Prepared by: Mark A. Hemphill-Haley

CONTENTS

FIGURES

1 Introduction: Vertical Land Motion

Vertical land motion (VLM) encompasses both uplift (positive) and subsidence (negative) of a datum on land. Relative sea level (RSL) change is the relative change between absolute changes in sea level and VLM. VLM can be caused by several factors which predominantly include crustal rebound due to the rapid unloading of glacial ice, referred to as glacial isostatic adjustment (GIA) and tectonic forces. Absolute sea level change can be influenced by changes in sea ice volumes, changes in water temperature and salinity, and changes in the bathymetry of ocean basins (Patton et al., 2017, 2023; Frederikse et al., 2020). Changes in RSL can be quantified by accounting for VLM and absolute sea level changes at a site. Along an active tectonic margin two influences of VLM occur at different temporal and physical scales. They are coseismic and interseismic land-level changes. Coseismic changes tend to be episodic, occurring over periods of seconds to minutes and can be accompanied by significant amounts of uplift or subsidence (up to 10’s of meters). Interseismic land-level changes occur between coseismic events, occur slowly (decades to centuries) and have small rates of change (mm or cm per year).

Coseismic land-level changes may accompany large magnitude earthquakes, including those possible from rupture of the CSZ megathrust and large local thrust faults in the accretionary prism in the vicinity of Humboldt Bay (see *Geologic Technical Memo 1: Strong Ground Motion*).

Coseismic land-level changes refer to abrupt movements either up (uplift) or down (subsidence) during large earthquakes. The vertical motion is the result of land movement from fault rupture, and in the case of subduction zone earthquakes (such as those along the CSZ megathrust) areas of sudden vertical land-level change may be found in coastal areas along the length of the subduction zone (Atwater et al., 2003; Imakiire and Koarai, 2012). In subduction zone earthquakes, whether the vertical land movement is up, down, or neutral depends on the location of the site relative to the flexure point in the overriding plate above the megathrust. For example, for the 1964 M9.2 Alaska earthquake, areas of uplift occurred largely offshore, whereas areas of subsidence, as much as 2-3 m in some places (Plafker, 1969), occurred onshore along the coast (Carver and Plafker, 2008; Freymueller et al., 2013; Shennan et al., 2014). In the most recent full-margin rupture of the CSZ, in 1700 C.E., all coastal sites evaluated between Northern California and Vancouver Island experienced coseismic subsidence; there is no evidence for areas of coseismic uplift during this event. For the 1964 Alaska earthquake, the absolute amounts of subsidence measured at some locations was attributed to vertical land motion from crustal deformation with the added effects of liquefaction of unconsolidated deposits (Walsh et al., 1995). Field evidence for liquefaction associated with other evidence for coseismic subsidence has been documented for past megathrust earthquakes along the Cascadia subduction zone (Clague et al., 1997; Jacoby et al., 1997; Atwater, 2000; Kelsey et al., 2002; Takada and Atwater, 2004; Hemphill-Haley, 2017).

2 Coseismic Subsidence

Unlike the temporary inundation from climatic events such as coastal storms or floods, coseismically subsided areas abruptly drop from elevations unaffected by sea level to areas permanently inundated by tides. A clear modern example of this are the large industrial and agricultural areas on the Sendai plain that subsided during the 2011 M9.2 Tohoku-aki earthquake and are now continuously inundated by seawater (Imakiire and Koarai, 2012). Relatively high-density geodetic stations throughout Japan recorded abrupt coseismic VLM during the earthquake where up to 1.2 m of subsidence occurred (Figure 1). Therefore, the inherent risk to buildings or infrastructure close to sea level in areas adjacent to subduction zones, such as the southern CSZ, lies in their potential to become submerged and unusable following the earthquake-induced subsidence.

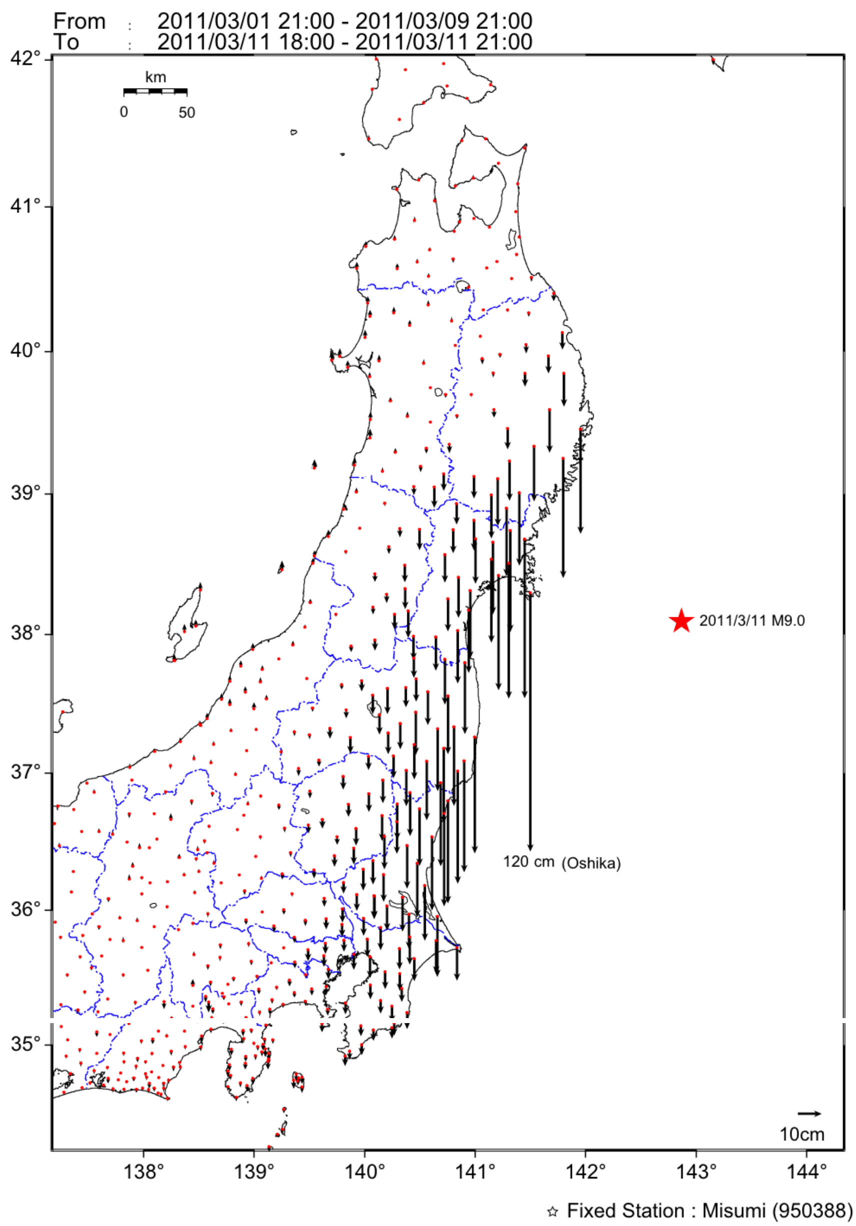

Figure 1. Vertical crustal deformation associated with the 2011 M 9.2 earthquake off the Pacific Coast of Japan.

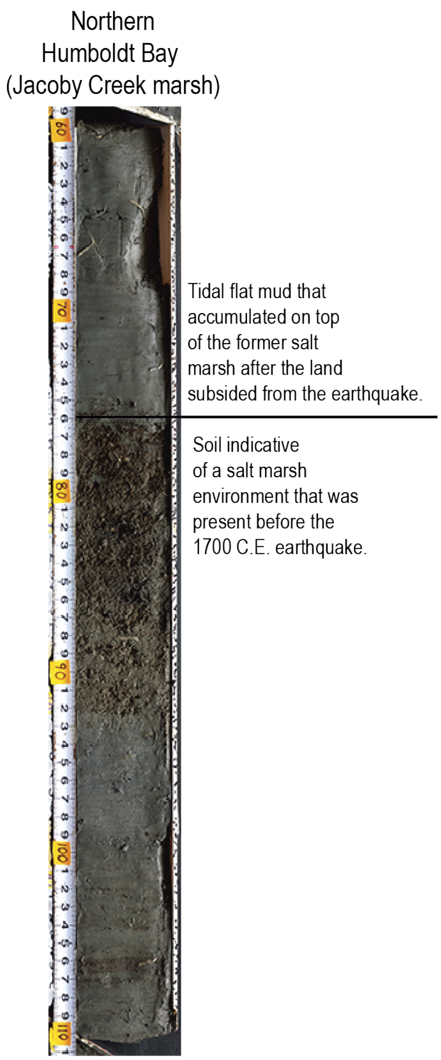

Figure 2. Photo of a core collected from Jacoby Creek marsh at the edge of northern Humboldt Bay (Arcata Bay). The stratigraphy shows the remains of a marsh soil that was buried by tidal flat mud through coseismic subsidence following the CSZ earthquake in 1700 CE.

Evidence for past instances of abrupt coseismic subsidence at coastal sites is recognized by the stratigraphic juxtaposition of 2 dissimilar kinds of sedimentary deposits in sharp contact with one another: an organic-rich soil (peat) indicating a former marsh, meadow, or coastal woodland—a type of environment which would be infrequently or possibly never submerged by tides—abruptly overlain by thick deposits of mud indicative of a lower intertidal setting such as a tidal flat (Figure 2). This stratigraphic signature is observed at coastal and estuarine sites along the length of the CSZ, and records the conversion of vegetated areas to tidal flats as a result of coseismic subsidence. These anomalous mud-over-soil sequences are similarly observed at numerous locations along Humboldt Bay and the Eel River estuary (Hemphill-Haley, 2017; Jacoby et al., 1995; Padgett, 2019; Padgett et al., 2021; Patton, 2004; Pritchard, 2004; Valentine, 1992; Valentine et al., 2012; Vick, 1988; Li, 1992) and are interpreted, as elsewhere, of recording coseismic subsidence from past CSZ megathrust earthquakes.

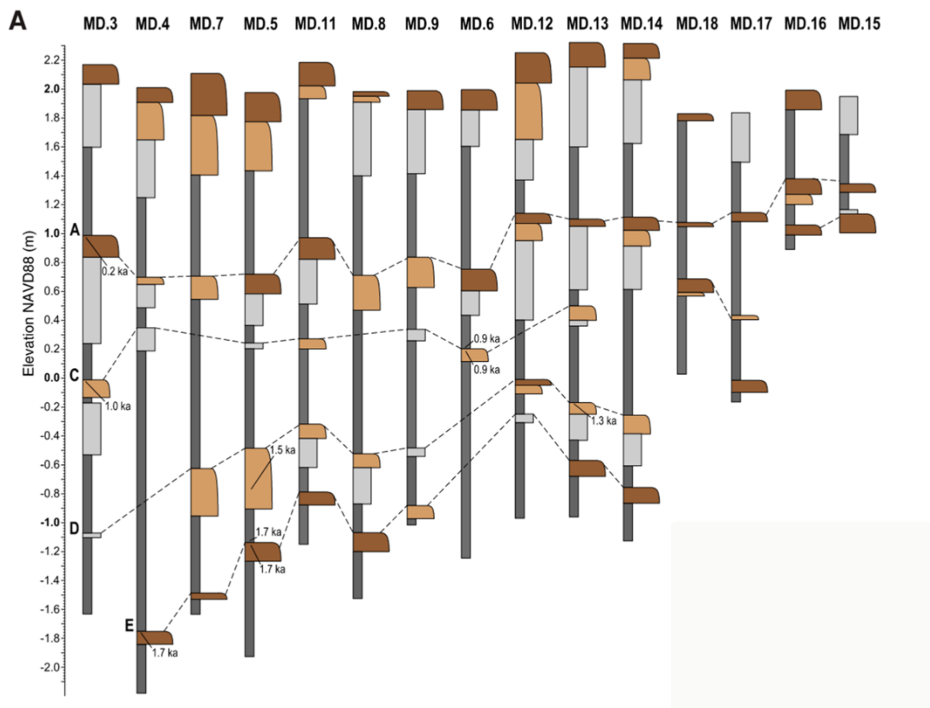

Figure 3. Core diagrams from Padgett et al. (2021, 2022) showing multiple times in the past that areas of northern Humboldt Bay coseismically subsided

The most recent of the paleoseismic studies in Humboldt Bay (Padgett et al., 2019, 2021, 2022) (Figure 3) focused on sites in northern Humboldt Bay (Arcata Bay) where they described 4 past incidences of earthquake-driven subsidence from CSZ earthquakes. From multiple radiocarbon dates, the ages of the 4 events are identified as (1) 1700 C.E.; (2) ~875 cal yrs B.P.[1]; (3) 1,120 cal yrs B.P.; and (4) ~1,620 cal yrs B.P. The estimated amounts of coseismic subsidence from these past earthquakes, determined statistically from changes in microfossil assemblages across the soil-mud contacts, are about 0.8 ± 0.5 m (2.6 ± 1.6 ft) for the earthquake in 1700 C.E.; 0.4 ± 0.4 (1.3 ft) for the earthquake in 875 cal yr B.P.; 0.8 ± 0.5 m (2.6 ±1.6 ft) and likely greater than 0.9 m (3ft) for the oldest recorded event in 1,620 cal yr B.P. (Padgett et al., 2021). Comparable qualitative or semi-quantitative estimates for subsidence were determined from earlier studies, although without the precision of the later study by Padgett et al. (2021, 2022).

The Padgett et al. (2022) study revised the subsidence estimates by using stratigraphic control and analysis of multiple cores collected during at each of the 2021 sites. By using multiple cores, they were able to assess the variability of the subsidence estimates for the last 3 events reported in Padgett et al. (2021). Their analysis did not include the 1,620 cal yr B.P. event. They were able to estimate an average and range for those events (Table 1). Thus, the revised estimates are an average of 0.6 ± 1 m (2 ± 0.3 ft)

[1] The unit "cal yrs B.P." refers to "calibrated radiocarbon years before present" with "present" defined as the year 1950 C.E.

for the 1700 C.E. earthquake; an average of 0.4 ± 0.2 m (1.3 ± 0.7 ft) for the ca. 875 cal yr BP earthquake and 0.7 ± 0.2 m (2.6 ± 0.7 ft) for the ca. 1120 cal yr BP event (Padgett et al., 2022).

Thus, the combined results of the various paleoseismic studies for Humboldt Bay suggest that coseismic subsidence on the order of 0.5 - 1 m (1.6 – 3.3 ft) or more is a possibility for future CSZ earthquakes.

Both Valentine et al. (2012) and Padgett et al. (2021, 2022) note the occurrence of at least one possible episode of subsidence about 500 years ago that does not appear to correlate to well-documented CSZ earthquakes. Padgett et al. (2021) do not specify a possible source of the buried soil of this age in the Mad River slough, cautioning that the dynamic sedimentary processes in Mad River slough, including past altering of the slough channel from dredging, may make the stratigraphic record at that site particularly more complex and less reliable. Valentine et al. (2012, p. 1070) speculate that the possible evidence for subsidence at about 500 years ago in Mad River slough and sites farther to the south in Humboldt Bay may be recording coseismic land-level change from past rupture on faults in the fold and thrust belt (see also *Geologic Technical Memo 1: Strong Ground Motion*). They noted that the "expected effects" of rupture on the Little Salmon fault or Mad River fault zone would be "*minor amounts of subsidence within the frontal syncline adjacent to the fault, larger amounts of subsidence in the syncline behind the fault, or uplift.*" They also state that "*For an event on the Mad River fault zone, subsidence would be expected in the Freshwater syncline (Mad River slough)… Subsidence would be variable from 0.25 – 1 m in the frontal portion to 1–3 m in the back basin*." However, they express uncertainties as to the possible record of subsidence from fold and thrust earthquakes, conceding that (p. 1074): '*There is not sufficient evidence from the data to evaluate the cause(s) of this RSL*[2] [Relative Sea Level] *event* [500 years ago] *or whether it represents a coseismic subsidence due to an earthquake or coincidental RSL changes at several sites. If an earthquake caused the observed RSL changes, then based on the distribution of the changes the earthquake was probably a local event*."

At southern Humboldt Bay, Witter et al. (2001, p. 44) compiled evidence for coseismic subsidence accompanying rupture of the Little Salmon fault and reported that the "*data suggest that submergence in the footwall of the Little Salmon fault occurs during upper-plate earthquakes." Significantly, based on the results at their study sites near College of the Redwoods and Hookton Slough, they concluded that although subsidence accompanied rupture on the LSF, the LSF ruptures were in turn triggered by and coincident with ruptures in the CSZ megathrust." Evidence for subsidence of the [LSF] western fault scarp along with stratigraphic records of abrupt soil submergence suggests that coseismic subsidence of the Humboldt Bay region also accompanied upper-plate seismicity. We conclude that where evidence for slip on the Little Salmon fault and regional coseismic subsidence coincide, the evidence supports an interpretation of upper-plate faulting triggered by rupture on the southern Cascadia plate-interface*" (Witter et al., 2001, p. 41). Therefore, it is possible that for Humboldt Bay coseismic subsidence may have, at times in the past, included forcing from rupture on faults in the accretionary prism in addition

[2] RSL – "relative sea level."

to the deformation associated with rupture of the southern CSZ megathrust. This is a situation unique to the North Coast where the accretionary wedge of the subduction zone is located onshore.

3 Coseismic Uplift

Coseismic uplift has been documented along the north coast of Humboldt County (Woodward-Clyde Consultants, 1980; Burke and Carver, 1992; Swan et al., 2002; McCrory, 2000). They are represented as a series of marine terraces that occur along the hills and coastal exposures of Humboldt Bay (Figure 4). They record the progressive regional uplift of the accretionary sediments above the megathrust while adjacent synclines are absent of terraces. Relative dating (soil development and vertical position) and few absolute dates suggest that these terraces record at least 200,000 years of uplift along these structures (Figure 4). Evidence of a longer record of uplift is not apparent in the terraces due to erosion. An older record of uplift is recorded in separation of the base of Neogene sediments forming the cores of the folds where it is estimated that more than 3,400 m of separation exists across the Little Salmon and Table Bluff faults (Ogle, 1953; Kelsey and Carver, 1988; Swan et al., 2002; Vadurro, 2006). These terraces record a longer-term trend of tectonic uplift that is accumulated over many episodes of megathrust activity and not the interspersed, episodic coseismic events.

4 Interseismic Subsidence at Humboldt Bay

In addition to episodic coseismic subsidence at Humboldt Bay from great earthquakes, Patton et al. (2017, 2023) have shown that Humboldt Bay is interseismically subsiding on the order of millimeters per year (Figure 5, 6 and 7), resulting in relative sea level rise at Humboldt Bay that is “2-3 times greater than anywhere else in California” (Patton et al., 2017, p.3). Patton et al. (2017) report the rates of land subsidence for 5 locations on Humboldt Bay: South Humboldt Bay/Hookton Slough (-3.56 mm/yr); Fields Landing (-1.48 mm/yr); North Spit (-2.33 mm/yr); Samoa (-0.25 mm/yr); and Arcata Bay/Mad

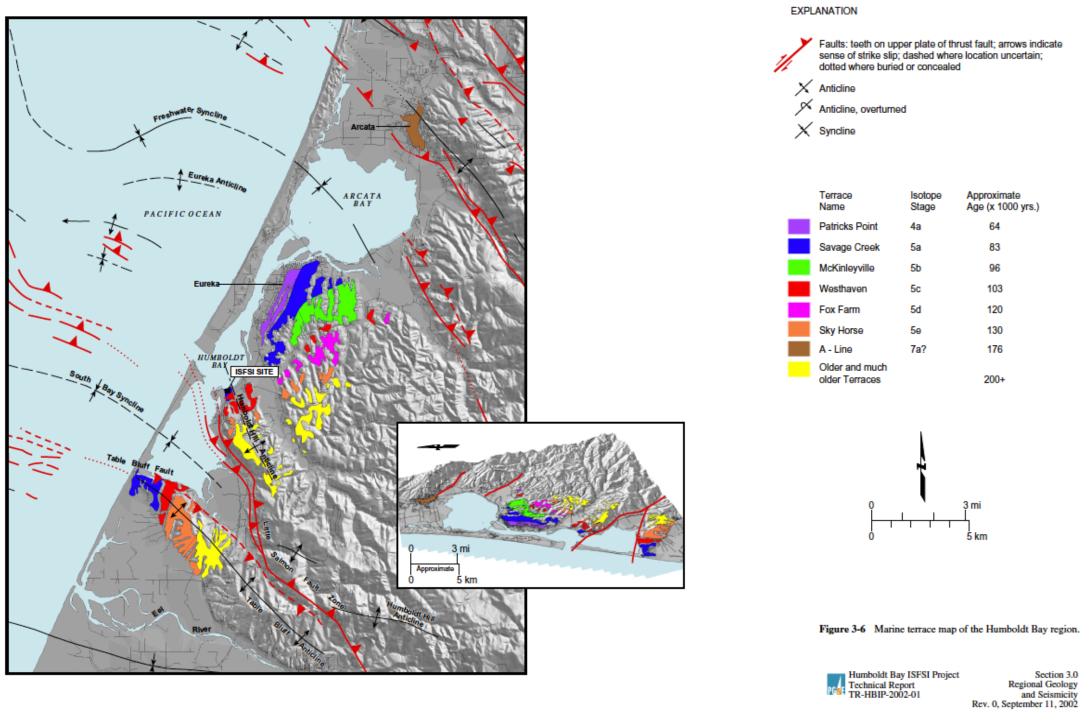

Figure 4. Marine terrace sequence within Humboldt Bay, CA. Note that the terraces record progressive uplift of anticlinal folds as they grow, presumably coseismically, above thrust faults, including the Table Bluff fault, Little Salmon fault, and an unnamed structure beneath Eureka. Marine terrace geomorphology is absent from intervening synclines. (From Swan et al., 2002, his Figure 3-6).

River Slough (-1.11 mm/yr). Patton et al. 2023 use data from tide gages, benchmark releveling and Global Navigational Satellite System (GNSS) to reevaluate vertical land motion (VLM) rates in the Humboldt Bay area. The implication is that these relatively high rates of interseismic subsidence are recording the effects of a locked megathrust boundary, with the overriding North America plate being pulled downward as subduction of the Gorda plate continues beneath it (Savage et al., 1991; Hyndman and Wang, 1995; Wang et al., 2003; Wang and Tréhu, 2016). Which direction, up or down, of coseismic land level change may occur when the megathrust ruptures next is uncertain.

A suggestion is that the upper plate will rebound, resulting in coseismic uplift, a model proposed by Plafker (1972) based on studies in Alaska and Chile following the great earthquakes in 1964 and 1960, respectively. However, pre-seismic subsidence has been documented for the 1964 and earlier earthquakes in the Upper Cook Inlet region of Alaska (Zong et al., 2003; Shennan and Hamilton, 2006), that is, the area was slowly subsiding prior to the 1964 M9.2 earthquake, and with the megathrust rupture, dropped >2 m within minutes. Whether the current interseismic subsidence at Humboldt Bay is foreshadowing future uplift or subsidence from the next CSZ earthquake is unknown.

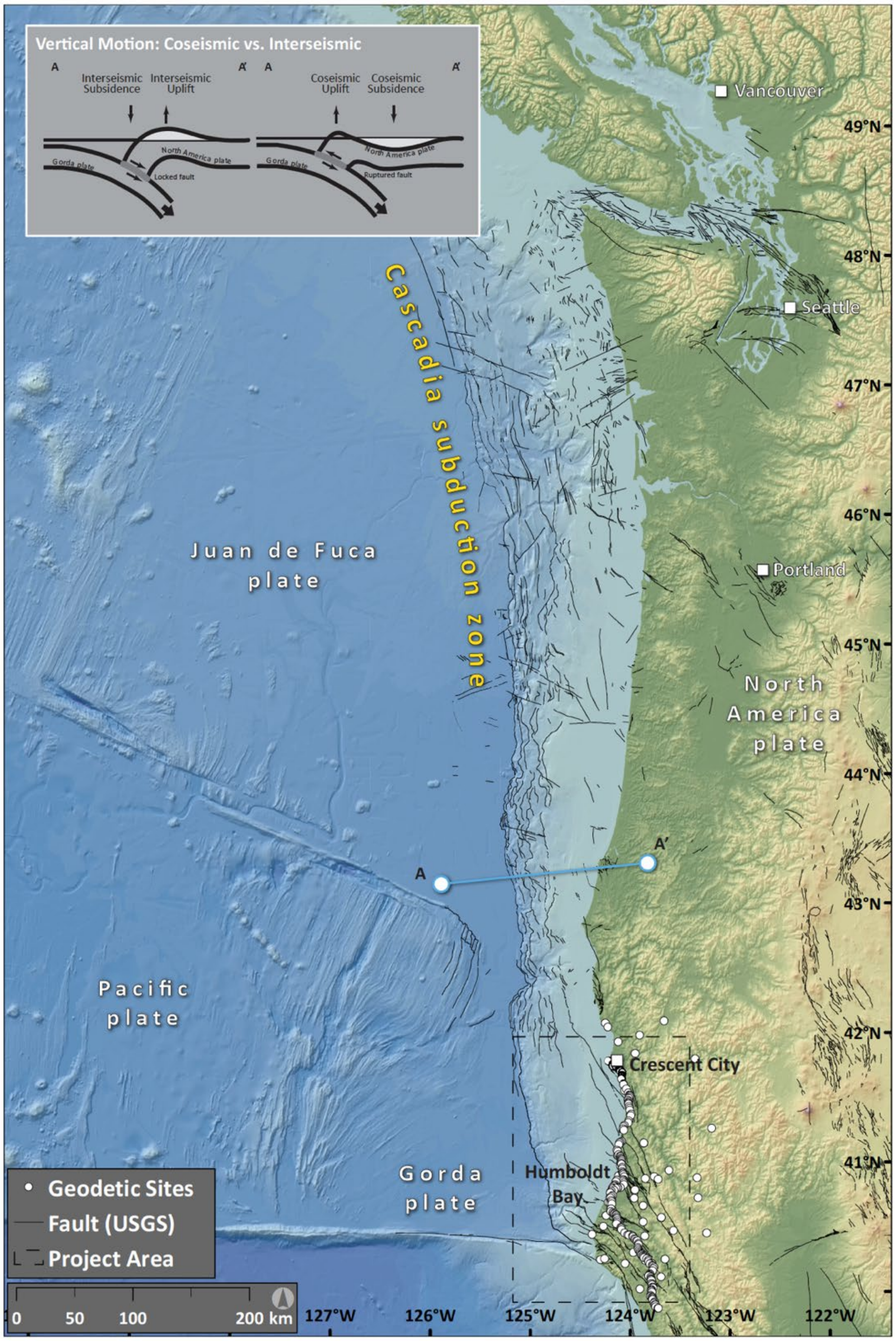

Figure 5. Map showing locations of faults, geodetic sites and profile (A-A') across the Cascadia subduction zone megathrust and overlying accretionary prism. Inset image depicts interseismic and coseismic deformation across a typical section of the accretionary prism directly above the locked megathrust interface is pulled downward along with the subducting oceanic plate. At the same time, the portion of the accretionary prism immediately landward is bowed upward causing local uplift. Typically, the subsiding part of the accretionary prism is submerged, however, in the Humboldt Bay region, this portion of the upper plate is partially onland which accounts for some of the complexity of the uplift signal. Also note the position of Crescent City relative to Humboldt Bay. Crescent City, located almost twice the distance from the megathrust than Humboldt Bay is experiencing interseismic uplift, Humboldt Bay is experiencing subsidence (From Patton et al., 2023).

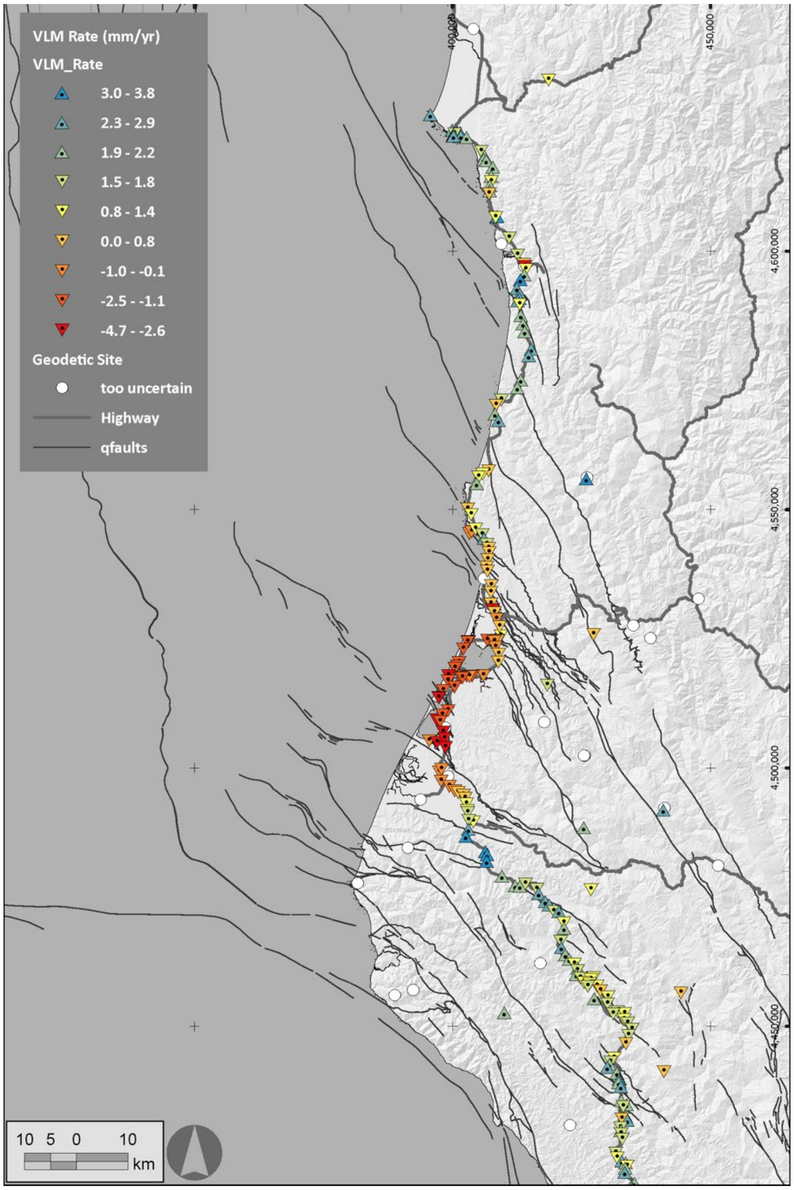

Figure 6. Vertical Land Motion (VLM) for the North Coast region (from J. Patton, personal communication, 2024). Interseismic VLM estimates are based on GNSS Geodetic data and first-order level-line surveys and tide-gauge data. Downward pointing triangles denote subsiding areas while upward-pointing triangles indicate uplift. Triangles are color-coded to indicate ranges of rates. Highest rates of subsidence occur along margin of Humboldt Bay (red to orange colors). They are largely bound on the north by the Mad River fault zone and by the Little Salmon fault zone to the south. Lower rates of subsidence occur immediately to the north and south of the maximum subsidence zone. Farther south, within the lateral displacement San Andreas fault zone, the area is characterized to have minor amounts of interseismic uplift. Likewise, to the north of Trinidad and Sumeg Park, the area is farther from the locked zone of the CSZ and is uplifting (see Figure 4 insert for explanation). Figure 6 provides a profile of interseismic VLM along the same area as this figure.

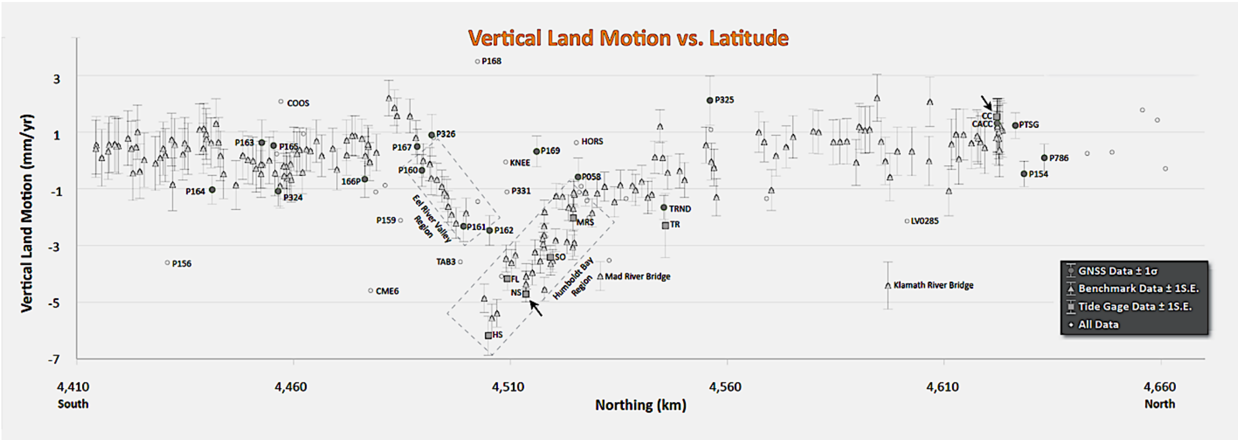

Figure 7. Plot of vertical land motion (VLM) versus latitude inland of the Cascadia subduction zone (from Patton et al., 2023). Black arrows point to the locations of North Spit (NS) and Crescent City (CC). North Spit is closer to the megathrust and also within the zone of crustal faults such as the Little Salmon and Mad River fault zones. Note the significant negative vertical motion within Humboldt Bay relative to CC. Data points south of station COOS are within the San Andreas fault system and reflect zero to minor uplift.

5 Vertical Land Motion uncertainty complications at Humboldt Bay

Patton et al. (2023) suggest that complications in resolving VLM around Humboldt Bay are not only due to the interseismic loading along the Cascadia subduction megathrust but also the local crustal faults. A large part of the uncertainty is due to the presence of the fold and thrust belt structures located within the accretionary prism that transect the inland and near offshore part of the coast at Humboldt Bay (Figure 8). As described earlier, there is paleoseismic evidence that coseismic events on the Little Salmon fault are accompanied by upper plate folding that may include uplift directly above the fault and subsidence on either side (Witter et al., 2001). This is a smaller scale deformation than one would expect along the Cascadia megathrust but over time results in a significant geomorphic feature (i.e., Arcata Bay is largely a syncline formed with the lower plate of the Fickle Hill fault).

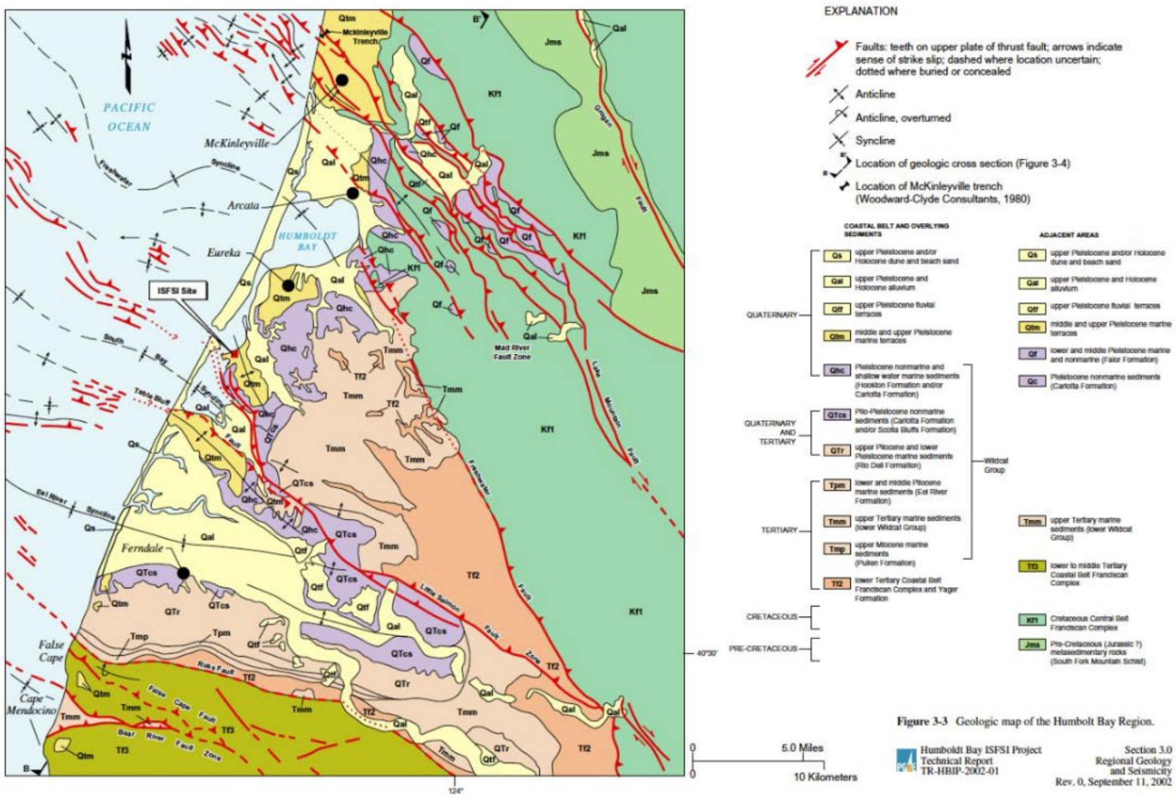

Figure 8. Geologic map of the Humboldt Bay Region. Of special note are the locations of the Eel River, South Bay, and Freshwater synclines and the Table Bluff and Little Salmon faults which extend offshore and are part of the Cascadia accretionary prism. (From Swanet al., 2002, their Figure 3.3).

6 Vertical Land Motion and Sea Level Rise

Along the Hwy 101 Safety Corridor VLM estimates (Patton et al., 2017, 2023) suggest that that portion of Humboldt Bay is interseismically subsiding at a rate ranging from 0 to -1.1 mm/yr. In addition, paleoseismic evidence from portions of northern Humboldt Bay (Padgett et al., 2019, 2021) indicate that co-seismic subsidence of up to 1 m has accompanied large CSZ earthquakes. An online Hazards Tool implemented by the American Society of Civil Engineers (ASCE) allows one to select a site along the margin of Humboldt Bay to estimate coseismic subsidence and tsunami inundations heights (https://asce7tsunami.online). A survey of points along the project highway transect provides a range of estimated coseismic subsidence of 0.15 to 0.24 m (0.5 to 0.8 ft). It should be noted that Padgett et al. (2021, 2022) at locations at the northern end of Humboldt Bay, to the west of the project, have estimated an average of 0.5 - 1 m (1.6 – 3.3 ft) of subsidence for the last 4 events along the CSZ suggesting the ASCE model may underestimate future subsidence. Models of sea level rise projected over the next few decades all suggest relative sea level rise, that include interseismic and coseismic values, will increase the potential hazard along the project.

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