The Abdus Salam
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Educational, Scientific and
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IAEA
International Atomic Energy Agency

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Conference and School on Predictability of Natural Disasters for our Planet in Danger. A System View; Theory, Models, Data Analysis

25 June - 6 July, 2007

Tsunami -- Hazards from Earthquakes, Landslides, Asteroid Impact

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ICTP 6/26/07

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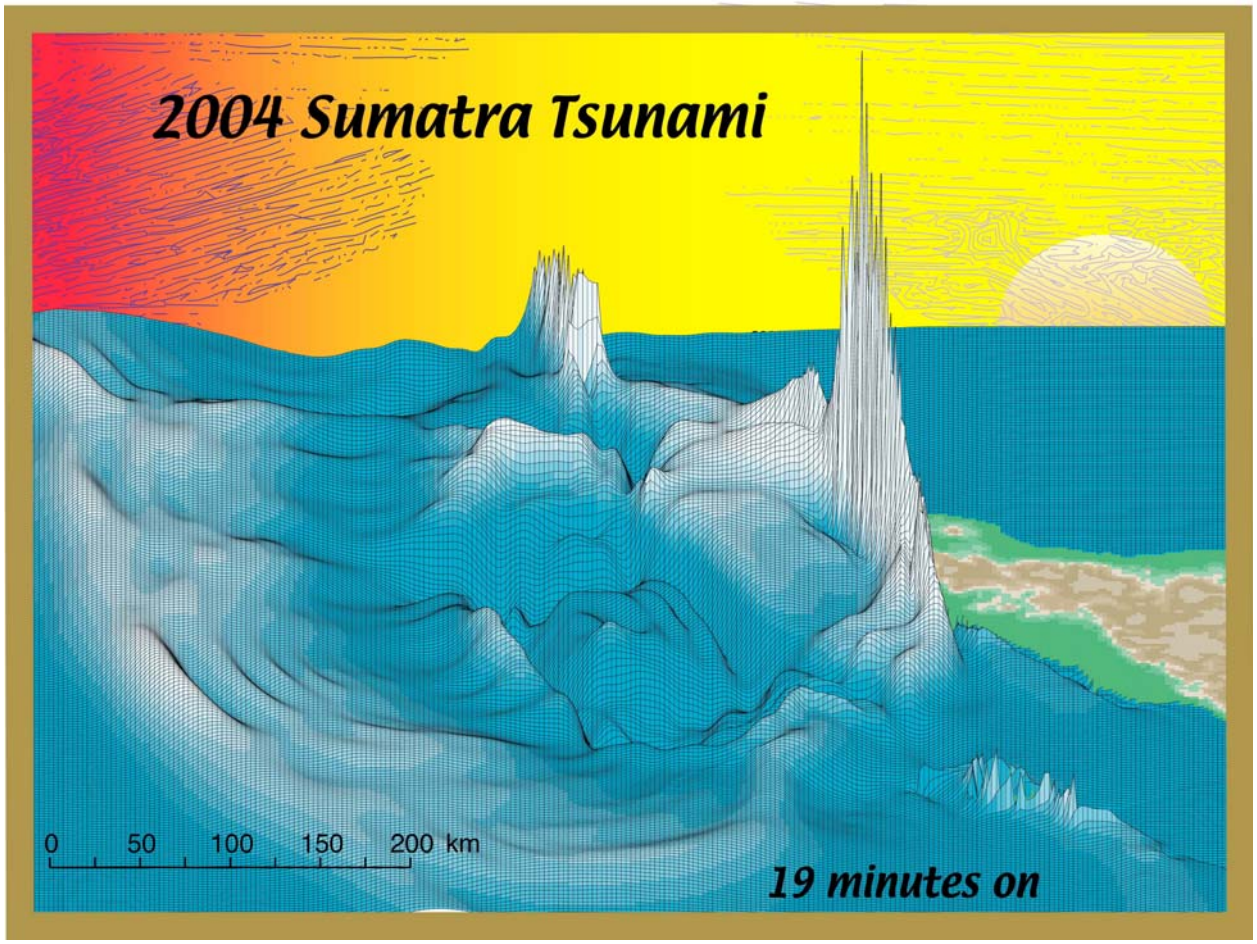


Tsunami Hazard - A sleepy field ….

*Tsunami Hazard - A sleepy field …. **with rude awakenings***

BULLETIN

PUBLIC TSUNAMI MESSAGE NUMBER 1

NWS WEST COAST/ALASKA TSUNAMI WARNING CENTER PALMER AK 833 PM PST FRI JAN 12 2007

AT 823 PM PACIFIC STANDARD TIME ON JANUARY 12 AN EARTHQUAKE WITH PRELIMINARY MAGNITUDE 8.4 OCCURRED EAST OF THE KURIL ISLANDS RUSSIA. THIS EARTHQUAKE MAY HAVE GENERATED A TSUNAMI. IF A TSUNAMI HAS BEEN GENERATED THE WAVES WILL FIRST REACH SHEMYA ALASKA AT 934 PM AKST ON JANUARY 12. ESTIMATED TSUNAMI ARRIVAL TIMES AND MAPS ALONG WITH SAFETY RULES AND OTHER INFORMATION CAN BE FOUND ON THE WEB SITE WCATWC.ARH.NOAA.GOV.

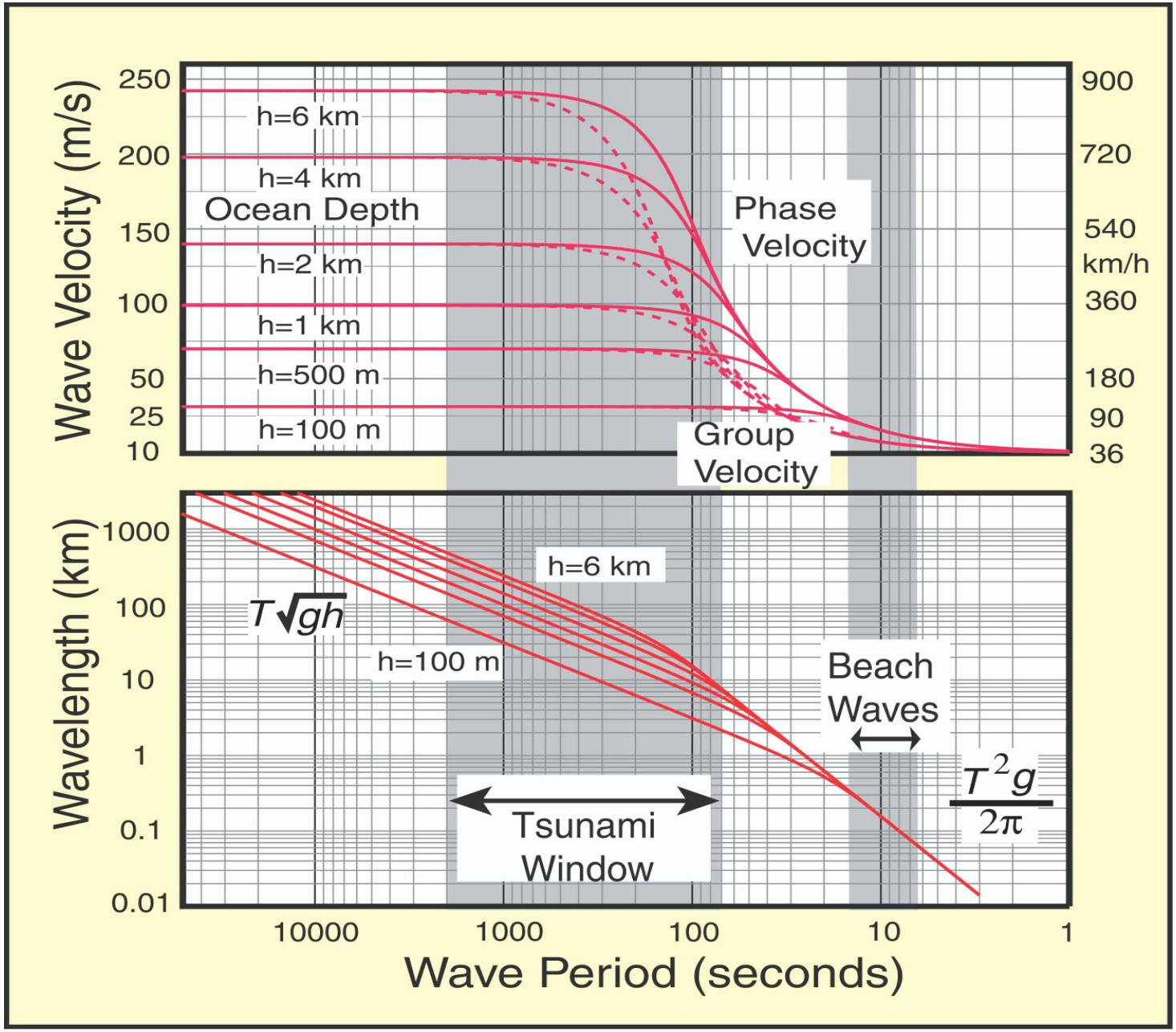
...A TSUNAMI WARNING IS IN EFFECT WHICH INCLUDES THE ALASKA COASTAL AREAS FROM NIKOLSKI ALASKA TO ATTU ALASKA.....

A TSUNAMI WATCH IS IN EFFECT FOR THE ALASKA COASTAL AREAS FROM SEWARD ALASKA TO NIKOLSKI ALASKA.....

AT THIS TIME THIS MESSAGE IS ADVISORY ONLY FOR OTHER AREAS OF CALIFORNIA - OREGON - WASHINGTON - BRITISH COLUMBIA - AND ALASKA...

Tsunami waves have far greater period, faster speed, and longer wavelength than familiar beach waves

In deep ocean, a 10m wave rising over 50 km is as flat as Kansas.



Ships at sea don't see tsunami.

Wave field decomposed by Eigenmodes, propagated individually from source, then reconstructed at specified receiver point.

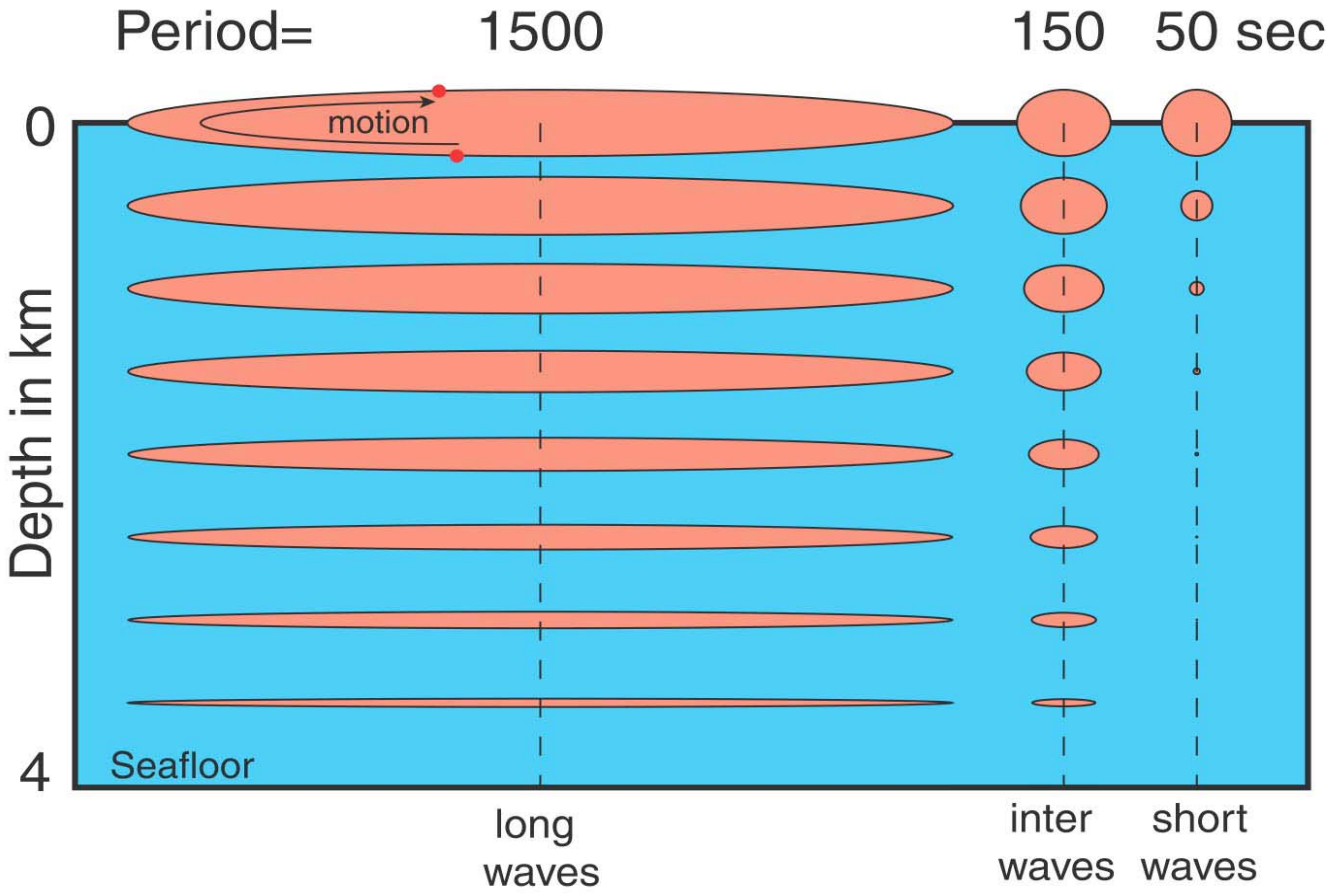
Unlike regular waves, tsunami reach all the way to the sea bottom.

Generate Bedforms

--You can't out dive a tsunami.

$$u_z(x,z,t,\omega) = \frac{k(\omega)g}{\omega^2}\frac{\sinh(k(\omega)(H-z))}{\cosh(k(\omega)H)}e^{i(k(\omega)x-\omega t)}$$

$$u_x(x,z,t,\omega) = -\frac{ik(\omega)g}{\omega^2}\frac{\cosh(k(\omega)(H-z))}{\cosh(k(\omega)H)}e^{i(k(\omega)x-\omega t)}$$



Tsunami slow and grow as they near the coast.

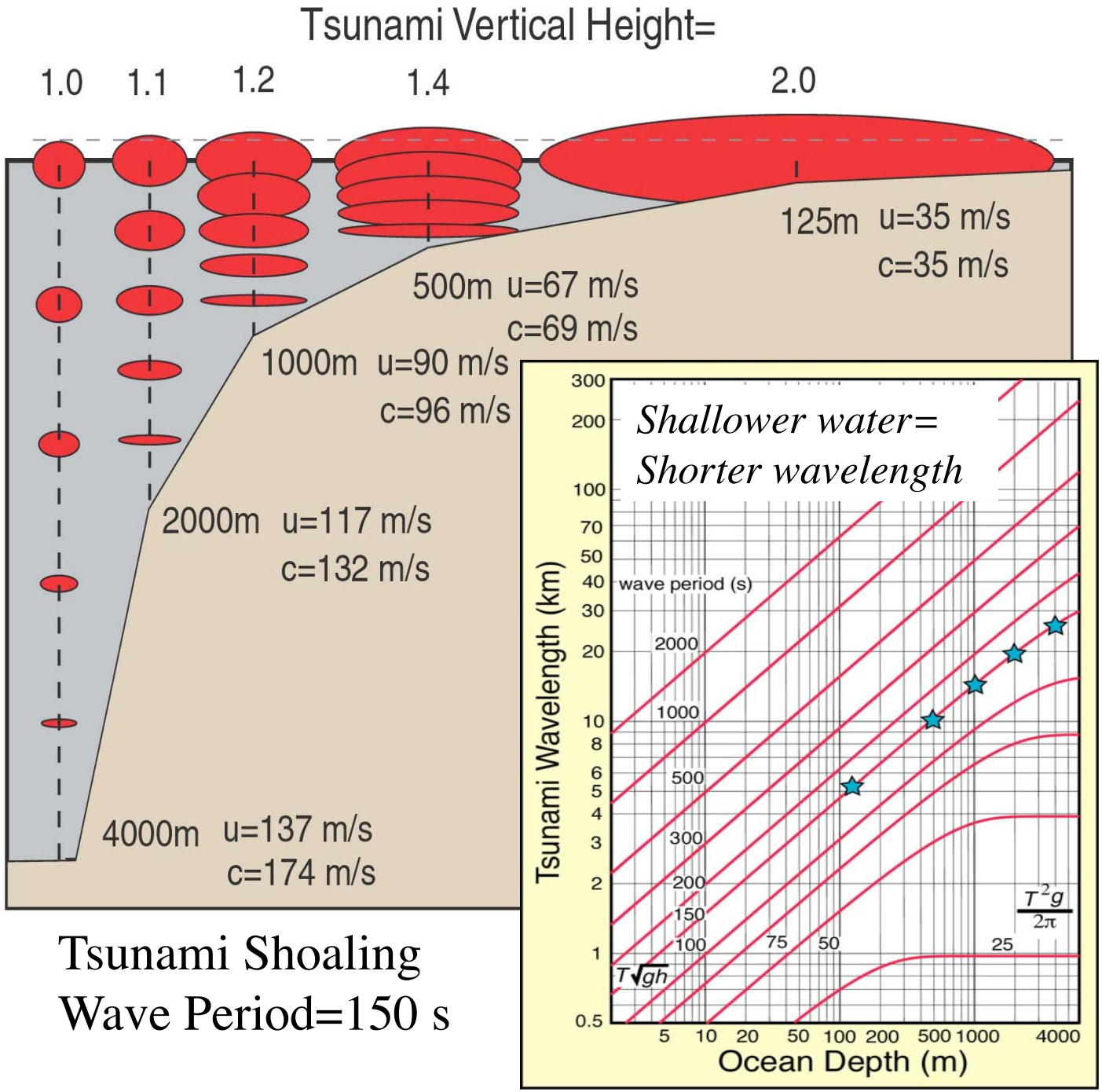
In deep water

V~500 mph

They come ashore about 20-30 mph.

Still -- Can't outrun one to high ground.

Grow by 3 -4x



Tsunami Shoaling
Wave Period=150 s

Best description: The ocean turns into a river …….a river flowing right toward you.

Best description: The ocean turns into a river
…….a river flowing right toward you.

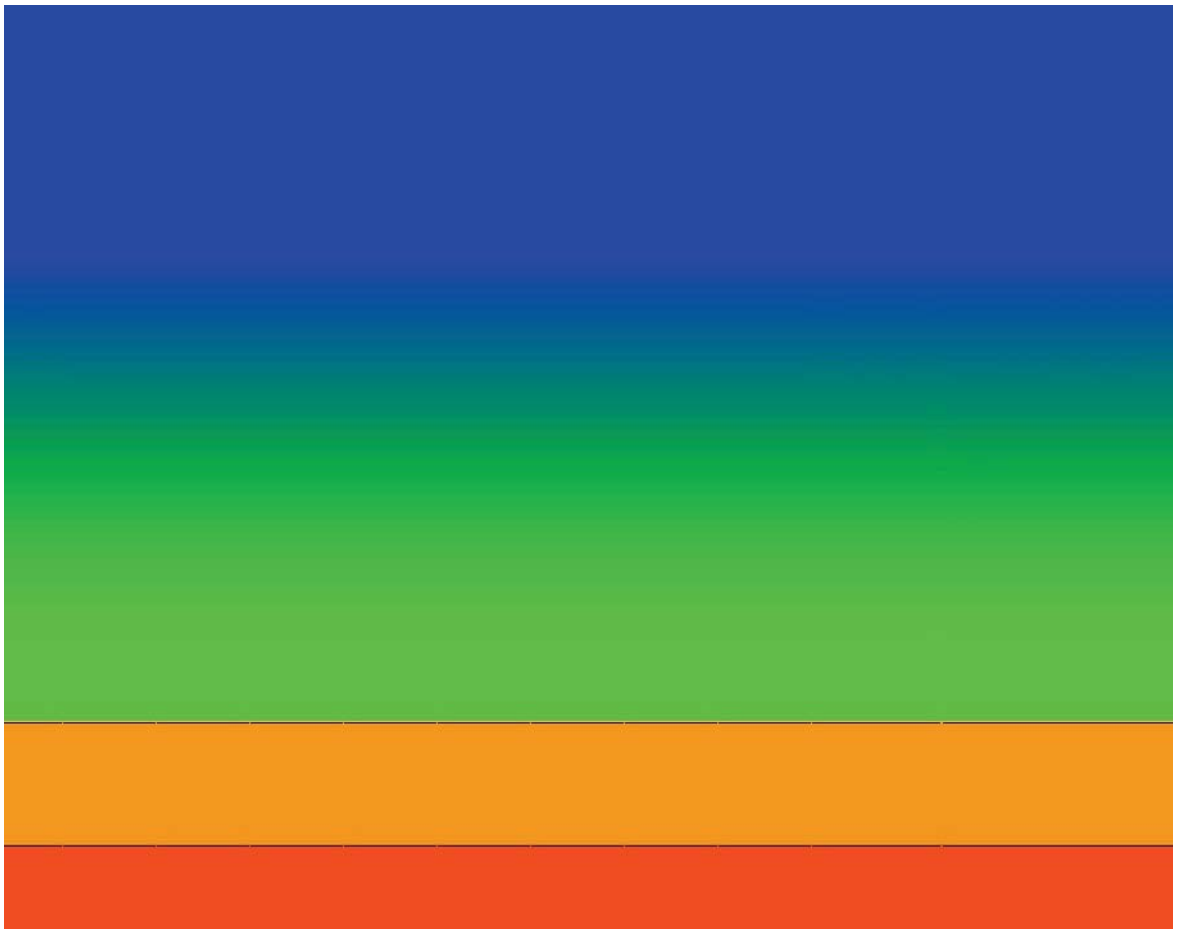
At 20 mph, water exerts

~800 lbs/sq ft $P=\rho_w v^2/2$

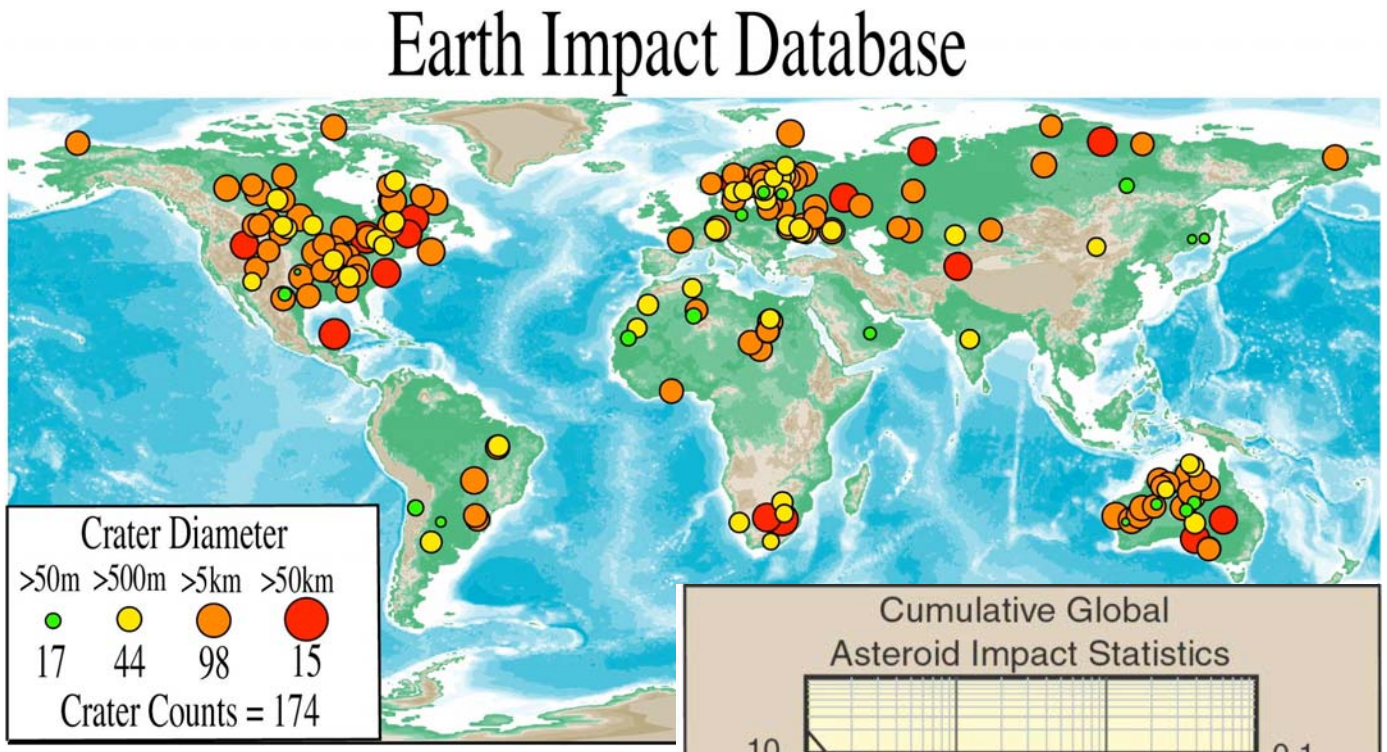
How Do Tsunami Get Started?

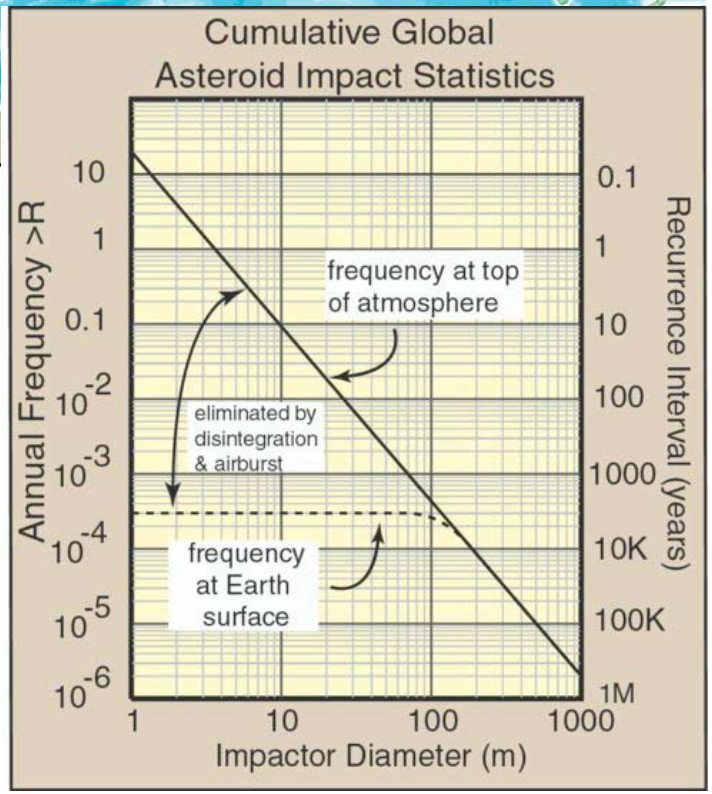
1) Disturb the sea surface.

Say, Drop an Asteroid in the Ocean.



You might think asteroid impact is crazy, but there are ~175 known impact structures on Earth





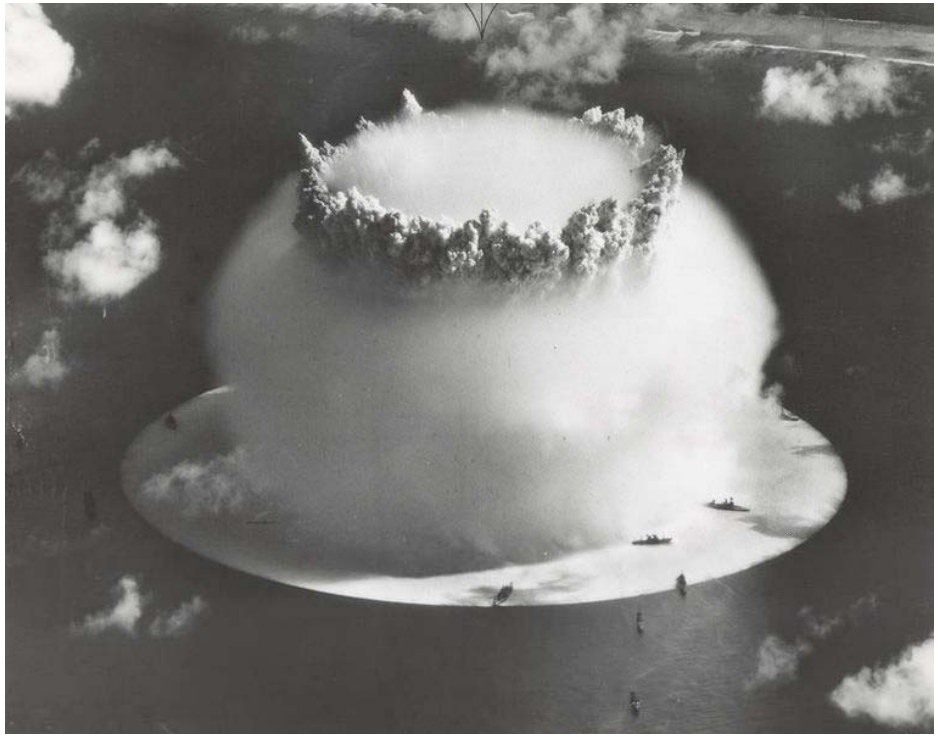
Like many things in nature, asteroids follow a power law distribution of size versus number.

D~3-4 m is Annual Event (Fireball)

D~50m 500y Event (Tunguska Level 1908)

D~500m 100,000y Event

D~5000m 20,000,000y Event (~Extinction Level)



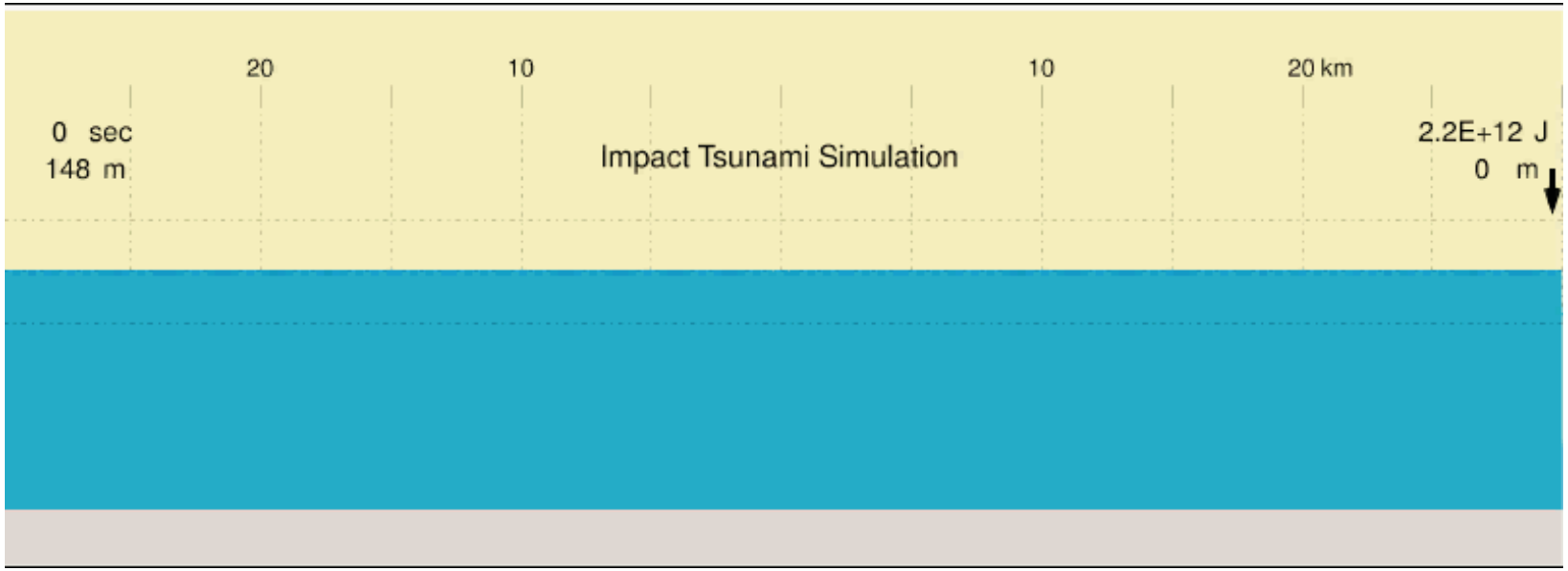
We have some feeling for impact-like effects from nuclear tests.

Baker Test: 1946

Bikini Atoll, Y=23Kt

Cavity Diameter ~ 1000 feet

Local Tsunami Height ~100 feet



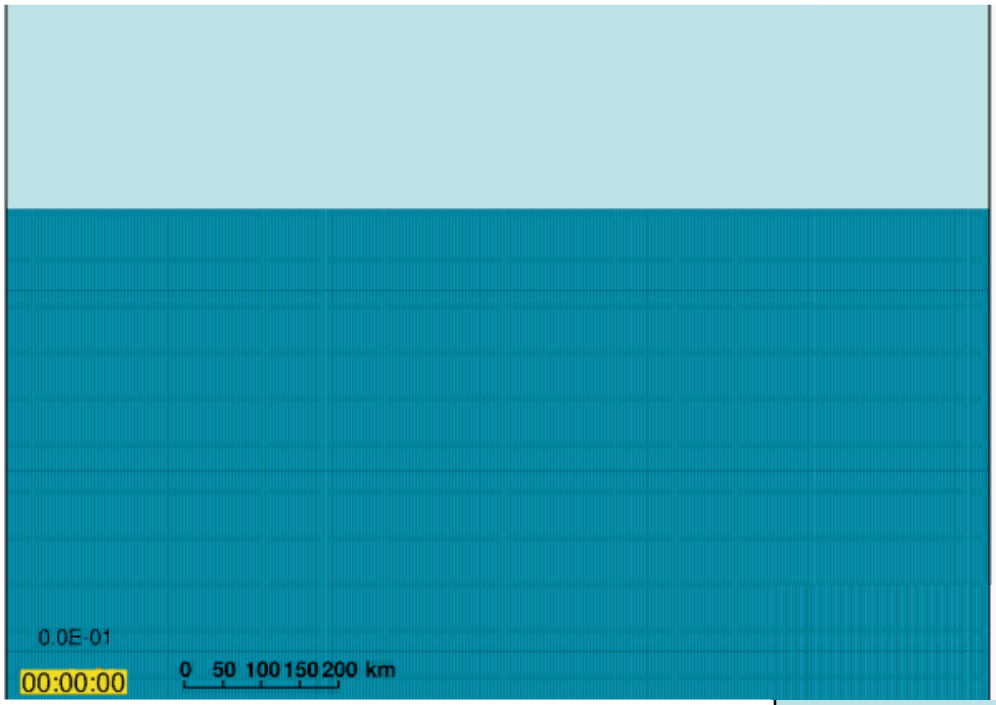
The biggest of the N-tests hardly holds a candle to even a "smallish" 500 m diameter asteroid at 40,000 mph.

Energy=9400 Mt = 400,000 x Baker Test

Blows a hole in the ocean about 12 km across.

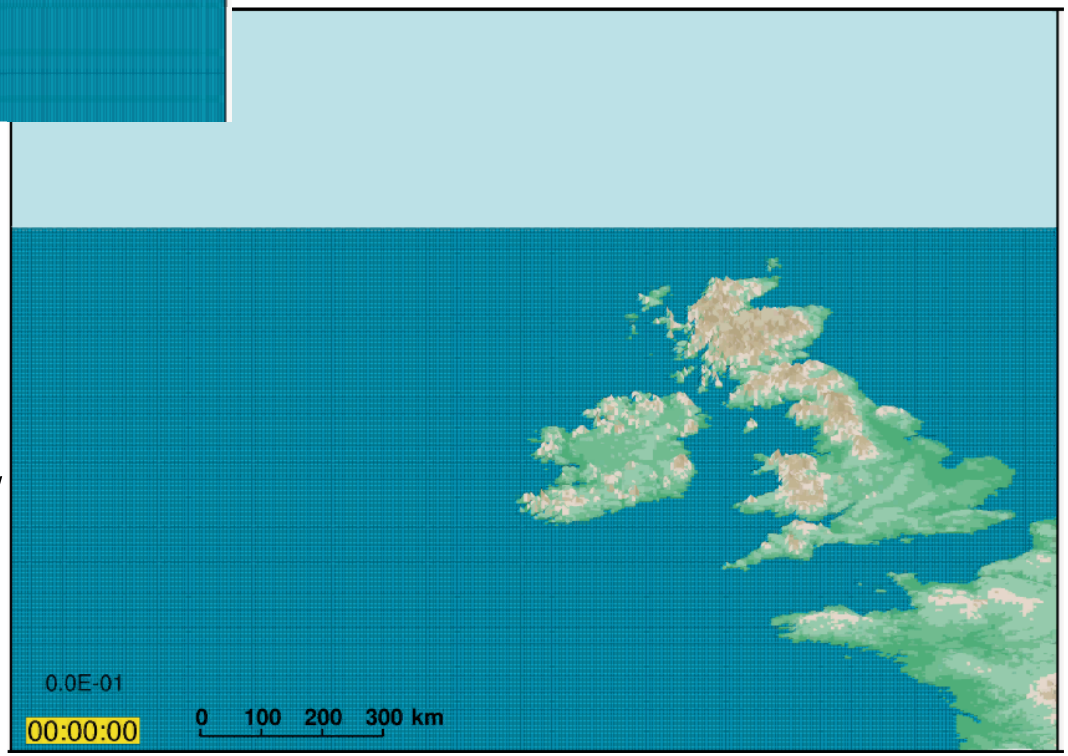
Wave heights from asteroid impacts can be 1000 meters locally

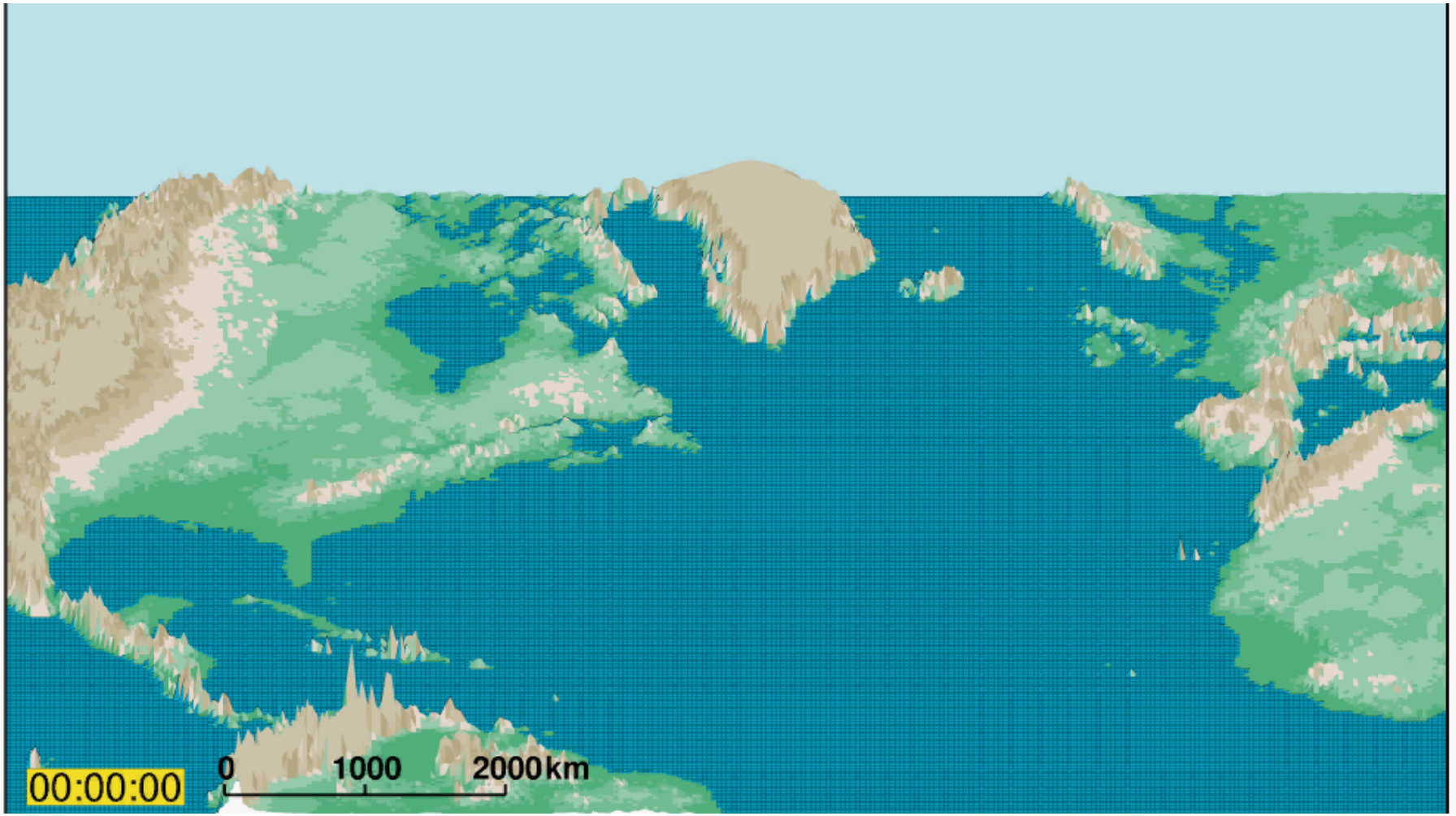
Impacts of this size happen about every 100,000 years.



Impact tsunami are very dispersive. Long periods travel faster than short periods. Dispersion reduces impact tsunami size with distance faster than EQ tsunami.

Propagation of tsunami beyond the cavity is not widely in dispute. Tsunami waves crush together in the shallows and "bend around" obstacles.
Watch out Ireland!





Tsunami take ~8-15 hours to cross ocean basins. Tsunami envelope shown here.

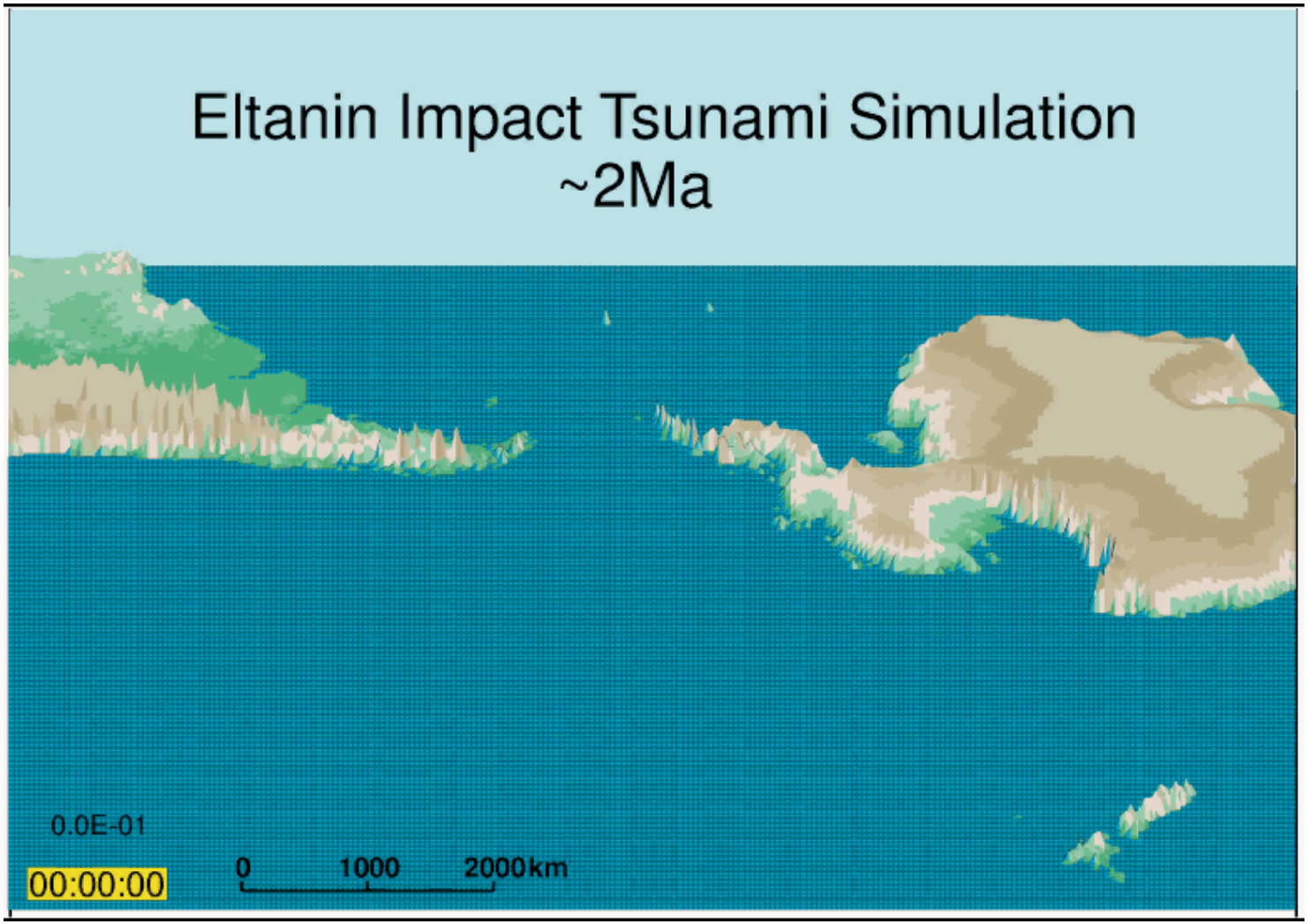
Historical Example Asteroid Eltanin Diameter: 1100m

When: 2.15 Million Years Ago. Where: South Pacific

Impact Tsunami this large potentially affect entire ocean basins

Evidence found D.S.D.P. Cores.

Deposits in New Zealand or Australia?



In terms of *"Predictability of Natural Disasters"* asteroid impacts can be one of the easiest to quantify -- Example: Asteroid 1950 DA has a 0.3% chance of Earth Impact on March 16, 2880.

No kidding.

WHERE NEXT?

Asteroid Apophis
Diameter: 350m
Discovered: 12/26/04

Passes <30,000km from earth in 2029!!

Projected Earth Impact probability: ~1/40000

On April 13, 2036

Apophis Impact Scenario:
North of Panama Expect:
20m+ waves onshore

Est. Infrastructure loss:

400 Billion US$

“Everyone talks about natural disaster, but no one does anything about it.”

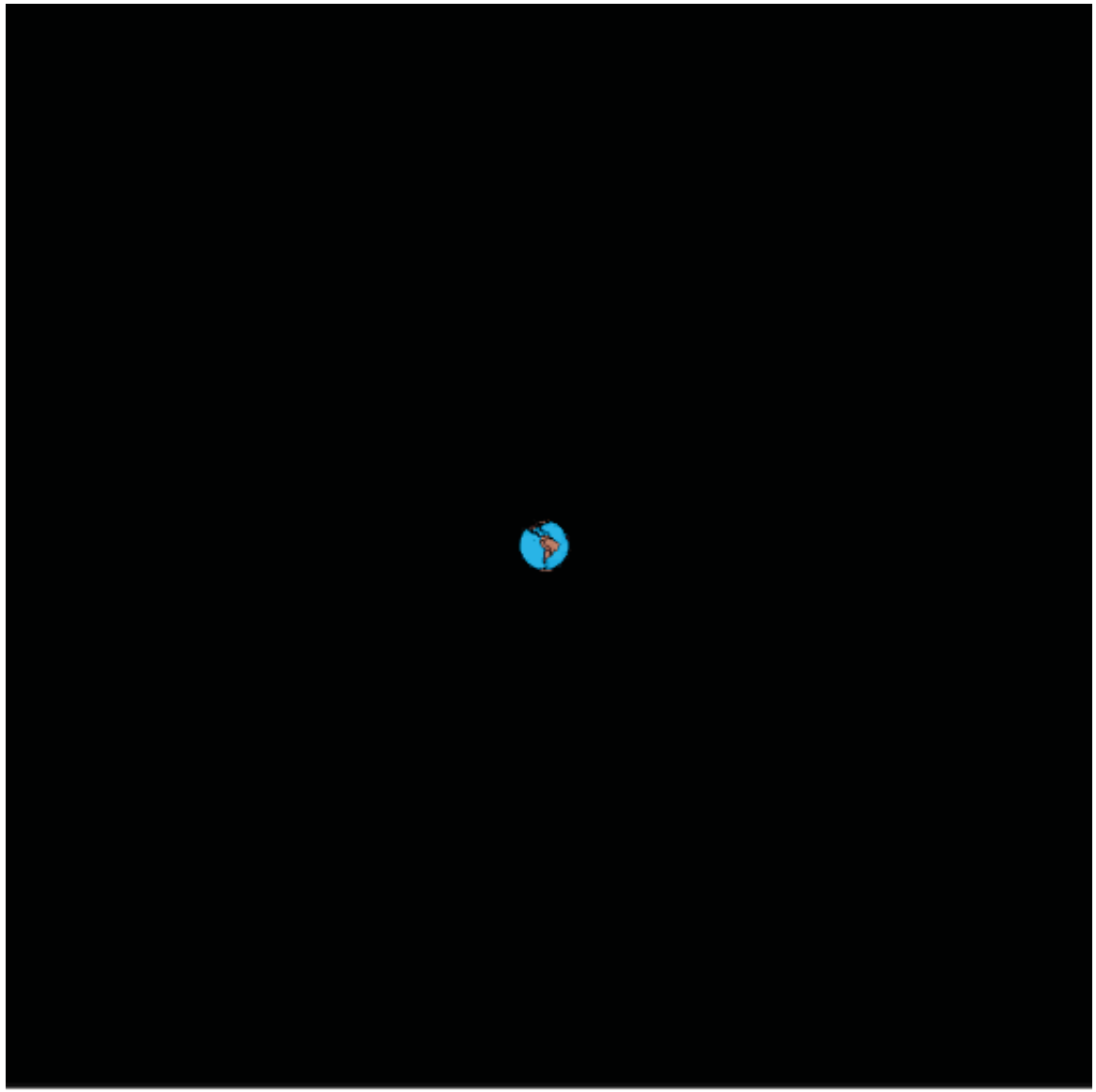
Asteroid Defense-

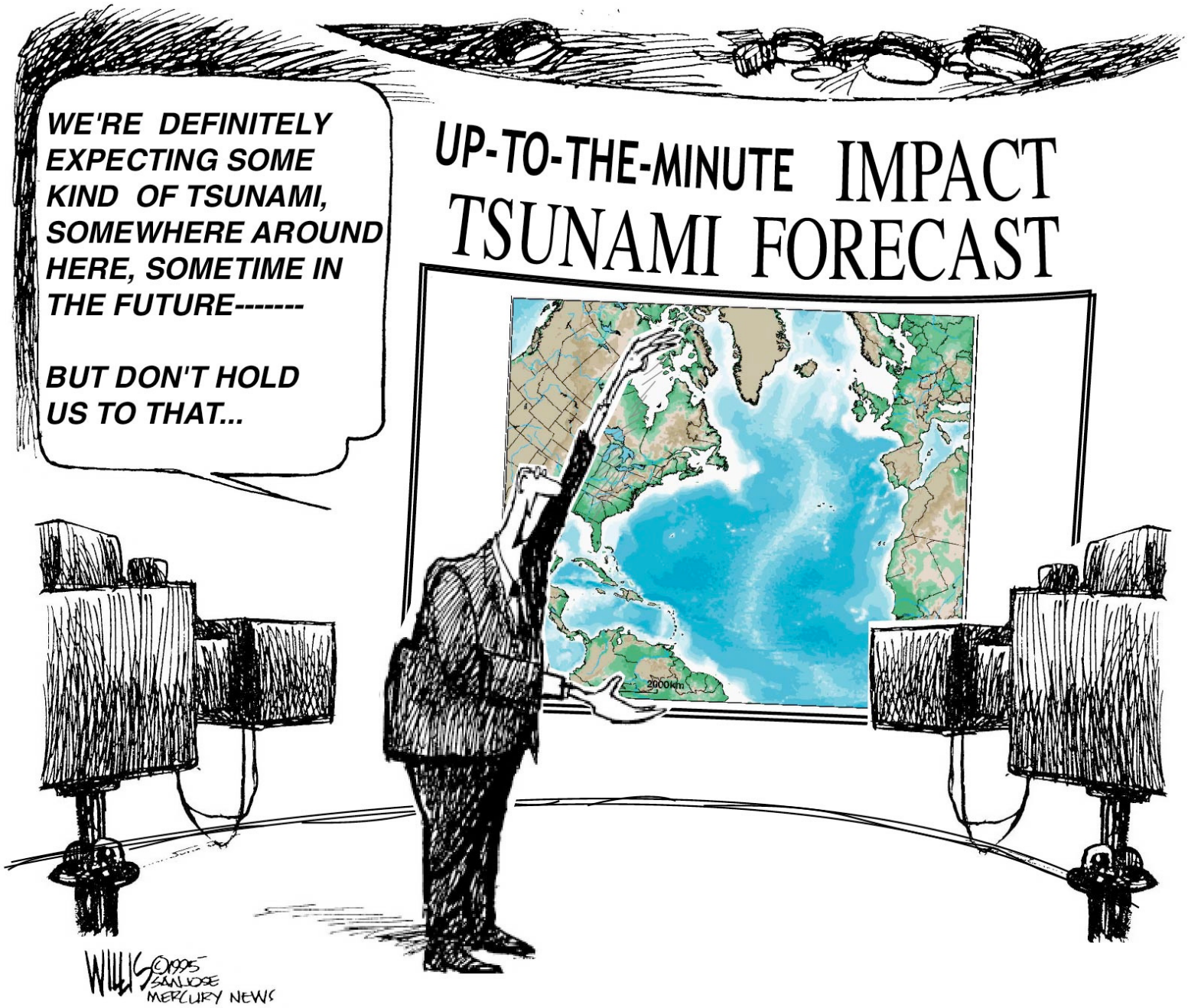
1) Gravity Tug

2) Kinetic Impact

3) Standoff Explosion

4) Surface Explosion





Predictability of Disaster --> Statistics of Hazard --> Statistics of Risk

What are the actual rates, diameters and velocities of asteroids targeting Earth?

What role does the atmosphere play during their transit to the surface?

What size of transient cavity do asteroids blast after striking the ocean?

To what extent do turbulent processes dissipate ocean waves spawned in those first few violent minutes?

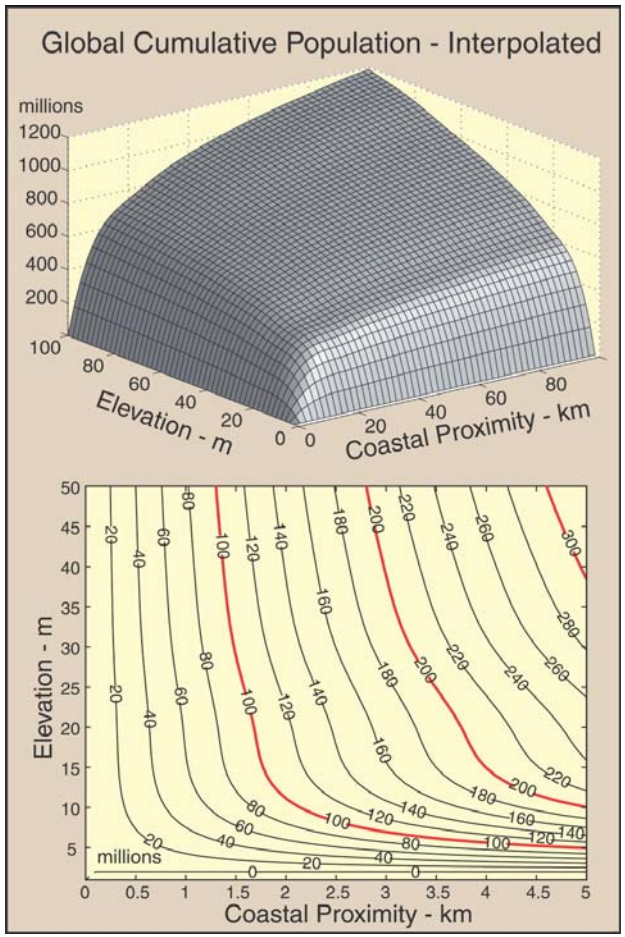
How do those tsunami that mange to escape the impact zone disperse in propagating to coasts 500 or 5000 km away?

How much tsunami energy vanishes in the “last mile” as waves break on continental shelves?

How high might the water run up? How long would the flooding last? How far inland will water penetrate?

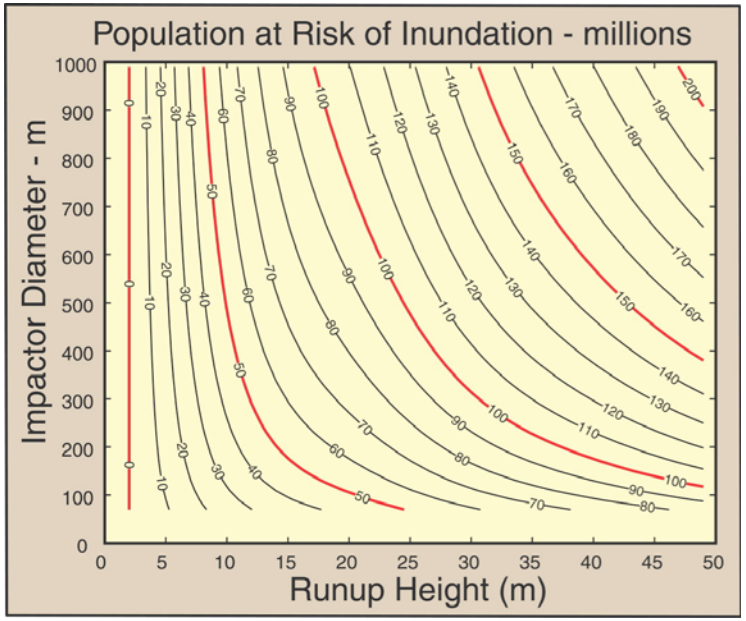
Impact-generated tsunami: A quantitative assessment of human and economic hazard

Annually, on average, 182(+197/-123) people will be affected by impact-induced waves with a corresponding infrastructure loss of $18(+20/-12)M/y.



Half of the tsunami hazard stems from impactors with diameters less than 300 m.

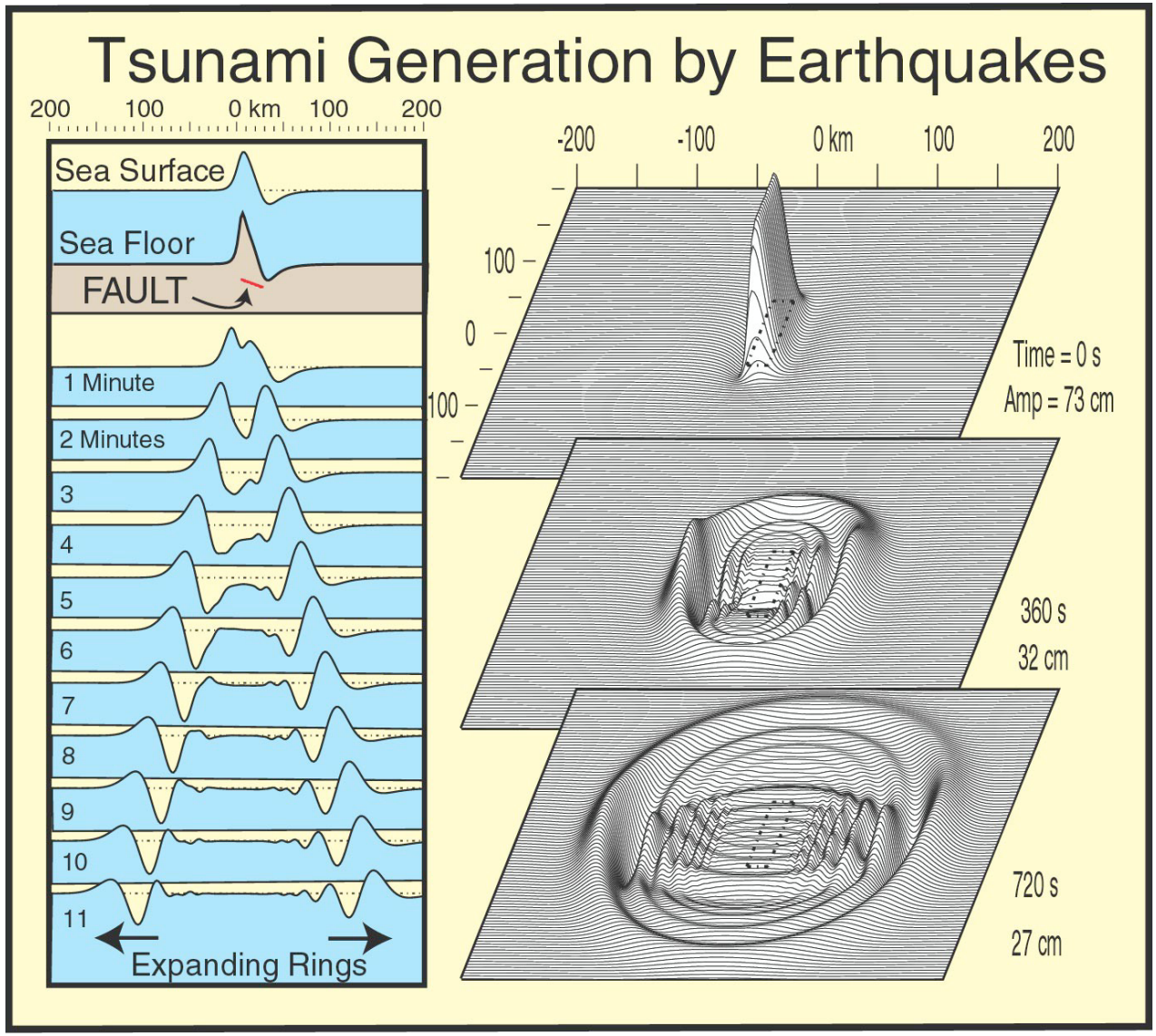
The mean loss scenario displaces about one million people and destroys $100B of infrastructure in impact events 5200 years apart.



How Do Tsunami Get Started? 2) Disturb the sea bottom. Permanently Say, push it up or down in an Earthquake.

After all the shaking is done, earthquakes leave vertical deformations on the sea floor and sea surface.

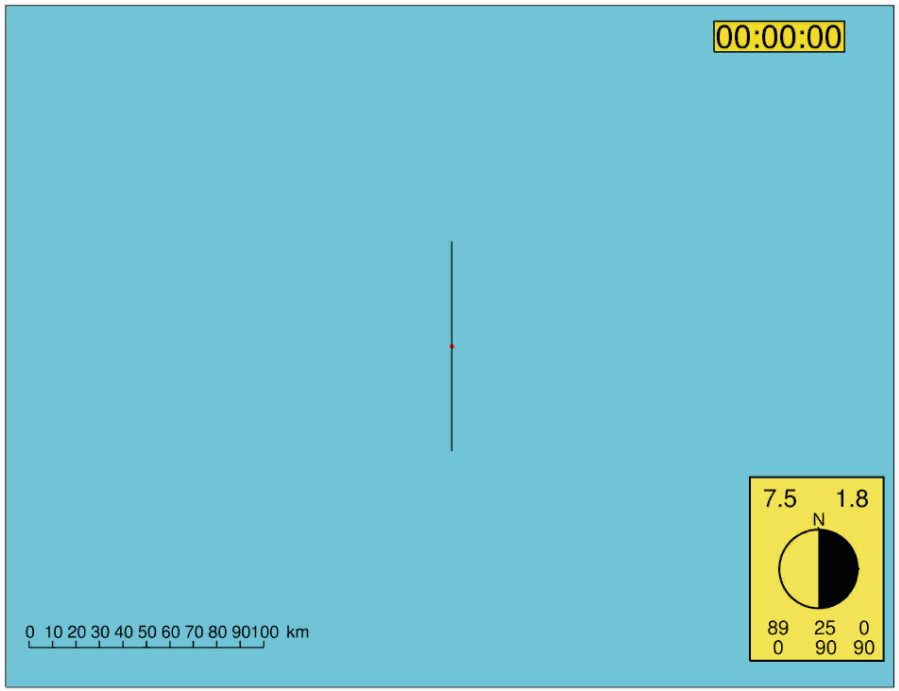
The sea floor deformations stay put, but the sea surface deformations propagate away as tsunami

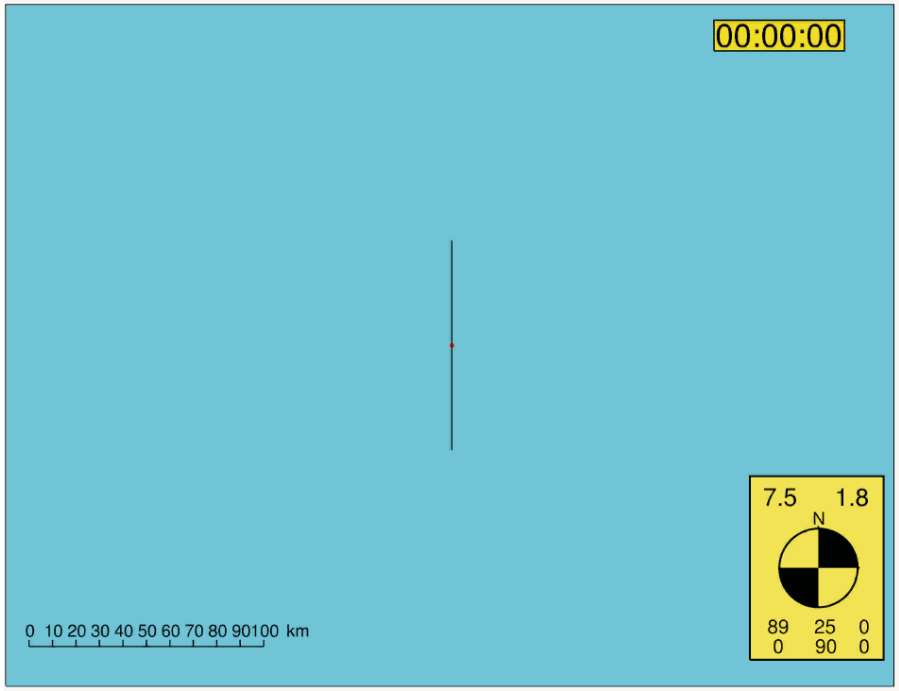


How big of tsunami depends on how much seafloor uplift there is. The amount of uplift depends mostly on the magnitude of the quake and the “Style” of faulting. Dip Slip or Strike Slip

Dip Slip on vertical fault here. One side up, one side down. Ditto for the tsunami. Peak amp 49cm

Strike Slip on vertical fault here. Four lobes now. Ditto for the tsunami. Peak amp just 4cm!

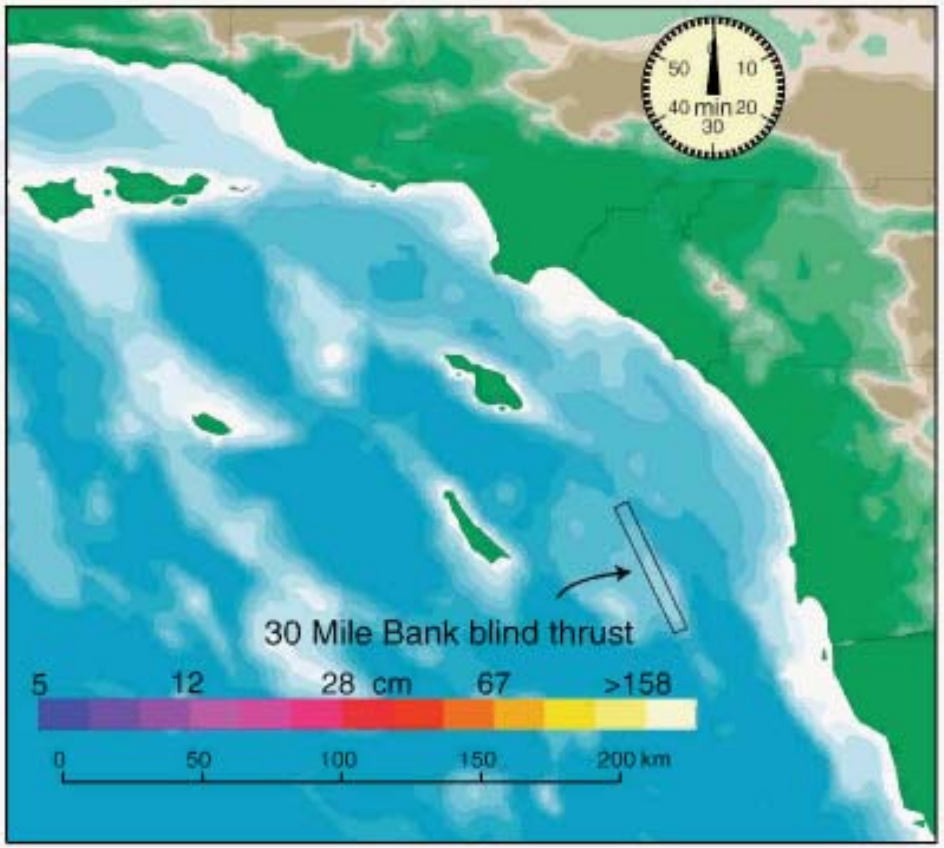




Here is a magnitude 7.5 quake off San Diego.

Makes about 2 m wave

Earthquake tsunami limited in height to the maximum slip in earthquakes, about 10-15 m tops

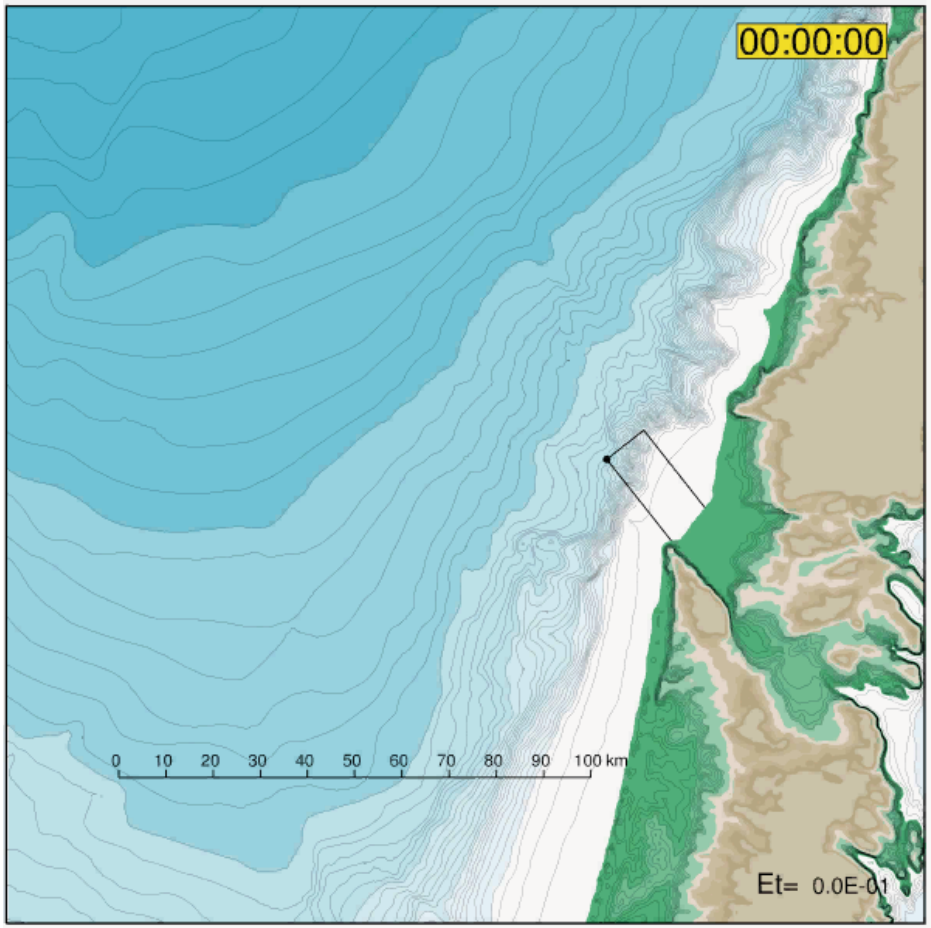


100s of M5 M6 quakes happen per year. These make “inch high” tsunami

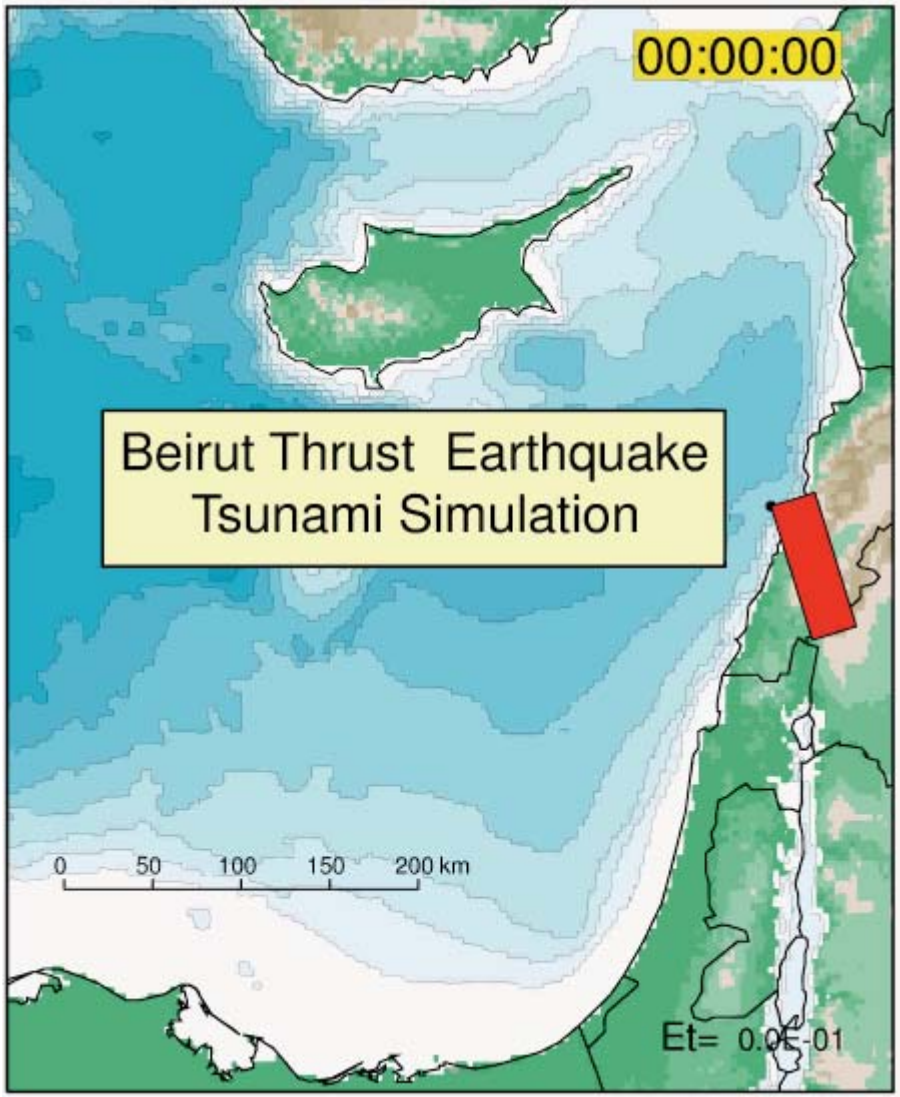
Earthquake tsunami generally radiate most strongly in directions perpendicular to the long axis of fault.

Some Smaller Mediterranean Examples

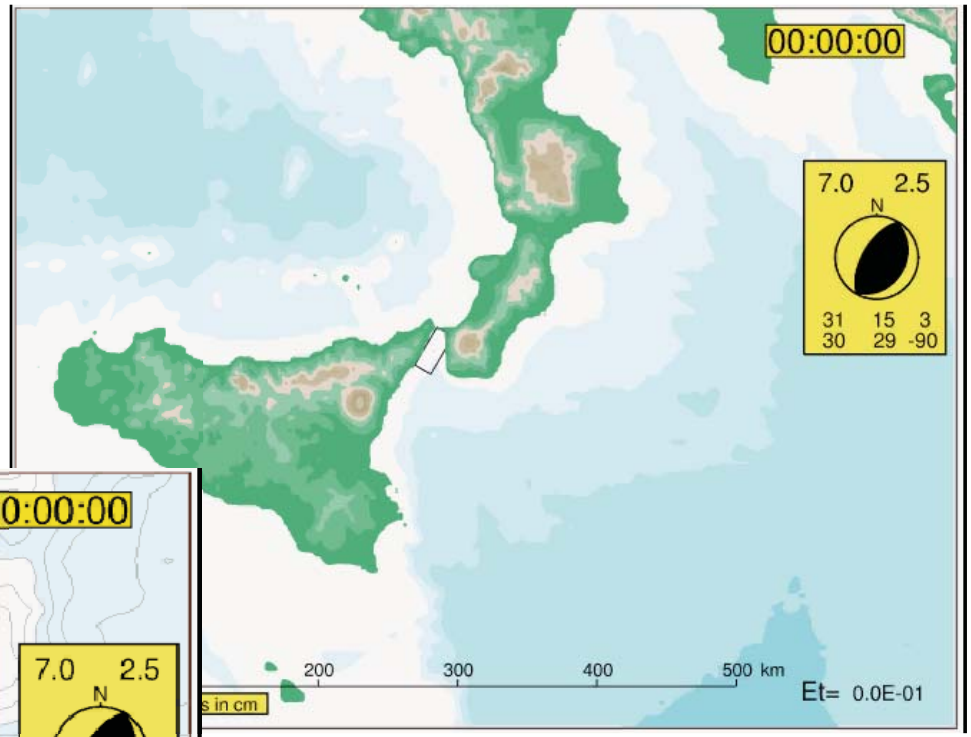
Carmel Fault at Haifa

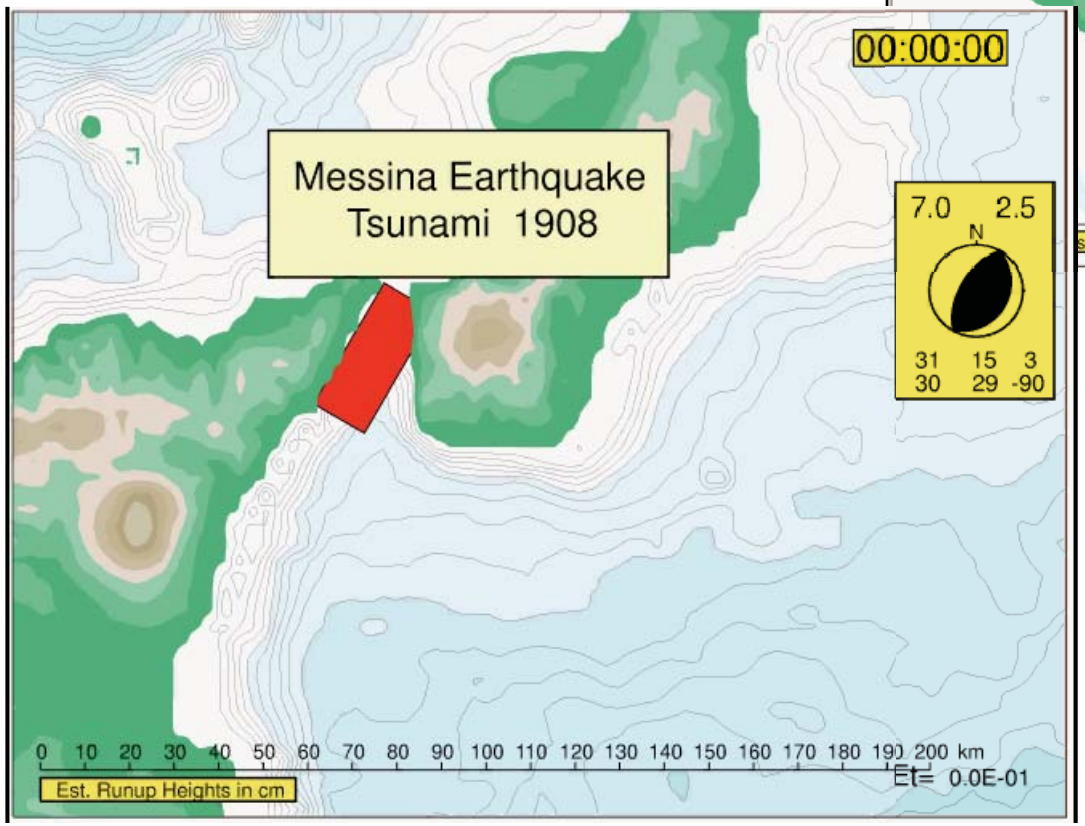


Beirut Thrust



Here in Italy, we can't forget the Messina Earthquake of 1908





I use 2.5m of slip here. Peak mean runups of 3 1/4 m. Peak Peak runups might be about twice that.

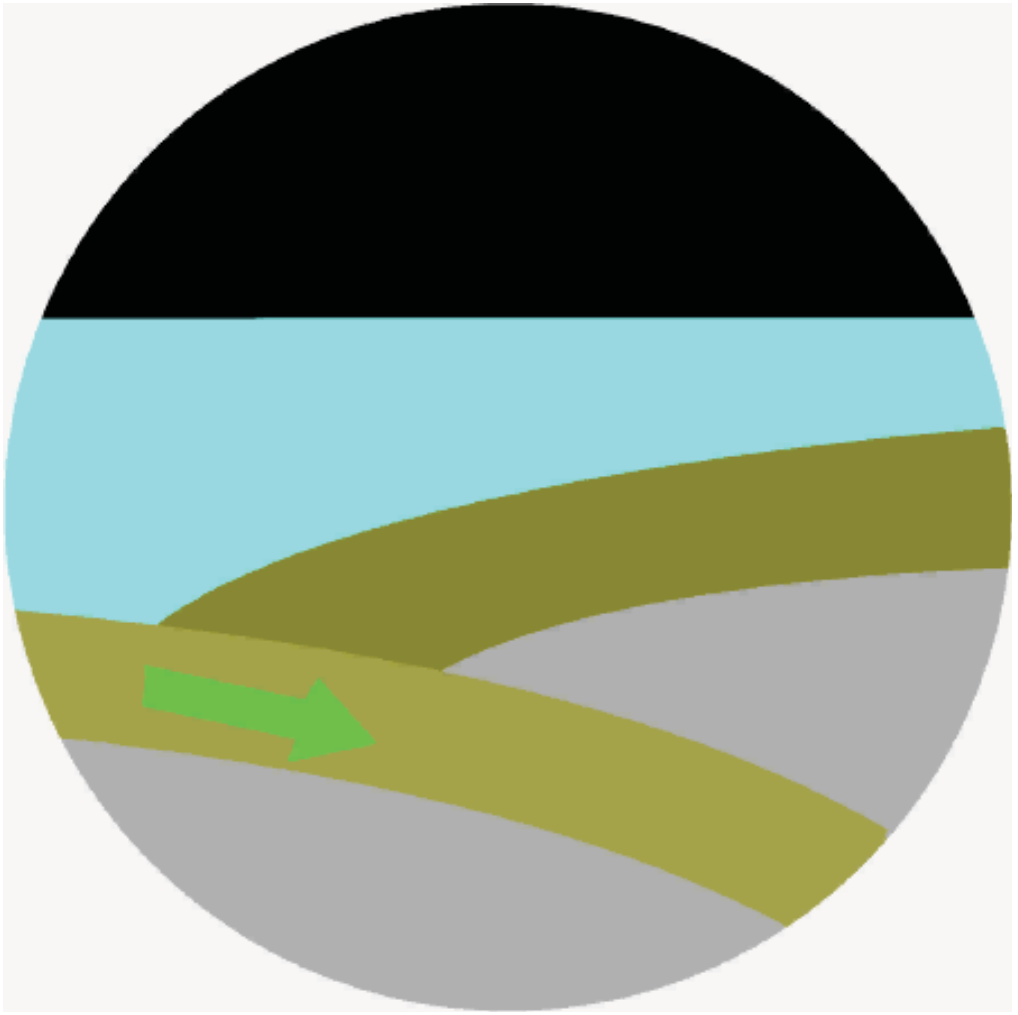
Most large tsunami originate in subduction zone settings.

Earthquake Cycle
INTERSEISMIC:

Oceanic Plate subducts beneath Continental plate but fault interface is locked

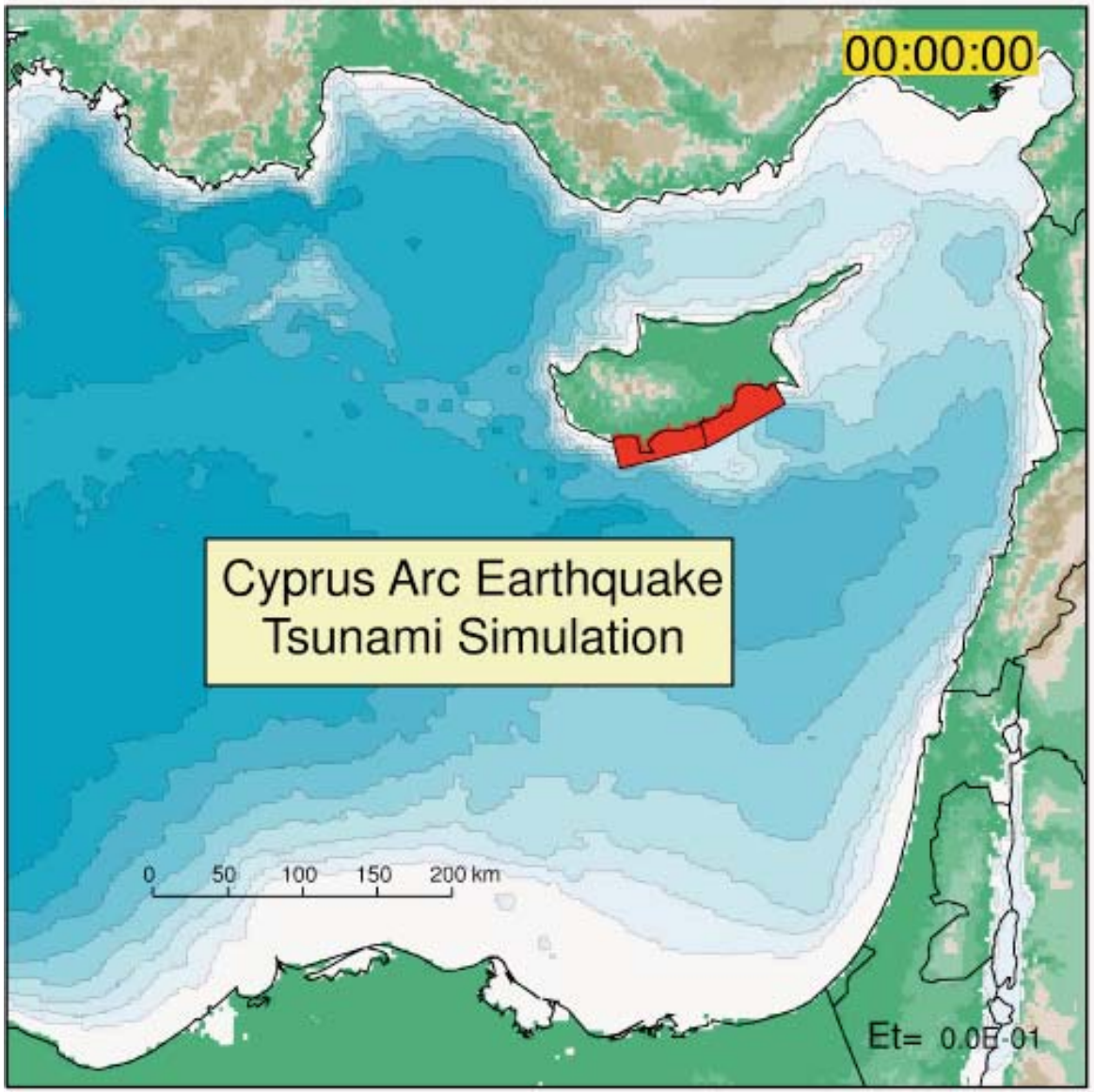
COSEISMIC:

Fault interface slips, overriding plate rebounds, releasing accumulated strain



Mediterranean Example of subduction style tsunami

Cyprus Arc

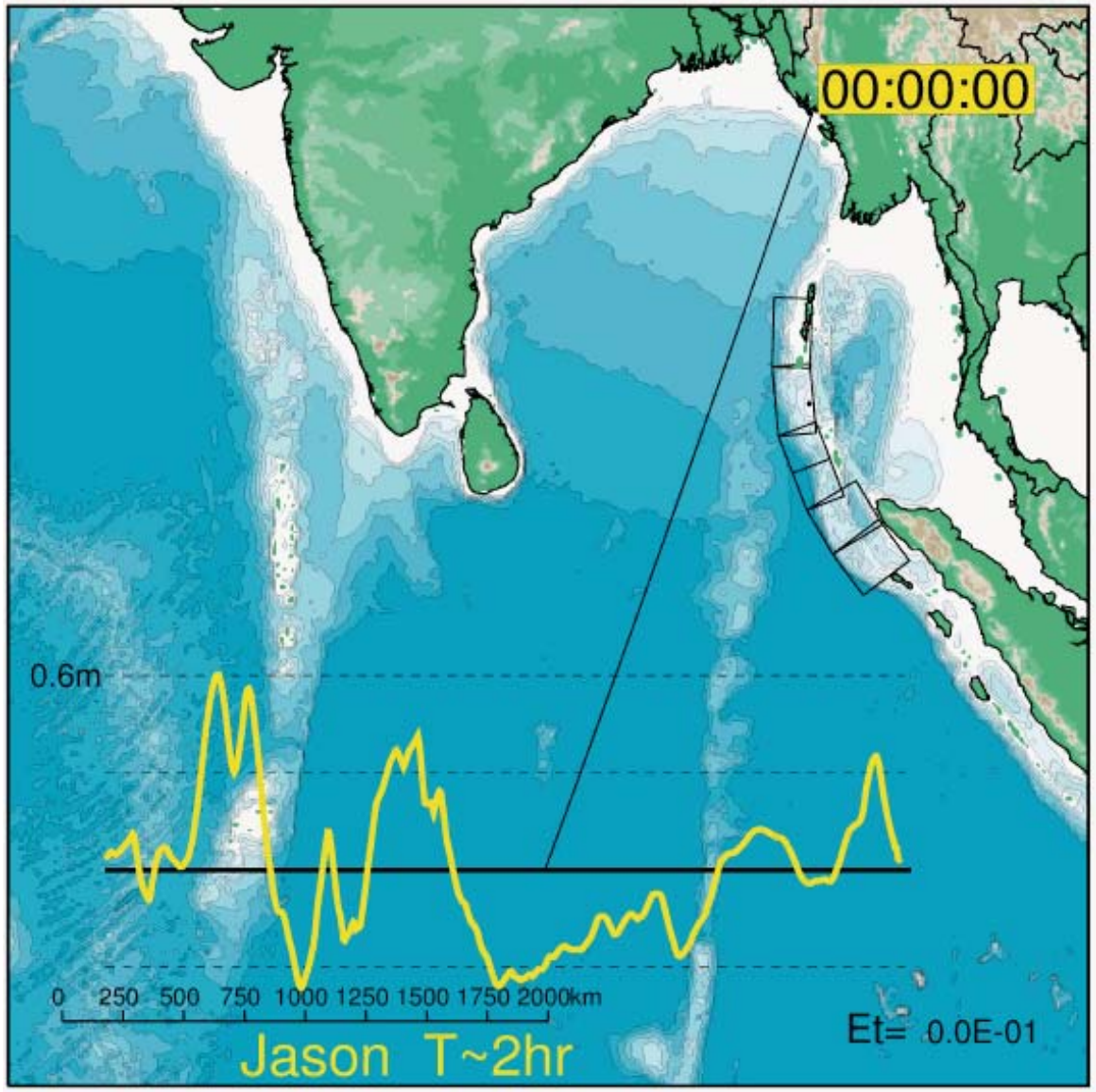


In Sumatra 2004, most energy goes east and west. Most deaths happened in those directions.

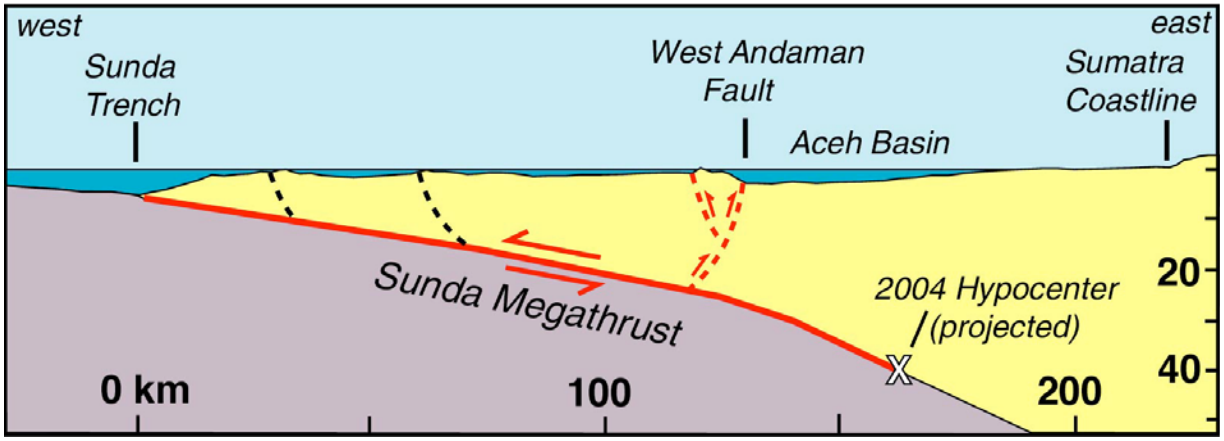
Quake energy ~500 Megaton. Tsunami took 1/2% of that.

SOON, may track tsunami in deep ocean in real time by satellites.

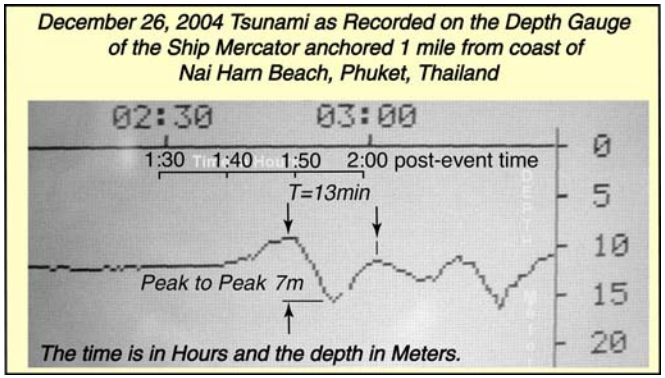
2004 Jason radar track. Not available in real time, but proof of concept.

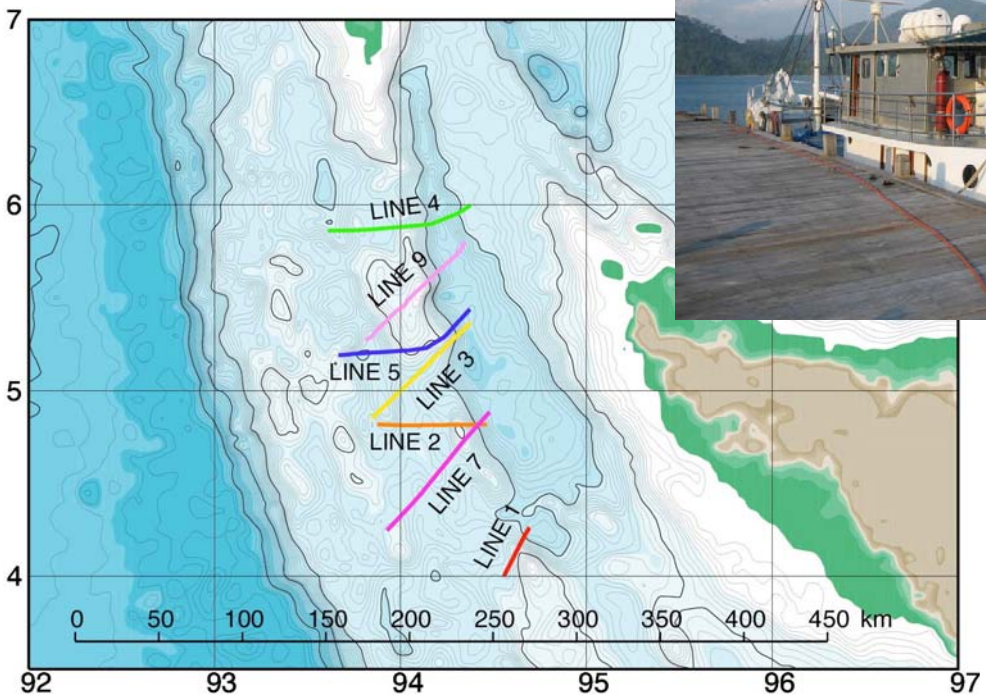


PROBLEMS: (a) How do we get such great waves at Aceh, but not violate radar data to west and "fish finder" data to the east? (b) 20 min wave arrival?



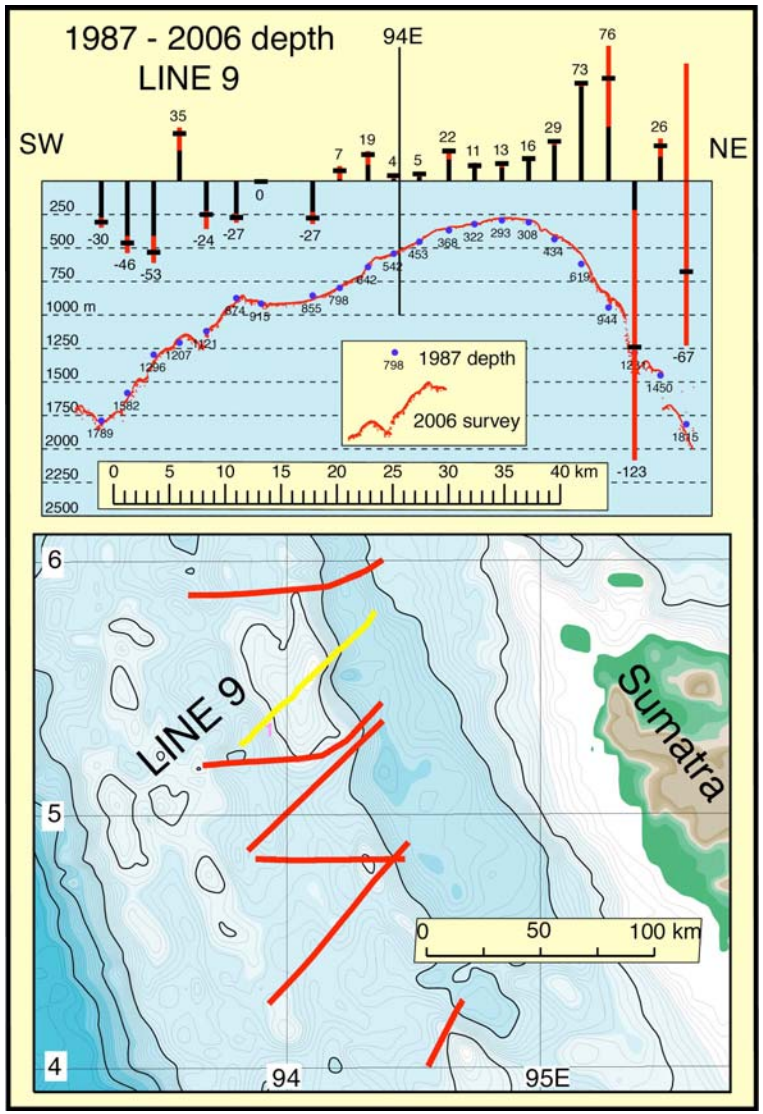
In October, 2006 we re-surveyed several 100 miles of track looking for evidence of concentrated uplift.



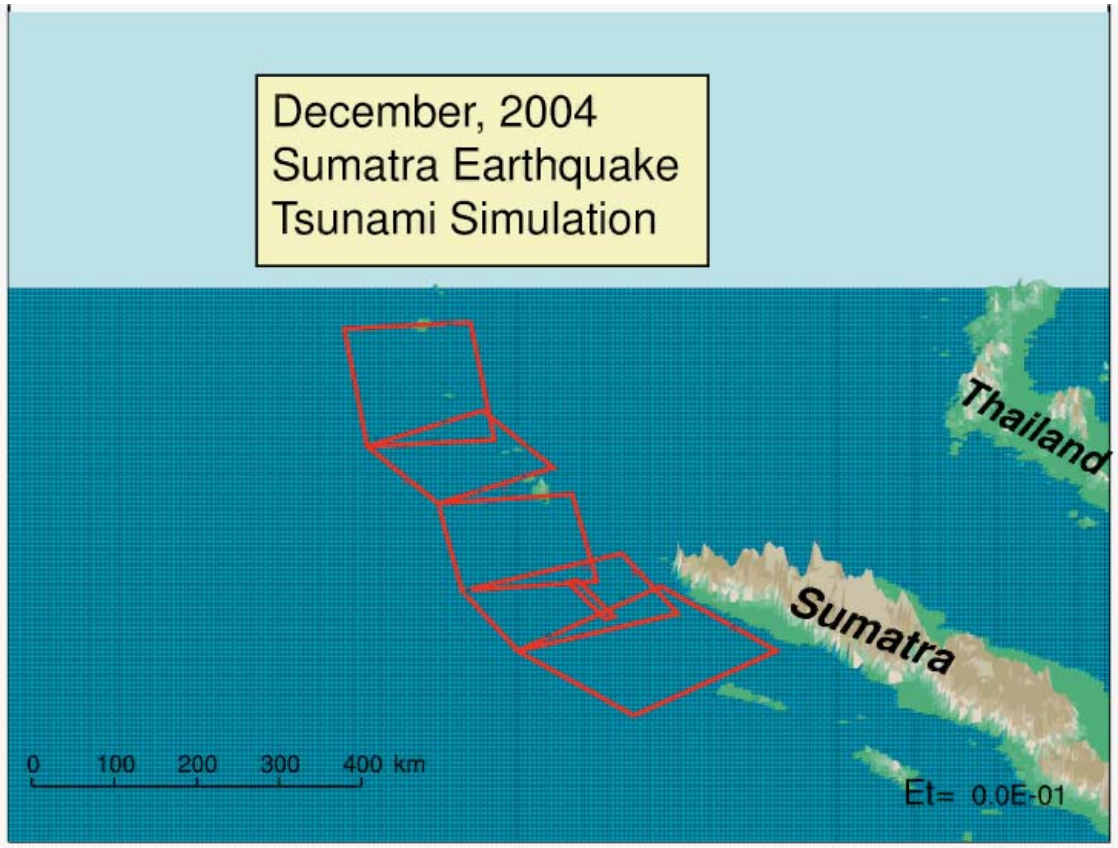


Best concept: Back Thrust or "Pop-Up" Know such popups exist in Alaska 1964 quake and others.

Documenting ~20 m depth change in 600-1000 m of water is challenging: Navigation issues, repeatability of soundings over uneven bottom, quality of older surveys, etc.



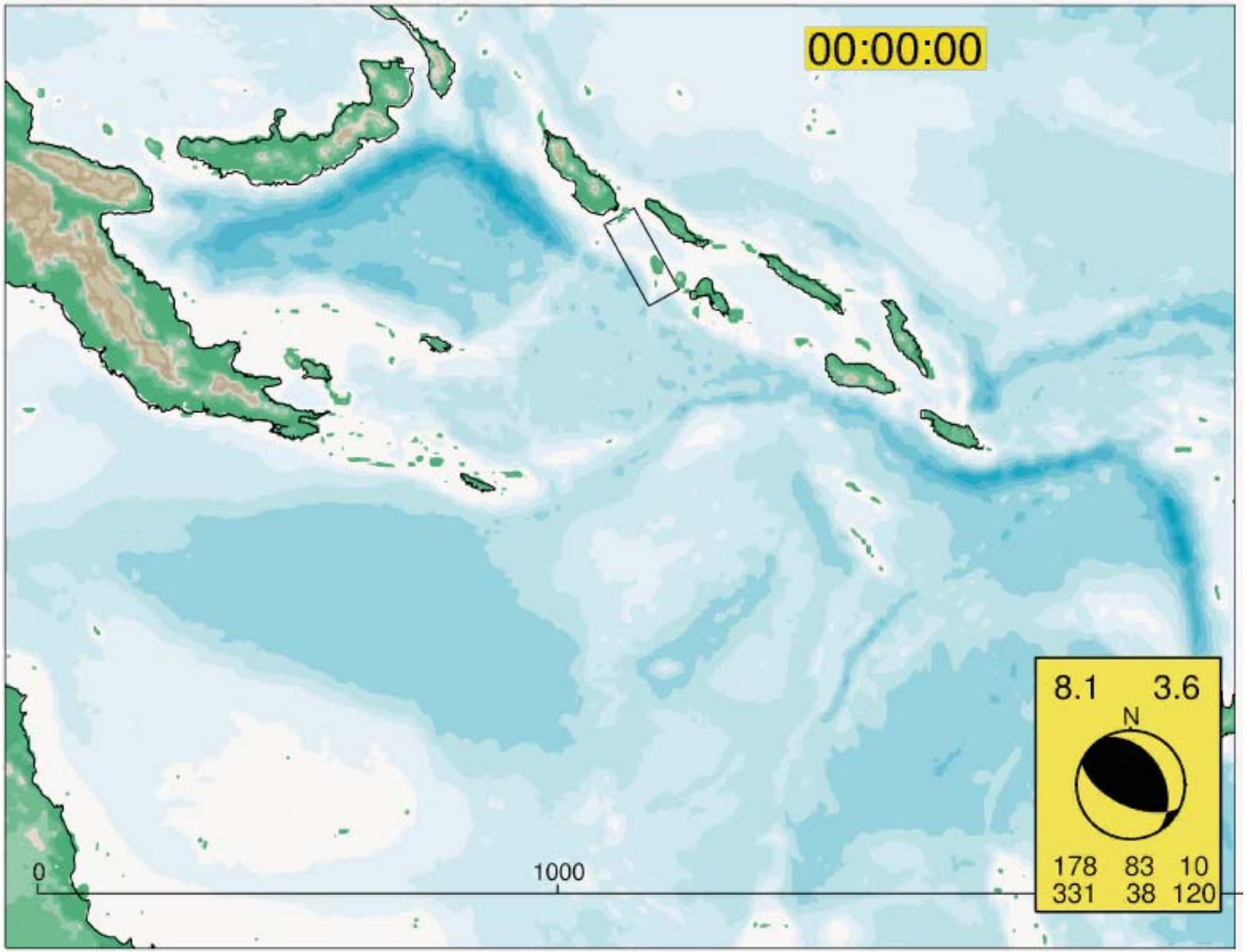
But, on Line 9, we think we found the uplift source of the large tsunami waves at Aceh.



Given estimate of earthquake parameters (and the quake is well behaved), I can provide a wave height estimate in about 1/2 hour on my laptop.

I suppose this counts as a *prediction* if you beat the wave to the beach!

Solomon Sea Earthquake, 4/1/2007 M8.1



Even this level of prediction would have helped the Australians make a decision.

Where Next?

Like Global Circulation Models

You can program the laws of earthquake physics and make

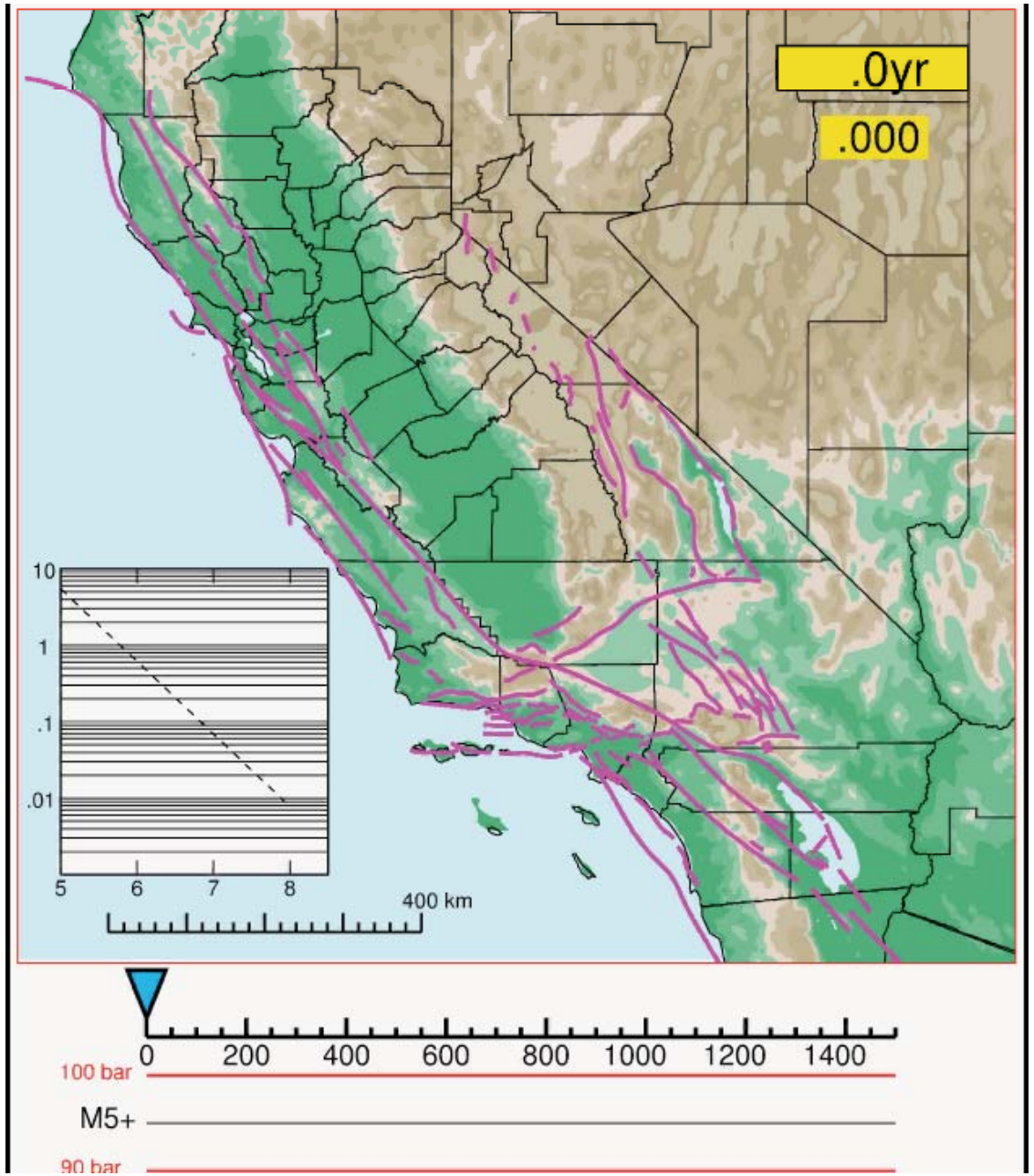
Global Earthquake Circulation Models

Stress, not fluid, circulates

But, no time today…

.

Back to tsunami

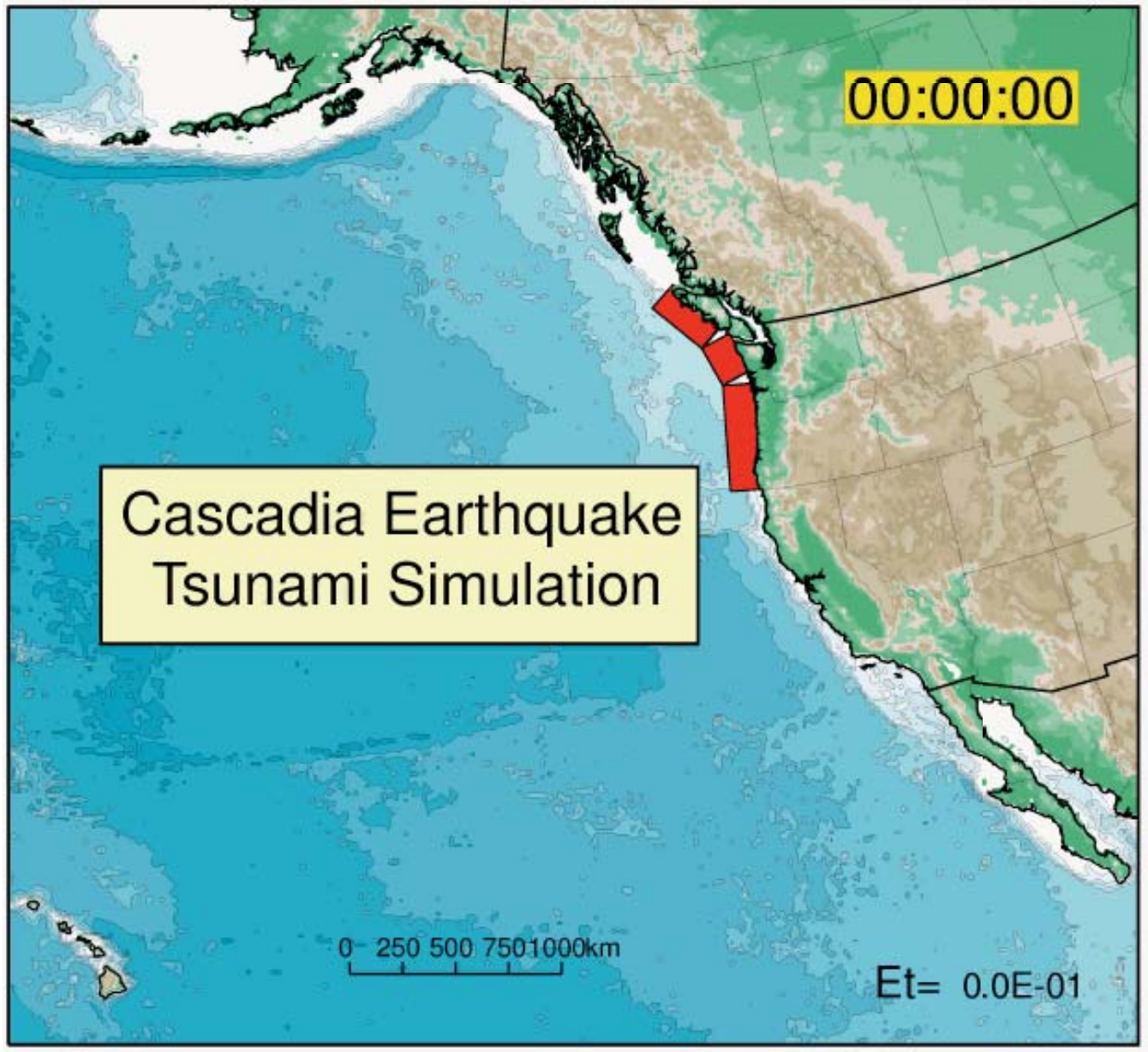


Where NEXT?

We expect the next Cascadia quake to be comparable to the Sumatra Event.

Here is what happened last time in 1700

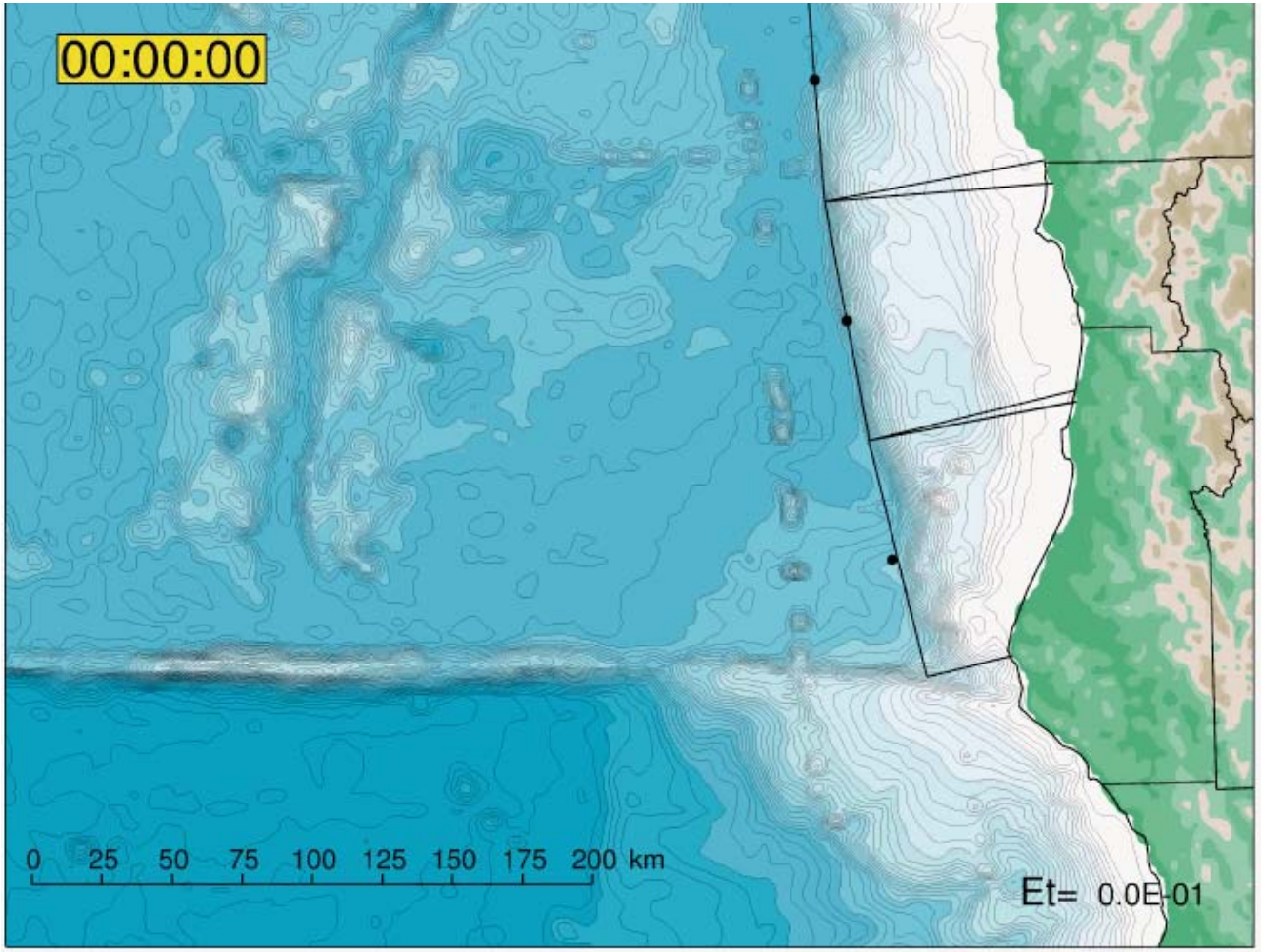
Likely we are getting toward the end of this cycle.



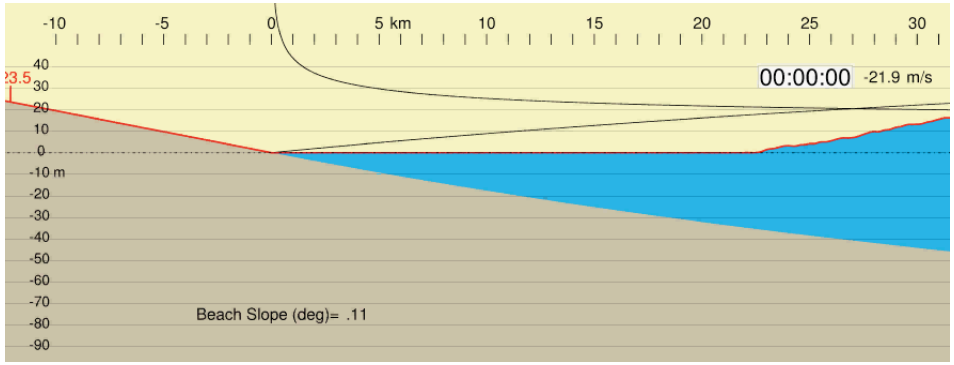
I guess this is another Prediction?

My concept of the next Cascadia Tsunami.

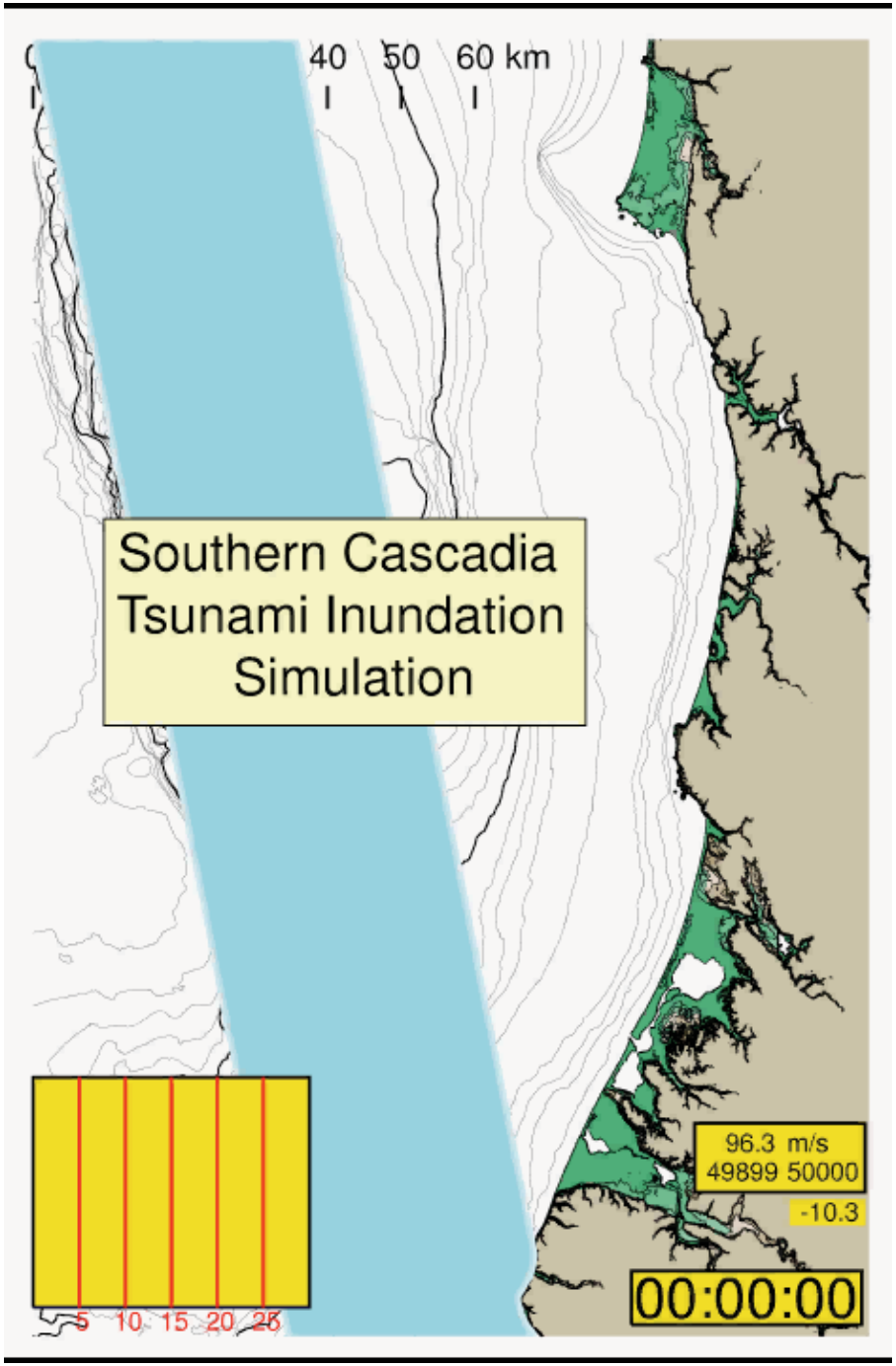
Humbolt and Del Norte counties are in the Red Zone



Runup/Inundation: *This is another aspect of predictability, but it is messy business.*

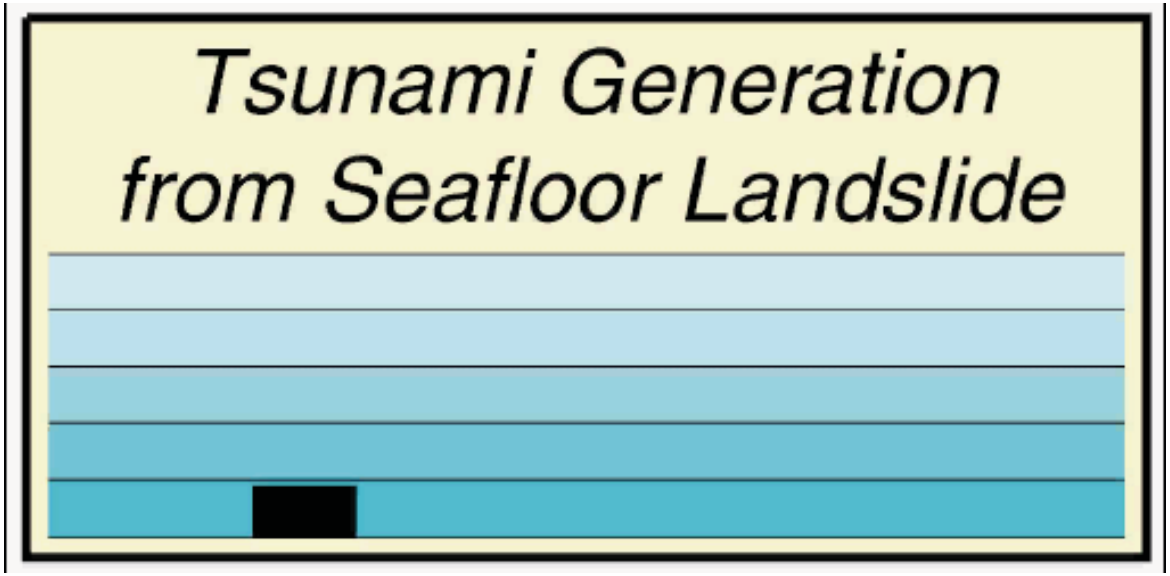


Runup depends on wave height, wave period, beach slope, wave train duration and random interference. Best to consider runup a random variable.



How Do Tsunami Get Started?

3) Disturb the sea bottom, transiently
Say, run a Landslide.



As material moves along the seafloor, the water must go UP, DOWN, or AROUND. This makes waves.

Landslide tsunami can be very directional.

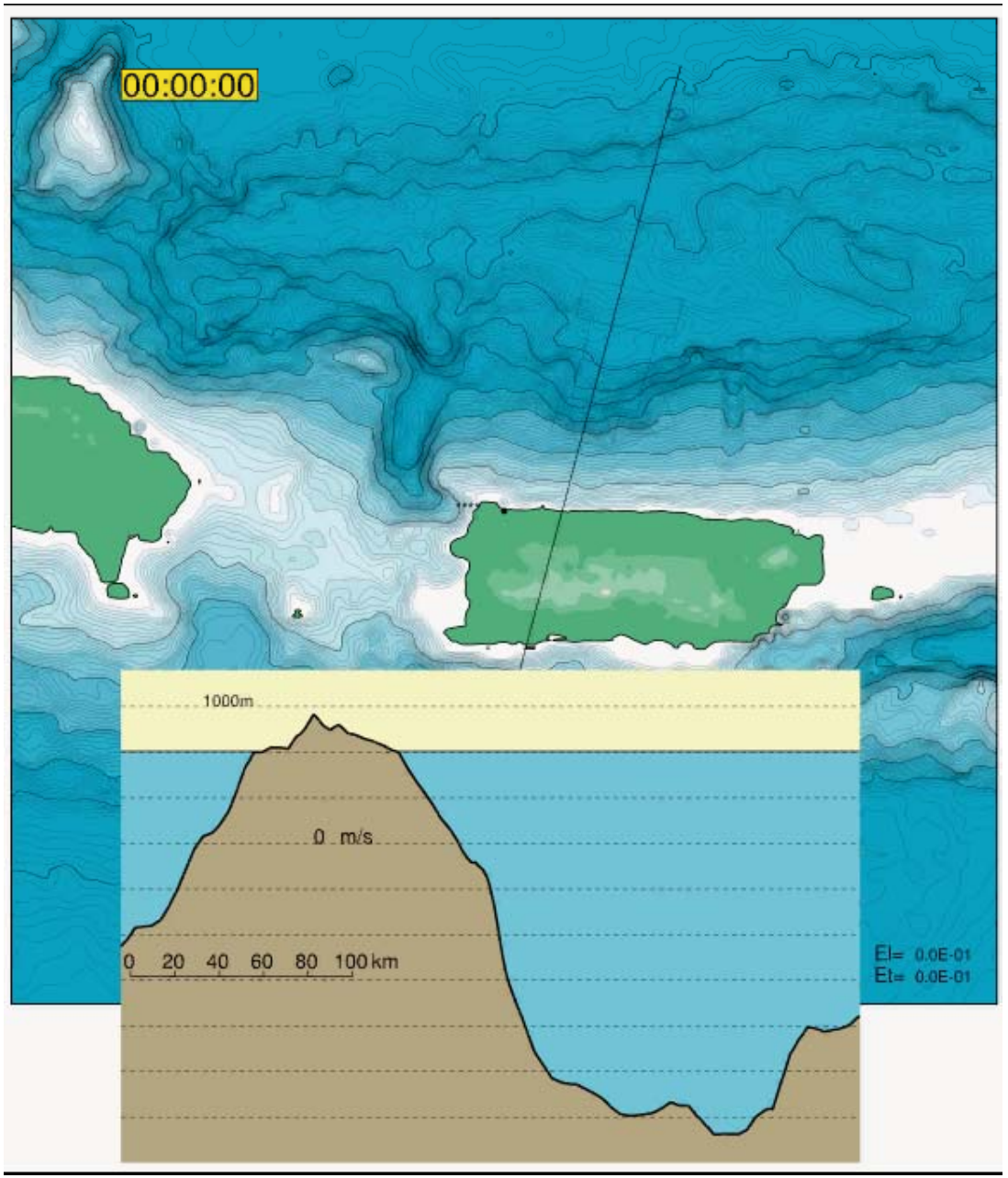
Typical Situation:

Slide material falls from high on a slope, possibly far under water.

The process stirs tsunami waves on the surface of the ocean.

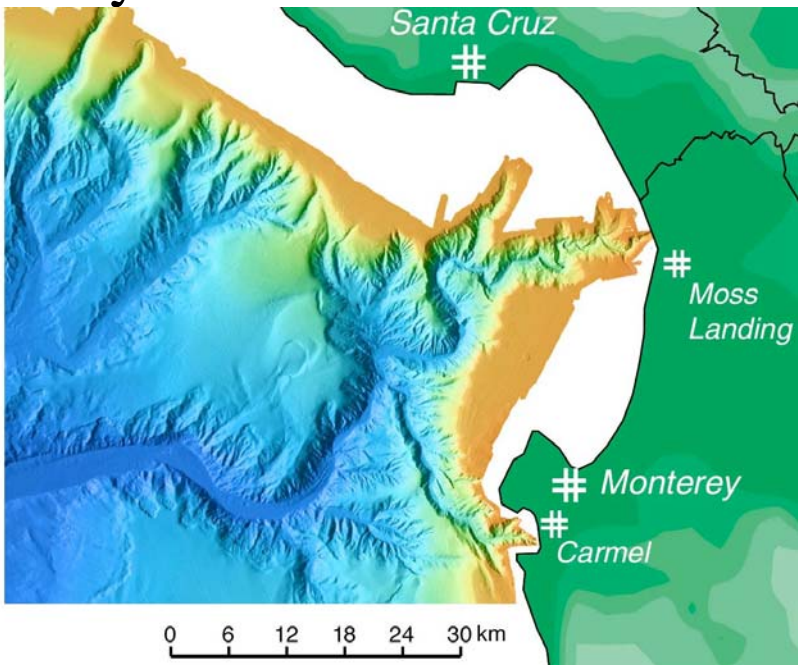
This could be Oregon continental slope.

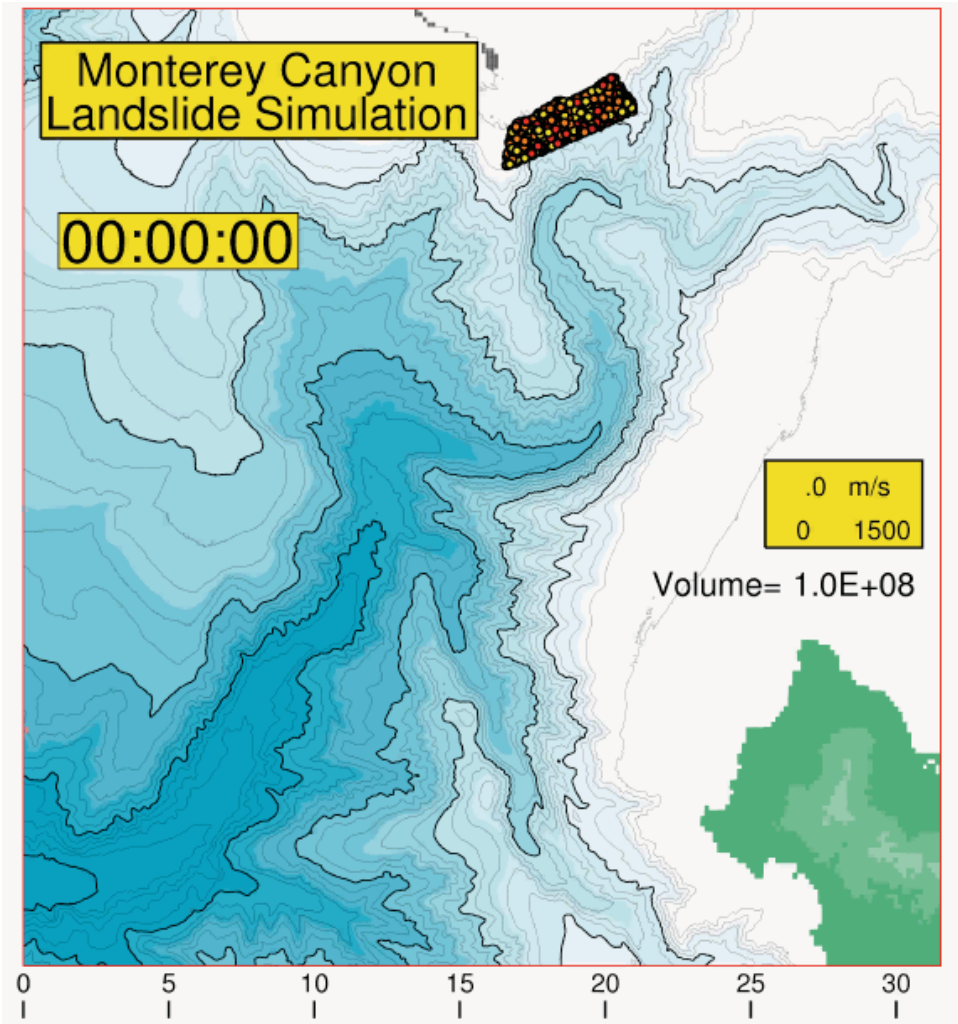
Real world landslides are complex. We need good deposit mapping to make good tsunami models



Submarine landslides come in all sizes, and they occur on both passive and active continental margins.

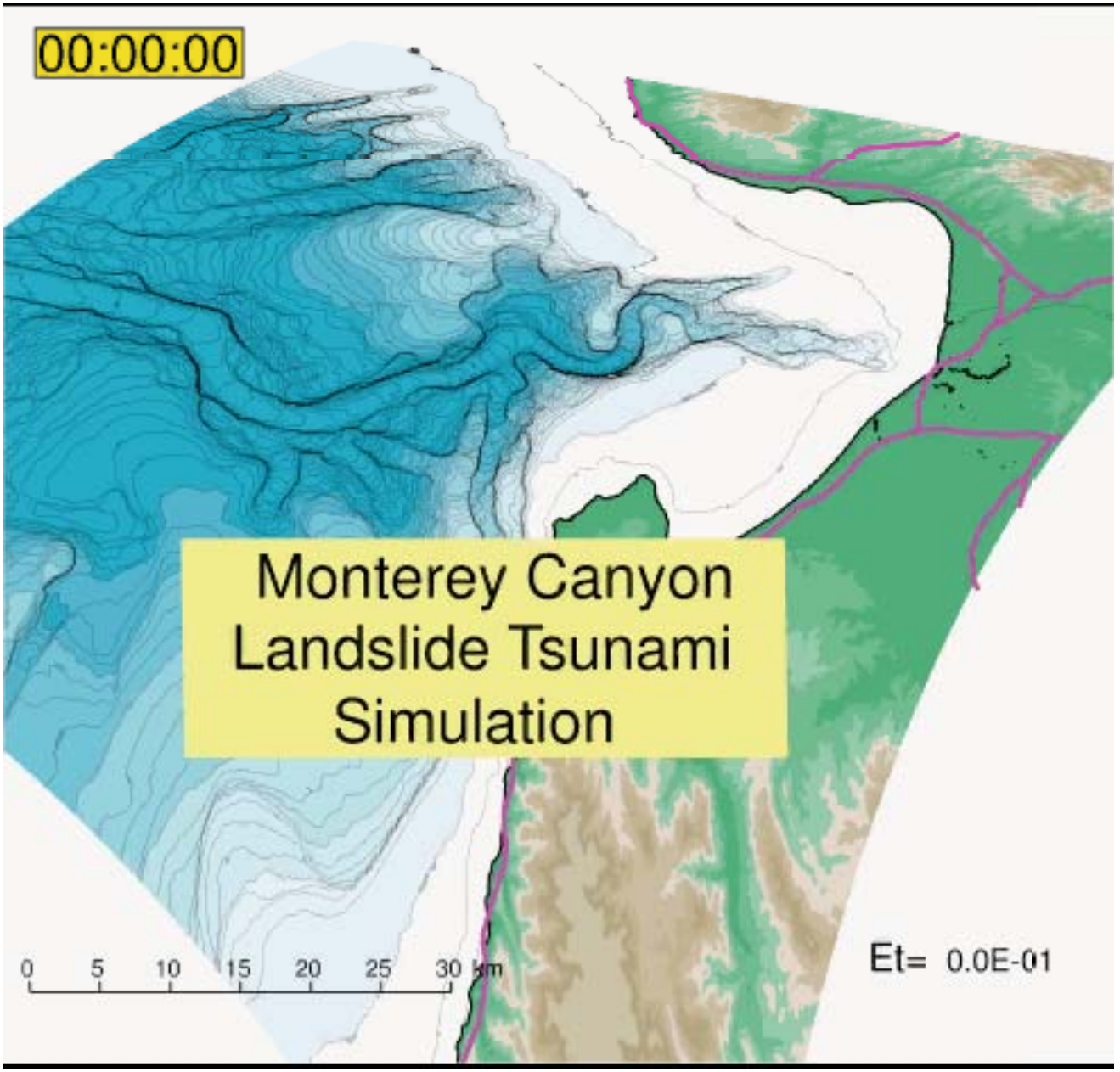
Many slide scars are found on continental slopes and on sides of submerged river canyons.





Simulation of 0.1 km^3 slide in Monterey Canyon, California.

Submarine canyon landslides of 0.1 km^3 can send local tsunami of several meters height toward just about any coastline on Earth



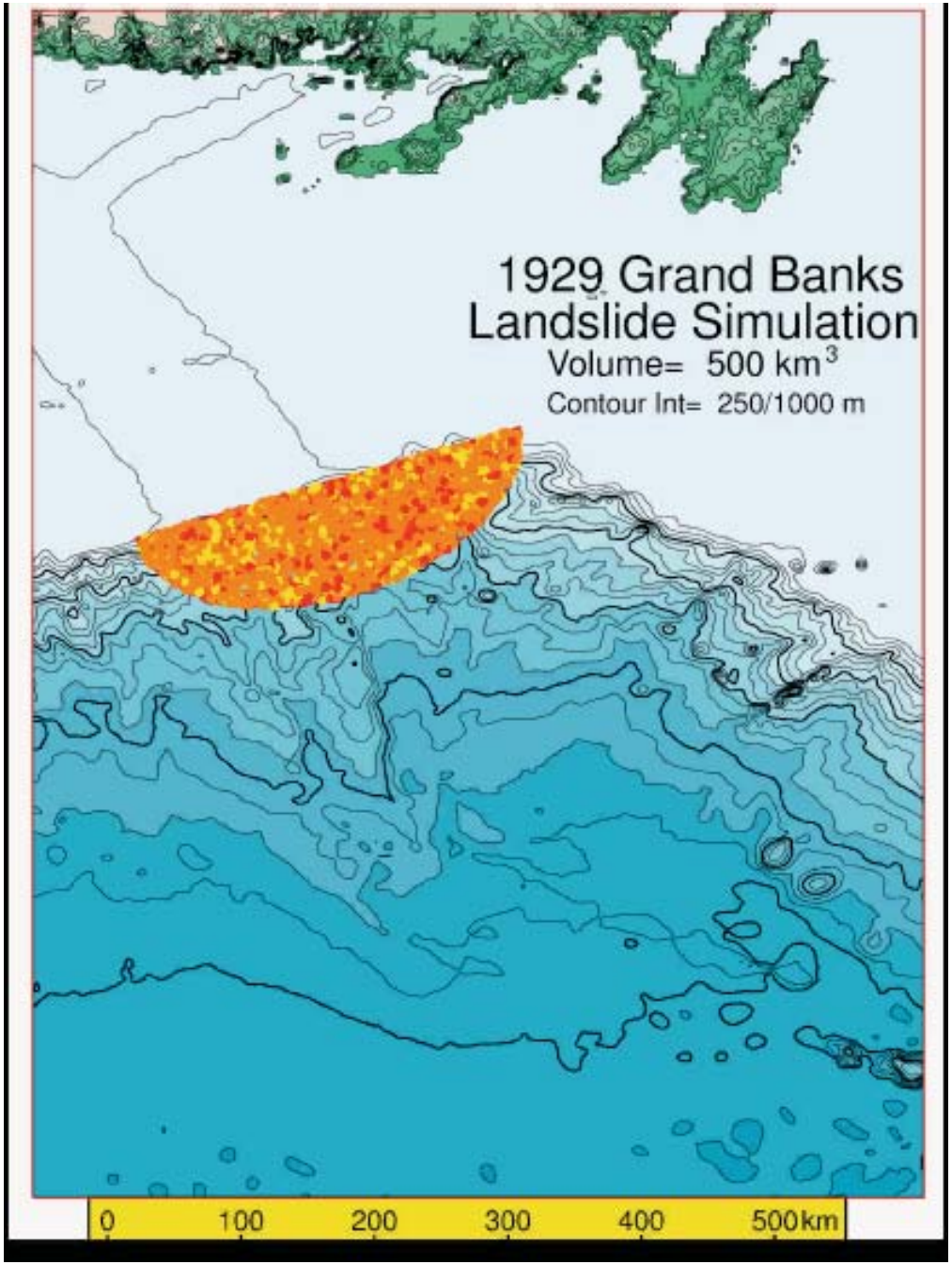
Continental slope landslides can be bigger.

1929 Grand Banks slide triggered by M7 quake.

By 20 minutes, slide sheet concentrates in a handful of channels.

Tsunami generation largely over by 40 min.

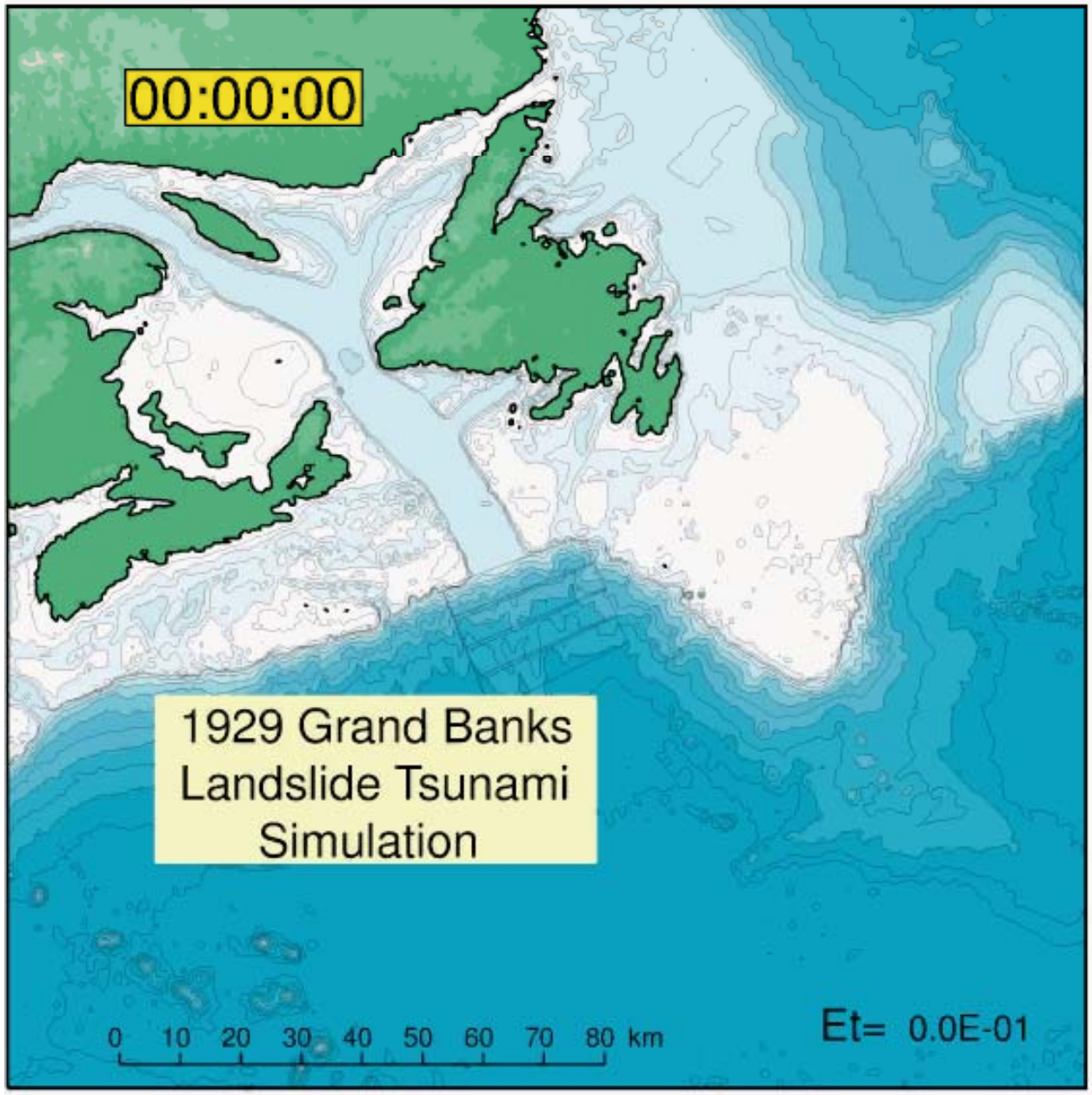
Turbidites flow on for hours and several 100 km more. Constraining early slide details from these distant flows is very dicey.



1929 Tsunami Simulation

Submarine landslides of this scale can spawn destructive water waves.

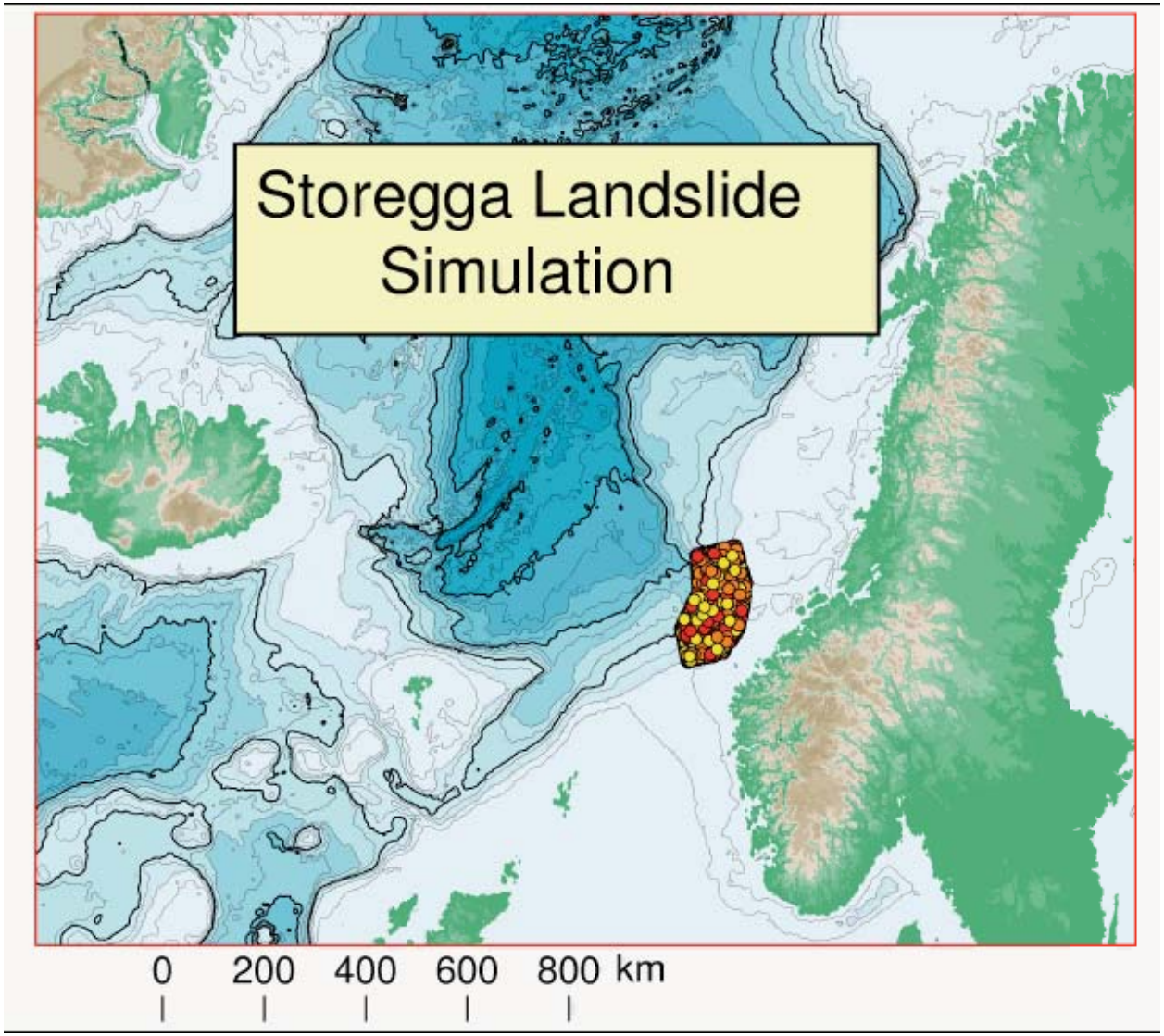
No need to tell the folks of Newfoundland this!



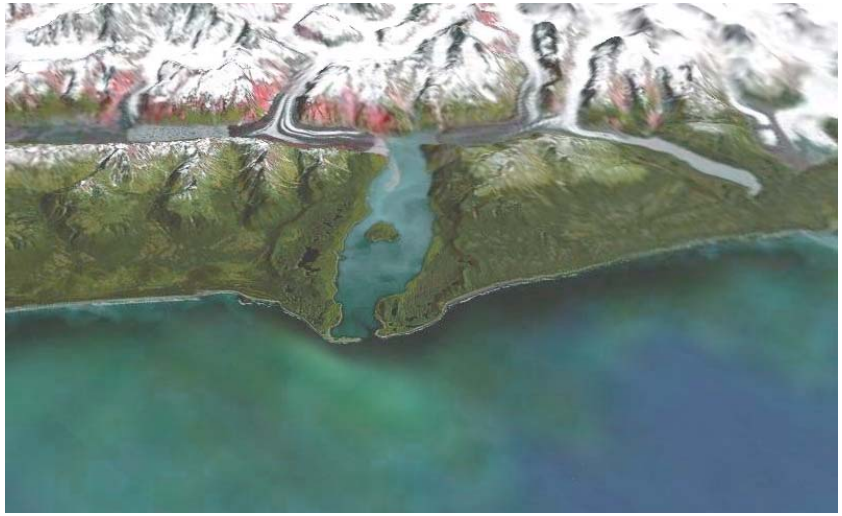
Continental slopes have failed many times in geologic history - slide clusters may be associated with low stands of sea level.

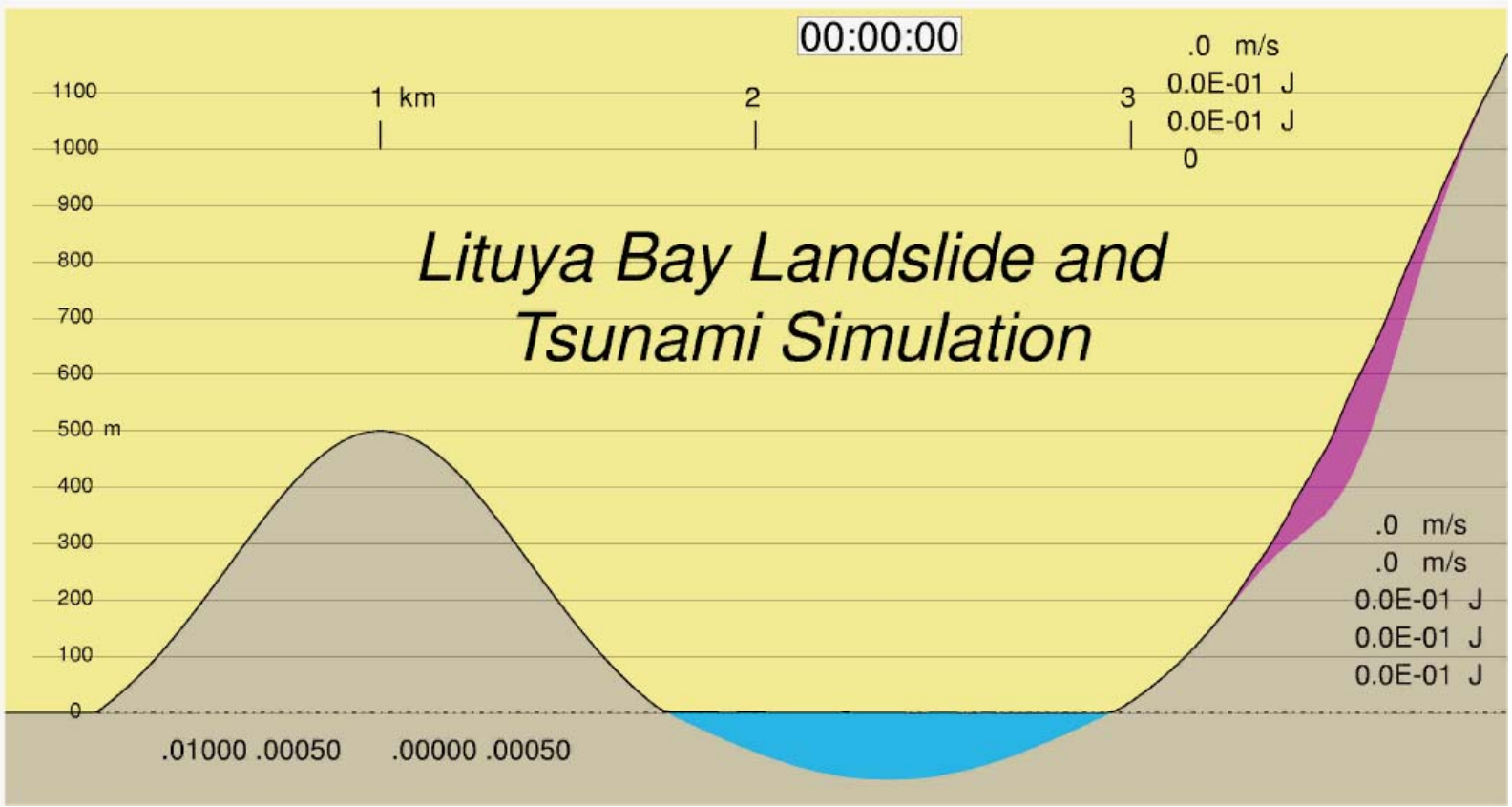
Sea level has been rising for ~5,000 y.

Storegga Slides off Norway 5-35ka left tsunami deposits in many locations



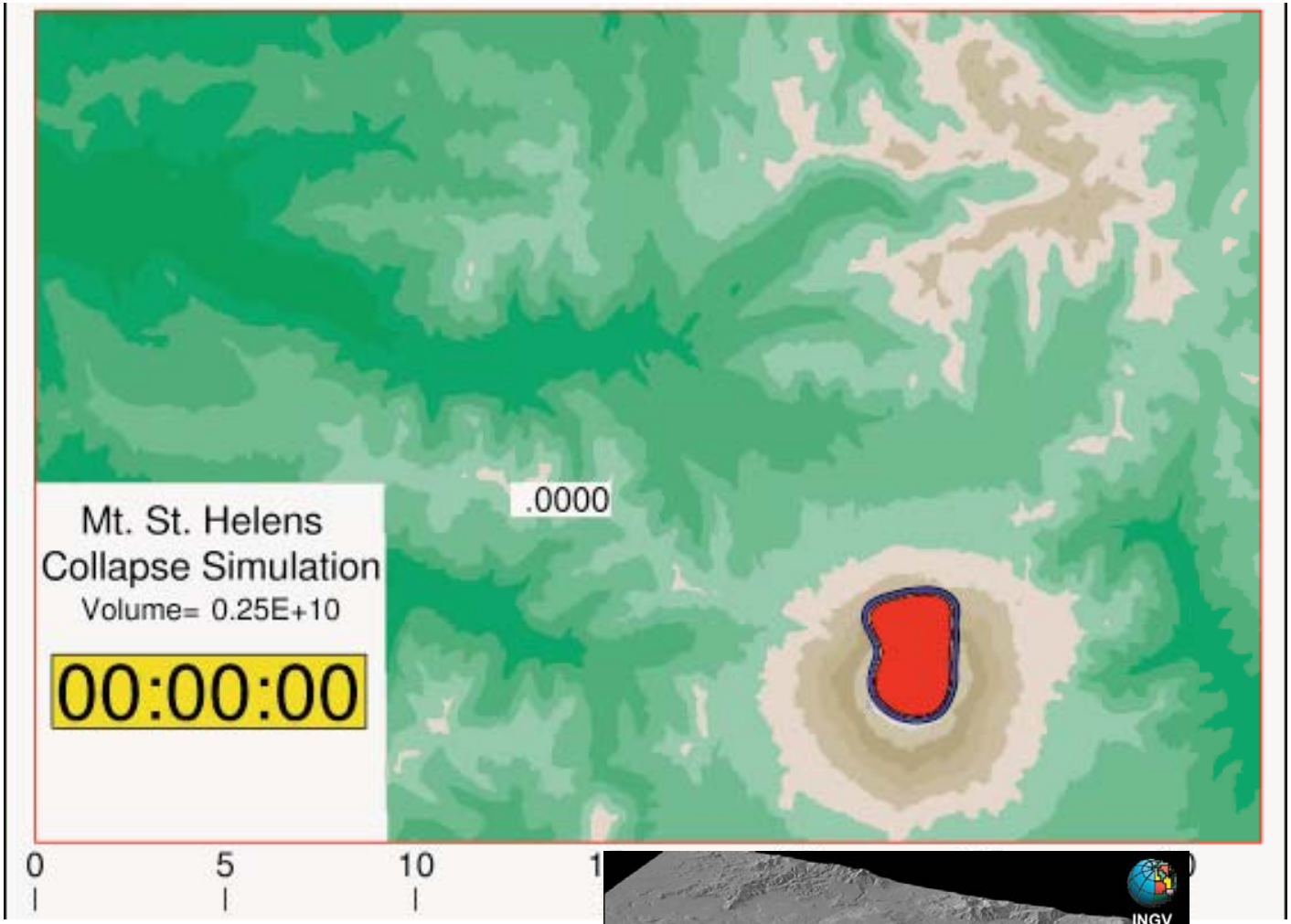
Some tsunami start from trans-shore landslides into oceans, lakes and fiords. Most everyone has heard of the Lityua Bay Alaska tsunami of 1958. A quake-induced rockfall pushed water 500m up the opposite slope



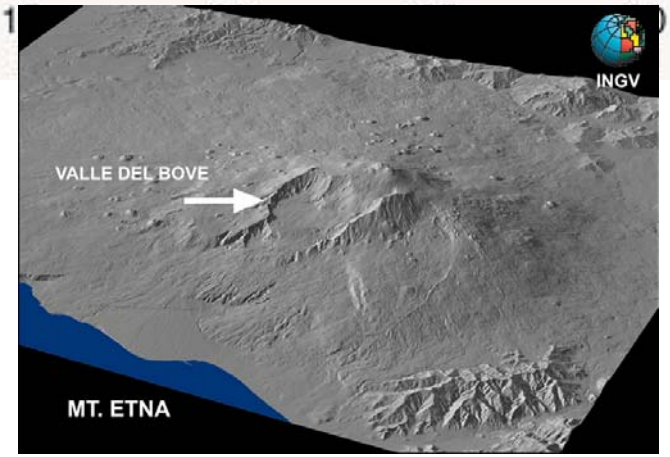


Some of the largest landslides originate from the collapse of volcanoes.

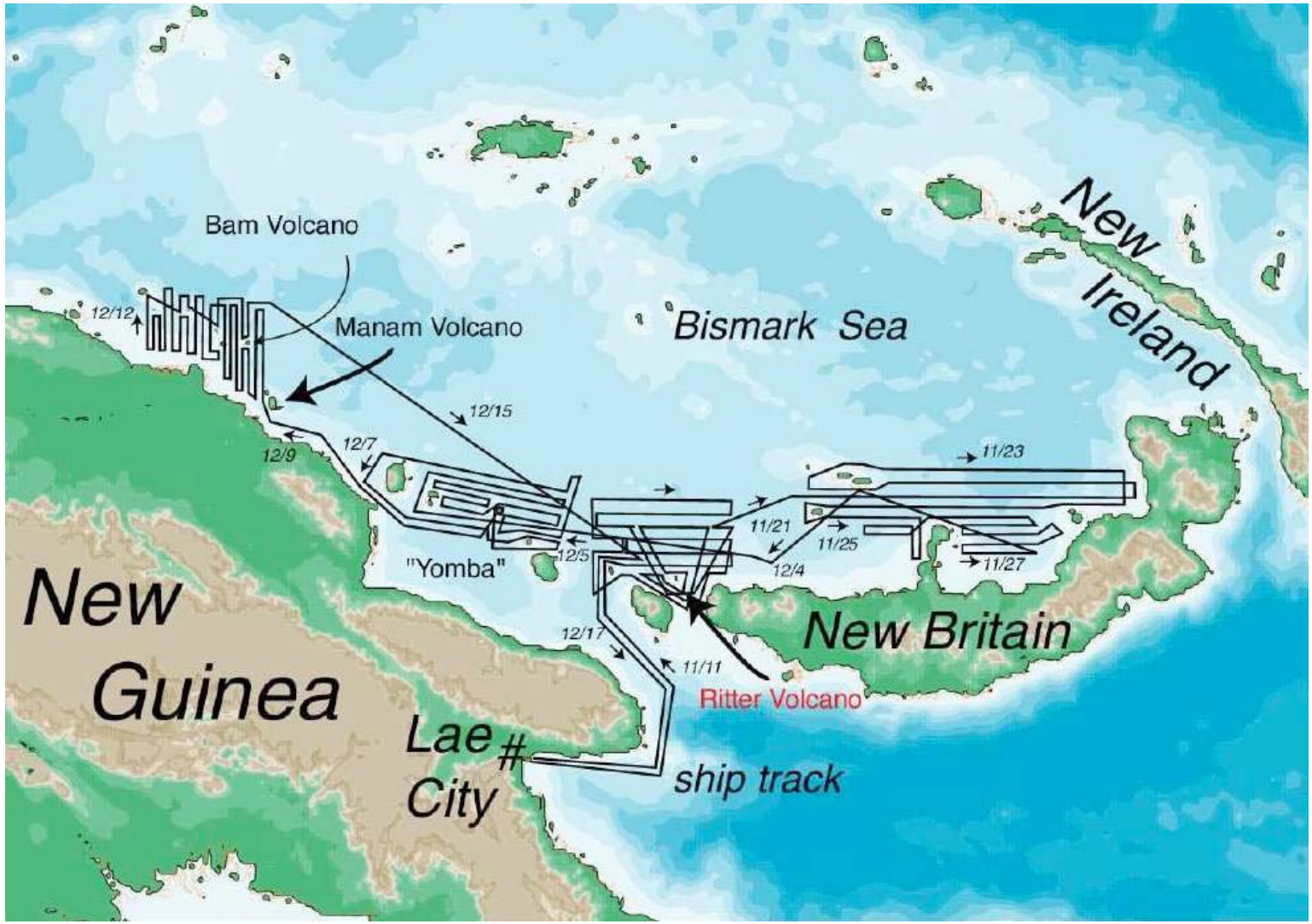
Remember Mt. St. Helens in 1980 (~3km^3)



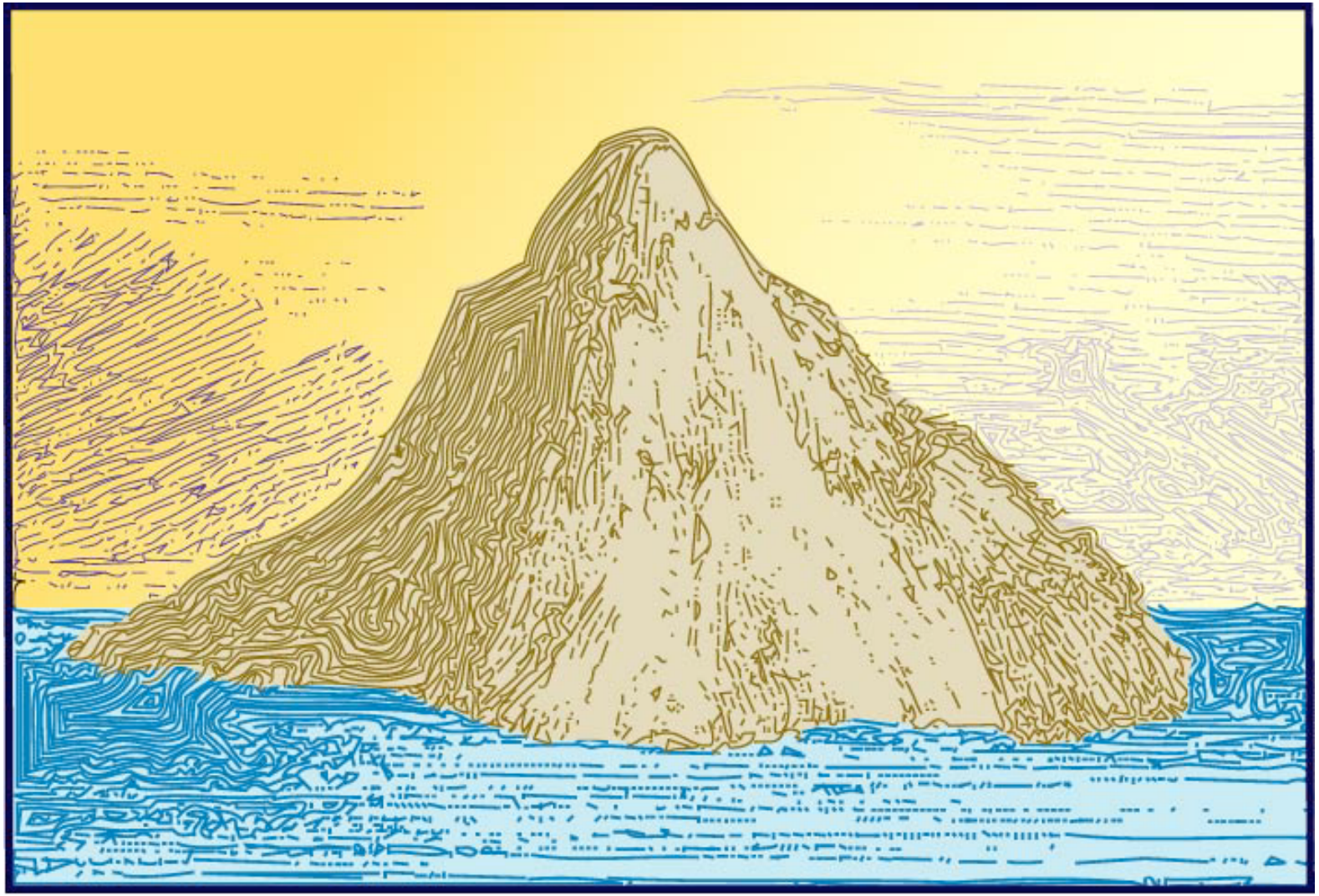
Imagine the tsunami if this happened in the ocean! Fact is, such things are fairly common, geologically speaking. *i.e. Italy's Own Mt. Etna*



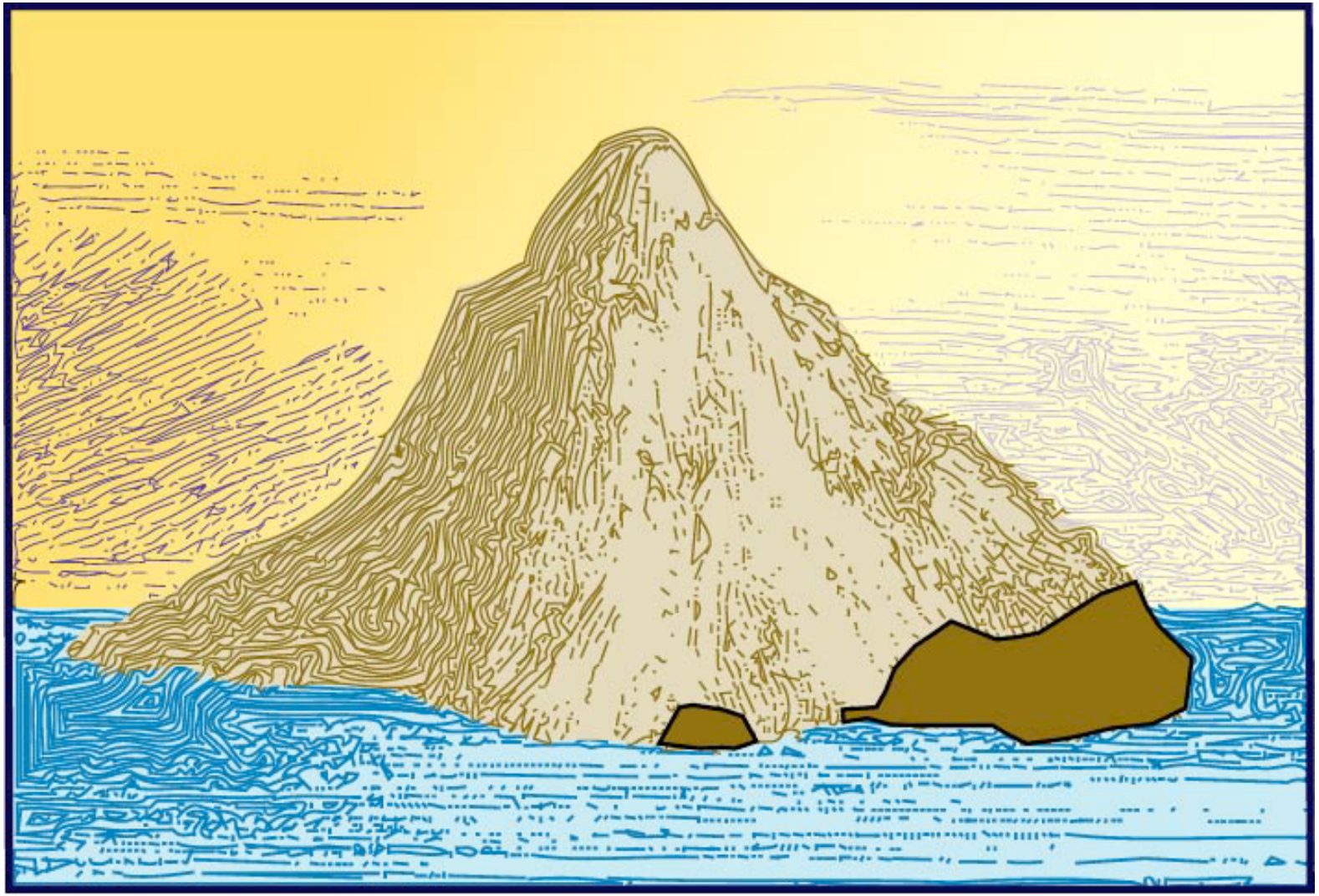
I spent November and December 2004 at sea in search of landslides from volcano collapses in Papua New Guinea

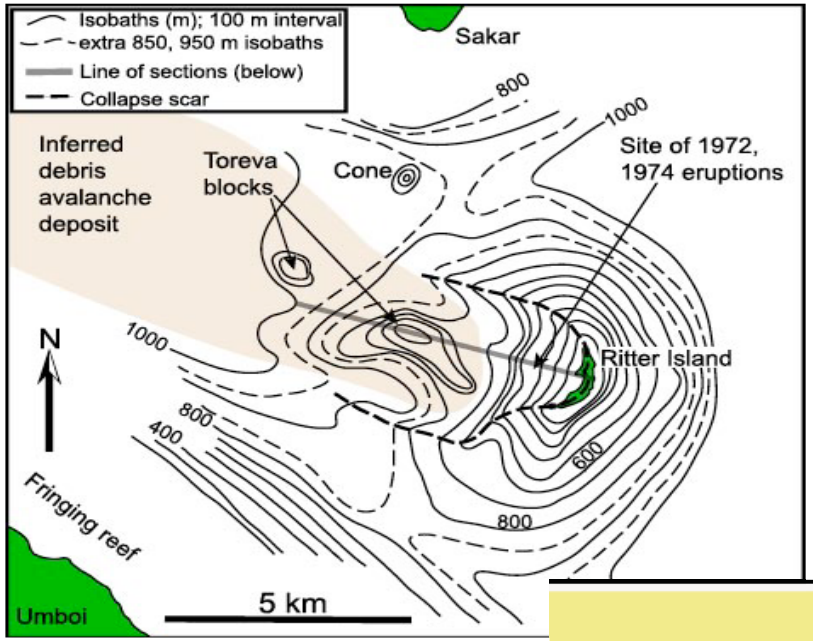


Ritter Island March 13, 1888



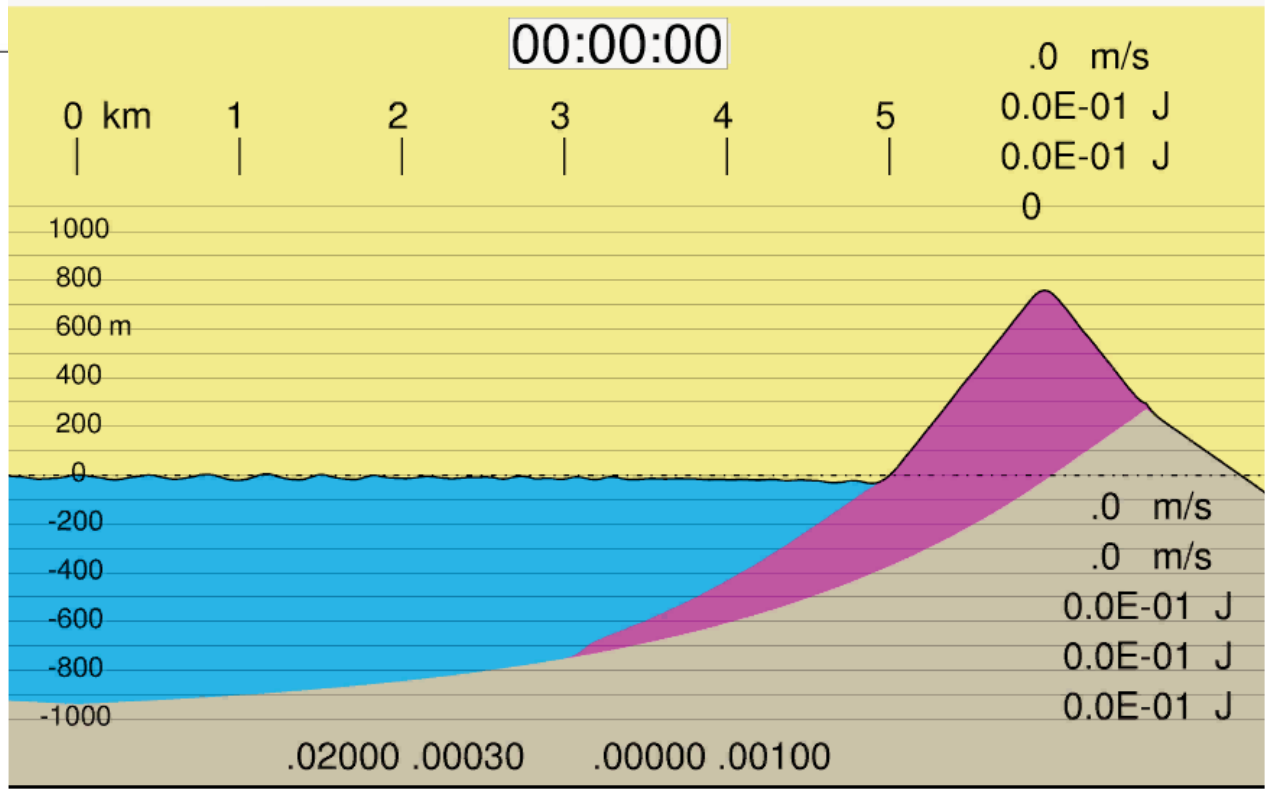
Ritter Island March 14, 1888





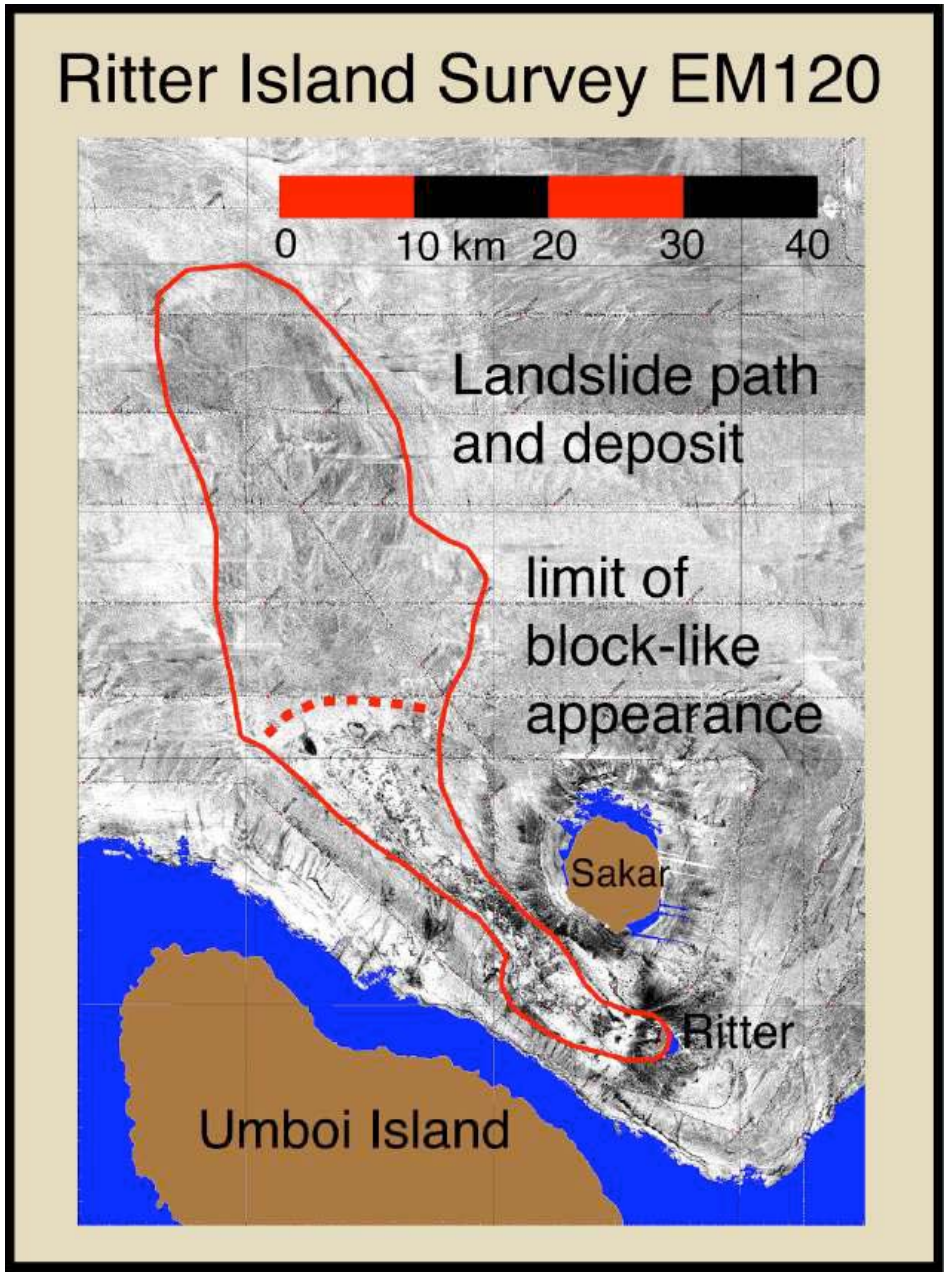
Ritter Island Collapse:1888

Before this cruise we knew slide stuff ran off somewhere to the west then northwest, but not much else.



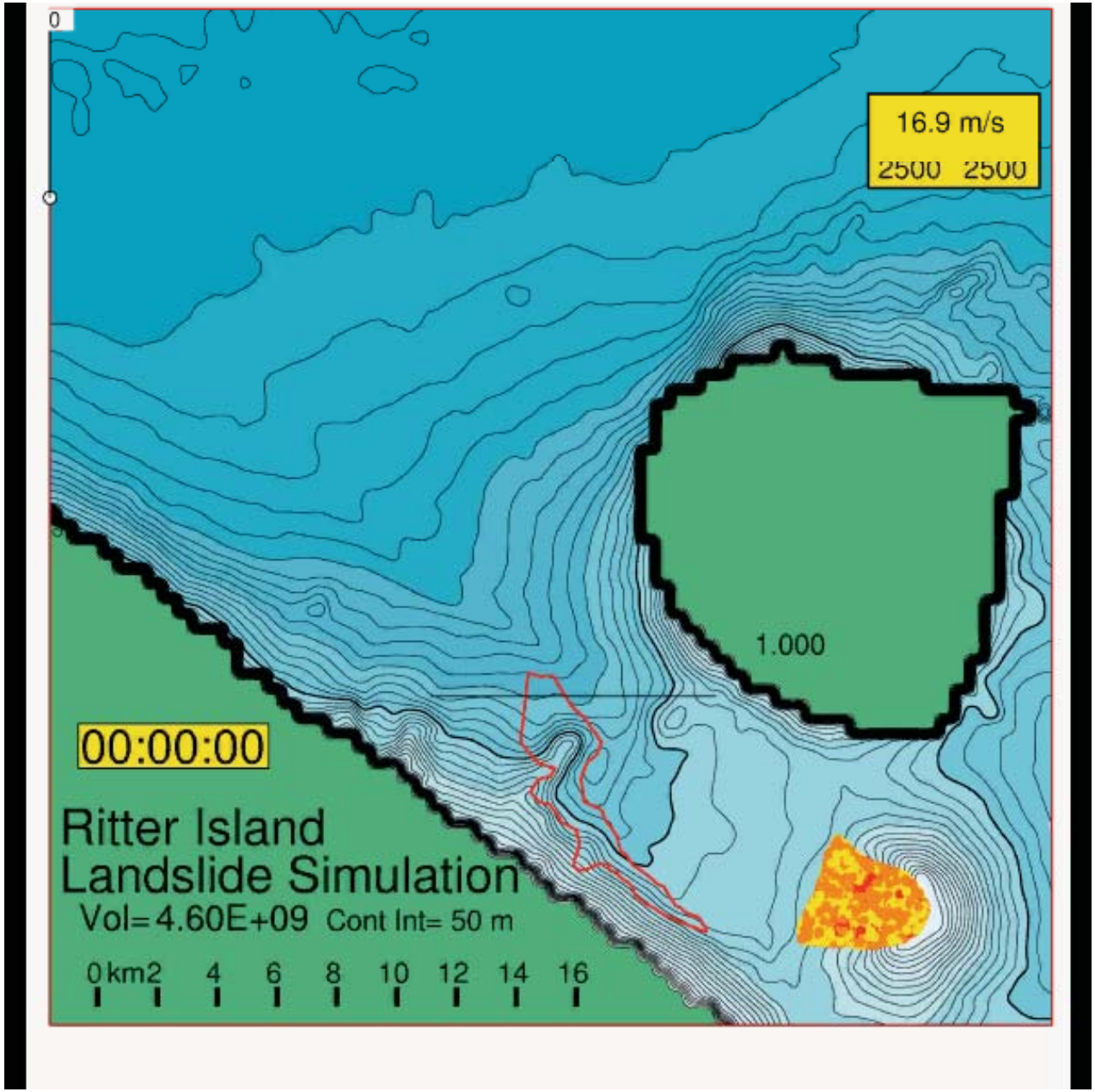
After the cruise, from very detailed sonar mapping of the seafloor, we have a pretty complete picture of what went where….

Some stuff went out as far as 70 km. Must mean very low friction.



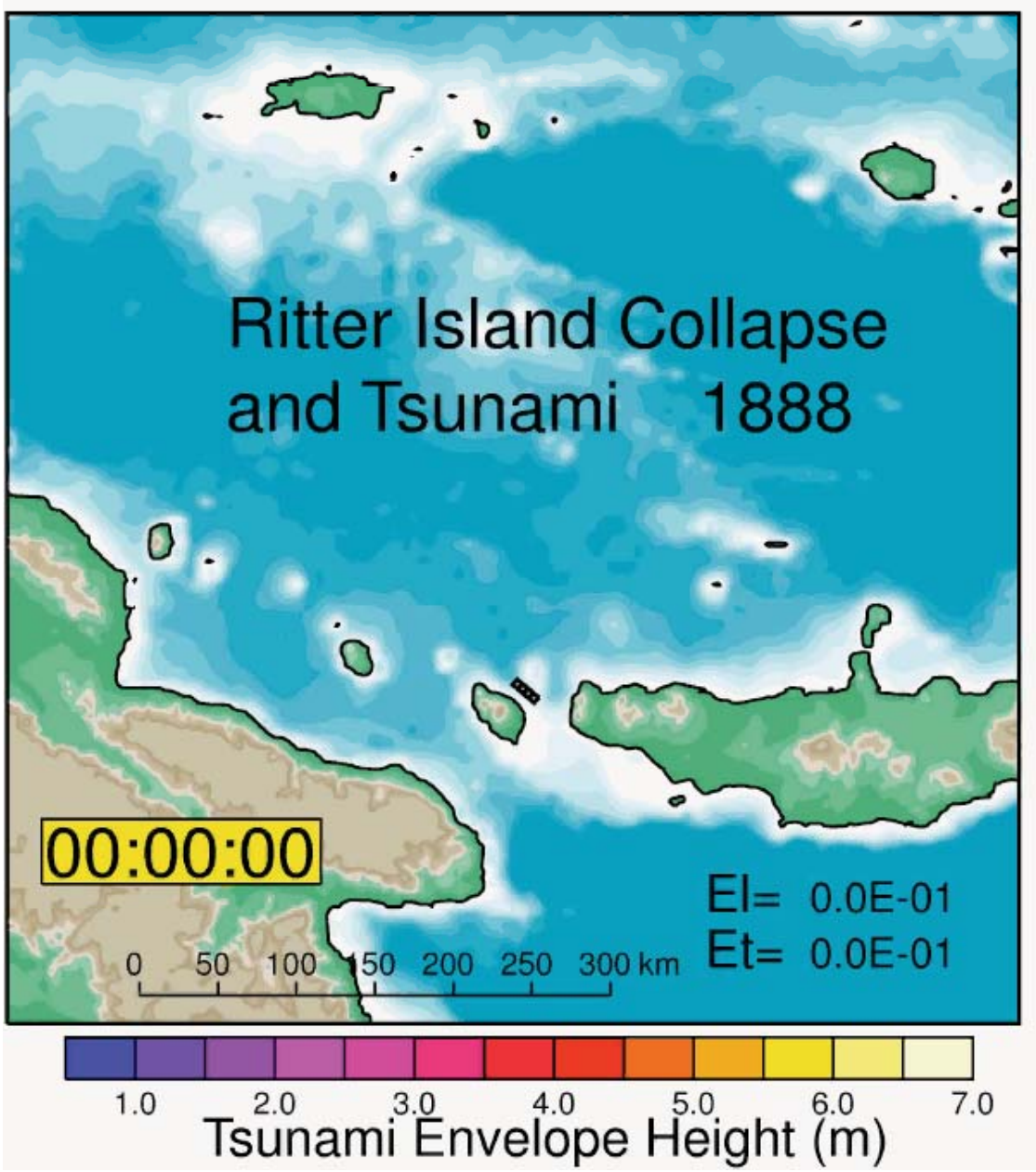
Bathymetric data that we collected on this cruise helped refine Ritter Island Landslide models.

Visible scars on canyon wall indicate slide material did a “Daytona Raceway” turn



Eyewitness observations suggest wave heights of 10-20 meters on nearby Islands and the New Britain Coast. Observations span outward to Madang (4m), Rabaul (2m),and the Lae coast (2m).

Wave likely affected the entire Bismark Sea



While the Ritter Island Event was Impressive at 5 km^3 (Mt. St. Helens size)

Far more Gigantic landslides have occurred in Geological History

In the past 20 million years, the Earth has experienced scores of landslides 10, 100 or even 1000 times larger!

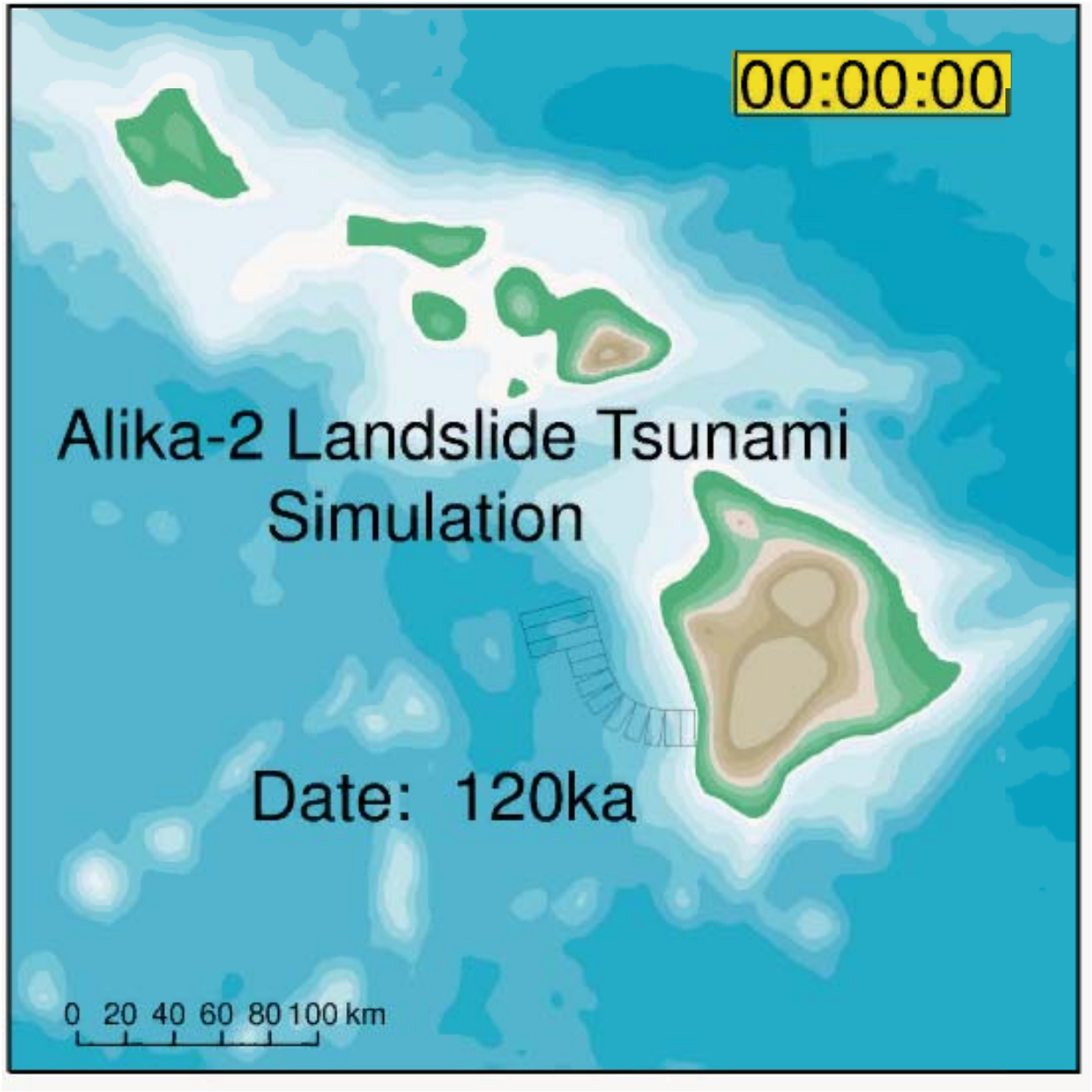
Waves from such superslides are called "Mega-Tsunami"

Hawaii has suffered 70 mega-landslides in the past 20Ma Alika-II is a recent slide off the Big Island just 120ka.

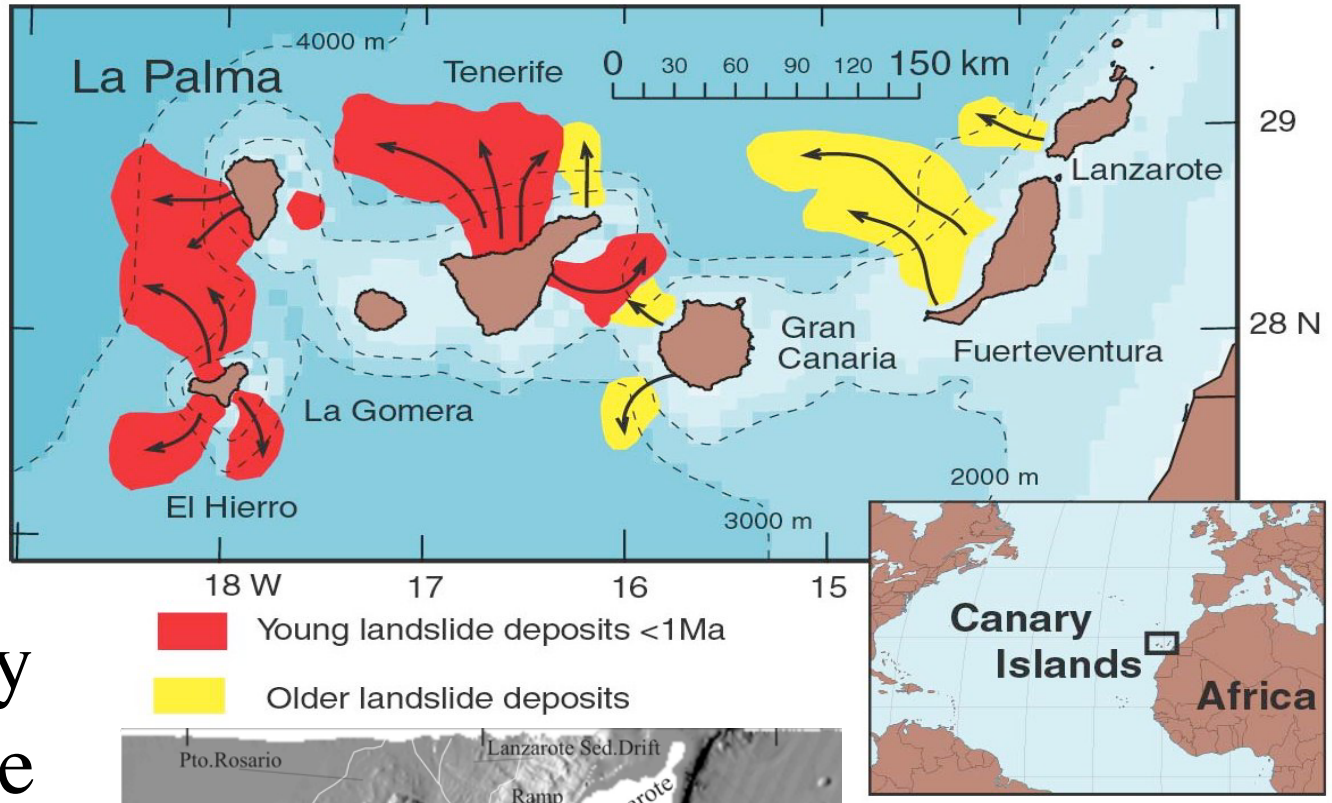
Deposits from this wave found at 400m elevation above the sea at that time and four miles inland

Other deposits several 100 m up on Lanai also likely date to this wave.

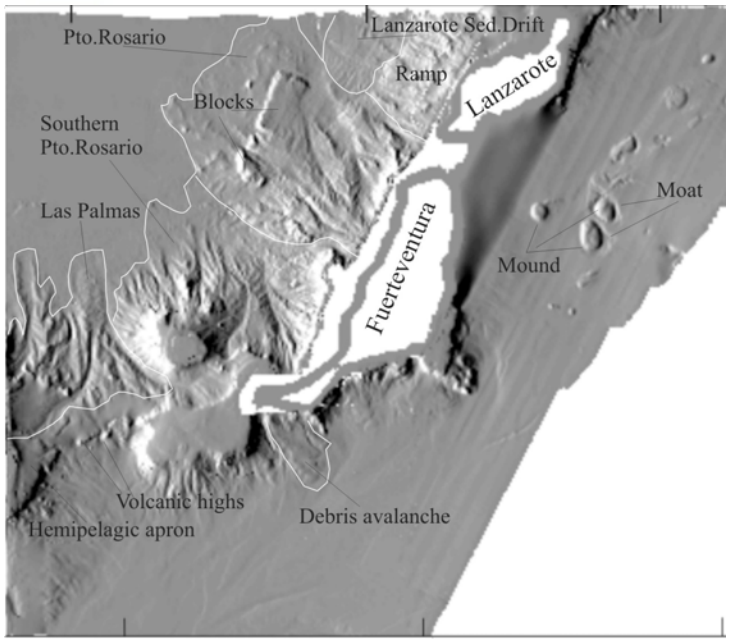
Some people suggest that the wave swept all the way across the Maui isthmus.



Where Next?



The Canary Islands have experienced about a dozen superslides in the past 2 million years.



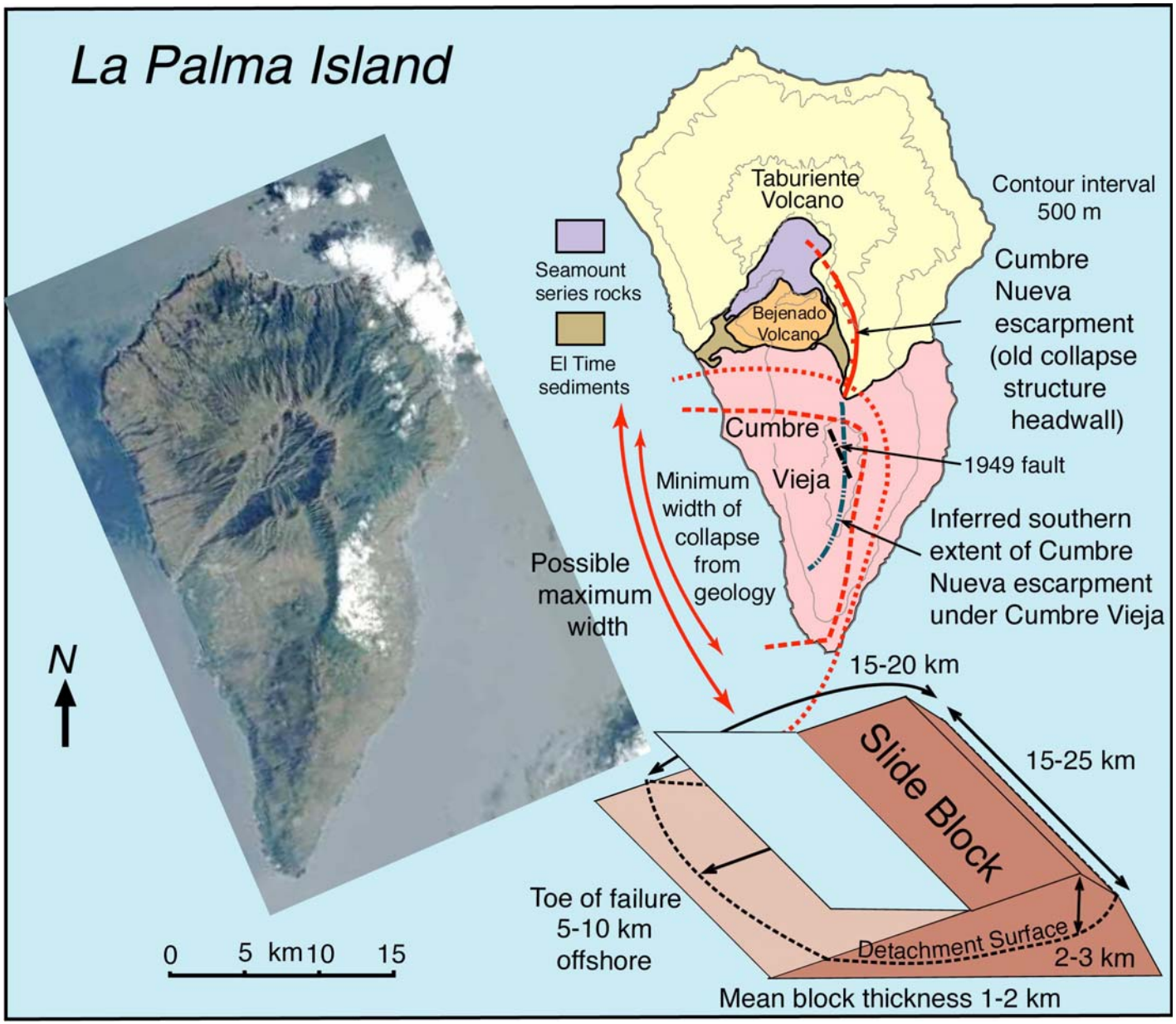
How do we know this?

The slide stuff is still lying there!

Volcano Cumbre Vieja on La Palma Island last collapsed 550,000 years ago.

According to Dr. Simon Day, the mountain is primed for another show.

Expected to drop as much as 500 km^3 into the deep Atlantic Basin-- about the same as last time

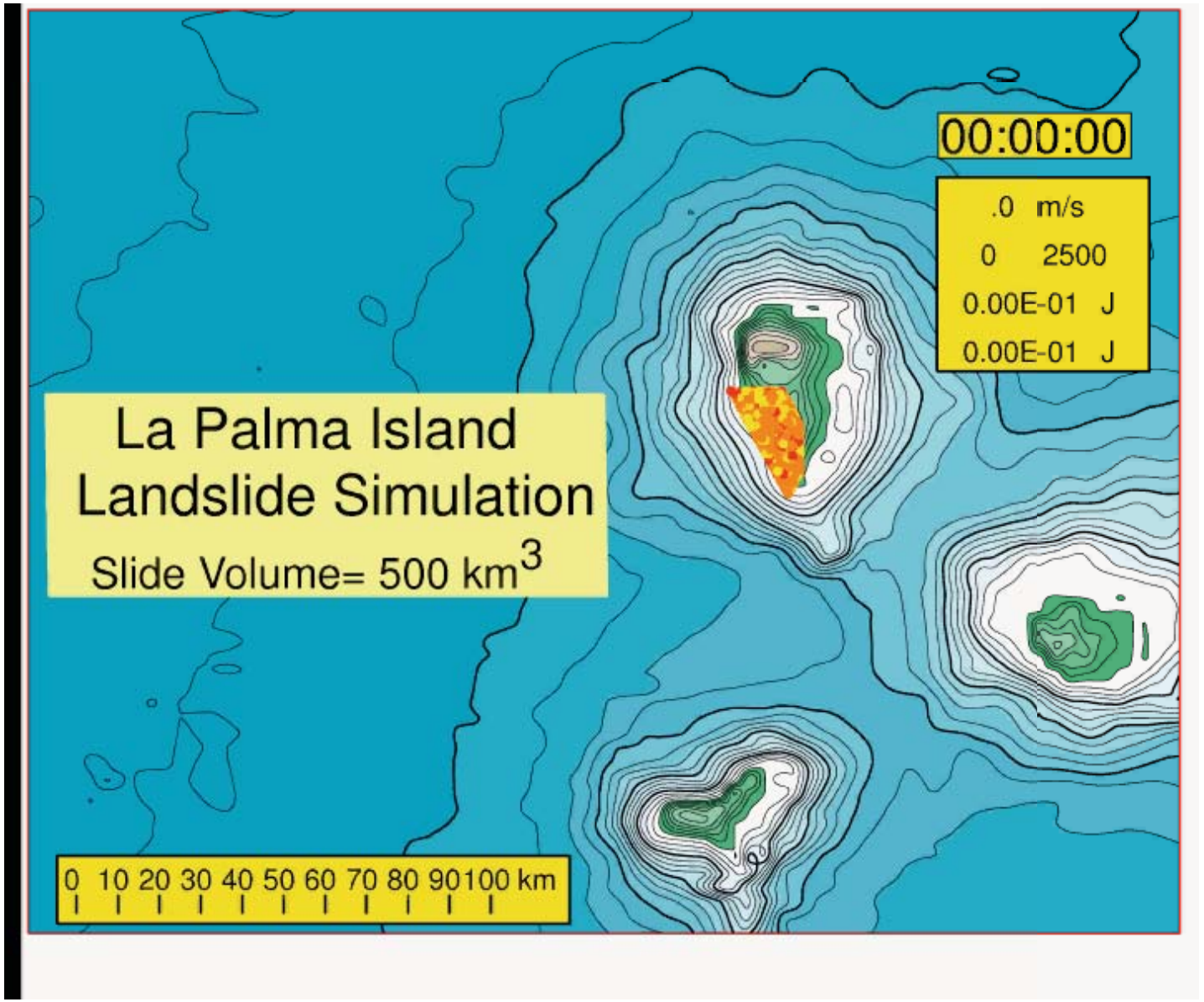


When this happens--

STAND BACK

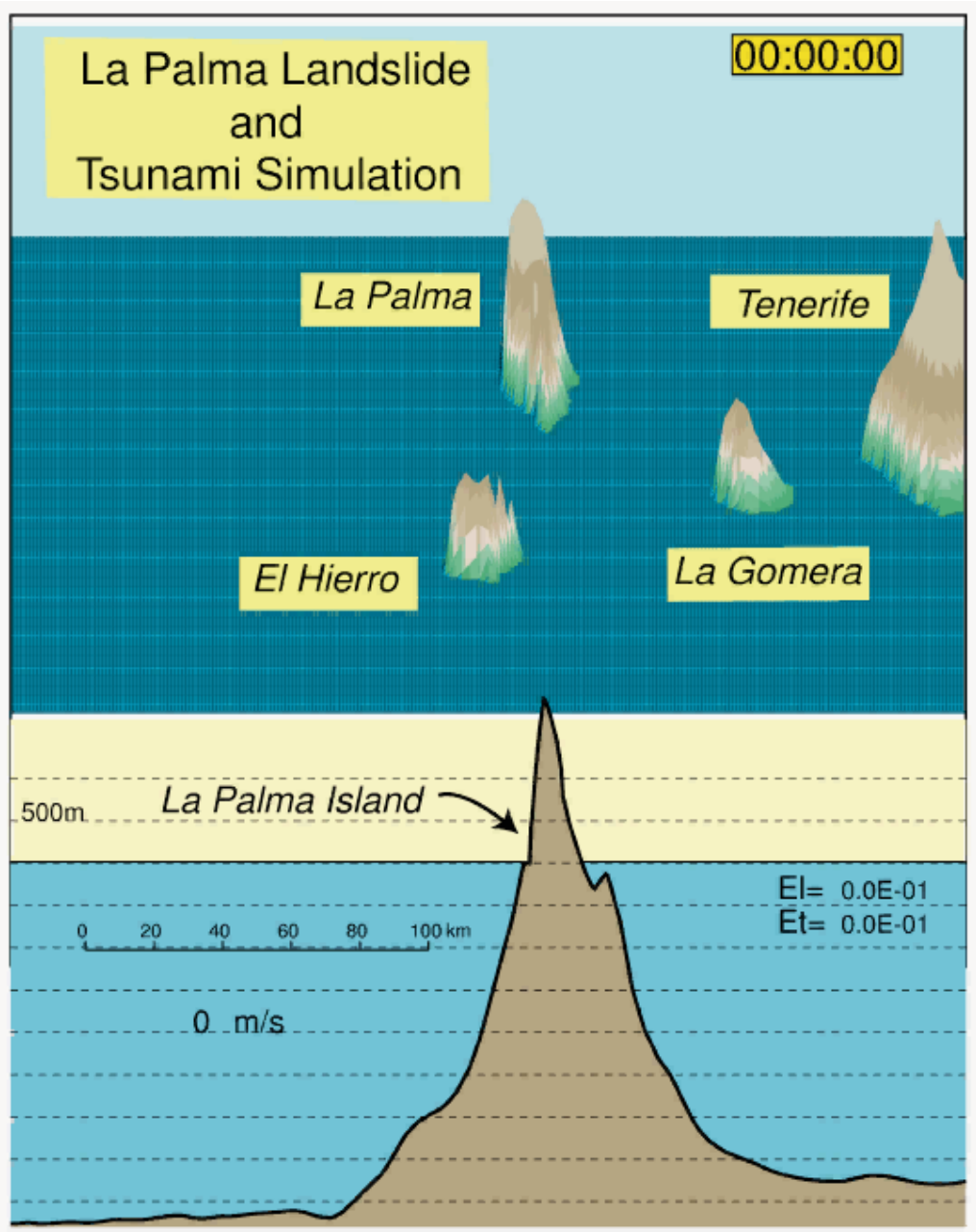
The slide will release about $3x10^{19}$ J of energy.

Roughly equivalent to detonating the entire world's nuclear weapons stockpile all at once. 8,000 Mt.



Only about 10-15% of slide energy goes into tsunami, but still...

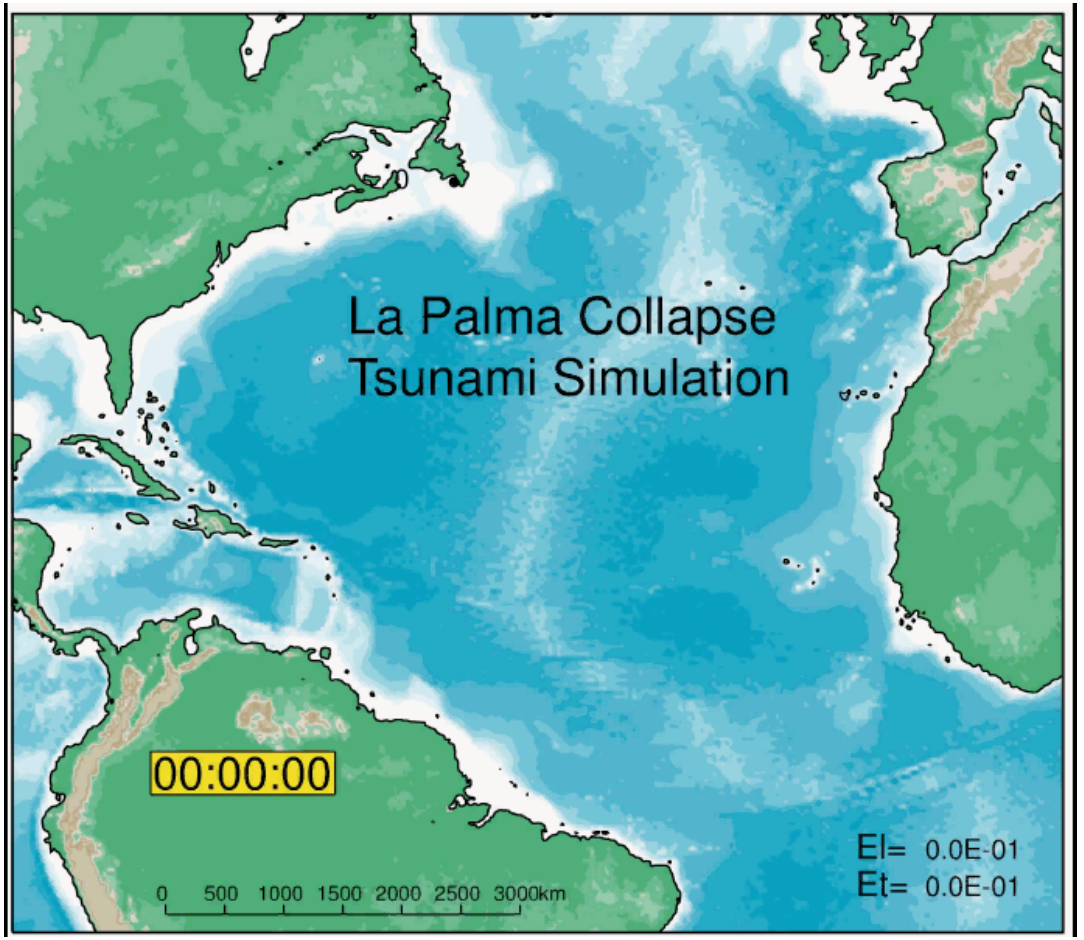
Within 20 minutes, a wave will wet local islands to 150+ meters.

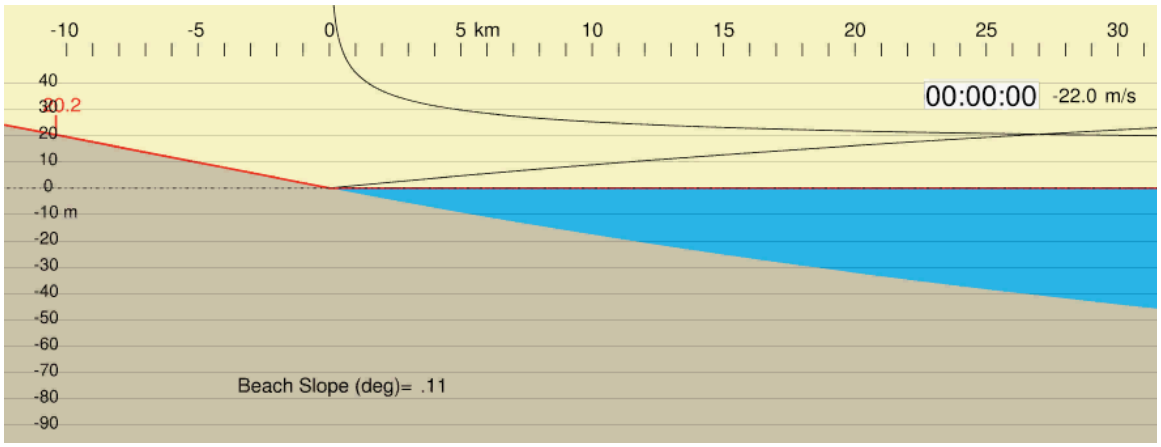


A La Palma Tsunami will affect coasts along entire Atlantic Basin.

Lisbon 40m Ireland: 40m Florida:30m
NYC:25m Brazil:40m

Not just one wave.
WAVE SET UP Storm surge-like



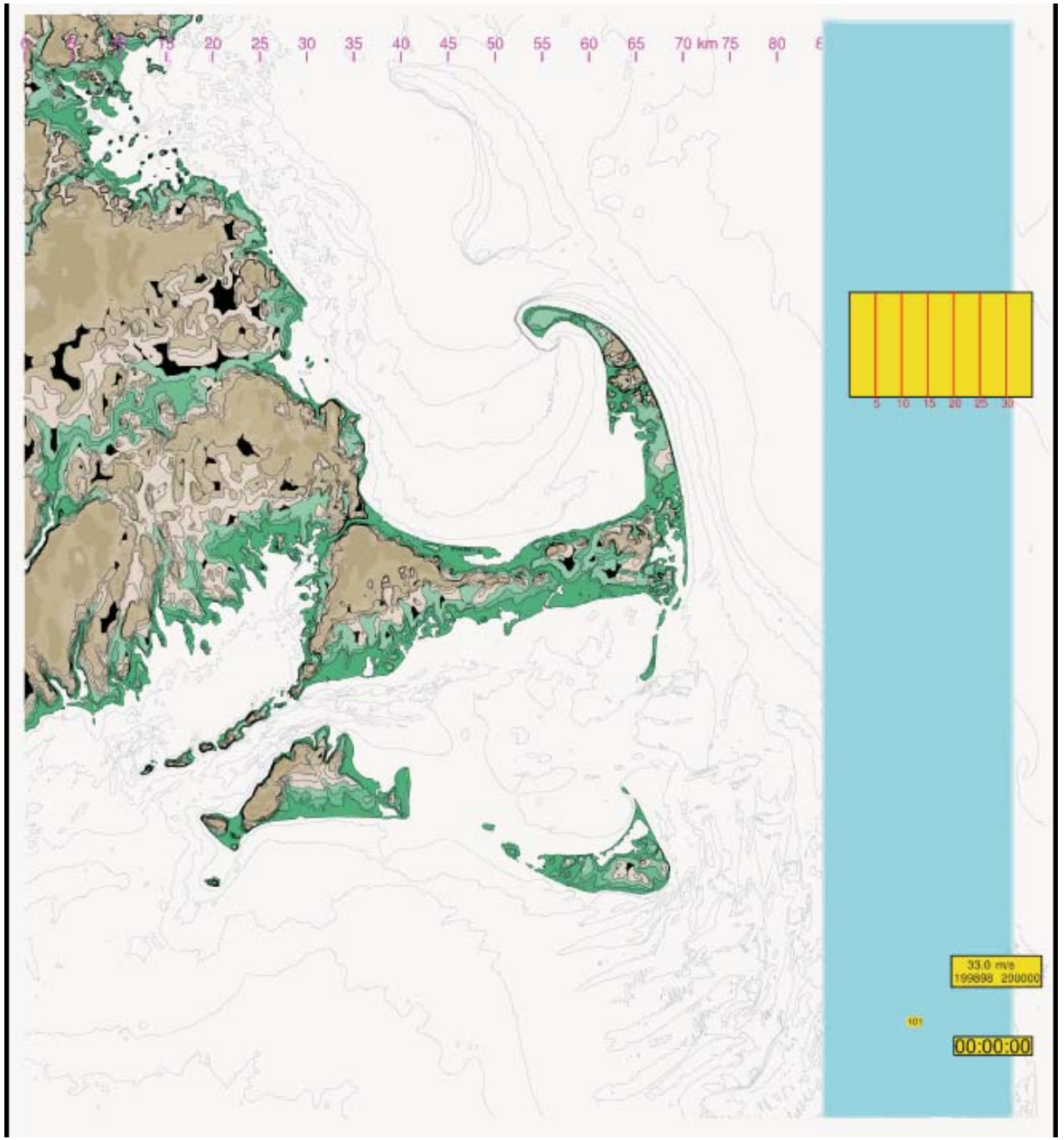


One 10m high wave - coming in to Cape Cod

Flooding several to many miles inland.

Nantucket folks will not be happy.

A LA PALMA TSUNAMI WON'T BE THE END OF THE WORLD, JUST PRETTY EXCITING.



Tsunami Forecasting. Distant tsunami take 2-24 hours to run from quake to coast. People can spend that time preparing if warned.

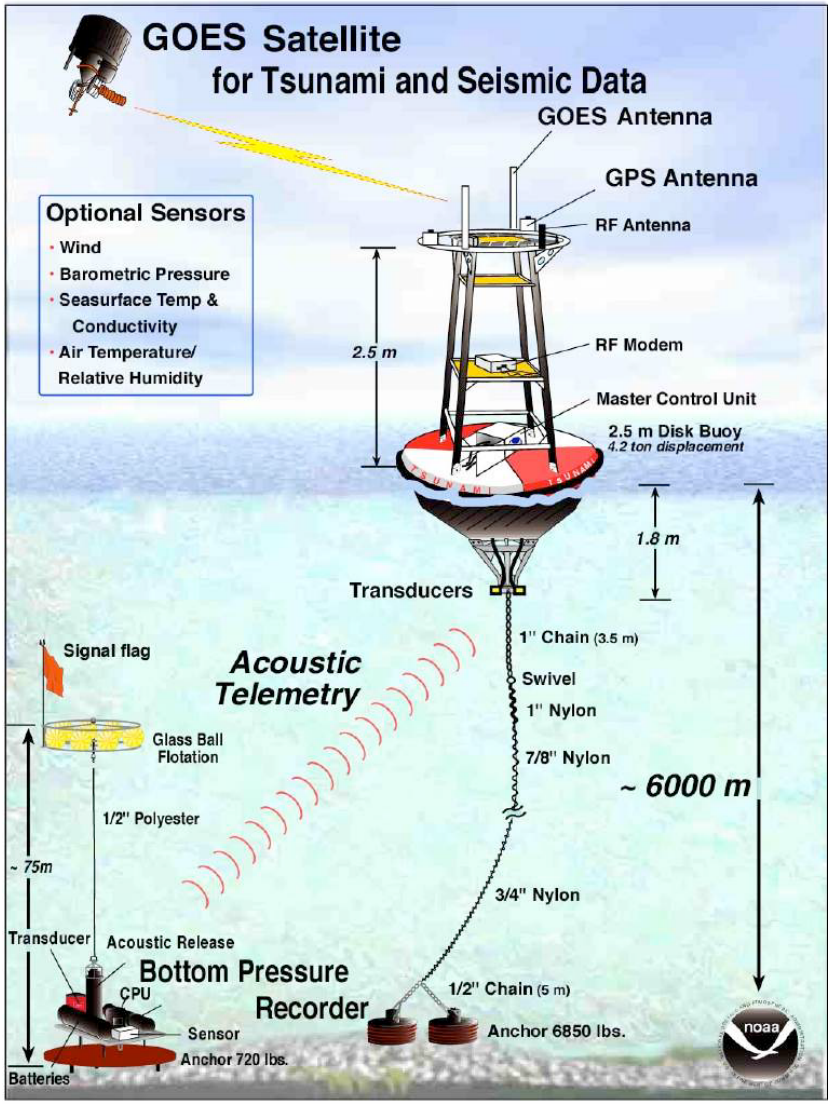
PREVIOUSLY had to depend on earthquake information alone.

Guess work=false alarms

TODAY, we can see tsunami coming with ocean bottom sensors.

Direct check on prediction

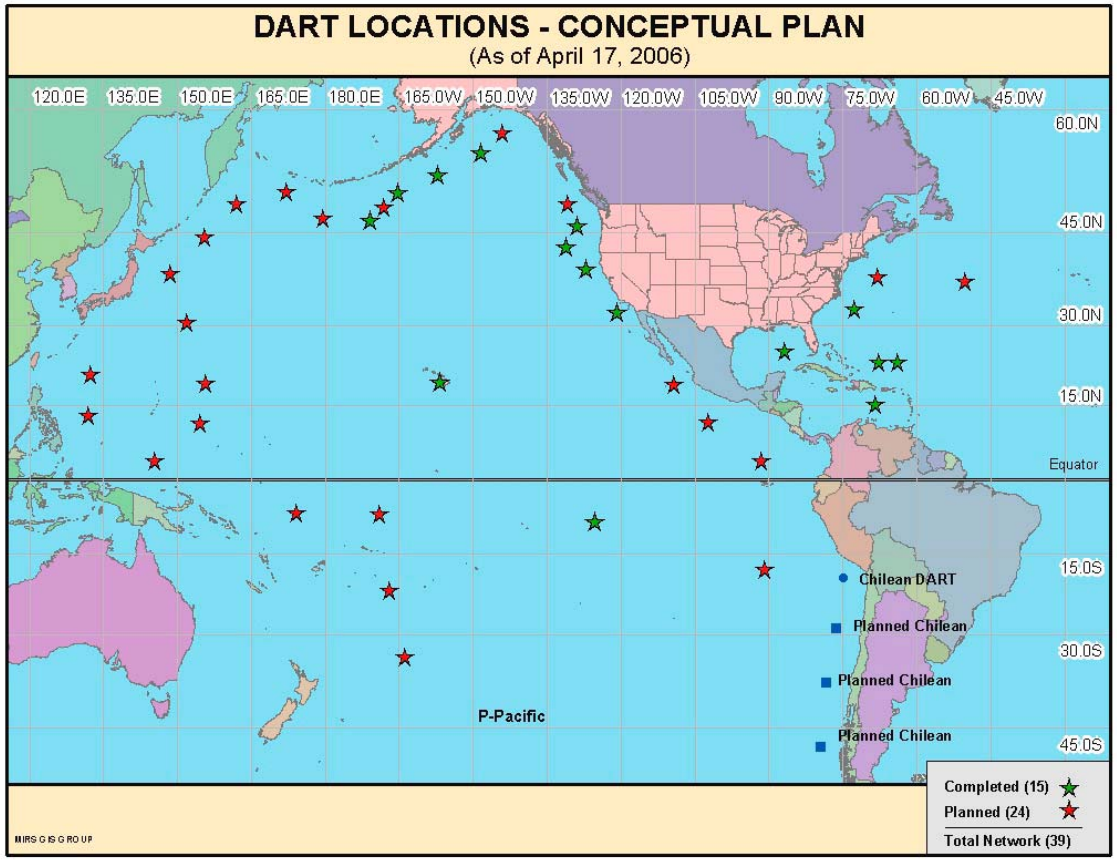
1)Bottom Pressure Sensor
-2)Acoustic Link to Buoy
-3)Radio Link to Satellite and warning center



Existing “buoy-based” tsunami warning system consists of about eight stations mostly off Alaska and Pacific Northwest

There have been several proposals introduced recently in U.S. Congress and other countries to expand tsunami warning system.

Several new stations exist now -- even in the Atlantic



IN NEAR FUTURE, we will be able to track tsunami in deep ocean in real time by satellites, Doppler Radar, Buoy GPS?

Still, technology alone is not the answer- *Predictability* goes hand-in-hand with *Preparation*

Warning Center: Who to call? What level to warn?

Local Emergency Response Teams: What steps to take when called? [Java quake 7/17/06]

Man-on-street: What to do when warned? =Education

Thanks for Attending

This talk is on the web at:

http://es.ucsc.edu/~ward/powerpoint/ICTP-07(big).mov