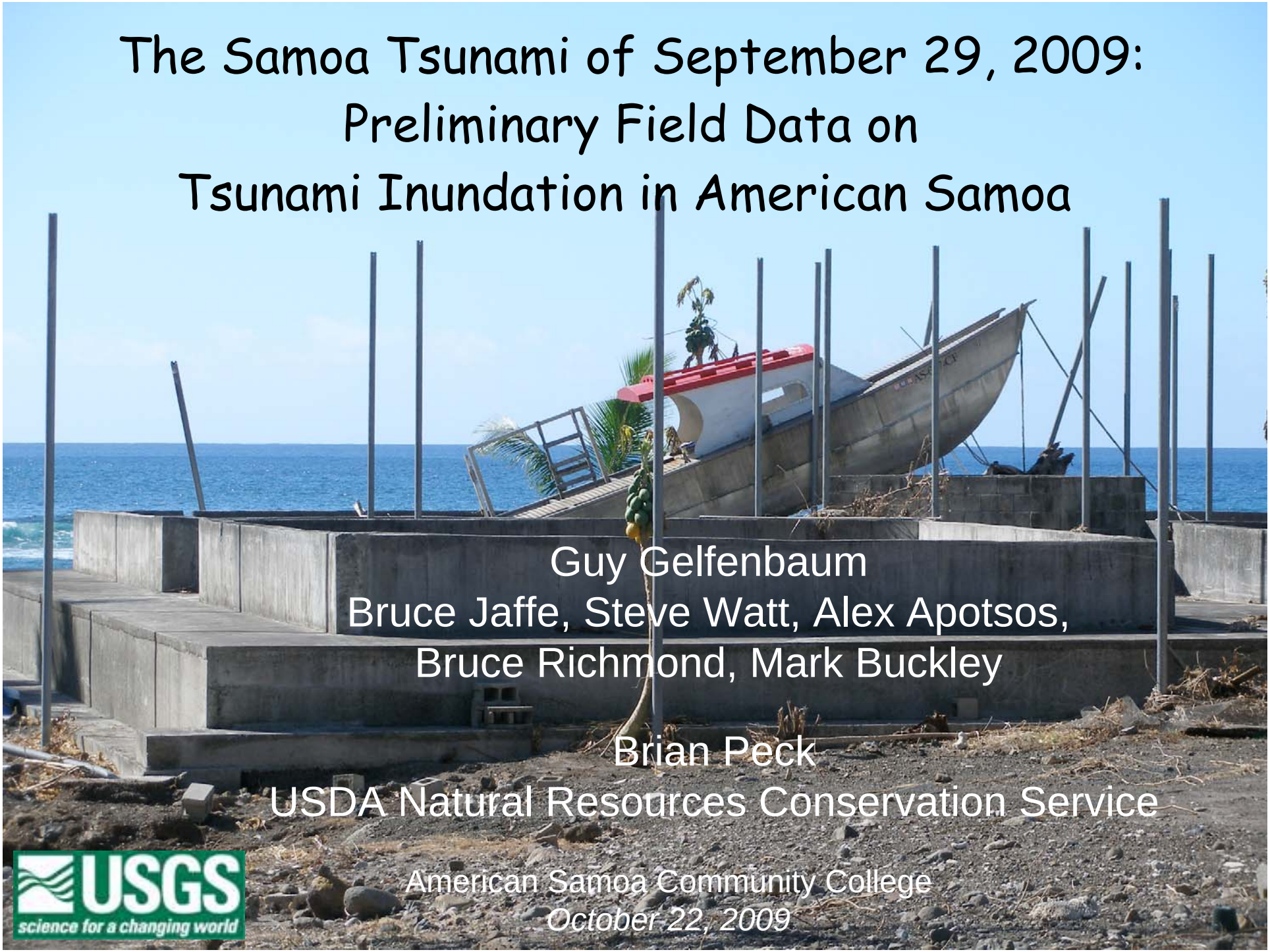
The Samoa Tsunami of September 29, 2009: Preliminary Field Data on Tsunami Inundation in American Samoa



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Bruce Richmond, Mark Buckley

Brian Peck
USDA Natural Resources Conservation Service

USGS
science for a changing world

American Samoa Community College
October 22, 2009

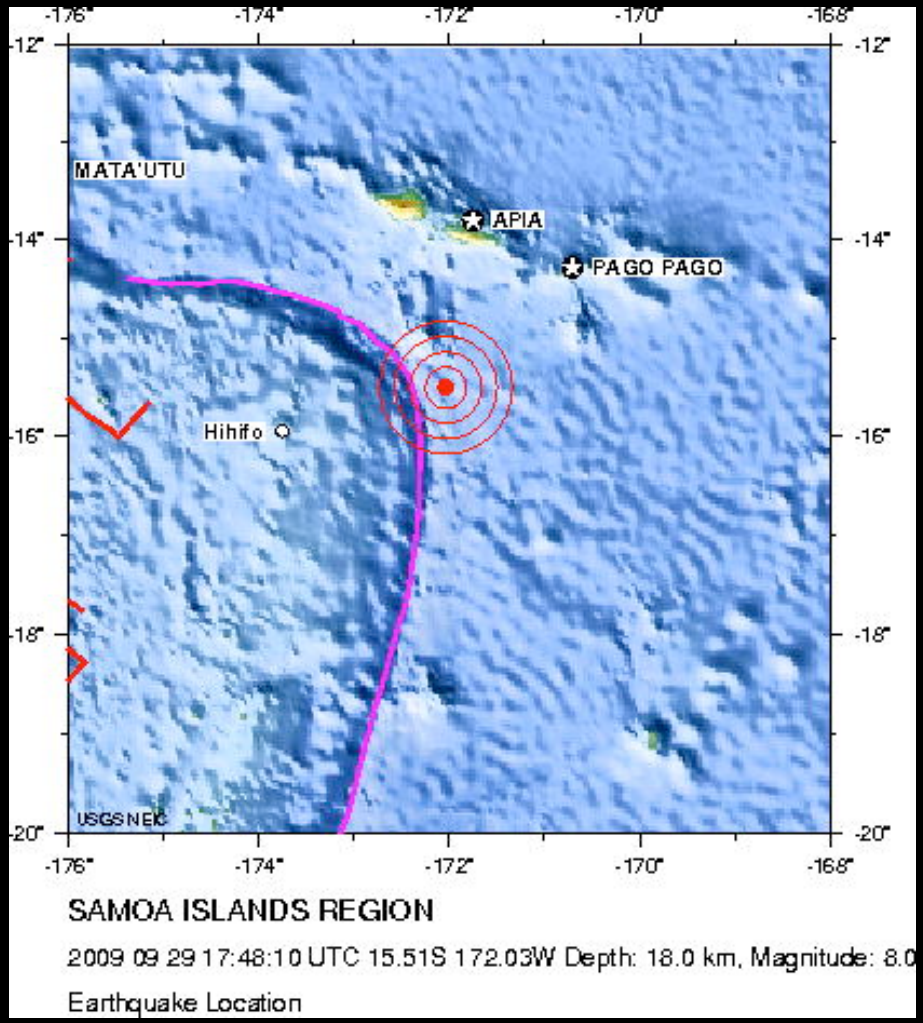
Goals

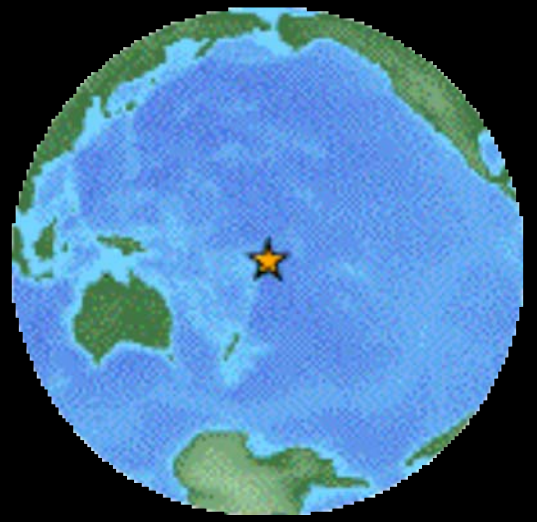
- Measure tsunami wave heights, run-up, and inundation distances (data that are ephemeral)
- Understand magnitude and pattern of inundation
- Improve models of tsunami inundation to help prepare against future tsunami hazards

Outline

- Introduction
  - earthquake
  - tsunami
- Field methods
- Field observations
- Inundation Model
- Conclusions

September 29, 2009 Samoa Earthquake

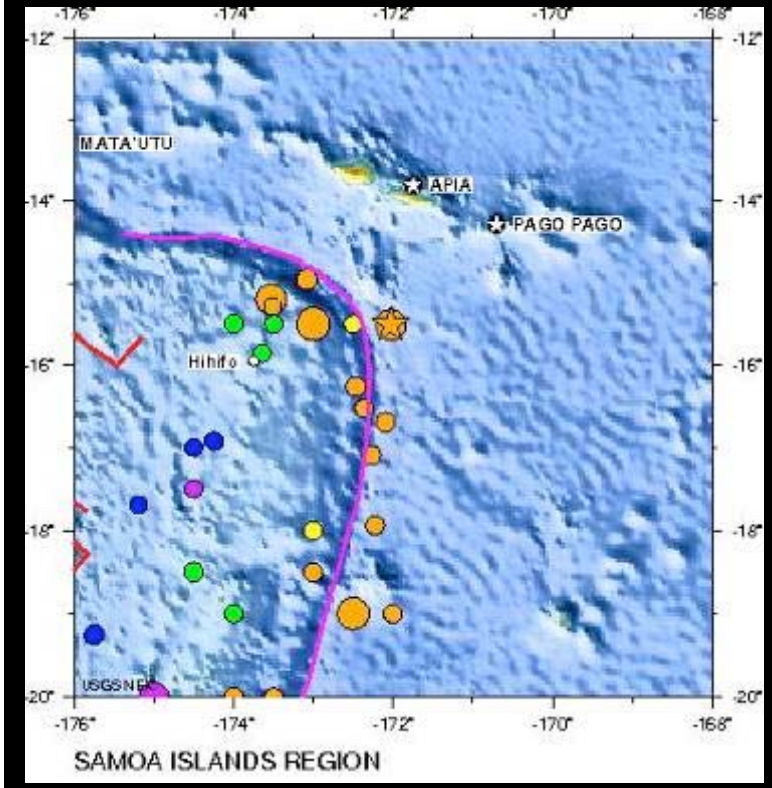




Earthquake occurred at 6:48 am local time

Historical Earthquakes

Since 1900

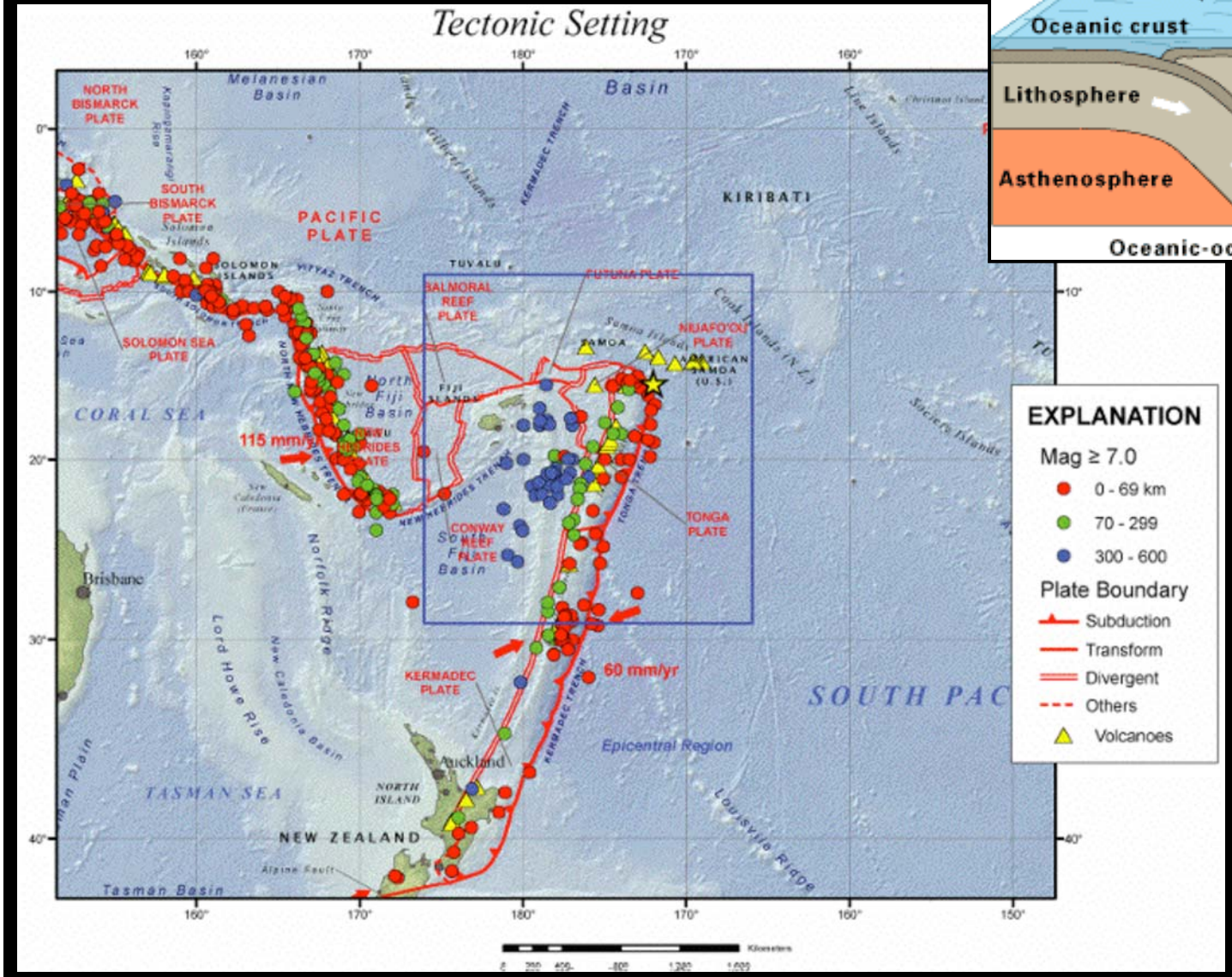


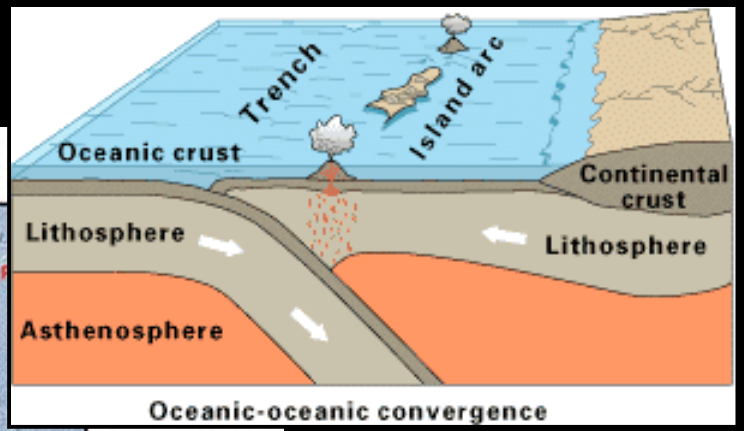
Significant Earthquakes Mag >= 7.5

Year	Mon	Day	Time	Lat	Long	Dep	Mag
1903	01	04	0507	-20.000	-175.000	400	8.0
1913	06	26	0457	-20.000	-174.000	0	7.7
1917	06	26	0549	-15.500	-173.000	0	8.5
1919	01	01	0300	-19.971	-177.914	202	7.7
1919	04	30	0717	-19.823	-172.215	35	8.2
1937	04	16	0301	-20.768	-177.144	348	7.5
1948	09	08	1509	-21.000	-174.000	0	8.0
1950	12	14	0152	-19.250	-175.750	200	7.5
1957	04	14	1918	-15.403	-173.129	35	7.5
1962	05	21	2115	-19.962	-177.272	416	7.5
1975	12	26	1556	-16.241	-172.364	15	7.7
1981	09	01	0929	-15.112	-173.019	14.2	7.5
2006	05	03	1526	-20.187	-174.123	55	8.0
2009	09	29	0648	-15.560	-172.070	18	8.0

Source: http://neic.usgs.gov

Tectonic Setting





earthquake occurred as a normal fault rupture on or near the outer rise of the subducting Pacific plate.

Plates converging: 1.5 in/yr

Map prepared by U.S. Geological Survey
National Earthquake Information Center

http://earthquake.usgs.gov

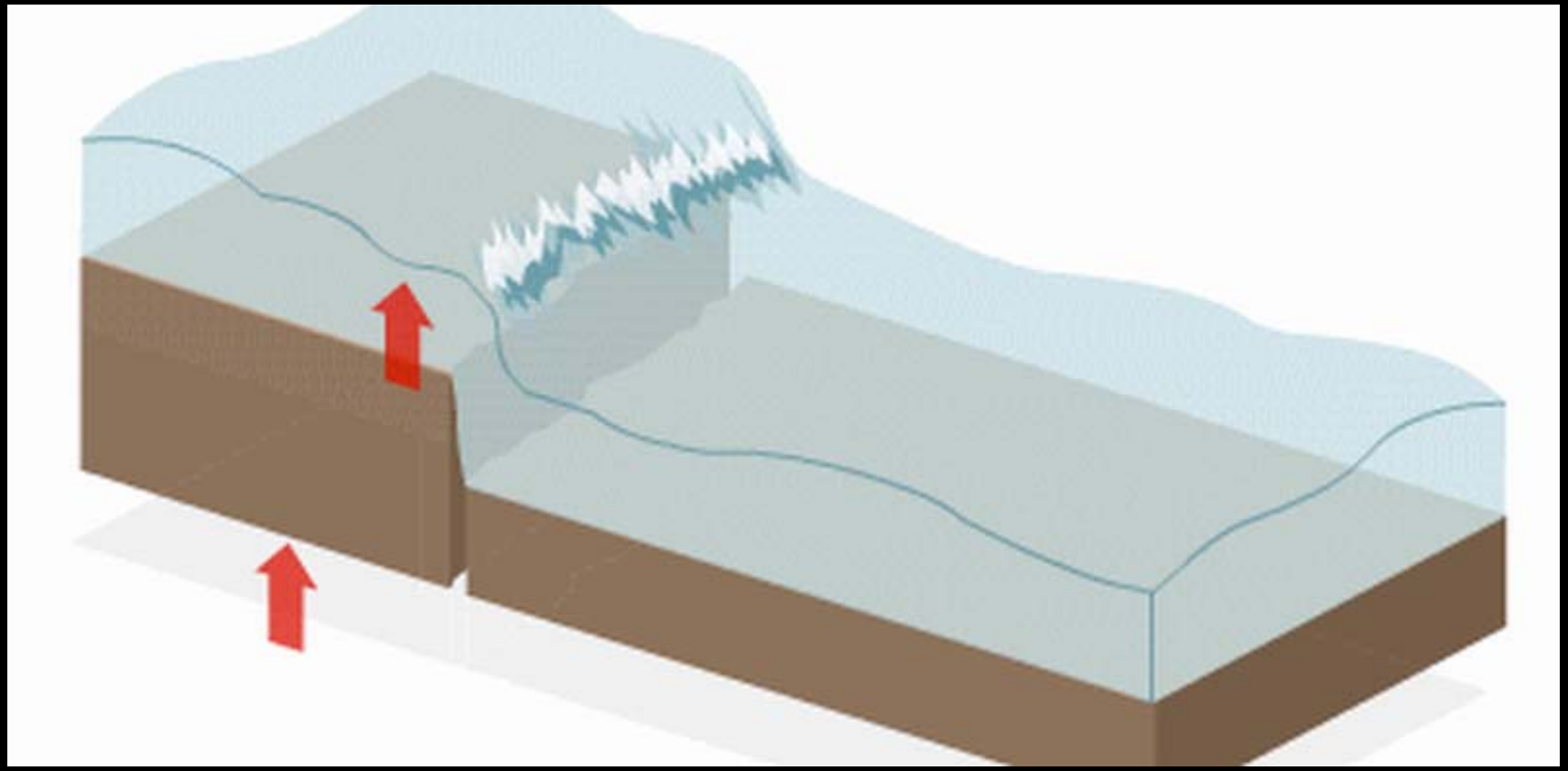
Historical Tsunamis

Source	Run-up	Damage
Local tsunami (Tonga Trench) June 17, 1917	Pago Pago Harbor, Tutuila	Run up 4 feet (1.2 meters)	Many houses destroyed, church damaged.
Aleutian tsunami April 1, 1946	Pago Pago Harbor	Run up 2.6 feet (0.8 meter)	Pacific-wide impacts. Several huts washed away.
Kamchatka, Russia tsunami November 4, 1952	Pago Pago Harbor	Run up 2.7 feet (0.9 meter)	Pacific-wide tsunami. No documented damage.
Aleutian tsunami March 9,1957	Pago Paga Harbor, Tutuila	Run up 4 feet (1.2 meters)	Road flooded.
Chilean tsunami May 22, 1960	Pago Pago Harbor, Tutuila	Run up 4.5 feet (1.4 meters) at harbor entrance, 10.7 feet (3.3 meters) at the inner end of harbor (PPG), Run up 16 feet (4.9 meters) Tutuila, 8 feet (2.4 meters) Pago Pago (NGDC website)	No documented damage.
Local tsunami (Loyalty Islands) May 16, 1995	Pago Paga Harbor	Run up 1.6 feet (0.5 meter)	No documented damage.

Found on Fagatele Bay National Marine Sanctuary web site

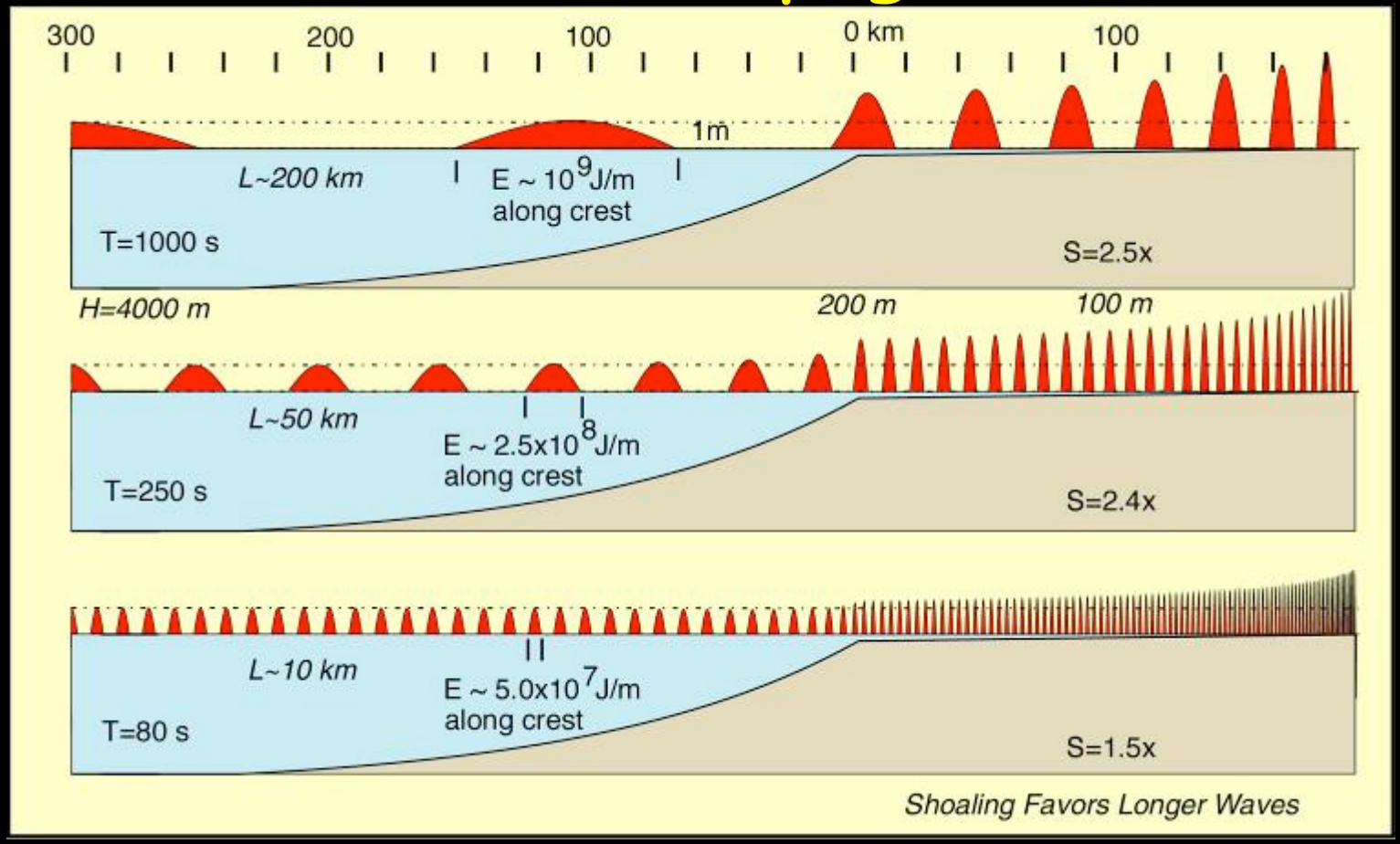
Tsunami Generation

Tsunami forms when earthquake vertically displaces seafloor and water above it



Cornell tsunami website

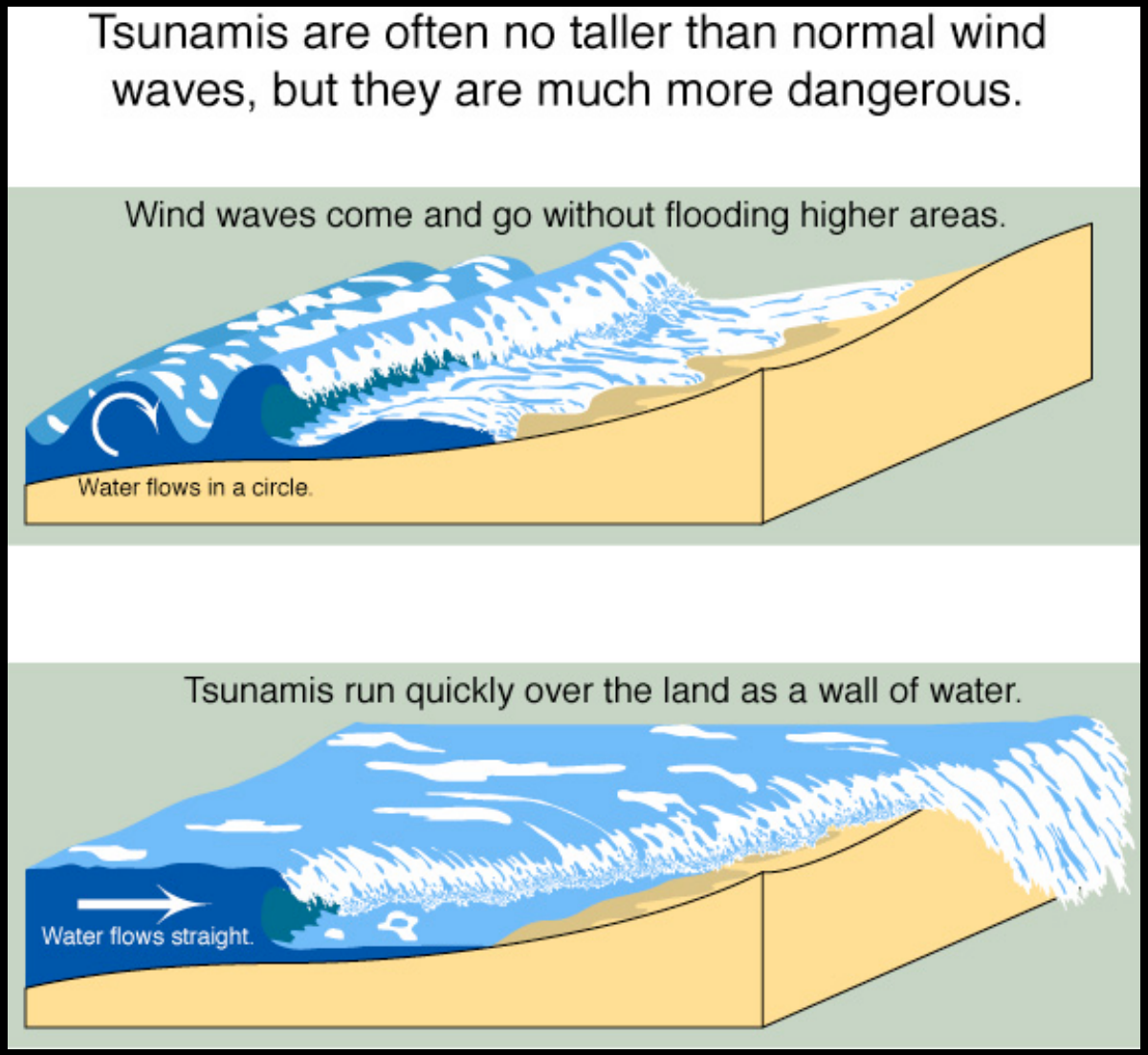
Tsunami Propagation



- Tsunami wavelength decreases in shallow water
- Tsunami height increases in shallow water
- Propagation speed is $\sqrt{gh}$ ~300 mph in 2000 m depth

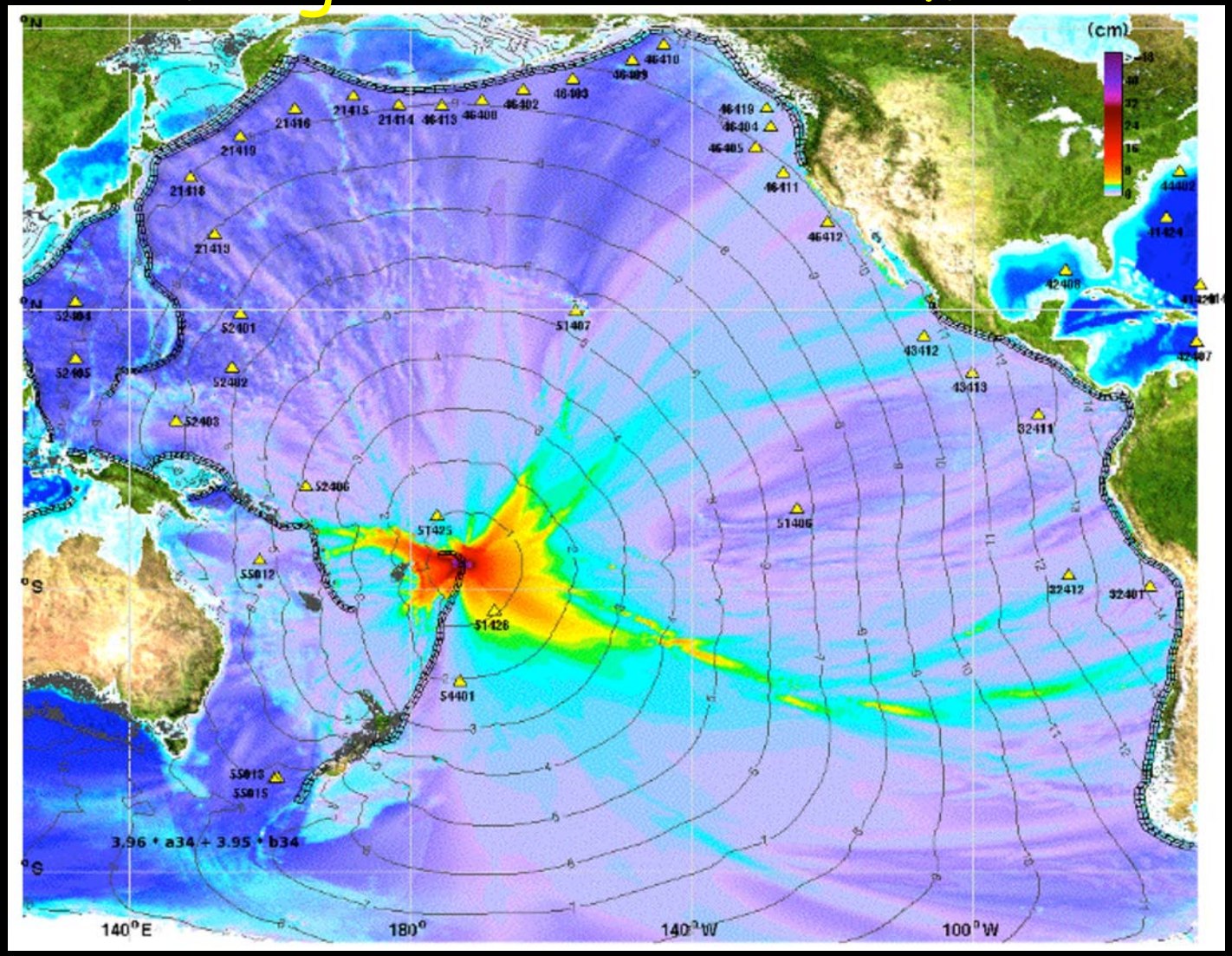
Slide courtesy of Steve Ward. UCSC

Tsunami Inundation

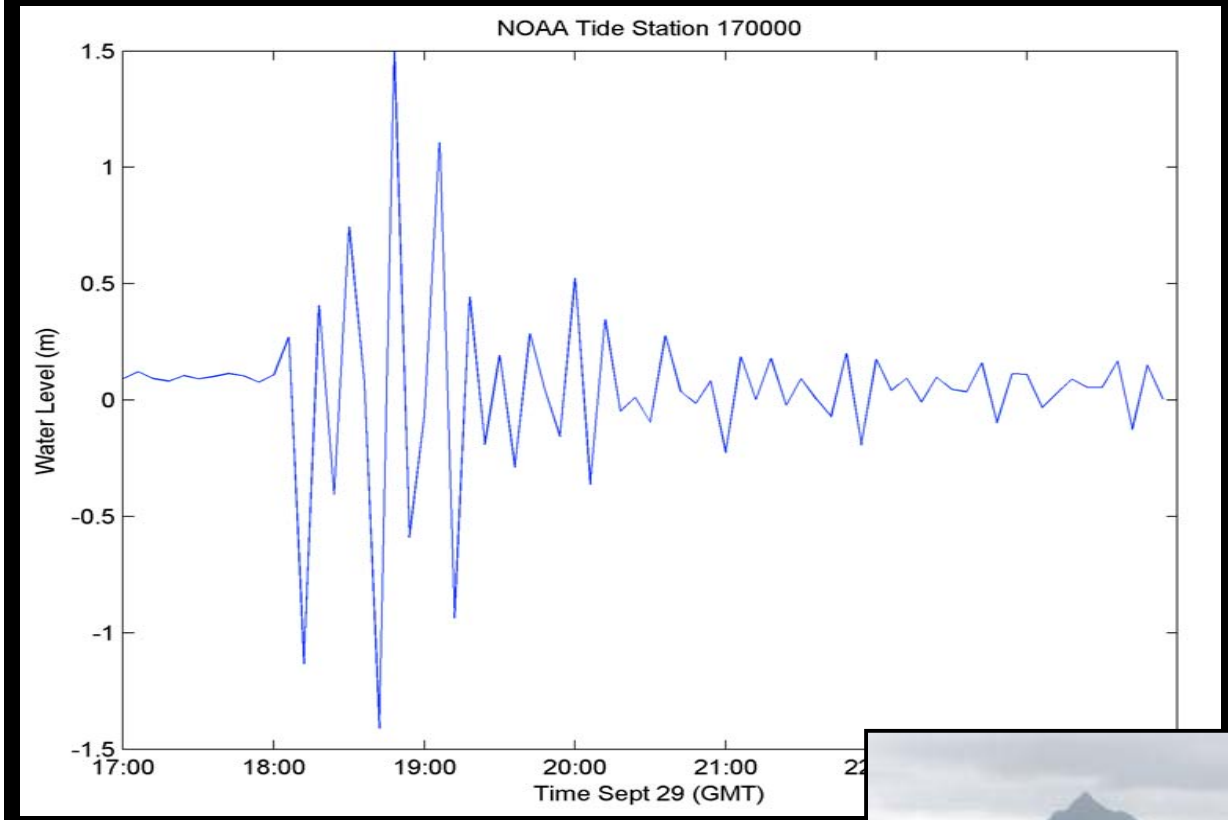


Slide Courtesy of Eric Geist, USGS

Modeled Maximum Wave Heights and travel times



NOAA, PMEL

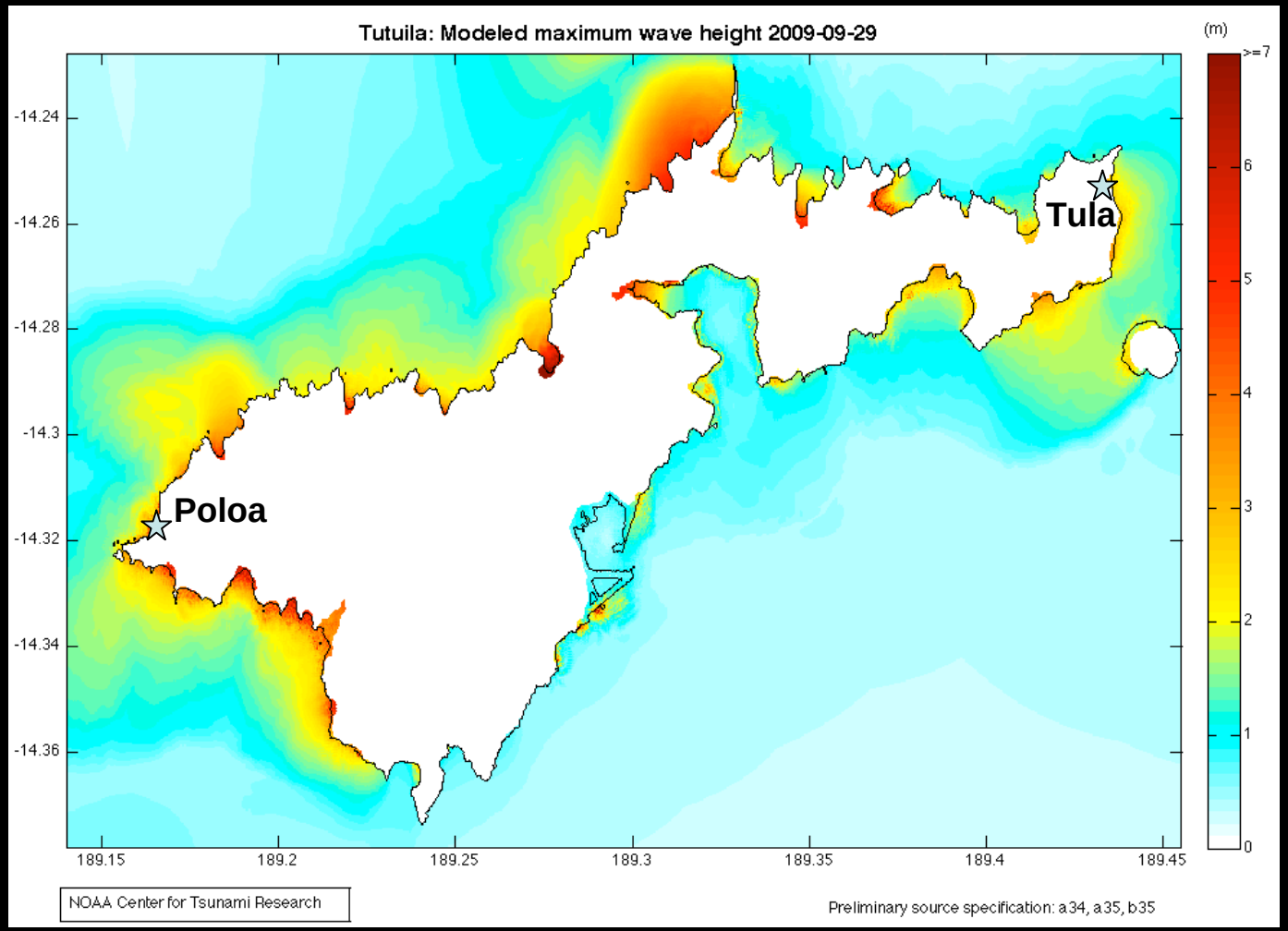


Samoa Tsunami

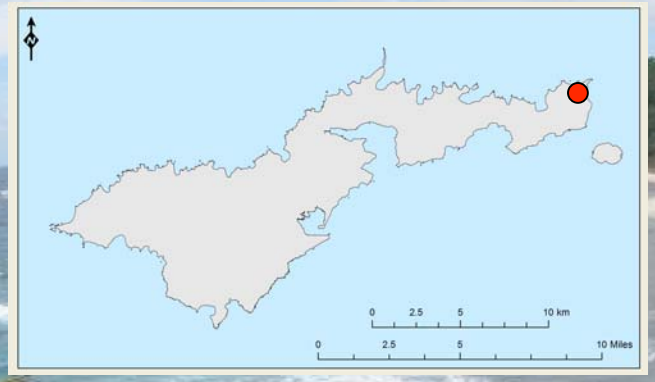
Pago Pago Harbor Tide Gauge

- initial drawdown
- many waves, including reflections and sloshing
- 3 large waves
- wave period about 12 minutes

Modeled Maximum Wave Heights

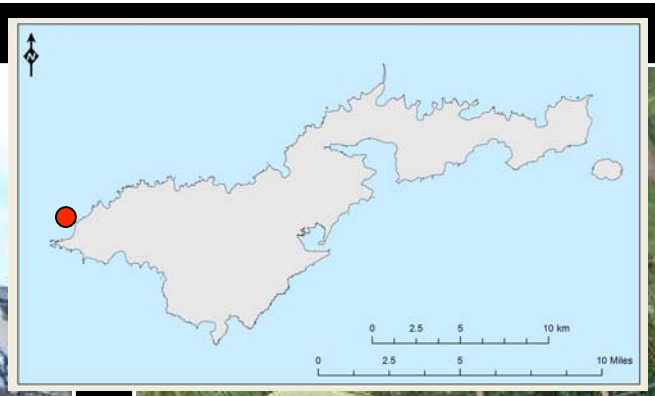


- Compare measured wave heights to modeled and where they do not match figure out why
- Understand the complex pattern of wave heights around Tutuila



Tula

Low-lying coastal plain
R = 5-7 m
I = 230 m



Poloa

Entire village destroyed; no fatalities

Steep coast
R = 11-12 m
I = 70 m

International Tsunami Survey Team

Data Types Collected During Surveys

- Eyewitness accounts
- Water levels (at beach, inland, and run-up)
- Flow directions
- Inundation distance
- Topographic & bathymetric profiles
- Sediment deposit & paleo-tsunami data
- Subsidence
- Coastal change

Why scientists conduct rapid post-tsunami investigations

Sumatra after Dec '04 Indian Ocean tsunami

- Critical wave height and inundation data are ephemeral
- Provide inundation data to local planners

Eyewitness Accounts

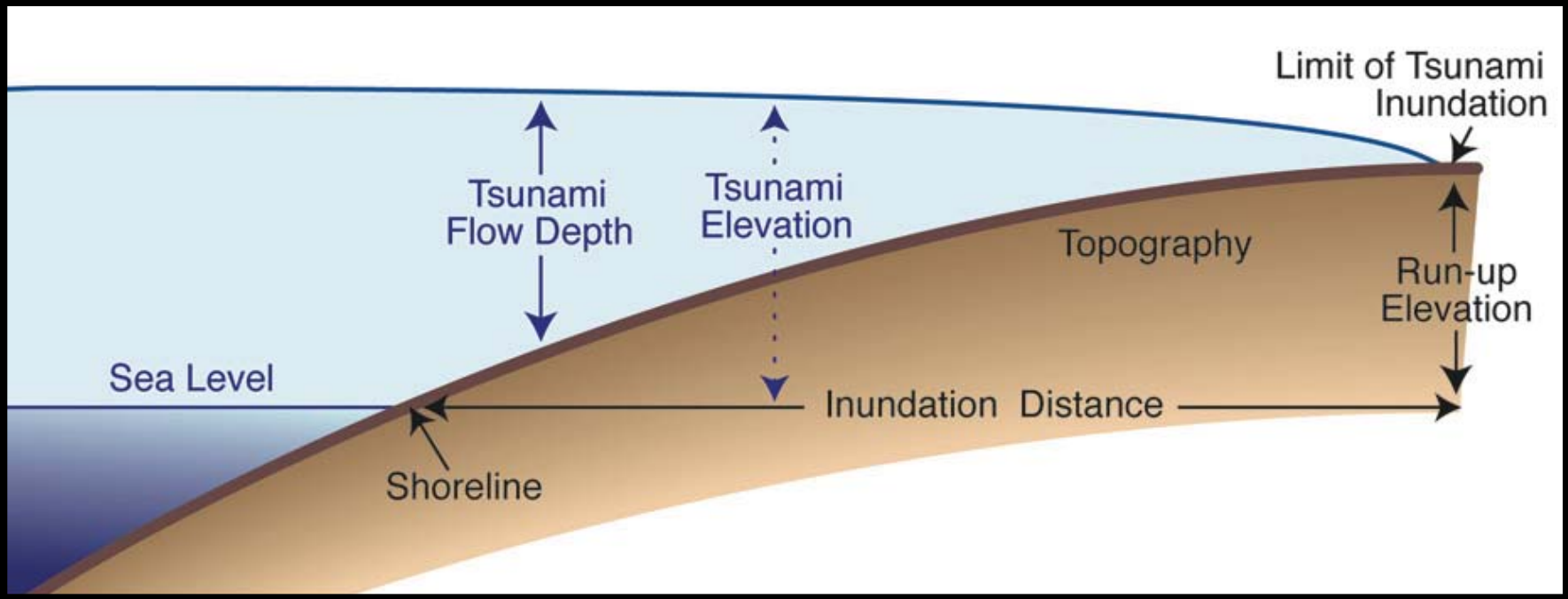
- Earthquake shaking did not destroy building, tsunami did
- Tsunami arrived 15-20 min after EQ
- Second wave was the largest
- How people responded to EQ

Wave heights, run-up, and inundation distances

Interface between dead and living vegetation

Broken branches and debris in trees

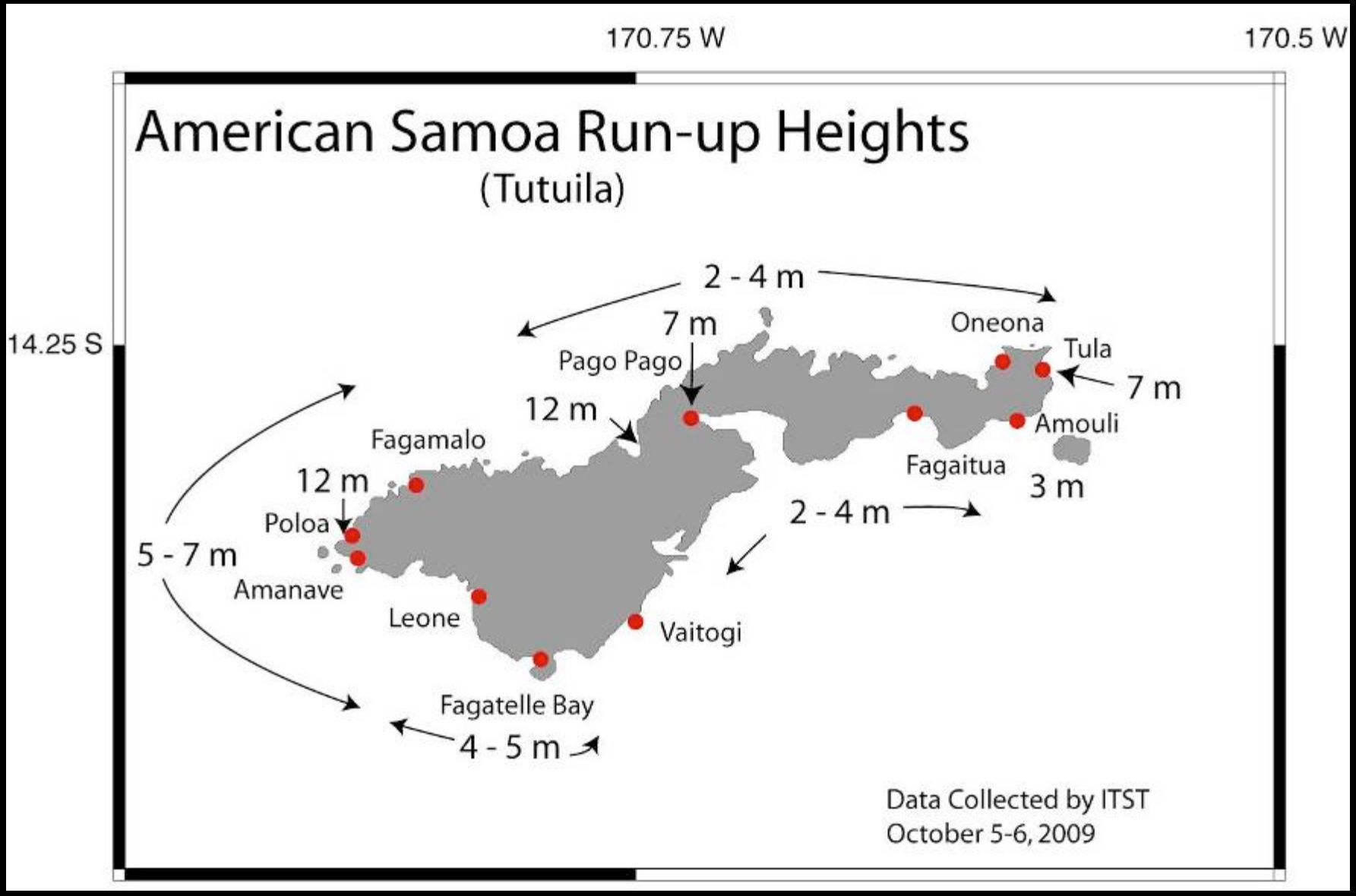
Tsunami Terminology



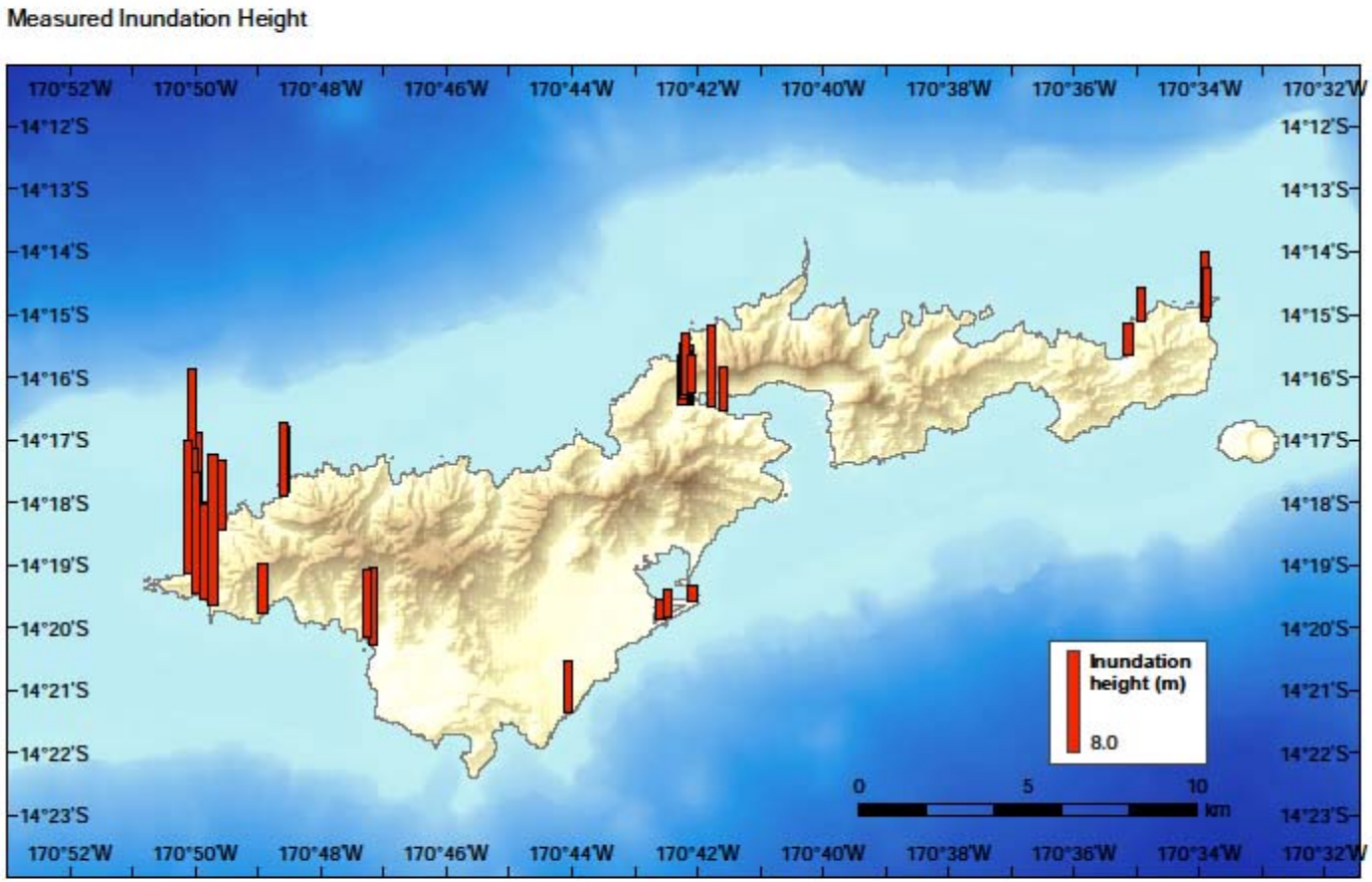
Inundation Distance = distance tsunami travels inland

Run-up = elevation at limit of tsunami inundation

Measured Tsunami Run-up Heights

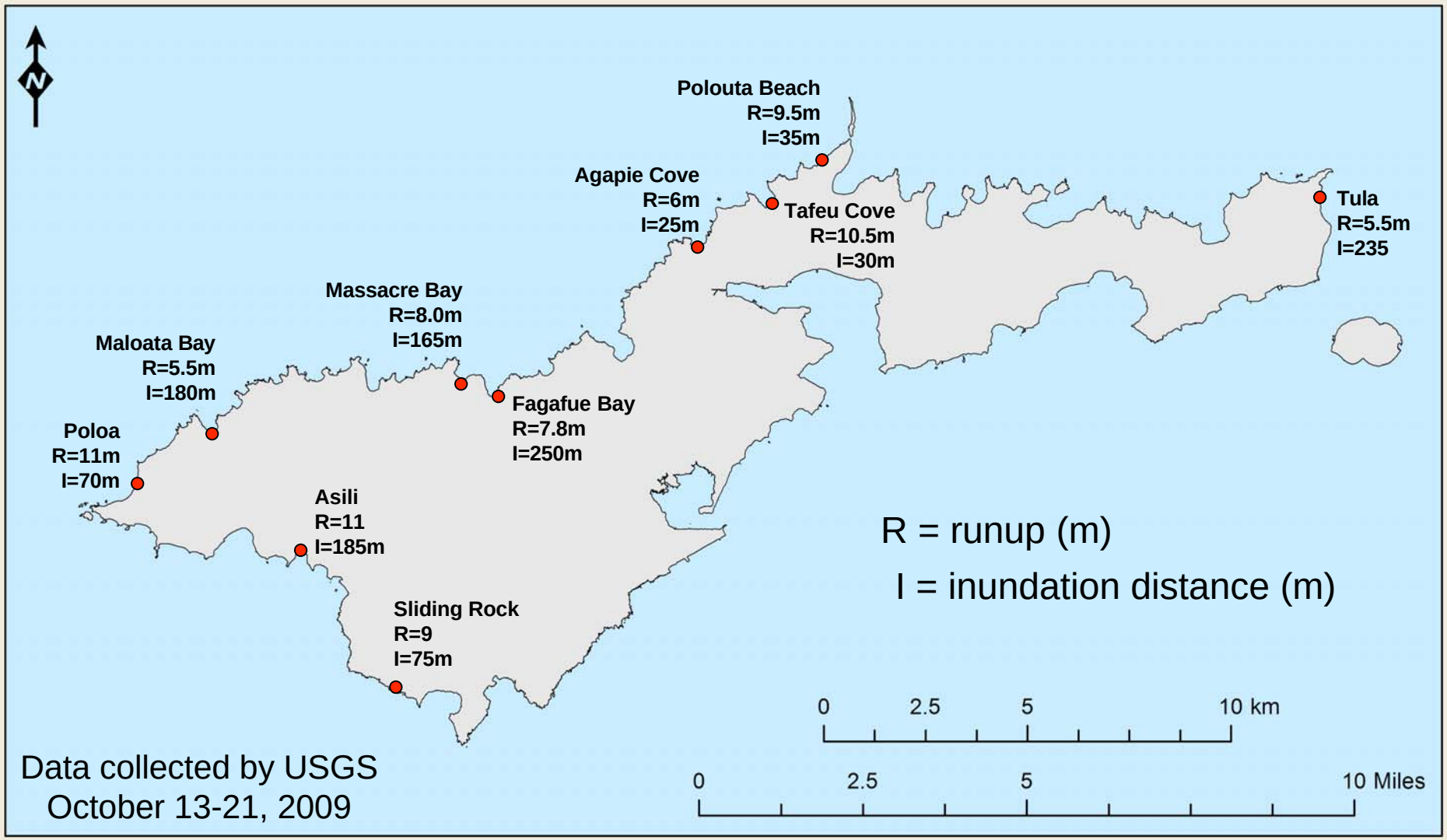


Measured Tsunami Run-up Heights



Japanese Tsunami Survey Team
Koshimura et al., Post-tsunami survey report, Oct 2009

Preliminary run-up elevations and inundation distances



Satellite Imagery

Pre-tsunami

Post-tsunami

Can be useful in assessing tsunami inundation

Satellite Imagery

Pre-tsunami

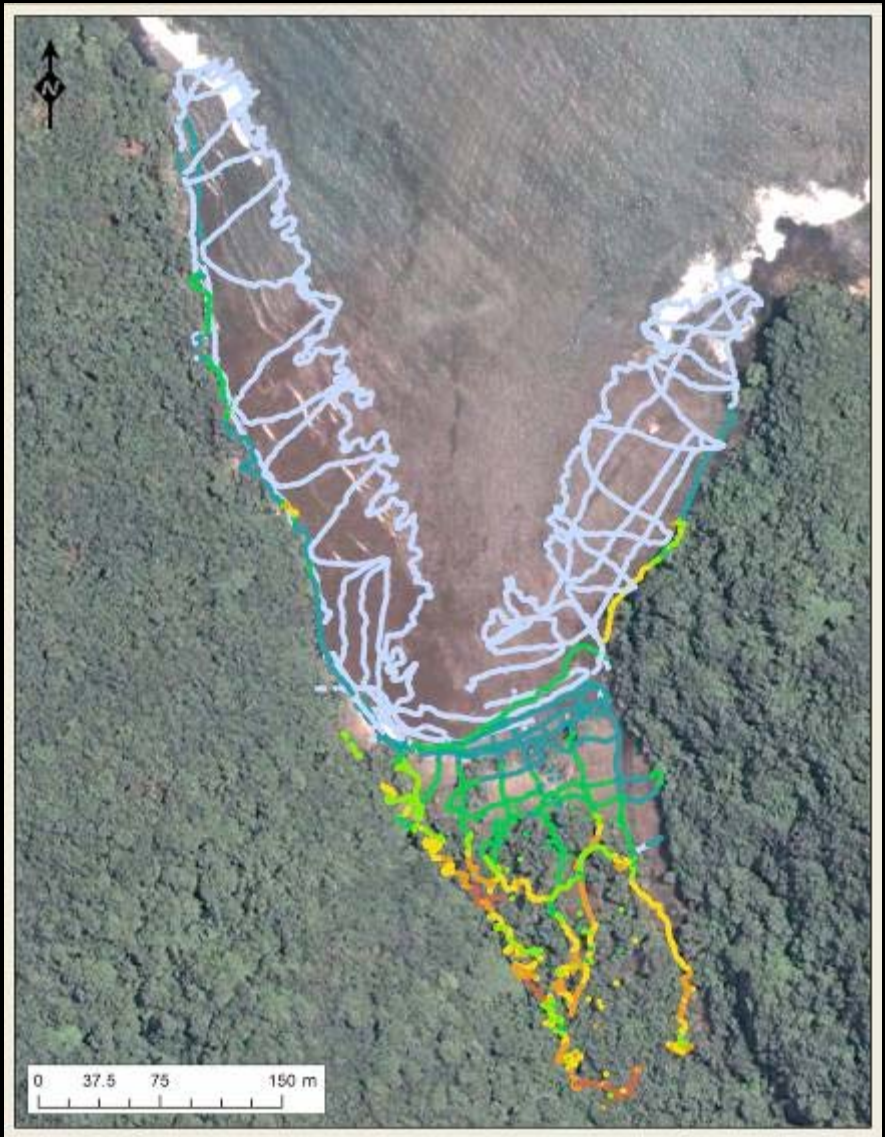
Post-tsunami

But can be inaccurate if tree canopy remains after tsunami

Factors influencing tsunami inundation

- coastal topography
- nearshore bathymetry
- shape of coast
- bottom roughness
- coastal vegetation

Coastal Topography

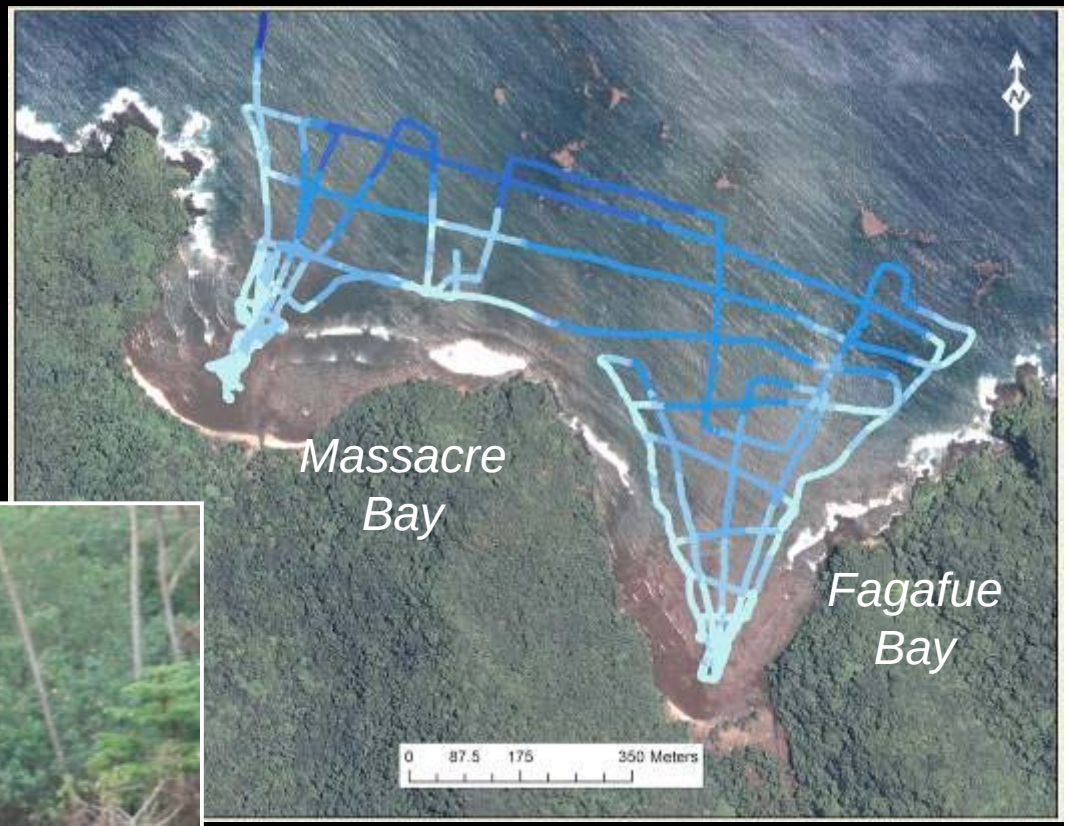


Topography on reef flat and on coastal plain at Fagafue Bay

Collecting topography with DGPS (differential GPS)

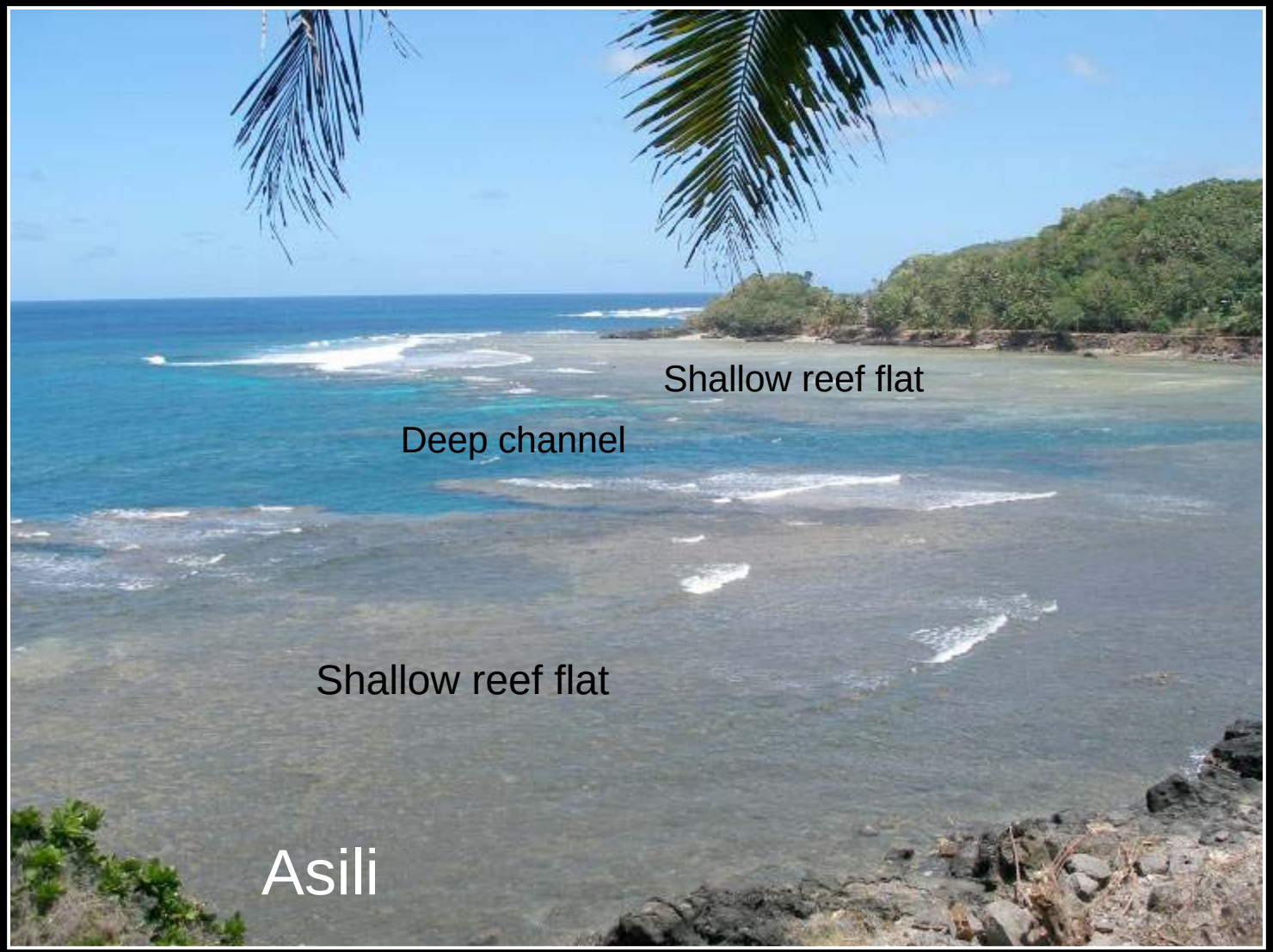
Nearshore bathymetry controls tsunami inundation

Good multibeam bathymetry exists in deeper water around Tutuila Island



We collected nearshore bathymetry with single beam echo sounder and GPS in a few bays on the north side of the island

Deep channels in embayments direct tsunami landward with farther inundation and higher run-up



Bottom roughness effects tsunami inundation

Tsunami waves slow down and pile up over a rough bed relative to a smooth bed

We measured medium-scale irregularity on reef flat to estimate bottom roughness

Coastal vegetation reduces tsunami inundation

Measuring vegetation characteristics

Factors effecting flow resistance:

- tree density
- tree diameter
- tree height

Tsunami Caused Coastal Erosion

Tsunami waves eroded sand and gravel from the beach and large clumps of coast and transported them landward

Tula

Tsunami Caused Coastal Erosion

Soil eroded and streams widened by tsunami return flow transporting sediment and debris offshore

Sand Transport

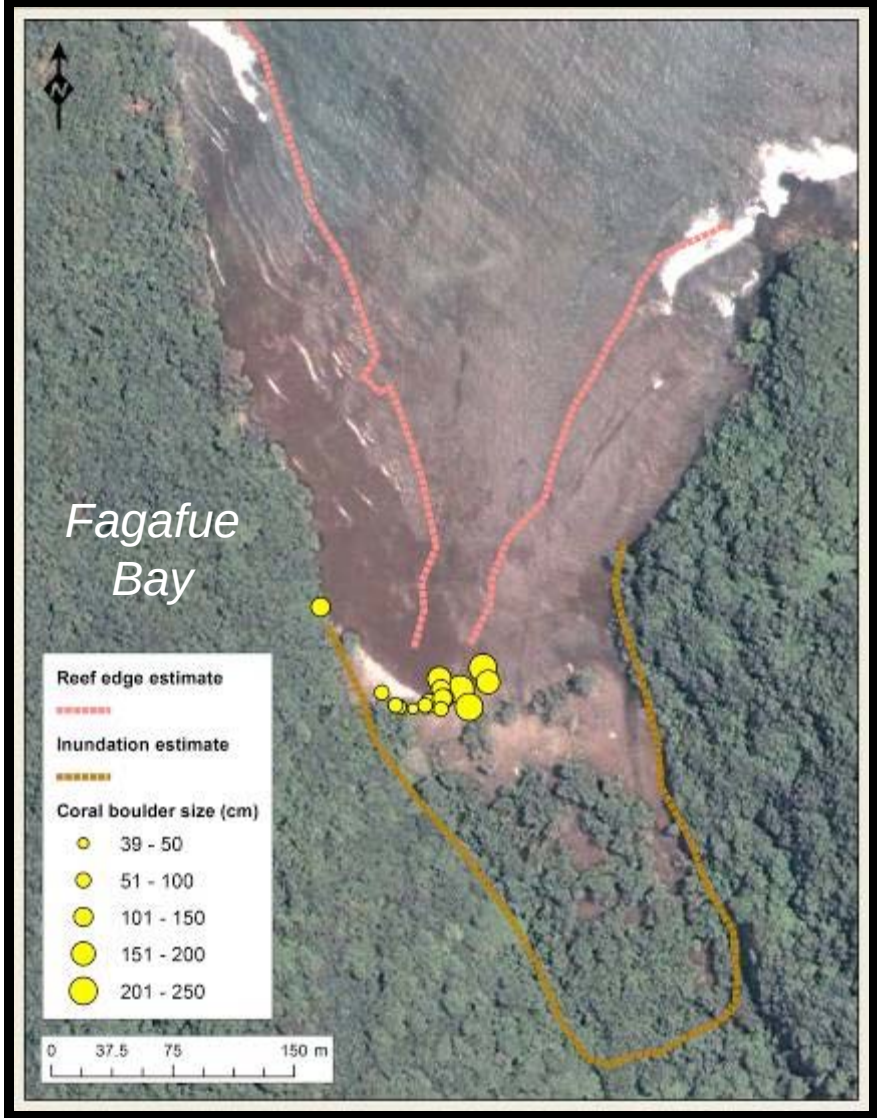
Tsunami transported sand long distances inland

Measuring tsunami deposits in Fagafue

Sand deposits can be a record of past extreme wave events

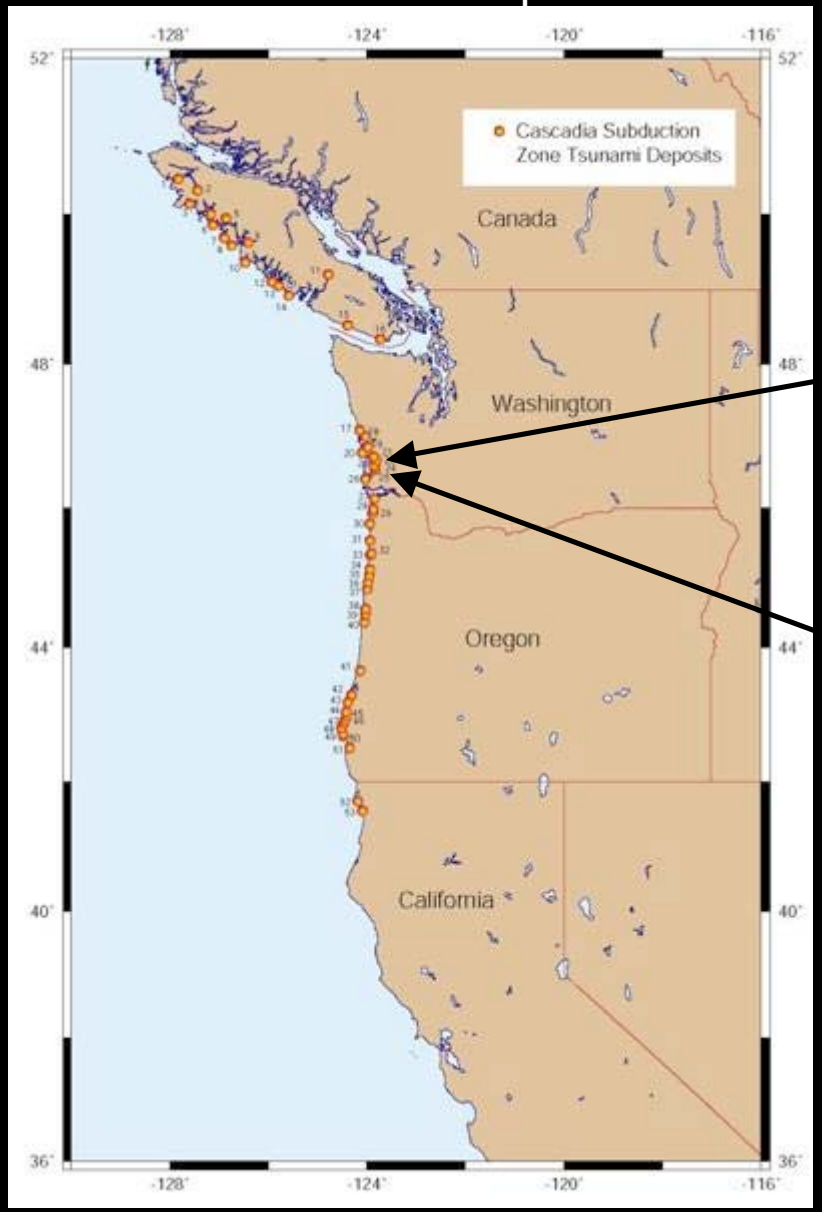
Boulder Transport

Tsunami moved live coral from reef flat inland to beach



What can we learn from paleo-tsunami deposits?

Paleo-tsunami deposits



Peters *et al.* (2002; 2007)

Niawiakum River

Johns River

10 cm

EARTHQUAKE YEAR

1960

position of 1837 and 1737

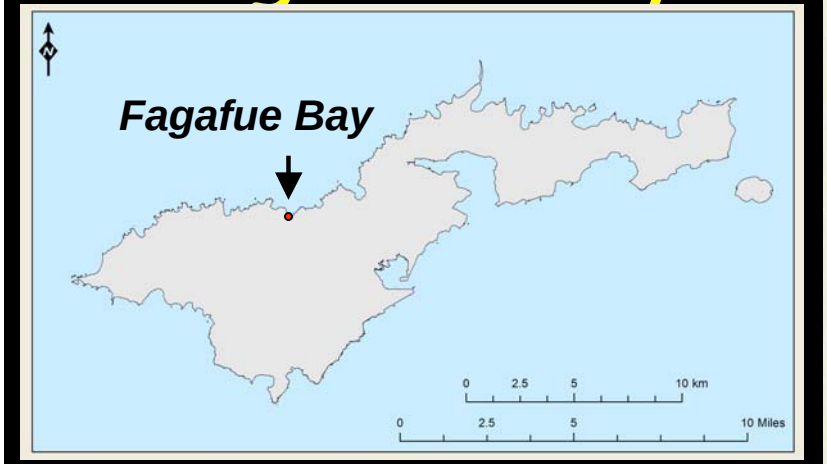
1575

undated

1100 (approx)

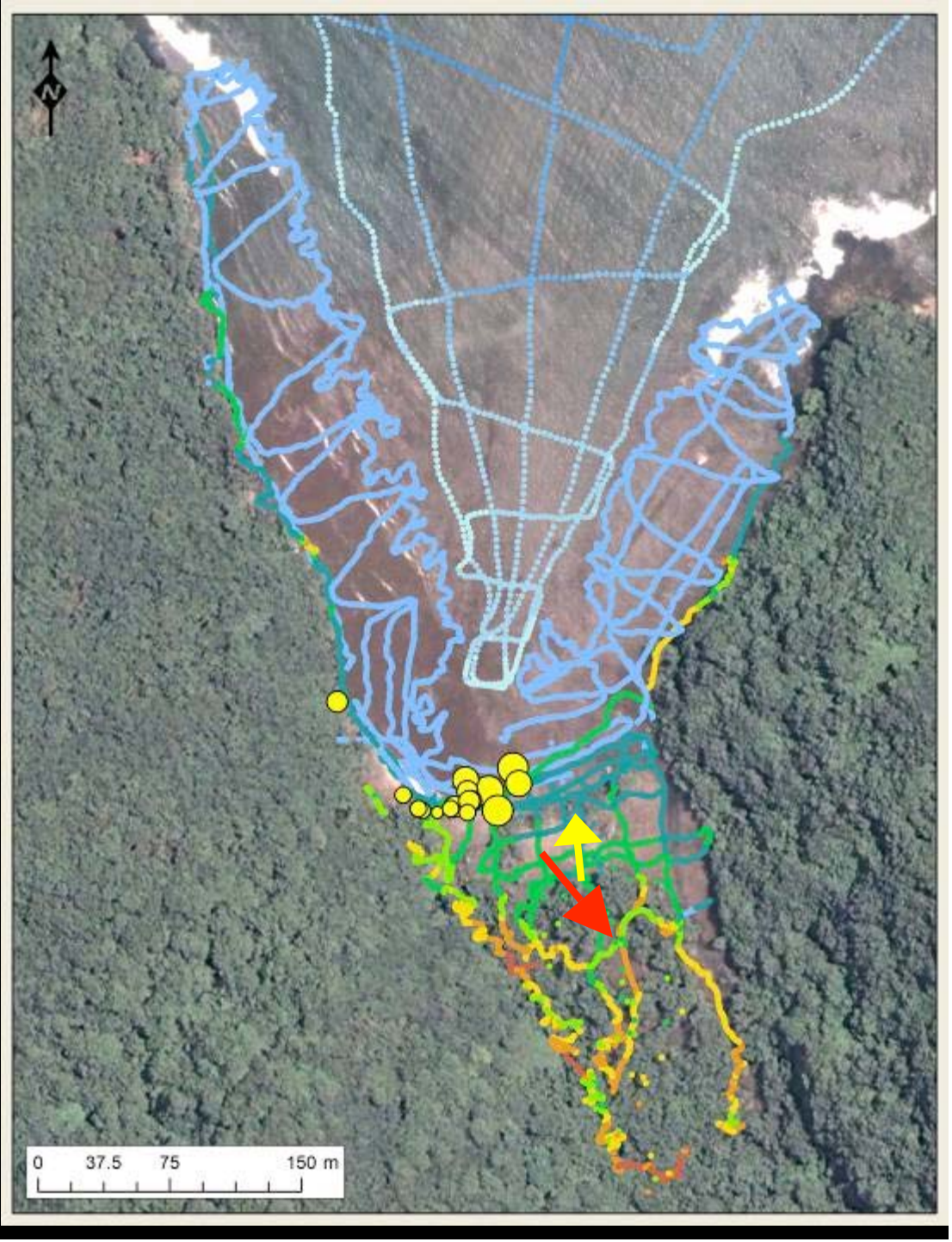
Paleotsunami Record in Chile
(from Brian Atwater, USGS)

Fagafue Bay



We collected data needed to verify/calibrate models:

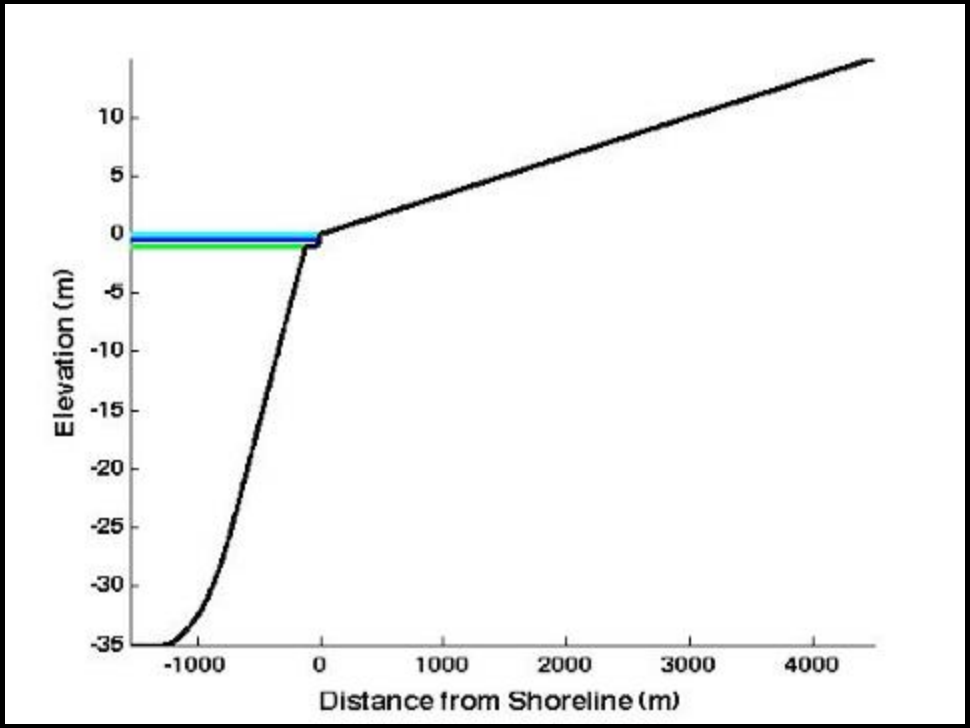
- wave height, run-up
- inundation
- topography
- bathymetry
- flow direction
- vegetation roughness
- boulder transport
- sand transport



Modeling Tsunami Inundation

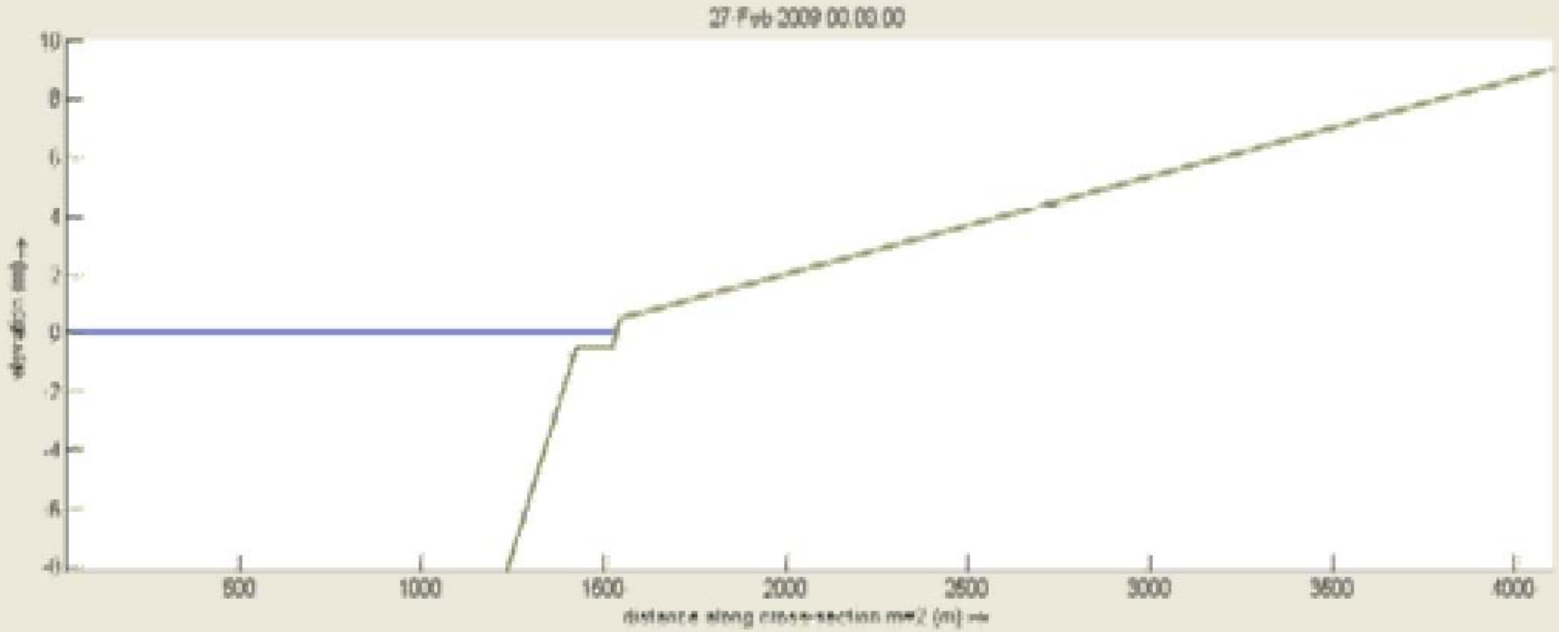
What would happen if tsunami occurred at low tide, or high tide?

How important is the width of the reef flat for tsunami inundation?

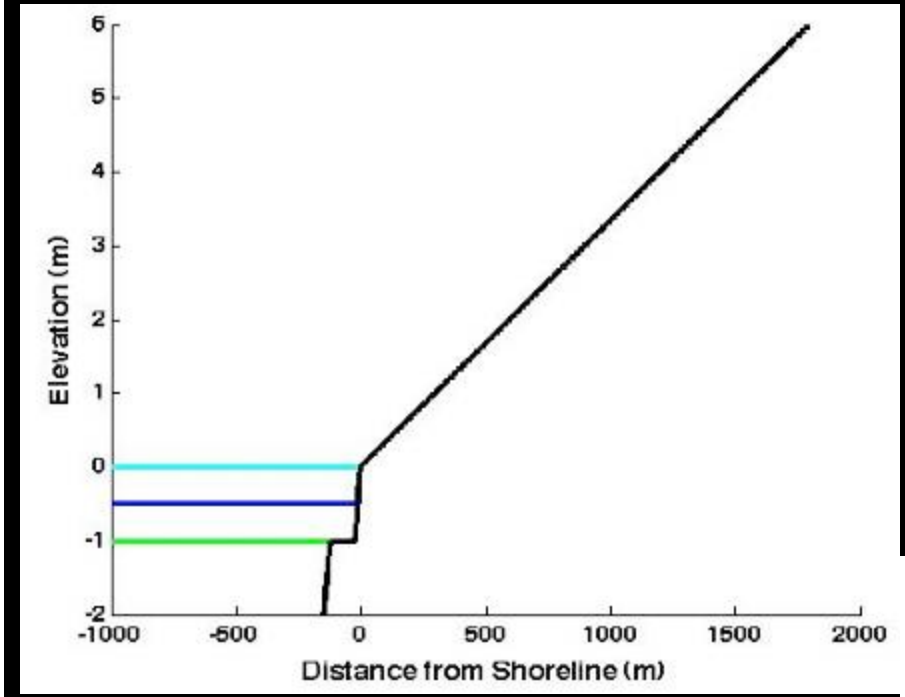


Hypothetical cross-shore profile from deep water, across reef flat and up on to land

Modeling Tsunami Inundation



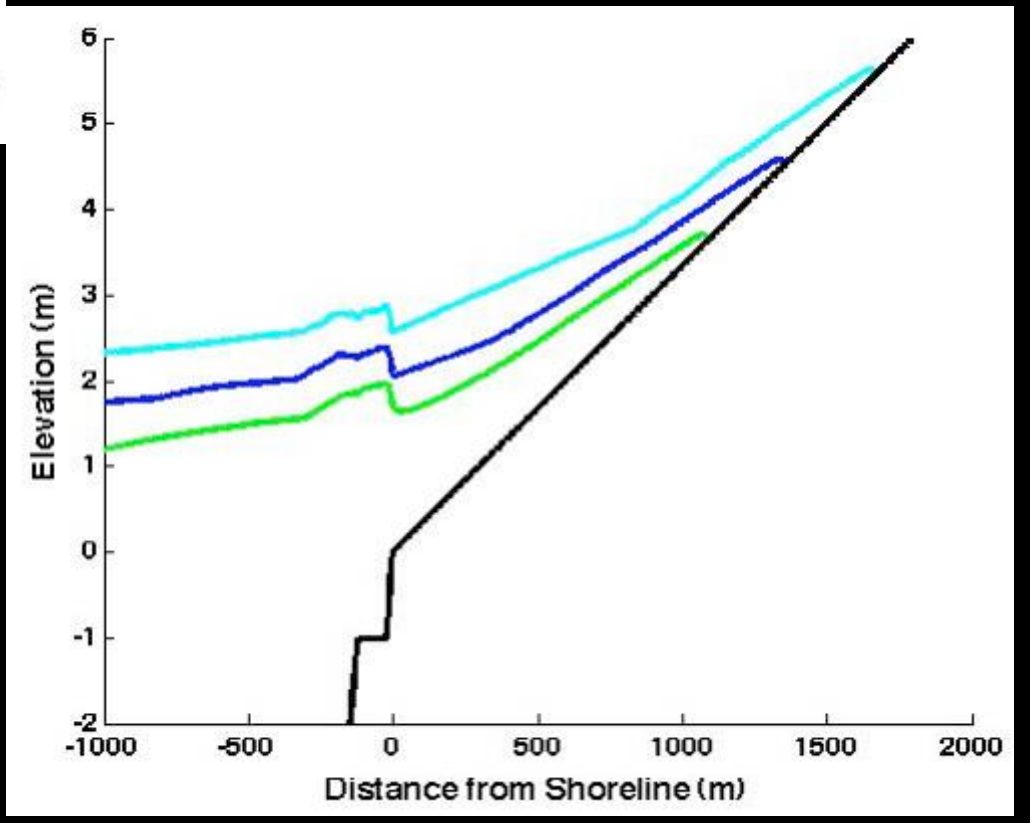
We model tsunami inundation with Delft3D, which solves the non-linear shallow water wave equations on a staggered grid, with an advanced wetting and drying algorithm

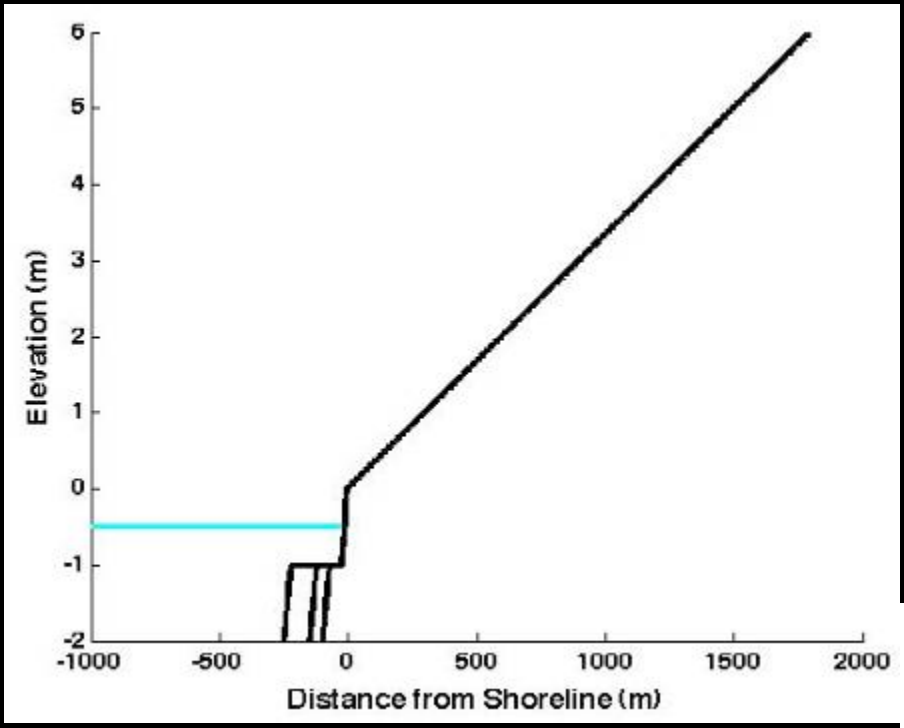


Effect of Tide Height on Tsunami Inundation

Depth of reef flat (or tide level at time of tsunami) does effect tsunami run-up

Tide	Inund Dis	Runup Height
High	1660	5.5
Med	1345	4.5
Low	1080	3.6

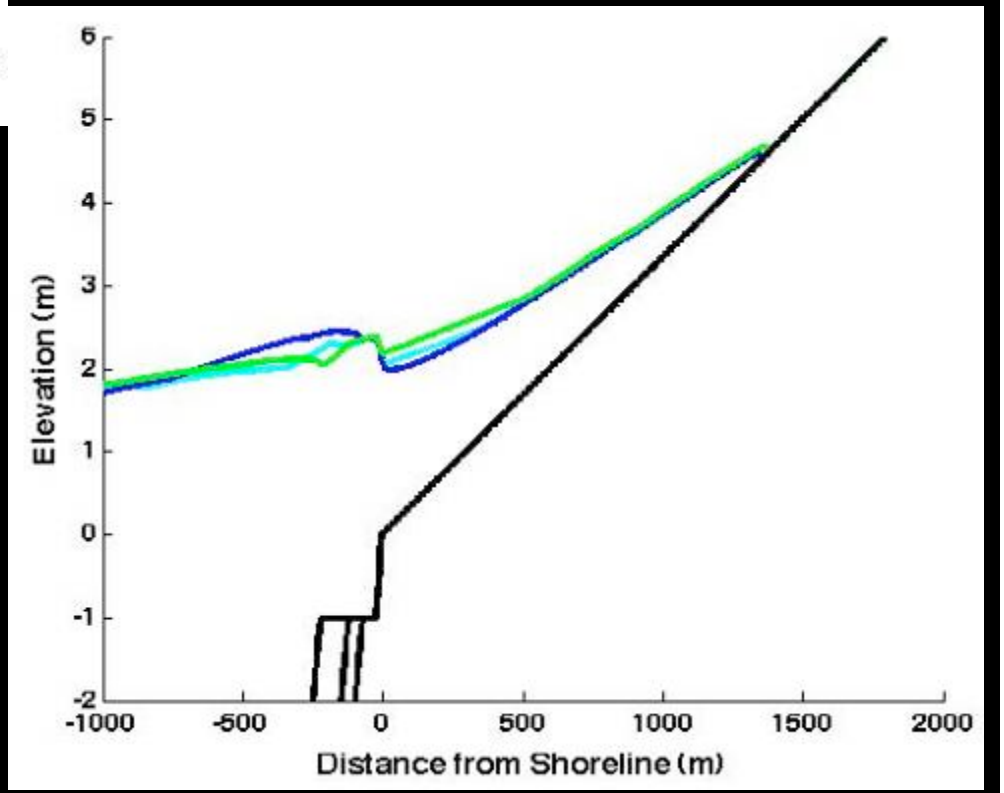




Effect of Reef Width on Tsunami Inundation

Width of reef flat does not appear to effect tsunami run-up as much as reef depth

Reef Width	In Dis	Runup Height
Narrow	1340	4.5
Med	1345	4.5
Wide	1370	4.6



To reduce losses in future tsunamis:

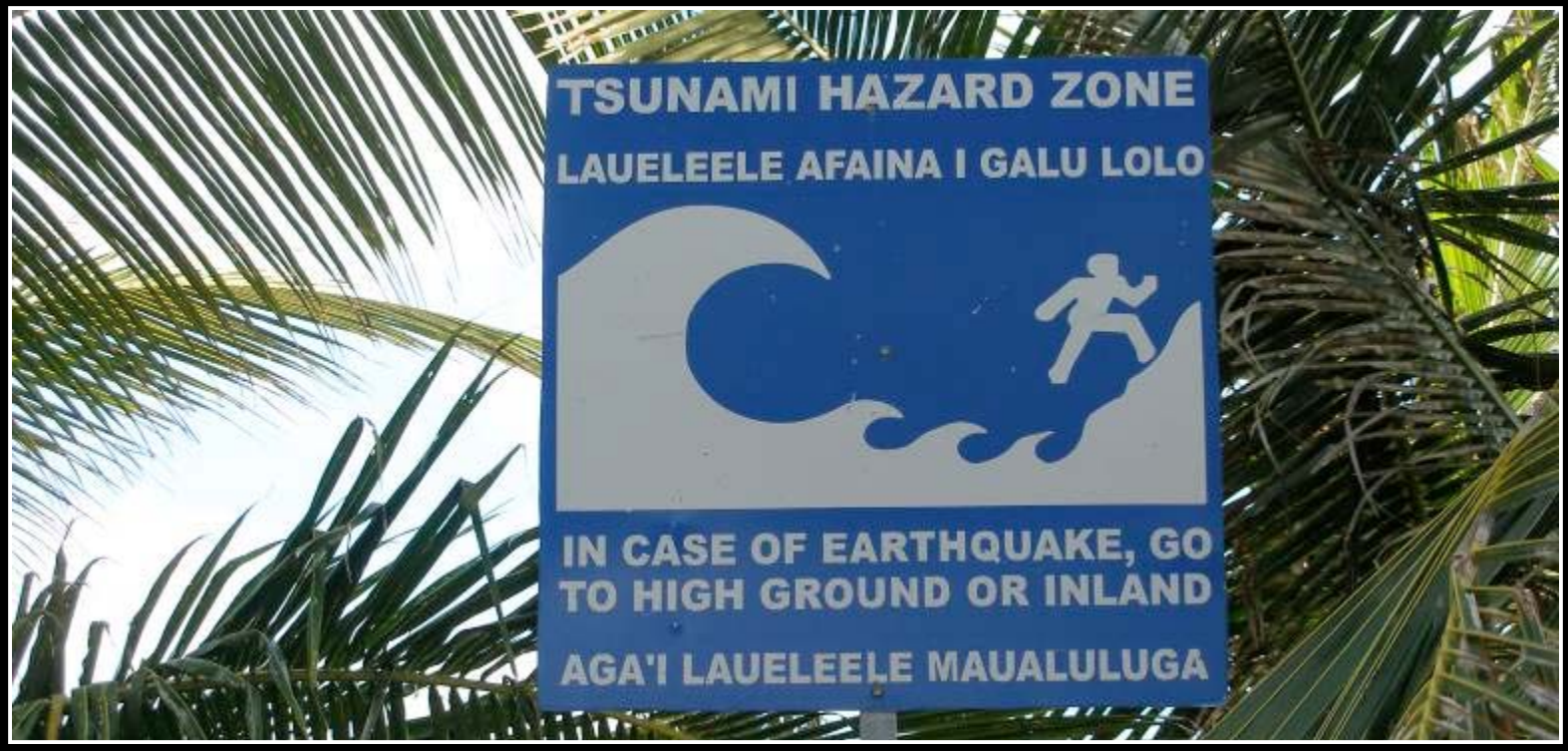
- Promote tsunami education programs
- Keep the memory of September 2009 catastrophe

Future museum site on west coast of Sumatra

- Construct markers showing the inundation area

- Plan reconstruction to include routes and paths to easily lead people to safe areas

- Locate critical structures (hospitals, schools, …) out of inundation zone



There is no easy solution to the local tsunami risk

- The earthquake is the warning
- Long-term planning is essential
- Education is the tool
- Individuals must know what to do

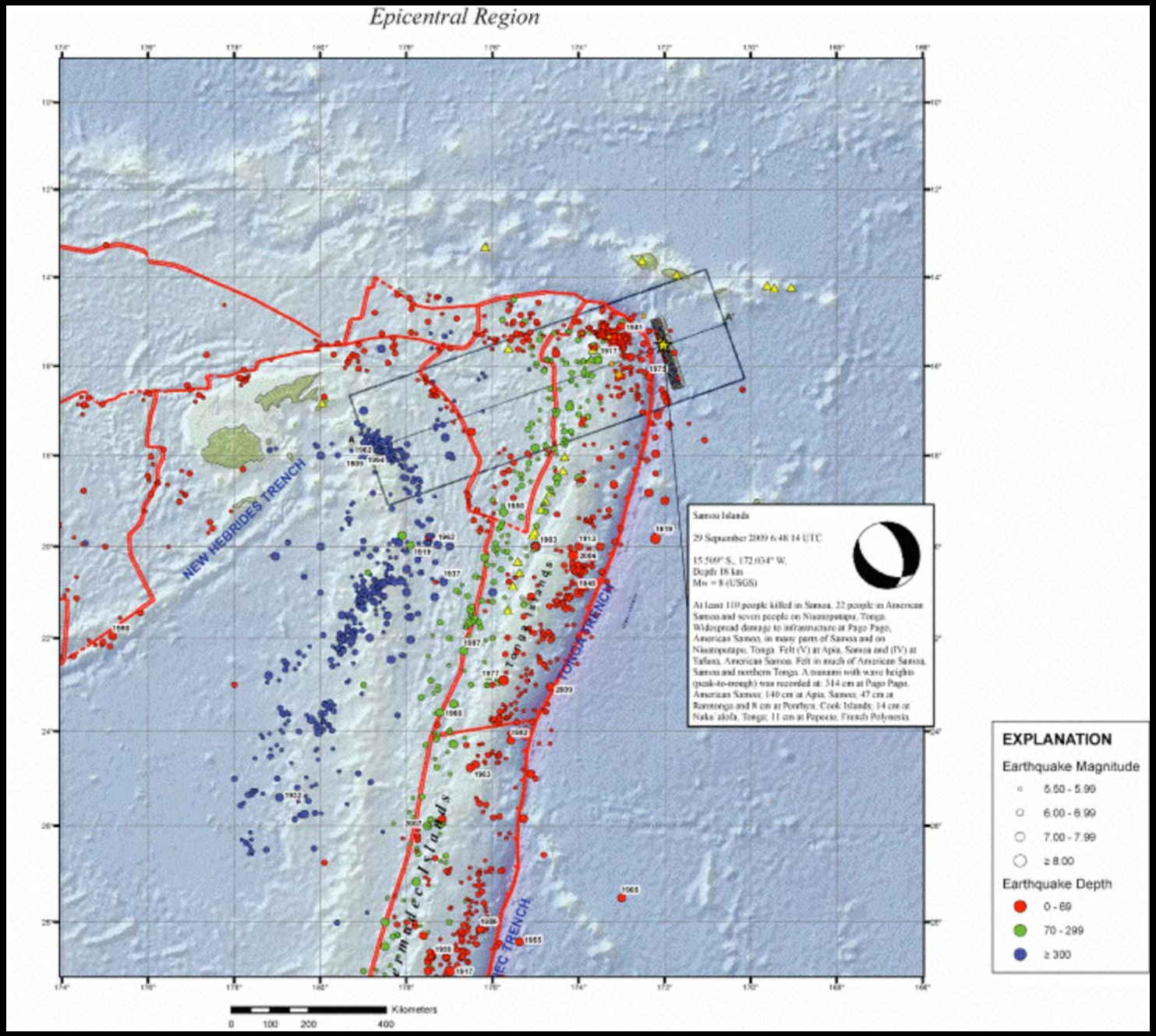
Thank you to all who helped

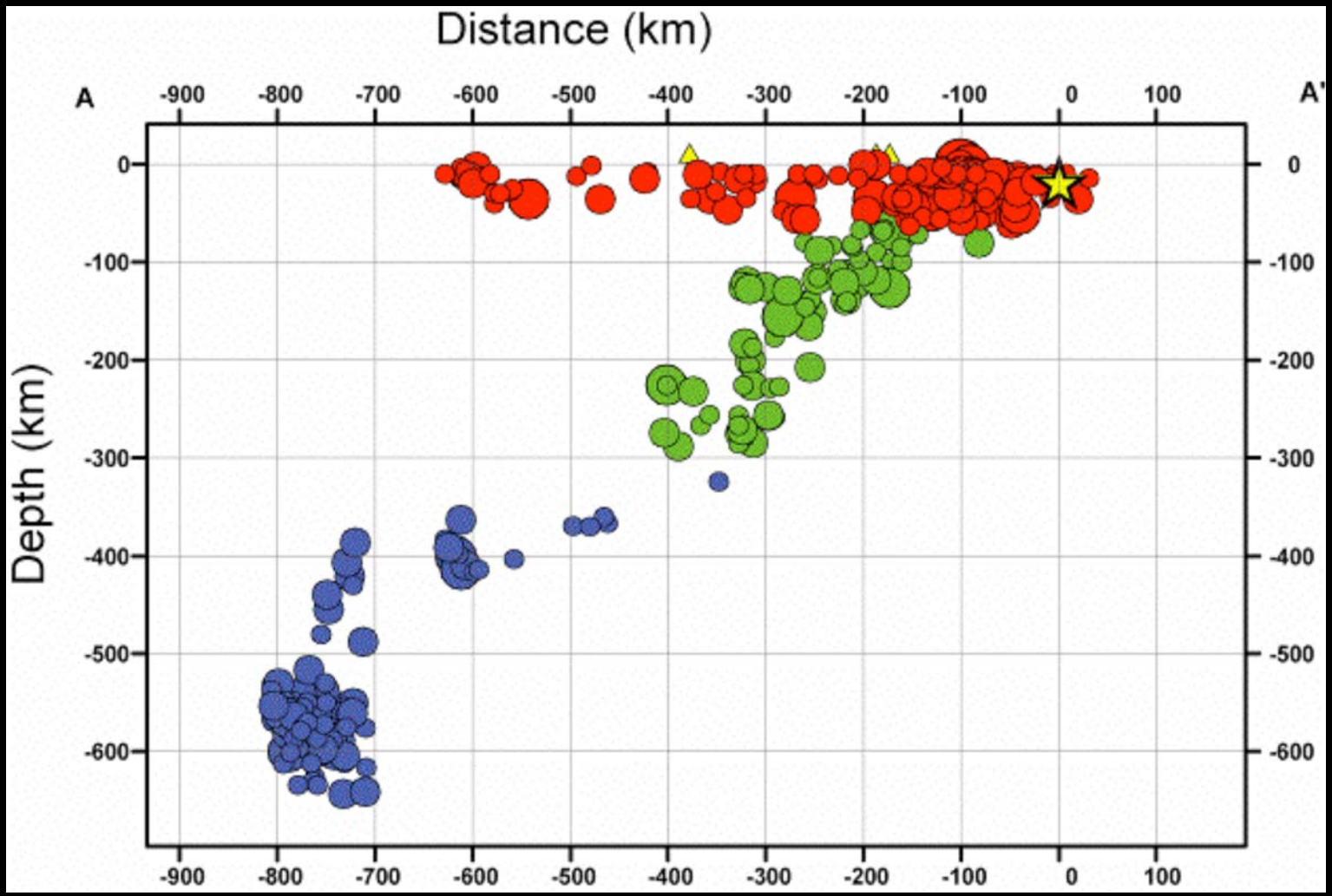
and to all of the people of American Samoa

Marie Chan-Kam, Sharon Fanolua, Lauren Wetzell
ASCC

Brian Peck
USDA Natural Resources Conservation Service


Questions?
Information from tsunami surveys can be found at:
http://walrus.wr.usgs.gov/tsunami


Epicentral Region
NEW HEBRIDES TRENCH
TONGA TRENCH
KERMADEC TRENCH
Kermadec Islands
Samoa Islands
29 September 2009 6:48:14 UTC
15.509° S., 172.034° W.
Depth 18 km
Mw = 8 (USGS)
At least 110 people killed in Samoa, 22 people in American Samoa and seven people on Niuatoputapu, Tonga. Widespread damage to infrastructure at Pago Pago, American Samoa, in many parts of Samoa and on Niuatoputapu, Tonga. Felt (V) at Apia, Samoa and (IV) at Tafuna, American Samoa. Felt in much of American Samoa, Samoa and northern Tonga. A tsunami with wave heights (peak-to-trough) was recorded at: 314 cm at Pago Pago, American Samoa; 140 cm at Apia, Samoa; 47 cm at Rarotonga and 8 cm at Penrhyn, Cook Islands; 14 cm at Nuku'alofa, Tonga; 11 cm at Papeete, French Polynesia.
EXPLANATION
Earthquake Magnitude
5.50 - 5.99
6.00 - 6.99
7.00 - 7.99
≥ 8.00
Earthquake Depth
0 - 69
70 - 299
≥ 300
Kilometers
0
100
200
400


Distance (km)
A
A'
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
Depth (km)
0
-100
-200
-300
-400
-500
-600