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# Modern foraminifera, $\delta^{13}\text{C}$ , and bulk geochemistry of central Oregon tidal marshes and their application in paleoseismology

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1 **Modern salt-marsh foraminifera, flora and stable carbon isotopes of Siletz**  
2 **Bay, Oregon, and their application in paleoseismology**

3

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23

24 **Abstract**

25 We compared foraminifera, flora and geochemical ( $\delta^{13}\text{C}$ , total organic content and  
26 C:N) analyses to reconstruct the magnitude of coastal subsidence during the  
27 AD1700 great megathrust earthquakes at the Cascadia subduction zone. Four  
28 modern transects collected from three intertidal zones at Siletz Bay, Oregon, USA,  
29 produced three elevation dependent groups in both the foraminifera and  
30 geochemical datasets. Foraminiferal samples from the tidal flat and low marsh are  
31 identified by *M. fusca* abundances of > 45%, middle and high marsh by *M. fusca*  
32 abundances of < 45% and highest marsh by *T. irregularis* abundances > 25%. The  
33  $\delta^{13}\text{C}$  values from the geochemically defined groups decrease with increasing  
34 elevation;  $-24.1 \pm 1.7\text{‰}$  in the tidal flat and low marsh;  $-27.3 \pm 1.4\text{‰}$  in the middle  
35 and high marsh; and  $-29.6 \pm 0.8\text{‰}$  in the highest marsh samples. We applied these  
36 modern foraminifera and geochemical distributions to a core that contained the AD  
37 1700 earthquake. Both techniques produced similar results for the coseismic  
38 subsidence ( $0.88 \pm 0.39\text{m}$  and  $0.71 \pm 0.56\text{m}$ ) suggesting that  $\delta^{13}\text{C}$  has potential as a  
39 efficient proxy for use in paleoseismology.

40

41 **1. Introduction**

42 To evaluate and prepare for the impacts of future great earthquakes along the  
43 Cascadia subduction zone of North America, it is necessary to understand the  
44 magnitude and recurrence interval of previous earthquakes over geological  
45 timescales (Atwater, 1987; Charland and Priest, 1995; Clague, 1997; Wang and

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46 Clark, 1999; Peterson et al., 2000; Frankel et al., 2002; Kelsey et al., 2002; Petersen  
47 et al., 2002; Priest et al., 2010). Estuaries along Cascadia coasts archive stratigraphic  
48 evidence of great earthquakes (M 8-9) during the Holocene as records of abrupt  
49 relative sea-level (RSL) changes (Darienzo and Peterson, 1995; Nelson et al., 1996b;  
50 Shennan et al., 1998; Clague et al., 2000; Kelsey et al., 2002; Witter et al., 2003;  
51 Atwater et al., 2005; Nelson et al., 2006). Microfossil-based reconstructions have the  
52 potential to produced precise estimates of coseismic subsidence (Guilbault et al.,  
53 1995; Hemphill-Haley, 1995; Nelson et al., 1996a; Sherrod, 1999; Hughes et al.,  
54 2002; Nelson et al., 2008; Hawkes et al., 2011), because of the relationship between  
55 species distributions and elevation with respect to the tidal frame (Horton and  
56 Edwards, 2006).

57

58 Salt-marsh foraminifera have been commonly utilized to reconstruct changes in RSL  
59 in tectonically quiescent areas in Europe (Horton, 1999; Gehrels et al., 2001; Horton  
60 and Edwards, 2005; Edwards, 2006) and eastern North America (Scott and Medioli,  
61 1978; Gehrels et al., 2002; Gehrels et al., 2004; Leorri et al., 2006; Horton et al.,  
62 2009; Kemp et al., 2009b; Kemp et al., 2011; Wright et al., 2011). Quantitative  
63 foraminiferal-based reconstructions such as transfer functions (Kemp et al., 2011)  
64 have a precision of less than  $\pm 0.1$  m, which has led to similar applications in  
65 tectonic areas such as Cascadia (Guilbault et al., 1995; Guilbault et al., 1996; Nelson  
66 et al., 2008; Hawkes et al., 2010; Hawkes et al., 2011). Despite the obvious  
67 advantages, this technique is prone to problems associated with the site-specific

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68 nature of the assemblages (Wright et al., 2011) that necessitates the collection of  
69 multiple local datasets (e.g., Horton and Edwards, 2006; Kemp et al., 2011).  
70  
71 Stable carbon isotope analyses ( $\delta^{13}\text{C}$ , total organic carbon (TOC), Carbon to Nitrogen  
72 ratios (C:N) potentially provides the means to produce an alternative proxy for the  
73 reconstruction of past RSL changes (Tornqvist et al., 2004; Gonzalez and Tornqvist,  
74 2009; Kemp et al., 2010; Kemp et al., 2012). Its utility is derived from the  
75 assumption that bulk sediment stable carbon isotope values should reflect the  
76 botanical origin (Chmura and Aharon, 1995; Lamb et al., 2006; Gonzalez and  
77 Tornqvist, 2009; Kemp et al., 2010). Similar to foraminifera, plant species  
78 communities with different isotopic signatures are controlled by the strong  
79 elevational and environmental gradient found along the transition from freshwater  
80 to salt marsh and sub-tidal environments (Chmura et al., 1987; Goni and Thomas,  
81 2000). The application of stable carbon isotopes in bulk sediments in sea-level  
82 reconstructions is in its infancy, including studies in the UK (Lloyd and Evans, 2002;  
83 Wilson et al., 2005; Lamb et al., 2007; Mackie et al., 2007), US Atlantic (Kemp et al.,  
84 2010; Kemp et al., 2012) and US Gulf (Tornqvist et al., 2004; Gonzalez and  
85 Tornqvist, 2009) coasts.

86  
87 In this study, we investigated the modern distributions of foraminifera, flora and  
88 geochemistry from three salt marshes in Siletz Bay, Oregon that have differing  
89 salinity regimes. We defined elevation dependent ecological zones of foraminifera

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90 and compared them with  $\delta^{13}\text{C}$ , TOC and C:N to offer a method to reconstruct former  
91 sea levels, which we applied to a record of the AD 1700 earthquake at Siletz Bay.

## 92 **2. Study Area**

93 Siletz Bay is an estuarine system separated from the Pacific Ocean by Salishan spit  
94 (Figure 1B). The bay formed when the river valley was drowned by rising RSL  
95 during the Holocene transgression (Bottom et al., 1979; Peterson et al., 1984). The  
96 Bay drains an area of 524 km<sup>2</sup> (Seliskar and Gallagher, 1983) and contained 1.07 –  
97 1.46 km<sup>2</sup> of salt marsh in the early 1970s (Eilers, 1975; Jefferson, 1975), with an  
98 additional 0.4 km<sup>2</sup> reclaimed from previously dyked pastureland by the Siletz Bay  
99 National Wildlife Refuge in 2003. The Siletz River produces spatially variable  
100 salinity within the estuary with highest values near the inlet to the Pacific Ocean in  
101 the northwest of the Bay (Gallagher and Kibby, 1980). Salinity peaks from August to  
102 October with minimum values from January to March, associated with seasonal  
103 variations in flow (Oglesby, 1968). Salinity from open water measurements taken in  
104 July from surface waters in front of each site were recorded with values of 22 at  
105 Salishan Spit, 16 at Siletz East, and 11 at Millport Slough.

106

107 Siletz Bay has a mixed semidiurnal and diurnal tidal cycle with a tidal range (mean  
108 lowest low water (MLLW) to mean highest high water (MHHW) of 2.64 m (Hawkes  
109 et al., 2010). Short term tide gauges installed in the bay at Siletz Keys and upriver in  
110 Millport Slough indicated that there was less than 7 cm difference in mean high

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111 water (MHW) and MHHW elevations relative to North American Vertical Datum  
112 (NAVD) 88 (Brophy et al., 2011).

113

114 13 species of vascular plants were found in Siletz Bay in zones ranging from tidal  
115 flat, to salt marsh and terrestrial environments (Figure 2; Table 1). Dominant  
116 vegetation types included salt marsh species such as *Gaultheria* spp., *Potentilla*  
117 *palustris*, *Juncus* spp., *Agrostis* spp., *Salicornia virginica*, *Distichlis spicata*, *Scirpus*  
118 spp., *Carex lyngbyei* and *Zostera nana* and terrestrial taxa such as *Picea* spp. and  
119 *Conium maculatum*.

120

### 121 **3. Methods**

122 We collected samples from four modern intertidal transects. We established two  
123 transects at Salishan Spit (SS (A to A') and SS2 (B to B')) that were 115 and 146 m  
124 long respectively and 3 km from the Pacific Ocean inlet (Figure 1B and 1C). A 123 m  
125 transect 1.2 km inland of Salishan spit was established at Siletz East (D to D'), west  
126 of Route 101 (Figure 1B and 1D). The fourth transect was 95 m long at Millport  
127 Slough (E to E'), 1.8 km inland of Siletz East (Figure 1B and 1E). Stations were  
128 positioned along an elevational gradient to capture the full range of environments.  
129 Salt marsh plants at each sampling station were identified from lists of common  
130 species found in Pacific Northwest tidal marshes (Seliskar and Gallagher, 1983). We  
131 ascertained the elevation of each sample using a total station, which was tied to a  
132 local benchmark. The height of the local benchmark was obtained using real time



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133 kinematic (RTK) satellite navigation and reported relative to NAVD88. Elevations  
134 were converted to MSL to enable the use of site-specific tidal predictions (e.g. mean  
135 high water, MHW) generated for every 3 km of the Oregon coastline (Hawkes et al.,  
136 2010).

137

138 We collected a sample of 10 cm<sup>3</sup> of surface sediment (0-1 cm) at each station for  
139 foraminiferal analysis. The effects of infaunal foraminifera in Oregon marshes has  
140 been shown to be minimal with the highest concentration of living specimens in the  
141 top 1 cm and no live specimens found at depths greater than 5 cm (Hawkes, 2008;  
142 Hawkes et al., 2010). Samples were treated with buffered ethanol after collection  
143 and stained in the field using Rose Bengal to allow differentiation of live and dead  
144 specimens. Only the dead foraminiferal data used in the analysis as they most  
145 accurately reflect the subsurface assemblages (Murray, 1982; Horton, 1999; Culver  
146 and Horton, 2005). Each sample was divided in the laboratory using sieves to isolate  
147 the 63-500 µm fraction. The greater than 500 µm fraction was checked for large  
148 foraminifera. We counted the foraminifera using a binocular microscope from a  
149 known proportion until greater than 200 dead individuals were counted, or until the  
150 entire sample had been used. Our taxonomy follows Hawkes et al. (2001) with  
151 *Ammobaculites* spp. was identified as a single taxon.

152

153 We collected an additional 5cm<sup>3</sup> of surface sediment at each station geochemical  
154 analyses. Samples were prepared for δ<sup>13</sup>C and total organic carbon and nitrogen  
155 following REFS. The samples were washed with 5% hydrochloric acid for 24 hours

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156 before rinsing with deionised water, then dried at 45°C and ground to a fine powder  
157 using a mortar and pestle.  $\delta^{13}\text{C}$  values were obtained using a Costech Elemental  
158 Analyzer, coupled on-line to an Optima dual-inlet mass spectrometer. The values  
159 were calibrated to the Vienna Pee Dee Belemnite (VPDB) scale using cellulose  
160 standard Sigma Chemical C-6413 that was included within the runs. Sample %C and  
161 %N were calculated on the same instrument with C:N ratios calibrated through an  
162 acetanilide standard and presented on a weight-to-weight basis. Replicate  
163 measurements on well-mixed samples were never different by greater than 0.2‰.

164

165 To describe the distribution of foraminifera and geochemistry ( $\delta^{13}\text{C}$ , TOC, C:N), we  
166 used Partitioning Around Medoids (PAM) method (Kaufman and Rousseeuw, 1990;  
167 Kemp et al., In Press) and the 'cluster' package in the computer program R  
168 (Maechler et al., 2005). The most appropriate number of zones is identified by the  
169 highest average silhouette width of all zones. We ran the analysis for all four  
170 individual transects as well as a combined dataset; one foraminiferal and  
171 geochemical transect is shown as an example with the remaining transects in the  
172 appendix. For the foraminiferal data all analysis used percentages with no cutoff  
173 value for taxa inclusion (Kemp et al., In Press).

174

175 **4. Results**

176 **4.1 Modern foraminiferal, floral, and stable carbon isotope distributions**

177 **4.1.1 Salishan Spit Transect 1 (SS)**

178 At Salishan Spit transect 1 (A-A', Figure 1C), 12 species were identified in 24  
179 samples (Figure 2; Figure 3). The four highest elevation samples (SS-24 to SS-21)  
180 associated with highest marsh floral environments of *Gaultheria* spp. and *Juncus*  
181 spp. mixed with *Picea* spp. and ferns (Table 1) were dominated by *Trochamminita*  
182 *irregularis* (> 65%). This zone was associated with low  $\delta^{13}\text{C}$  values (-29 to -29.5‰),  
183 high TOC (12.2 to 28.8%) with C:N ratios from 14.3 to 16.9 (Figure 4). The high  
184 marsh of *Agrostis* spp., *Juncus* spp., *S. virginica* and *D. spicata* (SS-20 to SS-15) was  
185 characterized by *Trochammina inflata* (36 to 54%) and *Haplophragmoides*  
186 *manilaensis* (12 to 18%).  $\delta^{13}\text{C}$  values were greater than the highest marsh (-25.7 to -  
187 28.4‰), with reduced TOC (8.4 to 18.6%) but similar C:N values (11.8 to 13.7).

188

189 The *S. virginica* and *D. spicata* middle marsh (SS-14 to SS-10) recorded a switch in  
190 the dominance from *T. inflata* (37 to 0%) to *M. fusca* (22 to 99%) with decreasing  
191 elevation. The elevation of the middle marsh ranged from 1.14 to 0.67 m MSL. The  
192 input of  $\text{C}_4$  material from *D. spicata* may be evident in the  $\delta^{13}\text{C}$  values (-23.6 to -  
193 26.2‰), with a further fall in TOC (4.9 to 12.4%) but similar C:N values (10.6 to  
194 13.7) compared to the high marsh. The low marsh, vegetated by *Scirpus* spp. (SS-9 to  
195 SS-5) was characterized by near-monospecific *Milliammina fusca* assemblage (89 to  
196 99%).  $\delta^{13}\text{C}$  values continue to increase with further marine influence (-21.1 to -  
197 24.2‰), associated with a fall in TOC (0.3 to 1.5%) and C:N (1.7 to 8.7). The *Z. nana*

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198 tidal flat (SS-4 to SS-1) was also dominated by *M. fusca* (83 to 89%) but with the  
199 addition of *Reophax* spp. (5 to 10%). Despite the presence of the C<sub>4</sub> *Z. nana*,  $\delta^{13}\text{C}$   
200 values are similar to the low marsh (-23.2 to -23.6‰). TOC (1.0 to 1.4%) and C:N  
201 ratios (9.0 to 9.4) are also comparable to the low marsh.

202

203 PAM identified three foraminiferal groups (Figure 3): Group SS-Ia (average  
204 silhouette width 0.81) is dominated by *T. irregularis*; Group SS-Ib (average  
205 silhouette width 0.70) is identified by *T. inflata* and Group SS-II (average silhouette  
206 width 0.80) is dominated by *M. fusca*. PAM identified two geochemical groups.  
207 Group SS-G-I had an average silhouette width of 0.53 with  $\delta^{13}\text{C}$  value of  $-27.5 \pm$   
208  $1.4\text{‰}$ , TOC of  $14.5 \pm 5.6\%$  and C:N of  $13.3 \pm 1.5$ . Group SS-G-II (average silhouette  
209 width 0.73) is associated with  $\delta^{13}\text{C}$  values of  $-23.2 \pm 1.1\text{‰}$ , TOC of  $1.7 \pm 1.5\%$  and  
210 C:N of  $8.4 \pm 2.5$ . Group SS-G-I is associated with *T. inflata* and *T. irregularis* whilst SS-  
211 G-II is dominated by *M. fusca*.

212

#### 213 4.1.2 Salishan Spit Transect 2 (SS2)

214 At Salishan Spit transect 2 (B-B'; Figure 1C), 14 species were identified in 27  
215 samples (Figure 2; Supplementary Figure 1). The three highest elevation samples  
216 (SS2-1 to SS2-3) taken in the transition between highest marsh communities (*P.*  
217 *palustris* and *Gaultheria* spp.) and terrestrial environments (*C. maculatum* and  
218 ferns) did not contain any foraminifera. The  $\delta^{13}\text{C}$  are -27.5 to -28.4‰ with TOC  
219 ranging from 34.6 to 39.6% and C:N ratios of 21.0 to 29.2 (Figure 4). The highest  
220 sample with foraminifera (SS2-4) was dominated by *T. irregularis* (59%) with a low

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221 concentration (790 per 10cm<sup>3</sup>) and associated with *Juncus* spp. vegetation. The  
222 *Agrostis* spp., *S. virginica*, *Juncus* spp., *D. spicata* and *P. palustris* vegetated high  
223 marsh (SS2-4 to SS2-13) was dominated by *T. inflata* (maximum 66%) with  
224 contributions from *Jadamma macrescens* (maximum 23%) and *H. wilberti*  
225 (maximum 35%).  $\delta^{13}\text{C}$  values in this zone ranged from -28.5 to -24.8‰ and are  
226 associated with high TOC (9.1 to 29.9%) and C:N (11.6 to 19.2) values.

227

228 The middle marsh (SS2-14 to SS2-18) was vegetated by *D. spicata* and *S. virginica*  
229 and associated with increasing *M. fusca* (2 to 64%) and decreasing *T. inflata* (4 to  
230 60%) over an elevation range from 0.83 to 1.15 m MSL.  $\delta^{13}\text{C}$  values were lower than  
231 the high marsh (-21.3 to -24.6‰), with an associated decrease in TOC (3.6 to 7.1%)  
232 but similar C:N ratios (10.2 to 17.2). This vegetation zone is associated with  
233 increasing *M. fusca* and decreasing *T. inflata* abundances (0.83 to 1.15 m MSL). The  
234 *Scirpus* spp. low marsh (SS2-19 to SS2-22) is dominated by *M. fusca* (68 to 92%).  
235  $\delta^{13}\text{C}$  values are similar to the middle marsh (-22.2 to -23.6‰) but with a decrease in  
236 TOC (0.7 to 2.1%) and C:N ratios (8.5 to 9.6) The *Z. nana* vegetated tidal flat samples  
237 (SS2-23 to SS2-27) are also dominated by *M. fusca* (79 to 92%) with the addition of  
238 *Reophax* spp. (1-6%).  $\delta^{13}\text{C}$  values are similar to the low marsh (-23.1 to -24.2‰).  
239 TOC values remain stable (0.8 to 1.9%) as do C:N ratios (8.8 to 9.9).

240

241 PAM identified two foraminiferal groups (Supplementary Figure 1): Group SS2-I had  
242 an average silhouette width of 0.51 and was dominated by *T. inflata*; and Group SS2-  
243 II (average silhouette width 0.79) is identified by high abundances of *M. fusca*. PAM

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244 also identified two geochemical groups. Group SS2-G-I had an average silhouette  
245 width of 0.74 with  $\delta^{13}\text{C}$  value of  $-28.0 \pm 0.5\text{‰}$ , TOC of  $35.5 \pm 4.2\%$  and C:N of  $25.5 \pm$   
246 4.4. Group SS2-G-II (average silhouette width 0.71) is associated with  $\delta^{13}\text{C}$  values of  
247  $-24.3 \pm 2.0\text{‰}$ , TOC of  $6.2 \pm 5.9\%$  and C:N of  $11.8 \pm 2.8$ . Group SS2-G-1 is associated  
248 with samples absent of foraminifera or dominated by *T. irregularis* whilst SS2-G-II is  
249 dominated by *T. inflata* and *M. fusca*.

250

#### 251 4.1.3 Siletz East Transect (SE)

252 At Siletz East (C-C'; Figure 1D), 11 species were identified in 17 samples (Figure 2;  
253 Supplementary Figure 2). The highest marsh vegetation identified at the Salishan  
254 Spit transects was absent at Siletz East. The *Agrostis* spp., *Juncus* spp. and *D. spicata*  
255 high marsh zone (SE1 to SE3) was characterized by *T. inflata* (4 to 30%), *J.*  
256 *macrescens* (16 to 54%), *Balticammina pseudomacrescens* (3 to 28%) and *H. wilberti*  
257 (8 to 53%).  $\delta^{13}\text{C}$  values are consistent with input from  $\text{C}_3$  vegetation ( $-25.2$  to -  
258  $26.9\text{‰}$ ). TOC (2.1 to 5.6%) and C:N ratios (10.6 to 14.0) are similar to the bordering  
259 low marsh (Figure 4). The middle marsh vegetation zone seen at Salishan Spit is  
260 absent at Siletz East. The low marsh dominated by *C. lyngbyei* (SE4 to SE8) is  
261 associated with increasing *M. fusca* abundances (54 to 97%) with decreasing  
262 elevation (from 0.91 to 0.67 m MSL).  $\delta^{13}\text{C}$  are lower than the high marsh ( $-23.8$  to -  
263  $28.1\text{‰}$ ), with a fall in TOC (1.8 to 6.3%) and C:N ratios (8.4 to 14.0) with decreasing  
264 elevation. The unvegetated tidal flat (SE9 to SE17) was almost monospecific *M.*  
265 *fusca* (82 to 97%).  $\delta^{13}\text{C}$  were greater than the low marsh ( $-22.3$  to  $-25.4\text{‰}$ ), a trend  
266 also seen in TOC (1.4 to 2.9%) and C:N ratios (7.9 to 11.6).

267

268 PAM identified two foraminiferal groups (Supplementary Figure 2): Group SE-I  
269 (average silhouette width 0.46) is composed of *T. inflata*, *J. macrescens*, *B.*  
270 *pseudomacrescens*, and *H. wilberti*; Group SE-II (average silhouette width 0.87) is  
271 dominated by *M. fusca*. Similarly, PAM identified two geochemical groups. Group SE-  
272 G-I had an average silhouette width of 0.70 with  $\delta^{13}\text{C}$  values of  $-27.7 \pm 0.7\text{‰}$ , TOC of  
273  $5.4 \pm 1.0\%$  and C:N of  $13.9 \pm 0.2$ . Group SE-G-II (average silhouette width 0.63) is  
274 associated with  $\delta^{13}\text{C}$  values of  $-24.9 \pm 1.1\text{‰}$ , TOC of  $2.2 \pm 0.7\%$  and C:N of  $10.2 \pm 1.0$ .  
275 Group SE-G-I is associated with *J. macrescens*, *B. pseudomacrescens* and *H. wilberti*  
276 whilst SE-G-II is dominated by *M. fusca* and *T. inflata*.

277

#### 278 4.1.4 Millport Slough Transect (MS)

279 At Millport Slough (D-D'; Figure 1E), 11 species were identified in 11 samples  
280 (Figure 2; Supplementary Figure 3). Sample MS-4, the highest elevation sample on  
281 the transect (1.39 m MSL) associated with *C. maculatum* did not contain  
282 foraminifera. The *Picea* spp. swamp (MS-11 to MS-10) was associated with a mixed  
283 assemblage of *T. irregularis* (26 to 38%), *H. wilberti* (2 to 27%), *B. pseudomacrescens*  
284 (14 to 16%) and *J. macrescens* (14 to 31%).  $\delta^{13}\text{C}$  values were low ( $-29.1$  to  $-29.6\text{‰}$ )  
285 with high TOC (29.6 to 31.0%) and C:N ratios (20.7 to 21.9) (Figure 4). The high  
286 marsh was vegetated by *P. palustris*, *Triglochin maritima* and *Juncus* spp. (MS-9 to  
287 MS-5) and characterized by increased abundances of *T. irregularis* (30 to 61%), *M.*  
288 *petilla* (0 to 18%), *H. manilaensis* (3 to 24%), *H. wilberti* (2 to 35%), and *B.*  
289 *pseudomacrescens* (1 to 24%).  $\delta^{13}\text{C}$  was greater than in the *Picea* spp. swamp ( $-29.6$

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290 to -30.8‰) but with decreasing TOC (13.4 to 39.0%) and C:N ratios (14.1 to 28.0).  
291 The elevation ranged from 1.27 to 1.30 m MSL. Middle marsh vegetation is absent at  
292 this site. The *C. lyngbyei* low marsh (MS1 to MS3) is dominated by *M. fusca* (46 to  
293 93%) with *J. macrescens* (5 to 20%) and *H. wilberti* (1 to 17%).  $\delta^{13}\text{C}$  are lower  
294 relative to the *Picea* spp. swamp and high marsh (-27.5 to -28.1‰), a trend also  
295 seen in the lower TOC values (5.4 to 6.4%) and C:N ratios (13.2 to 15.3).  
296  
297 PAM identified two foraminiferal groups (Supplementary Figure 3): Group MS-I  
298 (average silhouette width 0.61) is dominated by *T. irregularis*; and Group MS-II  
299 (average silhouette width 0.57) is composed primarily of *M. fusca*. PAM also  
300 identified two geochemical groups. Group MS-G-I had an average silhouette width of  
301 0.61 with  $\delta^{13}\text{C}$  value of  $-29.9 \pm 0.6\text{‰}$ , TOC of  $30.2 \pm 5.5\%$  and C:N of  $21.4 \pm 4.0$ .  
302 Group MS-G-II (average silhouette width = 0.70) is associated with  $\delta^{13}\text{C}$  values of -  
303  $28.8 \pm 1.1\text{‰}$ , TOC of  $9.9 \pm 4.7\%$  and C:N of  $14.5 \pm 0.7$ . Group MS-G-I is associated  
304 with *T. irregularis*, *B. pseudomacrescens* and *H. wilberti* whilst MS-G-II is dominated  
305 by *M. fusca*, *J. macrescens*, *H. wilberti* and *T. irregularis*.  
306

#### 307 4.1.5 Combined Siletz Bay Dataset

308 We recorded 14 taxa (12 agglutinated and 2 calcareous) in the dead assemblage of  
309 79 samples from four modern surface transects at three sites in Siletz Bay.  
310 Foraminifera were absent in four samples, all of which occurred at greater than 1.39  
311 m MSL in areas of upland vegetation. The assemblages are dominated by



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312 agglutinated species including *B. pseudomacrescens*, *H. manilaensis*, *H. wilberti*, *J.*  
313 *macrescens*, *M. fusca*, *T. inflata* and *T. irregularis* (Table 1).

314

315 PAM identified three foraminiferal groups in the combined Siletz Bay dataset  
316 (Figure 5). Group SB-Ia (average silhouette width 0.44) is dominated by *T.*  
317 *irregularis* (Figure 5D). This foraminiferal assemblage is associated with highest  
318 high marsh environments at Salishan Spit transects 1 and 2 and the high marsh and  
319 *Picea* spp. swamp environments at Millport Slough. Group SB-Ib (average silhouette  
320 width 0.47) is dominated by *T. inflata* with *H. wilberti* and *J. macrescens* present in  
321 all samples. This foraminiferal group is associated with high and middle marsh  
322 vegetation. Group SB-II has the highest average silhouette width of 0.82 and is  
323 dominated by *M. fusca* and occurred at all sites.

324

325 We recorded  $\delta^{13}\text{C}$ , TOC and C:N for 71 samples of bulk sediment (Figure 4). All  $\delta^{13}\text{C}$   
326 measurements were less than -21.0‰ (range of -21.1 to -30.8‰). As expected, TOC  
327 was lowest in tidal flat environments and increased in vegetated environments  
328 (range of 0.3 to 39.0%). C:N values ranged from 1.7 to 28.0.

329

330 PAM identified three groups in the geochemistry of the combined Siletz Bay dataset  
331 (Figure 6). Group SB-G-I (average silhouette width = 0.64) is associated with  $\delta^{13}\text{C}$  of  
332  $-29.6 \pm 0.8\text{‰}$ , TOC of  $30.0 \pm 4.6\%$  and C:N of  $20.4 \pm 3.7$ . Group SB-G-II (average  
333 silhouette width = 0.45) has  $\delta^{13}\text{C}$  of  $-27.3 \pm 1.4\text{‰}$ , TOC of  $12.4 \pm 4.0\%$  and C:N of

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334  $13.6 \pm 1.4$ . Group SB-G-III (average silhouette width = 0.60) is characterized by  $\delta^{13}\text{C}$   
335 of  $-24.1 \pm 1.7\text{‰}$ , TOC of  $2.5 \pm 1.8\%$  and C:N of  $10.4 \pm 2.7$ .

## 336 **5. Discussion**

### 337 **5.1 Modern distribution of foraminifera in Siletz Bay**

338 We have used PAM to quantitatively sub-divide 79 modern samples of foraminifera  
339 from Siletz Bay into three faunal groups, which reflect the highest high marsh (SB-  
340 Ia), high and middle marsh (SB-Ib) and low marsh and tidal-flat (SB-II)  
341 environments. Previous studies of foraminifera along the Cascadia coastline (Figure  
342 7) have presented similar foraminiferal assemblages (Jennings and Nelson, 1992;  
343 Guilbault et al., 1996; Hawkes et al., 2010) though there are some noticeable site-  
344 specific differences.

345

346 Group SB-Ia represents the foraminiferal assemblages found at the highest  
347 elevations in salt marshes and into the upland transition. The group elevational  
348 range extends from 1.18 to 1.60 m MSL ( $1.36 \pm 0.15$  m). This zone is dominated by  
349 *T. irregularis* (> 25%). This species has previously been identified as occupying the  
350 high marsh and upland floral zones at Salmon River, South Slough and Coquille  
351 River in Oregon (Hawkes et al., 2010) and Tofino, British Columbia (Guilbault et al.,  
352 1996). *Trochamminita* spp. including *T. irregularis* and *T. salsa* appear to be  
353 endemic to the Pacific salt marshes having been found in South America (Jennings et  
354 al., 1995) and Australasia (Hayward and Hollis, 1994; Callard et al., 2011) as well as  
355 Cascadia (Jennings and Nelson, 1992; Guilbault et al., 1996; Nelson et al., 2008;

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356 Hawkes et al., 2010), but not along the US Atlantic coast (Gehrels, 1994) or in  
357 Europe (Horton and Edwards, 2006). *H. wilberti* is also found sporadically in group  
358 SB-Ia. *Haplophragmoides* spp. are generally identified as occupants of the high and  
359 middle marsh (Jennings and Nelson, 1992; Guilbault et al., 1996; Scott et al., 1996;  
360 Gehrels and van de Plassche, 1999; Patterson et al., 1999; Horton and Edwards,  
361 2006; Kemp et al., 2009a; Hawkes et al., 2010), but it has also been found in similar  
362 highest marsh environments associated with *Trochammina* spp. in Oregon  
363 (Hawkes et al., 2010) and British Columbia (Guilbault et al., 1996). *T. inflata* was  
364 generally absent in this zone, which is similar to the proximal Salmon River  
365 (Hawkes et al., 2010) and Alsea Bay (Nelson et al., 2008) sites, but contrasts with  
366 other Cascadia sites (Sabeau, 2004; Hawkes et al., 2010).

367

368 Group SB-Ib contains foraminiferal assemblages associated with high and middle  
369 salt marshes. The group elevational range extends from 0.77 to 1.49 m MSL ( $1.20 \pm$   
370  $0.18$  m). The group is dominated by *T. inflata* with *B. pseudomacrescens*, *H. wilberti*  
371 and *J. macrescens* significant contributors to the assemblage. *T. inflata* has been  
372 found in the high and middle salt marsh in studies from Cascadia (Jennings and  
373 Nelson, 1992; Nelson and Kashima, 1993; Guilbault et al., 1996; Scott et al., 1996;  
374 Nelson et al., 2008; Hawkes et al., 2010), but in contrast to results presented here is  
375 rarely the dominant species in this assemblage. It is also common along temperate  
376 coastlines on the eastern seaboard of North America (Scott and Medioli, 1978;  
377 Culver et al., 1996; Horton and Culver, 2008; Kemp et al., 2009a), Europe (Horton  
378 and Edwards, 2006) and Australasia (Horton et al., 2003; Southall et al., 2006;

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379 Callard et al., 2011). It has previously been suggested that *J. macrescens* and/or *B.*  
380 *pseudomacrescens* (often combined as *T. macrescens*) form a dominant or  
381 monospecific assemblage at the limit of tidal inundation (Scott and Medioli, 1978;  
382 Scott and Medioli, 1980; Edwards et al., 2004; Hayward et al., 2004; Horton and  
383 Edwards, 2006) in contrast to their presence in the middle and high marsh at Siletz  
384 Bay.

385

386 Group SB-II represents the foraminiferal assemblages found in the tidal flat and low  
387 salt marsh environments that is always identified from MHW to below MSL with an  
388 unknown lower limit (elevational range -0.43 to 0.91 m MSL ( $0.32 \pm 0.35$  m). This  
389 zone is dominated in high abundances by *M. fusca* (> 45%). This species is found in  
390 all studies along the Pacific coast. In contrast, *M. fusca* is dominant only in the low  
391 marsh environment along the North American Atlantic coast (Wright et al., 2011)  
392 and is replaced by calcareous foraminifera on the tidal flats (Kemp et al., 2009a).  
393 This assemblage is also seen in worldwide distributions (Hayward and Hollis, 1994;  
394 Horton, 1999; Murray and Alve, 1999). Calcareous foraminifera represented by  
395 *Ammonia parkinsoniana* and *Elphidium* spp. were only present in low abundances (<  
396 10%) in the tidal flats at Siletz Bay. This is consistent with selected published data  
397 from Cascadia (Jennings and Nelson, 1992; Guilbault et al., 1996; Shennan et al.,  
398 1996; Patterson et al., 2005; Nelson et al., 2008; Hawkes et al., 2010) but higher  
399 abundances of calcareous species have been identified in Netarts Bay (Hunger,  
400 1966). Hawkes et al. (2010) have suggested that the absence of calcareous species  
401 may be due to the low pH of most Oregon intertidal environments.

••••• are any found in deeper waters?

402

## 403 5.2 Stable carbon isotopes in bulk surface sediments

404 Geochemical proxies potentially have a crucial role to play in elucidating the  
405 depositional environment of a sample. TOC (Figure 8a and 8b) demonstrates a  
406 pattern of increasing values from seaward tidal flat and low marsh to highest marsh  
407 communities. This is likely due to both a decreasing input of minerogenic material  
408 with distance from open water, an increase in the total amount of biomass  
409 preservation, due to reduced flushing of the system with decreasing tidal inundation  
410 and *in-situ* organic growth (Brain et al., 2011). C:N ratios also show a relationship  
411 with elevation (Figure 8) and  $\delta^{13}\text{C}$  (Figure 9), but are not suitable for  
412 reconstructions due to a tendency for upland and marsh environment values to  
413 converge (Goni and Thomas, 2000; Kemp et al., 2010; Kemp et al., 2012). This may  
414 be due to marine input of carbon from algae, POC, and DOC (Cifuentes, 1991; Lamb  
415 et al., 2006) or selective diagenesis of carbon over immobile nitrogen (Chmura et al.,  
416 1987; Ember et al., 1987). This limitation of C:N ratios has previously been observed  
417 at west coast estuarine systems including San Francisco Bay (e.g., Cloern et al.,  
418 2002). Unlike previous studies (CHV please add appropriate refs here) C:N is not  
419 able to distinguish between tidal flat and low marsh sediments; the ranges also  
420 overlap for the low marsh and tidal flat group (SB-G-III) and middle and high marsh  
421 group (SB-G-II).

422

423 If floral zones can be recognized based upon the  $\delta^{13}\text{C}$  of bulk sediment, then  
424 geochemistry has potential as a sea-level indicator. Previous research has shown

••••• so wh not just use this instead of delta carbon...this is simple and cheap

SEE: IS IT CHRIS? THE PREP IS THE SAME AS FAR AS I'M AWARE AND I THINK THE CAVEAT IN THE NEXT LINE COVERS WHY WE DON'T USE IT OVER 13C

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425 that the dominant control on the  $\delta^{13}\text{C}$  values of bulk sediment is the proximal  
426 vegetation communities (Chmura and Aharon, 1995; Malamud-Roam and Ingram,  
427 2001; Lamb et al., 2006; Lamb et al., 2007), although differential decomposition may  
428 produce sediments with lower  $\delta^{13}\text{C}$  values than the local vascular plant material  
429 (Buchan et al., 2003; Vane et al., 2003; Lamb et al., 2007). The vegetation  
430 assemblage of geochemical group SB-G-I is solely  $\text{C}_3$  vascular plants (*P. palustris*,  
431 *Gaultheria* spp., *Juncus* spp., *T. maritima*, *Picea* spp., *C. maculatum* and ferns). The  
432 group elevational range extends from 1.18 to 1.60 m MSL ( $1.30 \pm 0.14$  m). All  
433 samples within these zones had  $\delta^{13}\text{C}$  values less than  $-28.5\text{‰}$ . This is significantly  
434 lower than has been found at other highest high marsh and freshwater zones in  
435 North America. Bulk sediment from freshwater environments in San Francisco bay  
436 had  $\delta^{13}\text{C}$  values from  $-23.3$  to  $-27.2\text{‰}$  (Cloern et al., 2002), freshwater marshes in  
437 Louisiana had an average value of  $-27.8\text{‰}$  (Chmura et al., 1987) and four upland  
438 samples from New Jersey ranged from  $-25.1$  to  $-26.5\text{‰}$ . (Kemp et al., 2012) found  
439  $\delta^{13}\text{C}$  values of  $-22$  to  $-27\text{‰}$  in the brackish transition zone in New Jersey. The values  
440 presented here are even further removed from a result of  $-24.5\text{‰}$  obtained from  
441 upland border sediments in Massachusetts (Middleburg et al., 1997). However, the  
442 results are consistent with the  $\delta^{13}\text{C}$  values for plant material of the dominant  
443 vegetation types found in the highest high marsh and terrestrial environments at  
444 Siletz that range from  $-28.3$  to  $-29.6\text{‰}$  (Table 2). This result highlights the  
445 importance of collecting local bulk sediment samples when undertaking  
446 paleoenvironmental reconstructions using  $\delta^{13}\text{C}$ . The  $\delta^{13}\text{C}$  values for this group are  
447 consistent with those for foraminiferal group SB-Ia ( $-29.6 \pm 0.8\text{‰}$  and  $-29.5 \pm$

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448 0.6‰, respectively). TOC values (24.5 to 39.0%) are higher than found in 6 samples  
449 from New Jersey (Kemp et al., 2012) freshwater sediments (<10%) but consistent  
450 with values found at the freshwater/salt marsh boundary (2 to 35%). C:N ratios are  
451 also higher at Siletz Bay(16.9 to 28.0) than found in either of these environments in  
452 New Jersey (12 to 16; Kemp et al., 2012).

453

454 Geochemical group SB-G-II is composed of C<sub>3</sub> (*Agrostis* spp., *Juncus* spp. and *S.*  
455 *virginica*) with sparse presence of C<sub>4</sub> (*D. spicata*) vascular plants. The group  
456 elevational range extends from 0.16 to 1.60 m MSL ( $1.19 \pm 0.35$  m). A number of  
457 samples that were classified within foraminiferal group SB-Ib are not found in  
458 geochemical group SB-G-II. The effect of this can be seen in the difference between  
459 the bulk sediment  $\delta^{13}\text{C}$  for the foraminiferal ( $-25.6 \pm 2.0\text{‰}$ ) and geochemical ( $-27.3$   
460  $\pm 1.4\text{‰}$ ) groups. This is driven by the species *D. spicata*. Removing samples  
461 dominated by this species (>50%) in the foraminiferal derived groups results in a  
462 bulk  $\delta^{13}\text{C}$  of  $-26.7 \pm 1.8\text{‰}$  in greater agreement with the geochemical group.

463

464 Geochemical group SB-G-III is composed of tidal flats (unvegetated or sparsely  
465 covered with *Z. nana*), low marsh (*Scirpus* spp. and/or *C. lyngbyei*) and middle  
466 marsh (*D. spicata* and *S. virginica*). The group elevational range extends from -0.43  
467 to 1.24 m MSL ( $0.48 \pm 0.44$  m). *C. lyngbyei* plant material has a low  $\delta^{13}\text{C}$  value (-  
468  $28.0\text{‰}$  (Wooller et al., 2007); Table 2). The dominant effect of local vegetation on  
469 bulk sediment  $\delta^{13}\text{C}$  values is again seen in this group. Compared to an average bulk  
470 sediment  $\delta^{13}\text{C}$  value of  $-24.1 \pm 1.7\text{‰}$ , samples not associated with *C. lyngbyei* have a

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471 lower value of  $-23.9 \pm 1.6\text{‰}$  in contrast to samples in a dominant *C. lyngbyei*  
472 vegetation zone ( $-26.6 \pm 1.6\text{‰}$ ). This is also reflected in greater TOC ( $2.8 \pm 1.4$  and  
473  $2.5 \pm 1.8\%$ ) and C:N ( $11.6 \pm 2.0$  and  $10.3 \pm 2.7$ ) values although there is significant  
474 overlap.

475

### 476 **5.3 Application of salt marsh foraminifera and stable carbon isotopes to** 477 **reconstruct coseismic land level change**

478 The coastline of Cascadia is subject to a major seismic hazard as the Juan de Fuca  
479 plate subducts beneath North America (Clague, 1997). This is recorded in coastal  
480 stratigraphic sequences as tidal flats, grading upwards into organic tidal marsh or  
481 upland soil deposits. When the strain builds to a point where the plate boundary  
482 ruptures, the North American plate responds elastically and the coast of Cascadia  
483 subsides almost instantaneously while areas formerly locked rebound. This is  
484 archived at the coastline as an abrupt stratigraphic boundary due to the organic  
485 deposits dropping lower in the tidal frame (Nelson et al., 1996b; Atwater and  
486 Hemphill-Haley, 1997; Kelsey et al., 2002; Witter et al., 2003; Hawkes et al., 2011).  
487 The plates once again become locked, strain starts to build and the cycle  
488 recommences.

489

490 Stable carbon isotopes may provide an alternative solution to microfossil-based  
491 methods to reconstruct the magnitude of coseismic subsidence due to a great  
492 earthquake. To test the utility of this method we compared the reconstructions



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493 produced by the new geochemical plus qualitative foraminifera method with those  
494 produced using the foraminiferal zonations presented in this paper to a record of  
495 the AD 1700 earthquake (Atwater et al., 2005) from Siletz Bay .

496

497 At Salishan Spit, we sampled a vibracore taken towards the rear of the salt marsh.

498 Five foraminiferal and geochemical samples (Figure 10) were taken across the AD

499 1700 contact in core SSV2 in Siletz Bay (Figure 1C). In core SSV2 at 60 cm depth

500 there is an abrupt (< 1mm) contact between underlying organic sandy silt and an

501 overlying upward fining silty sand unit interpreted as a tsunami deposit. A silty clay

502 unit in turn overlies this. The three foraminiferal samples below the contact have

503 high abundances of agglutinated foraminifera, dominated by *B. pseudomacrescens*

504 (60 to 82%) with low to absent *M. fusca* (0 to 3%) and *T. irregularis* (0 to 3%). These

505 indicate that the sample formed in the middle/high marsh environment (SB-Ib).

506  $\delta^{13}\text{C}$  values range from -25.7 to -26.2‰ indicating that the marsh formed in

507 geochemical zone SB-G-II. This is further supported by TOC (11.0 to 11.8%) and C:N

508 ratios (13.4 to 13.8). The first sample in the silty clay unit is predominantly *M. fusca*

509 (59%). This indicates that the sample formed in the low marsh/tidal flat group SB-II.

510 The  $\delta^{13}\text{C}$  increased to -24.6‰ and TOC reduced to 7.7% indicative of formation in

511 geochemical zone SB-G-III. The C:N ratio (12.6) is inconclusive for this sample. The

512 magnitude of subsidence for both methods can be calculated by subtracting the

513 difference between the center points of the elevations of groups. For foraminifera:

514

515 Coseismic Subsidence = SB-Ib – SB-II

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516  $= 1.20\text{m MSL} - 0.32\text{m MSL}$

517  $= 0.88\text{m}$

518

519 The error is calculated by taking the square root of the sum of half the ranges of

520 groups SB-Ib and SB-II:

521

522 Error  $= \sqrt{(0.18\text{m}^2 + 0.35\text{m}^2)}$

523  $= \pm 0.39\text{m}$

524

525 And for stable carbon isotopes:

526

527 Coseismic Subsidence  $= \text{SB-G-II} - \text{SB-G-III}$

528  $= 1.19\text{m MSL} - 0.48\text{m MSL}$

529  $= 0.71\text{m}$

530

531 Error  $= \sqrt{(0.35\text{m}^2 + 0.44\text{m}^2)}$

532  $= \pm 0.56\text{m}$

533

534 Both methods produce estimates that overlap, providing some measure of

535 confidence in the ability of the carbon isotope technique. Both methods produce

536 results that equivocally confirm subsidence with minimum estimates greater than

537 0m (0.49m versus 0.15m) and are above the threshold values of 0.5m (Nelson et al.,

538 1996a) used to definitively ascribe the subsidence to a megathrust earthquake.

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539 Indeed, the correlation of the AD 1700 soil and a high tsunami from over 900 km of  
540 the Cascadia coastline (Atwater et al., 1995; Nelson et al., 1995; Clague et al., 2000;  
541 Nelson et al., 2006) allows us to ascribe the subsidence to a megathrust earthquake.  
542 The estimates from both methods are consistent with the previous value obtained  
543 for the Siletz site by Darienzo et al. (1994) of 0.5 to 1.0 m using a qualitative  
544 interpretation based on plant macrofossils and lithology.

## 545 **6. Conclusions**

546 We documented the distribution of salt-marsh foraminifera and  $\delta^{13}\text{C}$ , TOC and C:N  
547 from four transect, at three salt marshes with differing salinity regimes in Siletz Bay,  
548 Oregon. We used PAM to identify elevation-dependent ecological zones, which are  
549 similar to those observed at other sites in Cascadia as well as globally. The highest  
550 marsh occupies a narrow elevational range and is dominated by *T. irregularis*. High  
551 and middle marsh environments are dominated by *T. inflata* with *B.*  
552 *pseudomacrescens*, *H. wilberti* and *J. macrescens*. Low marsh environments form  
553 near monospecific assemblages with *M. fusca*. Calcareous taxa are limited in the  
554 tidal flat (< 10%). PAM analysis of the  $\delta^{13}\text{C}$ , TOC and C:N also revealed three  
555 elevation dependent zones, which broadly correspond to those identified by  
556 foraminifera. The highest marsh is defined by low  $\delta^{13}\text{C}$  ( $-29.6 \pm 0.8\text{‰}$ ), high TOC ( $30$   
557  $\pm 4.6\%$ ) and high C:N ( $20.4 \pm 3.7$ ). The high and middle marsh are identified by  $\delta^{13}\text{C}$   
558 of  $-27.3 \pm 1.4\text{‰}$ , TOC of  $12.4 \pm 4.0\%$  and C:N of  $13.6 \pm 1.4$ . The low marsh and tidal  
559 flat had the highest  $\delta^{13}\text{C}$  ( $-24.1 \pm 1.7\text{‰}$ ), lowest TOC ( $2.5 \pm 1.8\%$ ) and lowest C:N  
560 ( $10.4 \pm 2.7$ ) values. Lower  $\delta^{13}\text{C}$  values than are found in similar environments in

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561 North America highlight the importance of collecting a local dataset of bulk  
562 sediments for geochemical analysis.

563

564 The sub-division of the dataset into elevation dependent ecological zones allows the  
565 use of both foraminifera and  $\delta^{13}\text{C}$  (supported by TOC and C:N) as indicators of  
566 former sea level that can infer the amount of coseismic subsidence associated with  
567 megathrust earthquakes in Cascadia. We tested this by applying both methods to a  
568 record of the AD 1700 earthquake taken from Salishan spit. Foraminifera and  
569 geochemical analyses produced similar estimates of subsidence ( $0.88 \pm 0.39\text{m}$  and  
570  $0.71 \pm 0.56\text{m}$ , respectively), providing a measure of confidence in the new semi-  
571 quantitative  $\delta^{13}\text{C}$  technique. This approach provides a new method to obtain  
572 estimates of coseismic subsidence quickly before quantitative foraminiferal analysis  
573 and/or when microfossil abundances are not appropriate for quantitative analysis  
574 (e.g., transfer functions).

575

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577

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582 provided the tidal predictions used in this paper.

583

## 584 **Figure Captions**

585 Figure 1. Map of (A) the Cascadia subduction zone (USA) showing the location of  
586 Siletz Bay. Black circles mark the sites identified in Figure 5 (B) the location of three  
587 sites within Siletz Bay that were sampled for foraminifera and geochemistry (C)  
588 Salishan Spit, (D) Siletz East, and (E) Millport Slough. A core (SSV2) was collected  
589 from Salishan Spit (C)

590

591 Figure 2. Elevation profile of transects at A) Salishan Spit transect 1, B) Salishan Spit  
592 transect 2, C) Siletz East and D) Millport Slough. Vegetation zones correspond to  
593 Table 1. Distribution of dominant foraminifera along each transect in % with only  
594 dominant species being shown. SW = *Picea* spp. swamp; HHM = highest marsh; HM =  
595 high marsh; MM = middle marsh; LM = low marsh; TF = tidal flat.

596

597 Figure 3. Relative abundance of dead foraminifera at Salishan Spit transect 1 (SS).  
598 PAM cluster analysis sub-divides the data into two groups, SS-I (black bars) and SS-  
599 II (white bars). Silhouette plot for PAM clustering of foraminiferal samples  
600 partitioned into two groups. The silhouette plot shows widths between -1 and 1,  
601 where values close to -1 indicate that a sample was incorrectly classified and values  
602 close to 1 indicate that a sample was assigned to an appropriate group.

603

604 Figure 4. Elevation profile of transects at A) Salishan Spit transect 1, B) Salishan Spit  
605 transect 2, C) Siletz East, and D) Millport Slough. Vegetation zones correspond to  
606 Table 1. Distribution of  $\delta^{13}\text{C}$ , total organic carbon (TOC) and C:N ratios along each  
607 transect are shown. SW = *Picea* spp. swamp; HHM = highest marsh; HM = high  
608 marsh; MM = middle marsh; LM = low marsh; TF = tidal flat.

609

610 Figure 5. Relative abundance of dead foraminifera when combined into a single  
611 Siletz Bay dataset. PAM cluster analysis sub-divides the data into three groups, SB-Ia  
612 (grey bars), SB-Ib (black bars) and SB-II (white bars). Silhouette plot for PAM  
613 clustering of foraminiferal samples partitioned into three groups. The silhouette  
614 plot shows widths between -1 and 1, where values close to -1 indicate that a sample  
615 was incorrectly classified and values close to 1 indicate that a sample was assigned  
616 to an appropriate group.

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618 Figure 6. Stable carbon isotope values when combined into a single Siletz Bay  
619 dataset. PAM cluster analysis sub-divides the data into three groups, SB-G-I (grey  
620 bars), SB-G-II (black bars) and SB-G-III (white bars). Silhouette plot for PAM  
621 grouping of stable carbon isotope samples partitioned into three groups. The  
622 silhouette plot shows widths between -1 and 1, where values close to -1 indicate  
623 that a sample was incorrectly classified and values close to 1 indicate that a sample  
624 was assigned to an appropriate group.

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626 Figure 7. Distribution and elevational ranges of dominant foraminifera from Siletz  
627 Bay compared to other studies from Cascadia (Guilbault et al., 1996; Sabeau, 2004;  
628 Patterson et al., 2005; Nelson et al., 2008; Hawkes et al., 2010). Aspp =  
629 *Ammobaculites* spp.; Bp = *Balticamina pseudomacrescens*; Hm = *Haplophragmoides*  
630 *manilaensis*; Hw = *Haplophragmoides wilberti*; Hspp = *Haplophragmoides* spp.; Jm =  
631 *Jadammina macrescens*; Mf = *Miliammina fusca*; Ti = *Trochammina inflata*; Tm =  
632 *Trochammina macrescens*; Tr = *Trochammina irregularis*; Ts = *Trochammina*  
633 *salsa*. Solid line indicates minimal elevational overlap between groups. A dashed line  
634 indicates overlap between groups. Elevational ranges are shown in detail for the  
635 data presented here. Ranges are presented as box and whisker plots, where the box  
636 is the mean  $\pm$  one standard deviation and the whiskers represent the minimum and  
637 maximum elevation in each group.

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639 Figure 8. (A). The associated mean  $\pm$  one standard deviation in  $\delta^{13}\text{C}$ , C:N ratios, total  
640 organic content (TOC), and elevations for the modern samples based on the  
641 foraminiferal groups. (B) The associated mean  $\pm$  one standard deviations in  $\delta^{13}\text{C}$ ,  
642 C:N ratios, total organic content (TOC), and elevations for the modern samples  
643 based on the geochemistry groups. Ranges are presented as box and whisker plots,  
644 where the box is the mean  $\pm$  one standard deviation and the whiskers represent the  
645 maximum and minimum in each group.

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647 Figure 9.  $\delta^{13}\text{C}$  and C:N values in bulk organic sediment from sampling stations in  
648 Siletz Bay, Oregon. Samples are sub-divided by stable carbon isotope groups  
649 identified by PAM.

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651 Figure 10. Stratigraphy (including lithology and type of contact), foraminiferal  
652 assemblages,  $\delta^{13}\text{C}$  and results of semi-quantitative foraminifera and geochemistry  
653 analysis reconstruction of the paleomarch elevations in the sediment sequence  
654 bisecting the AD 1700 earthquake in core SSV2 taken at Salishan Spit in Siletz Bay.  
655 The calculated coseismic subsidence with the error in meters marked on both  
656 reconstructions.

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672 Table 1. Vascular plant zonation and foraminiferal associations at the three studied  
 673 sites in Siletz Bay. Bp = *Balticammina pseudomacrescens*; Hm = *Haplophragmoides*  
 674 *manilaensis*; Hw = *Haplophragmoides wilberti*; Jm = *Jadammina macrescens*; Mf =  
 675 *Miliammina fusca*; Ti = *Trochammina inflata*; Tr = *Trochamminita irregularis*  
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Site	Marsh Type	Vegetation	Foraminifera
Salishan Spit	Highest Marsh	<i>Gaultheria</i> spp., <i>Potentilla palustris</i> , <i>Juncus</i> spp. <i>Picea</i> spp., Ferns	Tr
	High Marsh	<i>Agrostis</i> spp., <i>Salicornia virginica</i> , <i>Juncus</i> spp., <i>Distichlis spicata</i> , <i>Potentilla palustris</i>	Ti, Hw, Hm
	Middle Marsh	<i>Distichlis spicata</i> , <i>Salicornia virginica</i>	Ti, Jm, Hw, Mf
	Low Marsh	<i>Scirpus</i> spp.	Mf
	Tidal Flat	<i>Zostera nana</i>	Mf
Siletz East	High Marsh	<i>Agrostis</i> spp., <i>Juncus</i> spp., <i>Distichlis spicata</i>	Ti, Jm, Bp, Hw
	Low Marsh	<i>Carex lyngbyei</i>	Mf
	Tidal Flat	Unvegetated	Mf
Millport Slough	Swamp	<i>Picea</i> spp.	Tr, Hw, Jm, Bp
	High Marsh	<i>Potentilla palustris</i> , <i>Triglochin maritima</i> , <i>Juncus</i> spp.	Tr, Hw, Hm, Bp, Mp
	Low Marsh	<i>Carex lyngbyei</i>	Mf

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696 Table 2. Published  $\delta^{13}\text{C}$  values for salt marsh species found in the marshes of Siletz  
697 Bay and discussed in this study  
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<b>Vegetation</b>	<b>Typical <math>\delta^{13}\text{C}</math> Value (‰)</b>	<b>Reference</b>
<i>Zostera nana/japonica</i>	-12.4	Thayer et al. 1978
<i>Scirpus maritimus</i>	-25.5	Byrne et al. 2001
<i>Carex lyngbyei</i>	-28.0	Wooler et al. 2007
<i>Distichlis spicata</i>	-12.7	Byrne et al. 2001
<i>Salicornia virginica</i>	-27.2	Byrne et al. 2001
<i>Juncus balticus</i>	-28.4	Byrne et al. 2001
<i>Agrostis capilaris/gigantea</i>	-25.99	Wedin et al. 1995
<i>Triglochin maritima</i>	-28.3	Cloern et al. 2002
<i>Potentilla palustris</i>	-29.6	Brooks et al. 1997
<i>Gaultheria shallon/salal</i>	-29.4	Brooks et al. 1997

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730 Table 3. Elevational ranges for six environmental groups defined at Siletz Bay on the  
 731 basis of foraminifera (SB-Ia, SB-Ib and SB-II) and geochemistry (SB-G-I, SB-G-II and  
 732 SB-G-III). MSL = mean sea level.  
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Group	Foraminifera	$\delta^{13}\text{C}$ (‰)	Elevation (m MSL)
SB-Ia	Agglutinated foraminifera of which >25% <i>T. irregularis</i>	-29.5 ± 0.6	1.36 ± 0.15
SB-Ib	Agglutinated foraminifera of which <45% <i>M. fusca</i>	-25.6 ± 2.0	1.20 ± 0.18
SB-II	Agglutinated foraminifera of which >45% <i>M. fusca</i>	-24.4 ± 1.8	0.32 ± 0.35
SB-G-I	Agglutinated foraminifera present	-29.6 ± 0.8	1.30 ± 0.14
SB-G-II	Agglutinated foraminifera present	-27.3 ± 1.4	1.19 ± 0.35
SB-G-III	Not required	-24.7 ± 1.7	0.48 ± 0.44

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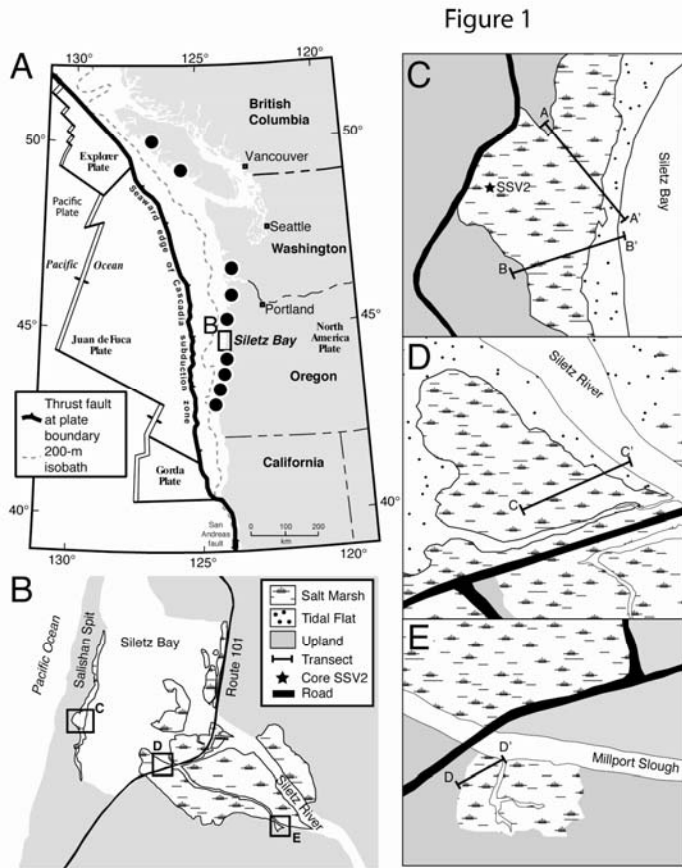
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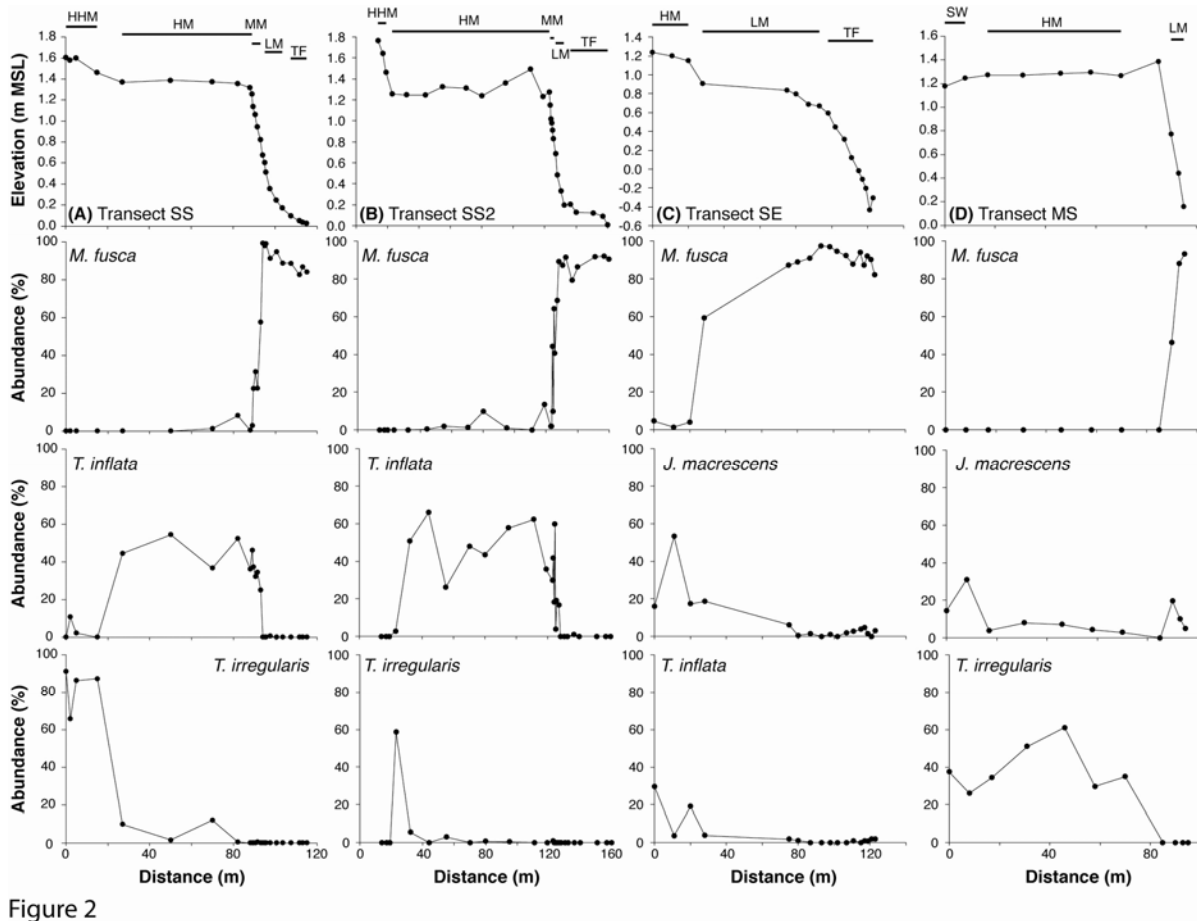
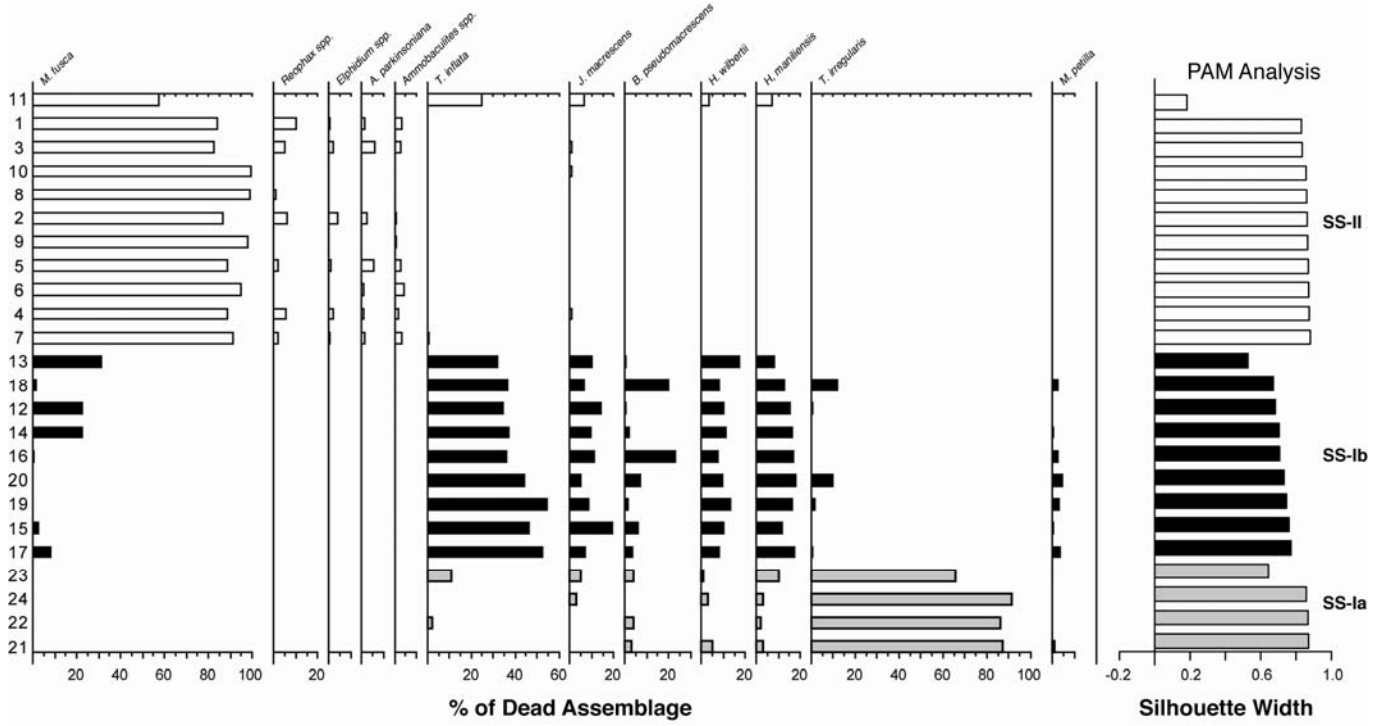


Figure 2

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Figure 3

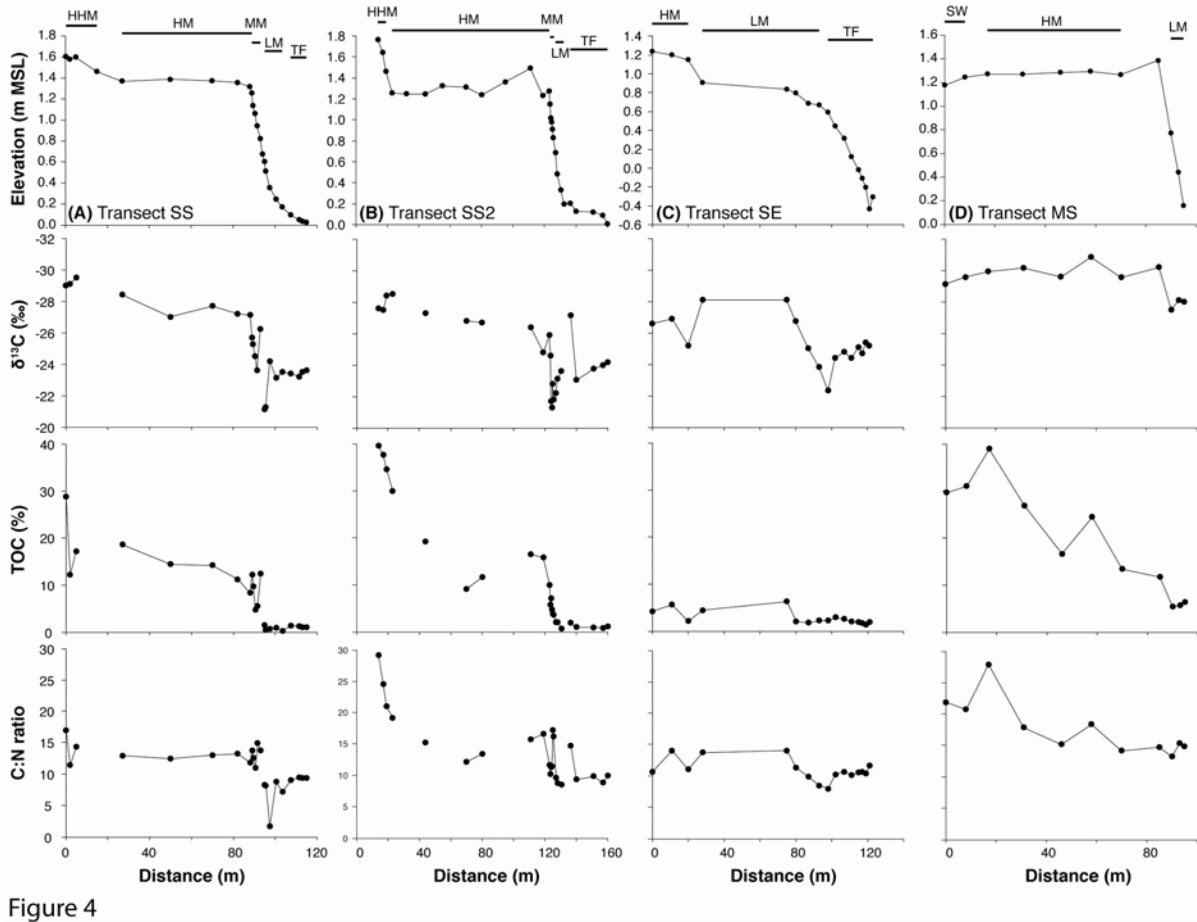
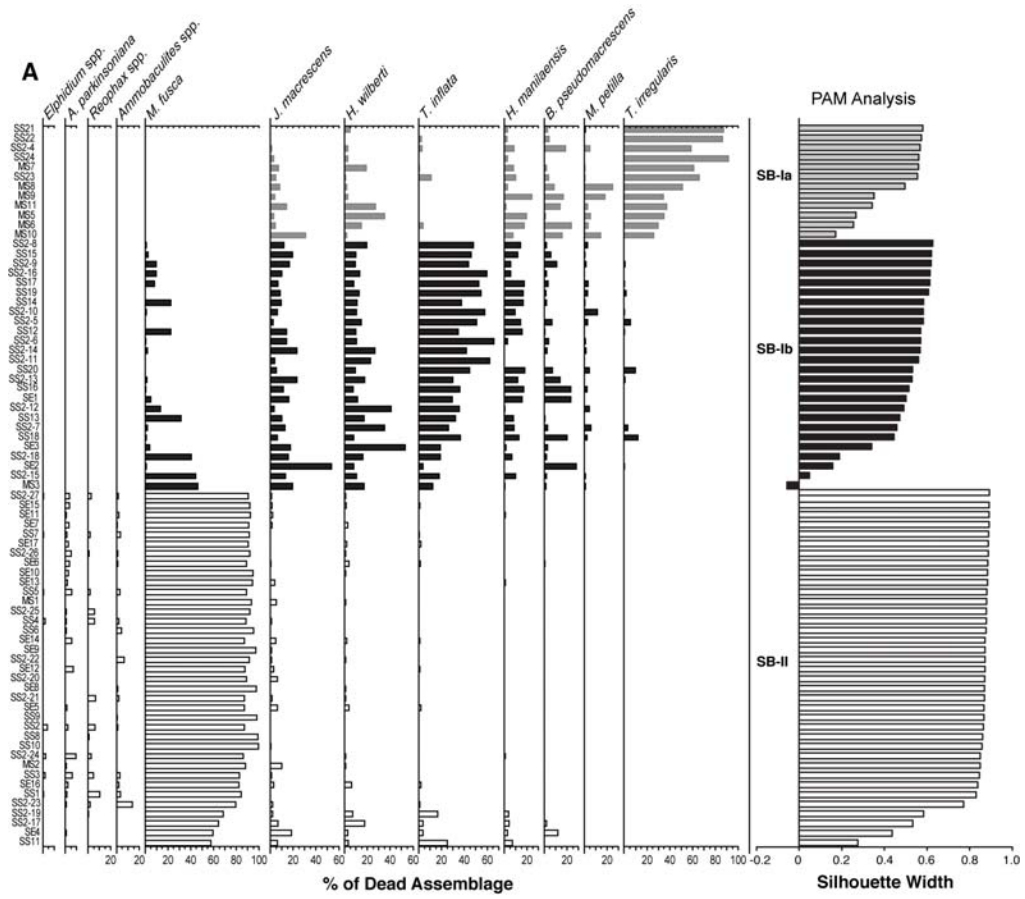


Figure 4

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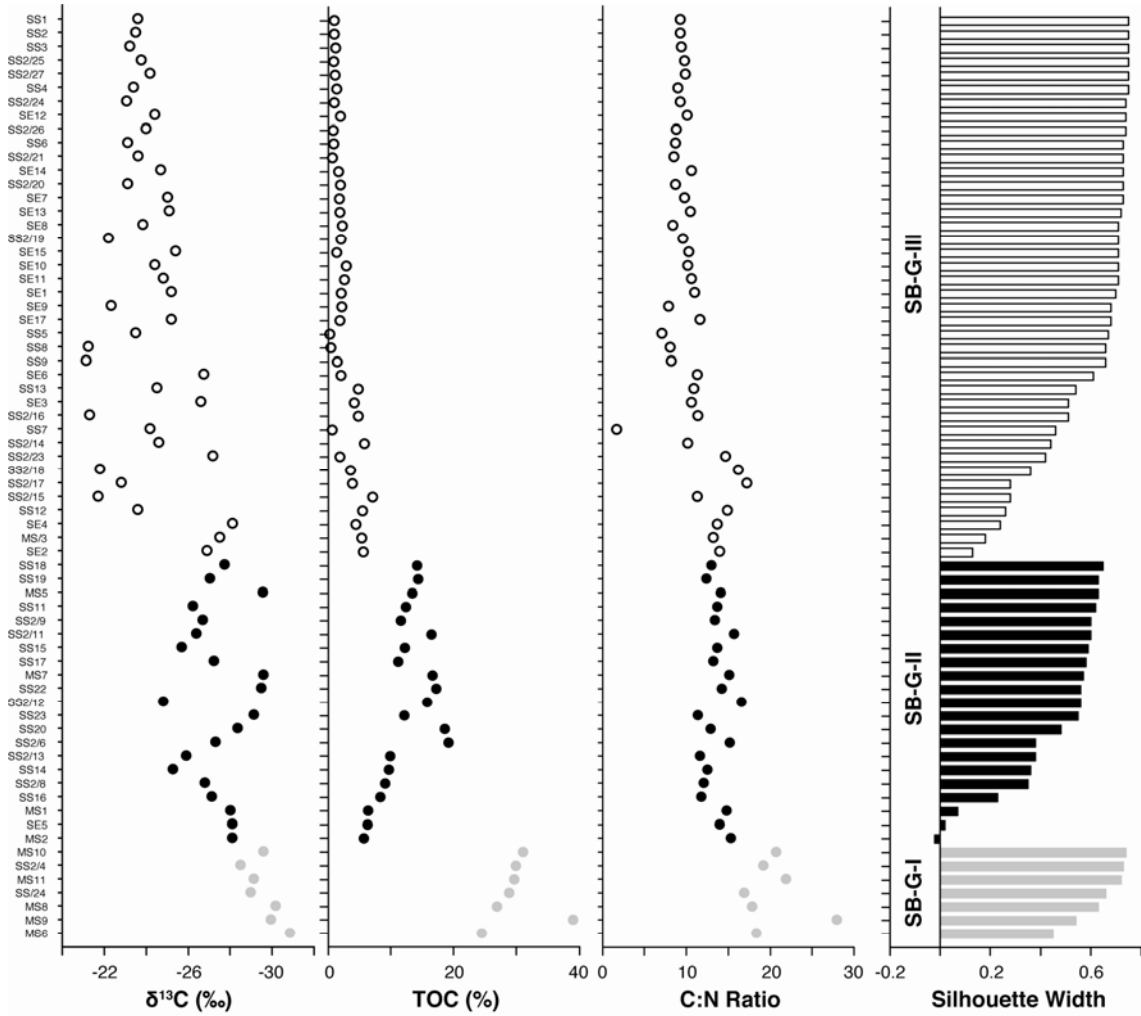


Figure 6



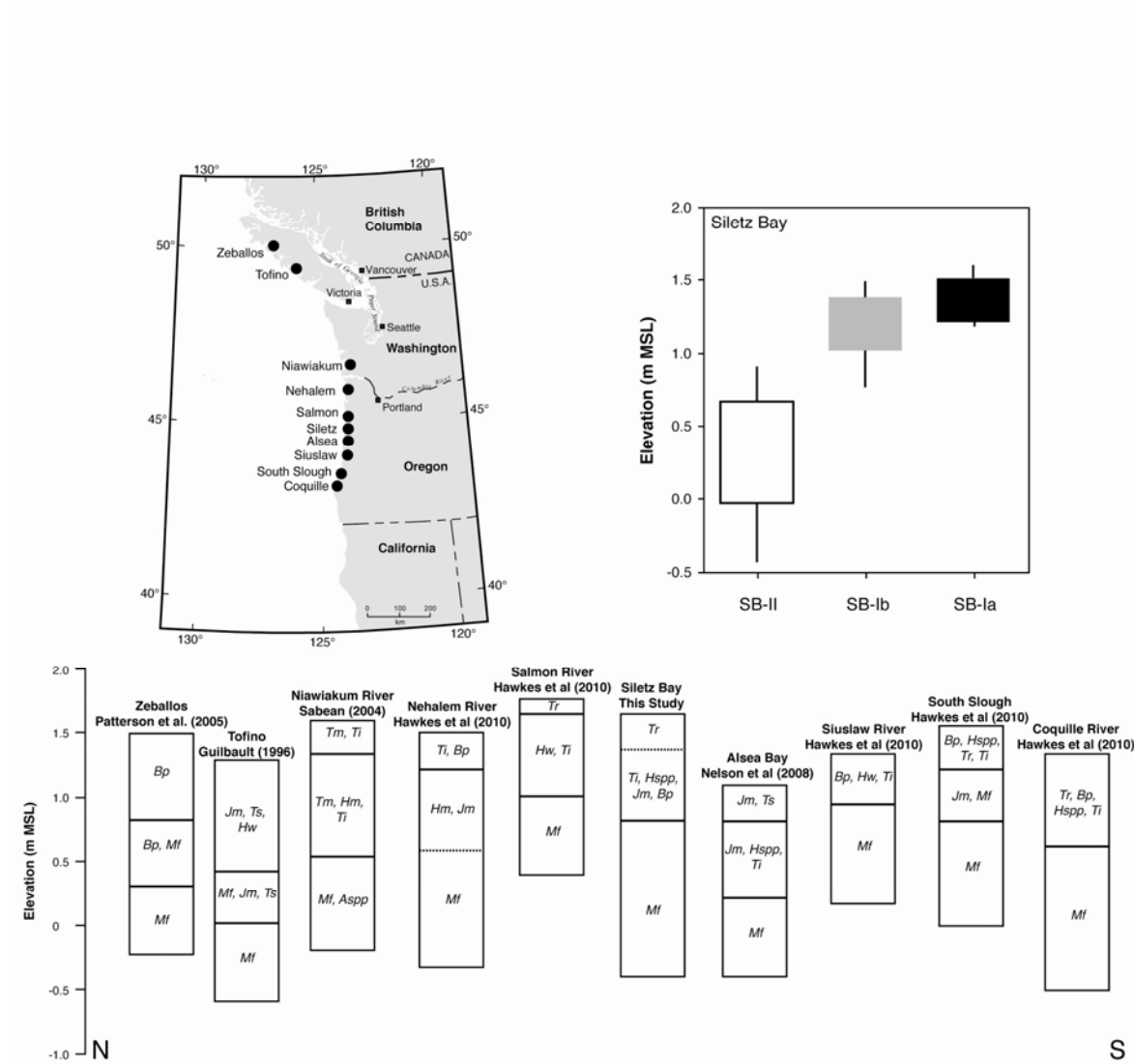


Figure 7

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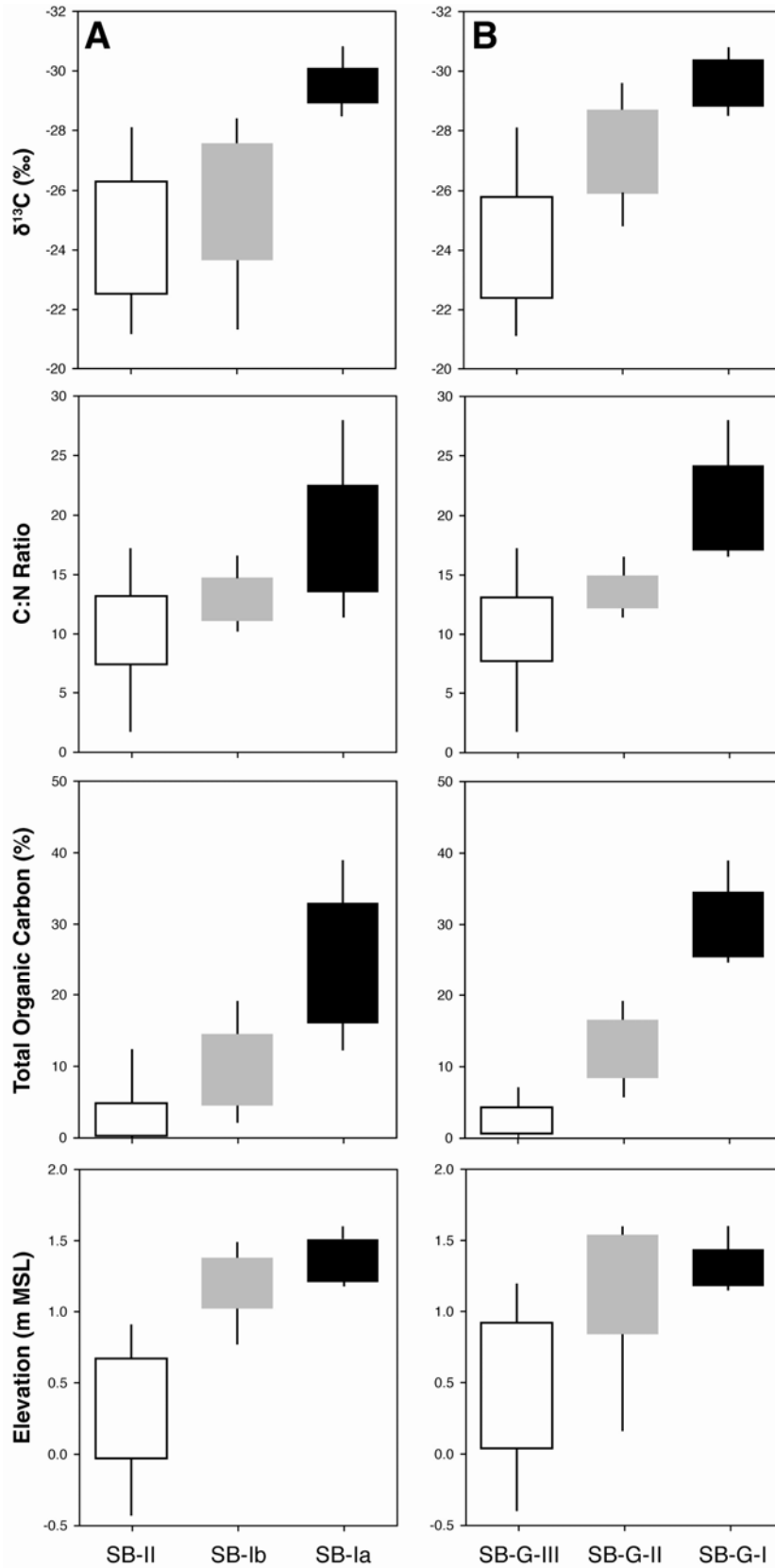


Figure 8

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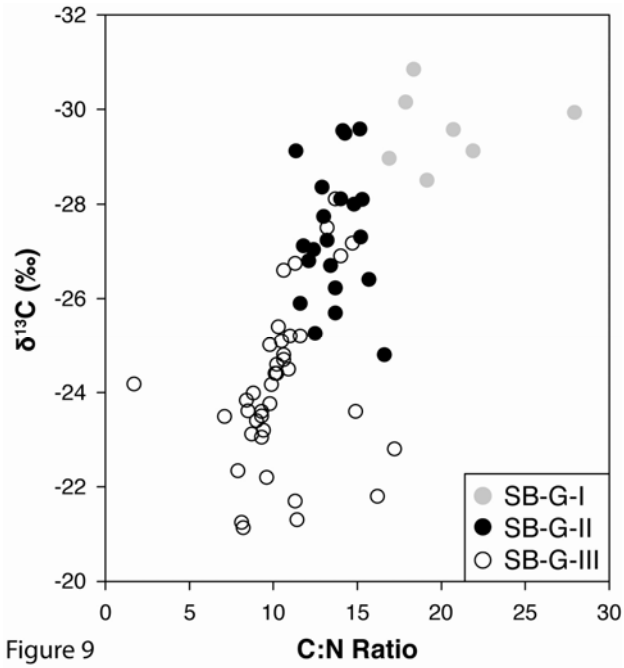


Figure 9

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