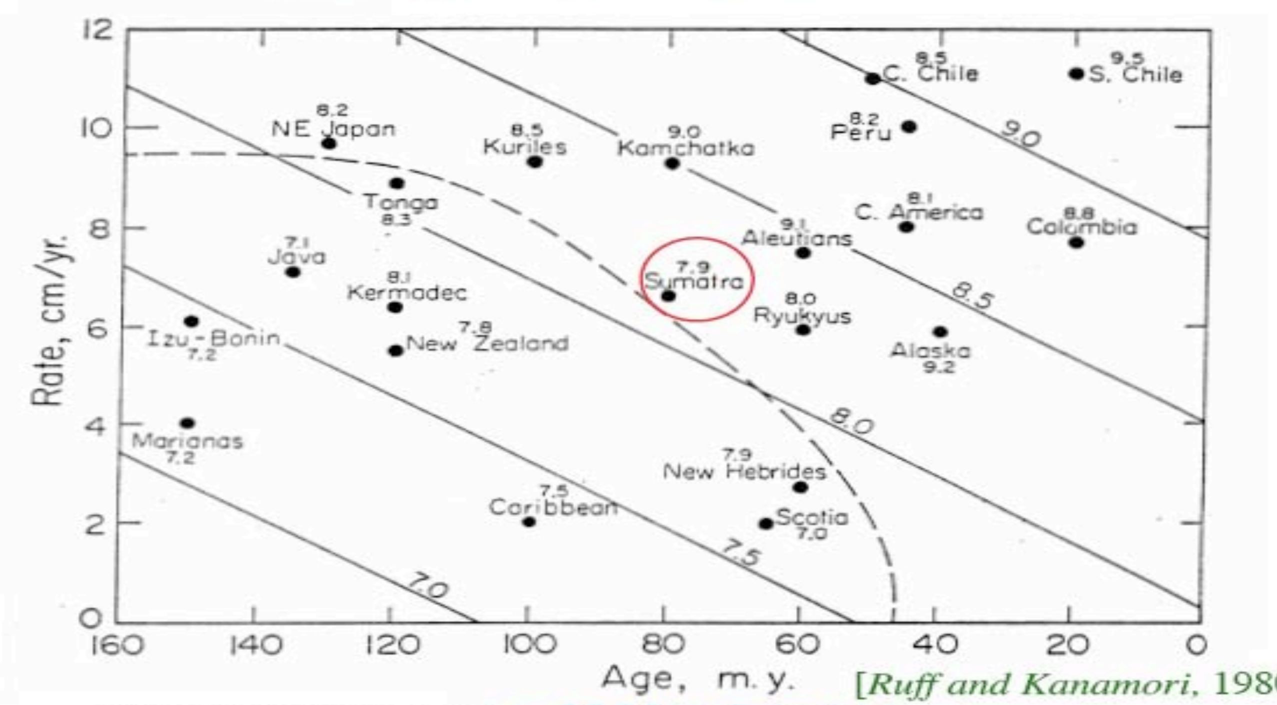
1. Mega-earthquakes occur in unsuspected areas

The 2004 [and 2005] **Sumatra earthquake[s] violated the concept of a**

maximum expectable

subduction earthquake controlled by

***plate age* and *convergence rate*.**



[*Ruff and Kanamori*, 1980]

Modern parameters: **> 55 Ma; 5 cm/yr**
Would predict Maximum **8.0–8.2 not ≥ 9...**

Do small-scale coastal features affect tsunami inundation ?

Patong Beach, Thailand

Extensive use of low seawalls

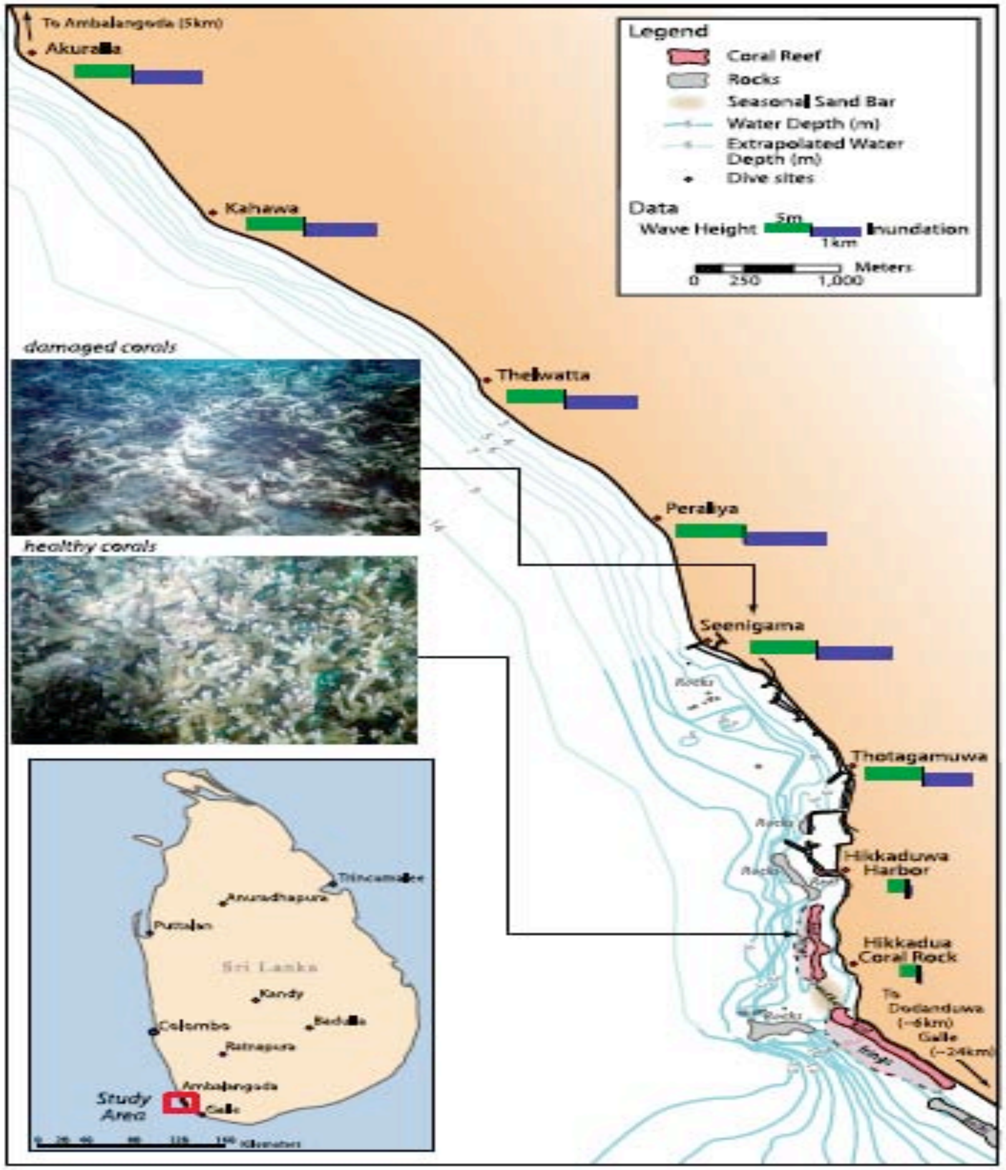
Seawalls were damaged,

but they limited impact velocities.

Scour due to overtopping and water receding through gaps in walls

Kriebel and Dalrymple, The Bridge, 2005

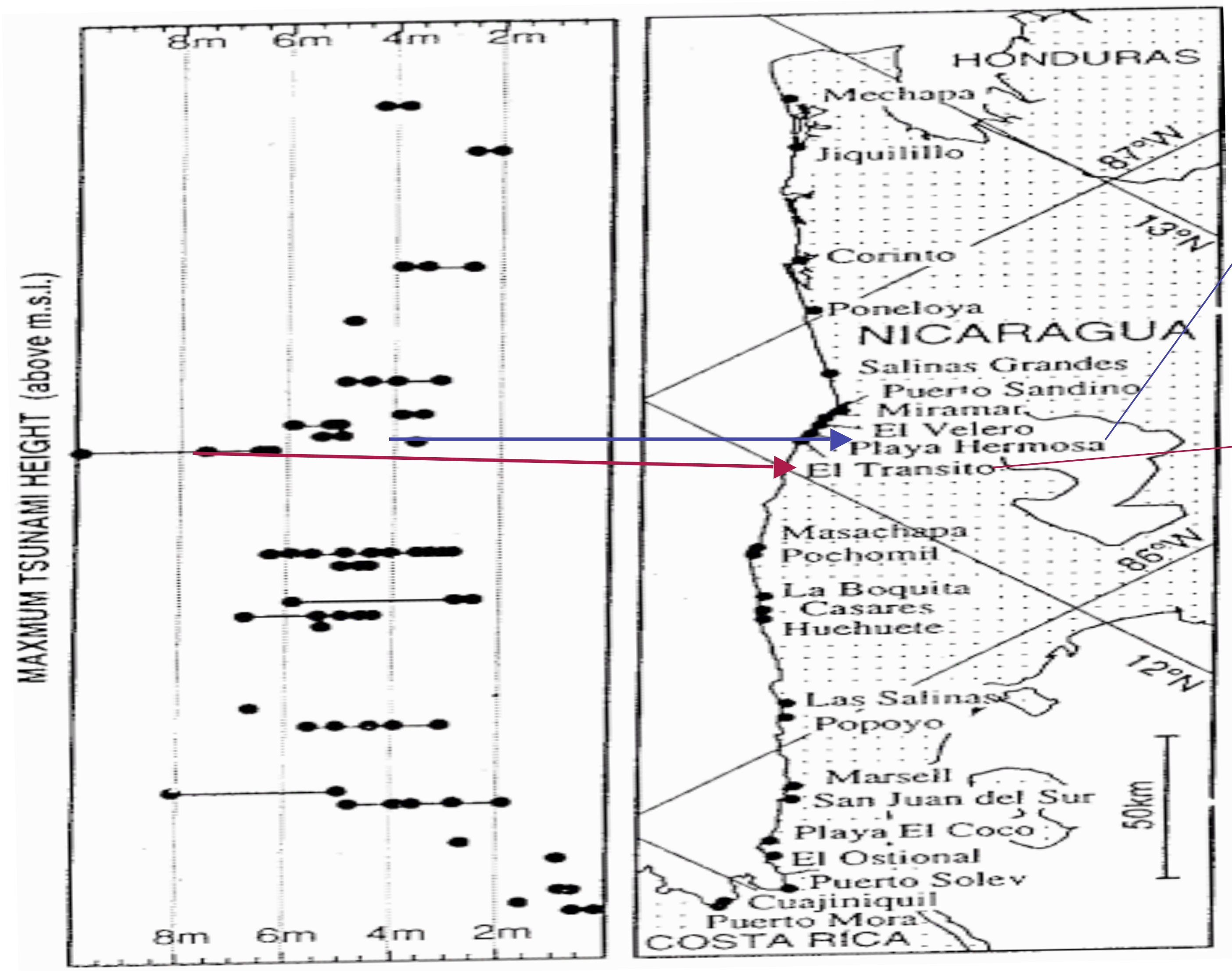
The effects of coral mining.



A map of western Sri Lanka, showing wave-heights (green) and inundation distances (blue). The pattern suggests that runup/inundation is correlated to absence of coral reefs - in view -of inundation results elsewhere.

Fernando et al, 2005

Nicaragua, Sept 1, 1992, revisited.



In Playa Hermosa, even the beach umbrellas had been left standing, while in El Transito inundation exceeded 900m.

Period figure from Satake et al, 1993

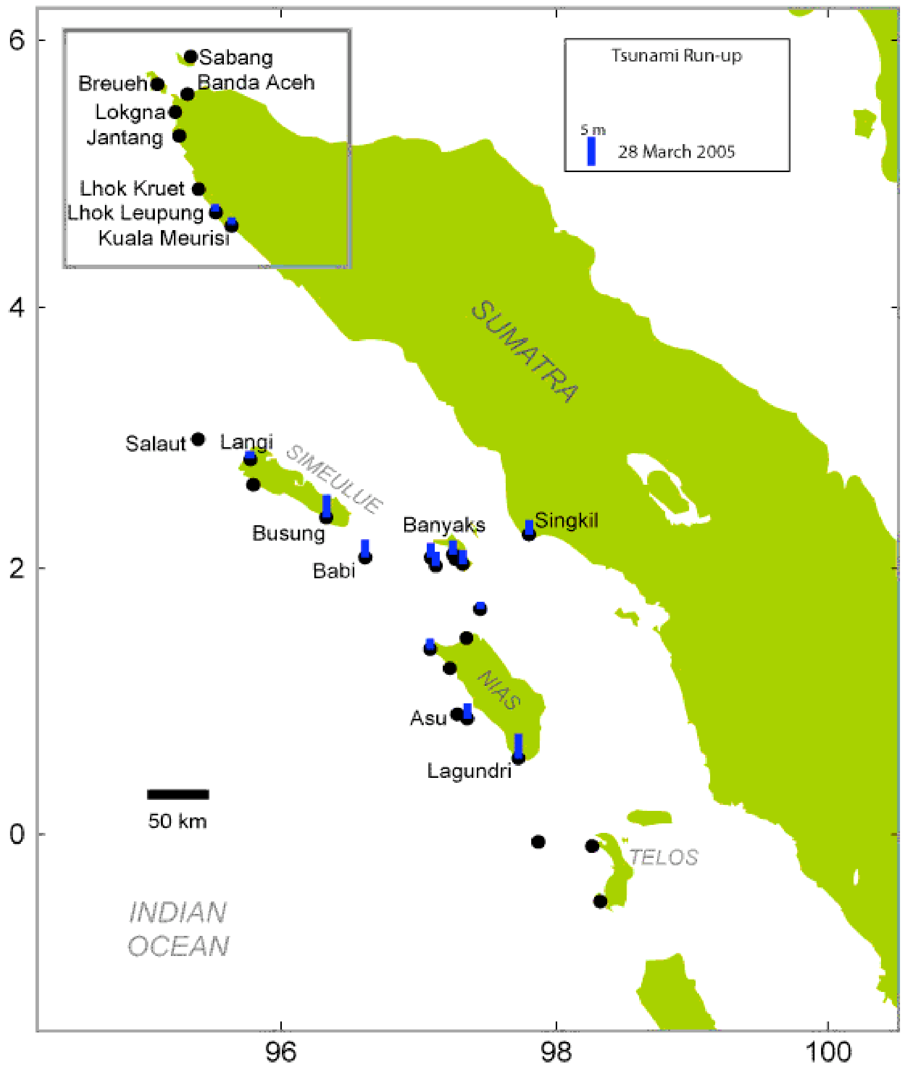
The reef in Playa Hermosa, Nicaragua

It was the reef, not just the "complex" fault motion!

(Without bathymetry/topography of sufficient resolution, misinterpretation was inadvertent, particularly by seismologists)

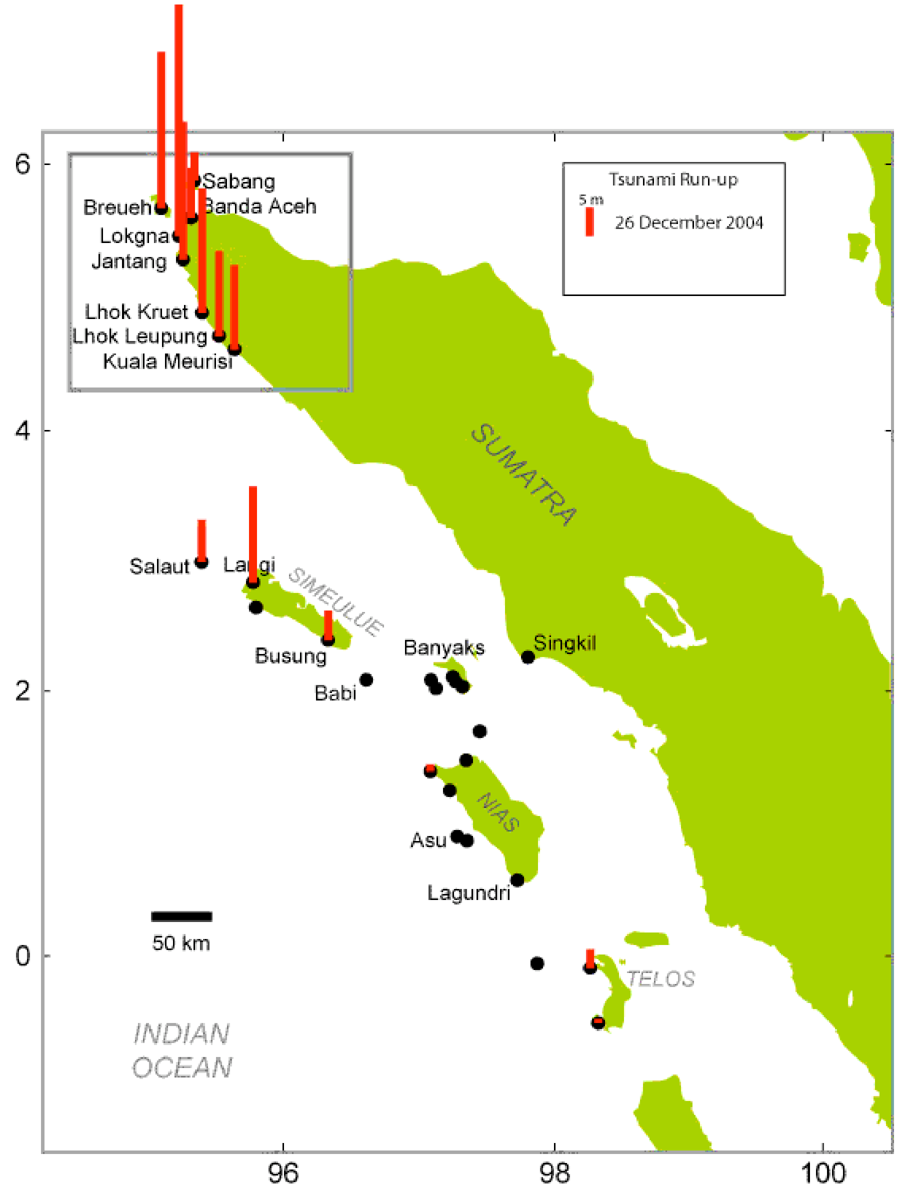
Can an earthquake of magnitude 9.2 have two orders of magnitude smaller impact than an 8.7 (both in the top ten among events with instrumented recordings)

A tale of two tsunamis...



28-Mar-2005

M=8.7



26-December-2004

M=9.3

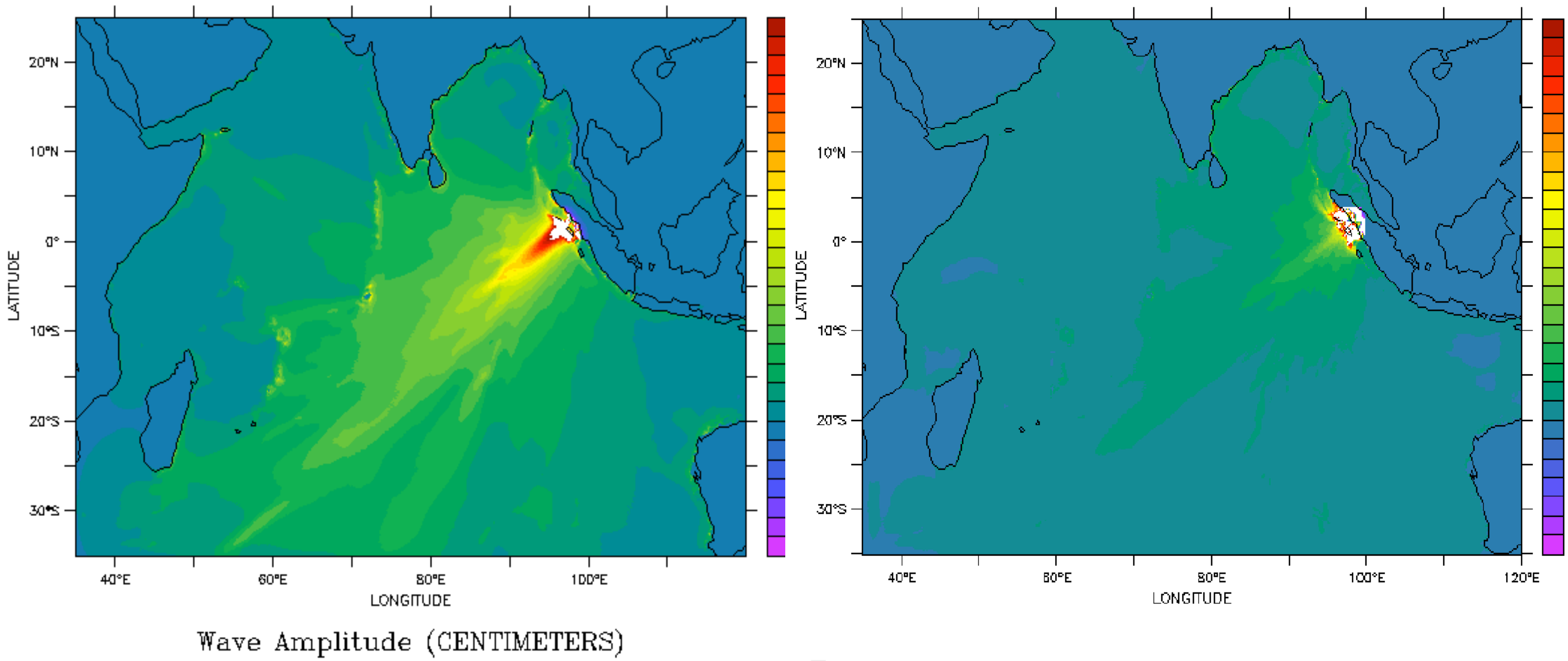
The tale of the two Sumatras -
*Almost no **far field** impact from Sumatra II,*
Hard to guess, by checking the closest tide gage in Cocos Island.

Station	12/26/2004 Peak Heights (m)	3/28/2005 Peak Heights (m)	Ratio
Colombo, Sri Lanka	>2.7	0.5	>5.4
Hanimaadhoo, Maldives	2.2	0.4	5.5
Male, Maldives	2.1	0.2	10.5
Gan, Maldives	1.4	0.3	4.7
Cocos Is., Australia	0.5	0.2	2.5

Mareogram measurements can be deceiving.

The 28-March 2005 tsunami ?

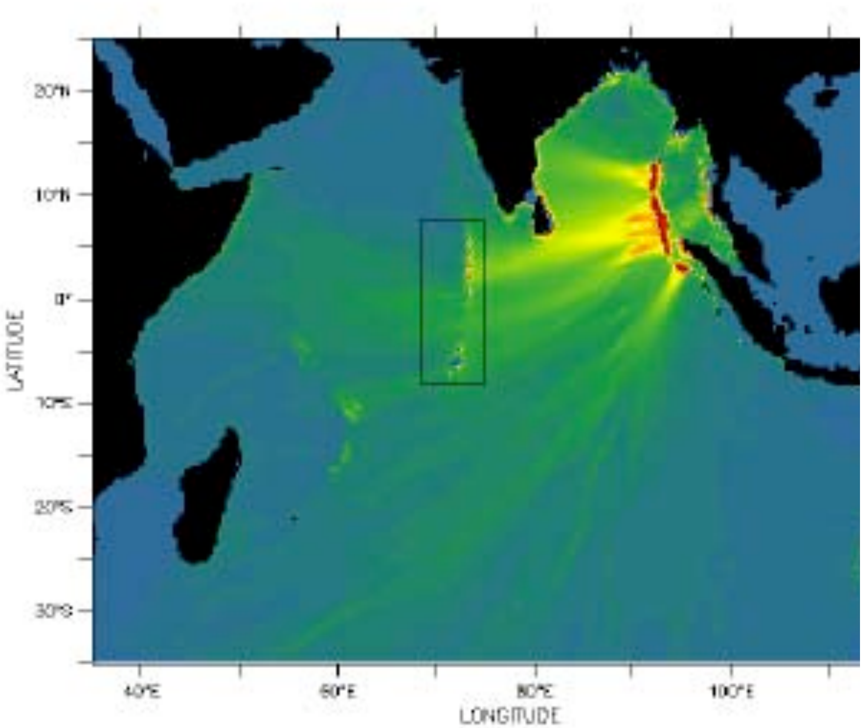
Maximum tsunami height



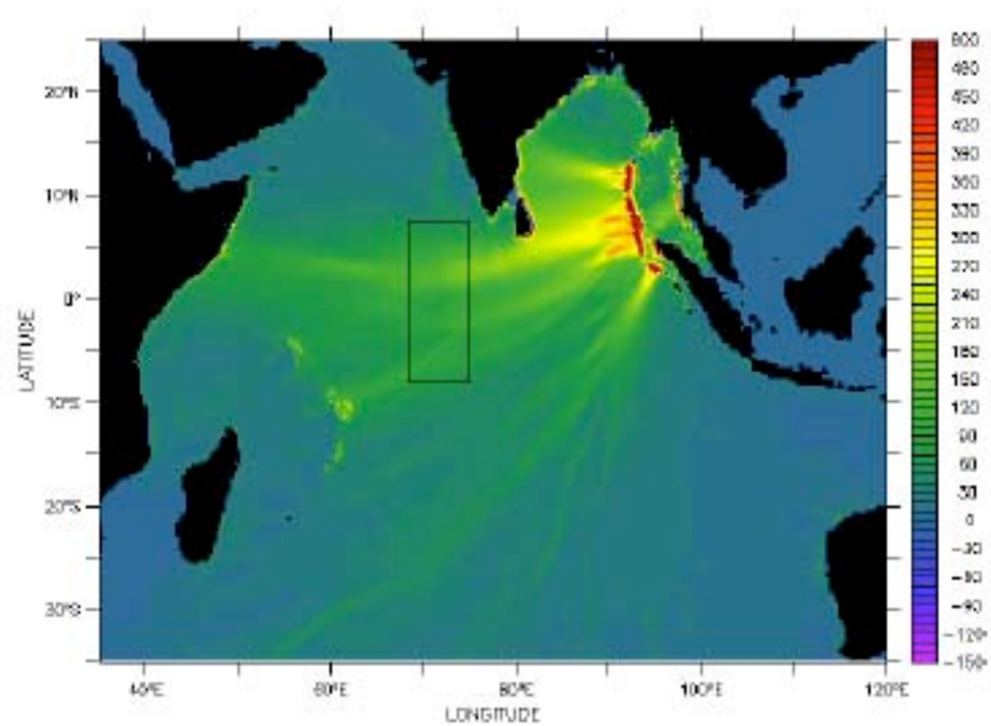
Without Nias & Simeulue ***With Nias & Simeulue***

Arcas & Synolakis, Science April 15, 2005

Could it had been even worse ?



With the Maldives in place

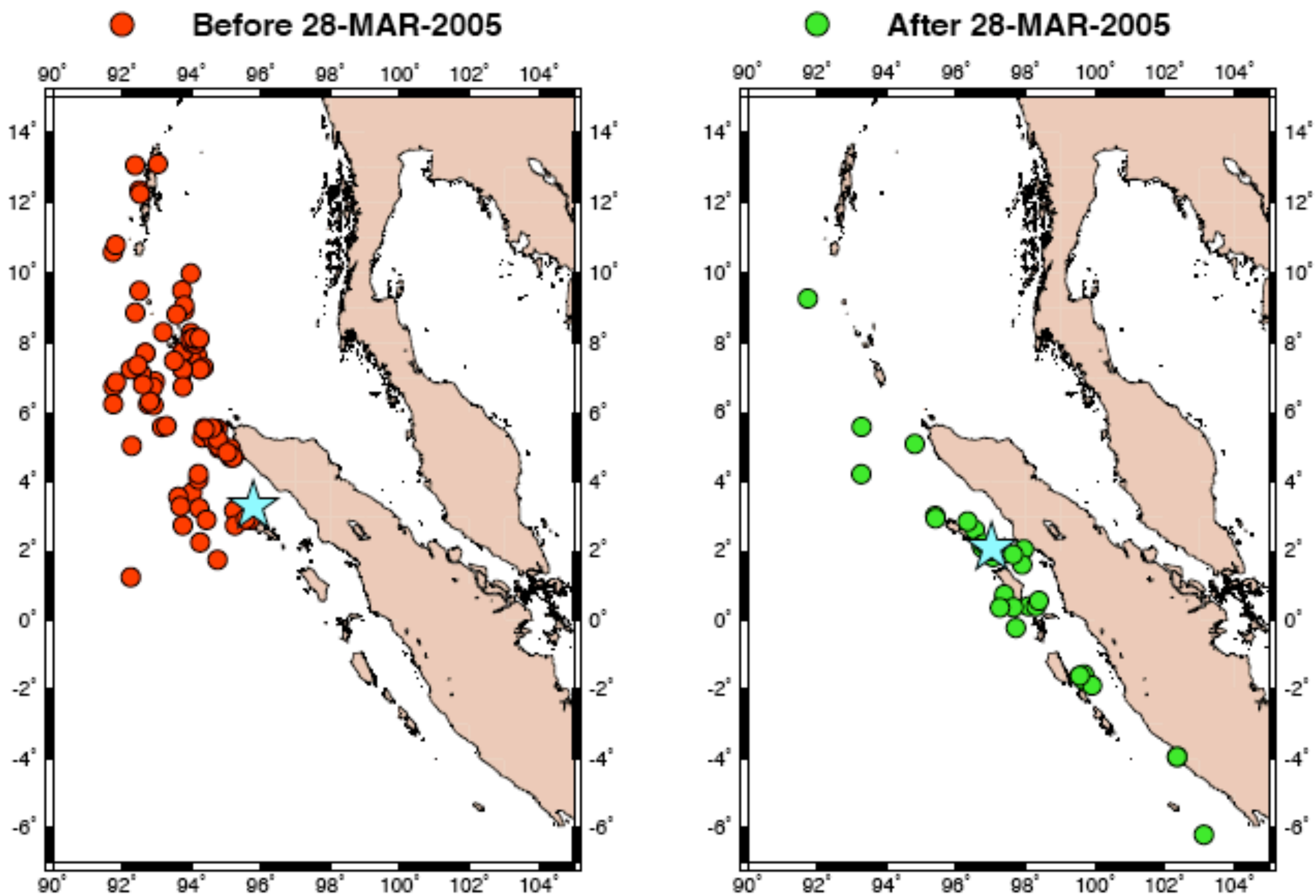


Without the Maldives

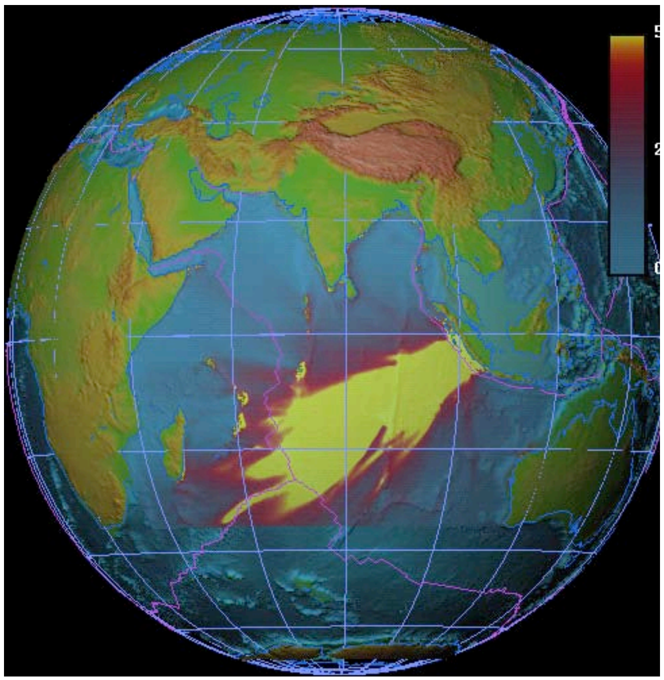
What next for Sumatra ?

28-MAR-2005 (SUMATRA-II) EARTHQUAKE PREDICTED ON THE BASIS of STRESS TRANSFER by McCLOSKEY *et al*. [*Nature*, 17 MAR 2005].

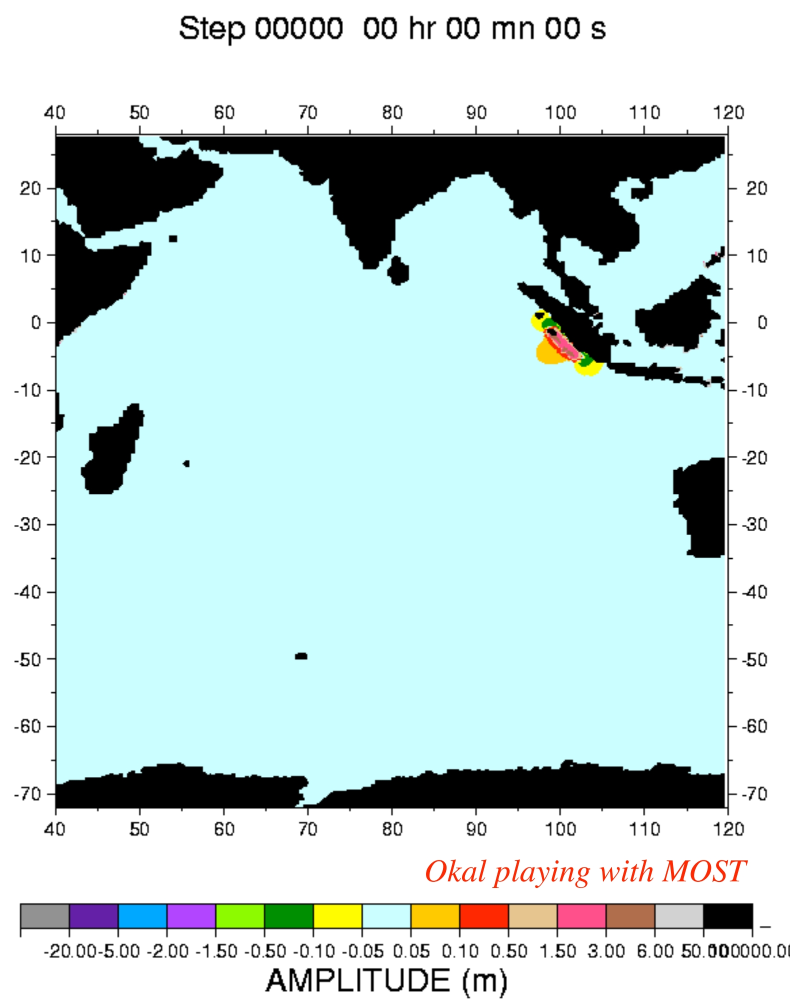
Events with CMT Solution (To 20-MAY-2005)



A repeat of the 1833 event in Soutwestern Sumatra ?

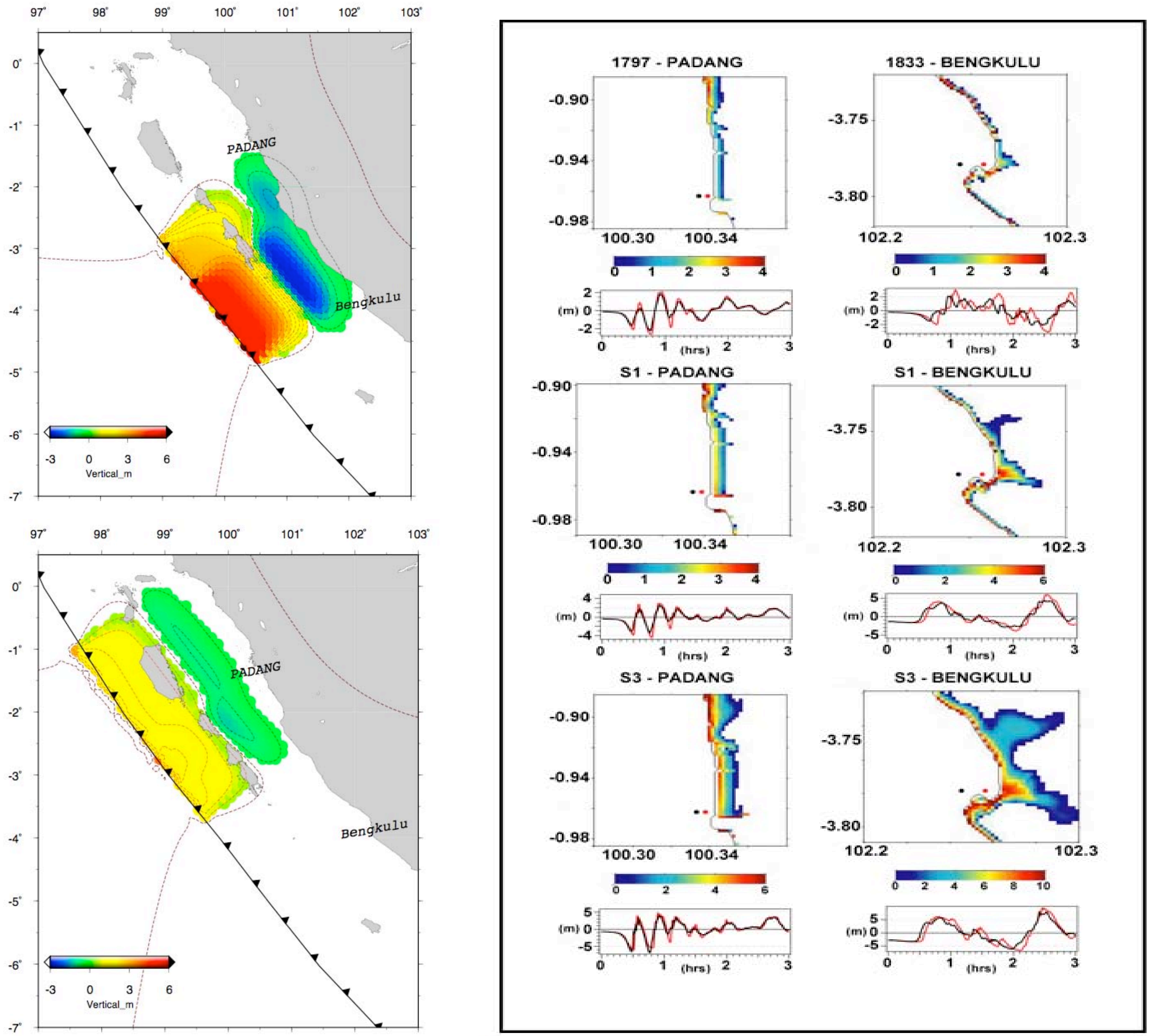


Diego Arcas & Vasily Titov, NOAA



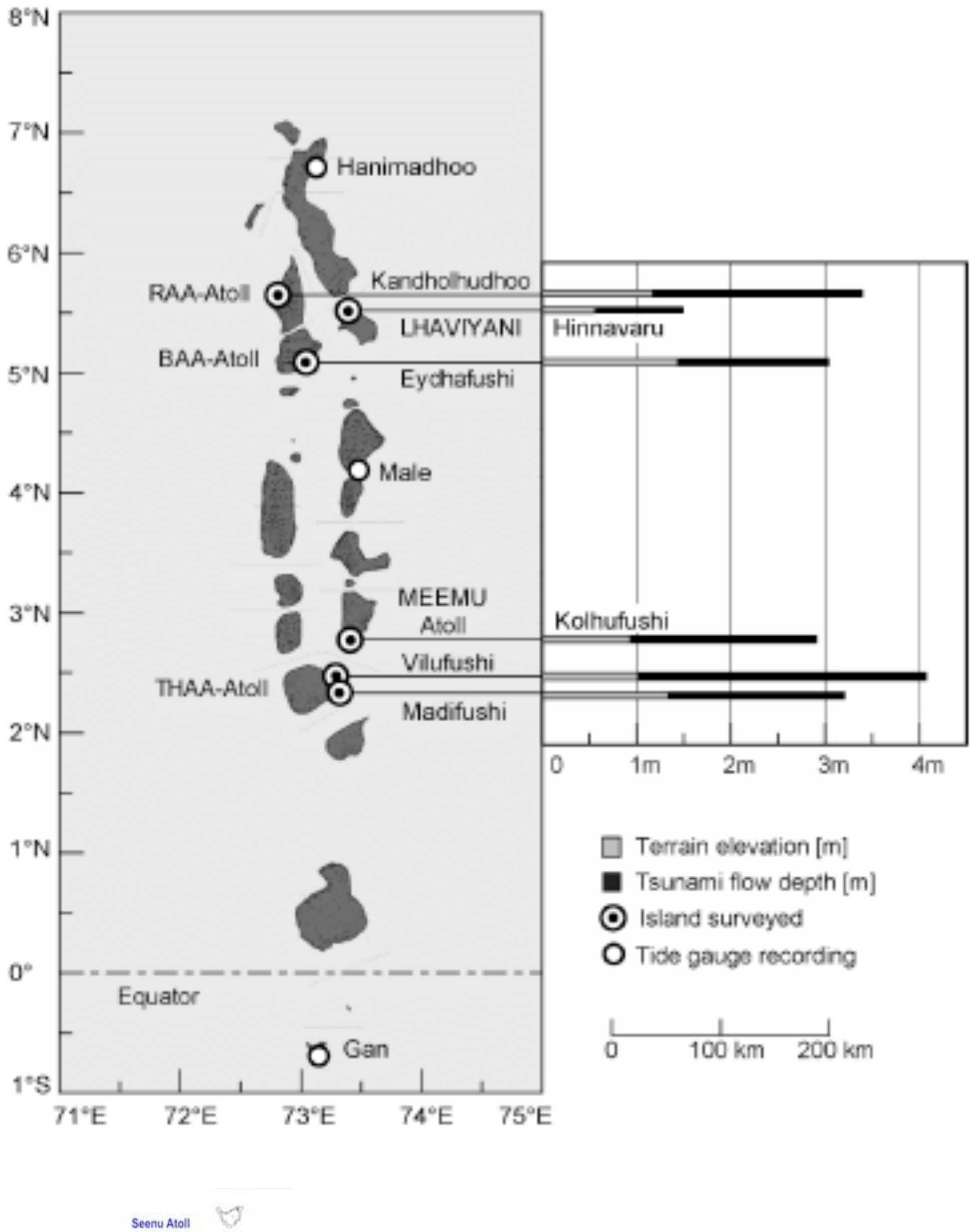
Okal playing with MOST

Getting ready for the next Sumatran tsunami



Borrero, Sieh, Synolakis, PNAS, 2006.

Why were the Maldives spared ?

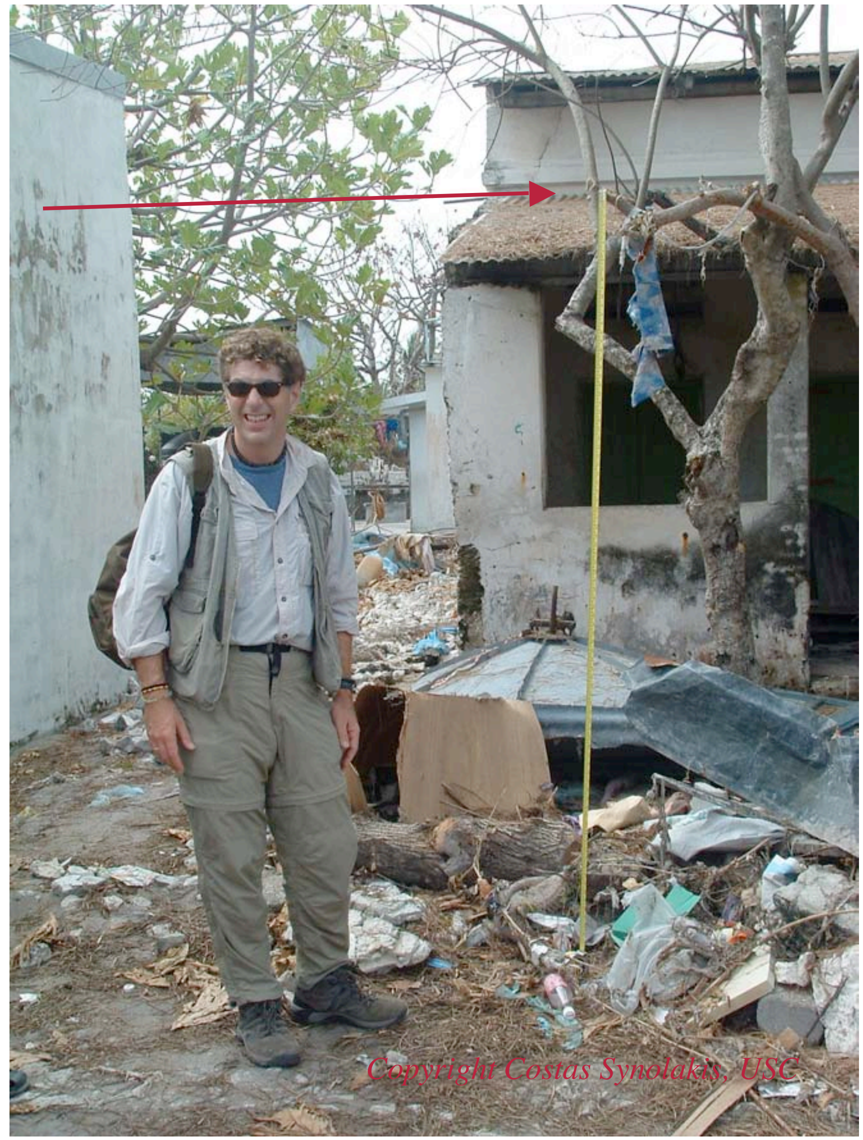


Tsunamis in the Maldives.

- 290,000 population
- 300 sq km
- 199 inhabited islands
- 82 deaths - 24 missing - compare with 300 in Somalia

Flow depth measurements in the Maldives.

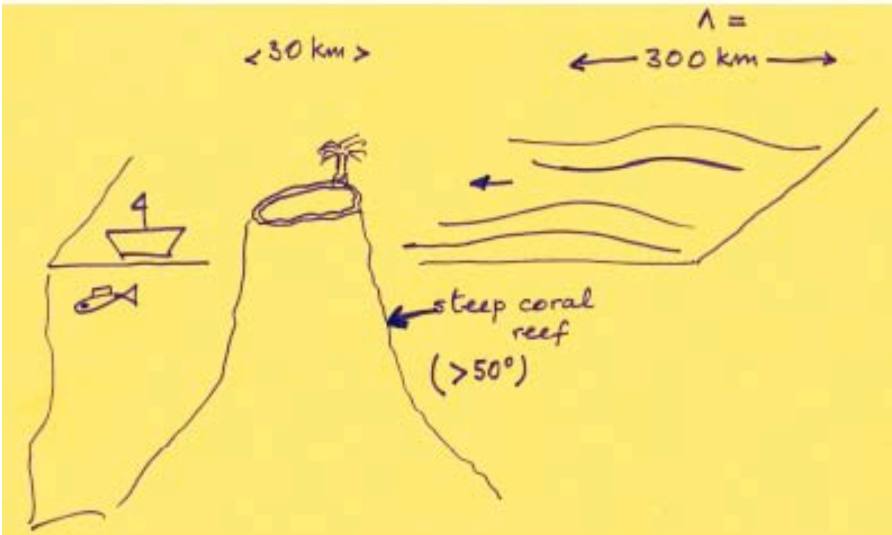
Debris in Trees



7. FURTHER LESSONS

3. The value of pillared structures, Large and Small

- Run up observed very low (2 m) on ***ATOLLS*** (Diego Garcia, Maldives) as opposed to high islands (Sri Lanka; 8 to 9 m).



- Small dimension of structure and steep slope minimize obstruction to tsunami [?]
- Flow depth on atolls more representative of amplitude on high seas.

With hindsight, implicit in the earlier work of Longuet-Higgins, Lautenbacher, Kanoglu and Synolakis.

Mosque at Banda Aceh, *Largely preserved*

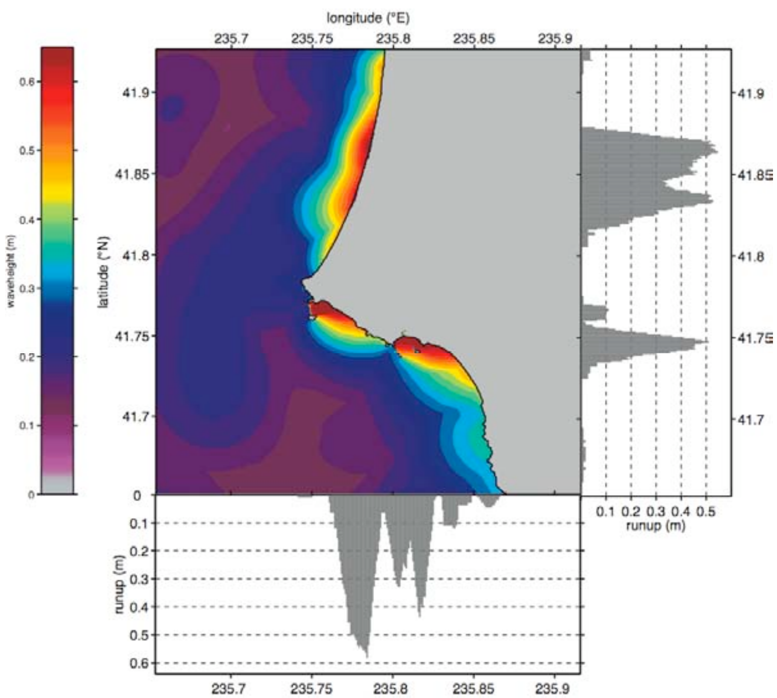
NOTE: Structure built on many pillars...

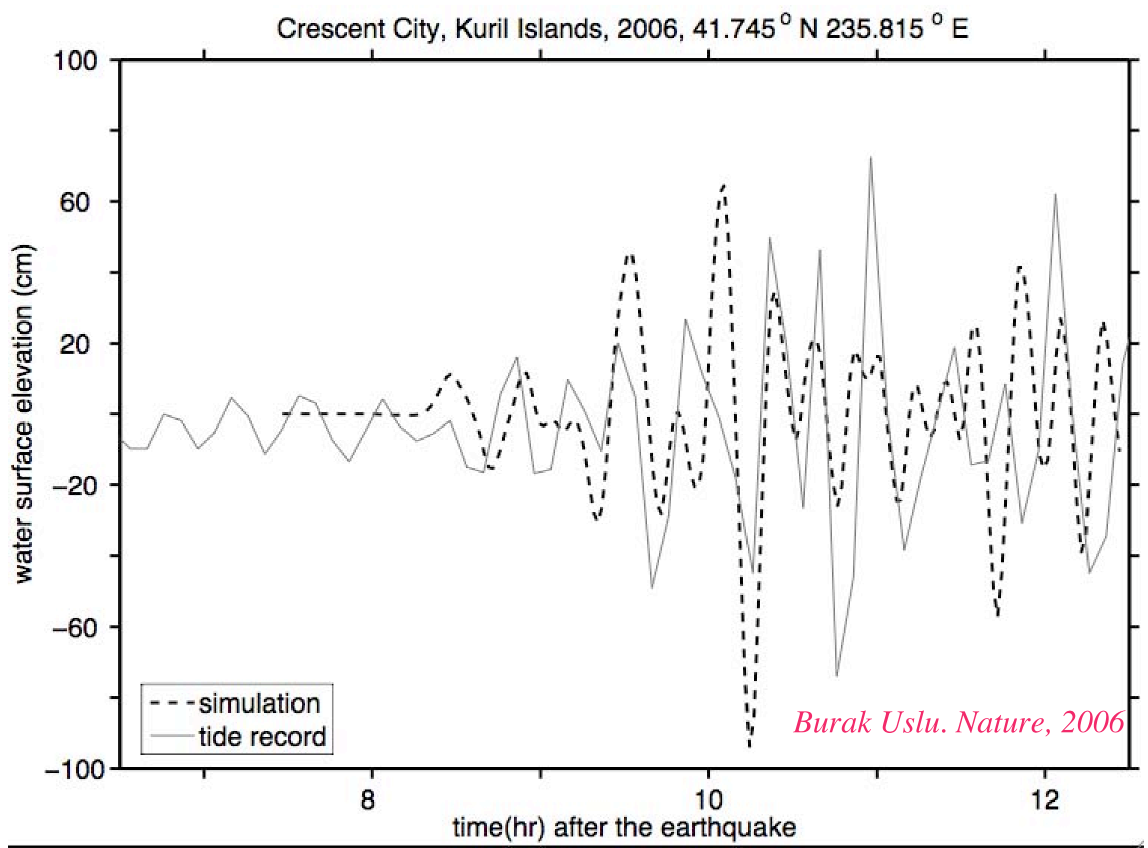
Emile Okal, 2005

Lessons from the two Sumatra tsunamis.

- Small scale features affect inundation to first order.
- The value of pillared structures whether natural or manmade.
- Well engineered reinforced concrete (RC) structures survive.
- Tsunamis can be detected by satellites, tide gages, seismometers and hydrophones - *yet tsunameters remain the golden standard for instrumentation for early warning and forecasting*.
- Tsunami hazard mitigation is a moving target - we always learn that we know far less than we thought we knew.
- Education, education, education.

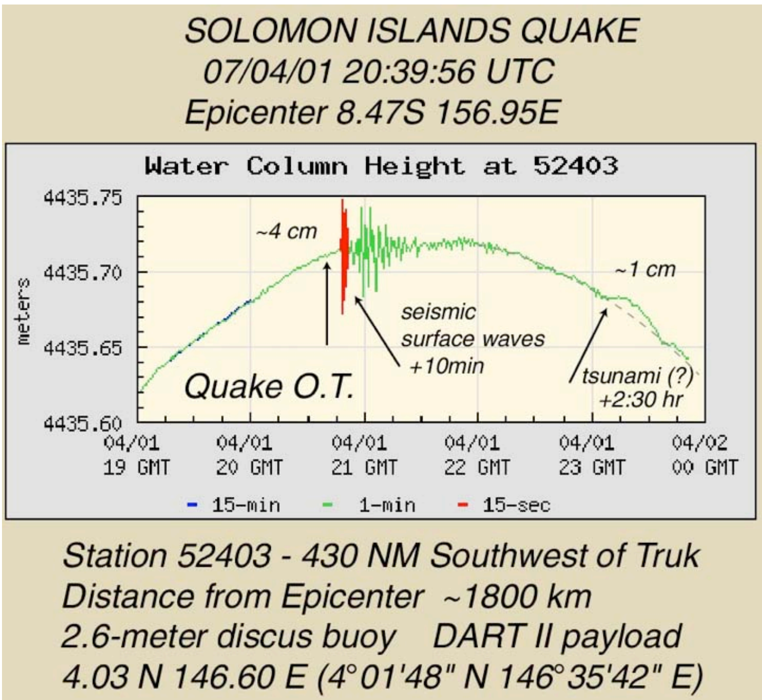
How well can we do ?
A real time prediction for Crescent City, California for the 15 November 2007 Kuril Islands event, based on NOAA's and USC's precomputed scenarios.





In the right figure, a comparison between the tide gage measurement (solid) with prediction (dashed).

The Solomon Islands, 1 April 2007



The ITST (Japan, US, Greece) is on the ground in the Solomon Islands, now.
Photos by Professor Hermann Fritz (Georgia Tech) and Nick Kalligeris (TUC).
Real time forecast for Hawaii done once again by Dr. Robert Weiss.

What is missing (for now)

How and why does the tsunami front accelarate far inland (>3km) from subcritical to supercritical conditions ?

Do real tsunami fronts accelarate when reaching the initial shoreline position or very close to it ?

(*Do not get mesmerized into a sense of false security by the initial "slow" motion of the advancing tsunami, whether on the* shoreline *or far inland.*)

What are really the effects of *small*-scale features - reefs, mangroves, small seawalls ?

Can we calculate the initial waves generated from cohesive or cohensionless slides ? Can we parametrize the process a la Okada ?

Can we do real time inundation forecasts for extreme *nearshore* events ?

Can we improve the real time forecasts for *farfield* events- beyond just predicting adequately the height of the largest wave ?

How can we best use sediment deposits to estimate vulnerability ?

Conclusions

(Huppert and Sparks, Phil. Trans., 2006)

- The World is becoming ever more susceptible to natural disasters. *It is likely that in the future we will experience several disasters per year that kill more than 10,000 people each*. A calamity with >*1,000,000* casualties seems just a matter of time.
- This situation is mainly a consequence of increased vulnerability. *Climate change* may also be affecting the frequency of extreme weather events as well as *vulnerability of coastal areas* due to sea level rise.
- Disasters *can only increase* unless better ways are found to mitigate the effects through improved forecasting and warning, together with more community resilience and preparedness.

The most basic defense, before anything else gets implemented.

Education, Education, Education and Public Outreach.