Mismatch Between Interseismic Ground Deformation and Paleoseismic/Paleogeodetic Observations, Humboldt Bay, Northern California, Cascadia Subduction Zone

15-485

Jason R. Patton[1,2], Tom H. Leroy[2,3], Todd Williams[2], Robert C. McPherson[1], Jeffrey K. Anderson[4], Reed Burgette[5], Mark Hemphill-Haley[1], Ray Weldon[6], Gary Carver[1], and Harvey M. Kelsey[1]

1. Humboldt State University, Dept. of Geology, 2. Cascadia GeoSciences, 3. Pacific Watershed Associates, 4. Northern Hydrology and Engineering, 5. New Mexico State University, 6. University of Oregon

Abstract

Observations made by Plafker in Chile (1960) and Alaska (1964) show that vertical deformation during earthquakes is generally opposite in sense of motion compared to interseismic deformation. This elastic rebound theory drives estimates of potential coseismic deformation on the Cascadia subduction zone (CSZ). Similar to other coastal marshes along the CSZ, paleoseismic investigations around Humboldt Bay reveal evidence of coseismic subsidence for the past 4 ka.

Tide gage data obtained from NOAA tide gages, as well as 'campaign' style tide gages, are used to infer interseismic ground deformation. Tide gage data from Crescent City and Humboldt Bay are compared to each other and also compared to estimates of eustatic sea-level rise to estimate rates of land-level change. Earthscope and USGS GPS permanent site data are also used to evaluate vertical interseismic deformation in this region. These rates of land-level change are then compared to paleoseismic proxies for vertical land-level change.

Cores collected for master's theses research at Humboldt State University were used to compile an earthquake history for the Humboldt Bay region. Some cores in Mad River and Hookton sloughs were used to evaluate magnitudes of coseismic subsidence by comparing diatom and foraminiferid assemblages associated with lithologic contacts (paleogeodesy). Minimum estimates of paleosubsidence for earthquakes range from 0.3 to 2.6 meters.

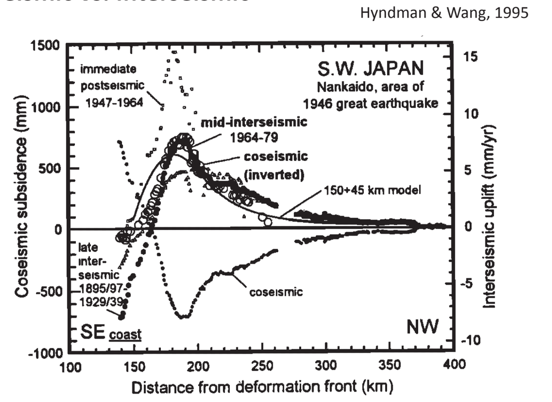
Subtracting eustatic sea-level rise (~2.3 mm/yr, 1977-2010) from Crescent City (CC) and North Spit (NS) relative sea-level rates reveals that CC is uplifting at ~3mm/yr and NS is subsiding at ~2.5 mm/yr. GPS vertical deformation reveals similar rates of ~3 mm/yr of uplift and ~2 mm/yr of subsidence in these two locations. GPS based subsidence rates show a gradient of subsidence between Trinidad (in the north) to Cape Mendocino (in the south).

The spatial region of ongoing subsidence reveals the depth of locking of the CSZ fault (differently from previous studies, like Wang et al., 2003), but Humboldt Bay has regions that subsided coseismically that are also subsiding interseismically. The sense of motion mismatch is probably due to at least (1) upper plate deformation (co- or inter-seismic) and/or (2) some process that is inconsistent with existing subduction zone models. Since the interseismic deformation is found across multiple upper-plate structures it is probably not influenced by those faults. However, coseismic motion on these faults cannot be ruled out.

Future geodetic measurements may further reveal the region of locking on the megathrust (and provide a measure for natural hazards), but paleoseismic records and their paleogeodetic record likely better reveal the catastrophic changes we expect in the future as they are measures of coseismic changes.

Coseismic vs. Interseismic

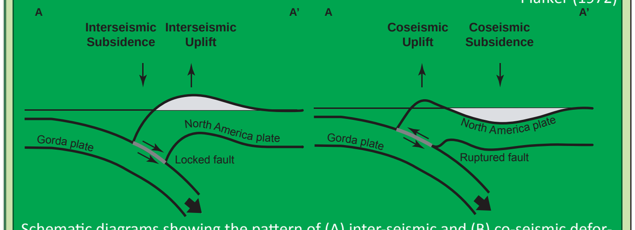
Hyndman & Wang, 1995



Repeated leveling results across the Nankai margin of southwestern Japan giving the coseismic subsidence (small solid dots), coseismic subsidence inverted (large solid dots), and the interseismic uplift rate for three intervals. The interseismic vertical axis is scaled relative to the coseismic axis by time interval between great earthquakes. Note the agreement in the location of the peaks for the coseismic (inverted) and the interseismic profiles, especially for the coseismic profile.

Vertical Motion: Coseismic vs. Interseismic

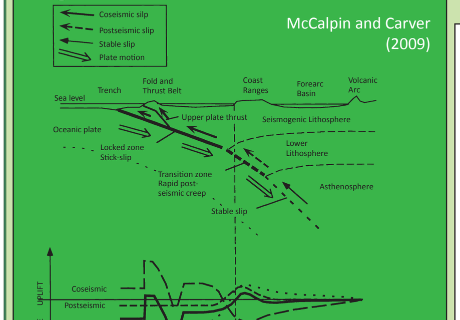
Plafker (1972)



Schematic diagrams showing the pattern of (A) inter-seismic and (B) co-seismic deformation associated with a subduction zone earthquake during an earthquake deformation cycle. Adapted from Plafker (1972) to reflect the spatial pattern of tectonic deformation during the earthquake cycle in Cascadia.

Megathrust and Crustal Relations

McCalpin and Carver (2009)



Cascadia subduction zone

Chaytor et al. (2004)
Nelson et al. (2004)

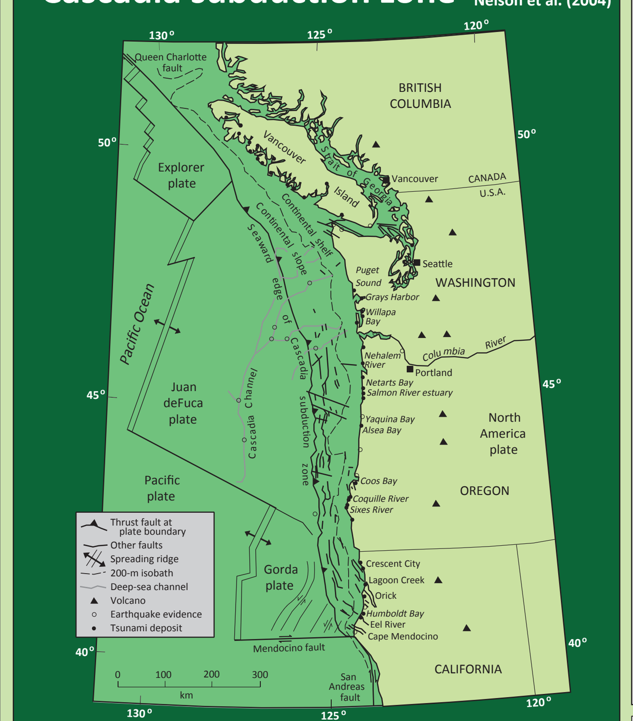
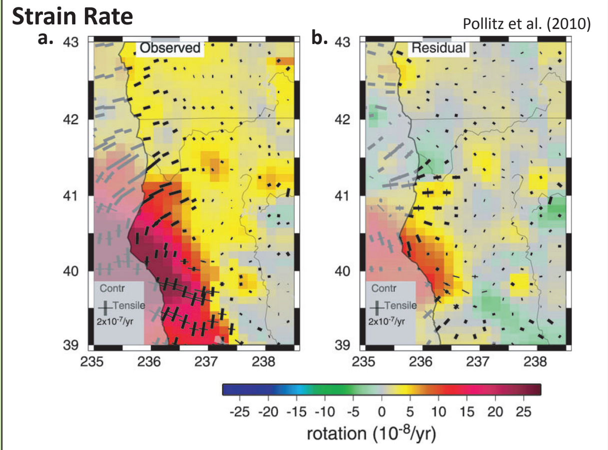


Plate configuration for the Cascadia subduction zone (CSZ). Juan de Fuca and Gorda plates are subducting northeastwardly oblique beneath the North America plate at ~36 mm/yr in the Humboldt Bay region. Paleoseismic core sites (marine and terrestrial) are plotted as circles.

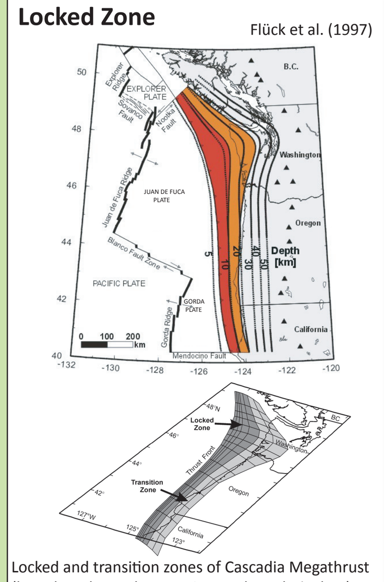
Strain Rate

Pollitz et al. (2010)



Locked Zone

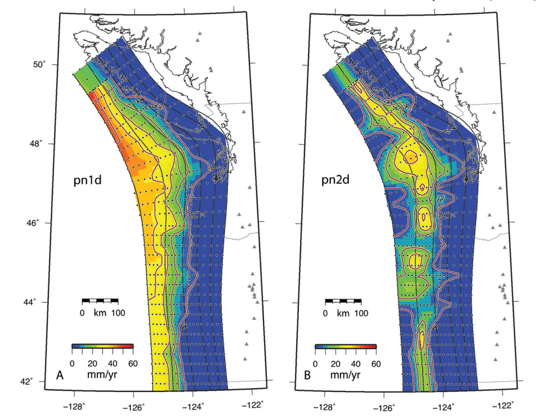
Flück et al. (1997)



Locked and transition zones of Cascadia Megathrust (based on thermal constraints and geodetic data) used in elastic dislocation model.

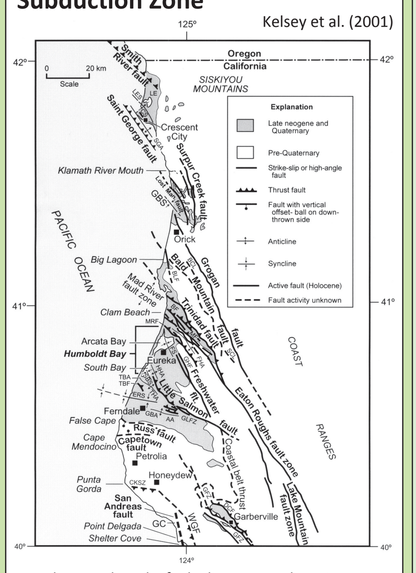
Locked Zone

McCaffrey et al. (2013)



Active Faulting Associated with the Southern Cascadia Subduction Zone

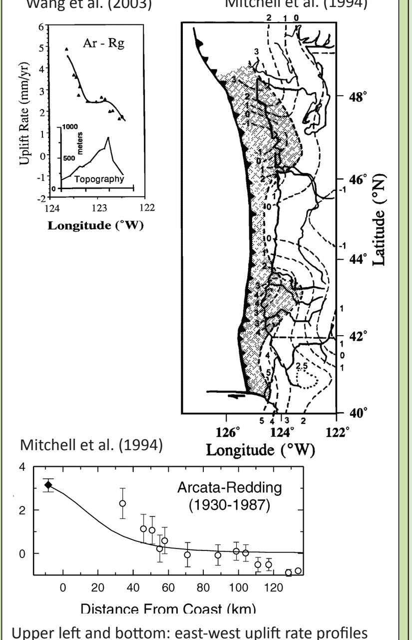
Kelsey et al. (2001)



Based on earthquake fault slip-rates and marine terrace uplift-rates, crustal faults in the North America plate may account for between 20% and 30% of the plate convergence in the Humboldt Bay region.

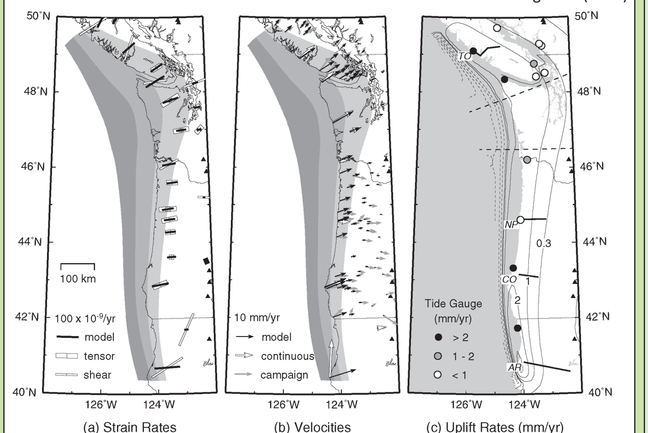
Tide Gages and Level Lines

Wang et al. (2003) Mitchell et al. (1994)



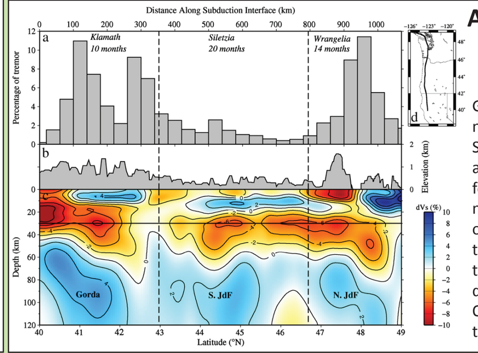
Locked and Transition Zones

Wang et al. (2003)

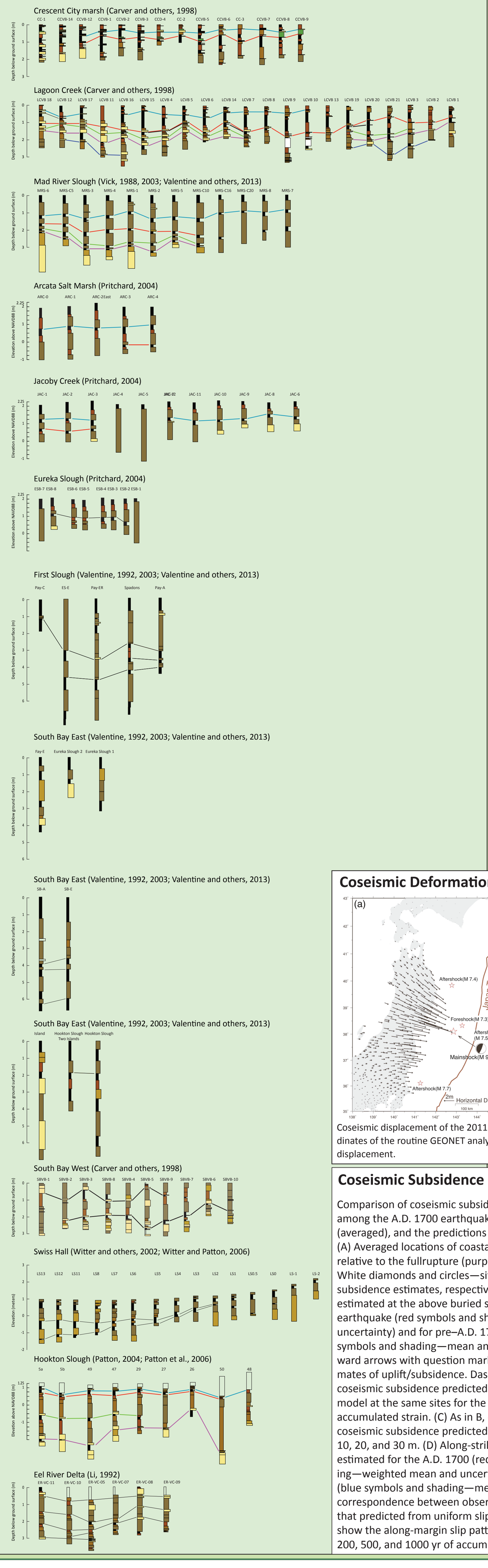


Ambient Noise Tomography

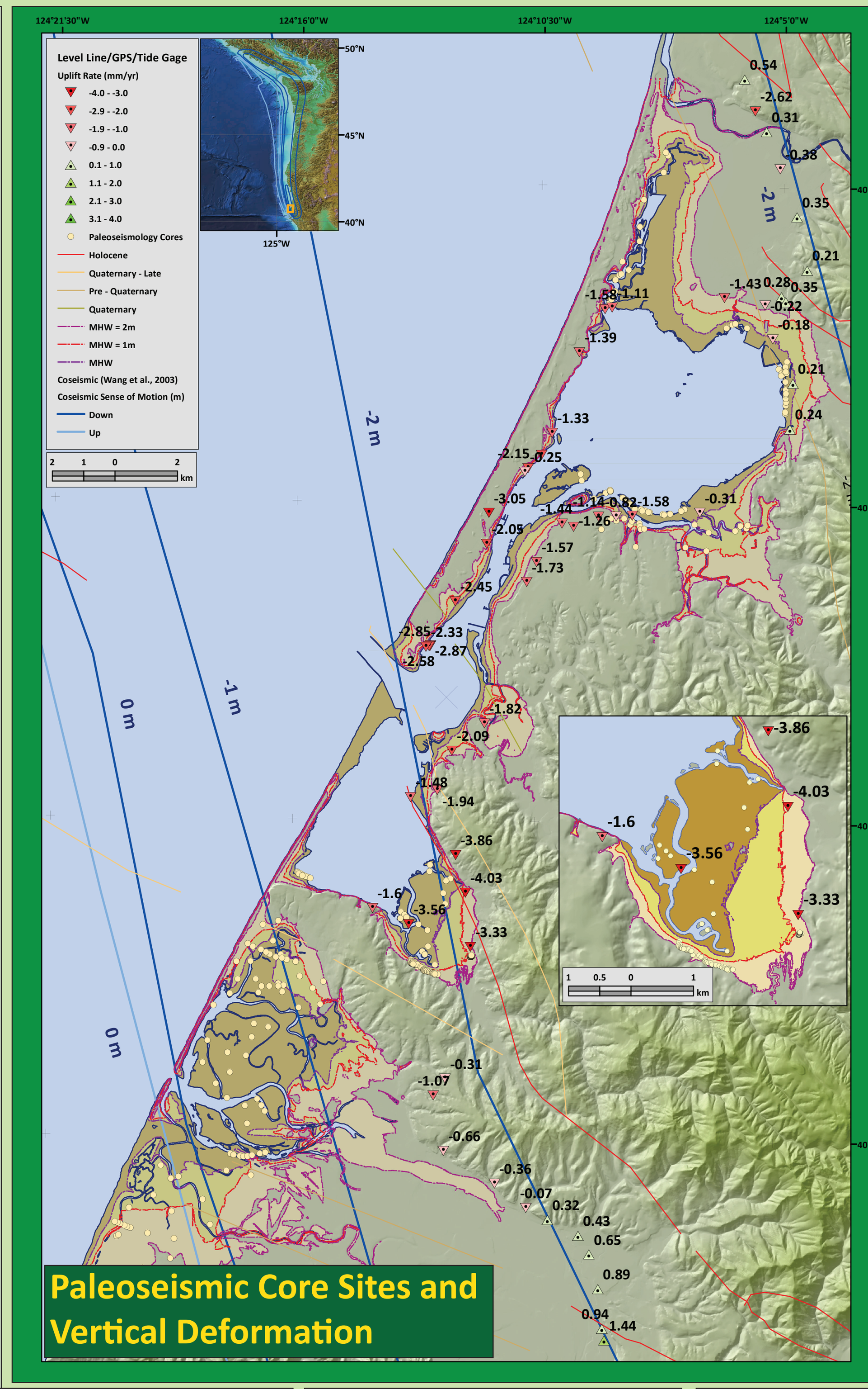
Porritt et al. (2011)



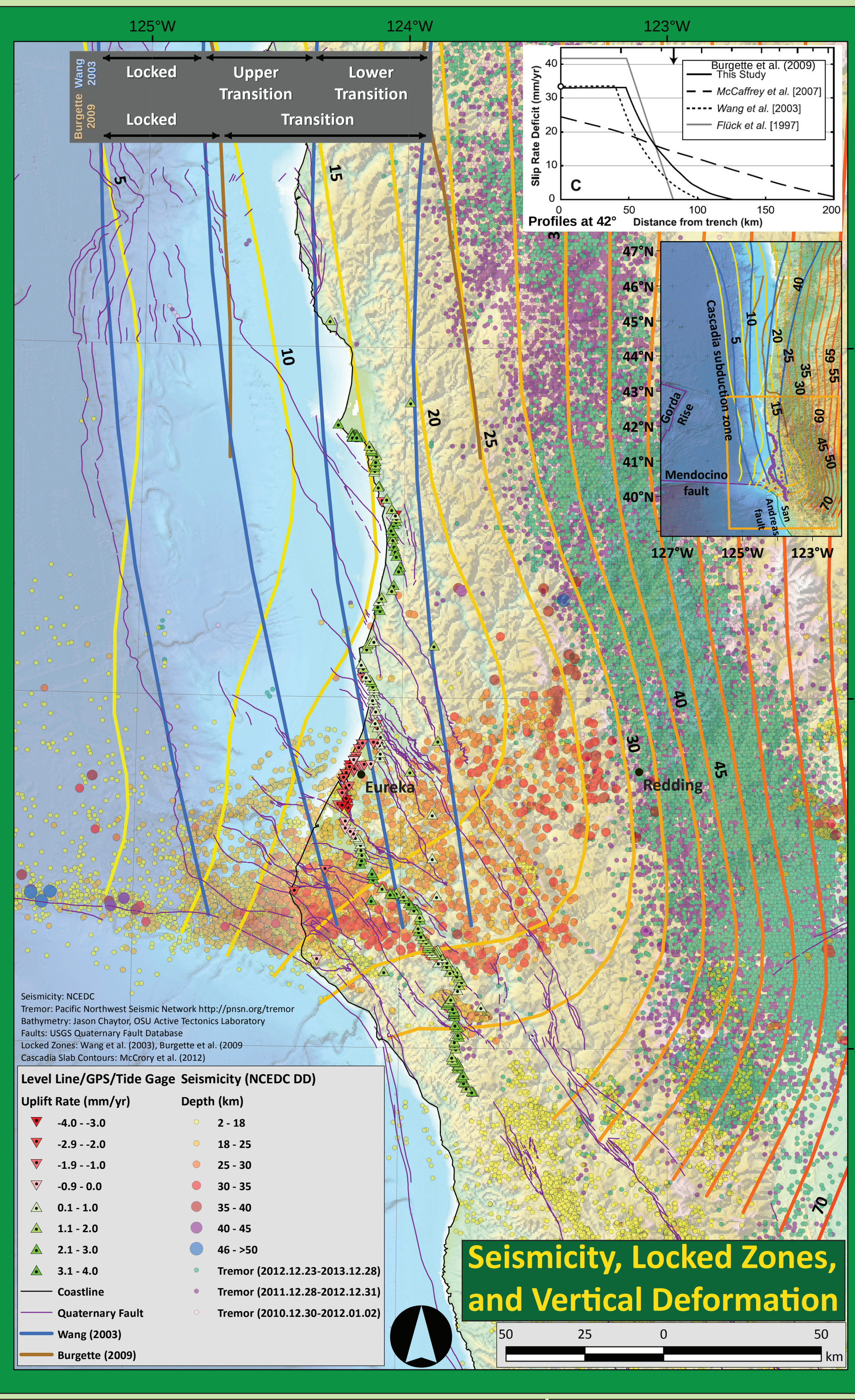
Sedimentary Record



Paleoseismic Core Sites and Vertical Deformation

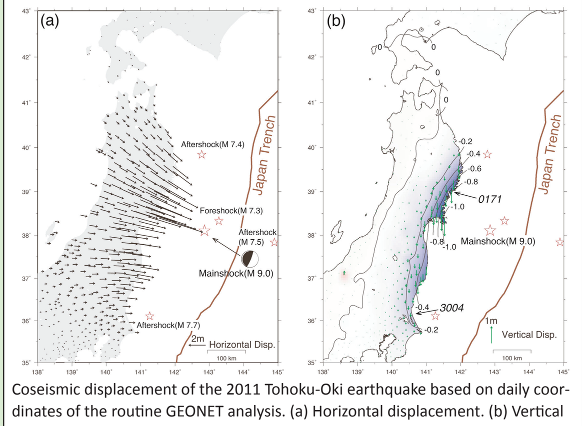


Seismicity, Locked Zones, and Vertical Deformation



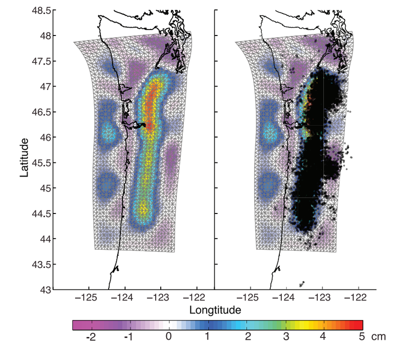
Coseismic Deformation

Nishimura et al., 2011



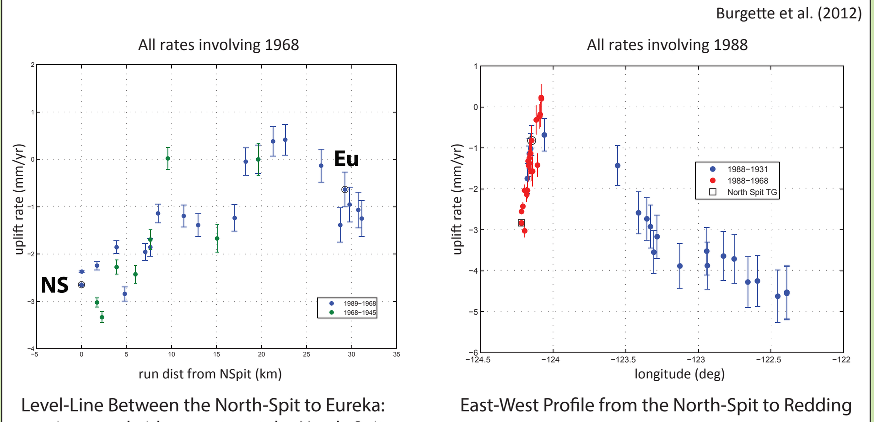
ETS Slip Aug. 2009

Barlow et al. (2011)



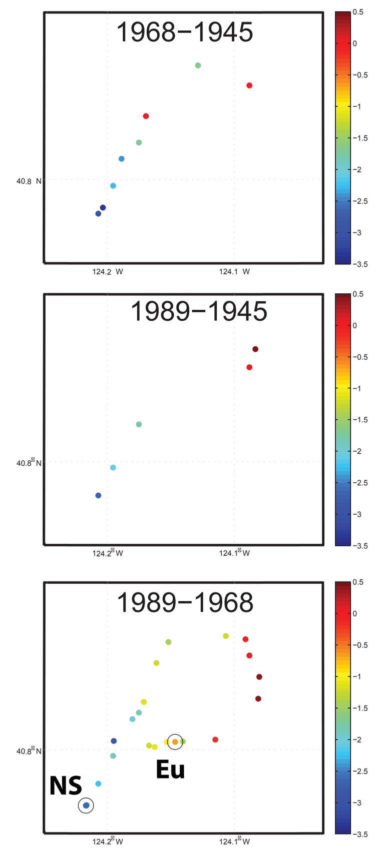
Interseismic Vertical Deformation: Level Lines

Burgette et al. (2012)



Interseismic Vertical Deformation: Level Lines Around Humboldt Bay

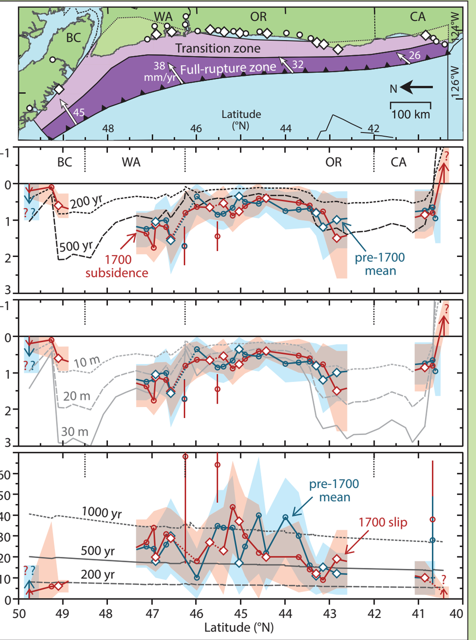
Burgette et al (2012)



Maximum subsidence rates in the west

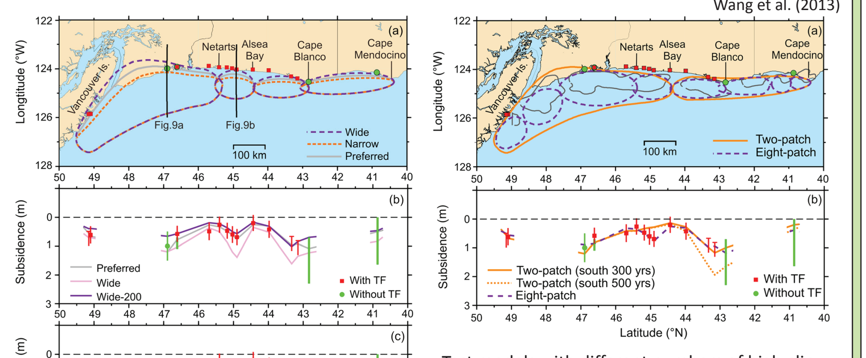
Coseismic Subsidence Model Estimates

Leonard et al. (2010)

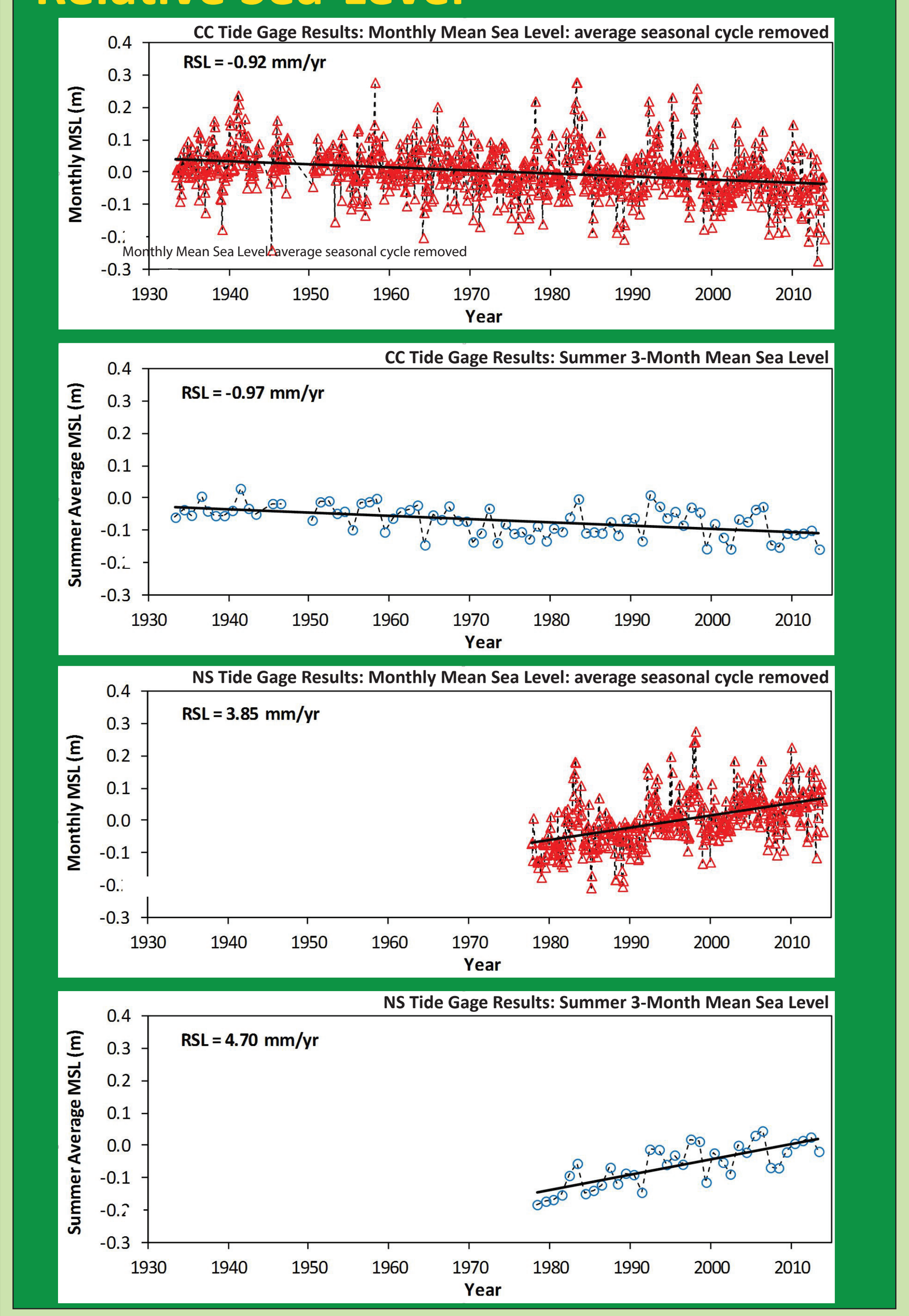


Coseismic Subsidence Model Estimates

Wang et al. (2013)



Relative Sea-Level



Relative Sea-Level

Tide Station	Tide Analysis	RSL or VLM (mm/yr)	N	R^2	RMSE (m)	CI (mm/yr)
Crescent City	Monthly with average seasonal cycle removed	-0.92	905	0.083	0.070	± 0.20
Crescent City	Summer 3 month average	-0.97	77	0.244	0.039	±0.39
North Spit	Monthly with average seasonal cycle removed	3.85	429	0.263	0.067	±0.61
North Spit	Summer 3 month average	4.70	36	0.587	0.041	±1.38
North Spit minus Crescent City	Monthly with average seasonal cycle removed	5.75	428	0.909	0.019	±0.17
North Spit minus Crescent City	Summer 3 month average	5.58	36	0.942	0.014	±0.48

[1]RSL = relative sea level, N = count, R^2 = R squared of regression, RMSE = root mean square error of residual, and CI = 95% confidence interval assuming independent observations.

Relative Sea-Level and Land-Level

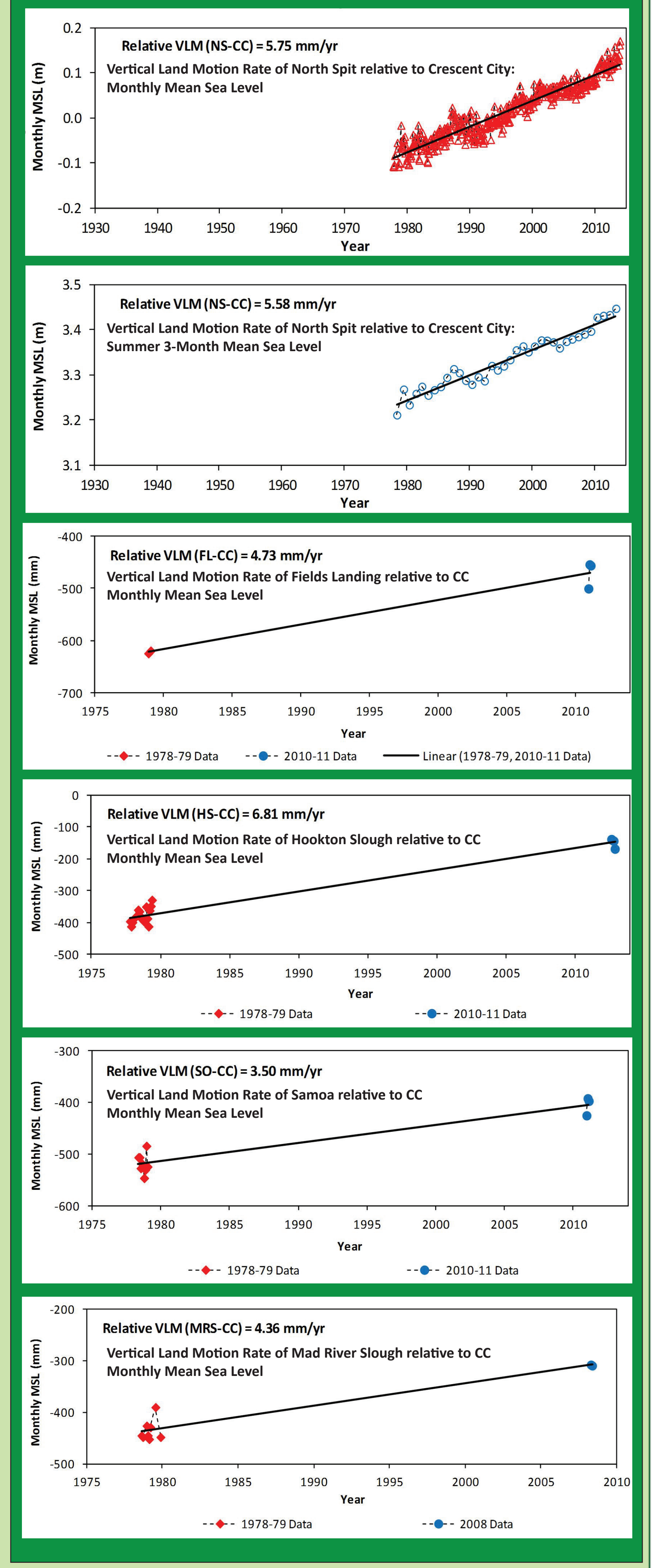
Tide Station (TS)	SLR and VLM Rates (mm/yr)			
	ReSL	RSL	TS - CC	VLM
Crescent City (CC)	2.28	-0.97		3.25
North Spit (NS)	2.28	4.61	5.58	-2.33
Mad River Slough (MRS)	2.28	3.39	4.36	-1.11
Samoa (SO)	2.28	2.53	3.50	-0.25
Fields Landing (FL)	2.28	3.76	4.73	-1.48
Hookton Slough (HS)	2.28	5.84	6.81	-3.56

[1]ReSL = regional sea level, RSL = relative sea level, and VLM = vertical land motion.

REFERENCES

Burgette, R. J., Weldon II, R. J., and Schmidt, D. A., 2009, Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone: Journal of Geophysical Research, v. 114, no. B01408, p. 24.
Burgette, R. J., Weldon II, R. J., Schmidt, D. A., and Williams, T. B., 2012, Constraints on interseismic locking along the southern Cascadia subduction zone from historic and recent leveling and sea level observations: EOS Trans. AGU.
Carver, G. A., Abramson, H. F., Garrison-Laney, C. E., and Leroy, T. H., 1998, Investigation of Paleotsunami Evidence Along the North Coast of California.
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.
Flück, P., Hyndman, R. D., and Wang, K., 1997, Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone Journal of Geophysical Research, B, Solid Earth and Planets v. 102, no. 9, p. 20,539-520,550.
Hyndman, R. D., and Wang, K., 1995, The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime: Journal of Geophysical Research, v. 100, no. B11, p. 22,133-122,154.
Kelsey, H. M., 2001, Active faulting associated with the southern Cascadia subduction zone in Northern California, Engineering Geology Practice in northern California, p. 259-274.
Leonard, L. J., Currie, C. A., Mazzotti, S., and Hyndman, R. D., 2010, Rupture area and displacement of past Cascadia great earthquakes from coastal coseismic subsidence GSA Bulletin, v. 122, no. 11/12, p. 1951-1968.
Li, W., 1992, Evidence for the late Holocene coseismic subsidence in the Lower Eel River valley, Humboldt county, Northern California: An application of foraminiferal zonation to indicate tectonic submergenc [M.S. Masters]: Humboldt State University, 98 p.
Li, W., 1992, The late Holocene subsidence stratigraphy in the Eel River Syncline, Northern California in Carver, G. A., and Aalto, K. R., eds., Field guide to the late Cenozoic subduction tectonics & sedimentation of northern coastal California Volume GB-71: Bakersfield, CA American Association of Petroleum Geologists, Pacific Section p. 55-57.
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.
McCaffrey, R., Qamar, A., King, R. W., Wells, R. W., Khazaradze, G., Williams, C., Stevens, C., Vollick, J. J., and Zwick, P. C., 2007, Fault locking, block rotation and crustal deformation in the Pacific Northwest: Geophysical Journal International.
McCalpin, J. P., and Carver, G. A., 2009, Paleoseismology of Compressional Tectonic Environments, in McCalpin, J. P., ed., Paleoseismology, Academic Press, p. 315-419.
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. v. 99, p. p. 12,257-212,277.
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.
Nishimura, Y., Munekane, H., and Yarari, H., 2011, The 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks observed by GEONET: Earth Planets and Space, v. 63, p. 631-636.
Patton, J. R., 2004, Late Holocene Coseismic Subsidence and Coincident Tsunamis, Southern Cascadia Subduction Zone, Hookton Slough, Wigi (Humboldt Bay), California [M.S. Masters]: Humboldt State University, 76 p.
Patton, J. R., and Witter, R. C., 2006, Late Holocene Coseismic Subsidence and Coincident Tsunamis, Southern Cascadia subduction zone, Hookton Slough, Wigi (Humboldt Bay), California, in Hemphill-Haley, M., McPherson, R., Patton, J. R., Stallman, J., Leroy, T. H., Sutherland, D., and Williams, T. B., eds., 2006 Pacific Cell Friends of the Pleistocene Field Trip Guidebook, The Triangle of Doom: Signatures of Quaternary Crustal Deformation in the Mendocino Deformation Zone (MDZ) Arcata, CA.
Pollitz., F. F., McCrory, P., Wilson, D., Svarc, J., Puskas, C., and Smith, R. B., 2010, Viscoelastic-cycle model of interseismic deformation in the northwestern United States: Geophysical Journal International, v. 181, p. 665-696.
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.
Pritchard, C. J., 2004, Late Holocene Relative Sea-Level Changes, Arcata Bay, California: Evaluation of Freshwater Syncline Movement Using Coseismically Buried Soil Horizons [M.S. Masters]: Humboldt State University, 64 p.
Valentine, D. W., 1992, Late Holocene stratigraphy and paleoseismicity, Humboldt Bay, California, [M.S. Masters]: Humboldt State University, 82 p.
-, 2003, Quaternary Stratigraphy, Paleoseismicity, and Crustal Thickening of the Southern End of the Cascadia Subduction Zone, Northwestern California, and Coastal Uplift Studies of the 1992 Cape Mendocino Earthquake [Ph.D. Ph.D.]: University of California Santa Barbara, 146 p.
Valentine, D. W., Keller, E. A., Carver, G. A., Li, W., Manhart, C., and Simms, A. R., 2012, Paleoseismicity of the Southern End of the Cascadia Subduction Zone, Northwestern California: BSSA, v. 102, no. 3, p. 1059-1078.
Vick, G., 1988, Late Holocene paleoseismicity and relative vertical crustal movements, Mad River slough, Humboldt Bay, California [M.S. Masters]: Humboldt State University, 88 p.
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.

Relative Land-Level



Take Away Points:

- Secular interseismic vertical geodesy and stratigraphic evidence of coseismic vertical land motion are not compatible with each other. Explanations?
  - Slip and Strain Partitioning in the Upper Plate
  - Locked Zone is Different
  - Deep Slip During Megathrust Earthquakes (e.g. Tohoku)

Future Work:

- Coulomb Crustal Model (fit to observations)
- Additional Sea-Level Observations
- cGPS installation collocated with tide gage at the North Spit
- Reevaluation of Stratigraphic Interpretations Around the Humboldt Bay Region
- Examine Interseismic Sediment Accretion Rates (as they relate to vertical land motion)