Variable Rupture Scenarios for Tsunami Simulations Inferred From a 10,000-Year History of Cascadia Megathrust Earthquakes

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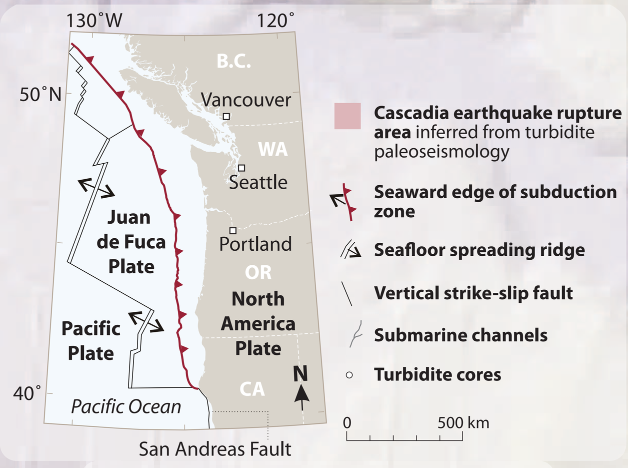
Introduction

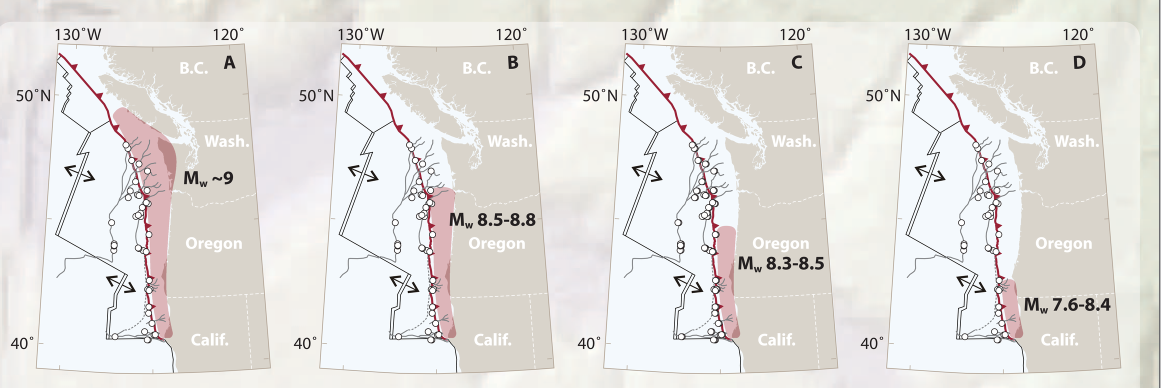
Differences in earthquake rupture scenarios for the Cascadia subduction zone contribute large uncertainties for simulations of tsunami inundation used to mitigate risk along the U.S. Pacific Northwest coast. Marine and coastal paleoseismic evidence now offer rare insight into rupture variability over multiple Cascadia earthquake cycles.

To explore an array of geologically reasonable Cascadia tsunami scenarios, we 1) characterize earthquake sources consistent with paleoseismology and forearc structure, 2) use elastic models of vertical coseismic deformation as inputs to simulate tsunami inundation at Bandon, Oregon, and 3) compare simulation results with tsunami deposits in Bradley Lake, ~10 km south of Bandon.



Tectonic setting of the Cascadia subduction zone (Data and graphics after Atwater et al., 2005; Goldfinger et al. 2010, in press).

1. Cascadia Earthquake Scenarios



A. Full-length ruptures of M_W ~9 from 19 turbidites; average recurrence interval, 500-530 years.

B. ¾-length ruptures of M_W 8.5-8.8 from 3-4 events; average recurrence interval, 410-500 years.

C. ½-length ruptures of M_W 8.3-8.5 from ~11events; average recurrence interval, 300-380 years.

D. ¼-length ruptures of M_W 7.6-8.4 from 7-8 events; average recurrence interval, 220-240 years.

Defining Earthquake Scenarios

We define 15 scenarios that cover a range of earthquake magnitudes, rupture lengths, fault geometries and coseismic slips inferred from marine turbidite paleoseismology spanning 10,000 years. 41 turbidites from submarine channels along the entire length of the plate boundary define a mean Holocene recurrence interval of ~530 yr for ruptures ≥800-km-long and ~240 yr for southern Cascadia earthquakes that ruptured 3 shorter segments.

Maximum slip in each scenario varies with latitude as the product of selected recurrence intervals and the convergence rate. Rupture models involve either: a) regional rupture with slip distribution symmetrically tapering to zero up and down dip; or b) regional rupture diverting slip onto an offshore splay fault, evident in seismic data, that dips 30 degrees and merges with the megathrust. Alternative scenarios terminate slip beneath the Pliocene accretionary outer wedge or allow slip to continue seaward beneath the Pleistocene wedge where seismic coupling may be near zero.

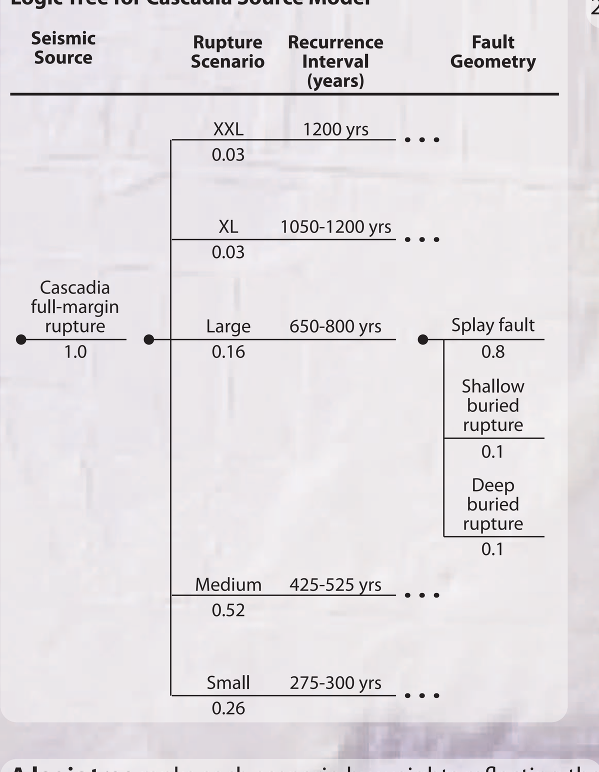
2. Source Characterization

Cascadia earthquake source parameters used to define 16 rupture scenarios. Logic tree weighting factors for each parameter shown in parentheses.

Rupture Scenario	Recurrence Interval (yrs)	Slip Range (m)	M_W	Fault Model	Total Weight
Full-length Ruptures					
XXL 1 (0.025)	1200	44	~9.4	Splay fault (0.8)	0.02
XXL 2 (0.0025)	1200	44	~9.4	Shallow buried rupture (01)	<0.001
XXL 3 (0.0025)	1200	44	~9.4	Deep buried rupture(0.1)	<0.001
XL 1 (0.025)	1050-1200	36-44	~9.3	Splay fault (0.8)	0.02
XL 2 (0.025)	1050-1200	36-44	~9.3	Shallow buried rupture (01)	<0.001
XL 3 (0.025)	1050-1200	36-44	~9.3	Deep buried rupture(0.1)	<0.001
L 1 (0.16)	650-800	22-30	~9.2	Splay fault (0.8)	0.13
L 2 (0.16)	650-800	22-30	~9.2	Shallow buried rupture (01)	0.02
L 3 (0.16)	650-800	22-30	~9.2	Deep buried rupture(0.1)	0.02
M 1 (0.53)	425-525	14-19	~9.1	Splay fault (06)	0.32
M 2 (0.53)	425-525	14-19	~9.1	Shallow buried rupture (02)	0.11
M 3 (0.53)	425-525	14-19	~9.1	Deep buried rupture(0.2)	0.11
S 1 (0.26)	275-300	9-11	~8.9	Splay fault (04)	0.10
S 2 (0.26)	275-300	9-11	~8.9	Shallow buried rupture (03)	0.08
S 3 (0.26)	275-300	9-11	~8.9	Deep buried rupture(0.3)	0.08

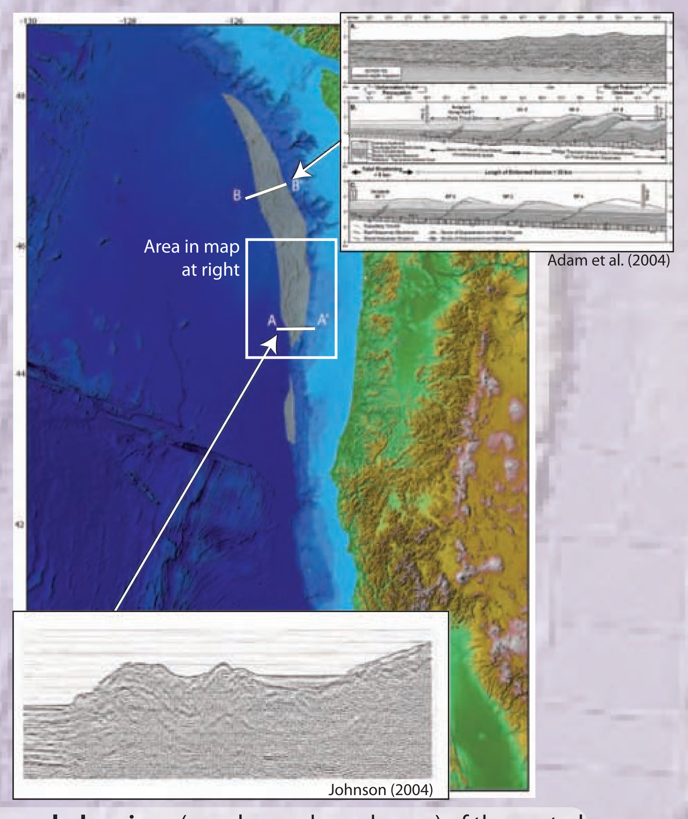
Maximum coseismic slip varies from 7 - 34 m at the latitude of Bandon for earthquakes varying from M_W ~8.3 - >9.

Logic Tree for Cascadia Source Model

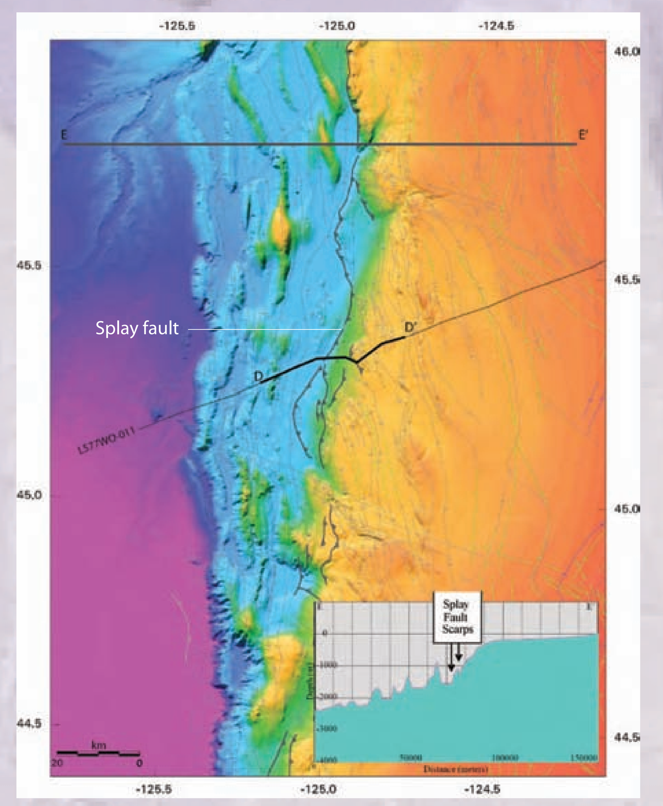


A logic tree ranks each scenario by weights reflecting the relative strength of supporting data.

3. Cascadia Forearc Structure

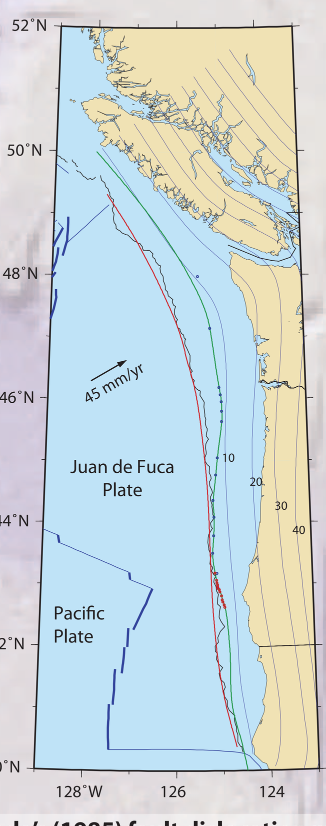


Decoupled regions (grey lense-shaped areas) of the central Cascadia margin (Priest et al., 2009) interpreted from variations in accretionary wedge slope, age and structural vergence. Landward vergence of folds in the young (Pleistocene) outer wedge (top inset) contrast with seaward-vergent folds of the inner wedge (bottom inset).



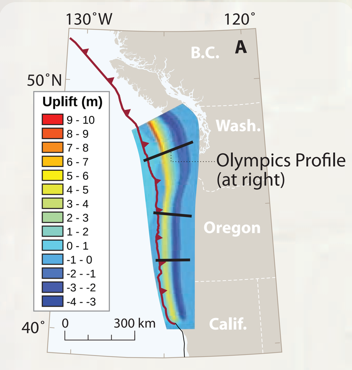
Structure of the Cascadia accretionary wedge west of northern Oregon (Goldfinger, 1994). Characteristics of the younger outer wedge (light blue) include low surface slope and landward- vergent, widely-spaced margin parallel folds. The older and steeper inner wedge (orange) includes folds with axes oriented normal to the convergence direction. A seaward-vergent splay fault (barbed grey line) separates the outer wedge from the inner wedge.

4. Earthquake Scenarios

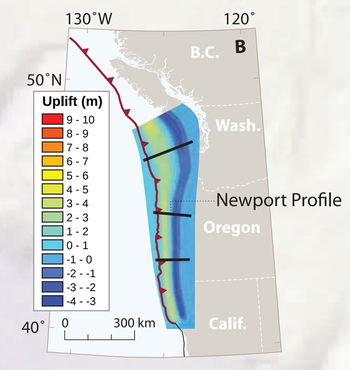


We use Okada's (1985) fault dislocation model (uniform elastic half space using Poisson's ratio of 0.25) to simulate surface deformation for three earthquake scenarios. The three scenarios differ by how slip is distributed across the megathrust or whether it is diverted to a splay fault.

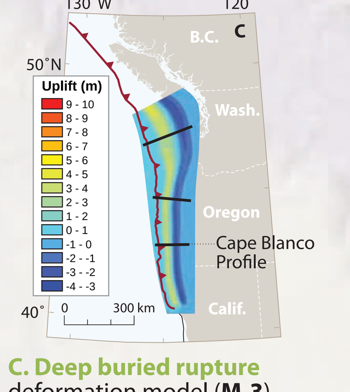
Map above shows the deformation front in red, the green line delineates a splay fault mapped by Goldfinger; structure contours (blue) on the downgoing plate are from McCrory (2004).



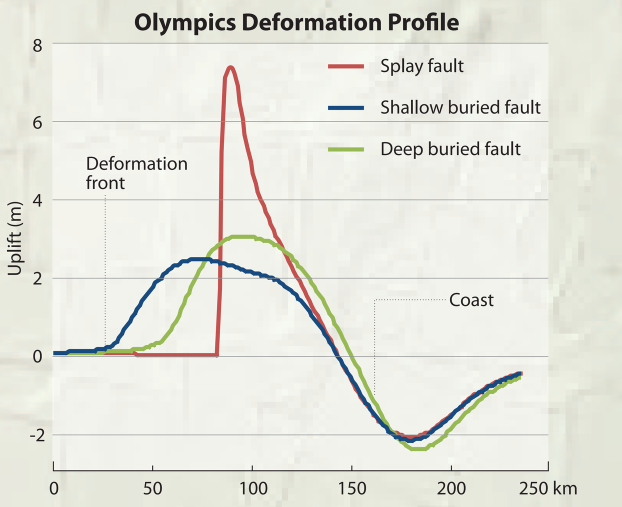
A. Splay fault rupture deformation model. Fault slip used in model **M-1** is estimated from 425 - 525 years of strain.

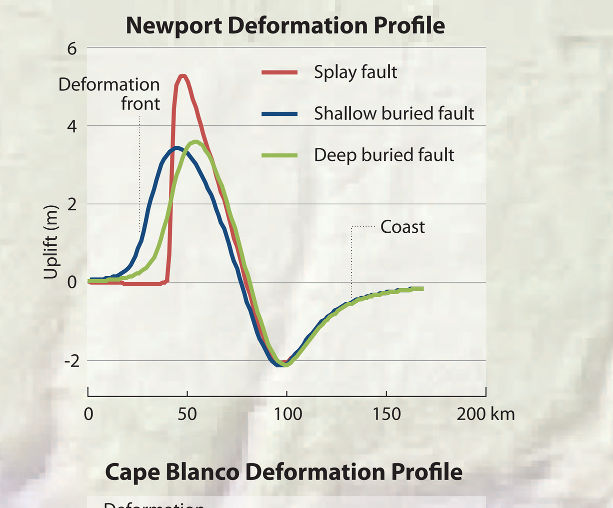


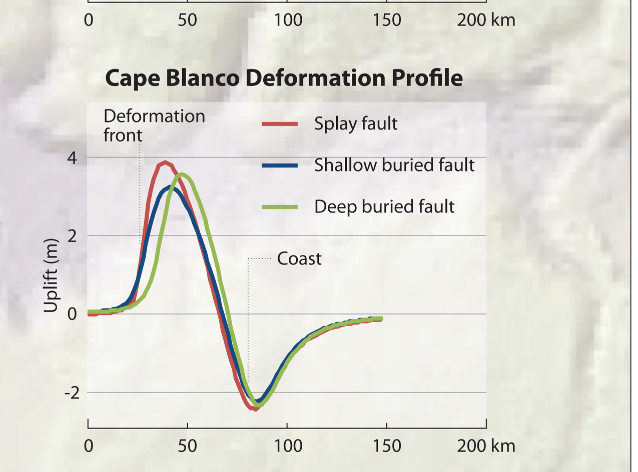
B. Shallow buried rupture deformation model (**M-2**).



C. Deep buried rupture deformation model (**M-3**).







Validating Tsunami Simulations

Tsunami simulations using the hydrodynamic model SELFE are compared to 13 tsunami deposits at Bradley Lake. Deposits of the 1700 tsunami require minimum slip of 13 m using a regional symmetric slip model. Augmenting uplift with a splay fault reduces slip by ~1 m. Earlier tsunamis, likely smaller than the 1700 wave, probably reached the lake when coastal erosion shifted the shoreline farther landward. Simulations with these conditions require minimum slip of ~9 m accrued over 280 yr —still longer than the shortest intervals between turbidites (~130-260 yr) that correlate with tsunami deposits in the lake. Disparities between the shortest turbidite recurrence intervals and tsunami evidence implying larger coseismic slip suggest release of strain stored over prior earthquake cycles or underestimation of tsunamis by the simulations.

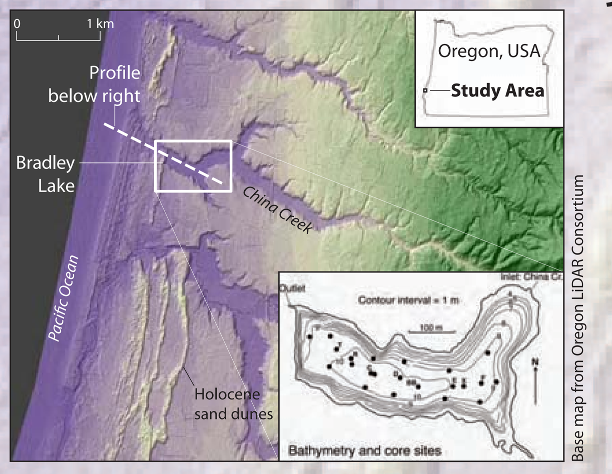
5. Conceptual Framework

Purpose: to validate tsunami simulations in southern Oregon against paleotsunami deposits in a small coastal lake.

Hypothesis: Turbidite recurrence intervals provide reasonable slip estimates for tsunami source models in southern Cascadia.

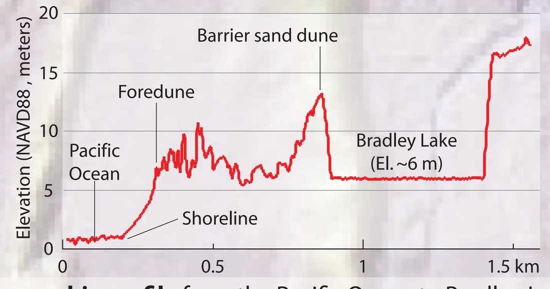
Test: We test the hypothesis by comparing the slip required for tsunami simulations to reach Bradley Lake to slip estimates derived from turbidite recurrence intervals.

Experiments simulate the smallest tsunamis capable of reaching the lake by varying three principal variables: *Landscape*, *sea level*, and *earthquake source*.



Dunes impound coastal lakes. (Above) Bradley Lake, located ~0.5 km from the Pacific Ocean at an elevation of ~6 m above sea level, contains a 4,500 year-long sedimentary record of 13 Cascadia tsunamis, including the most recent giant wave in 1700.

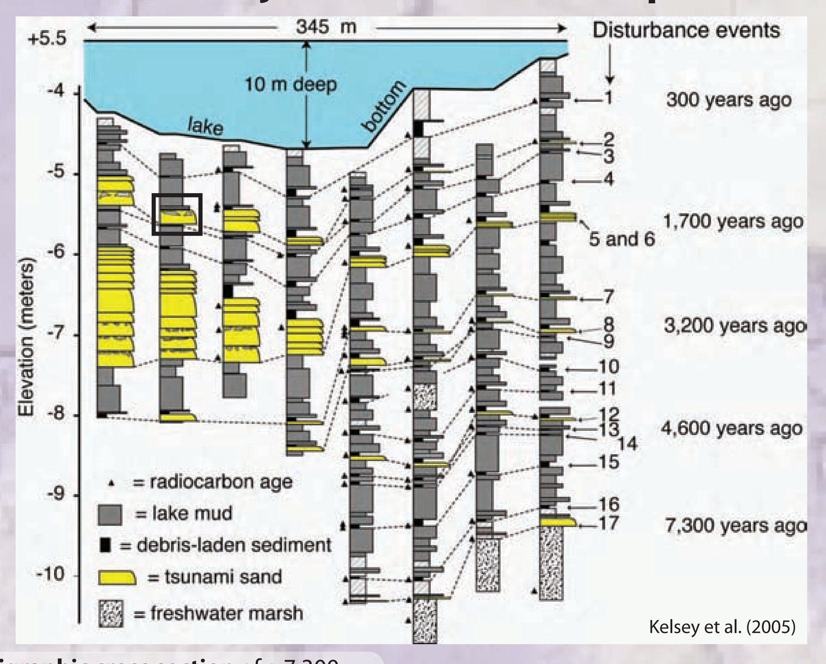
Dunes 12-13 m high dammed the lake ~7,000 years ago. Inset map (lower right)shows locations of 22 sediment cores collected to examine evidence for tsunami inundation by Kelsey et al. (2005).



Topographic profile from the Pacific Ocean to Bradley Lake.

Photographs of Bradley Lake, located near Bandon, Oregon, USA. (Left) View of Bradley Lake looking west toward barrier sand dune. (Middle) Standing on top of the barrier sand dune that dams Bradley Lake looking west toward the Pacific Ocean. (Right) Looking east from the sand dune toward the improvised drilling platform used to core lake sediment.

6. Bradley Lake Tsunami Deposits

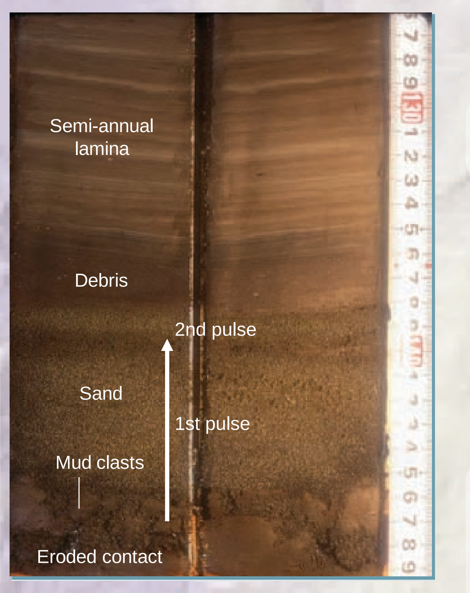


Stratigraphic cross section of a 7,300-year sedimentary record in Bradley Lake. Disturbances in lake sediment provide evidence for 13 marine incursions that deposited landward-thinning sand sheets into the lake from beach and dune sources to the west.

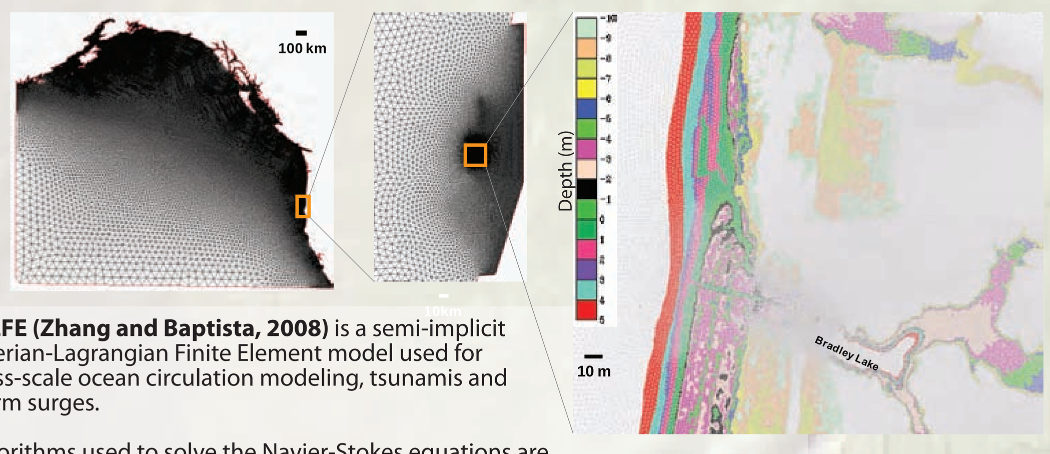
Kelsey et al. (2005) concluded that these events were best explained by Cascadia tsunamis that inundated Bradley Lake on average every 390 years.

Bradley Lake tsunami deposit. The photo at right shows the sequence of deposits related to a tsunami that entered the lake about 1,000 years ago.

Black box in above figure shows the location of the sand deposit in the context of the lake stratigraphy.

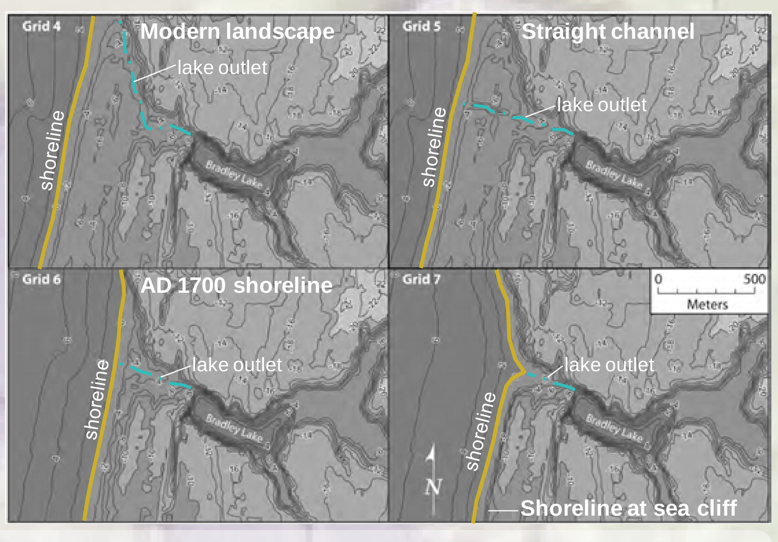


7. Hydrodynamic Model SELFE



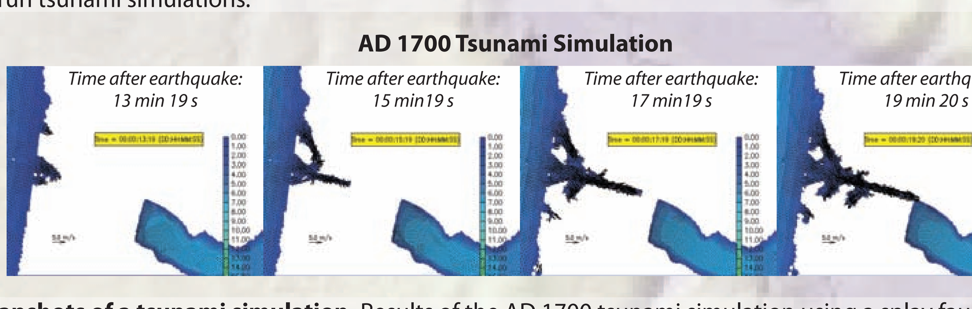
SELFE (Zhang and Baptista, 2008) is a semi-implicit Eulerian-Lagrangian Finite Element model used for cross-scale ocean circulation modeling, tsunamis and storm surges.

Algorithms used to solve the Navier-Stokes equations are computationally efficient and stable. This open-source model has been rigorously benchmarked and is available at: http://www.stccmop.org/CORIE/modeling/selfe/



Historical aerial photography (left) show changes in vegetation and coastal geomorphology over the last 70 years. We used this and other data to construct test grids to represent reasonable landscapes on which to run tsunami simulations.

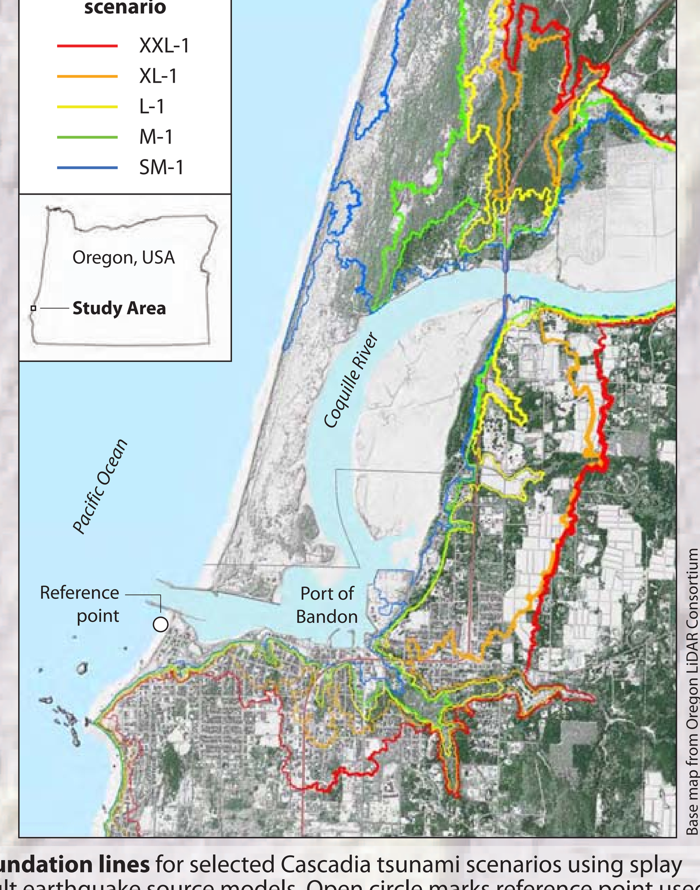
AD 1700 Tsunami Simulation



Snapshots of a tsunami simulation. Results of the AD 1700 tsunami simulation using a splay fault source model, 360 year recurrence interval (or ~12 m slip) run on the 1700 landscape with the AD 1700 tide hindcast by Mofjeld et al. (1997). Along the southern Cascadia subduction zone, turbidite recurrence intervals range between 175 - 340 yrs implying 6 - 11 m of slip per event.

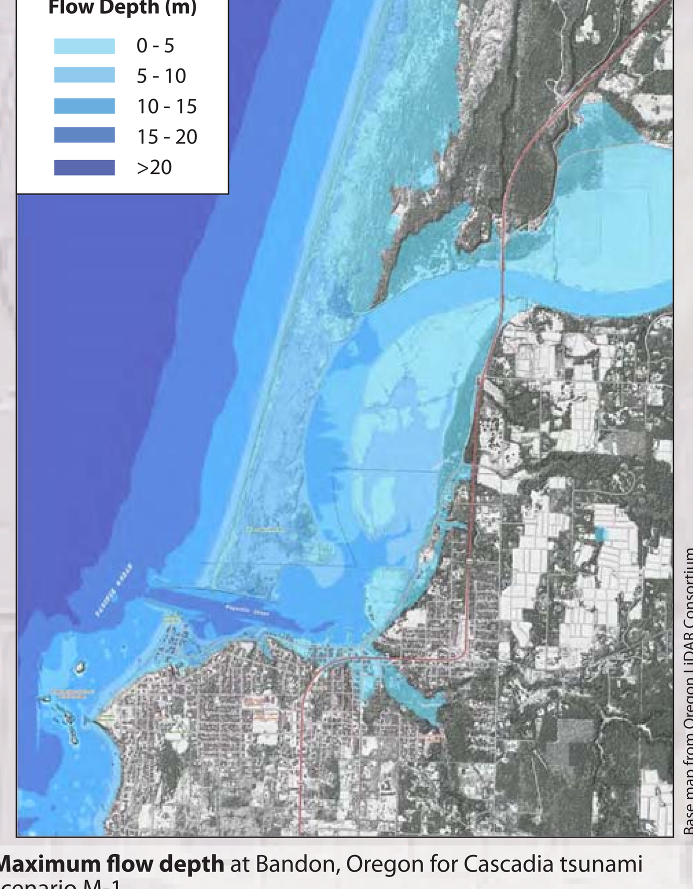
However, results from the AD 1700 simulations suggest longer recurrence intervals (360 - 400 years) and hence larger slips (12 - 13 m) are necessary to trigger a tsunami that reaches Bradley Lake.

8. Cascadia Tsunami Simulations at Bandon, Oregon

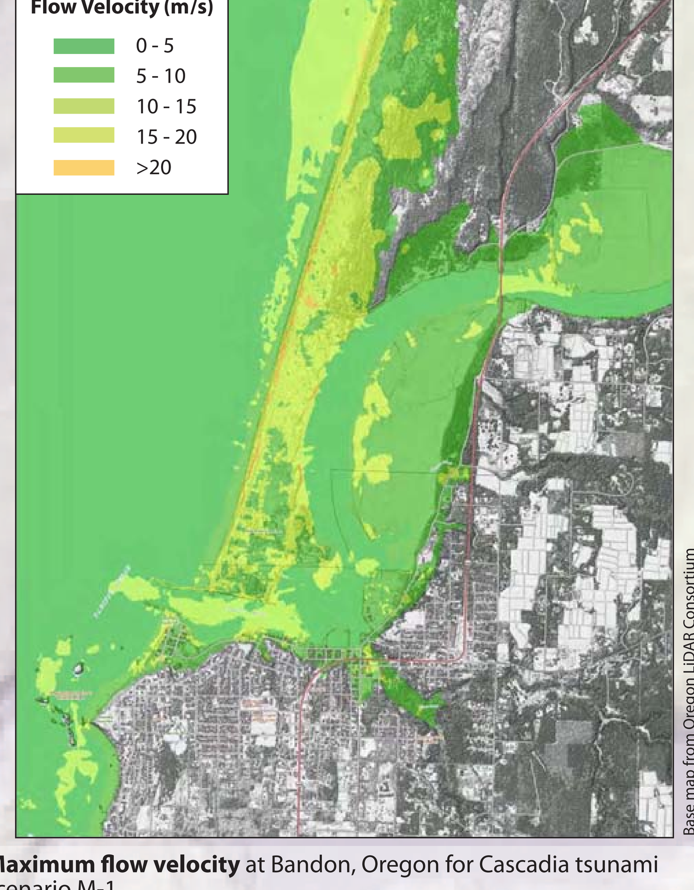


Inundation lines for selected Cascadia tsunami scenarios using splay fault earthquake source models. Open circle marks reference point used for time histories plotted at far right.

9. Maximum Flow Depth and Velocity Fields

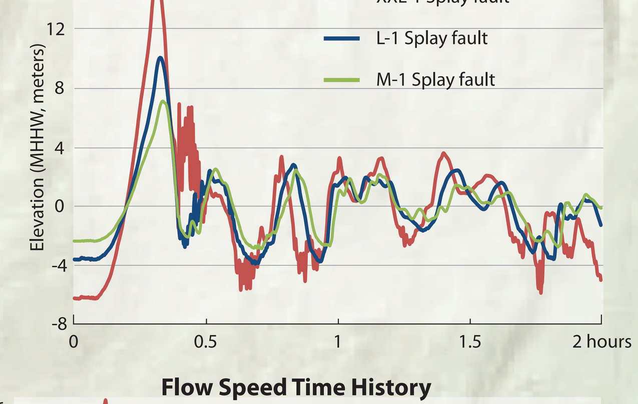


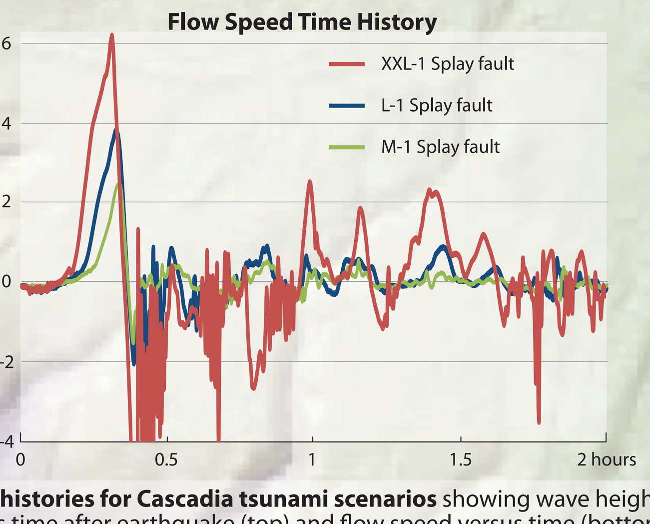
Maximum flow depth at Bandon, Oregon for Cascadia tsunami scenario M-1.



Maximum flow velocity at Bandon, Oregon for Cascadia tsunami scenario M-1.

10. Tsunami Time Histories





Time histories for Cascadia tsunami scenarios showing wave height versus time after earthquake (top) and flow speed versus time (bottom). See map (far left) for location of reference point.