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Differences in coastal subsidence in southern Oregon (USA) during at least six prehistoric megathrust earthquakes

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ABSTRACT

Stratigraphic, sedimentologic (including CT 3D X-ray tomography scans), foraminiferal, and radiocarbon analyses show that at least six of seven abrupt peat-to-mud contacts in cores from a tidal marsh at Talbot Creek (South Slough, Coos Bay), record sudden subsidence (relative sea-level rise) during great megathrust earthquakes at the Cascadia subduction zone. Data for one contact are insufficient to infer whether or not it records a great earthquake—it may also have formed through local, non-seismic, hydrographic processes. To estimate the amount of subsidence marked by each contact, we expanded a previous regional modern foraminiferal dataset to 174 samples from six Oregon estuaries. Using a transfer function derived from the new dataset, estimates of coseismic subsidence across the six earthquake contacts vary from 0.31 m to 0.75 m. Comparison of subsidence estimates for three contacts in adjacent cores shows within-site differences of ≤0.10 m, about half the ±0.22 m error, although some estimates may be minimums due to uncertain ecological preferences for *Balticammina pseudomacrescens* in brackish environments and almost monospecific assemblages of *Miliammina fusca* on tidal flats. We also account for the influence of taphonomic processes, such as infiltration of mud with mixed foraminiferal assemblages into peat, on subsidence estimates. Comparisons of our subsidence estimates with values for correlative contacts at other Oregon sites suggest that some of our estimates are minimums and that Cascadia's megathrust earthquake ruptures have been heterogeneous over the past 3500 years.

1. Introduction

Due to favorable (1–2 mm/yr) rates of Holocene relative sea-level (RSL) rise (e.g., Engelhart et al., 2015), coastal wetlands of the Cascadia subduction zone, from British Columbia to northern California (Fig. 1A), host the longest and best preserved stratigraphic record of great (magnitude 8–9) megathrust earthquakes and accompanying tsunamis (e.g., Atwater, 1992; Nelson et al., 1996a; Clague, 1997; Witter et al., 2003). Stratigraphic sequences beneath the coastal wetlands show abrupt lithologic contacts formed by sudden changes in tidal environments during coseismic subsidence. Because of subsidence during past great earthquakes, high tidal marshes or spruce swamps suddenly dropped into the lower intertidal zone and were subsequently buried by muddy intertidal sediment (and at some sites by sand beds deposited by tsunamis accompanying the earthquakes). Conversely, during slow interseismic recovery (uplift), the muddy sediment gradually aggraded and was ultimately capped by the peat of marshes or swamps above or high in the intertidal zone (e.g., Hemphill-Haley, 1995; Nelson et al., 1996b; Valentine et al., 2012). The coseismic peat-mud (mud-over-peat) contacts may record decimeters to more than a meter of land-level fall (the inverse of RSL rise) during the last 4–12 earthquake deformation cycles over the past 3000–7000 years (e.g., Darienzo et al., 1994; Atwater and

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Hemphill-Haley, 1997; Nelson et al., 1998; Kelsey et al., 2002; Graehl et al., 2014) .

Although geophysical models of megathrust earthquake ruptures are much improved for Cascadia's most recent 1700 CE earthquake (Wang et al., 2013), the location and length (a measure of earthquake magnitude) of ruptures during older earthquakes remains uncertain for three reasons. First, errors on radiocarbon ages yield broad age ranges for earthquake peat-mud contacts at individual sites (e.g., Nelson, 1992; Atwater and Hemphill-Haley, 1997; Graehl et al., 2014); second, peat-mud contacts at most sites lack distinctive characteristics that could be used to correlate earthquake ruptures along the 1200-km-long subduction-zone coast (Nelson et al., 1998, 2006); and third, estimates of coseismic subsidence across contacts are too few and imprecise to correlate earthquakes or estimate earthquake magnitude and rupture extent for all but the 1700 CE earthquake (Hawkes et al., 2011; Wang et al., 2013).

Early estimates of coseismic subsidence at Cascadia were qualitative or semi-quantitative and relied on floral and faunal differences between intertidal elevational zones with broad ranges, resulting in subsidence estimates with uncertainties of ±0.5 m to ±1 m (e.g., Nelson and Kashima, 1993; Darienzo et al., 1994; Hemphill-Haley, 1995; Atwater and Hemphill-Haley, 1997; Nelson et al., 1996a; Shennan et al., 1996; Shennan et al., 1998; Patterson et al., 2000; Kelsey et al., 2002; Nelson et al., 2004; Leonard et al., 2010). The application of microfossil-based transfer functions, which quantify the relationship between microfossil species and elevation in modern tidal wetlands, to reconstruct past RSL changes (e.g., Guilbault et al., 1995, 1996; Horton et al., 1999; Gehrels, 2000; Horton and Edwards, 2006; Kemp et al., 2009a) yield estimates of coseismic subsidence with sufficiently small errors (<±0.3 m) to constrain geophysical models of megathrust slip (e.g., Guilbault et al., 1995; Hughes et al., 2002; Hawkes et al., 2011; Wang et al., 2013).

Although microfossil-based transfer function methods have revolutionized studies of Holocene RSL change (e.g., Horton et al., 1999; Horton and Edwards, 2006), questions have been raised about how taphonomic processes have influenced the accuracy of foraminiferal transfer function estimates of RSL change (e.g., Edwards and Horton, 2000; Barlow et al., 2013). For example, foraminiferal assemblages may be altered due to oxidation in soils, or through bacterial degradation of test cement in selected species (e.g., Goldstein et al., 1995; Goldstein and Watkins, 1999; Culver and Horton, 2005; Berkeley et al., 2007). Such processes depend on many factors: sediment accumulation rate, the thickness of the zone of oxidation in now-submerged soils, the amount and depth of bioturbation, the residence time of agglutinated tests within the zone of oxidation, and temperature (Berkeley et al., 2007). At Cascadia and Alaska, the extent to which taphonomic processes, such as post-depositional downward mixing of microfossil species or reworking of species by tsunamis, influence the accuracy of coseismic subsidence estimates is little studied (e.g., Hemphill-Haley, 1995; Nelson et al., 1996b, 2008; Hamilton et al., 2005; Graehl et al., 2014). For example, in a transplant experiment simulating sudden subsidence during an earthquake in southern Oregon, Engelhart et al. (2013a) attributed an unexpected abundance of the typical tidal-flat foraminiferal species *Miliammina fusca* in the underlying peat to infiltration of overlying tidal-flat mud into the peat.

Although our work is limited to one site in a tidal marsh at Talbot Creek (South Slough, Coos Bay) in southern Oregon (Figs. 1 and 2; Nelson et al., 1996b, 1998), we address the problem of imprecise subsidence estimates for earthquakes by using the characteristics of and changes in foraminiferal assemblages to make subsidence estimates of improved precision. For the first time at Cascadia, we address the reproducibility of microfossil estimates of subsidence through comparison of independent estimates in adjacent cores. In concert with our foraminiferal analyses, three-dimensional X-ray tomography scans of cores (CT scans; e.g., Davies et al., 2011)—previously applied at Cascadia only to marine turbidite sequences (e.g., Goldfinger et al., 2012)—help us to assess the influence of taphonomic processes on the accuracy of subsidence estimates. Finally, we use our foraminiferal analyses and CT-scan sedimentology with previously studied tidal-marsh stratigraphy, additional radiocarbon ages, and correlation to other coastal stratigraphic sequences to interpret which contacts at our site formed as a result of subsidence during megathrust earthquakes (six contacts) and which contacts lack sufficient data from which to infer an earthquake versus non-earthquake origin (one contact).

2. Setting

We studied the stratigraphy beneath a small tidal marsh near the head of a 100-m-wide, steep-sided valley drained by Talbot Creek in a heavily forested part of the South Slough National Estuarine Research Reserve (NERR), a federally protected part of the Coos Bay estuary in southern Oregon (Fig. 1B–D; Rumrill, 2006). Grazing with modest drainage and compaction (Caldera, 1995; Cornu and Sadro, 2002) of the upper few tens of centimeters of sediment has not disturbed the stratigraphy beneath formerly diked marshes in South Slough (Nelson et al., 1996b, 1998). At the Charleston NOAA tide gauge station, at the mouth of South Slough, the observed great diurnal range (Mean Highest High Water, MHHW - Mean Lowest Low Water, MLLW) is 2.32 m (ID 9432780; http://tidesandcurrents.noaa.gov/index.shtml). Vascular plant communities near our core site in the Talbot Creek marsh are dominated by typical middle-to-high marsh flora including *Distichlis spicata*, *Carex lyngbeyi*, and *Deschampsia cespitosa*, with common *Triglochin maritima, Argentina egedii*, and *Agrostis alba*.

We selected the Talbot Creek site near the southern end of South Slough (Fig. 1C and D) because the existing tidal-marsh stratigraphic framework (Nelson, 1992; Ota et al., 1995; Nelson et al., 1996b, 1998; Figs. A1 and A2) shows that this estuary has an unusually long and distinct record of earthquake subsidence, and so is a key paleoseismic site along the Cascadia subduction zone. Stratigraphic sequences in the southern half of the slough consist of mud-peat couplets where tidal mud gradually grades into high marsh peat, and then the peat is sharply overlain by tidal mud of the next couplet, forming a peat-mud contact. Nelson et al. (1996b, 1998) identified as many as 10 mud-peat couplets in South Slough, but found only 3 to be widespread with consistently sharp upper contacts (contacts A, D, and E; Fig. 2). A distinct bed of clean sand forms a sharp contact at the top of the youngest buried couplet about 0.5 m below the present marsh surface at many sites in the slough (Nelson et al., 1998). The sand was probably deposited by the tsunami accompanying the great earthquake of 1700 CE (e.g., Satake et al., 2003; Nelson et al., 2004; Atwater et al., 2005). Older peat-mud contacts, which generally lack sand, are less distinct, more restricted in lateral extent, and found at fewer sites. At the Talbot Creek site, Ota et al. (1995) and Nelson et al. (1998) described 11 cores along two transects 140 m apart (Figs. 1D and A1), whose stratigraphy closely matched 8 of the 10 mud-peat couplets identified at the Winchester Creek site, 1.8 km to the southwest (Nelson et al., 1996b; Fig. A2).

3. Approach and methods

3.1. Stratigraphy and dating

In our three vibracores (70-mm diameter) from the Talbot Creek marsh we identified seven peat-mud contacts (A to G), which we