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. © 2016 Elsevier Ltd. All rights reserved.

1. Introduction
Due to favorable (1–2 mm/yr) rates of Holocene relative sea-level 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...
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; Corro and Sardo, 2002) of the upper few tens of centimeters of sediment has not disturbed the stratigraphic body 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-peat 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-peat 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
correlate with the peat-mud contacts of Nelson et al. (1996b) at Winchester Creek (Figs. 1D and 2, and A1–A5). Cores 1 and 2 were taken within 3 m of Core TC-1 of Nelson et al. (1998, their Fig. 2; Fig. A1); the three cores coincide with a southwest-trending transect of seven gouge cores (2.5-cm-diameter) described by Ota et al. (1995) and Nelson et al. (1998). Samples above and below contacts in cores 1 and 3, and from three contacts (A, E, G) in core 2, were used for foraminiferal analyses. Most radiocarbon samples came from core 2; contacts B and C were also sampled in cores 1 and 3.

In core 3, we identified an oldest contact (contact H; Figs. 2 and A5), but it is poorly dated (Table 1) and we have too little information about its origin to consider it further (analyses of contact H are summarized in Fig. A6). Inconsistent interpretations based on lithology and four diatom samples prevented Nelson et al. (1996b) from inferring an origin for their correlative contact 9 at Winchester Creek.

Cores were split, photographed, and wrapped for transport two days after collection. Later, we imaged the cores with a three-dimensional X-ray (CT) scanner (e.g., Fig. 3; methods of Rothwell and Rack, 2006; Davies et al., 2011), described their lithostratigraphy in detail using the Troels-Smith (1955) system for describing organic-rich sediment, and noted sediment color with Munsell color charts (methods of Nelson, 2015). Following Nelson et al. (1996b), we supplemented our descriptions of muddy units by examining smear slides (methods of https://tmi.laccore.umn.edu; Myrbo et al., 2011). Undistorted, color-corrected photo mosaics of each core were constructed from the photographs taken minutes after core splitting (Figs. A3–A5). Because the vibracores compacted (11–30%) during collection, our sampling depths are measured upward from the base (greatest depth reached) of each core. Depths of lithologies and contacts in the three cores, corrected for compaction, are shown only in Fig. 2.

Thirty samples of plant macrofossils from the cores were 14C dated by accelerator mass spectrometry (AMS; Tables 1 and A1; Fig. 4; including 10 ages from Nelson et al., 1998, their table 1) to determine maximum or minimum ages for the times when marshes were rapidly buried and sharp contacts A-G formed. Samples were selected by washing 3- to 5-mm-thick, vertical slices of sediment on a 1-mm sieve under a binocular microscope (6–50 ×; methods of Kemp et al., 2013a); most samples were from 0 to 40 mm above or below peat-mud contacts. To obtain maximum ages of the time of marsh burial, we used detrital plant materials, such as the needles, twigs, or leaves of trees that grow along the edge of the marsh, moss stems, or seeds. Minimum ages of the
times of burial were obtained from in situ post-contact plant macrofossils, such as the rhizomes of low-marsh colonizing plants (Triglochin maritima and Carex sp.) in mud above peat-mud contacts. In two cases (contacts F and G), we used ages on adjacent samples to infer that detrital samples in the mud above contacts gave minimum ages. We used OxCal stratigraphic ordering software (Bronk Ramsey, 2008, 2009; Lienkaemper and Bronk Ramsey, 2009) to calculate a probability distribution for the times of marsh burial (contacts A-G) from the calibrated-age probability distributions for 14C ages inferred to be the most accurate maximum and minimum ages (Table 1; methods described by DuRoss et al., 2011; and Nelson et al., 2014).

3.2. Foraminiferal transfer function analysis

With the exception of contact B in cores 1 and 3, we analyzed foraminiferal assemblages in four consecutive, 10-mm-thick sediment samples above each peat-mud contact and four below. In core 1 we took 52 samples above and below seven peat-mud contacts (A to G), and in core 2 we took 24 samples above and below peat-mud contacts A, E, and G. Contacts B to G were sampled with 50 samples from core 3. Samples were stored in 50% ethanol solution and refrigerated at 4 °C prior to analysis. If necessary, samples were treated with 5% sodium hexametaphosphate for 24 h to disaggregate flocculated clay. Samples were washed through 500 μm and 63 μm sieves. The greater than 500 μm fraction was examined for larger foraminifera before being discarded. For more abundant samples, we used a wet-splitter (Scott and Hermelin, 1993) to split the fraction between 63 and 500 μm into eight equal parts, as described by Horton and Edwards (2006).

Foraminiferal tests were counted wet to prevent drying of the organic residue (de Rijk, 1995), and identified following the taxonomic illustrations and descriptions in Gehrels and Newman (2004), Horton and Edwards (2006), Hawkes et al. (2010), and Wright et al. (2011; counts in Table A2, percentages in Figs. 5 and 6). The genus Jadamina was replaced by Entzia because Jadamina is a junior synonym of Entzia (Filipescu and Kaminski, 2011). Tests of the genus Ammobaculites were combined into a single group because the tests of these species were often broken, making it difficult to identify them to species level (Kemp et al., 2009b; Engelhart et al., 2013b). Calcareous species were absent in the cores, but we grouped their organic inner linings into a single calcareous species group to account for early diagenetic dissolution effects (e.g., Edwards and Horton, 2000; Hawkes et al., 2010; Milker et al., 2015a, b).

In developing our transfer function, we added modern foraminiferal data from a marsh at Toms Creek, South Slough (Milker et al., 2015b, Fig. 1C) to the previous regional data set of samples from six estuaries (Coquille River, Coos Bay, Suslal River, Siletz Bay, Salmon River and Nehalem River estuaries; Fig. 1A and B; Hawkes et al., 2010; Engelhart et al., 2013b) compiled by Engelhart et al. (2013a). The new data increased the number of modern samples from 158 to 174 (Table A3). The expanded data set includes 16 agglutinated foraminiferal species, and a group of calcareous species (including organic linings) and thecamoebians. Haplophragmoides species, except for H. manilaeensis and H. wilberti, were similarly grouped as Haplophragmoides spp. due to their low abundances. We standardized the elevation of each modern sample in the added data set to a standardized water level index (SWLI), which allows for differences in tidal range from site to site (e.g., Horton et al., 2000; Kemp and Telford, 2015).

For the transfer function analysis (C2 software of Juggins, 2003; version 1.7.2), we followed the widely used Weighted Averaging-Partial Least Squares (WA-PLS) method due to the unimodal nature of the foraminiferal data (Engelhart et al., 2013a). We ran an initial transfer function on our modern (percentage) data to identify samples with residuals larger than twice the standard deviation of the residuals (14 samples; 8.8%), which were then removed from the analysis. Using the remaining 160 samples, we selected the first component having a cross-validated (bootstrapped; 1000 cycles) coefficient of determination of $R^2_{\text{boot}} = 0.88$ between the observed and predicted elevations, and a root mean squared error of prediction (RMSEP) of 6.78 SWLI (0.16 m; Table 2; Fig. A7). This value is 6.8% of the tidal range, a performance that is comparable to other microfossil-based transfer functions (e.g., Barlow et al., 2013). By adding modern samples from Toms Creek (Fig. 1C) to those compiled by Engelhart et al. (2013a), we slightly improved the performance of the transfer function compared to the performance of their function. Because almost all the errors on our transfer function estimates of submergence across peat-mud contacts are ±0.22 m (Table 1), we do not list errors for estimates in the text.

Cross-validation was used for evaluating the sample-specific errors of prediction in the fossil datasets (Birks et al., 1990; Horton and Edwards, 2006). For calculation of the amounts of submergence and their errors, we followed Hamilton and Shennan (2005) and Hawkes et al. (2011), where submergence ($S_e$) is calculated by subtracting the estimated elevation, relative to North American vertical datum (NAVD)88, of the most reliable pre-contact (peat) sample ($E_{\text{pre}}$) from the most reliable post-contact (mud) sample ($E_{\text{post}}$) (Fig. 7). The errors are calculated by the square root of the squared sample specific error of the pre-contact sample ($E_{\text{pre error}}$) and the squared sample specific error of the post-contact sample ($E_{\text{post error}}$) (Eq. (1) and (2)).

$$S_e = E_{\text{pre}} - E_{\text{post}}$$

$$S_e \text{ error} = \sqrt{(E_{\text{pre error}})^2 + (E_{\text{post error}})^2}$$

We successfully tested the significance of our reconstructions by applying the random (transfer function)TF (999 random models) test of Telford and Birks (2011) to the core samples. We performed the test in R (Development Core Team, 2015) using the palaeoSig (version 1.1–3; Telford and Trachsel, 2015) rioja (version 0.9–5; Juggins, 2015) and vegan (version 2.3–3; Oksanen et al., 2016) packages. The randomTF test shows that the proportion of variance in our fossil core data explained by our reconstructions is >95% of the proportion explained by alternative models trained on random environmental data (Fig. A8).

We applied the Modern Analog Technique (MAT), which uses dissimilarity coefficients (MinDC, minimum distance to closest analog; Birks, 1995) to test the degree to which the foraminiferal assemblages in the modern samples provide close analogs for the fossil assemblages. We selected the squared chord distance (Overpeck et al., 1985) as the distance metric and the five closest modern samples for the MAT. Samples with coefficients lower than the 20th percentile were defined as close analogs and samples with coefficients larger than the 20th percentile as no close analogs (Horton and Edwards, 2006; Kemp and Telford, 2015). By adding new modern data from Toms Creek to those compiled by Engelhart (2013a), we expanded the range of modern analogs, resulting in a better similarity between modern and fossil assemblages that improved the ecological plausibility of our RSL reconstructions (Fig. A9).

4. Peat-mud contacts: stratigraphy, age, foraminiferal analyses, correlation, and origin

By comparing lithologic descriptions, mosaics of core photographs and CT imagery, we identified the same seven mud-peat
Fig. 2. Simplified lithology of vibracores 1 and 2 (43°17'18.94"N, 124°18'02.66"W; 2.35 m NAVD88) and 3 (43°17'18.78"N, 124°18'02.87"W; 2.28 m NAVD88) at the Talbot Creek site showing correlation of peat-mud contacts A-G. Analyses of contact H in core 3 are summarized in Fig. A6. Core depths are shown relative to present-day elevation (mean tide level). Depths of core contacts were corrected for 11–30% compaction during vibracoring using contacts in uncompacted gouge cores. Most of the compaction was in the upper 1.5 m of the cores. Calibrated 14C ages (ka; mode of 14C age distribution rounded to nearest century) are shown for samples above and below contacts (data in Tables 1 and A1).
Fig. 3. Color photographs (leftmost column) and three-dimensional X-ray (CT) scans (differences in sediment density shown by black and white, and color gradient (red, orange and yellow colors = denser sediment; blue and green colors = less dense sediment), images of the same scan) of peat-mud contacts A to G in core 1, and contacts A to G in cores 2 and 3. Successive vertical CT scans across these contacts show that the illustrated sections are representative of the distinctness and topography of these contacts in these cores. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
couplets described by Nelson et al. (1998) at the same site (Figs. A1 and A2) and use the same labels for their upper peat-mud contacts A through G (Figs. 2 and A3–A5). Most of the 25- to 60-mm-thick couplets consist primarily of 2–30 mm of silt grading upward into clayey silt; rooted, organic-rich clayey silt; rooted peaty silt; silty peat; and peat. The Data Depository of Nelson et al. (1996a) includes grain-size data and detailed descriptions of identical lithologies at the Winchester Creek site. Less distinct couplets below contacts B, C, and E are capped by peaty mud or muddy peat (Fig. 2). Freshly exposed peat units typically show 5YR to 7.5YR color hues, muddy peat commonly has 10YR hues, and the hues of muddy units range from 2.5Y to 5Y with lighter color values than darker peaty units.

4.1. Peat-mud contact A

Contact A is visually distinct and CT scans show that the contact spans <1 mm in cores 1 and 2 suggesting a rapid change in environment. The contact is less distinct in core 3 where it has a <10 mm-thick layer mud above it (Figs. 3 and A5). The 4- to 6-cm-thick fibrous peat below the contact in cores 1 and 2, and the 1-cm-thick peat of core 3, have a weak to moderate granular structure.
Fig. 5. Fossil foraminifera in samples across peat-mud contacts identified in Talbot Creek core 1. Shown are the relative abundance (percent) and total number (per 10 cm³ sediment volume) of the most common species. Samples containing mixed assemblages are shown in lighter colors. Peat-mud contacts are labeled A to G. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 6. Fossil foraminifera in samples across peat-mud contacts identified in Talbot Creek cores 2 and 3. Shown are the relative abundance (percent) of the most common species and total number of foraminifera (per 10 cm³ sediment volume) above and below peat-mud contacts E and G in core 2 and B, C, D and F in core 3. Samples containing mixed assemblages are shown in lighter colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
typical of the AO horizons of infrequently flooded soils near the high marsh-upland transition (Fig. 2; e.g., Nelson et al., 1996b, 1998). The 2- to 3-mm-thick beds of coarse silt with silty to very fine sand laminae, immediately overlying the contact in cores 1 and 2 reflect surges of water containing unusually coarse sediment (Figs. 3 and A4). Above the laminae, silt and clayey silt then grade...
Table 1
Estimated ages of contacts, submergence across contacts, and radiocarbon and other data for samples from Talbot Creek vibracores.*

<table>
<thead>
<tr>
<th>Contact</th>
<th>Estimated age (cal yr BP)b</th>
<th>Amount of submergence (m)c</th>
<th>Calibrated age (cal yr BP)b</th>
<th>Lab-reported age (14C yr BP)c</th>
<th>Old ages (Nelson et al., 1996a, 1998)d</th>
<th>Provenance interpretation</th>
<th>Coref</th>
<th>Depth (m)g</th>
<th>Description of dated material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact A</td>
<td>505–90</td>
<td>0.31(1)</td>
<td>505–330</td>
<td>390 ± 15</td>
<td>maximum 1</td>
<td>2 1.04</td>
<td>Fragments of soft woody herb stem in upper 1 mm of A horizon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact B</td>
<td>1020–545</td>
<td>0.01(1)</td>
<td>635–525</td>
<td>560 ± 20</td>
<td>minimum 1</td>
<td>1 1.94–1.98</td>
<td>Leaf sheaths, probably <em>Triglochin maritima</em>, in mud 3 cm above contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact C</td>
<td>1280–1190</td>
<td>0.63(3)</td>
<td>1290–1180</td>
<td>1310 ± 20</td>
<td>minimum 2</td>
<td>1 1.34–1.35</td>
<td>Least abraded fragment of bark from mud 1 cm above contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact D</td>
<td>1610–1535</td>
<td>0.53(1)</td>
<td>1700–1420</td>
<td>1670 ± 15</td>
<td>minimum 2</td>
<td>1 2.15</td>
<td>Fragments of leaves, probably Salal, in mud 1 cm above contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact E</td>
<td>2375–2180</td>
<td>0.31(1)</td>
<td>2425–2930</td>
<td>2350 ± 20</td>
<td>minimum 2</td>
<td>1 2.74–2.78</td>
<td>4 fragments of well preserved yellow roots in mud 0–4 cm above contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact F</td>
<td>2945–2775</td>
<td>0.57(1)</td>
<td>2980–2795</td>
<td>2800 ± 30</td>
<td>maximum 2</td>
<td>1 3.13–3.15</td>
<td>3 well preserved <em>Picea stichensis</em> leaves in mud above contact; thrust into mud by falling tree</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact G</td>
<td>3360–3210</td>
<td>0.61(1)</td>
<td>3450–3360</td>
<td>3170 ± 20</td>
<td>maximum 1</td>
<td>1 4.02–4.05</td>
<td>2 <em>Tsuga heterophylla</em> leaves; 2 moss (cf. <em>Fontinalis</em>) stems on contact</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Ages are on flat-lying or rooted plant parts collected above or below sharp peat-mud contacts in vibracores (Fig. 2).
* Ages of the age (in solar years BP) of contacts based on selected ages (shown in bold in third and fourth columns) using the sequence analysis feature of the program OxCal (version 4.3; Bronk Ramsey, 2009; probability method). Sample 14C ages selected on basis of quality of material dated and stratigraphic context (rightmost column). Estimates are 2σ time intervals of probability distributions between maximum and minimum ages calculated using OxCal and rounded to nearest 5 years. Estimates in parentheses give age interval for contact if selected age is a close maximum age rather than a minimum age (sixth column).
* Submergence (inferred to be coseismic subsidence for all but contact B) measured with foraminiferal transfer function. Estimates from core listed in parentheses. Estimates shown below one or both estimates for contact. Greater than symbol marks minimum estimate as explained in text.
* Maximum ages are on detrital samples containing carbon judged to be older than the contact, minimum ages are on samples judged younger than the contact, and " ages are those on samples judged to contain carbon produced within a few decades of the contact. Bold indicates ages that we use to set maximum and minimum limits on the ages of contacts with OxCal.
* Ages in supplementary data are on foraminiferal transfer function. Maximum ages are on detrital samples containing carbon judged to be older than the contact, minimum ages are on samples judged younger than the contact, and " ages are those on samples judged to contain carbon produced within a few decades of the contact. Bold indicates ages that we use to set maximum and minimum limits on the ages of contacts with OxCal.
* Depths (m; uncorrected for compaction). Depths of key units and contacts approximately corrected for compaction are shown in Fig. 2.
upward into peaty mud and muddy peat.

Contact A is younger than a detrital herb stem from the upper 10 mm of the peat (core 2) dated at 505–330 cal BP (solar years before 1950 CE, Table 1). Due to the broad plateau in the $^{14}$C calibration curve for the past 300 years, we conclude only that contact A predates settlement of southern Oregon in 1853 (e.g., Caldera, 1995).

In the peat below contact A in core 1, *Balticammina pseudomacrescens* is the dominant species, with a relative abundance between 63 and 88%, followed by *Trochammina inflata* (4–17%), *Trochammina irregularis* (2–9%) and *Entzia macrescens* (1–7%; Fig. 5). In the mud above the contact, *B. pseudomacrescens* decreases in abundance from 61 to 14%. An increasing abundance is observed for *T. inflata* (from 6 to 41%) and *E. macrescens* (from 12 to 42%) in the mud. *Miliammina fusca* has an abundance between 4 and 28% in the mud above contact A. The total number (concentration) of foraminifera (number per 10 cm$^3$ sediment volume) is considerably higher in samples of the peat (493–2603 specimens) compared to the mud (39–466 specimens; Fig. 5). From this consistent relationship, we infer high sedimentation rates for the muddy sediment, although other processes, such as differential test preservation among species and seasonal differences in reproduction, may also influence the concentration of foraminifera. Contact A in core 2, although more distinct than in cores 1 and 3 (Fig. A3–A5), has very low total numbers of foraminifera per 10 cm$^3$ sediment volume (260 specimens in peat; 118 specimens in mud), and many foraminifera are poorly preserved. For these reasons, we did not use core 2 faunas to estimate submergence for contact A. Because contact A is indistinct in core 3 and has <20 mm of peaty mud above it, we did not analyze it for foraminifera (Fig. A6).

Our transfer function gives 0.31 m (±0.23 m) of submergence (inferred below to be caused by coseismic subsidence) across contact A in core 1 (Fig. 7). For the measurement, we used the second sample in the mud above the contact because we interpret the first 8–18 mm of mud as a tsunami deposit (Fig. 3) containing mixed foraminiferal assemblages from different tidal environments (section 5). The low percentages of the tidal flat to low marsh species *M. fusca* with the high percentages of the middle and high marsh species *B. pseudomacrescens* in the mud (e.g., Hawkes et al., 2010; Engelhart et al., 2013b; Milker et al., 2015a, b; Fig. 5) is best explained by mixing. Nelson et al. (1998) interpreted changes in diatom florases across contact A at the site of cores 1 and 2 as reflecting >0.5 m and perhaps 1 m of coseismic subsidence, and Nelson et al. (1996b) made the same interpretation using foraminiferal and diatom assemblages across a correlative contact at Winchester Creek (labeled contact A on Fig. A2). At Winchester Creek, 2% *Ammodaculites* spp. and an increase in *M. fusca* to 78% in the mud just above contact A (Nelson et al., 1996b; their table DR3) suggest that transfer function results on Winchester Creek assemblages might yield a subsidence value of ~0.7 m, as they do for contacts with similar assemblages discussed below.

Based on its young age, shallow depth, submergence of 0.31 m, and widespread correlation to similar mud-peat couplets with sharp upper contacts throughout South Slough and Coos Bay (e.g., Nelson, 1992), we follow Nelson et al. (1996b; 1998) in inferring that contact A marks subsidence of the Oregon coast during the great earthquake of 1700 CE. The coarse silt and very fine sand laminae overlying the contact were probably deposited by a tsunami minutes after the earthquake, or perhaps by high tides carrying unusually high concentrations of sediment following disturbance of the estuary by subsidence and tsunamis (section 5). Earlier studies of Cascadia tidal marsh sequences have attributed similar contacts as much as 1100 km apart to the same earthquake and its tsunamis (e.g., Nelson et al., 1995, 2006; Benson et al., 1997; Valentine et al., 2012).

### 4.2. Peat-mud contact B

Contact B is one of the least distinct peat-mud contacts. Photographs of cores 1 to 3 show only a faint, grey-brown bed with a different texture (contact A); CT scans show a 1–2-mm-thick contact between peaty mud and >12 cm of overlying mud (clayey silt; Figs. 3, A3–A5). The scans also reveal 2–4 mm of coarse silt (higher density sediment shown by red colors on CT scans of Figs. 3, A3–A5) immediately above the contact.

The age of contact B is bracketed by a maximum age on a detrital fragment of bark 10 mm below the contact, and a minimum age on the leaf sheaths of a growth-position, low-marsh herb 30 mm above the contact. Using these maximum and minimum ages, the OxCal sequence analysis gives a broad age interval (2σ) of 1020–545 cal BP for the contact (Table 1; Fig. 4).

We found no distinct changes in foraminiferal assemblages across contact B in core 1. Samples above and below the contact are dominated by *T. inflata* (31–83%) and *E. macrescens* (10–20%). *B. pseudomacrescens* has a higher abundance (15–42%) in the peaty mud and a lower abundance of 6% in the overlying mud (Fig. 5). We found only low (<1%) percentages of *M. fusca* and *Trochammina ochracea* above and below contact B. However, total numbers of foraminifera (per 10 cm$^3$) are markedly higher in the peaty mud (6784–9374 specimens) than in the mud above the contact (1052 specimens; Fig. 5). In core 3, many foraminiferal tests were broken or flattened, with a relatively low total number of foraminifera (Fig. 6). We infer that many tests have been destroyed and that the assemblages are not representative of the environment in which they lived (section 5).

The transfer function analysis confirms little change in RSL across contact B in core 1 (submergence of 0.01 m, Fig. 7). Qualitative interpretation of diatom florases across contact B, and correlative contacts at Winchester Creek and Hidden Creek (Figs. 1C and A2), led Nelson et al. (1996b, 1998) to infer a probably gradual RSL rise of <0.5 m across contact B.

Although the age distributions for great earthquakes from Alsea Bay to the north (Nelson et al., 2008), Bradley Lake to the south (Kelsey et al., 2005), and from turbidites offshore (Goldfinger et al., 2012, Fig. 4) overlap with the broad age distribution for contact B, our data are insufficient to infer a coseismic origin for contact B. Even among sites in the southernmost part of South Slough, contact B is so indistinct that its correlation is uncertain (Nelson et al., 1998) and our transfer function analysis shows little change in RSL across the contact. Although inundation by a regional Cascadia tsunami remains a probable explanation for the coarse silt above contact B, our data are equally consistent with a local hydrodynamic origin, such as: (1) a local tsunami caused by coseismic vertical
deformation along a shallow fault or fold (Fig. 1B; Nelson et al. (1996b)); (2) breaching of a tidal restriction in the southern part of the slough (Nelson et al. (1996b; 1998); (3) a local tsunami produced by landsliding into the slough; or (4) seiches in the slough caused by strong ground motions during a large earthquake.

4.3. Peat-mud contact C

CT scans of contact C show a distinct, abrupt (0.5–1 mm), irregular (core 1) to planar (core 3) contact, with 2.2–40 cm of muddy peat and peaty mud below the contact grading down into rooted mud (Figs. 3 and A3–A5). As with contact A, 1–2 mm of coarse silt with some very fine sand capping the contact suggests an unusual surge of sand-laden water.

The age of contact C is bracketed by a maximum age on a detrital spruce needle in the muddy peat below the contact (with three other maximum ages are consistent), and by a minimum age on a growth-position rhizome of a common wetland sedge 60 mm above the contact. The OxCal sequence analysis gives an age (2σ) of 1281 ± 1150 cal BP for the contact (Table 1; Fig. 4).

The muddy peat and peaty mud below contact C are dominated by B. pseudomacrescens with an abundance of 67–89% in core 1 and 42–52% in core 3, followed by T. inflata (5–11% in core 1; 6–9% in core 3; Figs. 5, 6 and 8). T. irregularis and E. macrescens have a higher abundance in the muddy peat and peaty mud of core 3 with 6–8% and 7–13% compared to core 1 with an abundance of <1% for T. irregularis and 1–3% for E. macrescens. In the mud above the contact, M. fusca is the dominant species in both cores, with 33–48% in core 1 and 25–74% in core 3 and B. pseudomacrescens has an abundance of 17–27% in core 1 and 7–31% in core 3. Other important species and groups in the mud above the contact include organic linings of calcareous species (11–16% in core 1; 1–12% in core 3), E. macrescens (4–12% in core 1; 4–6% in core 3), and T. ochracea (2–10% in core 1; 0–5% in core 3). Paratrochammina haynesi is mainly restricted to core 1 with abundances of 2–10% and T. irregularis is mainly restricted to core 3, with abundances of 1–7%, respectively. The total number of foraminifera (per 10 cm³) is again higher in the peaty units (6442–11,091 and 8584–17,664 specimens) compared to the overlying mud (207–668 and 119–480 specimens) in cores 1 and 3, respectively (Figs. 5 and 6).

Amounts of submergence calculated for peat-mud contact C in cores 1 and 3 agree well: 0.63 m and 0.65 m, respectively. For the transfer function, we used the second mud sample above the contact for the transfer function estimates. The stratigraphic context of a detrital spruce twig—in the mud just above the contact—indicates that its age is a maximum. Three other maximum ages are consistent with the two limiting ages. If the tree leaf postdates contact C, the OxCal sequence analysis gives an age (2σ) of 1675–1545 cal BP for the contact (Fig. 4). If the leaf predates the contact (close maximum age), the OxCal analysis gives 1590–1320 cal BP for the age of the contact.

In the peat and muddy peat below contact D, B. pseudomacrescens is again the dominant species in cores 1 and 3 with 56–86% and 56–69%, respectively, followed by T. inflata with 3–11% and 17–33% (Figs. 5, 6 and 8). Other common species include T. irregularis, E. macrescens and M. fusca, with 2–9%, 1–4%, and 1–4% in the cores, respectively. The overlying mud is dominated by B. pseudomacrescens (36–48%) and M. fusca (24–30%) in core 1. In core 3, M. fusca is more abundant (33–54%) than B. pseudomacrescens (10–41%). Other common species and groups in cores 1 and 3 include organic linings of calcareous species (5–15%; 6–17%) and Ammobaculites spp. (2–13%; 1–4%). E. macrescens and T. ochracea are less abundant with 1–6% in the cores, respectively. As for most contacts, the total number of foraminifera (per 10 cm³) is much higher in peaty units: 3630–7085 specimens compared to 518–1191 specimens in the mud of core 1, and 6052–10,887 muddy peat specimens in core 3 compared to 180–341 mud specimens (Figs. 5 and 6).

Transfer function estimates of submergence for peat-mud contact D agree closely between cores: 0.53 m (core 1) and 0.56 m (core 3; Fig. 7). In both cores, the high numbers of B. pseudomacrescens in the first mud sample above the contact suggest mixing of faunas typical of tidal flat and high marsh environments, probably during rapid deposition of the first few millimeters of silt by tsunami or high tides (Figs. 3, 5 and 6). For this reason, we used the second mud sample above the contact for the transfer function estimates. Based on discriminant analysis of foraminiferal assemblages at Winchester Creek, and qualitative analysis of diatoms at Talbot Creek, Nelson et al. (1996b; 1998) inferred about 0.5–1.0 m of sudden submergence across contact D.

Nelson et al. (1996b; 1998) described contact D as one of two most distinct peat-mud contacts, widely correlated among all but the northernmost sites in the slough, and attributed it to submergence during a great earthquake. We affirm a coseismic interpretation, noting our estimates of substantial submergence across the contact, and that our narrow age distribution for contact D overlaps distributions for a great earthquake and/or tsunami at Bradley Lake, Coquille River, Alsea Bay, Yaquina Bay, Salmon River, and marine turbidite T5 (Figs. 1A and 4).
4.5. Peat-mud contact E

Contrasts in lithology across contact E, which can be confidently identified only through correlation of the CT scans, are less distinct than for most other contacts in the cores. The underlying mud-peat couplet is capped by muddy peat in cores 1 and 2 and peaty mud in core 3 rather than peat, as for most other contacts (Figs. 2 and 3 and A3–A5). CT scans show contact E to be abrupt (<1 mm) and irregular in core 2, sharp (1–2 mm) and very irregular in core 1, and gradational (3–8 mm) and irregular-to-broken in core 3 (Figs. 3 and A3–A5). The irregular contacts in cores 1 and 2 probably reflect sudden submergence of an originally irregular (trampled?) surface rather than erosion. Explanations for the less peaty lithologies beneath the contacts than for more distinct contacts include: submergence of a middle or low marsh rather than a high marsh, and erosion of the uppermost part of a marsh peat. The gradational contact in core 3, however, is inconsistent with an erosional origin.

 Fragments of probably in situ yellow roots in the mud above contact E provide a minimum age, whereas a detrital cedar bud and leaf tip in the mud provide a maximum age (Table 1; Fig. 4). Five other maximum ages are consistent with the selected maximum age. The OxCal sequence analysis gives an age of 2375–2180 cal BP for the contact (Table 1; Fig. 4).

Foraminiferal assemblages suggest little change in tidal environments across contact E in core 1 but a greater change in core 2. In the muddy peat below contact E, the assemblages are dominated by B. pseudomacrescens (54–57% and 35–53%) followed by T. inflata (17–28% and 14–44%), M. fusca (1–16% and <2%) and T. irregularis (3–7% and 9–22%) in cores 1 and 2, respectively (Figs. 5, 6 and 8). The assemblages in the rooted mud above contact E in core 1 are characterized by a lower abundance of B. pseudomacrescens (26–38%) but an increasing abundance of M. fusca (28–45%). The abundance of T. inflata is similar above and below the contact. The assemblages in the rooted mud above contact E in core 2 are dominated by M. fusca (32–61%) followed by B. pseudomacrescens (22–42%), T. inflata (7–15%) and H. wilberti (1–6%; Figs. 6 and 8). Only a few (<2%) organic linings of calcareous species, Ammobaculites spp. and E. macrescens were found above the contact. In core 1, the total number of foraminifera (per 10 cm$^3$) is slightly higher below contact E (1237–2509 specimens compared to 709–1352 specimens above the contact) and gradually increases upward (Fig. 5). In core 2, it is also slightly higher below contact E with 1523–4619 specimens compared to 1144–3867 specimens above the contact (Fig. 6). Due to the low total numbers of foraminifera in samples below contact E in core 3, and because up to 20% of the tests were badly preserved, we infer that many tests may have been destroyed and that assemblages may not be representative of the environment in which they lived (Fig. A6).

Transfer function estimates of submergence for peat-mud contact E are 0.61 m in core 2 but only 0.31 m in core 1 (Fig. 7). For the transfer function estimate of submergence in core 1, we used the fourth peat sample below the contact in core 1 because the high percentages of M. fusca in the first three peat samples below the contact suggest infiltration by muddy sediment containing mixed assemblages (section 5; Figs. 3 and 5). For this reason, the differences in the assemblages of the samples that we used to calculate submergence across this contact in core 1 do not represent the full range of submergence; the estimate is a minimum value. Our apparent submergence across contact E in core 2 is comparable to those in Nelson et al. (1996b; 1998) who inferred from discriminant and quantitative analyses of diatom assemblages at Winchester Creek and Talbot Creek, respectively, that subsidence across the contact was similar to that for contact D, about 0.5–1.0 m. Nelson et al. (1996b; 1998) found the lithologic changes marking contact E at Winchester Creek and Talbot Creek to be almost as distinct as for contacts A and D. They correlated contact E almost as widely among sites in South Slough as contact D and attributed it to subsidence during a great earthquake. Although contact E is less distinct in our cores, based on our estimate of 0.61 m for submergence in core 2, we infer contact E to record subsidence during a great earthquake. As our age distribution for contact E at Talbot Creek overlaps only the tails of age distributions for earthquake evidence at sites to the north and south (Fig. 4), correlation based on age distributions is not a strong argument for a coseismic submergence origin for contact E. Although our age distribution overlaps that for turbidite T5c, T5c is less distinct and less widely correlated than the primary turbidites correlated by Goldfinger et al. (2012, 2013) along much of the Cascadia margin. And although evidence for contact E is not well dated at other coastal sites, we follow Nelson et al. (1996b; 1998) in inferring the contact to record a great earthquake.

4.6. Peat-mud contact F

Contact F is very distinct in the three cores, with 9–16 cm of peat and muddy peat abruptly (<1 mm) overlain by silt to clayey silt (Figs. 2 and 3 and A3–A5). The topography of the contact, particularly in core 3, is irregular with 2- to 3-mm-long clasts of peat floating in the lower 25 mm of mud above the contact. Although no sand or coarse silt was noted overlying the contact in core descriptions, CT scans show a 20-mm thickness of coarse and fine silt laminations overlying the contact in core 3. The clasts and laminations suggest rapid deposition by tsunami or high tides immediately after submergence. Irregular, elongate patches of mud in the upper 30 mm of the peat in cores 1 and 3 suggest infilling of mud along cracks and root casts in the peat. Weak to very weak, fine, granular structure in the upper part of the peat in the three cores suggests a period of soil formation near the uppermost part of the marsh, like that inferred for the peat beneath contacts A and D.

Although we cannot be certain, the young age and excellent preservation of spruce needles in the mud above contact F suggests that they were thrust into the mud by a tree toppling into the marsh from its bordering steep forested slope (e.g., Nelson et al., 1996a, 1998). If so, the needles provide a minimum age for the contact. A well-preserved detrital moss stem in the mud probably provides a close maximum age for the contact. Three other maximum ages are consistent with the two limiting ages. With the selected maximum and minimum ages, the OxCal sequence analysis gives an age of 2955–2795 cal BP for the contact (Table 1; Fig. 4).

The assemblages from the peat below contact F in cores 1 and 3 are dominated by B. pseudomacrescens with 53–75% and 61–82%, respectively (Figs. 5, 6 and 8). T. inflata, T. Irregularis and E. macrescens are other important species, with 1–4%, 4–9% and 5–11% in core 1, and 4–13%, 4–8% and 1–4% in core 3. Miliammina petila and Entzia? sp. are abundant (9–28% and 3–10%) in the peat of core 1, but are absent from (M. petila) or occur in low numbers (Entzia? sp. with <2%) in the peat of core 3. Assemblages from the mud are dominated by B. pseudomacrescens with 35–43% and 16–57%, and by M. fusca with 24–31% and 23–48% in cores 1 and 3, respectively. Ammobaculites spp. (8–14%; 1–11%), organic linings (3–6%; 2–11%), T. inflata (3–9%; 5–11%) and E. macrescens (2–12%; 1–5%) are other common species in cores 1 and 3, respectively. Again, the total number of foraminifera (10 cm$^3$) is considerably higher in the peat (4194–5693 and 1925–5818 specimens) compared to the mud (163–323 and 206–653 specimens) in cores 1 and 3, respectively (Figs. 5 and 6). The transfer function estimates of submergence across contact F in cores 1 and 3 are 0.57 m in core 1 and 0.75 m in core 3 (Fig. 7). We used the second mud sample above the contact for the calculations in both cores, as we again observed a mixed assemblage (i.e., high...
percentages of $B.\ pseudomacrescens$ together with low percentages of species indicative of a tidal flat to low marsh environment, such as $M.\ fusca$, organic linings of calcareous species and $Ammobaculites$ spp.; Fig. 6) in the sediment just above the contacts. In core 1, we assume that the estimate is a minimum because for all mud samples in this core we found tidal flat-low marsh assemblages (abundant $M.\ fusca$, organic linings and $Ammobaculites$ spp.) mixed with apparently redeposited species indicative of a middle to high marsh (mainly $B.\ pseudomacrescens$ but also $T.\ irregularis$ and $T.\ inflata$; Fig. 5). Based on qualitative interpretation of diatom florases at Winchester Creek, Nelson et al. (1996b) inferred <0.5 m of sudden submergence across contact F.

Although the lithologic contrasts across contacts F and G were almost as distinct as those for contacts D and E, Nelson et al. (1996b; 1998) were able to correlate contacts F and G among only half their cores at Talbot Creek and Winchester Creek (Figs. A1 and A2). These authors attributed their uncertain correlations to other sites in the slough to incomplete older stratigraphic records. Our age distribution for contact F overlaps age distributions for earthquake and tsunami evidence at Sixes River, Bradley Lake, Coquille River, Yaquina Bay, and probably turbidite T7 (Fig. 4). Based on these probable age correlations and the 0.75 m of submergence measured in core 3, we infer contact F to record subsidence during a great earthquake.

4.7. Peat-mud contact G

Contact G is distinct in all cores, with clayey silt overlying 0.5–9 cm of peat and muddy peat (Figs. 2 and 3 and A3–A5). CT scans show the contact to be abrupt (<1 mm) and highly irregular-to-broken with clasts of peat in the overlying mud 1–5 cm above the contact. Particularly in core 3, the angular, broken contact and 1–3-mm diameter areas of coarse silt suggest erosion of the peat and(or) rapid deposition on an originally highly irregular surface (Fig. A5). In core 1, a few millimeters of coarse silt with <1-mm-thick very fine sand laminae support rapid deposition by an unusual pulse of sediment-laden water following submergence. Irregular patches of silt in the upper 3 cm of peat are distinct on CT scans of cores 1 and 2. The very weak, fine and granular structure of the peat in cores 1 and 3 again suggests a period of soil development near the upper edge of the marsh.

Because they are fragile, the dated detrital seeds and herb fragment in the mud above contact G probably provide a minimum age for the contact. Detrital fir needles and moss stems on the contact give a maximum age. Herb seeds from the underlying peat are a century older. Assuming the seeds in the mud above the contact give a maximum age. Herb seeds from the underlying peat and mud samples across the contact are dominated by $B.\ pseudomacrescens$ (48–81%) and contain high percentages of $M.\ fusca$ (2–21%) in the peat but low percentages of $M.\ fusca$ (5–9%) in the mud together with high percentages of $Ammobaculites$ spp. and organic linings (9–27% and 3–10%; Fig. A6). These differing assemblages on either side of the contact in core 3 suggest substantial mixing of faunas from different environments in the mud and infiltration of mud faunas into the peat. For this reason, the observed assemblages are not representative of the environment in which they lived, and we did not estimate submergence for this contact in core 3.

The transfer function gave substantial estimates of submergence across contact G: 0.61 m in core 1 and 0.67 m in core 2 (Fig. 7). For calculation in core 1, we used the third mud or peat sample above or below the contact, respectively, because we infer substantial mixing of faunas above the contact and significant infiltration below it (i.e., low percentages of $M.\ fusca$ but high percentages of $B.\ pseudomacrescens$ in mud samples and abundant $M.\ fusca$ in peat samples; Fig. 5). Similarly, for core 2 we used the second mud sample above the contact (e.g., high percentages of $B.\ pseudomacrescens$ in the first mud sample; Fig. 6). Although Nelson et al. (1996b) interpreted changes in foraminiferal assemblages across contact G at Winchester Creek as recording greater submergence than for any other contact (>0.75 m), lithologic, foraminiferal, and diatom evidence for submergence from the single studied core was inconsistent. Lithologic contrasts across a sharp contact and abrupt increases in $Ammobaculites$ spp., $Ammotium\ salsum$, and $Reophax\ nana$ suggested substantial coseismic subidence, whereas gradual changes in diatom florases were interpreted as a record of gradual submergence.

Our age distribution for contact G overlaps distributions for earthquake evidence at Sixes River, Coquille River, Yaquina Bay, and turbidite T8 (Fig. 4). Based on these age correlations and estimated submergence of 0.61–0.67 m, we infer contact G to record subsidence during a great earthquake.

5. Taphonomic processes that effect estimates of submergence

Taphonomic processes may have influenced faunas above and below submergence contacts, and so affected our transfer function estimates of submergence. Our data from three cores 2–43 m apart suggest that taphonomic alterations due to mixing of faunas from different tidal environments are highly variable and difficult to assess. We infer that mixing above and below contacts is primarily the result of two different processes: first, rapid deposition of muddy sediment containing faunas mixed from different environments above contacts; and second, infiltration of mud containing mixed faunas into cracks and pore spaces in marsh peat. In samples where they have a significant effect on assemblages, both processes will result in submergence estimates being minimum values. Bacterial degradation of foraminiferal tests may also have altered some assemblages (e.g., Berkeley et al., 2007).

5.1. Mixing above contacts

Our primary evidence for the mixing of faunas from different tidal environments above contacts is the unusual compositions of the faunas. As described above, substantial percentages of species most abundant in middle-to-high marshes, such as $B.\ pseudomacrescens$, $T.\ inflata$, and $T.\ irregularis$, in the mud above all contacts in at least one core are best explained by rapid deposition of sediment containing mixed faunas (Figs. 5, 6 and 8).

Lithology and sedimentary structures seen on CT scans support our inference of rapid deposition of 2–50 mm of coarse sediment above contacts. Contacts A, C, D, F, and G are overlain by a few
millimeters of coarse silt, and in the case of contacts A, C, and G, by minor amounts of very fine sand. Other signs of high sediment concentrations with rapid deposition above contacts include mud that fines upward, alternating coarse and fine laminations in mud (A, F), and clasts of peat in mud (D, F and G; Fig. 3). The abruptness of all contacts except B is also consistent with sudden changes in environment concurrent with rapid deposition.

Processes capable of mixing peat with mud faunas involve the remobilization of sediment from varied tidal environments following submergence during great earthquakes. Inundation by tsunamis accompanying great earthquakes is a primary process for eroding, transporting, and redepositing sediment (e.g., Dawson et al., 1996; Hawkes et al., 2007; Sawai et al., 2008; Milker et al., 2013; and the faunas therein) throughout South Slough. The lack of sand beds at Talbot Creek, like those commonly attributed to tsunamis, is easily explained by its distance inland (~7 km), by its location at the head of a sinuous, narrow valley protected by steep forested slopes (with heights up to 50 m), and its distance from sources of beach and dune sand commonly transported by tsunamis (Fig. 1B and C). But post-tsunami processes may have been equally important for mixing and depositing sediment and faunas above submergence contacts (Graehl et al., 2014). Higher tides in the weeks to months following coseismic subsidence and the erosion and redistribution of estuary sediment by tsunami backflow currents probably led to rapid tidal deposition of muddy sediment containing highly variable foraminiferal assemblages, even at inland sites like Talbot Creek. Tsunami and tidal erosion of blocks of marsh peat along tidal channels and the seaward edges of marshes throughout the slough could explain the high but variable percentages of middle-to-high marsh species in the mud above submergence contacts.

If this inference about depositional processes at Talbot Creek is correct, neither tsunamis nor subsequent tidal currents are likely to have been strong enough at our core site to significantly erode marshes following submergence. Although all contacts except B (and E in core 3) are sharp and irregular enough to be consistent with erosion of marsh surfaces, the crumbly soil structure of the upper few centimeters of the peat beneath contacts A, D, F, and G, which would reduce resistance to entrainment by strong currents, suggests minimal erosion of these contacts. Sharp contacts may mark sudden deposition as well as erosion. The irregular-to-broken topography of contacts D through G is similar to the topography of the modern marsh, and trampling by elk may have accentuated uneven contact topography. Peat clasts in the mud above contacts D, F, and G may have been eroded from marshes lower in the slough rather than from immediately underlying peat.

5.2. Mixing below contacts

We attribute the mixing of faunas below contacts to rapid infiltration of mud into cracks and decayed-root pore spaces in marsh peat immediately following coseismic subsidence. The best evidence of this mixing process includes the common to abundant tidal flat-low marsh species (i.e., M. fusca) in the peat beneath contacts D, E, F, and G (Figs. 3, 5 and 6, and A6), where middle-to-high marsh species would be most abundant. CT scans of peat show elongate, highly irregular, subhorizontal to subvertical, and 1- to 3-mm thick patches of mud 2–50 mm below contacts D, F, and G. Because the distribution of mud within the peat is so irregular and the variability of mixed assemblages in the infiltrated mud is probably high, we infer a highly variable degree of contamination of peat samples with mixed assemblages in infiltrated mud. Nelson et al. (1996b) inferred infiltration of foraminiferal assemblages across contact E at Winchester Creek (Fig. 1C) from the presence of Ammobaculites spp. and Ammotium salsum in the upper 5 mm of the peat below the contact. In a South Slough experiment simulating sudden submergence during an earthquake, Engelhart et al. (2013a) attributed tidal flat species in underlying peat to the infiltration of overlying mud.

Processes related to bioturbation, such as penetration of younger vascular plant roots across contacts followed by the gradual filling of root voids with younger muddy sediment when roots decay, faunal migration of foraminifera (e.g., Saffert and Thomas, 1998; Goldstein and Watkins, 1999; Culver and Horton, 2005), or burrowing by mollusks or crabs (e.g., Cisternas et al., 2005; Murray, 2006), may also influence foraminiferal assemblages below submergence contacts. However, these alternative processes either do not occur at Talbot Creek (mollusk or crab burrowing) or are unlikely to have influenced peat assemblages as much as rapid infiltration of mud following submergence. For example, total numbers of infaunal foraminifera were small compared to the total numbers of dead specimens in the surface samples in nearby Toms Creek marsh (Milker et al., 2015b), and hence, ifnaul migration of foraminifera should have little influence on fossil faunas at Talbot Creek.

5.3. Test decay through oxidation during interseismic emergence

Atwater and Hemphill-Haley (1997) interpreted the spotty occurrence and faint color of a buried marsh O horizon below the peat-mud contact of the 1700 CE earthquake in southwest Washington as the result of substantial oxidation of organic material in the buried O horizon during hundreds of years of emergence. At Talbot Creek, dominantly middle to high marsh species (such as B. pseudomacrescens and T. infilata) with as much as 20% degraded tests in the faint peaty horizons beneath contacts B and E in core 3 may indicate that these faunas have been altered through decay with possible oxidation of organic material in formerly more organic-rich (soil) horizons. However, the limitation of these effects to peaty samples from core 3, close to Talbot Creek near the center of the valley, suggests a localized, channel-margin increase in exposure of core 3 sediments rather than marsh-wide emergence during RSL fall. Thus, taphonomic alteration of foraminiferal assemblages through oxidation has not had a significant effect on our assemblages (except beneath contacts B and E, and then only in core 3) and, therefore, on our subsidence estimates.

6. Influence of ecology on submergence estimates

The ecological preferences of two foraminiferal species at Talbot Creek may, in some samples, lead to submergence estimates being minimums. The first is B. pseudomacrescens, which we find in high abundance in almost all mud samples above contacts (Figs. 5 and 6). In the mud this species co-occurs with high percentages of species common in modern tidal flat and low marsh environments (M. fusca, calcareous species, T. ochracea and Ammobaculites spp.) where B. pseudomacrescens mostly not has been observed (e.g., Hawkes et al., 2010, 2011; Engelhart et al., 2013b). High numbers of B. pseudomacrescens in modern salt marshes in southeastern Canada, southwestern Alaska and Newfoundland (Wright et al., 2011; Kemp et al., 2013b; Barnett et al., 2016), but lower numbers or its absence in Connecticut, Maine, New Jersey and North Carolina (Gehrels and van der Plassche, 1999; Edwards et al., 2004; Kemp et al., 2009b, 2012; Wright et al., 2011) may suggest a preference of this species for cool climates (Kemp et al., 2013b). However, high percentages of living B. pseudomacrescens in modern low marsh environments at Toms Creek marsh (up to 66%; Milker et al., 2015b, Fig. 1C), a site more influenced by brackish (23.8 psu; http://inss.nanos.org) than marine water (32.2 psu), imply that salinity as well as temperature may be an important control on the
distribution of *B. pseudomacrescens*. This inference is supported by dead foraminiferal assemblages in modern salt marshes of Massachusetts where high abundances (>20%) of *B. pseudomacrescens* (*T. macrescens* type A of de Rijk, 1995) are restricted to sites with mean salinities between 10 and 22 psu, with an optimum in abundance near 20 psu (de Rijk, 1995).

A second ecological reason why some of our samples might yield submergence minimums is due to the dominance of a single species—in this case *M. fusca*—near the lower end of the modern transects used to develop the transfer function. Our transfer function has low predictive ability below 60 SWLI units due to dominance by *M. fusca* (Fig. A7) and so submergence extending below this elevation at a site may not be included in a transfer function reconstruction of RSL change. When we encounter assemblages with abundances greater than ~70% of *M. fusca*, we flag subsidence estimates based on them as minimums.

7. **Significance and reproducibility of subsidence estimates**

Following Telford and Birks (2011) and Payne et al. (2016), we

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**Fig. 8.** Comparison of the relative abundance (percent) of foraminiferal species above and below peat-mud contacts C, D and G, used for submergence estimates in cores 1 and 3.
used the randomTF test to show that our transfer function reconstruction using fossil core data is statistically significant at the 95% level (Fig. A8). This contrasts with reconstructions from some other coasts where similar transfer functions frequently fail this test because the cores used for reconstructing RSL change were purposefully selected to display minimal downcore variability in species composition (Kemp et al., 2013c).

At Talbot Creek, we also tested the reproducibility of our transfer function estimates by comparing estimates for samples above and below peat-mud contacts C to F that are little influenced by mixing of foraminiferal assemblages (Figs. 7 and 8). The comparison shows close agreement of the amounts of coseismic subsidence for peat-mud contacts C, D and G (Fig. 7, Table 1). Our transfer function estimates in adjacent cores differ by less than half the analytical uncertainties (±0.22 to ±0.23 m) of each estimate. A greater difference is observed for contacts E and F (0.31 m versus 0.61 m, and 0.57 m versus 0.75 m, respectively), probably because core 1 estimates are minimums (section 4 and below).

Our results show that subsidence estimates agree closely for contacts C, D and G, despite some differences in species assemblage composition across each contact (Figs. 7 and 8). For contact C, assemblages in the mud samples are dominated by M. fusca (48 and 49%), pseudomacrescens (21% and 14%), organic linings (11% and 12%) and P. haynesi (0 and 12%) and assemblages in the peat samples are dominated by B. pseudomacrescens (67 and 43%), H. wilberti (11 and 0%) and T. inflata (9% each) in cores 1 and 3, respectively (Fig. 8). For contact D, the assemblages in the mud samples are dominated by M. fusca (30 and 33%), B. pseudomacrescens (36% and 29%), organic linings (15 and 10%) and T. inflata (3 and 9%) and the assemblages in the peat samples are dominated by B. pseudomacrescens (72 and 57%), T. inflata (11 and 20%) and T. irregularis (3 and 9%) in cores 1 and 3, respectively (Fig. 8). And for contact G, the assemblages in the mud samples are dominated by M. fusca (59 and 65%), B. pseudomacrescens (12 and 23%), T. inflata (18 and 8%) and Ammobaculites spp. (5 and 0%). The assemblages of the peat samples below contact G are dominated by B. pseudomacrescens (69 and 70%), T. inflata (17 and 14%) and T. irregularis.

8. Comparison of subsidence at Talbot Creek with other estimates in Oregon

We measured coseismic subsidence of 0.31 m for contact A, which we correlate with similar evidence attributed to the 1700 CE earthquake and tsunami along much of the subduction zone (e.g., Nelson et al., 1995, 2006; Witter et al., 2003; Graehl et al., 2014). Other estimates for the 1700 CE earthquake in central Oregon show variable amounts of coseismic subsidence, ranging between 0.20 m at Alsea Bay to >0.81 m at Coquille River (Figs. 1A and 9). Our low estimate may result from the influence on the transfer function of high percentages of B. pseudomacrescens in the mud above contact A at Talbot Creek. Alternatively, inter-site variability in coseismic subsidence during the 1700 CE earthquake has been attributed to a heterogeneous rupture pattern where patches of high-moment release were modeled with areas of low-moment release using a 3-D elastic dislocation model allowing slip to vary along both the strike and dip of the megathrust (Wang et al., 2013).

However, because Nelson et al.’s (1996b) qualitative data suggested 0.5–1 m subsidence across this contact, and Hawkes et al. (2011) used a similar foraminiferal transfer function to estimate subsidence at >0.67 m at Hidden Creek (only 2 km from Talbot Creek; Fig. 1C), our subsidence estimate is probably a minimum.

Contacts for which our transfer function gave more substantial (>0.3 m) estimates of subsidence, probably recording megathrust ruptures hundreds of kilometers long, include C, D, E, F, and G. Our estimates of 0.63 and 0.65 m for contact C are greater than estimates for correlative contacts at Alsea Bay (0.25 ± 0.21 m and 0.46 ± 0.12 m; Nelson et al., 2008), and at the Salmon River (<0.6 m; Nelson et al., 2004), although errors on estimates at all these sites overlap (Figs. 1A and 9). Our Talbot Creek estimates fall well within the Witter et al. (2003) broader, semi-quantitative estimates of subsidence for a contact C correlative at the Coquille River based on diatom zonations (0.4–2.3 m). For contact D, our estimates of 0.53...
and 0.56 m agree with the minimum estimate of 0.4–0.6 m for a correlative contact at Yaquina Bay (Graehl et al., 2014) and with the more qualitative estimate of <0.5 m based on pollen assemblages at the Salmon River (Nelson et al., 2004). Lower estimates for a contact D correlative at Alsea Bay (0.13 ± 0.12 m and 0.09 ± 0.20 m; Nelson et al., 2008) are problematic due to taxonomic uncertainties with foraminifera (Hawkes et al., 2011) and a diatom transfer function based on limited modern data. The broad range in subsidence (1–3 m) estimated from diatom zonation at the Coquille River easily encompasses our estimates for contact D (Witter et al., 2003).

Fewer comparisons are available for our estimated maximum subsidence of 0.61 m for contact E, 0.75 m for contact F, and 0.67 m for contact G. For contact E in South Slough, Nelson et al. (1996b, 1998) inferred 0.5–1.0 m of subsidence, whereas Witter et al. (2003) were only able to limit subsidence to 0–2.3 m for a possible correlative contact at the Coquille River (Fig. 9). Nelson et al. (2008) were unsure of the lateral extent, and therefore origin, of a contact of about the same age as contact F at Alsea Bay (their contact 2), for which they measured 0.21 m (+0.11 m) of subsidence. Graehl et al. (2014) estimated a minimum subsidence of 0.4–0.6 m for a contact G correlative at Yaquina Bay. Again using semi-quantitative estimates based on diatom zonation, Witter et al. (2003) and Kelsey et al. (2002) estimated broad ranges in subsidence of 0.4–2.5 m for contact F and G equivalents at the Coquille River (their contact 5) and Sixes River (their contact VI).

These comparisons suggest that the variable amounts of coseismic subsidence estimated for the 1700 CE earthquake (Fig. 9; Hawkes et al., 2011; Wang et al., 2013 and references therein) are probably also a feature of earlier earthquakes. The differences may reflect different rupture lengths, varying downdip rupture extents, or variations in the location of high-strength patches on the megathrust fault plane from earthquake to earthquake (e.g., Goldfinger et al., 2012; Wang et al., 2013).

9. Conclusions

Three vibracores from a protected, inland tidal marsh at Talbot Creek (South Slough, Coos Bay) show five distinct peat-mud contacts (A, C, D, F and G) and two less distinct contacts (B and E). We use the following evidence to infer that contacts A, C, D, E, F, and G record subsidence during great earthquakes on the Cascadia megathrust, most followed by tsunami inundation: changes in tidal environments across sharp contacts suggested by lithology and foraminiferal faunas; upward fining silt and sand, laminations, and peat clasts above contacts as observed on CT scans; transfer function estimates of submergence across contacts; correlation to other studied sequences in South Slough; and 14C-based correlations of Talbot Creek contacts to other Oregon sites with evidence for earthquakes and tsunamis. Talbot Creek data for contact B are insufficient to infer whether it records a great earthquake—perhaps it may have formed through local non-seismic hydrographic processes.

To estimate submergence across the contacts we used a new foraminiferal transfer function derived from an expanded (by 14%) regional dataset. Subsidence across the six earthquake contacts varies from 0.31 m to 0.75 m, although some of our estimates may be minimums due to the uncertain ecological preferences of B. pseudomacrescens and almost monospecific assemblages of M. fusca on tidal flats. Comparison of the coseismic subsidence estimates for contacts C, D and G in adjacent cores shows within-site differences of <0.10 m, less than the half the estimated errors of ±0.22 m.

Comparisons of our subsidence estimates with estimates from other Oregon sites suggest that the variable amounts of coseismic subsidence estimated for the 1700 CE earthquake are probably a feature of earlier earthquakes. But differences at sites such as Talbot Creek also reflect a host of variable site and process factors that affect the creation and preservation of stratigraphic evidence for coseismic subsidence (Nelson et al., 2006; Graehl et al., 2014). Not the least of these include taphonomic effects on microfossil assemblages, such as mixing and rapid deposition of mud following coseismic subsidence and tsunami inundation, and infiltration of mixed assemblages in mud into peat. Almost all evidence at most on-land sites along the subduction zone is exposed only in narrow-diameter (<70-mm) cores, and because of dating uncertainties, correlations of sharp contacts among sites using estimates of coseismic subsidence remain too problematic to settle debates about important aspects of Cascadia earthquake history, such as the lengths of past ruptures. Our results highlight the need for precise subsidence estimates from many more sites from which to draw a more comprehensive picture of the rupture extent and magnitude of great Cascadia earthquakes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2016.04.017.

References


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