Final Technical Report for USGS/NEHRP #G09AP00007 (UO #238550)

Project Title: More accurate uplift rates for western Washington to constrain models of locking along the Cascadia subduction zone.

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SUMMARY

This project is part of our ongoing effort to make a complete map of uplift along the Cascadia margin to constrain the depth of locking along the Cascadia subduction zone. In this report we present preliminary results for the Washington portion of the Cascadia margin, summarize some new interpretations from our previously completed Oregon work, and report on our discovery of uplift (and subsidence) associated with slow slip earthquakes on the Cascadia interface recorded in tidal records. The recognition of these transient events in tidal records will not only help us better understand these events by more precisely constraining their vertical deformation signal, but also may provide a much longer history of these events and their relationship to the depth of locking and the location and magnitude of both permanent and transient uplift along the Cascadia margin.

Report:

Our goal has been to use high order leveling and sea level records at tide gauges to identify a network of stable benchmarks with known uplift rates like our network on the Oregon coast (Figure 1, Burgette et al., 2009). We compare these point measurements of uplift with other deformation markers (e.g. GPS, strain meters, and geologic features, like marine terraces) and analyze them for the interseismic strain accumulation related to the Cascadia subduction zone. Transients and residuals that cannot be explained by inter-seismic strain (which dominates the signal) are also seen and are interpreted to be caused by slow slip earthquakes and permanent deformation, respectively.

As shown in Figures 1-3, we have complete finished this work in Oregon and have gained significant insights that are helping us progress in Washington. As discussed in the captions of these figures, we have made a map of interseismic locking that is consistent with both our leveling and tide gauge based uplift and horizontal GPS data, compared the locked zone to the region experiencing slow slip earthquakes, and have shown that the residual uplift that cannot be explained by strain associated with interseismic locking may be long term residual uplift due to the slow slip earthquake cycle. This latter speculative is supported by observations in Washing discussed in Figures 10 and 11 below.

In Washington we have reanalyzed all of the available leveling and tide gauge data (see Figures 4-7) and collected new water levels at temporary gauges deployed at Olympia, Point Grenville and Cape Disappointment. Because there are seasonal controls on the water levels we continued to collect data through the end of 2009 and are still analyzing the results. Once this analysis is completed we will combine the water levels and reanalyzed leveling results as we did in Oregon. While analyzing the water level data in Washington we discovered transient signals associated with slow slip earthquakes (Figures 8-11). This discovery may let us extend the slow slip event record >70 yrs and allows us to better distinguish interseismic, long term, and transient strain in Cascadia.

Figure 1

We have integrated all tidal and high order leveling data from coastal Oregon to determine the 3d uplift pattern along the coast. Each colored dot is a stable benchmark with calculated uplift rate (and formal uncertainty – see error bars on profiles).

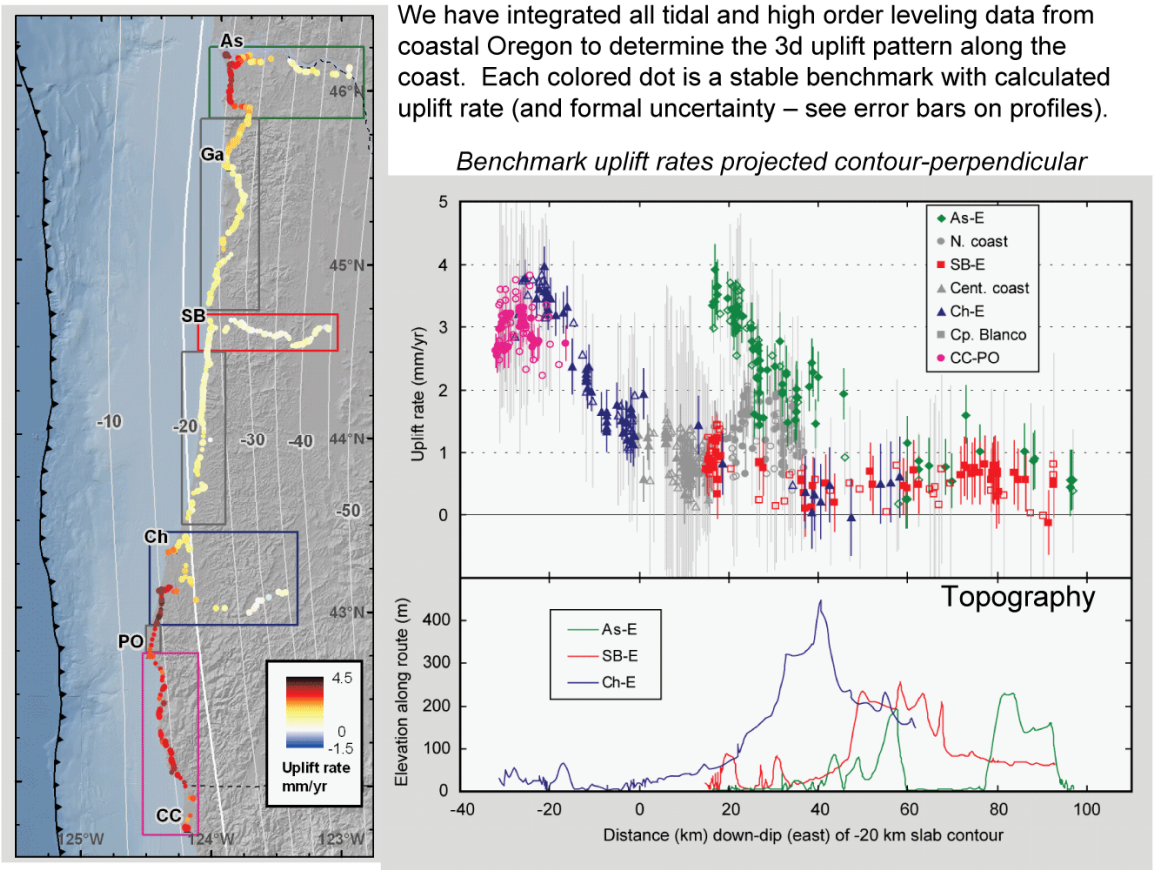
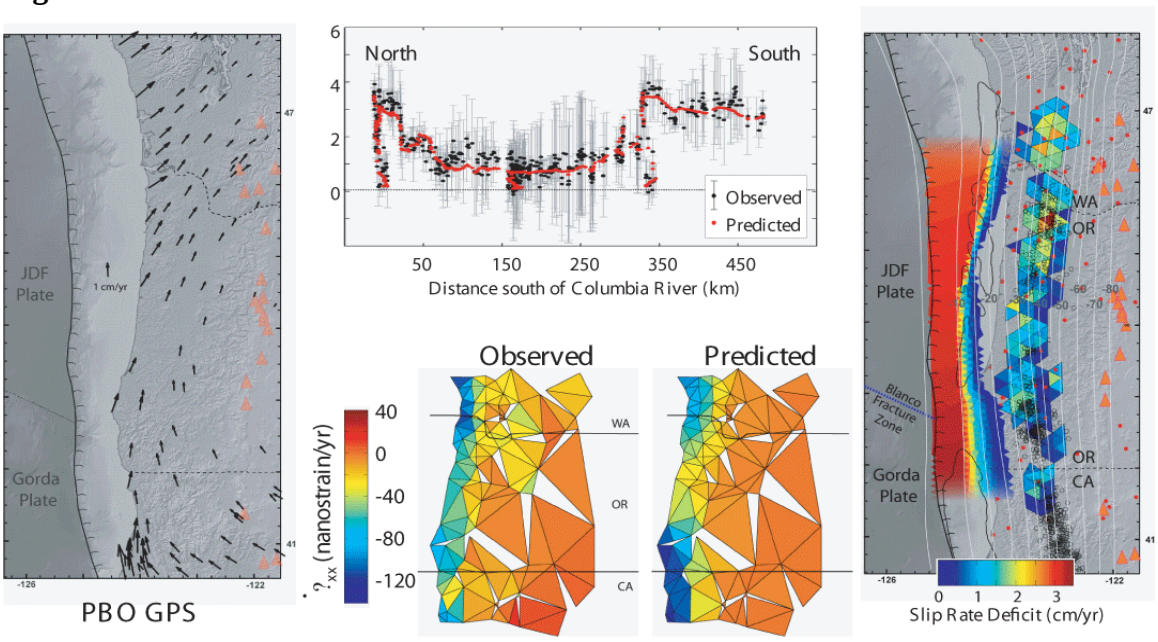


Figure 2



To make our locking model we took the horizontal component of GPS perpendicular to the plate convergence direction and calculated strain to avoid the contribution of the large forearc rotations. We then fit a simple elastic dislocation model to the GPS strain data, the combined leveling and sea level uplift data, and both; the three results are shown above.

As seen in the figure to the right, the regions of partial locking and slow slip events converge in the CA/OR border region and in Washington; however, in central Oregon there is a signifcant gap inbetween.

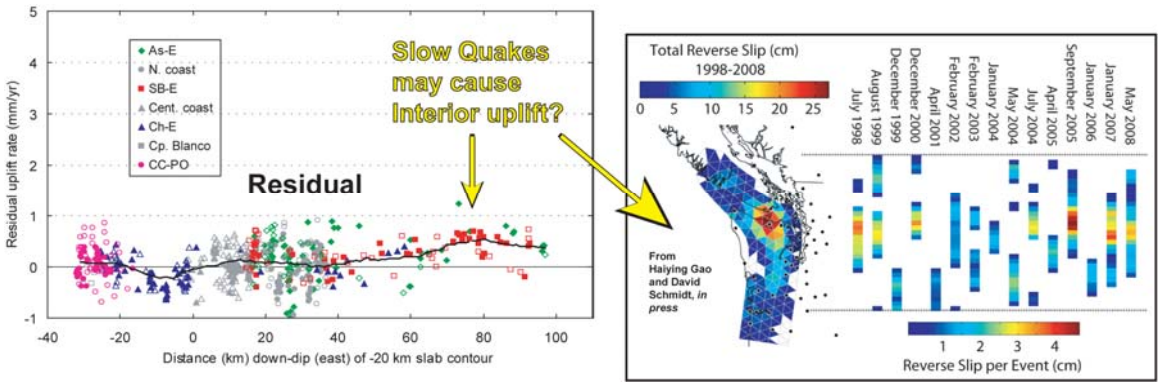
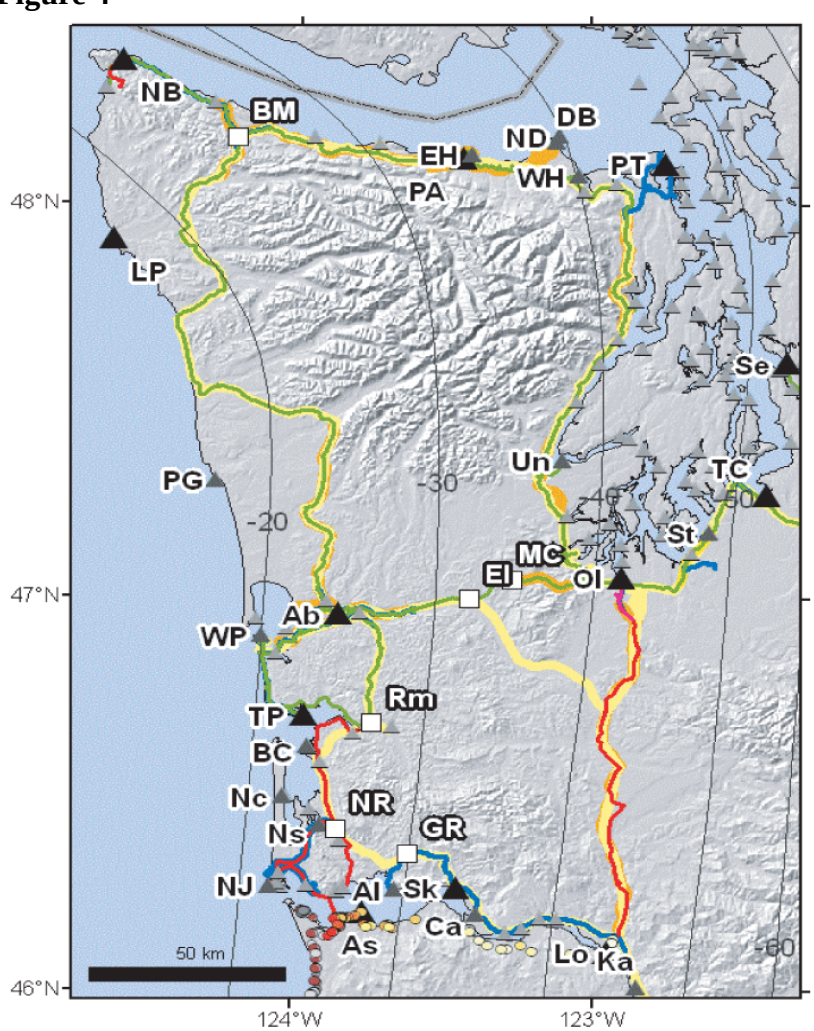


Figure 3 – a) Left side: Residual uplift produced by subtracting modeled uplift (Figure 2) from observed uplift (Figure 1). The uplift near the coast is almost completely described by our locking model on the subduction interface. However, there is persistent uplift inland that occurs where slow slip earthquakes are located. b) Right side: Cumulative slip associated with all (left side) and individual (right side) slow slip earthquakes. Spatial extend of individual earthquakes are shown as bars corresponding to their position along the Cascadia margin.

Figure 4



Preliminary results from Washington

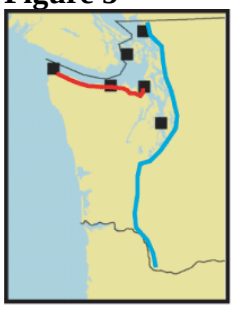
We have assembled all 1st and 2nd order leveling data for Western Washington and all of the water level records for NOAA stations. We have in stalled temporary tide gauges at Olympia, (Ol), Point Grenville (PG) and Cape Disappointment (NJ)

Colored lines are repeated (at least in part) 1st and 2nd order leveling lines; colors represent different time periods from the 1920s yellow to the late 1980s red (a few short late 1990s lines exist for GPS control).

Triangles are tide gauges, with the size and grey scale representing the relative amount and quality of the data.

Our goals is to establish uplift rate to a precision of ~0.4 mm/yr, as we did in Oregon, and to model depth of locking on the subduction zone.

Figure 5



Examples of EW (top) and NS (bottom) repeated leveling lines. Leveling yields RELATIVE uplift rates, which are converted to absolute uplift rates if tied to a reference (such as sea level, e.g. red stars; this preliminary figure assumes sea level rise of 1.8 mm/yr, which may be up to 0.5 mm/yr too low).

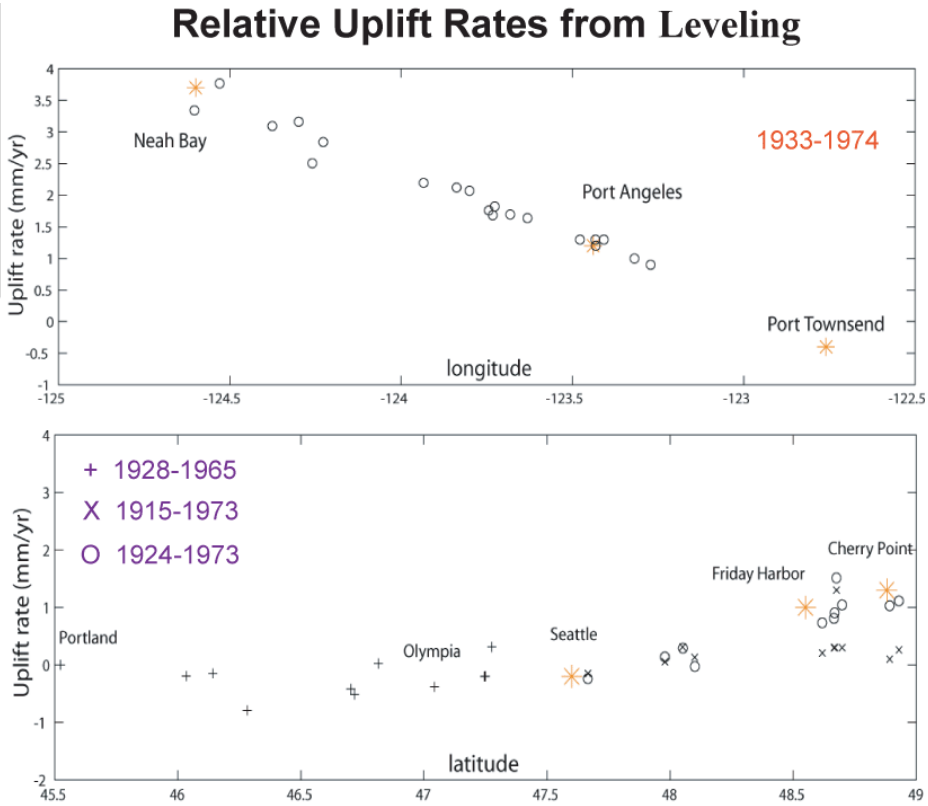
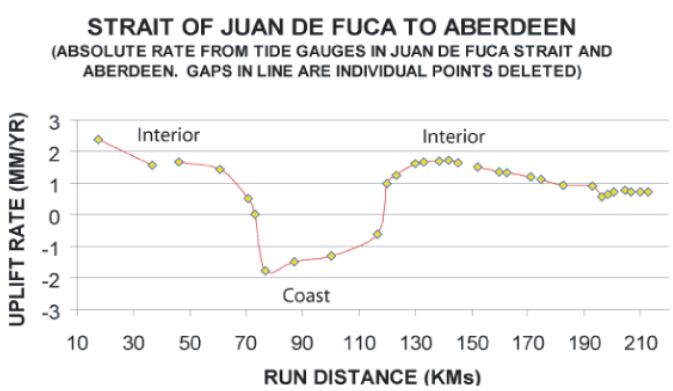
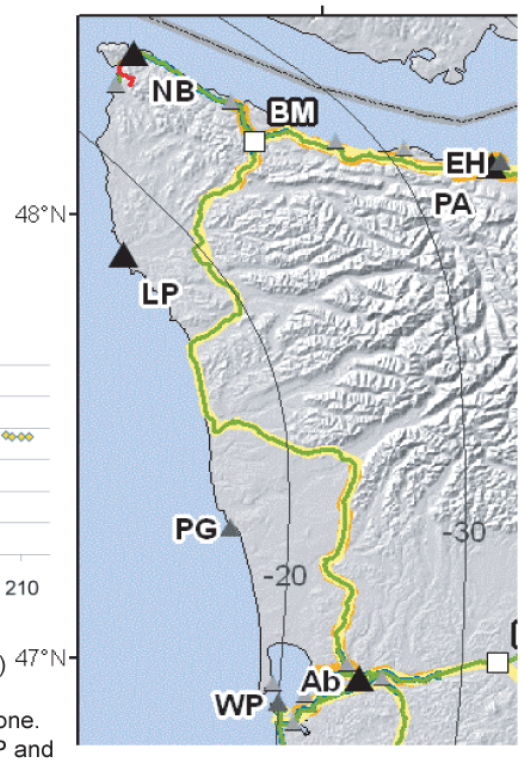


Figure 6

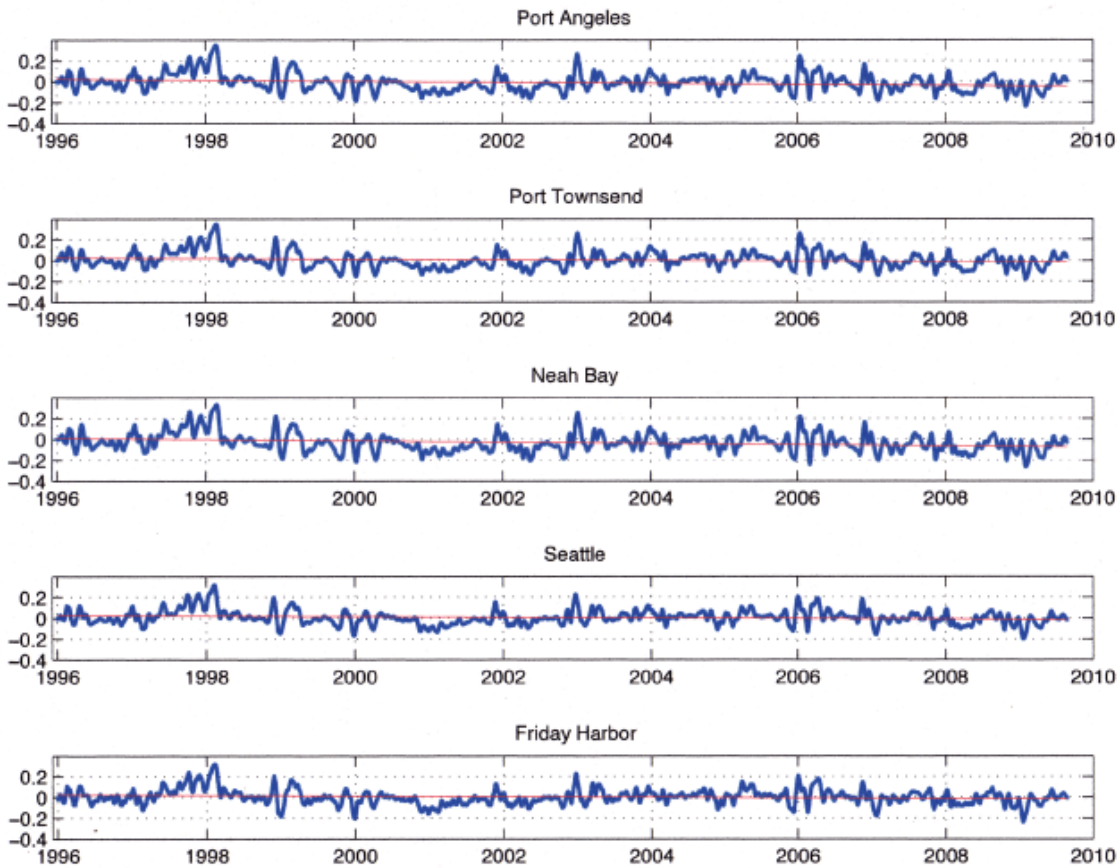
Preliminary reanalysis of the HW101 line from the Strait of Juan de Fuca (BM) to Aberdeen (Ab) supports the hypothesis that at least part of the westernmost coast is subsiding and there are very large gradients in uplift. However, this is based on a short repeat time in the re-leveling and is a very long distance unsupported by tide gauges to assess cumulative error in the leveling.





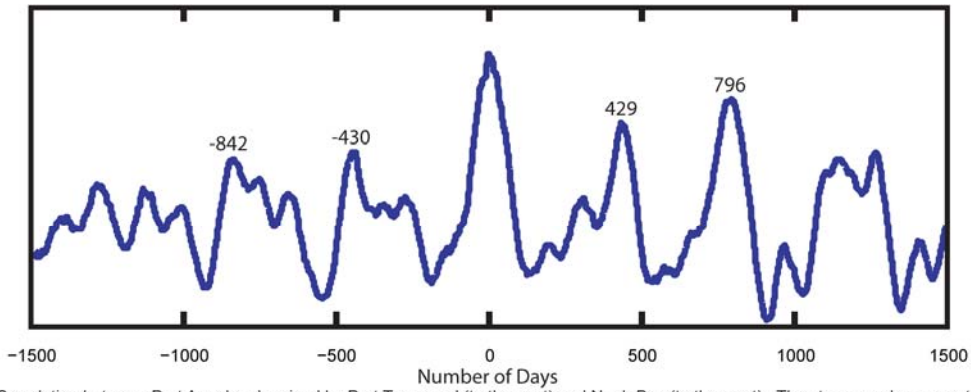
Tidal records from La Push (LP) and Point Grenville (PG) which we reoccupied last summer will confirm (or deny!) this hypothesis, which requires a much deeper locking zone. IF 2nd order leveling lines could be repeated between LP and PG and HW101 these tide gauges could stabilize the coast.

Figure 7



Hourly water level records (in meters) for 5 major sites in the Puget Sound region, detided and low pass filtered to preserve variations with periods longer than a month. The records are remarkably similar, which allows us to find signals that are not shared between sites, including the relative uplift or subsidence between sites, over the long term or during discrete events like slow slip earthquakes.

Figure 8



Cross Correlation between Port Angeles denoised by Port Townsend (to the east) and Neah Bay (to the west). The strong peaks suggest a periodicity of ~420 days (~14 months), which is the average interval between the slow slip earthquakes. Auto correlation of each individual denoised record shows similar results. This correlation cannot be distinguished from the noise by looking at any of the records individually or in pairs before denoising.

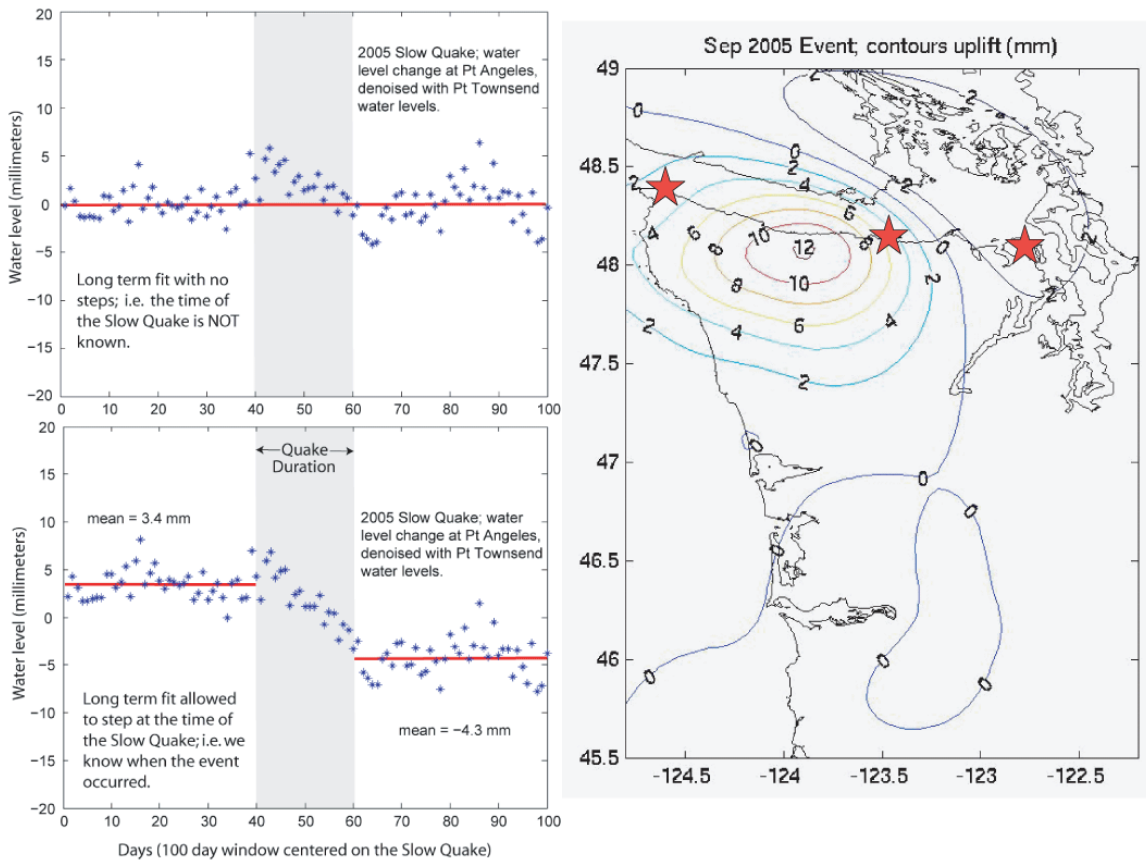
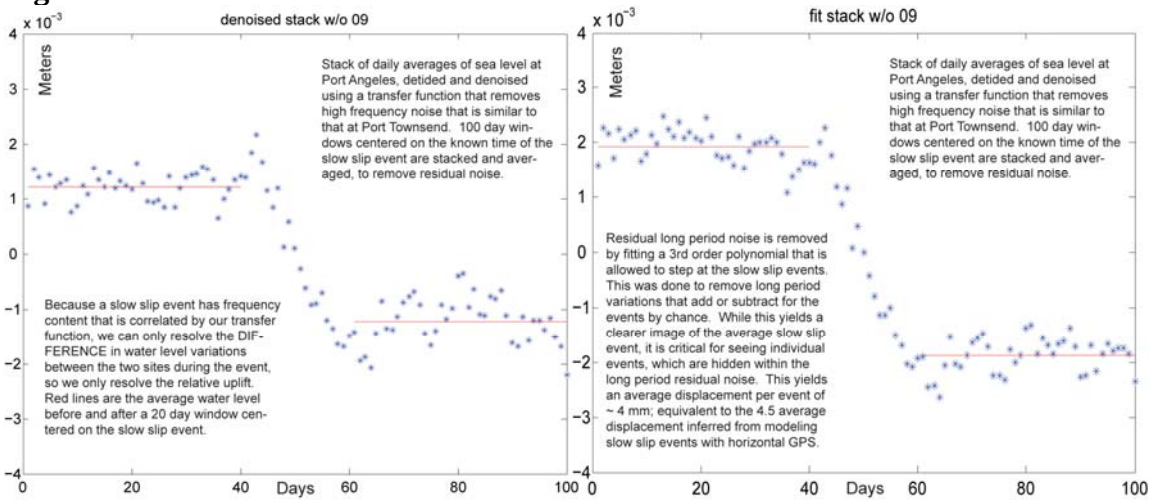
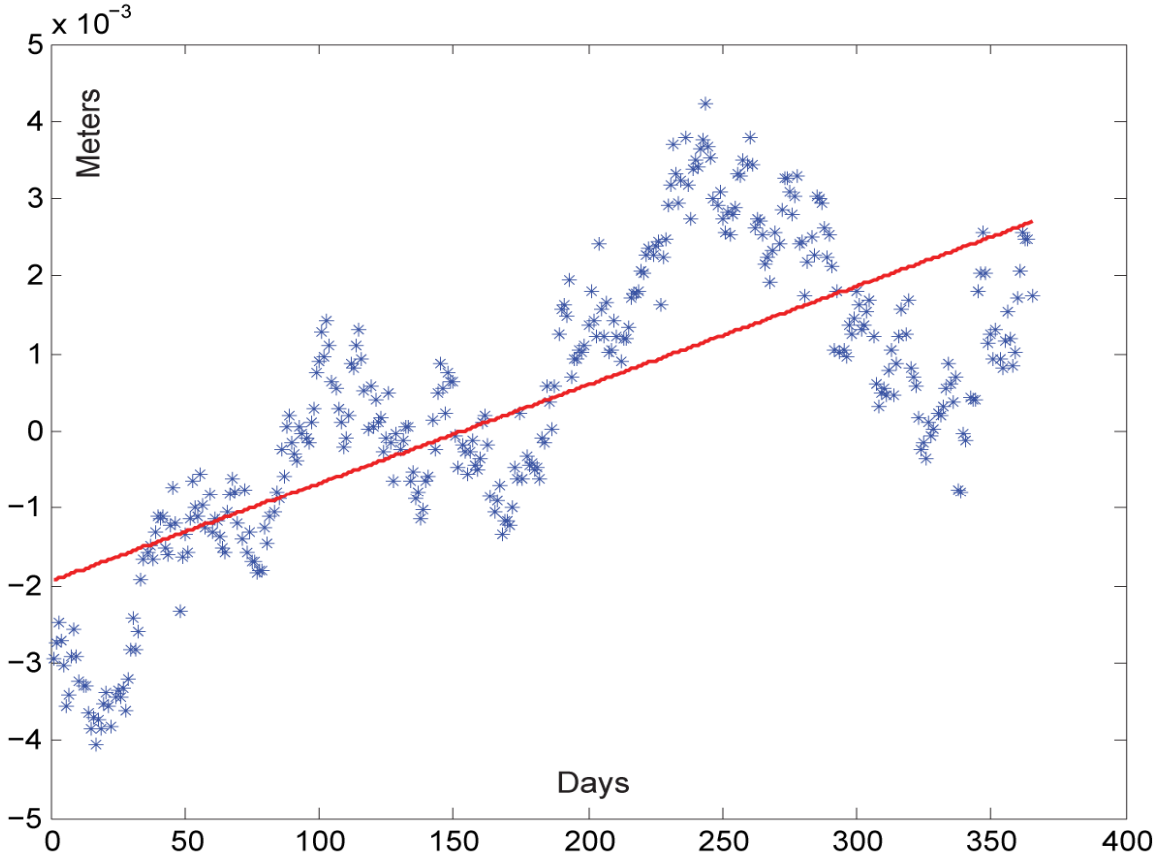


Figure 9– a) Left side: Daily average water level changes at Port Angeles relative to Pt. Townsend; upper has been smoothed to remove long period noise due to the seasonal cycle longer variations such as El Ninos; lower has same smooth but the smoothing function is allowed to step across the time of the slow slip earthquake (like smoothing GPS series across a hardware change such as replacing an antennae). b) Right side: Uplift pattern associated with the Sept 2005 event, predicted from horizontal GPS observations. Relative uplift of ~7.5 mm is identical to the ~7.7 mm observed in the water levels (a-lower).

Figure 10





Stack generated by adding the daily average of water level in 1 year windows centered at the day midway between slow slip events. At Port Angeles, the water rises on average about 5 mm between slow slip events and drops about 7 mm on average during a slow slip event, yielding a net uplift rate of about 2 mm/yr, which is the long term rate based on 70 years of monthly records.

Figure 11

Publications:

Burgette, R.J., Weldon, R.J.II, 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, B01408, doi:10.1029/2008JB005679.

Weldon, R., Livelybrooks, D., Schmidt, D., (2009), Uplift associated with slow slip events on the Cascadia subduction zone resolved in tidal records, Geological Society of America, *Abstracts with Programs*, v. 41, p.702.

Alba, S., Weldon, R., Livelybrooks, D., Schmidt, D., (2009), Absolute vertical uplift rates in western Washington inferred from historical leveling and tide gauge data, *Eos Trans. AGU, 90(52)*, Fall Meet. Suppl., Abstract G33B-0649.

Schmidt, D., Weldon, R., and Goa, H., (2009), Combining slow slip events, historical uplift, and contemporary geodesy to map interseismic strain along the central Cascadia Subduction Zone, *Eos Trans. AGU, 90(52)*, Fall Meet. Suppl., Abstract U52A-02.