Reconstructing Hydrodynamic Flow Parameters of the 1700 Tsunami at Ecola Creek, Cannon Beach, Oregon

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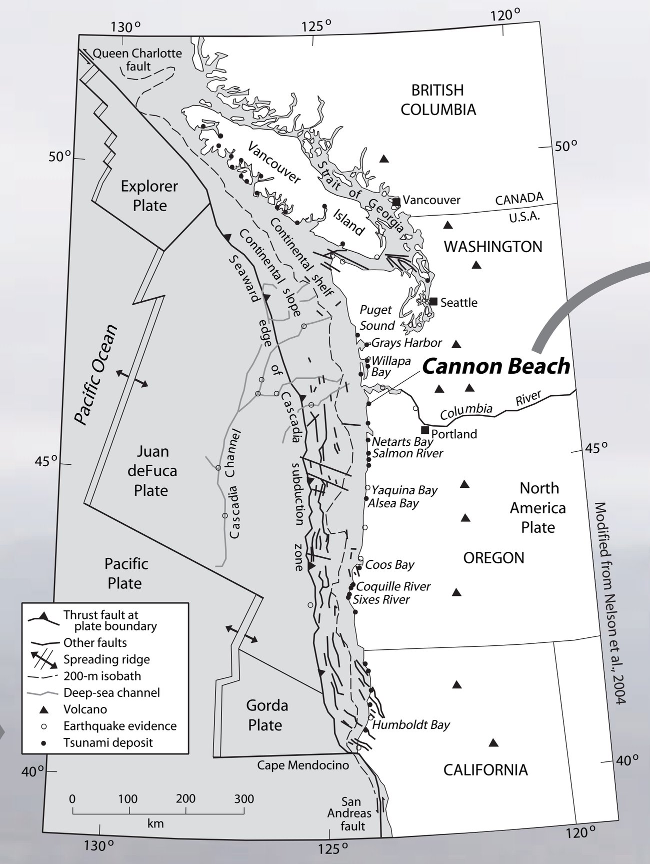
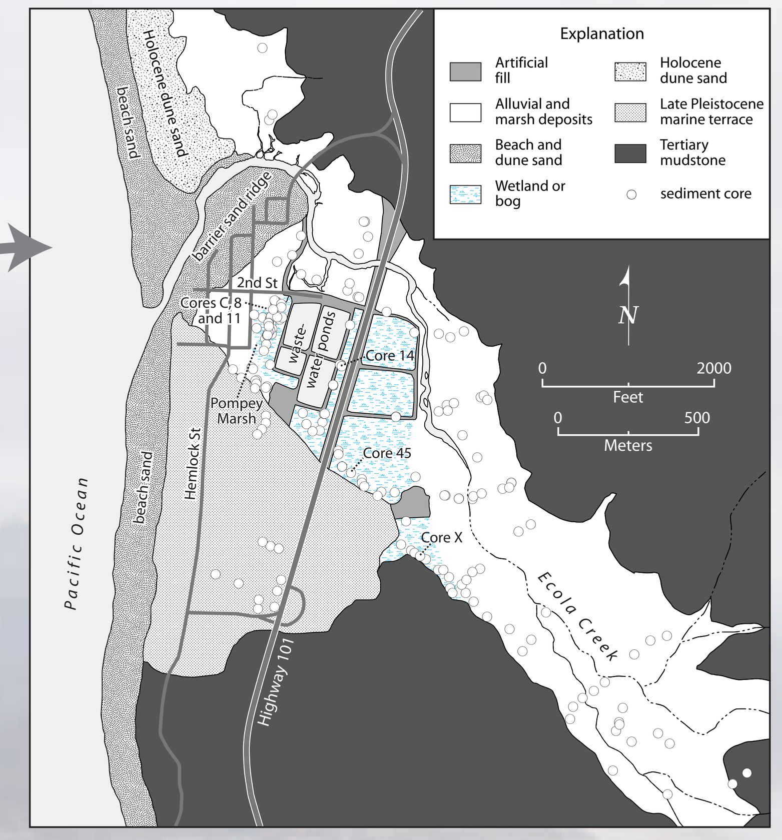
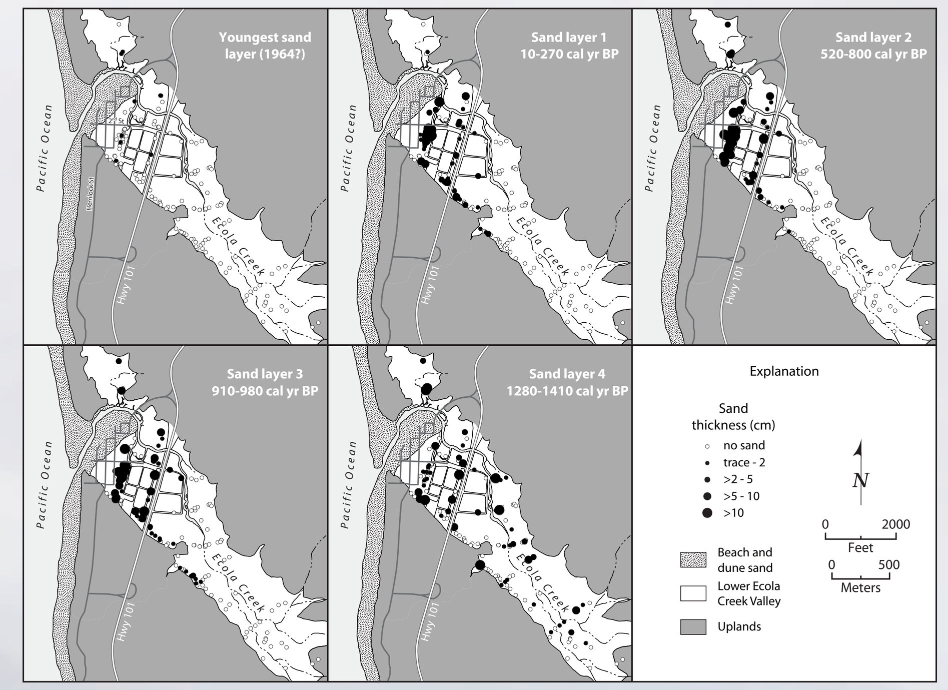
INTRODUCTION. Coastal communities in the western U.S. face risks of inundation by distant tsunamis that travel across the Pacific Ocean as well as local tsunamis produced by great (M >8) earthquakes on the Cascadia subduction zone. In 1964 the M 9.2 Alaska earthquake generated a distant tsunami that flooded Cannon Beach, a small community (population 1640) in northwestern Oregon, causing over $230,000 in damages. However, in the wake of the 2004 Indian Ocean tsunami, renewed concern about the potential impacts of a local Cascadia tsunami, has motivated a need for closer examination of the hazard.



1. Tectonic setting of the Pacific northwestern U.S. showing the Cascadia subduction zone, Quaternary faults in the North American plate, and the location of the study site at Cannon Beach in northwestern Oregon. The deformation front of the Cascadia megathrust (barbed line) is defined by bathymetry where the abyssal plain meets the continental slope. Open and closed circles represent sites with evidence for prehistoric Cascadia earthquakes and tsunamis. Closed circles mark sites with deposits interpreted to record tsunami inundation caused by a M9 Cascadia earthquake on January 26, 1700 (Satake et al., 1996).

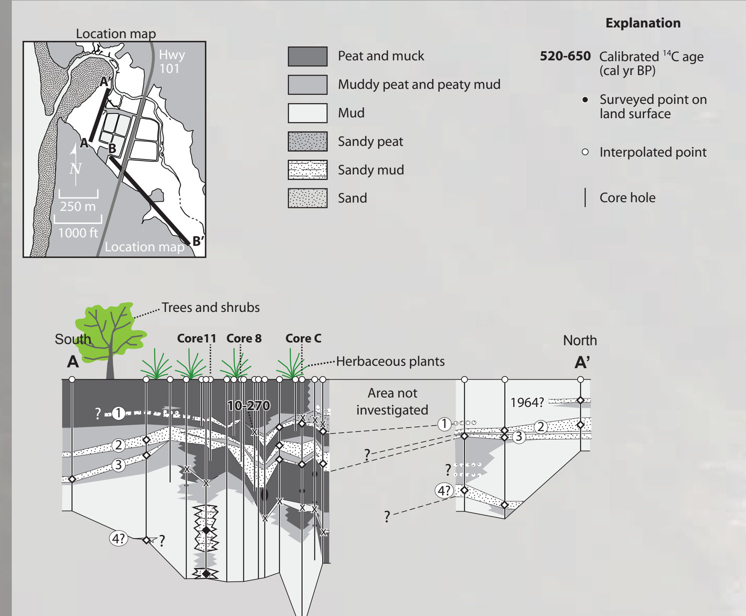


2. Map of the Cannon Beach study area, including the lower Ecola Creek valley and surrounding uplands. Open circles show locations of 177 sediment cores examined for evidence of sand layers deposited by tsunamis or creek floods.

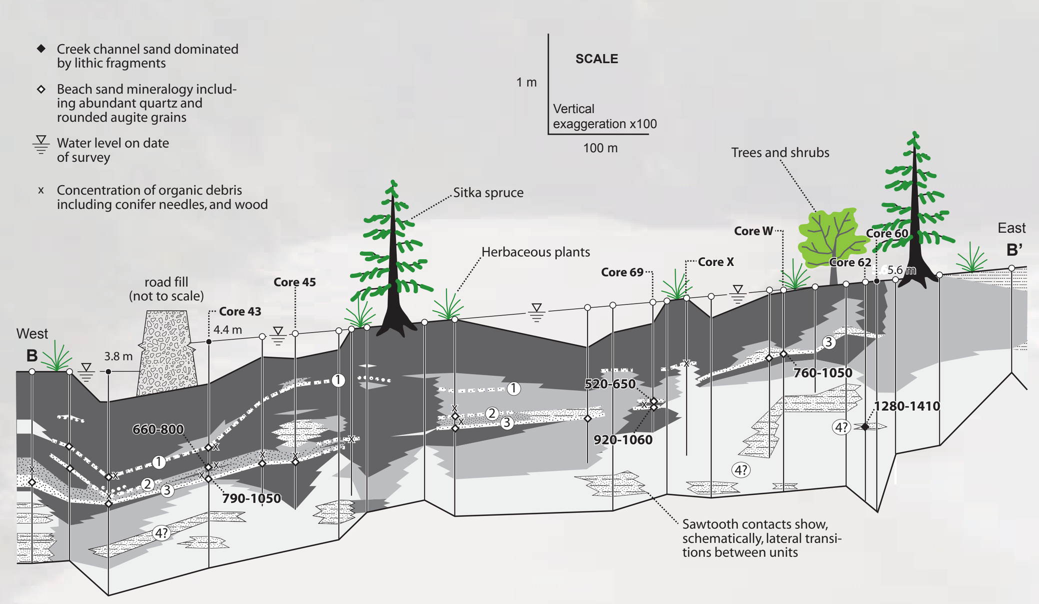


3. Maps of the lower Ecola Creek valley depicting the distribution of five sand deposits correlated among numerous sediment cores (black circles) and shown in stratigraphic profiles (Figs. 4 and 5). Variations in the thickness of each sand layer are indicated by the diameters of black circles. Open circles show cores without a correlative sand layer. Calibrated ^{14}C ages are shown for each sand layer; the youngest deposit may reflect deposition by the 1964 Alaska tsunami based on historical documents.

STRATIGRAPHIC PROFILES

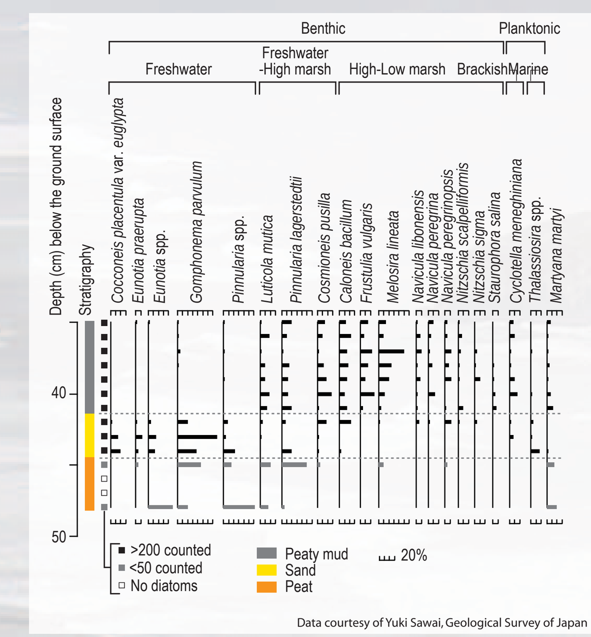


4. Stratigraphic profile A–A' showing five sand layers preserved beneath Pompey marsh near downtown Cannon Beach.

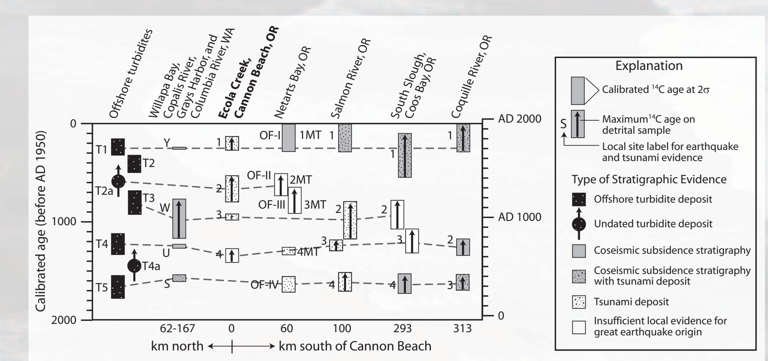


5. Stratigraphic profile B–B' showing four sand layers along the southeastern margin of the lower Ecola Creek valley.

6. Photographs showing sand layers deposited by the 1700 Cascadia tsunami.



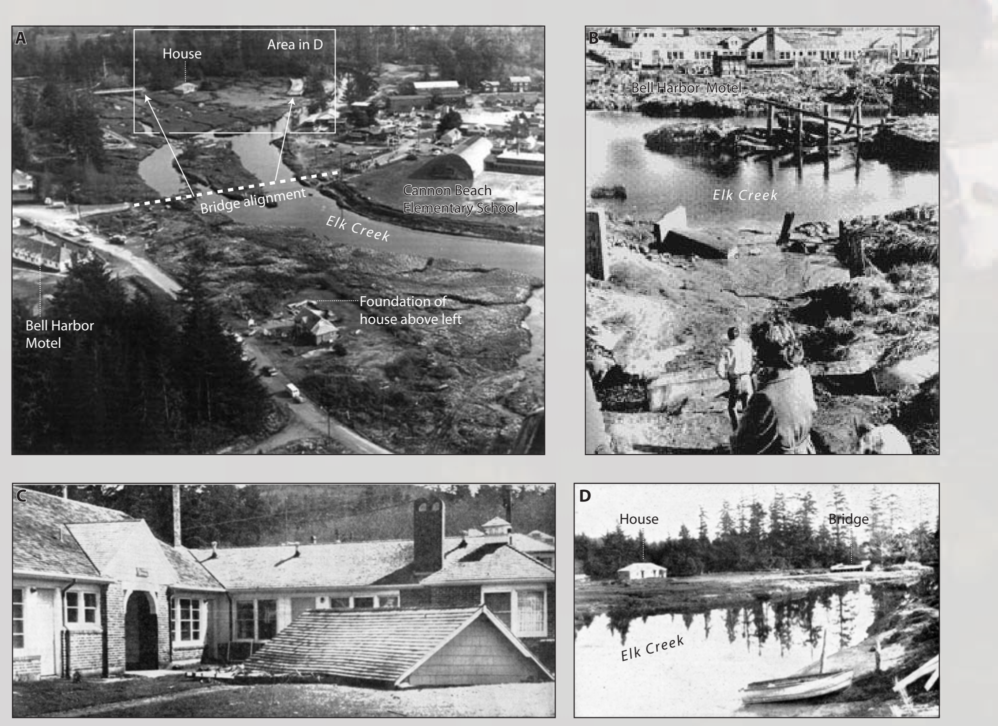
7. Diatom assemblages present in 1700 Cascadia tsunami deposit, underlying peat and overlying peaty mud. The change in assemblage from predominantly freshwater species in the peat to diatoms that inhabit high-to-low salt marshes implies that an earthquake subsided the soil prior to sand deposition by the tsunami.



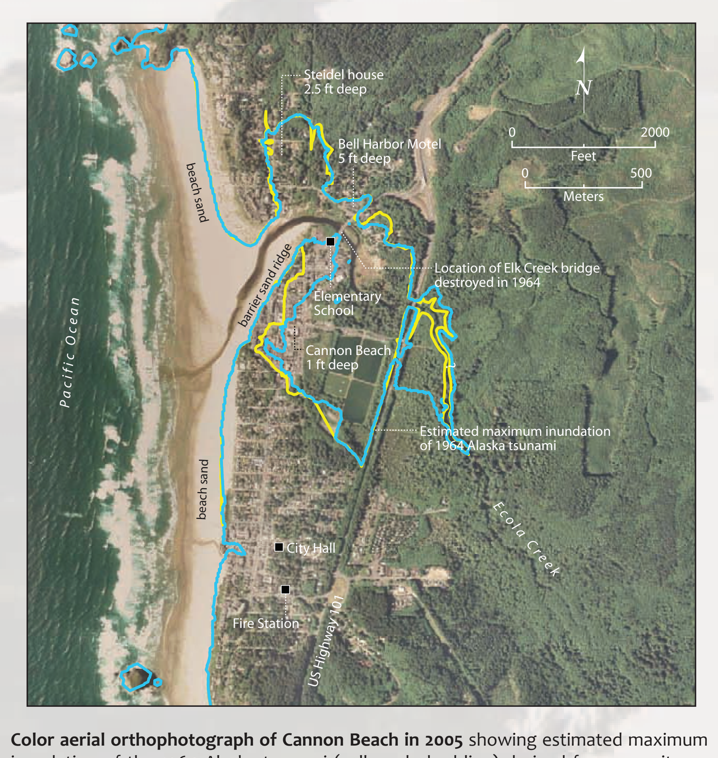
8. Comparison of calibrated ^{14}C ages and coastal evidence for great Cascadia earthquakes and tsunamis over the last two millennia at six sites in southwestern Washington and northwestern Oregon (modified from Nelson et al., 2004). Black rectangles represent ages for offshore turbidite deposits inferred to record strong shaking during prehistoric Cascadia earthquakes (from Goldfinger et al., 2007). Arrows indicate maximum limiting ^{14}C ages based on dates of detrital plant fossils. Data sources available upon request.

1964 ALASKA TSUNAMI.

The 1964 Alaska tsunami damaged City infrastructure and private property in Cannon Beach. Estimates of the inundation extent and runup elevation are inferred from eyewitness accounts released days after the March 27 tsunami. Maximum runup probably reached 5.8 to 6.1 m (MLLW) derived from estimates of tsunami flow depth at two sites. The inferred extent of inundation comes from reports of damage to Highway 101, extensive flooding of the business district and from extrapolation of flow depth estimates from eye-witness accounts.

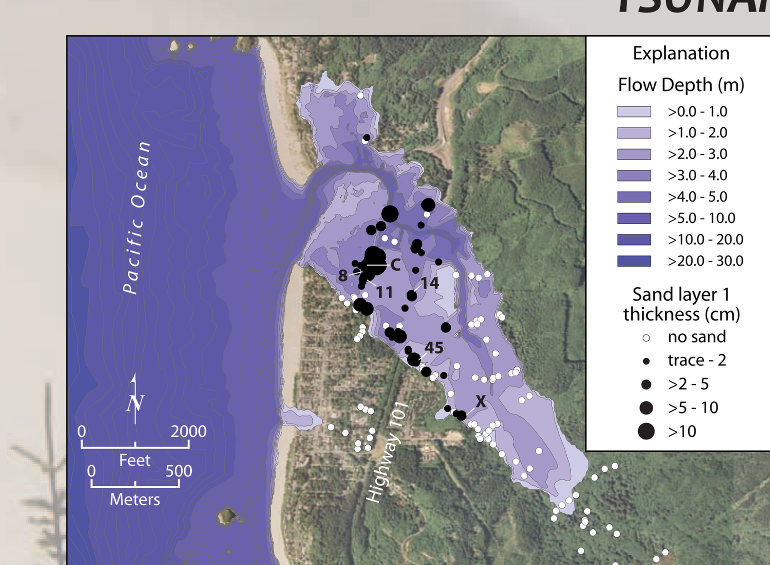


Photographs showing the impact of the 1964 Alaska tsunami. (A) Oblique aerial photograph of the lower Elk Creek valley (now Ecola Creek) that flows through downtown Cannon Beach. The old Elk Creek bridge and a house were transported approximately 300 to 400 m upstream (photo from the Hillsboro Argus, March 30, 1964). (B) Bridge pilings and piers are all that remain after the tsunami destroyed the Elk Creek bridge in 1964. (photo from The Sunday Oregonian, March 29, 1964). (C) The Bell Harbor Motel suffered considerable damage from flooding during the tsunami, including broken windows, water damage and destruction caused by drift logs. The roof of a different building, in the foreground, was carried several hundred yards by the waves (photo from The Daily Astorian, March 30, 1964). (D) The remains of the bridge and house transported by the tsunami (photo from The Daily Astorian, March 30, 1964).

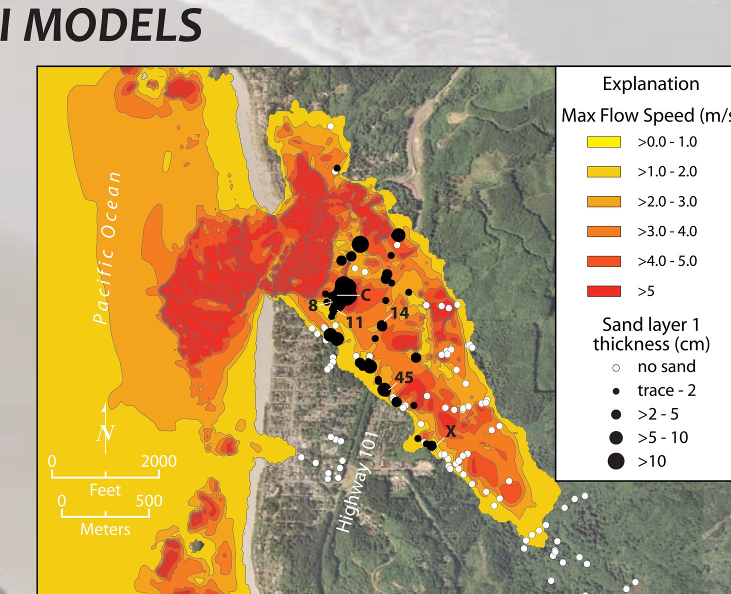


Color aerial orthophotograph of Cannon Beach in 2005 showing estimated maximum inundation of the 1964 Alaska tsunami (yellow dashed line) derived from eyewitness observations of water depth and 2-ft (0.6-m) contour lines from a topographic map of the City. The inundation line coincides with the 16-ft (4.9-m) contour line (NGVD 29) along the ocean front and north of Ecola Creek near the Steidel house and Bell Harbor Motel. The 10-ft (~3-m) contour line (NGVD 29) was used to approximate inundation in downtown Cannon Beach and east to US Highway 101. East of the highway the inundation line coincides with the 8-ft (2.4-m) contour line (NGVD 29) but there is no information from which to evaluate the extent of inundation in this area. Observations of the 1964 tsunami inundation were used in benchmark tests of numerical modeling employed to simulate the 1964 tsunami (shown by turquoise line).

TSUNAMI MODELS



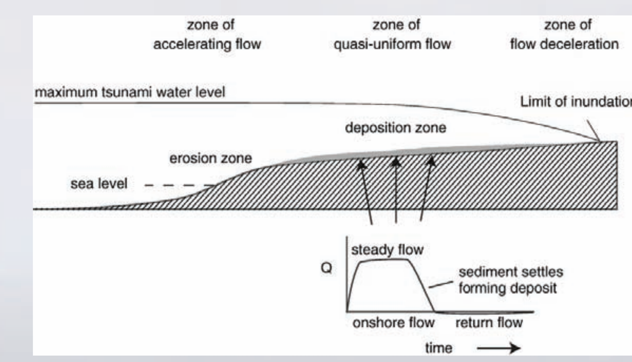
9. Tsunami flow depths for Cannon Beach tsunami simulation using earthquake model "Average 9" of Priest et al. (2008). The simulation uses a digital elevation model for a 1000-year old prehistoric landscape derived from geologic information. Numbers and letters designate core site locations sampled for tsunami sediment analyses.



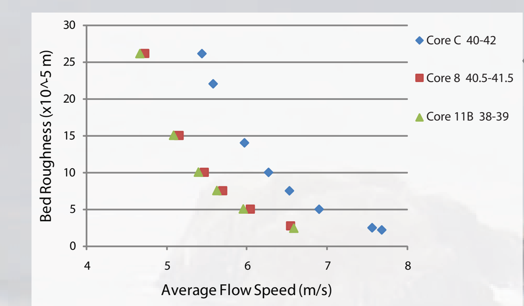
10. Maximum tsunami flow speed for Cannon Beach tsunami simulation using earthquake model "Average 9" of Priest et al. (2008). The simulation uses a digital elevation model for a 1000-year old prehistoric landscape derived from geologic information. Numbers and letters designate core site locations sampled for tsunami sediment analyses.

THE APPLICATION OF A SIMPLE SEDIMENT TRANSPORT MODEL.

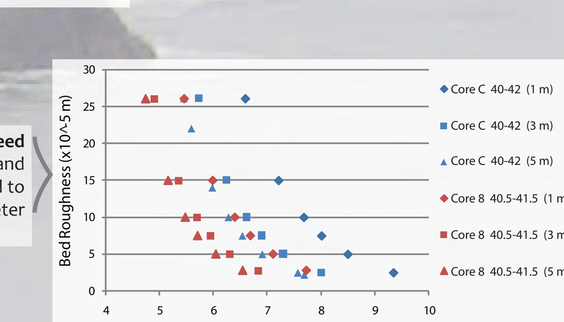
This study applies a simple sediment transport model, TsuSedMod (Jaffe and Gelfenbaum, 2007), to reconstruct the flow speed of the most recent Cascadia tsunami that flooded the region in 1700 using the thickness and grain size of sand layers deposited by the waves. Sand sheets recording the 1700 tsunami were sampled in the field and analyzed in the laboratory to produce model inputs. TsuSedMod calculates tsunami flow speed from the shear velocity required to suspend the quantity and grain size distribution of the observed sand layers. The model assumes a steady, spatially uniform tsunami flow and that sand deposits form from sediment falling out of suspension when the flow stops. Assuming sensitivity analyses test the appropriate parameter values found in nature, flow speeds estimated for the 1700 tsunami range from about 5 to 9 m/s.



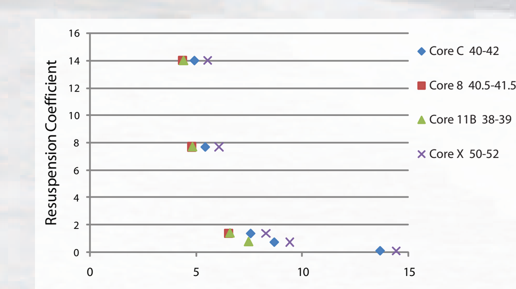
11. Conceptual model of tsunami sedimentation (Jaffe and Gelfenbaum, 2007). Deposit is formed in a zone of spatially quasi-uniform flow by sediment settling out of suspension when the tsunami flow speed goes to zero at the end of the onshore flow. Because the deposition zone is spatially quasi-uniform, the same temporal variation in flow speed applies to all locations in this zone. Quasi-uniform flow limits the amount of sediment deposited by sediment flux convergences, resulting in deposition from suspension being the primary process for tsunami deposit formation. The return flow is weak and concentrated in topographic lows and does not erode much of the deposit that formed during the onshore flow.



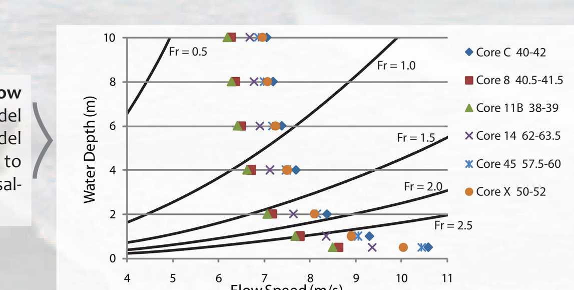
13. Variations in average flow speed versus bed roughness for cores C, 8 and 11. Model runs use a 5 m flow depth parameter.



14. Variations in average flow speed versus bed roughness for cores C and 8, sample interval 40-42 cm related to varying the water depths parameter from 1 to 5 m.

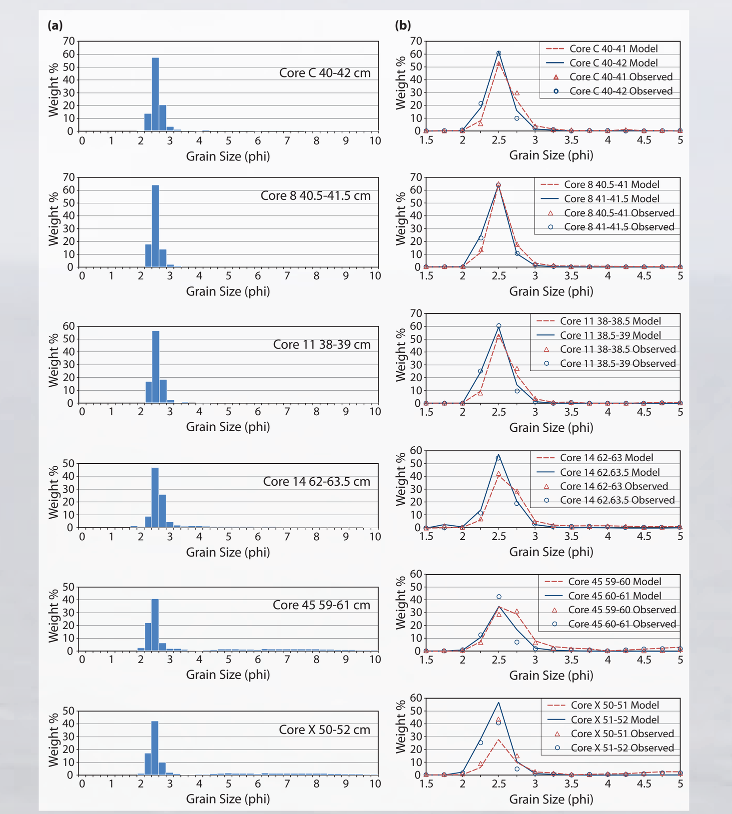


15. Average flow speed versus resuspension coefficient model parameter.

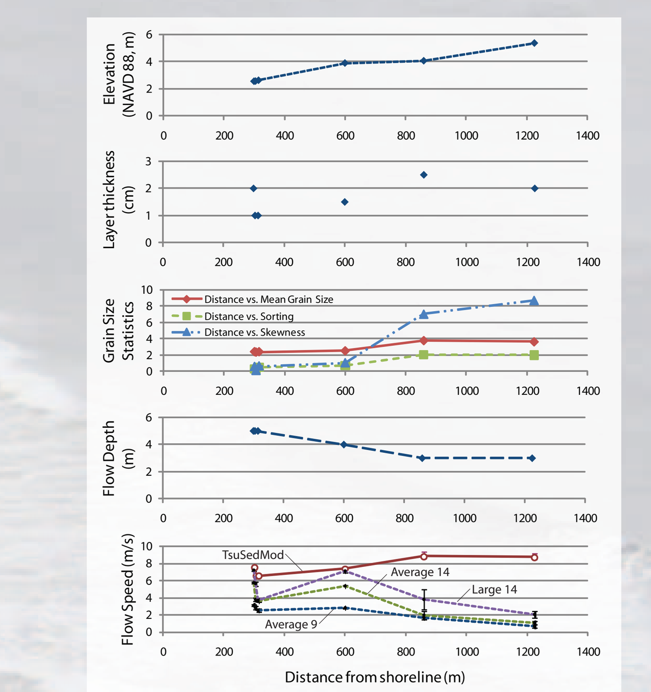


16. Relations between average flow speed and water depth for model runs of six sand samples. The model varies the roughness parameter to account for roughness created by saltating sediment.

RESULTS



12. Grain size analyses for selected sand layers from six core sites at Cannon Beach. (a) Bulk grain size distributions for multiple sand layers used as model inputs. (b) Comparison of sand particle size distribution measured in the lab (open symbols) to grain size distributions calculated by TsuSedMod (lines). Good matches between data suggest the sand layers settled from suspension.



17. Maximum tsunami flow speed calculated by sediment transport modeling versus numerical simulations of tsunami inundation. Red line shows flow speed calculated by TsuSedMod for sand layers at Cannon Beach. Error bars represent range of flow speeds for runs using flow depths of ±1 m. Dashed lines show maximum velocities predicted by three tsunami simulations for Cannon Beach (Priest et al., 2008).

FINDINGS. Using flow depths constrained by tsunami simulations for Cannon Beach, the sediment model calculated flow speeds of 6.5 to 7.6 m/s for sites within 0.3 km of the beach and higher flow speeds (7.4 to 8.8 m/s) for sites 0.6 to 1.2 km inland. The higher flow speeds calculated for the two sites furthest landward contrast with much lower maximum velocities (<3.8 m/s) predicted by the simulations. Grain size distributions of sand layers from the most distal sites are inconsistent with deposition from sediment falling out of suspension. We infer that rapid deceleration in tsunami flow caused convergences in sediment transport and, therefore, the higher flow speeds calculated by the sediment model may overestimate the actual wave velocity. Key recommendations for future research include investigations focusing on sites with low-relief and simple geography and multidisciplinary studies that couple tsunami sediment models with inundation models to more accurately estimate flow parameters from tsunami deposits.

ACKNOWLEDGMENTS. Bruce Jaffe (USGS) trained Witter in the use of the sediment transport model, TsuSedMod, and provided critical guidance throughout the entire modeling process. Without his open collaboration, this project would not have been possible. We are grateful to Mike Torresan, Gary Schneider and Angela Lam for training and assistance with particle size analysis at the USGS Menlo Park Sedimentology Laboratory. Yuki Sawai (Geological Survey of Japan), generously contributed analyses of fossil diatoms that aided in paleoecological interpretations. The USGS's National Earthquake Hazards Reduction Program (award number 07HQGR0089) supported this investigation. Technical report available at http://earthquake.usgs.gov/research/external/reports/07HQGR0089.pdf.