Bradley Lake Revisited: Sedimentary Evidence for Shorter Return Periods

Jason R. Patton [1], Chris Goldfinger [2]

1. Humboldt State University, Arcata, CA, USA, Jason.Patton@humboldt.edu 2. Oregon State University, Corvallis, OR, USA, gold@ceoas.oregonstate.edu

16-644

HUMBOLDT STATE UNIVERSITY

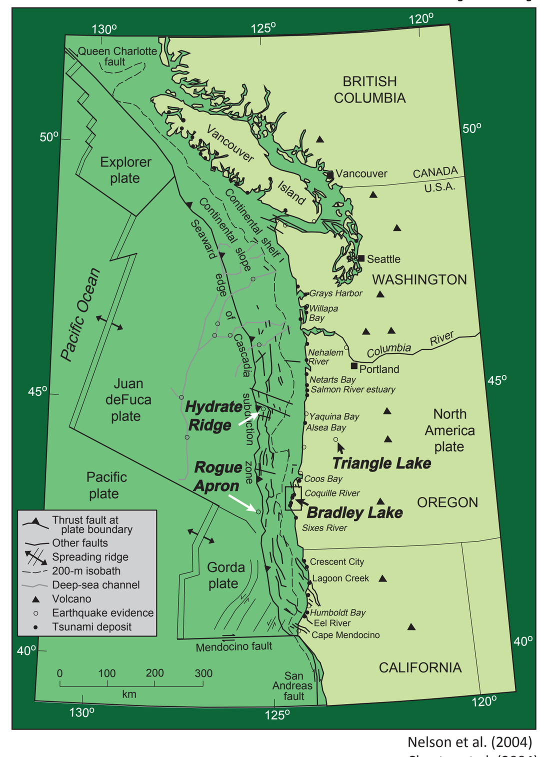
Oregon State University OSU College of Earth, Ocean, and Atmospheric Sciences

Recurrence of southern Cascadia subduction earthquakes is constrained by stratigraphic evidence onshore and offshore. The seismoturbidite record offshore has a higher frequency that the tsunami record in several locales. Bradley Lake contains the temporally longest and highest-frequency record of paleotsunamis along the Cascadia margin. Probably because tsunamis have a higher recording threshold in onshore lakes, the paleoseismologic record onshore most likely includes only a subset of the offshore paleoseismic record. Using additional geophysical methods, we are re-evaluating the stratigraphic record from Bradley Lake using sediment cores archived at the Oregon State University Core Facility. We are interested in whether additional analysis of these cores will yield a paleoseismic record equivalent to the offshore record at the same latitude.

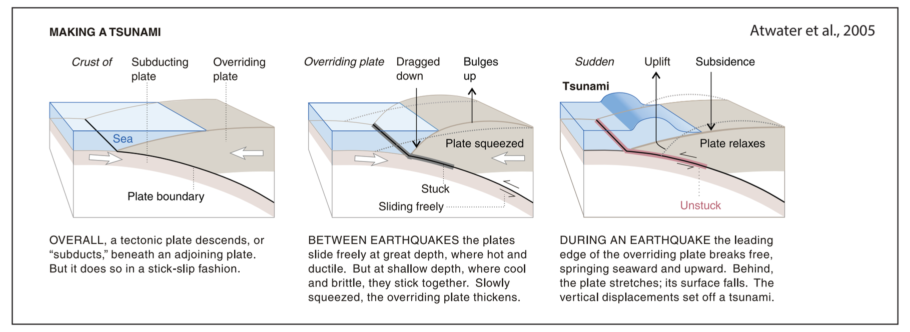
Using new CT data, we use the published sedimentary facies to characterize and interpret the stratigraphic record from the lake. Using these facies interpretations and CT density-based well log correlation techniques, we correlate strata between each core and compare our results with those from the original 2005 published results and offshore cores.

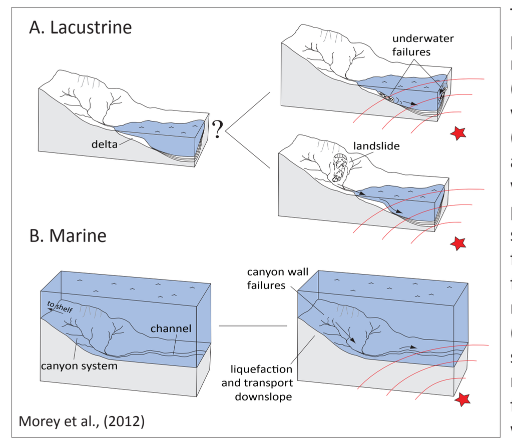
In addition to published facies associations, we interpret an upward fining facies, commonly directly below the tsunami sand sheets, but also found between the tsunami deposits. Many of these units appear to be paired with an organic rich facies as are the tsunami deposits. This facies may result from hyperpycnal flow, storm flow, sublacustrine seismo-turbidites, or inundation from tsunamis of magnitude smaller than that required to transport sediment from the dunes to the west. The return period of the additional lake turbidites and sand sheets is combined is ~ 280 years, consistent with the offshore turbidite record and with tsunami models published in 2014 showing that some of the southern-most Cascadia earthquakes are unlikely to produce tsunami deposits in the lake.

Cascadia subduction zone (CSZ)



The Explorer, Juan de Fuca, and Gorda plates are subducting beneath the North America plate. Paleoseismic core sites are plotted as circles. Rogue Apron, Triangle Lake, Hydrate Ridge, and Bradley Lake sites are designated.





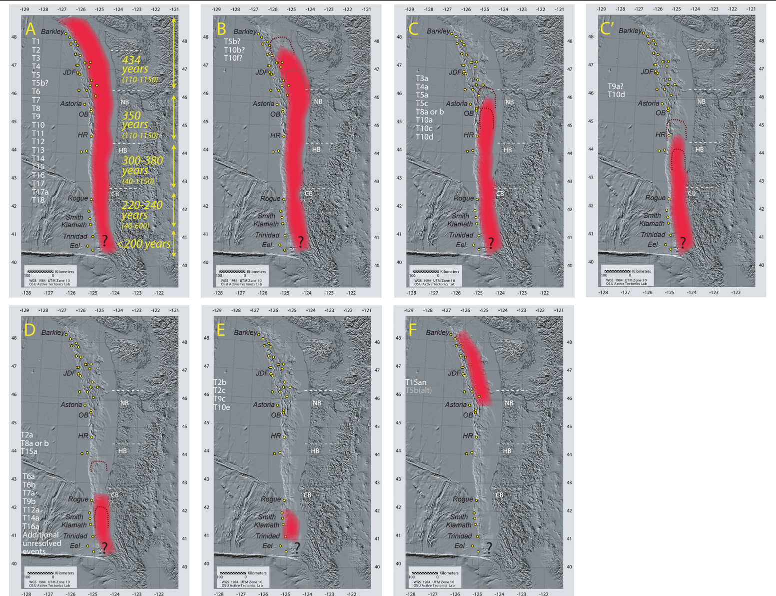
Two possible scenarios for mechanisms to explain seismogenic terrigenous layers in lake sediments.

(A) Shaking from a subduction zone earthquake will either dislodge material internal to the lake (above) or external to the lake (below). This creates a mixture denser than the surrounding water, which is then transported as a gravity flow producing a turbidite deposit with fining upward structure. Sediment transported into the lake from the drainage is unlikely to produce a gravity flow deposit and would have inverse then normal grading and thin from the source.

(B) An interpretation of the mechanism creating seismogenic turbidite deposits in marine sediments. Shaking dislodges and entrains sediment from shallower water creating density flows which are then transported to the abyssal plain via submarine channels and as sheet flows where sediments are deposited as fining upward sequences.

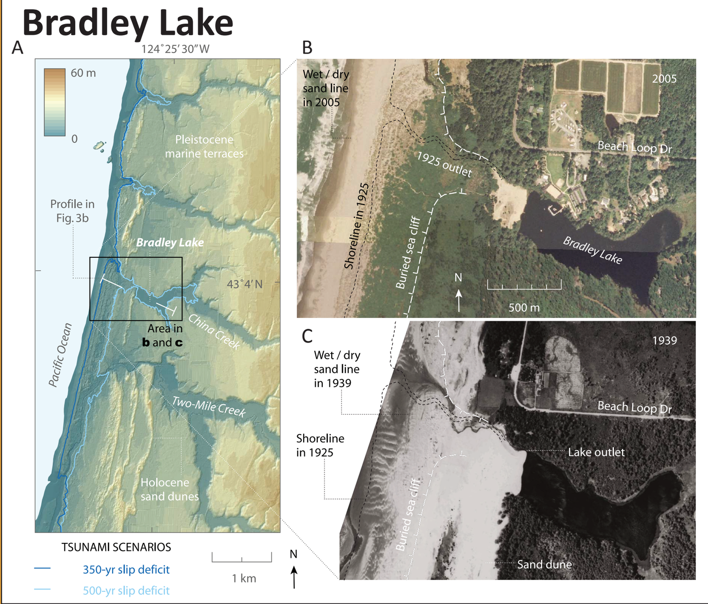
Earthquake Recurrence

Segmented rupture model, revised from Goldfinger et al. (2012). This model reflects revision of the northern boundaries of Segments B, C, and D, with subdivision to include C' and addition of segments E and F based on new core data (this study) and tsunami modeling at Bradley Lake (Priest et al. 2014). Marine core sites controlling rupture-length estimates are shown as yellow dots. Addition of several small ruptures in northern California are shown in Segment E, and a single northern rupture is identified off Washington in Segment F, both from Goldfinger et al., (2013). Preferred latitudinal limits shown with red shading. Estimated minimum and maximum limits shown with dashed lines. Widths and up and downdip limits approximate. Widths and up and downdip limits approximate. Paleoseismic segmentation shown also is compatible with latitudinal boundaries of episodic tremor and slip (ETS) events proposed for the downdip subduction interface (Brudzinski and Allen, 2007) and shown by white



Bradley Lake

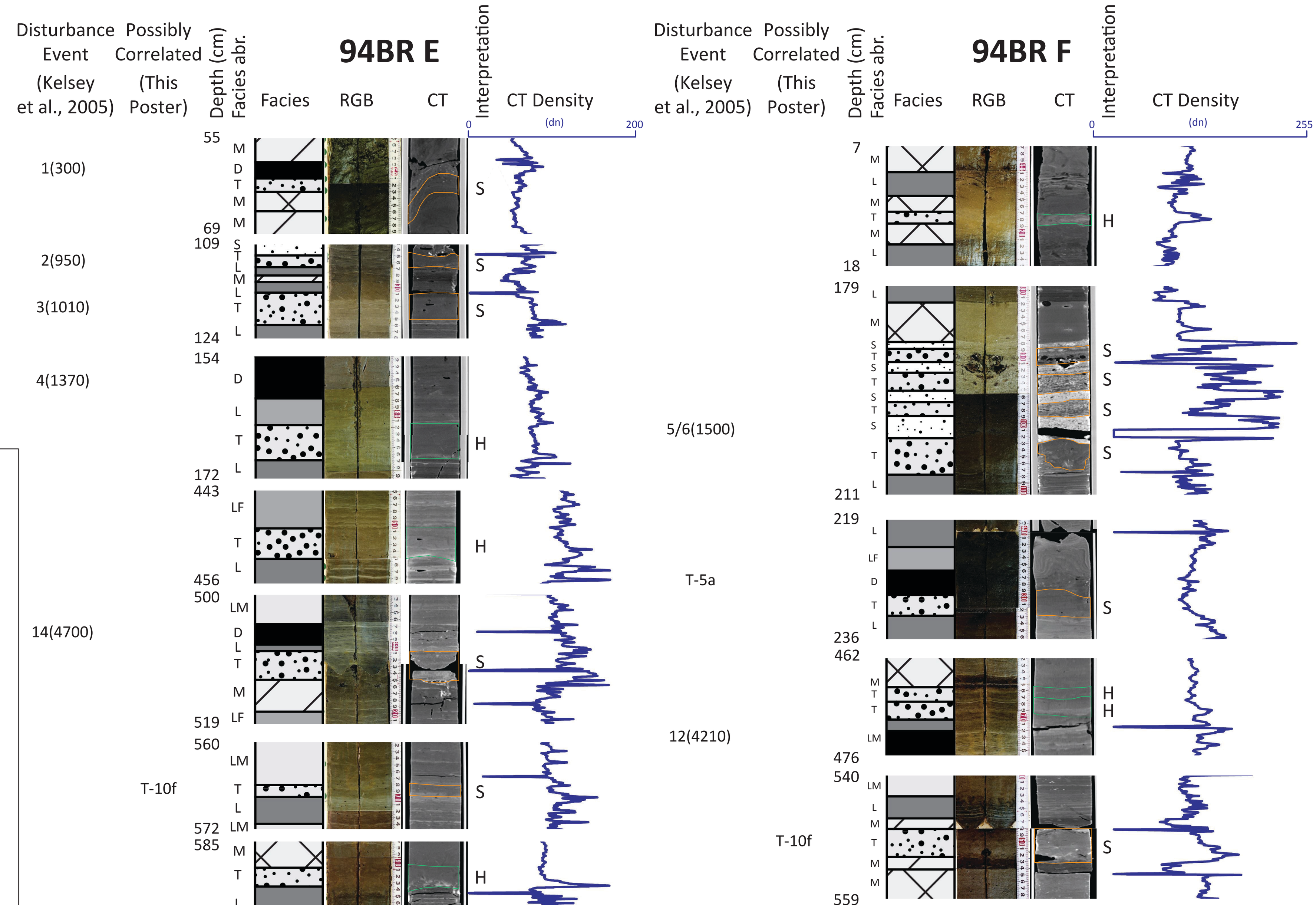
Witter et al. (2012)



"(A) Holocene sand dunes ornament broad Pleistocene marine terraces along the coast near Bradley Lake in southern Oregon. Blue lines show landward limit of simulated tsunami inundation using a model grid with historical topography. The lines depict inundation using earthquake scenarios with 11 and 16 m of fault slip, equivalent to 350 years (dark blue) and 500 years (light blue) of plate convergence, respectively.
(B) Evidence for recent seaward shift in shoreline position includes a wave eroded sea cliff mantled by dune sand and the shoreline in 1925 mapped by early coastal surveyors compared to the wet/dry sand line in the 2005 orthophoto.
(C) The shoreline probably reached its most landward position in 1939 when winter storms lowered the beach and shifted the shoreline landward of its position in 1925"

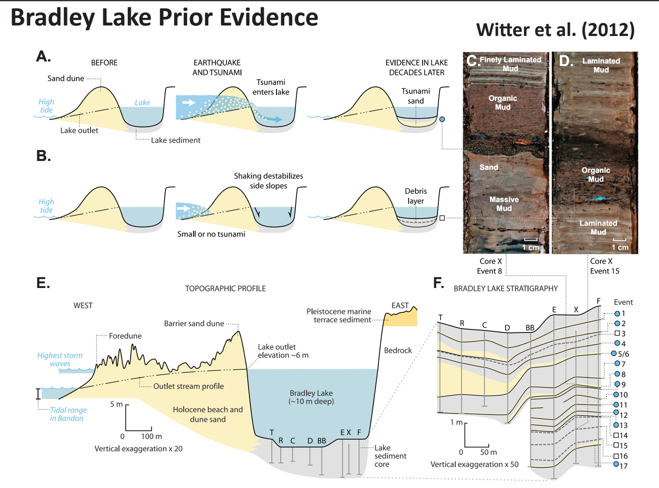
Upward Fining Facies: Bradley Lake

Examples of upward fining facies in Bradley Lake cores E & F. For each core, plotted left to right: Disturbance Event Number (Kelsey et al., 2005), Possibly Correlated T-# (Goldfinger et al., 2012; Witter et al., 2012), Depth Interval (cm), facies abbreviation, Modified Facies (Kelsey et al., 2005), Real Color Imagery (RGB), CT X-Ray imagery (CT), CT Density (dn) in dark blue. Upward fining facies deposits are interpreted as either hyperpycnite (light blue) or seismo-turbidite (orange).



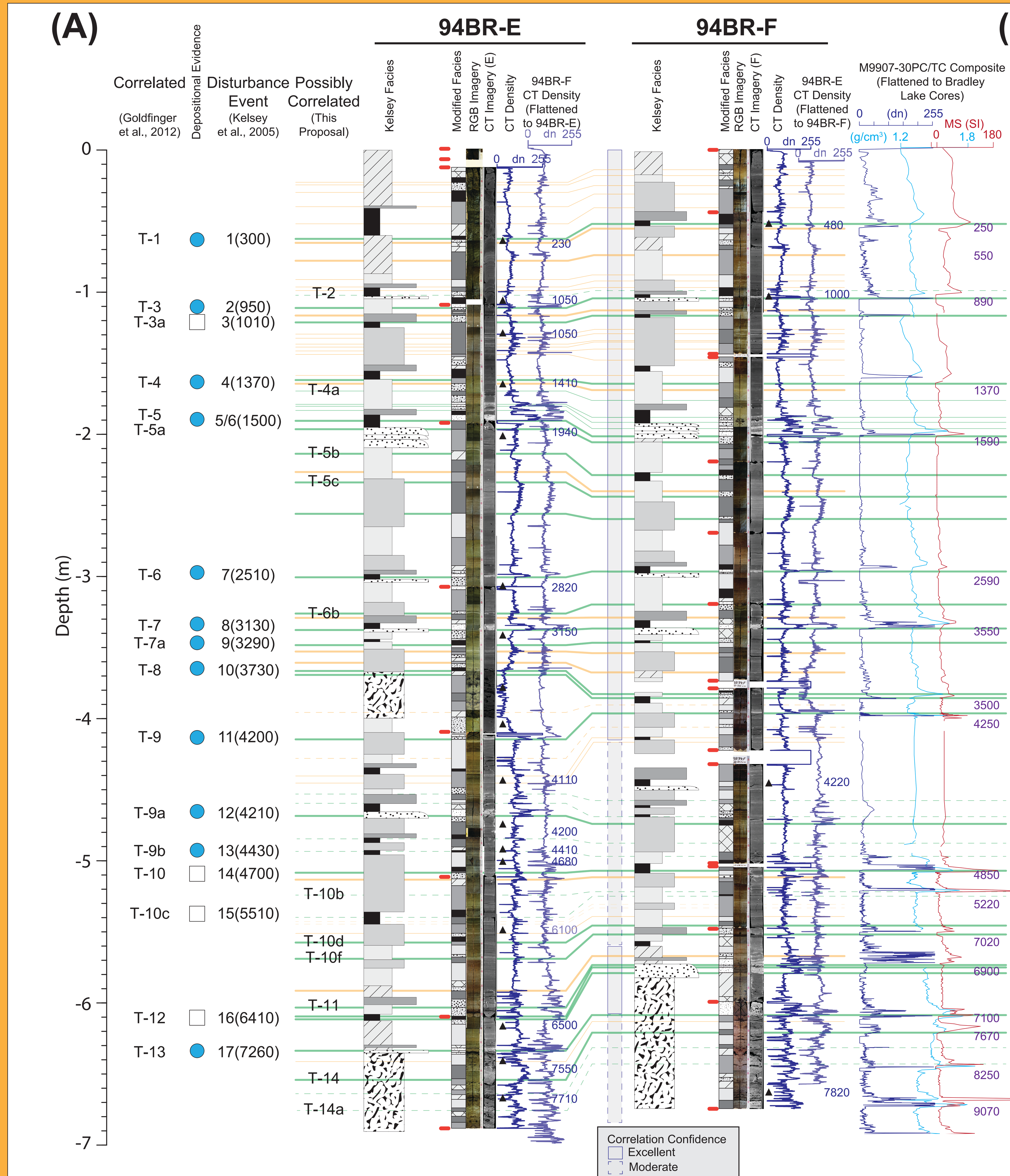
Bradley Lake Prior Evidence

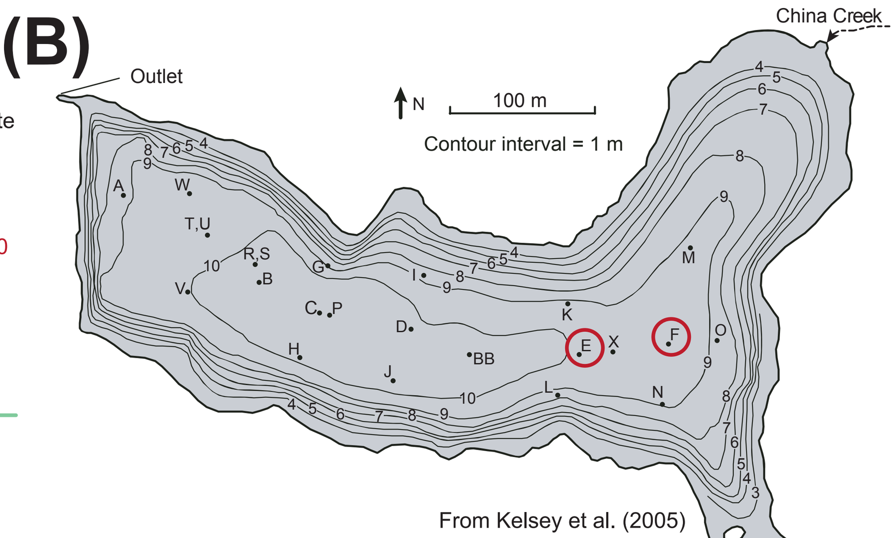
Witter et al. (2012)

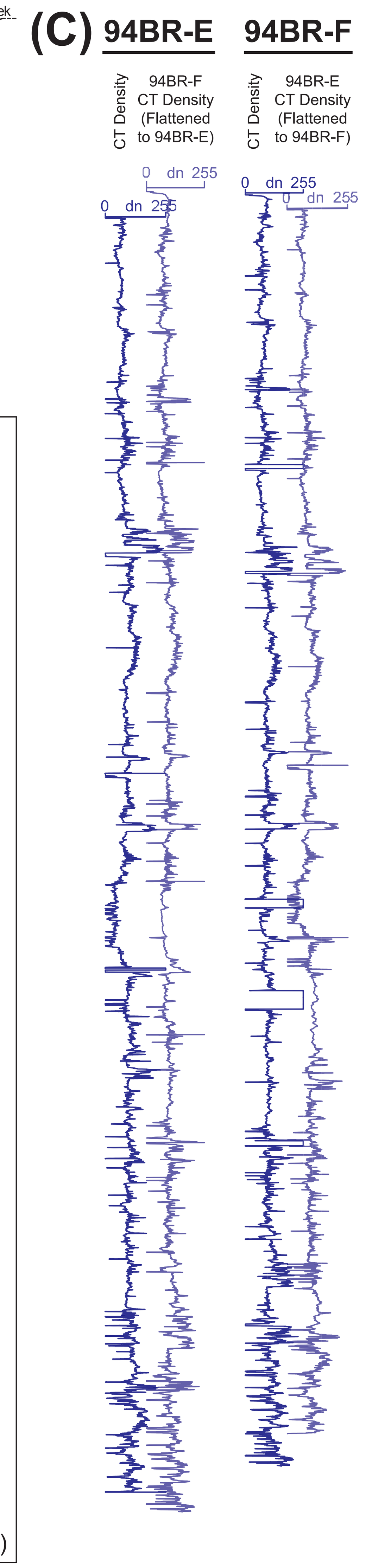


"Stratigraphic evidence of disturbances in Bradley Lake sedimentary record caused by great Cascadia earthquakes and their tsunamis (Kelsey et al., 2005). (a) Conceptual model of tsunami inundation in a coastal lake that leaves a sand deposit in the sedimentary record. (b) Debris layers lacking evidence for tsunami inundation consist of organic mud that interrupts normal laminated lake mud and are inferred to reflect earthquake shaking that destabilizes basin walls. (c) Photo showing sand deposit interpreted to reflect tsunami inundation. (d) Photo showing organic mud layer inferred to reflect seismic shaking. (e) Topographic profile of coast between the Pacific Ocean and Bradley Lake. (f) Stratigraphic profile of Bradley Lake sediment. Blue circles denote evidence for tsunami inundation. White squares denote evidence for strong shaking without tsunami overtopping the lake outlet."

Modified Facies (from Kelsey)	Possible Interpretation
S - Sand	Hyperpycnite? (H)
D - Debrite	Seismoturbidite? (S)
T - Upward Fining	
M - Massive - Low Density	
M - Massive - High Density	
LM - Massive with rare laminations	
LF - Faintly Laminated	
L - Laminated	







Correlation Tie Lines

- Non-Varve
- Varve or ?
- More Certain
- Less Certain

Depositional Evidence (Witter et al., 2012)

- Tsunami Inundation
- Ground Shaking

Kelsey et al. (2005) Facies

First facies association
- Laminated mud
- Faintly laminated mud
- Massive mud

Second facies association
- Finely laminated mud
- Debris-rich and massive organic-rich mud
- Sand or muddy sand
- Rip-up clasts in sand

- Freshwater marsh sediment

Modified Facies (from Kelsey)

- S - Sand
- D - Debrite
- T - Upward Fining
- M - Massive - Low Density
- M - Massive - High Density
- LM - Massive with rare laminations
- LF - Faintly Laminated
- L - Laminated

Core Section Break

T - # T number (Goldfinger et al., 2012)

X(YYYY) Disturbance Event # and ^{14}C age (Calendar yr B.P. Goldfinger et al., 2012)

▲ ^{14}C Sample Location (Kelsey et al., 2005)

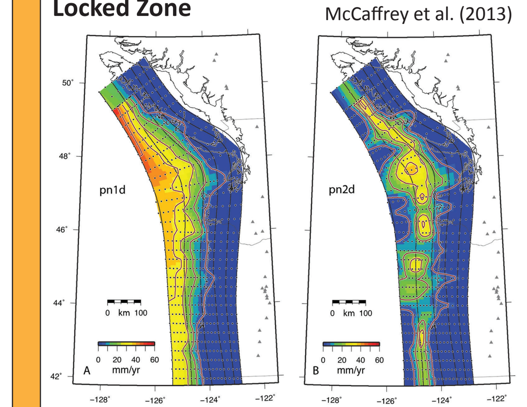
2820 ^{14}C age (Calendar yr B.P., Kelsey et al., 2005)

3320 ^{14}C age (Calendar yr B.P., Goldfinger et al., 2012)

Tentative correlation diagram comparing Bradley Lake cores BR94E, BR94F, and offshore composite core 30PC/TC. (A) Bradley Lake cores E and F with data plotted left to right: Kelsey Facies (Kelsey et al., 2005), Modified Facies (this proposal), RGB Imagery, CT Imagery, CT Density, and CT Density from the adjacent core. CT Density data from adjacent core are "flattened" to correlated stratigraphic horizons. On left is an accounting of which published sedimentary deposits are correlated in these cores (T-# are turbidites, Goldfinger et al., 2012; DE are disturbance events, Kelsey et al., 2005). The form of depositional evidence reported by Witter et al. (2012) is plotted as blue circles and white squares. Correlation tie lines have symbols related to type of deposit and relative confidence of the correlation (see legend). On right are core geophysical data (CT density and magnetic susceptibility) from core 30PC/TC flattened to core F. (B) Map of Bradley Lake with 1 meter depth contours and core locations plotted as dots (Kelsey et al., 2005). (C) Flattened CT density data for cores E and F.

Locked Zone

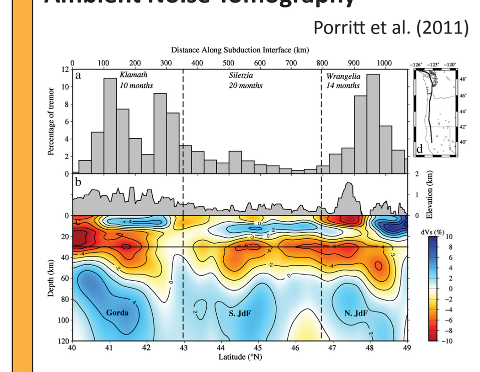
McCaffrey et al. (2013)



"Locking model results. Colors and contours are of the slip deficit rate, in mm/yr. Slip deficit rate contours are 5, 15, 25, 35, and 45 mm/yr. (A) Tapered transition zone of variable width, depth, and taper but locked to trench (pn1d). (B) Gaussian distribution of locking with depth (pn2d)."

Ambient Noise Tomography

Porritt et al. (2011)

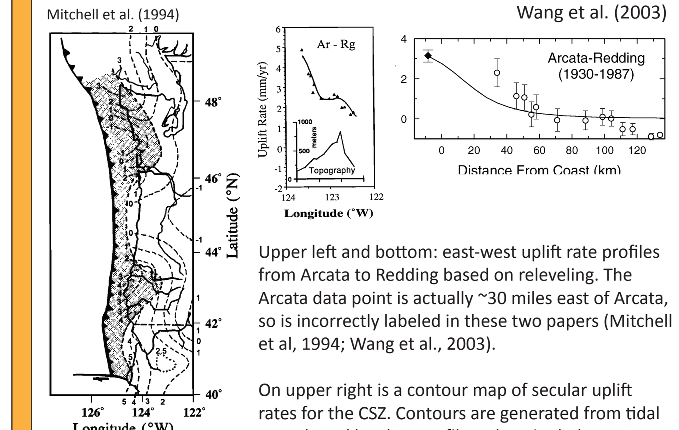


Gorda plate dips to the north possibly due to Sierra Block migration and the backstop formed by the Klamath mountains. These and other factors may contribute to a locked zone that is not entirely depth dependent (as in Oregon and Washington).

Tide Gages and Level Lines

Mitchell et al. (1994)

Wang et al. (2003)

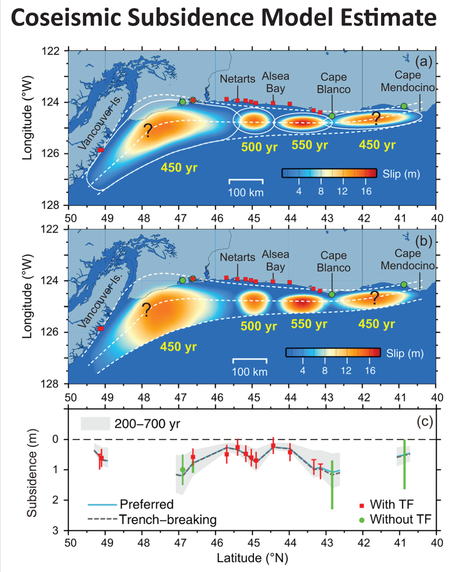


Upper left and bottom: east-west uplift rate profiles from Arcata to Redding based on releveling. The Arcata data point is actually ~30 miles east of Arcata, so is incorrectly labeled in these two papers (Mitchell et al, 1994; Wang et al., 2003).

On upper right is a contour map of secular uplift rates for the CSZ. Contours are generated from tidal records and leveling profiles. The stippled area is an interpretation of the region of elastic strain accumulation, assuming that the most rapid uplift at the surface approximately overlies the down-dip edge of the portion of the subduction zone interface.

Coseismic Subsidence Model Estimate

Wang et al. (2013)



"The preferred model and a trench-breaking rupture model for the 1700 Cascadia earthquake. (a) Slip distribution of the preferred model consisting of high-moment slip patches delineated bywhite lines. Peak slip (warmest color) labeled for each patch ismeasured in terms of equivalent time of slip deficit accumulation. The white dashed lines are represent previously used down-dip limits of uniform coseismic slip zone and linear transition zone, corresponding roughly to the 350°C and 450°C isotherms, respectively, defined by Wang et al. (2003). (b) Slip distribution of the trench-breaking rupture model. (c) Model-predicted coseismic subsidence in comparison with paleoseismic estimates. The upper and lower bounds of the shaded area are obtained by assigning 200 year and 700 year slips, respectively, to all the four patches of the preferred model."

References

Atwater, B. F., Satoko, M.-R., Satake, K., Yoshinobu, T., Kazue, U., and Yamaguchi, D. K., 2005, The Orphan Tsunami of 1700, USGS Professional Paper #1707: Reston, Virginia, U.S. Geological Survey, p. 144.

Brudinski, M. R., and Allen, R. A., 2007, Segmentation in episodic tremor and slip all along Cascadia: Geology, v. 35, no. 10, p. 907-910.

Chaytor, J. D., Goldfinger, C., Dziak, R. P., and Fox, C. G., 2004, Active deformation of the Gorda plate: Constraining deformation models with new geophysical data: Geology, v. 32, no. 4, p. 353-356.

Goldfinger, C., Morey, A. E., Black, B., Beeson, J. W., Nelson, C. H., and Patton, J., 2013, Spatially limited mud turbidites on the Cascadia margin: segmented earthquake ruptures?: Natural Hazards Earth System Sciences, v. 13, p. 2109-2146.

Goldfinger, C., Nelson, C. H., Morey, A., Johnson, J. E., Gutierrez-Pastor, J., Eriksson, A. T., Karabanov, E., Patton, J., Gracia, E., Enkin, R., Dallimore, A., Dunhill, G., and Vallier, T., 2012, Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone: U.S. Geological Survey.

Kelsey, H. M., Nelson, A. R., Hemphill-Haley, E., and Witter, R. C., 2005, Tsunami history of an Oregon coastal lake reveals a 4600 yr record of great earthquakes on the Cascadia subduction zone: GSA Bulletin, v. 117, no. 7-8, p. 1009-1032.

McCaffrey, R., King, R. W., Payne, S. J., and Lancaster, M., 2013, Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities: Journal of Geophysical Research, v. 118, no. doi:10.1029/2012JB009473, p. 15.

Mitchell, C. E., Vincent, P., Weldon II, R. J., and Richards, M. A., 1994, Present-day vertical deformation of the Cascadia margin, Pacific northwest, U.S.A.: Journal of Geophysical Research, v. 99, p. 12,257-212,277.

Morey, A. E. G., C., Briles, C. E., Gavin, D. G., Colombaroli, D., and Kusler, J. E., 2013, Are great Cascadia earthquakes recorded in the sedimentary records from small forearc lakes?: natural Hazards and Earth System Sciences, v. 13, p. 2441-2463.

Nelson, A. R., Asquith, A. C., and Grant, W. C., 2004, Great earthquakes and tsunamis of the past 2000 years at the Salmon River Estuary, central Oregon coast, USA: Bulletin of the Seismological Society of America, v. 94, no. 4, p. 1276-1292.

Porritt, R. W., Allen, R. M., Boyarko, D. C., and Brudzinski, M. R., 2011, Investigation of Cascadia segmentation with ambient noise tomography: Earth and Planetary Science Letters, v. 309, p. 67-76.

Wang, K., Wells, R., Mazzotti, S., Hyndman, R. D., and Sagiya, T., 2003, A revised dislocation model of interseismic deformation of the Cascadia subduction zone Journal of Geophysical Research, B, Solid Earth and Planets v. 108, no. 1.

Wang, P., Englehart, S. E., Wang, K., Hawkes, A., Horton, B. J., Nelson, A. R., and Witter, R. C., 2013, Heterogeneous rupture in the great Cascadia earthquake of 1700 inferred from coastal subsidence estimates: Journal of Geophysical Research, v. 118, no. doi:10.1002/jgrb.50101, p. 2460-2473.

Witter, R. C., Zhang, Y., Wang, K., Goldfinger, C., Priest, G., and Allan, J. C., 2012, Coseismic slip on the southern Cascadia megathrust implied by tsunami deposits in an Oregon lake and earthquake-triggered marine turbidites: Journal of Geophysical Research, v. 117, p. 17.