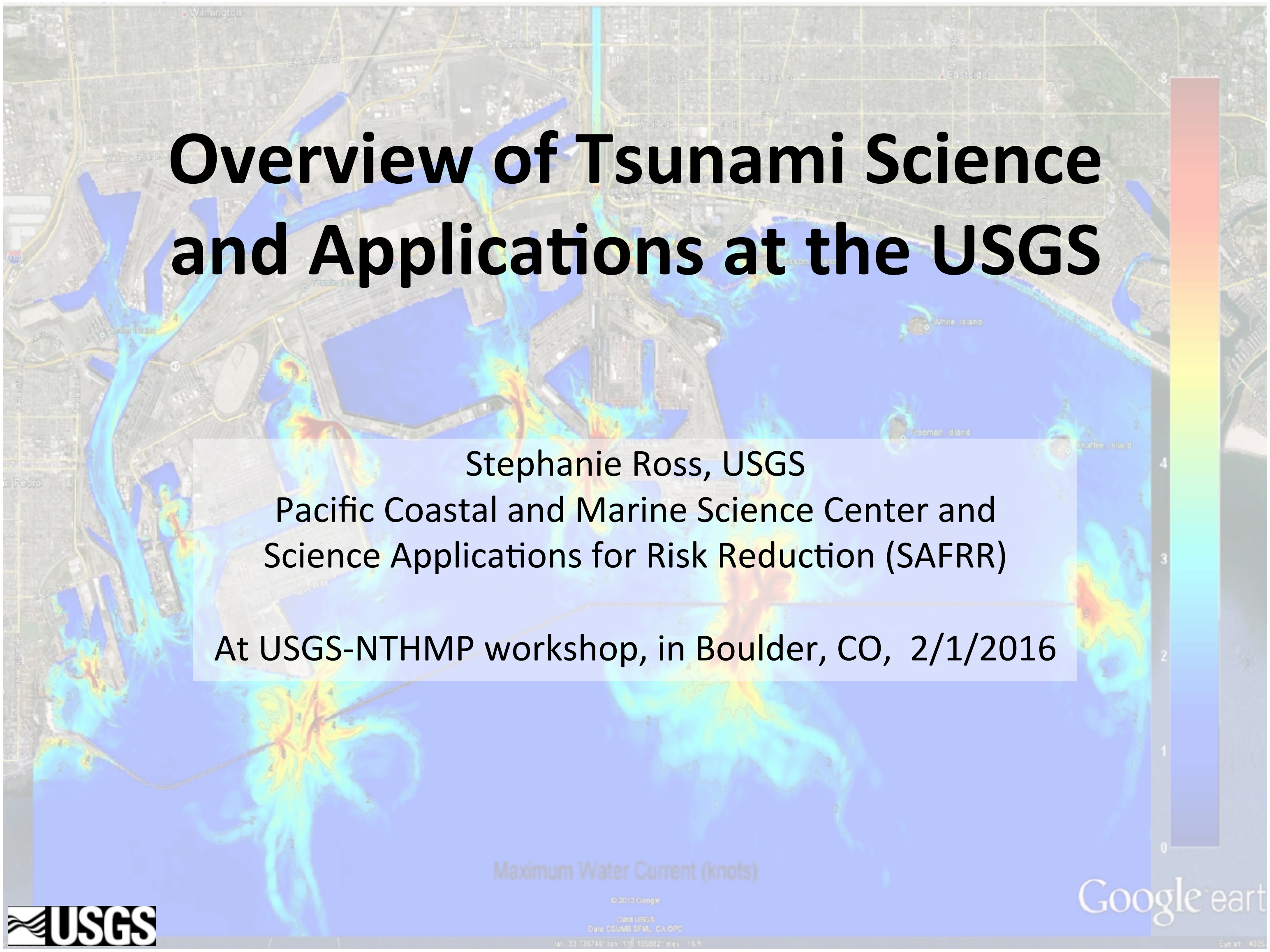
Overview of Tsunami Science and Applications at the USGS

Stephanie Ross, USGS
Pacific Coastal and Marine Science Center and
Science Applications for Risk Reduction (SAFRR)

At USGS-NTHMP workshop, in Boulder, CO, 2/1/2016



From the U.S. Geological Survey Natural Hazards Science Strategy

Official USGS priorities in tsunami hazards are:

(1) identify and quantify tsunami sources, such as earthquake faults, volcanoes, and landslides,

(2) assess tsunami sources and hazards and model tsunami generation,

(3) improve understanding of how tsunamis are generated and determine probabilities of tsunami hazards in different areas,

(4) assess tsunami inundations by interpreting tsunami effects.

Data from USGS national and global seismic networks feed directly to the tsunami warning centers of NOAA.

Tsunami investigations by the USGS span five different USGS Programs and six different Science Centers.

USGS

From the U.S. Geological Survey Natural Hazards Science Strategy: USGS assessment products in use

Assessment name	Description and current use
USGS tsunami source input data for NTHMP tsunami inundation assessments	Inundation assessments are used by others to plan evacuation routes, locate warning sirens, and to identify especially vulnerable facilities. Also used by FEMA to set rates in National Flood Insurance Program.
Tsunami inundation scenarios	Based on the most credible earthquake tsunami sources and tsunami wave-field modeling. Facilitate assessment of coastline inundations in demonstration projects.
Factor analysis of demographic sensitivity to tsunami	Geospatial modeling to identify hot-spots of demographic sensitivity related to preparing for and responding to tsunami. Used by State emergency managers to prioritize type and location of outreach.
Pedestrian evacuation modeling	Geospatial modeling to determine pedestrian travel times out of tsunami-prone areas. Used by State and local emergency managers to guide education efforts and to identify potential sites for vertical-evacuation strategies.

USGS


Paleotsunami

Paleotsunami Investigations

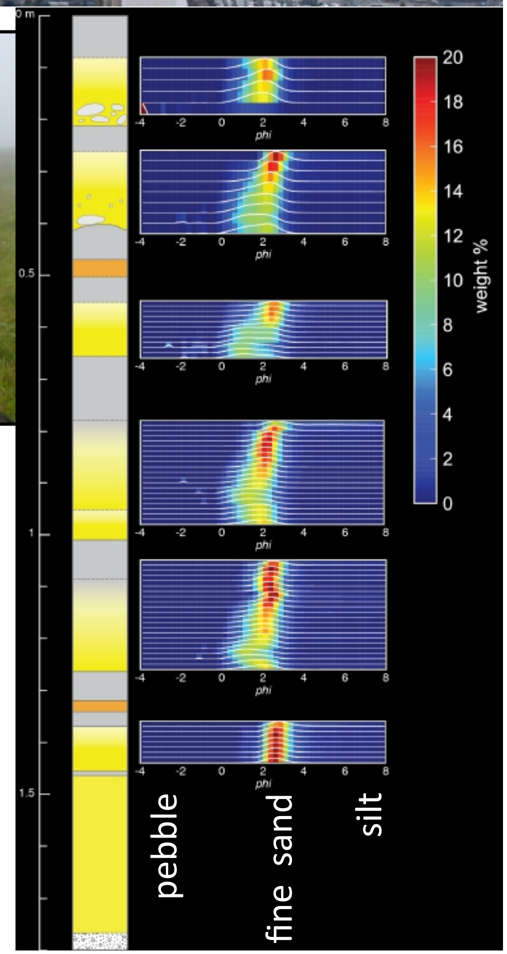
- **Goals**: Improve public safety and community resiliency through scientific research to better understand past tsunami frequency, magnitude, and location.
- **Site Selection**: Use combination tsunami inundation modeling results, historical tsunami records, and logistic considerations.
- **Field Studies**: Use a variety of trenching, coring, and sampling techniques to map and sample prospective tsunami deposits with a focus on identifying extreme events.
- **Laboratory Analysis**: Determine the age, sediment source, and deposit origin through age dating, grain-size distribution, and geochemical, lithologic, and microfossil composition.
- **Regional Characterization**: Correlate deposits from a number of sites to develop a history of past tsunamis with an emphasis on identifying the largest events.

USGS

Tsunami Hazards, Modeling, and the Sedimentary Record Project

Tasks	Personnel
Pacific Paleotsunamis:	Richmond (Task Lead), Jaffe, La Selle, Gelfenbaum, Griswold, collaborators from University of Hawaii, University of New South Wales, Tohoku University, California Geological Survey, Humboldt State, UC Santa Barbara
Alaska Paleotsunamis:	Gelfenbaum (Task Lead), La Selle, Jaffe, Griswold, collaborators from USGS Alaska Science Center, USGS Golden, Humboldt State, Yale, URI, Alaska GGS, Rutgers, Baylor, British Geological Survey
Paleotsunami Identification and Interpretation:	Jaffe (Task Lead), Gelfenbaum, Richmond, La Selle, Griswold, collaborators from Tohoku University

What we do: Paleotsunami studies



- Find and map paleotsunami deposits
- Date layers to determine tsunami inundation frequency
- Use sediment deposits to constrain size and speed of tsunami and location of seafloor rupture

Improving Tsunami Hazard Assessment

- Improve tsunami hazard assessment in the US and Territories using geologic evidence (tsunami deposits) to extend the historical record of tsunami inundation
- Develop paleotsunami record in Hawaii, Aleutians, Caribbean and Cascadia
- Develop inverse and forward models of tsunami inundation and sediment transport to improve tsunami hazard assessment

Mapping

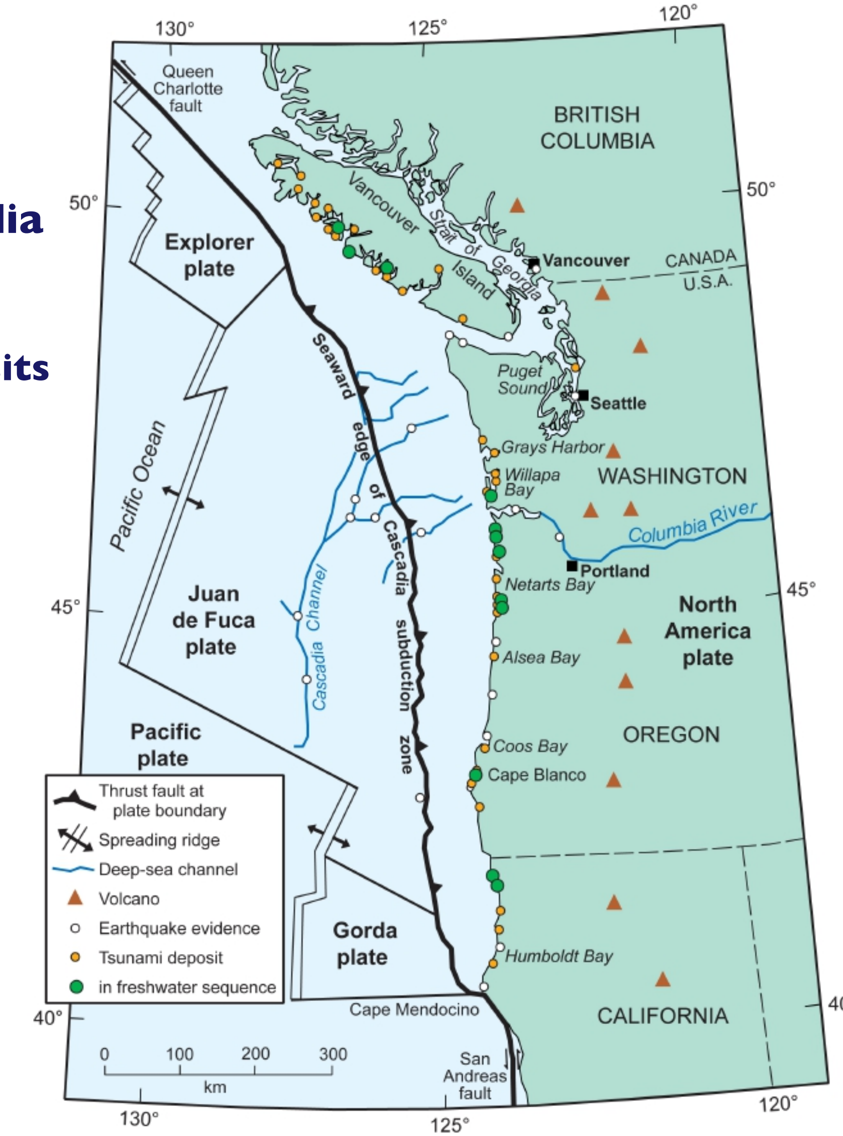
Tsunami deposits in Cascadia freshwater sequences

- better preservation of deposits

- deposits nearer limit of inundation

- host sediment has uniform rates of deposition, which improves age models

(Kelsey et al., 2005; Peterson et al., 2006; 2008; 2009; 2010; 2011; 2013; 2014; 2015)



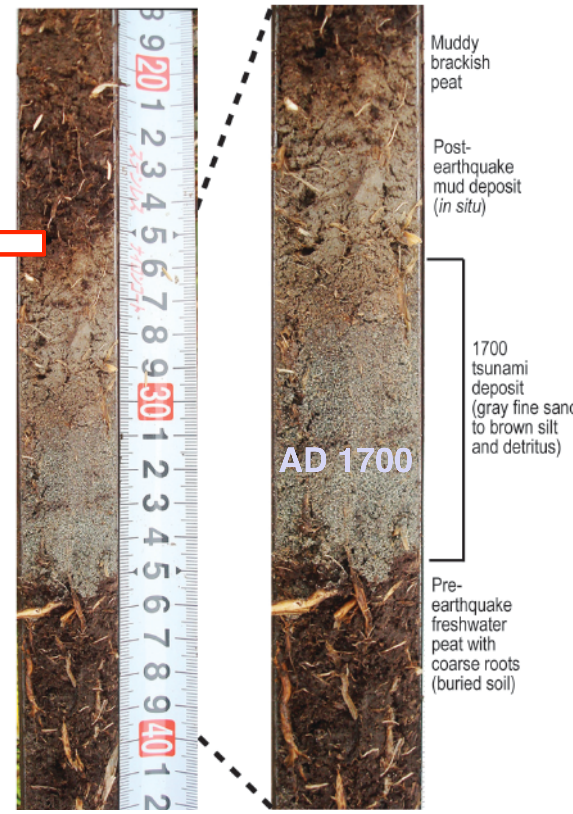
Base from USDA 2010 NAIP Imagery
UTM Zone 10N, NAD83

0 50 100 METERS
0 100 200 300 FEET

EXPLANATION

Gouge cores

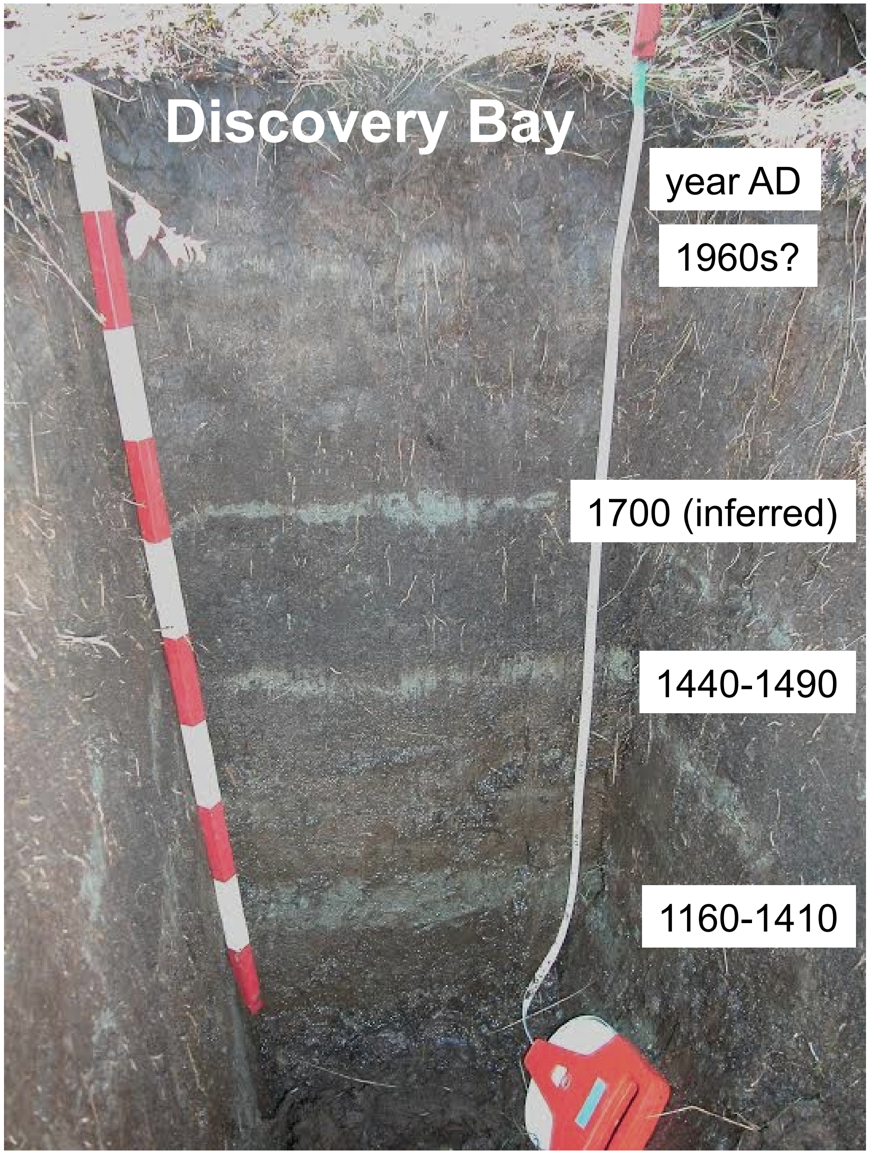
- 1964 tsunami deposit observed
- 1700 tsunami deposit observed
- Both 1964 and 1700 tsunami deposits observed
- No tsunami deposits observed



Mapping

Tsunami deposits in freshwater peat, Crescent City (Hemphill-Haley et al., in progress)

USGS



Dates from Williams et al., 2005
and Garrison-Laney, unpublished

Deciphering the record of prehistoric Aleutian megathrust earthquakes and tsunamis west of Kodiak Island, Alaska

USGS PIs:

Rich Briggs

Peter Haeussler

Guy Gelfenbaum

Rob Witter

Alan Nelson

Collaborators:

Simon Engelhart

Tina Dura

Jeff Freymueller

Breanyn MacInnes

Dmitry Nicolsky

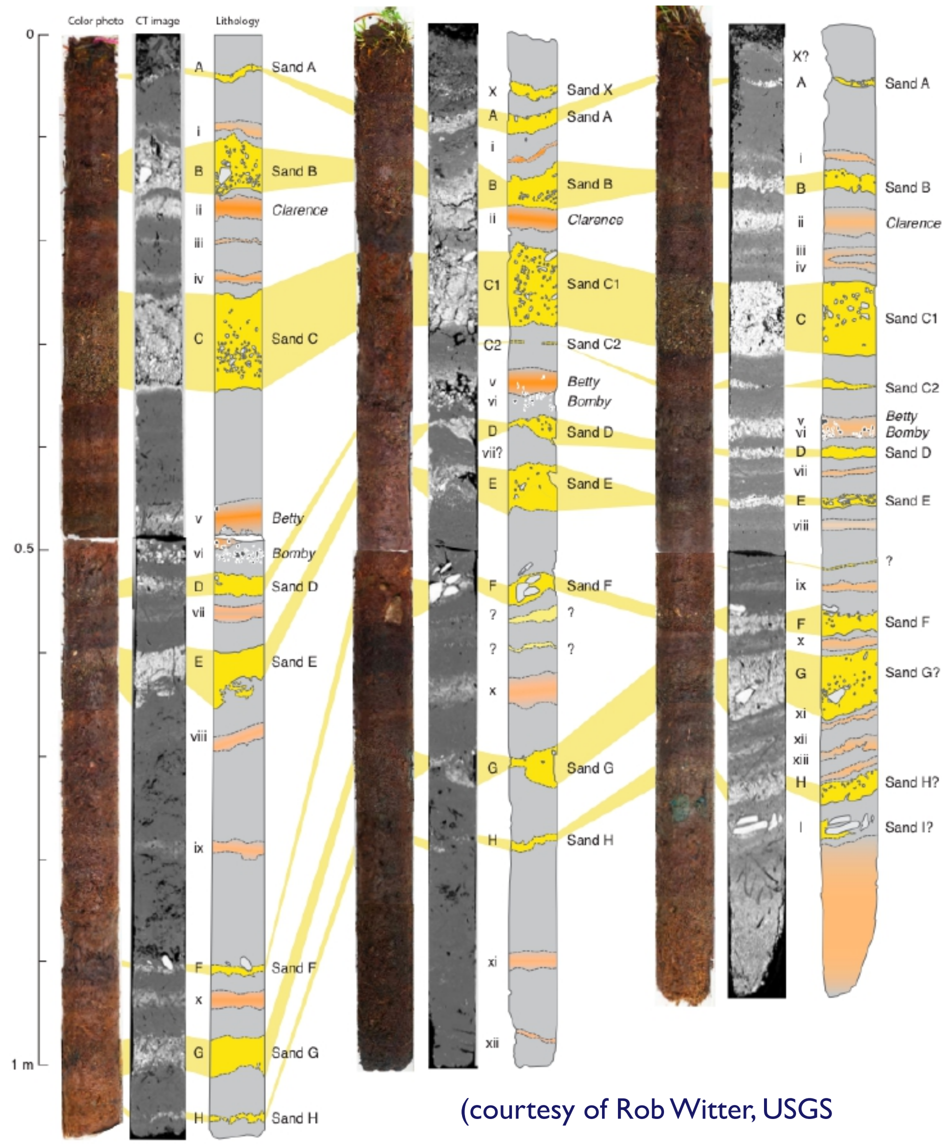
Jason Padgett

Yuki Sawai

USGS science for a changing world

Mapping

CT scans (gray-scale) of tsunami deposits in cores of freshwater peat from Umnak Island, Aleutians



(courtesy of Rob Witter, USGS

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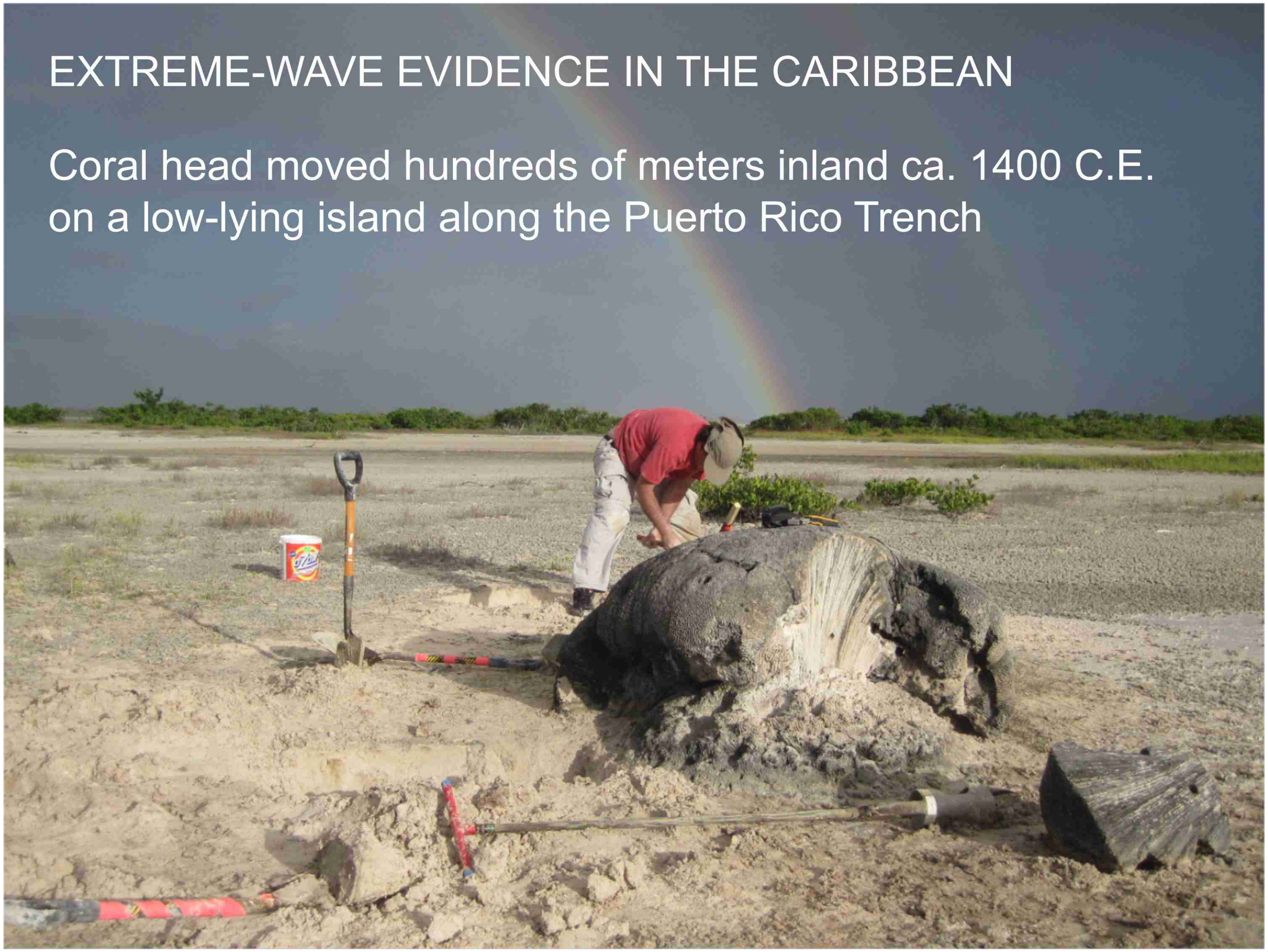

EXTREME-WAVE EVIDENCE IN THE CARIBBEAN
Coral head moved hundreds of meters inland ca. 1400 C.E.
on a low-lying island along the Puerto Rico Trench

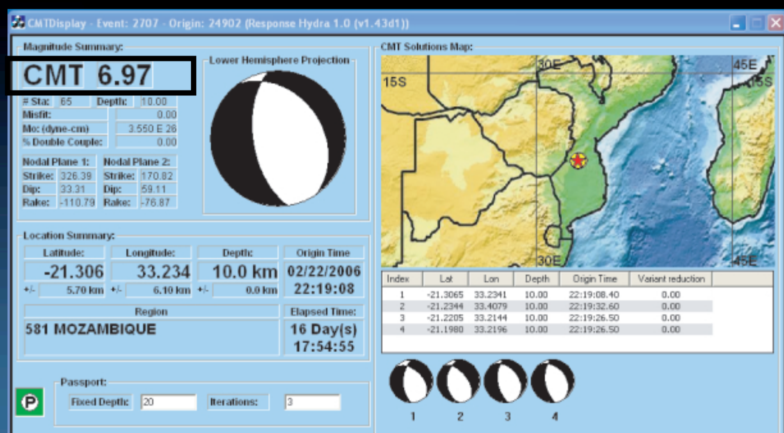
Earthquakes ★ Floods ★ Hurricanes ★ Landslides ★ Tsunamis ★ Volcanoes ★ Wildfires

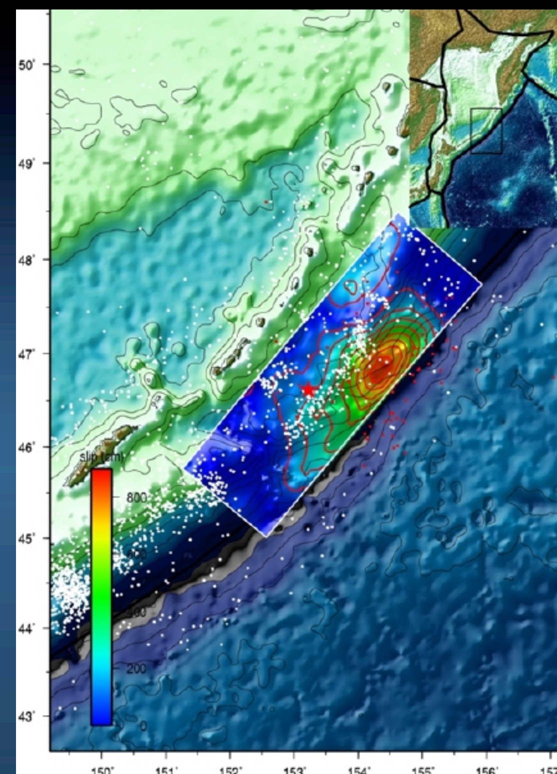
NEIC & Subduction Zone EQ Monitoring

USGS

National Earthquake Information Center

Earthquake Source Characterization

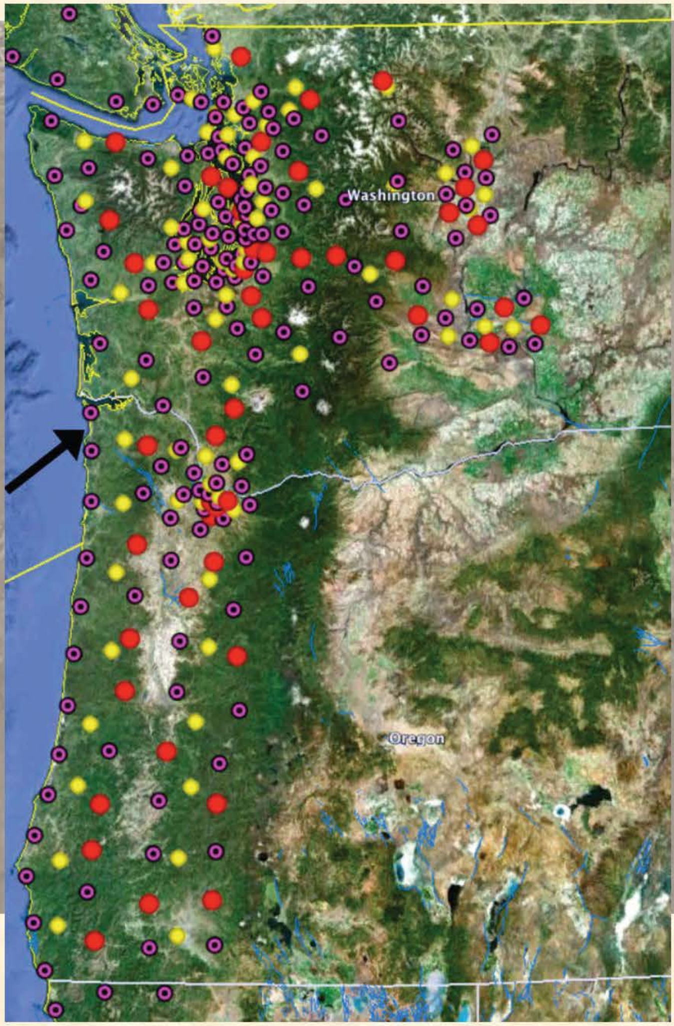




Good global coverage critical for characterizing megathrust earthquakes

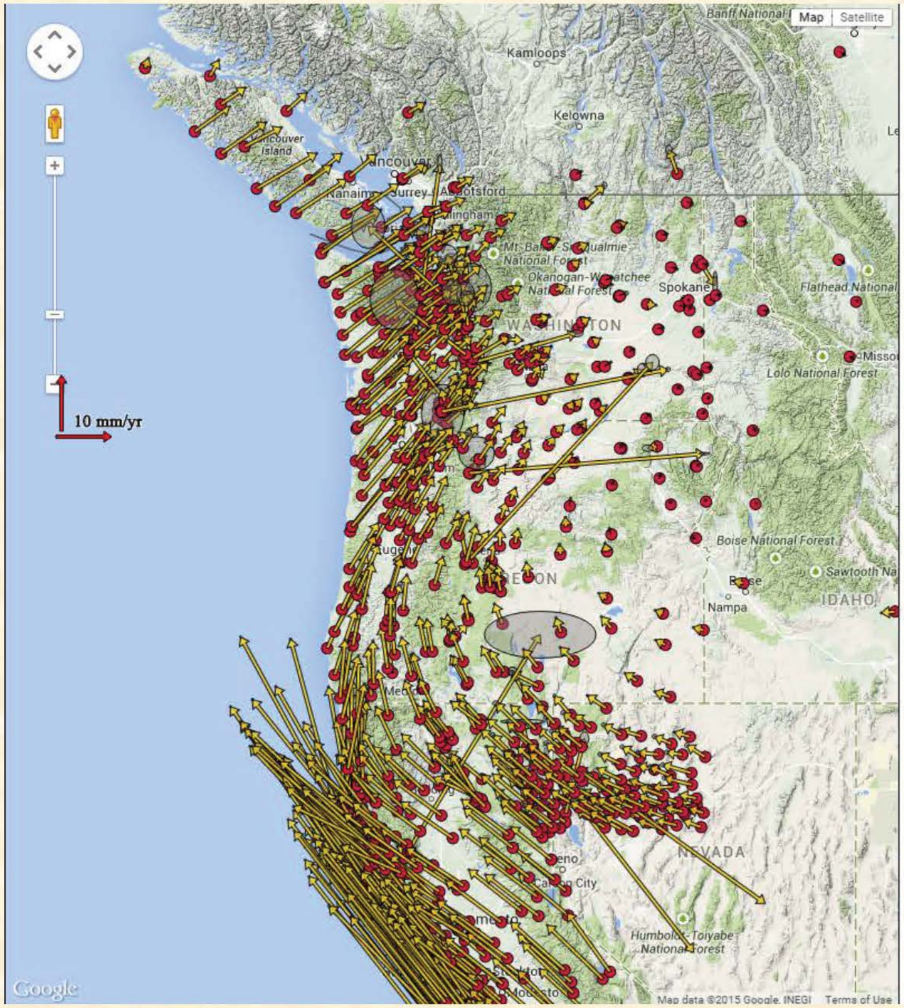
Pacific Northwest EEW Network

- **Low-latency backbone**
  - 66 BB, 150 GPS, 210 SM
  - Uniform instrumentation
  - 6 field centers
- **Processing at Seattle**
  - Backup across 3 West Coast system centers.
  - Coordinated and funded by USGS
- **Warnings may be distributed in a variety of ways.**



From John Vidale, Univ. WA

Cascadia Continuous GPS Stations



Real-Time GPS coverage:

- PBO and Pacific NW Geodetic Array (PANGA)
- PANGA run by Central Wash. U (USGS provides partial funding).
- PBO sites upgraded to real time with ARRA funds; many PANGA sites also real-time.
- USGS funding is supporting completion of dedicated radio telemetry for coastal PANGA sites.

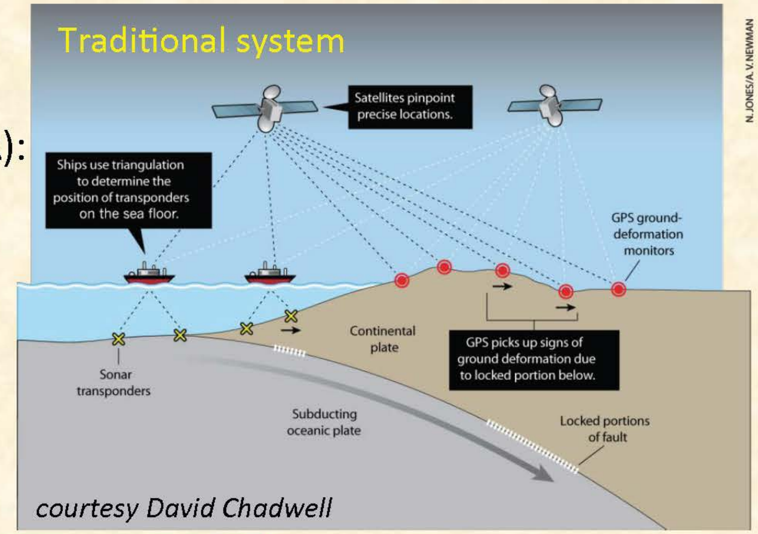
Seafloor Geodesy in Cascadia

Near-term objectives for envisioned network (June 2012 workshop at Univ. WA):

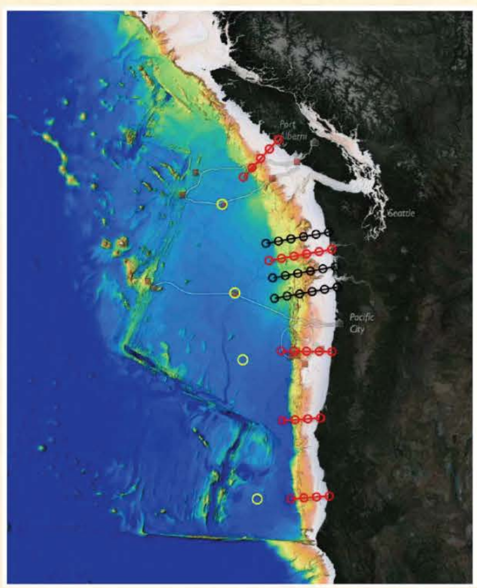
- Motion & deformation of Juan de Fuca plate
- Spatially variable coupling
- Characteristics of offshore transients

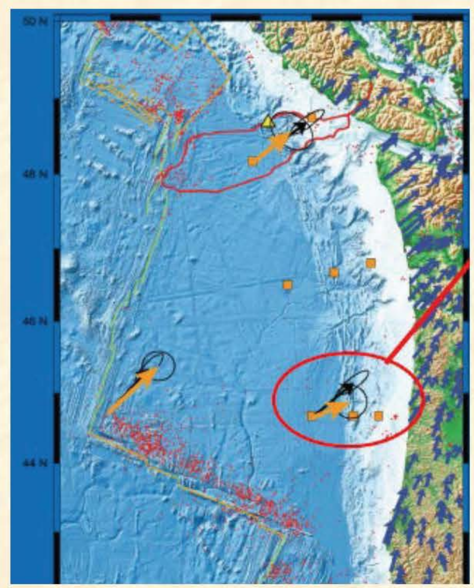
Long-term objective:

- Real-time monitoring for earthquake and tsunami early warning.



courtesy David Chadwell





Far left: envisioned network schematic

Near left: David Chadwell project (funded 2013 – 2016), to establish and survey initial set of benchmarks

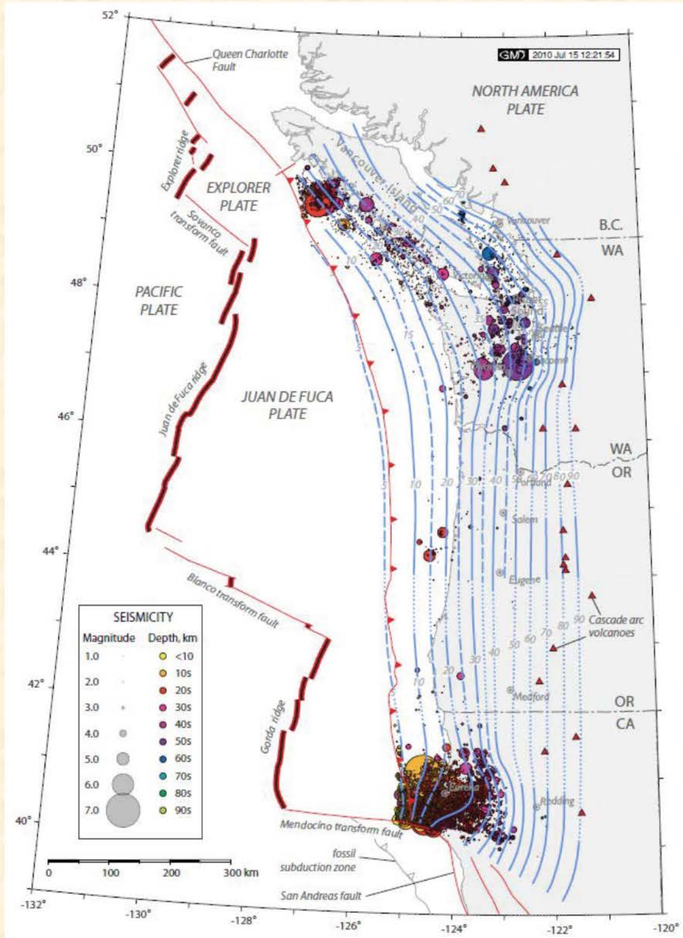
Framework and Sources

Slab1.0: covers ~ 90% of global subduction zones.

Geometry of a Subduction Zone

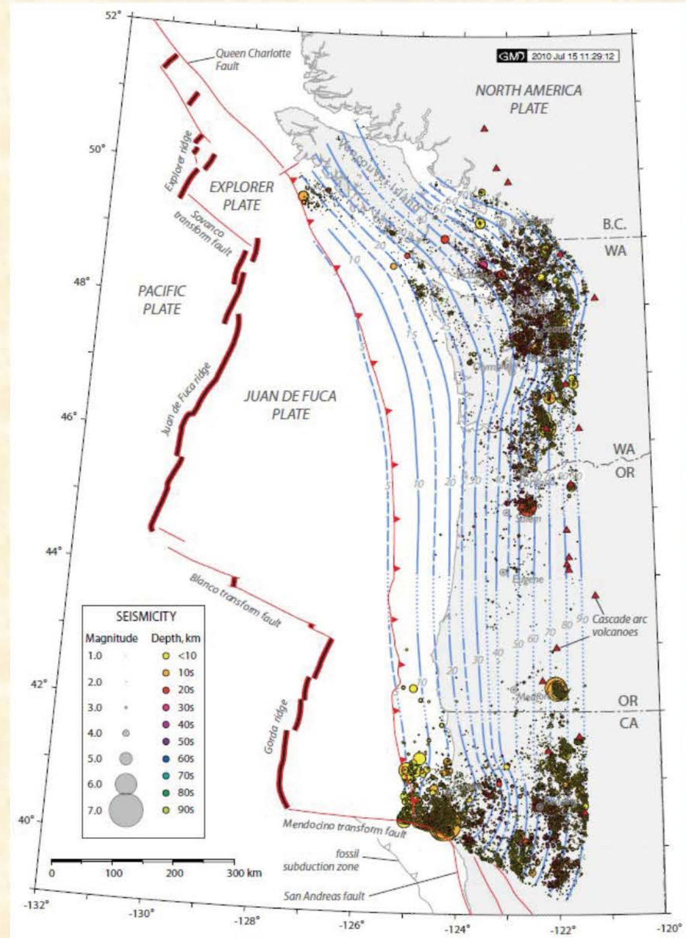
Slab1.0: covers ~ 90% of global subduction zones.

Cascadia Lower Plate (left) and Upper-Plate (right) Seismicity, ANSS & CNSN catalogs, 1975 – 2009



DISTRIBUTION OF WADATI-BENIOFF EARTHQUAKES

Modified from McCrory et al., 2012, J. Geophys. Res.

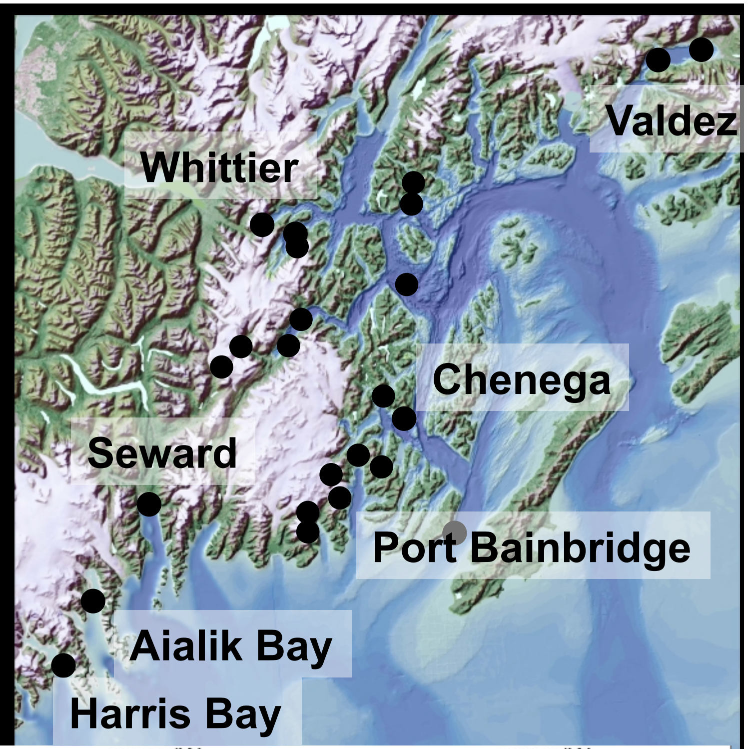


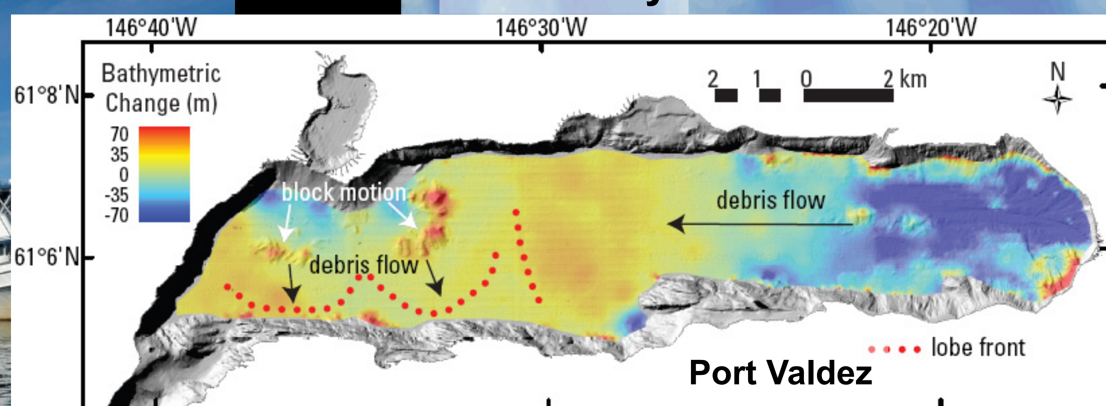
DISTRIBUTION OF FOREARC EARTHQUAKES

Modified from McCrory et al., 2012, J. Geophys. Res.

Submarine landslide studies

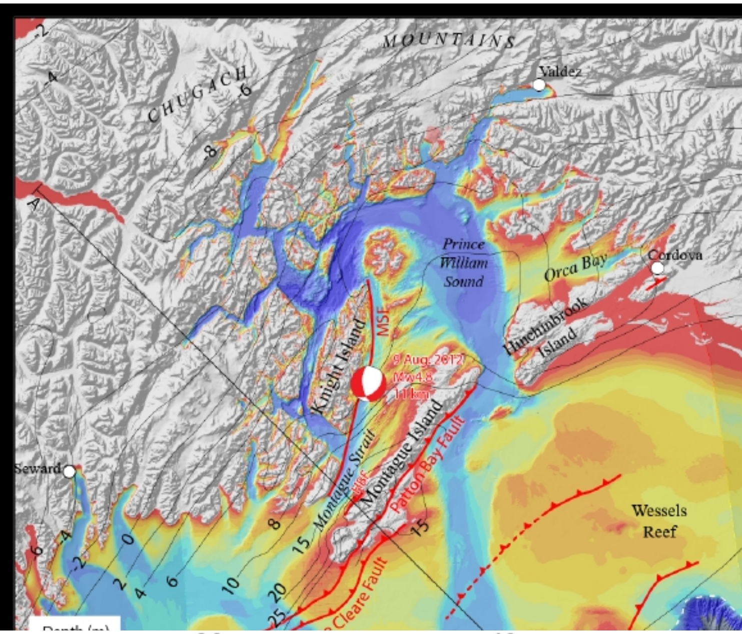
- These were the big killer in the 1964 earthquake
- Conducted detailed studies in 7 fjords
- Mostly utilize bathymetry differencing and seismic imaging

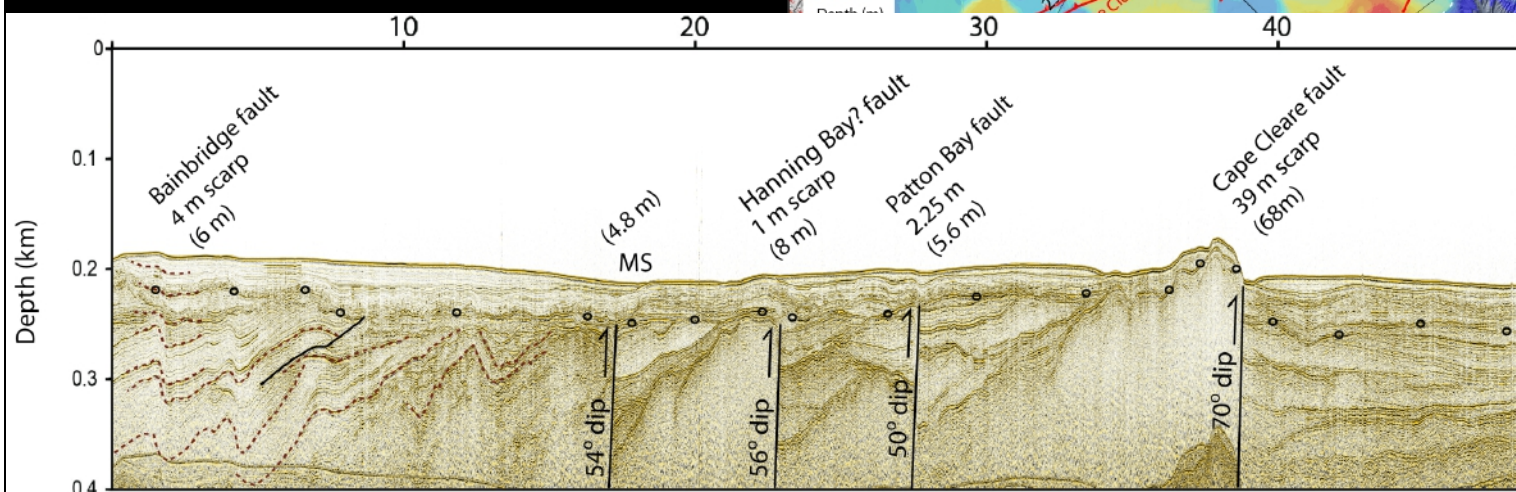


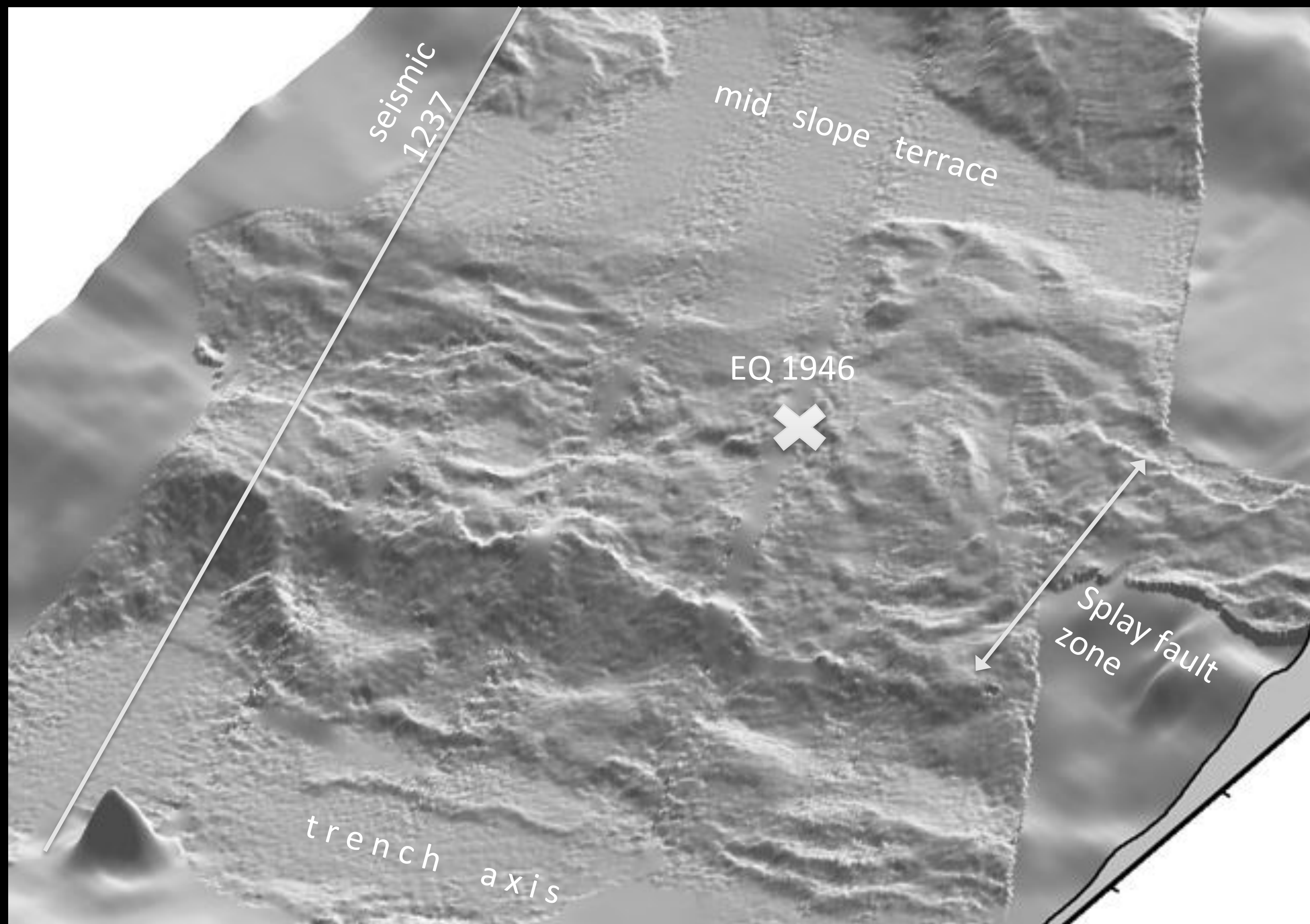


Megathrust splay faults

- Examined Patton Bay and other splay faults and behavior over longer (10kya+) time scales





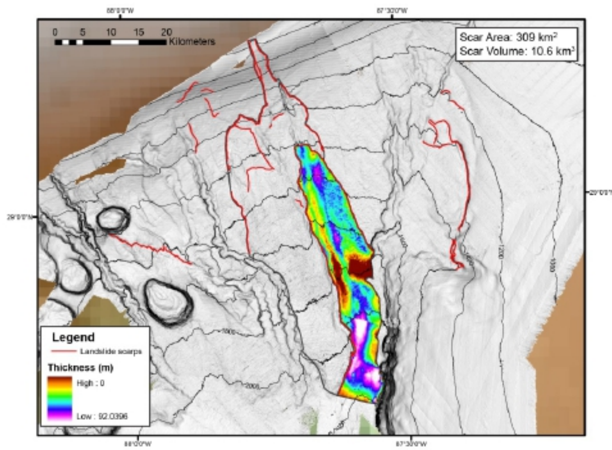


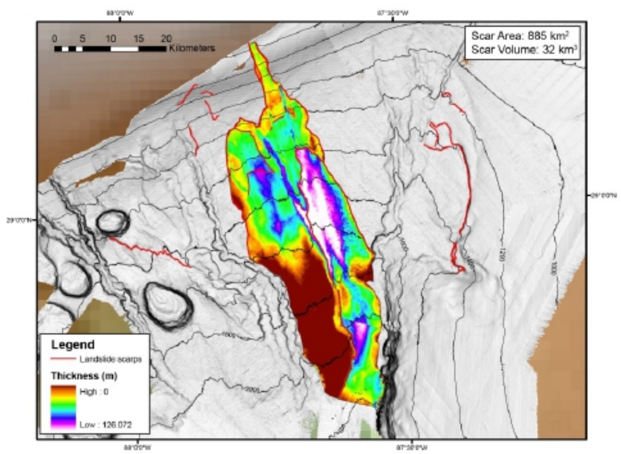
Legacy geophysical data processed with current technology images a 120 km long splay fault zone that could explain the 1946 tsunami high magnitude.

USGS studies of submarine landslides and tsunamis from Homa Lee and others

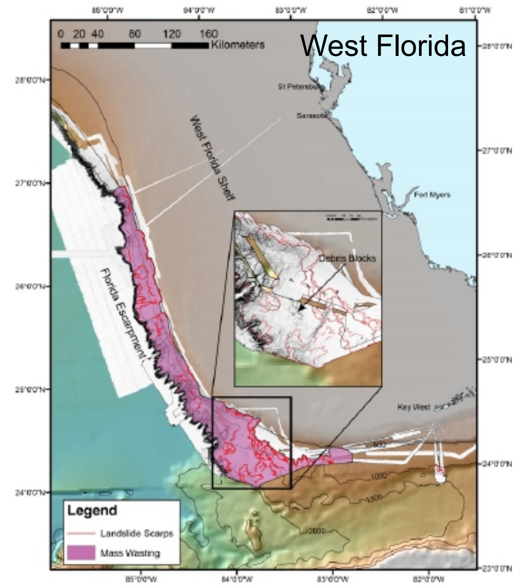
- 2000 to present
  - Mapping and analysis of landslides known to have caused recorded tsunamis (e.g., Port Valdez and Resurrection Bay, Alaska)
  - Studies of recurrence intervals of large submarine landslides with an eye toward probabilistic hazard assessment (e.g., Santa Barbara Channel failures
  - Coupling of landslide motions with tsunami generation in well-defined situations where known landslides caused known tsunamis

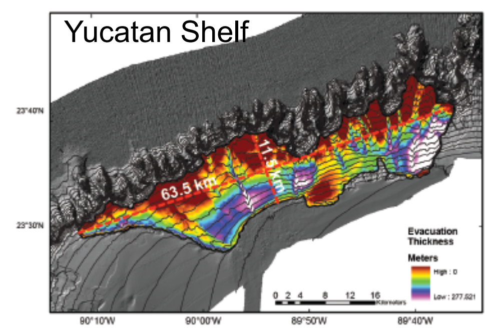
Gulf Of Mexico – Sources ID & Mapping





De Soto Canyon





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From Jason Chaytor

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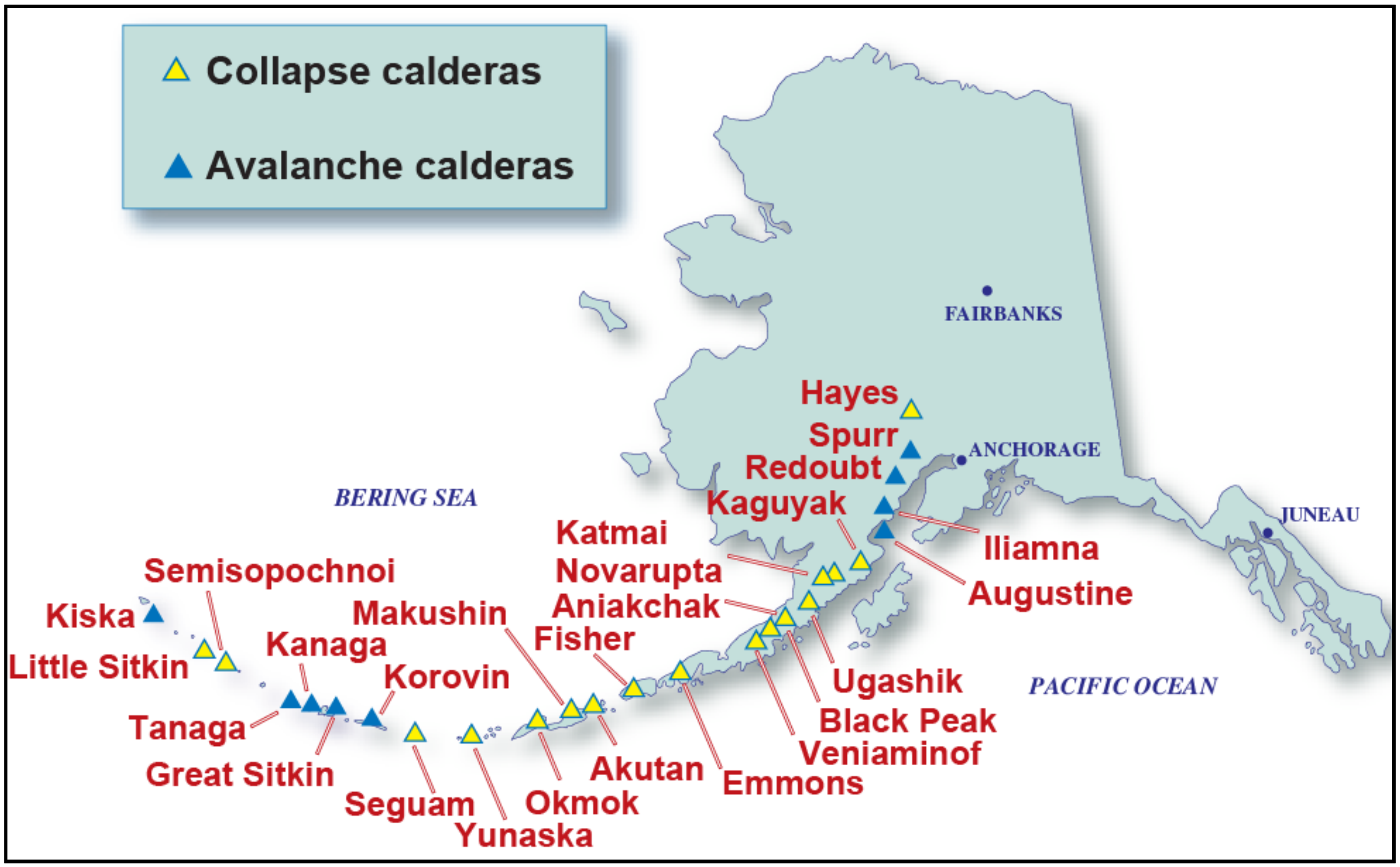
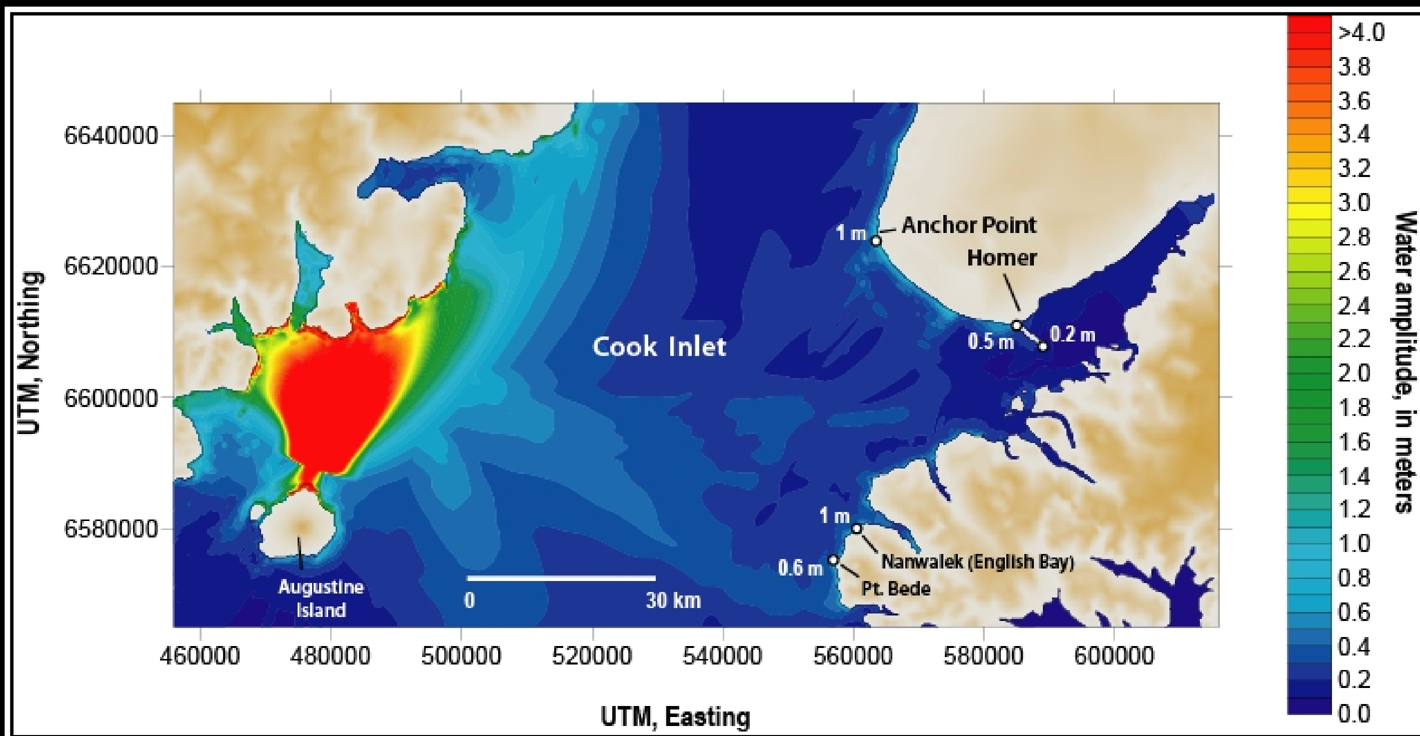
Aleutian Arc Calderas & Tsunami Generation during Caldera Formation



Maximum Water Amplitude:
Augustine Volcano
North Directed Mass Flow Source



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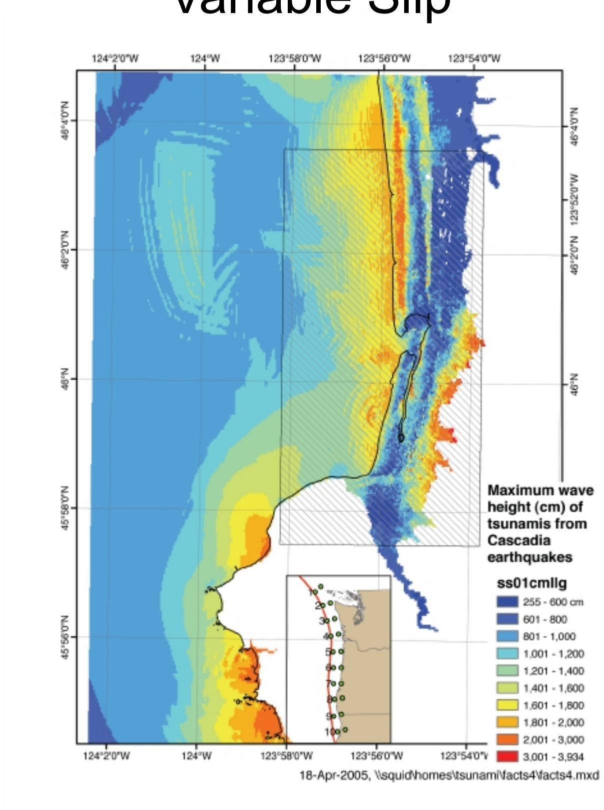
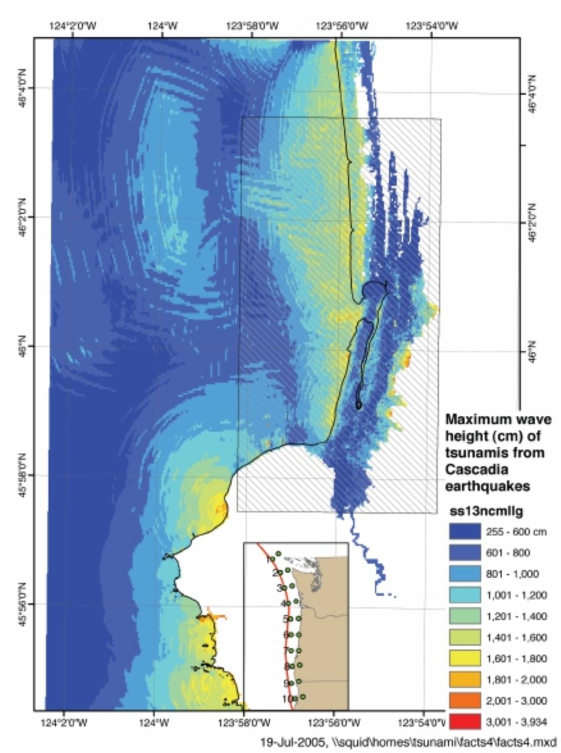
Tsunami Modeling

Effect of Source Model on Inundation

Variable Slip

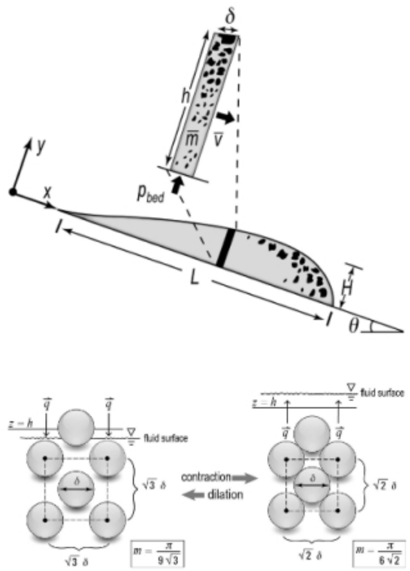


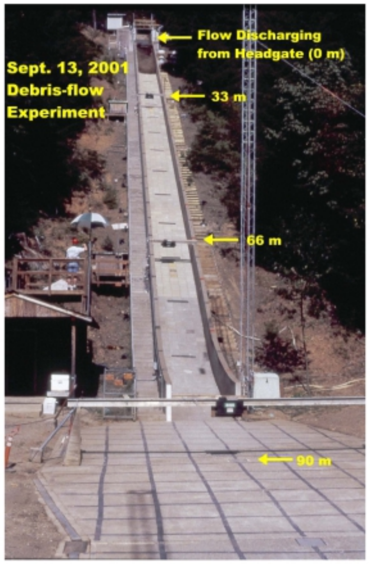
Uniform Slip

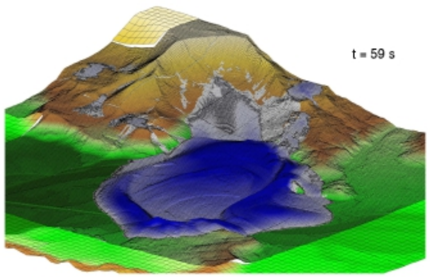


Models and software for Earth-surface flows

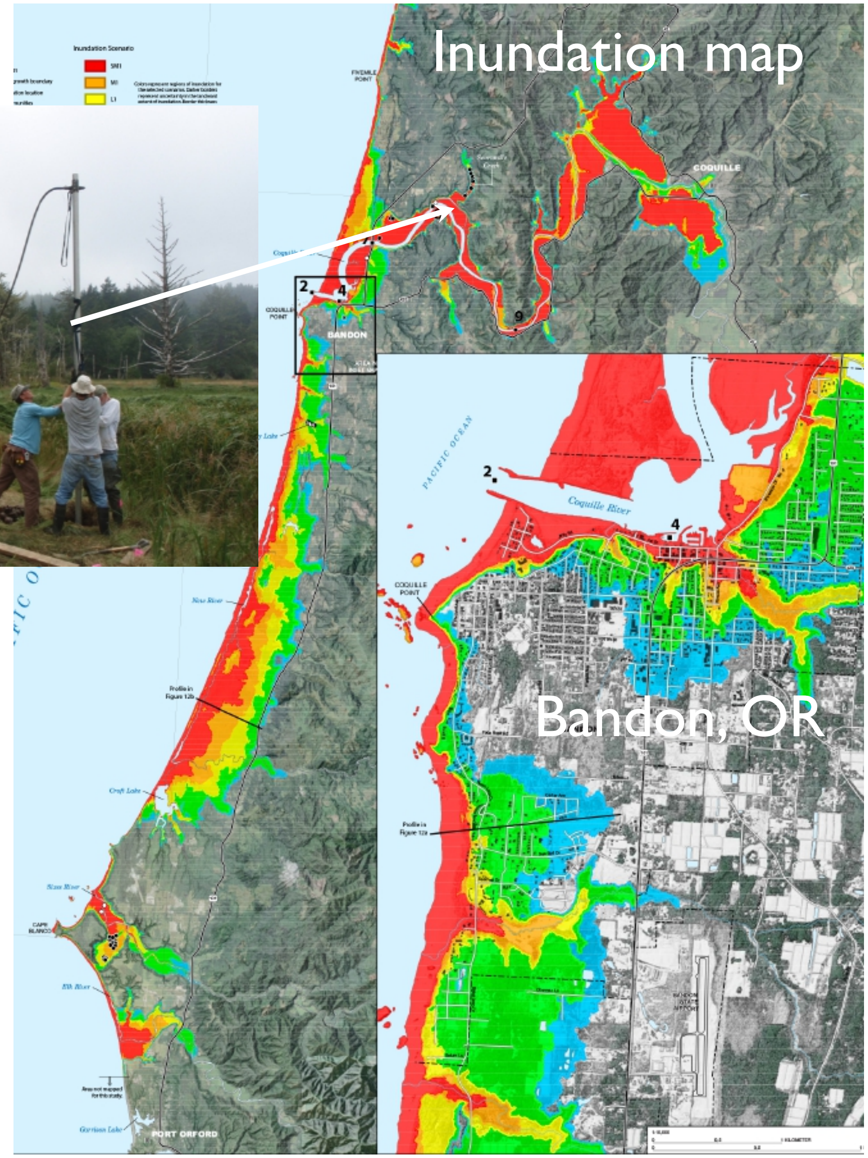
- Landslide modeling with D-Claw
  - GeoClaw extension for landslides and debris-flows
  - depth-averaged, two-phase, granular-fluid models
  - model for initiation and stability as well as run-out







Modeling



Calibration of inundation models using prehistoric tsunami deposits

Witter et al., 2011; 2012; 2013

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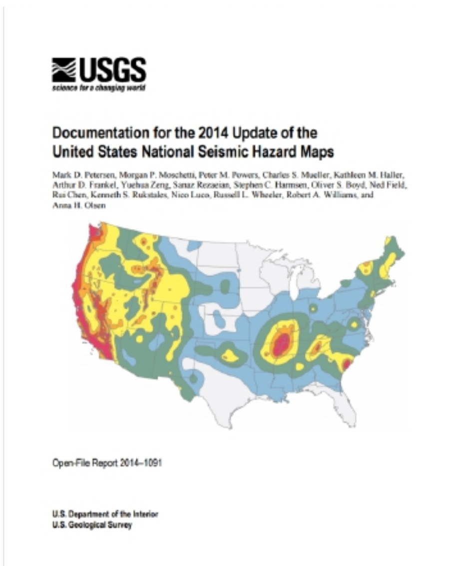
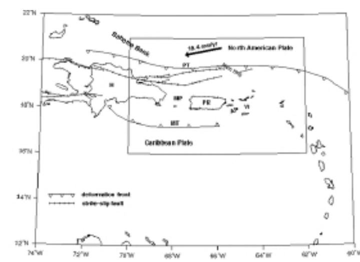
Plan for updating National Seismic Hazard Assessments for Cascadia, Alaska, Puerto Rico, others



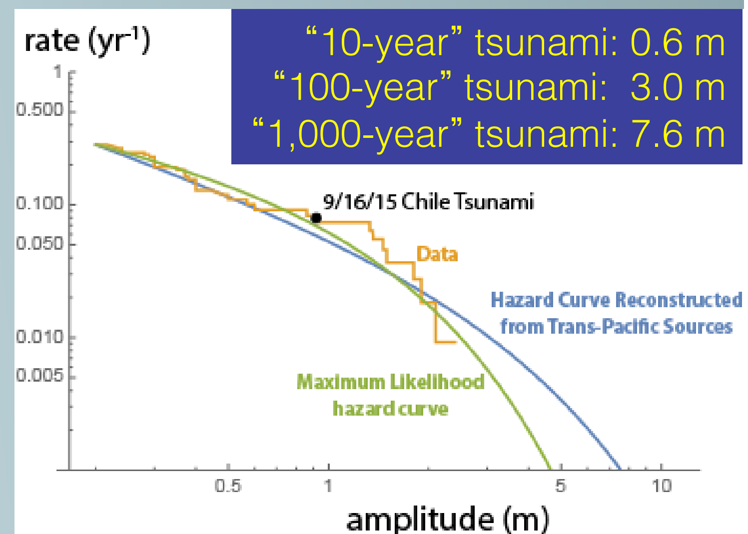
Documentation
Seismic Hazard Maps for Puerto Rico and the U. S. Virgin Islands
C. S. Mueller, A. D. Frankel, M. D. Petersen, and E. V. Leyendecker
U. S. Geological Survey, Golden, CO (2003)



Also subduction sources for Guam (Mueller and others, 2012) and American Samoa (Petersen and others, 2012)

Probabilistic Tsunami Hazard Analysis (PTHA)

- Work in Progress:
  Empirical and Reconstructed Tsunami Hazard Curve for Hilo, Hawai'i



- Future 5-year Science Goals
  - Global Tsunami Model (probabilistic)
  - Non-linear aspects: Edge waves (Cascadia tsunami probability at San Francisco)
  - Short-term probabilistic forecasting (days-years)
  - Incorporation of landslide sources (most difficult!)

Global Tsunami Model (GTM)

Global Tsunami Model (GTM)

Topic: generate, share and promote improved modelling techniques, standards, tools, and datasets to improve our capability to analyse tsunami hazard and risk globally.

The GTM network has emerged from the probabilistic tsunami hazard analysis for the UN-ISDR on the Global Assessment Report (GAR), aimed at quantifying multi-risk from natural hazards.

Initial GTM scope primarily limited towards hazard, but including all potential sources (not solely earthquakes).

Istituto Nazionale di Geofisica e Vulcanologia
terremoti

USGS
science for a changing world

Updated National Tsunami Hazard Assessment - Weaver

- First assessment published in 2008 (based on observational record)
- NTHMP requested update after recent events
- Changes in 2015 update
  - Hazard levels correlated with inundation guidelines used by Tsunami Warning Centers (e.g., <1.0m, >3.0m)
  - Frequency of occurrence at inundation levels included in assessment of hazard levels
  - Better accounting of tectonic setting—all subduction zone coasts are given a minimum hazard level of high (2008 used only historical record)
- Results/changes from 2008
  - California hazard raised to very high based on frequency >3m
  - American Samoa, Guam, Northern Marianas raised to high
  - Observations since 2006 did not change hazard levels

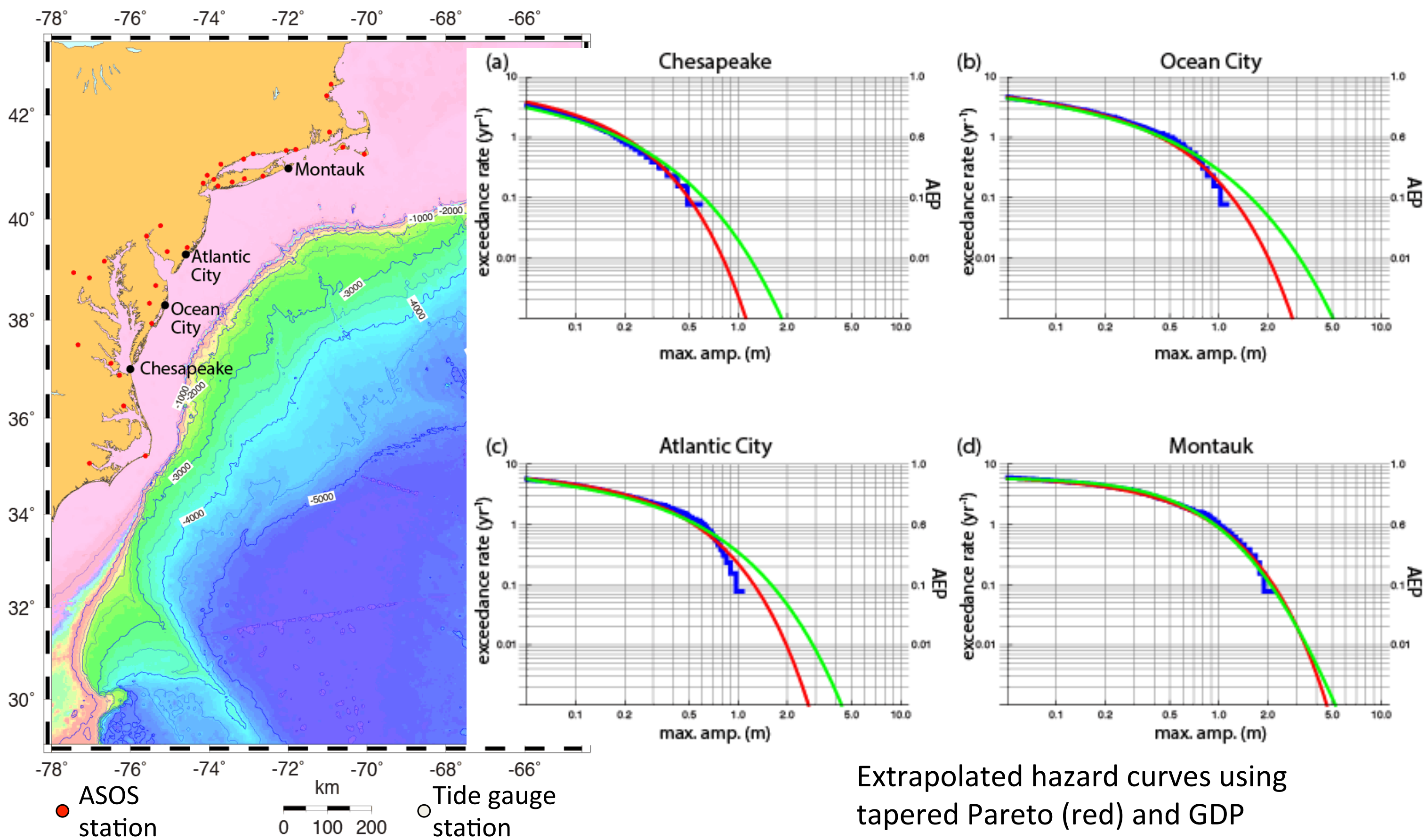
Tsunami hazard assessment projects for the Atlantic, Caribbean and the Gulf of Mexico (2006-2016)

- Marine geohazards sources and probabilities (USGS funded, 2013 -)
- Earthquake and tsunami hazard potential in the Caribbean (USGS funded, 2006-2013)
- Tsunami Landslide Source Probability and Potential Impact on New and Existing Power Plants (U.S.-NRC funded, 2009-2016)
- Physical study of tsunami sources (U.S. NRC funded, 2007-2008)
- Regional assessment of tsunami potential in the Gulf of Mexico (NTHMP funded, 2009)

Reports written to the funding agencies

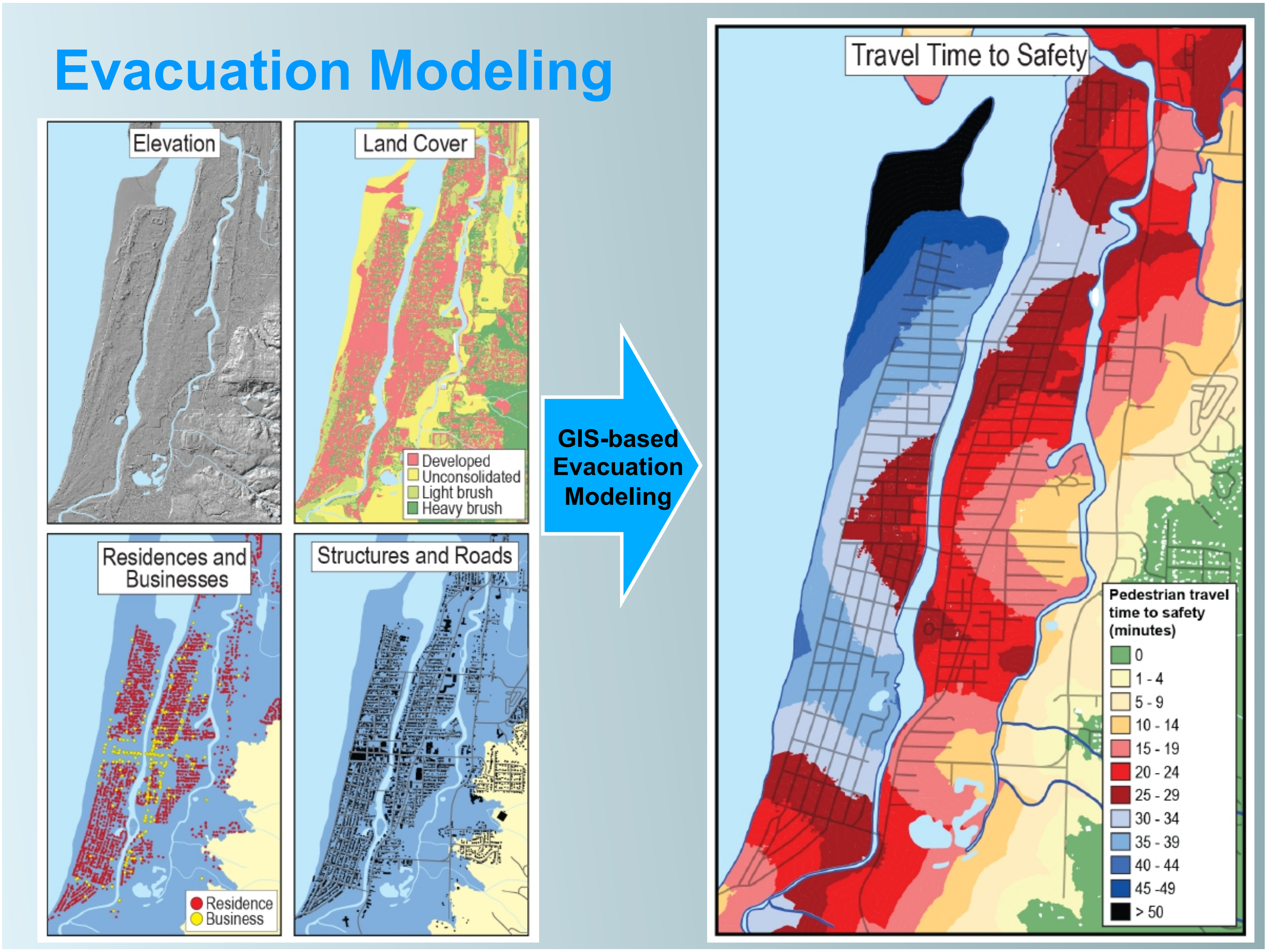
- The current State of Knowledge regarding potential tsunami sources affecting the U.S. Atlantic and Gulf of Mexico Coasts (375 pp., 2007),
  Evaluation of Tsunami Sources with the Potential to Impact the U.S Atlantic and Gulf Coasts (375 pp., 2008)
- NRC/USGS Workshop Report: Landslide Tsunami Probability (43 pp., 530 pp. appendix 2012).
- Tsunami Hazard Assessment for the U.S. Atlantic and Gulf Coasts (375 pp., in review)
- Report to NTHMP: Regional assessment of tsunami potential in the Gulf of Mexico (90 pp., 2009)

Meteo-tsunami probability: Squall Sources Northeast U.S.



Pressure difference, Front Length, Speed estimates and Period of pressure disturbance are from From Automated Surface Observing System (ASOS) station data

Extrapolated hazard curves using tapered Pareto (red) and GDP model (green) probability models. Blue – Mean hazard curves from Monte Carlo simulations.

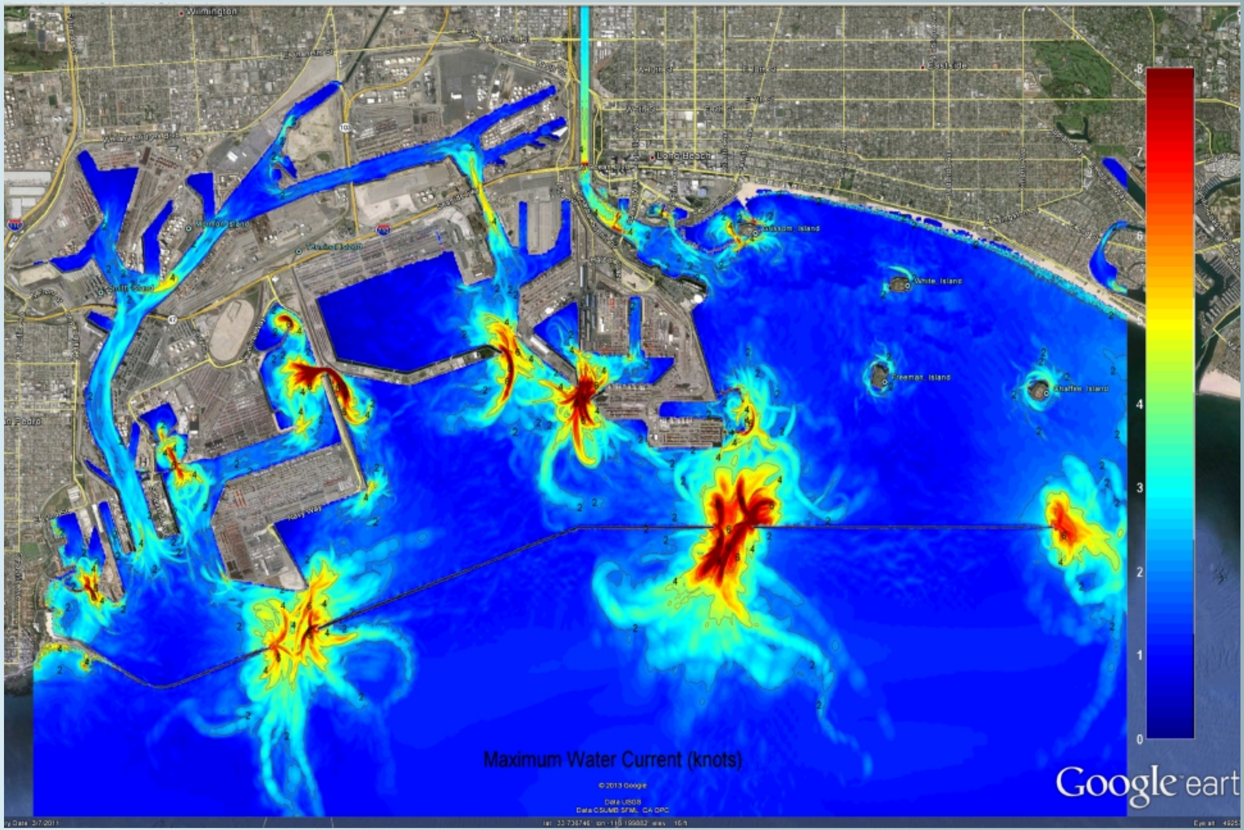

Evacuation Modeling
Elevation
Land Cover
Developed
Unconsolidated
Light brush
Heavy brush
Residences and Businesses
Residence
Business
Structures and Roads
GIS-based Evacuation Modeling
Travel Time to Safety
Pedestrian travel time to safety (minutes)
0
1 - 4
5 - 9
10 - 14
15 - 19
20 - 24
25 - 29
30 - 34
35 - 39
40 - 44
45 -49
> 50

Projects by Nate Wood and colleagues (USGS Western Geographic Science Center)

Recent and Ongoing Work:

1) Community clusters of vulnerability in the PNW to CSZ tsunamis
2) Tsunami evacuation modeling in five Alaskan communities
3) Historical tsunami evacuation modeling in Seward, Alaska
4) Vertical-evacuation siting related to CSZ tsunamis
5) Tsunami evacuation modeling in Napier, NZ (with GNS Science)
6) Modeling evacuation pathways in Aberdeen, WA, related to CSZ tsunamis
7) "Beat the Wave" evacuation modeling in Seaside, OR (with DOGAMI)
8) Projected changes in community exposure in the PNW to Cascadia tsunamis based on future development scenarios
9) Evacuation modeling on north shore of Oahu
10) Evacuation modeling in American Samoa for local tsunami threats

Example of results from SAFRR Tsunami Scenario: Maximum Currents at Ports of Los Angeles and Long Beach



The highest currents would occur at constricted passageways, such as breakwater entrances. Currents would be up to 8 knots, enough to do serious damage and to pull ships off moorings.