Upper Plate Deformation Across Active Faults in the Southern Cascadia Subduction Zone, Northern California: Geodetic Slip Rate Estimates Compared with Geologic Rates

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Abstract

Fault slip rates in the North America plate are a key factor when considering northern California seismic hazard. Crustal faults in the north coast region are capable of producing > M 7 earthquakes. Observations here may help us understand fault behavior elsewhere. In regions of higher population density, the majority of slip rates for these faults are geologic slip rates, based on uplifted marine terraces and offset Tertiary and older geologic units.

We incorporate secular geodetic observations (tide gage, GPS, level analyses) to compare with known geologic rates. We use tide gage data obtained from NOAA, as well as 'campaign' style tide gages, to infer interseismic vertical land motion (VLM). We autocorrelate tide gage data from Crescent City to Humboldt Bay, California and, after regional sea level is removed, we estimate rates of VLM. We also use first-order leveling data collected by the National Geodetic Survey, along with USGS Global Positioning System permanent site data, to evaluate vertical interseismic deformation.

Land subsidence in and around Humboldt Bay contributes to sea-level rise up to 2-3 times greater than anywhere else in California. These observations confirm land is subsiding in Humboldt Bay, in contrast to Crescent City, to the north, where land is rising. Rates of sea-level rise are 5.84 mm/yr in South Humboldt Bay, 3.76 mm/yr at Fields Landing, 4.61 mm/yr at the North Spit, 2.53 mm/yr at Samoa, and 3.39 mm/yr in Arcata Bay.

An East-West trending variation in VLM is primarily due to the Cascadia subduction zone. We associate a heterogeneous North-South trend in VLM to crustal fault related strain. We use offsets in VLM rates across these crustal faults, primarily thrusts with associated folds, to derive estimates for rates of vertical separation. Cumulative vertical separation slip deficit across the Humboldt Bay region from geologic slip rates is 5.3 mm/yr, while the geodetic slip deficit is 4.9 mm/yr. Including estimates for the Russ fault system near Cape Mendocino (or to the south), the geodetic vertical separation slip deficit increases to 8.3 mm/yr. Offsets in geodetic VLM derived vertical separation rates match well with the geologic vertical separation rates, even though these rates are calculated over different time periods.

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.

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.

Tide Gages and Level Lines

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

Upper left and bottom: east-west uplift rate profiles from Arcata to Redding based on no leveling. 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). However, the longitude range is correct in the Wang et al. (2003) plot. The general location of the profile is shown as a red line on the map.

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.

Heterogeneous Coupling

Schmalzle et al., 2014

Maps of (A) Gaussian and (B) Gamma decade-scale model locking fraction with pink dotted line that marks the downdip 20% locked contour. Solid white lines mark the 10 mgal gravity anomaly contour of Blakely et al. (2005). Dashed white line (B) indicates where 96% of tremors are located from the PNSN catalog between 2009 to 2012. Green lines mark modeled plate boundaries and thin gray lines are 10 km depth contours from McCrory et al. (2004)

1. North America plate structures

Active Faulting Associated with the Southern Cascadia Subduction Zone

Kelsey et al. (2001)

Mad River Fault Zone

McLaughlin et al., 2000

Mendocino Triple Junction Tectonics

Map and cross-section (below) showing stratigraphic-structural relations between Cretaceous/Tertiary Franciscan and Tertiary Wildcat geologic units. Compare the cross section with Carver and Burke (1992), which extends further to the northeast. Cross section A-A' is labeled in blue.

Carver and Burke, 1992

Map and cross-section showing southwest vergent active faults in the Mad River fault zone including the Fickle Hill, Mad River, Mckinleyville, Blue Lake, and Trinidad faults.

McLaughlin et al., 2000

Pleistocene Marine Terrace Profiles

Topographic profiles across uplifted marine terraces. Active faults are labeled: BLF Big Lagoon fault, EF Eureka fault, FHF Fickle Hill fault, LSF Little Salmon fault, MCF Mckinleyville fault, MRF Mad River fault, TF Trinidad fault, TBF Table Bluff fault, RF Russ fault. Ages are based on relative ages from soil descriptions and comparisons with Pleistocene sea level curves.

Carver and Burke, 1992; summarized by McCrory, 2000

2. Geodetic Data

Geodetic rates are calculated from tide gage (1977-2018), GPS (~2000-2018), and repeated (1967-1988) benchmark survey data.

MAP: The map on the left shows the spatial distribution of geodetic sites colored relative to the rate at that site. Green symbols show uplift and red symbols show subsidence. USGS active faults are displayed relative to age of most recent movement.

PROFILES: The profiles show these vertical land motion rates relative to latitude (upper panel) and longitude (lower panel). 1 Sigma uncertainty error bars are shown for sites included in this analysis (gray dots). We highlight geodetic sites that are nearly adjacent to Highway 101 so it makes it easier to visualize the changes in rate with latitude. Sites more distant to the 101 and sites with large uncertainty (e.g. campaign GPS survey data) are plotted as white dots.

Vertical Land Motion vs. Latitude

Vertical Land Motion vs. Longitude

3. Offsets in Vertical Land Motion Rates

- There are offsets in vertical land motion rates across active faults in the area. We attribute these offsets to represent strain accumulation on these faults.
- Five of these "geodetic faults" are associated with known active faults: Big Lagoon/Bald Mountain fault, Trinidad fault, Fickle Hill fault, Little Salmon fault, and the Table Bluff fault. Two geodetic faults are associated with lesser well known faults: Eureka fault and the Shively fault.
- We calculate vertical separation rates across these faults in 2 ways: (1) we calculate a rate by differencing the two closest geodetic sites (single offset rate), (2) we calculate the mean block rate on either side of these faults and difference those rates (block rate).

Big Lagoon / Bald Mountain fault | Trinidad fault | Fickle Hill fault | Eureka fault | Little Salmon fault | Table Bluff fault

4. Geodetic and Geologic Rate Comparisons

We show our vertical separation rates and use these rates to calculate slip and shortening rates across these faults given published fault dips. These rates are compared with rates summarized in McCrory (2000). We present the cumulative rates at the bottom of the table.

	HBV VLM Slip Rate (Block Offset)				HBV VLM Slip Rate (Single Offset)				McCrory (2000): Slip Rate			
	Vertical Separation Rate (mm/yr)	Uncertainty (mm/yr)	Dip (°)	Dip-Slip Rate (mm/yr)	Vertical Separation Rate (mm/yr)	Uncertainty (mm/yr)	Dip (°)	Dip-Slip Rate (mm/yr)	Vertical Separation Rate (mm/yr)	Uncertainty (mm/yr)	Dip (°)	Dip-Slip Rate (mm/yr)	Shortening Rate (mm/yr)
Big Lagoon / Bald Mountain fault	0.6	0.4	30	1.2	0.8	1.1	1.2	0.6	30	2.5	1.3	2.1
Trinidad fault	0.8	0.3	33	2.1	0.6	1.7	2.4	0.4	33	4.2	0.7	3.5
Fickle Hill fault	1.6	0.3	35	2.8	0.8	2.3	1.4	0.3	35	2.4	0.8	2.0
Eureka fault	1.6	0.2	35	2.7	0.3	3.2	3.4	0.3	35	3.2	0.7	1.8
Little Salmon fault	2.1	0.3	42	3.2	0.7	3.7	1.9	0.3	30	3.8	0.3	2.5
Table Bluff	3.0	0.5	45	4.3	0.6	3.0	2.4	0.5	45	3.4	2.4
Shively fault	1.2	0.5	38	1.9	1.8	1.9	5.6	38	3.1	1.0
Total	11.3	0.4		19.3		15.6	12.6	0.5		21.7		17.6	6.4

5. Geodetic Rate Summary

Dip Slip Rate vs. Latitude

Dip slip rates from the table at the left are plotted. Block offset and single offset data are outlined in the table as blue and green rectangles respectively.

6. Geodetic Shively fault

Shively fault — Vertical Land Motion vs. Latitude

7. Geologic Shively fault

Shaded Relief Map of Shively Terraces. Lower terraces T-2, T-3, and T-4 on the left and the upper terrace T-7 on the right (see geomorphic map). View in Photo A (see below) was acquired in the view directed shown by the yellow arrows. The building in the photo is labeled on the map. Note the anthropogenic modification of the scarp on the left (walls built into the scarp, see photo below). The ends of the scarp in this map are shown as red arrows (though there is evidence the scarp extends further to the west).

Photo A

wall built into scarp / Base of Topographic Scarp / Bldg.

8. Quaternary Stratigraphy

Photo B

Photo of T-7: Approximately 15m of brown colored fluvial sediments unconformably overlie strath terrace cut into NE dipping Tertiary Wildcat Fm (gray muddy sandstone (fine grained turbidites).

Fluvial Seds / Wildcat Fm

9. Scarp Profiles

Topographic profiles A-G used to calculate slip rates. Bickner (1992) calculated an incision rate (0.9 mm/yr) for Eel River terraces (~40 km to the south) using soil development. Stallman and Kelsey (2006) used soil profiles and calibrated radiocarbon ages to calculate an incision rate of 0.85±0.05 mm/yr for bedrock strath fluvial terraces in the Elk River drainage (approximately 35 km to the north). We use the incision rate from Stallman to calculate a slip rate using each scarp height measurement. These slip rate estimates are listed below in a table and plotted to the right (10 Quaternary Slip Rate) shown as a purple line (labled T3).

Profile A — 3.9 m
Profile B — 2.0 m
Profile C — 6.9 m
Profile D — 6.1 m
Profile E — 7.3 m
Profile F — 15.2 m, 16.9 m
Profile G — 19.3 m, 15.6 m

Hillshade

Shively / Holmes Flat

Aspect | Slopeshade

Shively / Holmes Flat

Geomorphology

Shively

Shively Fault Slip Rate

Slip Rate (T3) — A B C D E F G

10. Quaternary Slip Rate

Based on the Stallman and Kelsey (2006) incision rate, T-3 is about 18 ky old, T-4 is ~25 ky old, T-5 is ~34 ky old, and T-7 is ~104 ky old. The slip rate using this rate (T3) is plotted in purple.

11. Offshore Seismic

Hogarth et al., 2013

CHIRP seismic profiles offshore of Humboldt Bay. General location for Line 17 is shown on map.

Take Away Points:

- Geodetic Observations:
  - 7 geodetic active faults
  - slip rates can be compared with geologic rates
- New Quaternary active "Shively" Fault is identified
- fault cuts across possibly Holocene fluvial terraces

Future Work:

- coulomb crustal model (fit to observations)
- stratigraphic descriptions / chronostratigraphy
- field mapping
- fault trenching