

Microfossil measures of rapid sea-level rise: Timing of response of two microfossil groups to a sudden tidal-flooding experiment in Cascadia

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ABSTRACT

Comparisons of pre-earthquake and post-earthquake microfossils in tidal sequences are accurate means to measure coastal subsidence during past subduction earthquakes, but the amount of subsidence is uncertain, because the response times of fossil taxa to coseismic relative sea-level (RSL) rise are unknown. We measured the response of diatoms and foraminifera to restoration of a salt marsh in southern Oregon, USA. Tidal flooding following dike removal caused an RSL rise of ~1 m, as might occur by coseismic subsidence during momentum magnitude (M_w) 8.1–8.8 earthquakes on this section of the Cascadia subduction zone. Less than two weeks after dike removal, diatoms colonized low marsh and tidal flats in large numbers, showing that they can record seismically induced subsidence soon after earthquakes. In contrast, low-marsh foraminifera took at least 11 months to appear in sizeable numbers. Where subsidence measured with diatoms and foraminifera differs, their different response times may provide an estimate of postseismic vertical deformation in the months following past megathrust earthquakes.

INTRODUCTION

Although the Cascadia subduction zone (northern Vancouver Island, Canada, to Cape Mendocino, California, USA) lacks a written history of great earthquakes (Heaton and Kanamori, 1984), their occurrence over the past 3–7 k.y. is reflected in stratigraphic records of repeated relative sea-level (RSL) change that is preserved beneath salt marshes of Cascadia's estuaries (e.g., Witter et al., 2003). Gradual interseismic uplift (RSL fall) during strain accumulation is punctuated by instantaneous coseismic subsidence (RSL rise) caused by strain release during earthquakes.

Coseismic subsidence during past earthquakes has been estimated from intertidal microfossils across mud-over-peat contacts in salt-marsh stratigraphic sequences, assuming that tidal sediment is deposited in the first few weeks following an earthquake (e.g., Nelson et al., 1996). Changes in the species assemblages of intertidal microfossils, chiefly foraminifera and diatoms, give more reliable and precise estimates of sudden

paleoenvironmental change than can be inferred from individual plant fossils or lithology (e.g., Engelhart et al., 2013). Foraminifera and diatoms are sensitive to differences in tidal exposure, substrate, and salinity. Because species vary in their sensitivity to such environmental factors, species assemblages of these groups precisely reflect differences in elevation within the intertidal zone (Gehrels et al., 2001). However, the accuracy of these elevation reconstructions relies on how quickly foraminifera and diatoms respond to coseismic subsidence. A delayed response could lead to subsidence estimates that include contributions from postseismic land-level changes, which display complex patterns of vertical motion depending on the distance to the rupture zone (e.g., Feng et al., 2015).

To quantify how quickly intertidal foraminifera and diatoms respond to RSL changes similar to those caused by megathrust earthquakes, we measured their response times to the restoration of the Ni-les'tun salt marsh in the central Cascadia subduction zone (Fig. 1). Removal of

tidal gates at this site simulated an instantaneous, ~1 m RSL rise (approximately equivalent to a M_w 8.1–8.8 earthquake; Wang et al., 2013); we sampled the marsh before, during, and after this rise.

MONITORING THE RESTORATION OF THE NI-LES'TUN SALT MARSH

The Ni-les'tun salt marsh (Figs. 1B and 1C) was diked in the late 19th to early 20th centuries (Brophy et al., 2014). Diking strongly influenced the tidal regime, salinity, and vegetation; fish-friendly tide gates decreased the frequency and duration of tidal inundation, which allowed the establishment of a high salt-marsh plant community at lower elevations. Prior to restoration in 2011, tidal creeks were constructed and tide gauges, groundwater wells, and salinity and temperature loggers were installed (Brophy et al., 2014). In August 2011, the dikes were removed and the tide gates opened to restore a natural tidal hydrology (Fig. 2).

We selected three sampling stations along an elevational gradient (station 1 at 0.33 m mean tide level, MTL; station 2 at 0.72 m MTL; station 3 at 0.95 m MTL) within the marsh to monitor the response of foraminifera, diatoms, sediment grain size, and vegetation to restoration. Surface (0–1 cm) sampling for foraminifera, diatoms, and sediment began prior to restoration. We analyzed the live (see the GSA Data Repository¹) and dead foraminiferal assemblages and the total diatom assemblages. Sediment sampling ended a year later, whereas

¹GSA Data Repository item 2017167, microfossil, grain-size, water-level, and salinity data, is available online at <http://www.geosociety.org/datarepository/2017/>, or on request from editing@geosociety.org.

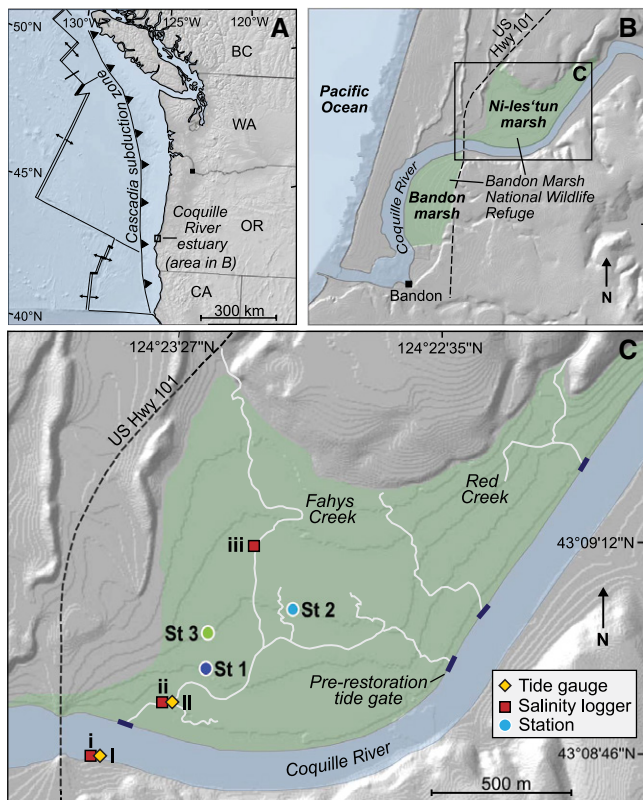


Figure 1. A: West-central North America showing location of the study area. B: Map of the Bandon Marsh National Wildlife Refuge (NWR). C: Station (St 1–St 3), tide gauge (I, II), and salinity logger (i–iii) locations at the restoration site. Color of station symbols corresponds to respective species abundance data shown in Figure 3. Base maps are 3 m digital elevation models.

microfossil samples were collected until March 2016 (Fig. 2; see the Data Repository). Vegetation community composition was measured in 1 m² quadrats prior to restoration and in 2012, 2013, and 2015 (Brown et al., 2016). To compare changes in a control, i.e., an undiked marsh, with those at the Ni-les'tun marsh, we analyzed 10 stations from the Bandon salt marsh to the southwest (Fig. 1B; Milker et al., 2015; see the Data Repository).

RESTORATION CHARACTERISTICS

Hydrological and Physical Properties and Plant Community Composition

Restoration of tidal hydrology at the Ni-les'tun salt marsh had an immediate (<24 h) effect on flooding frequency and salinity (Figs. 2A–2D). Mean daily maximum water level was -0.06 m MTL prior to restoration and rose to 0.91 m MTL a month later. Over the same time, daily mean salinity increased from 0.1‰ to 16.6‰. Data from groundwater wells show that tides propagated freely throughout the marsh (Brophy et al., 2014). With changes in hydrology, new sediment was delivered to the marsh; the foraminifera and diatom assemblages suggest that the sediment was sourced from low marsh and tidal flat environments (Fig. 3B). A month after restoration, the silt and clay fraction increased by 9%–36% at stations 1–3 (Fig. 2E). Field observations suggest deposition of 1.5 cm during the first ~4.5 yr after flooding (~3.3 mm/yr; see the Data Repository).

Marsh plant communities changed between 2011 and 2015; salt-tolerant early colonizers

spread across the site and pasture grasses declined (Brown et al., 2016). Before restoration, high-marsh species such as *Juncus balthicus* and *Agrostis stolonifera* reflected muted tidal influence with occasional brackish inflow at station 1. Post-restoration communities showed an increase in the abundance of the salt-marsh taxa *Distichlis spicata*. At station 2, the wetland taxon *Lotus* spp. was common pre-restoration, while the salt-tolerant *Atriplex patula* colonized the site thereafter. Station 3 showed minimal changes in vegetation after restoration.

Foraminifera and Diatom Assemblages

Foraminiferal assemblages show distinct and lasting changes following restoration, but with a delayed response (Fig. 3A). Prior to restoration at station 1, 611 dead specimens (per 10 cm³ sediment volume) were counted with an assemblage characterized by middle- and high-marsh species (e.g., *Jadammina macrescens*, *Trochammina irregularis*) and the presence of the low-marsh taxa *Miliammina fusca*. The number of dead foraminifera remained low and variable for the first 11 months after restoration (388 ± 230 per 10 cm³ sediment volume) with a similar diverse assemblage, but in July 2012 (month 11), the number of foraminifera increased to 828 specimens per 10 cm³ sediment volume. The post-restoration assemblage from July 2012 to March 2016 was dominated (91%–100%) by *M. fusca* with a high number of specimens (931 ± 435 per 10 cm³ sediment volume).

Foraminifera were absent at stations 2 and 3 prior to restoration. At station 2, the first dead

foraminifera are observed 14 months (October 2012) after restoration in low numbers (66 per 10 cm³ of sediment volume). *Miliammina fusca* was the dominant species with a relative abundance of 69%–100% between 2012 and 2014, but by March 2015 middle- to high-marsh species such as *Haplophragmoides manilaensis*, *J. macrescens*, and *T. irregularis* appeared in high numbers (3399 per 10 cm³ of sediment volume). At station 3, high numbers of dead foraminifera (1176 specimens per 10 cm³ of sediment volume) first appeared 25 months after restoration (September 2013). Diverse high-marsh species (e.g., *H. manilaensis* and *B. pseudomacrescens*) dominated the assemblage.

Diatoms at stations 1 and 2 responded within two weeks of restoration with significant and lasting changes in assemblages (Fig. 3B). Prior to restoration, station 1 diatom assemblages consisted of ~80% high-marsh taxa (e.g., *Denticula subtilis*, *Navicula cryptonella*). Two weeks after restoration, low-marsh (e.g., *Navicula peregrina*, *Rhopalodia musculus*) and tidal-flat (e.g., *Melosira moniliformis*, *Planothidium delicatulum*) taxa increased by 50%. The resulting mixed assemblage persisted until July 2012 (11 months), after which low-marsh (e.g., *Gyrosigma acuminatum*, *Surirella brebissonii*) and tidal-flat (e.g., *Tryblionella levidensis*, *Thalassiosira pacifica*) diatoms dominated.

Prior to restoration, station 2 diatom assemblages included ~85% freshwater (e.g., *Gomphonema parvulum*, *Pinnularia microstauron*) and high-marsh (e.g., *D. subtilis*, *Luticola mutica*) taxa. Two weeks after restoration, low-marsh (e.g., *Nitzschia dubia*, *S. brebissonii*) and, to a lesser extent, tidal-flat (e.g., *Nitzschia sigma*, *Delphineis surirella*) taxa had increased by 30%. The relative abundance of low-marsh and tidal-flat diatoms continued to rise to ~85% of the assemblage in month 25.

Prior to restoration, the diatom assemblage at station 3 included ~90% freshwater (e.g., *G. parvulum*, *P. microstauron*) and high-marsh (e.g., *Cosmioneis pusilla*, *L. mutica*) taxa. Two weeks after restoration, tidal-flat taxa (e.g., *N. sigma*, *T. pacifica*) increased by ~10%, but freshwater and high-marsh species remained dominant.

The concentration of diatom valves remained consistent in pre-restoration (e.g., station 1, 7.51×10^4 valves/g) and post-restoration assemblages (e.g., station 1, $7.69 \times 10^4 \pm 5.23 \times 10^3$ valves/g).

SIGNIFICANCE OF MARSH RESTORATION FOR MEASURING EARTHQUAKE-INDUCED SUBSIDENCE

Reconstructions of earthquake-induced subsidence using microfossils have begun to answer questions about the spatial heterogeneity of megathrust slip during Cascadia earthquakes (e.g., Wang et al., 2013, and references therein). Our results, however, raise questions about the rate of post-subsidence foraminifera and diatom

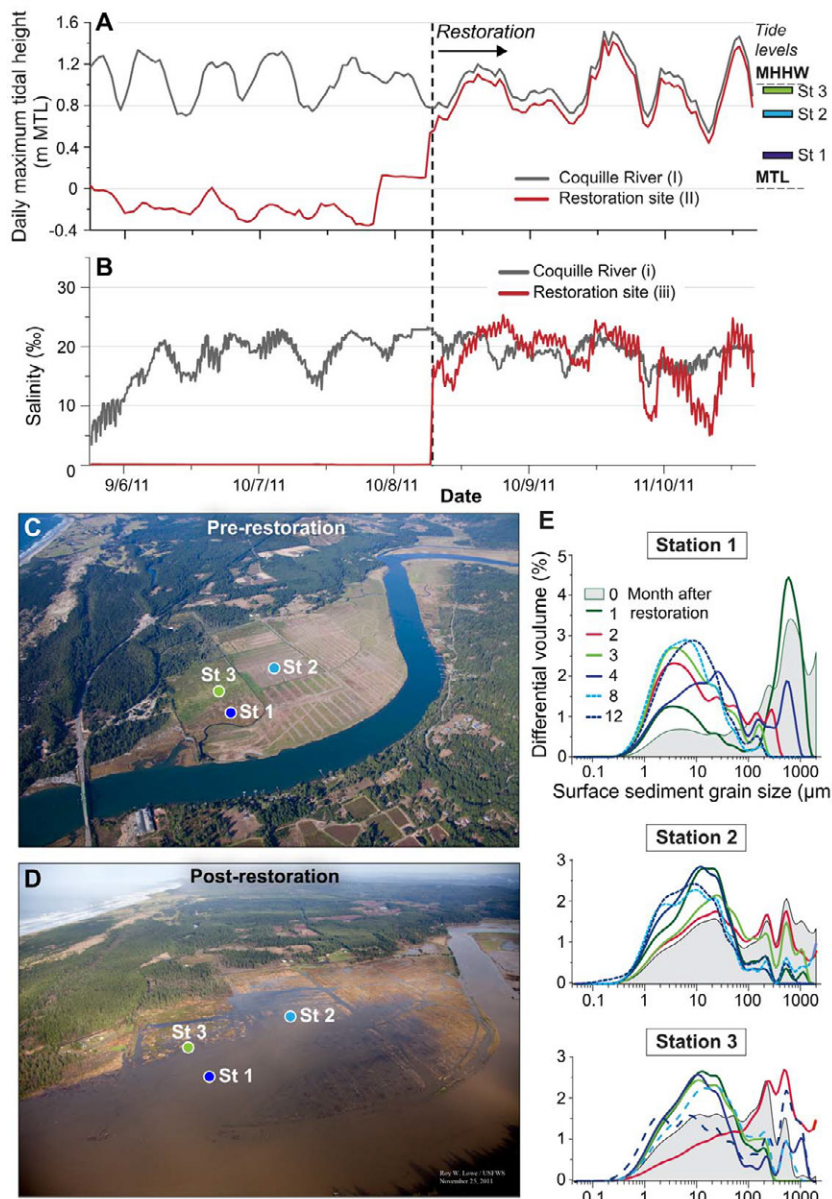


Figure 2. A: Pre-restoration and post-restoration water level for the Ni-les'tun marsh restoration site and the Coquille River, Oregon, USA. MTL—mean tide level; MHHW—mean higher high water. B: Salinity. C, D: Aerial photos of the Ni-les'tun salt marsh (R.W. Lowe, U.S. Fish and Wildlife Service). Locations of stations (St) 1–3 are shown. E: Grain-size distribution at stations 1–3; differential volume is the percentage of total volume that each size class occupies.

colonization. Although tidal inundation and salinity increased immediately post-restoration, the appearance of high numbers of dead foraminifera (e.g., low-marsh species *M. fusca*) lagged until July 2012 (11 months) at station 1. The first presence of foraminifera at stations 2 (14 months) and 3 (25 months) took even longer. The foraminiferal distribution in the control, the undiked Bandon marsh, had a high number of dead foraminifera from August 2011 to October 2012 with similar diversity (see the Data Repository). Although there are no studies of foraminiferal colonization specific to salt marshes, the rate of colonization among other coastal habitats varies between weeks and months (e.g., Buzas, 1993). The delay may be due to the effect of temperature

on the foraminiferal reproductive cycle (Murray, 2006). The living foraminifera generally showed higher numbers in the spring and summer (see the Data Repository). Salt-marsh foraminiferal populations demonstrate seasonal growth patterns, with reproduction commonly occurring in the warmer months of spring and summer (e.g., Horton and Murray, 2007) in response to seasonal food supply (Lesen, 2005).

In contrast, diatoms responded within two weeks to restoration at all sampling stations with the appearance of low-marsh and tidal-flat taxa that were absent prior to restoration. Our results are consistent with field and laboratory studies that showed that the composition of diatom assemblages responded to environmental

changes (e.g., acidification, pollution) within days to weeks (e.g., Hirst et al., 2004). The dominance of low-marsh and tidal-flat diatom taxa was not immediate. Immediate post-restoration samples at station 1 contained the same high-marsh diatoms (see the Data Repository), low numbers of dead low-marsh foraminifera, and coarse sediment observed pre-restoration. We suggest that this is mainly because pre-restoration sediment was included in post-restoration samples (0–1 cm depth); foraminifera and especially diatoms live in the top few millimeters of the sediment surface. Once sufficient post-restoration sediment had accumulated at station 1, foraminifera and diatom counts reflected the dominant low-marsh and tidal-flat assemblages resulting from restoration. Alternatively, the persistence of high-marsh diatom taxa may reflect the time taken for the assemblages to reach a steady-state response to restoration.

The rapid response of diatoms suggests that they may more accurately record the coseismic component of subsidence than foraminifera. The delayed recolonization of foraminifera suggests that estimates of subsidence may be influenced by months of postseismic land-level motion. Depending on whether net postseismic motion is uplift or subsidence in the months following megathrust earthquakes, foraminiferal-based reconstructions may underestimate or overestimate, respectively, coseismic subsidence.

Coastal geodetic measurements immediately after great subduction earthquakes consistently show postseismic movement in the same horizontal direction as during the earthquake, a relation explained by viscoelastic mantle relaxation and megathrust afterslip (Wang et al., 2012). However, the complex vertical postseismic motions at coastal sites are more sensitive to their distance from the rupture zone (Sun and Wang, 2015) and are incompletely understood. For example, after the 2010 Mentawai earthquake in Sumatra, nearby global navigation satellite system sites continued to subside, quickly exceeding the amount of coseismic subsidence (Feng et al., 2015). Within a year of the 2011 Tohoku-oki (Japan) earthquake, which induced widespread coseismic subsidence, most sites to the south of the main rupture area that coseismically subsided rose 10%–20% (some >50%), whereas some to the north continued to subside by 0%–100% of coseismic subsidence (e.g., Ozawa et al., 2012). If microfossil-based reconstructions are sufficiently precise, the differing response times of foraminifera and diatoms to sudden tidal flooding at the Ni-les'tun salt marsh suggest a new way to unravel such complex postseismic vertical deformation for past great subduction-zone earthquakes.

CONCLUSIONS

The restoration of tidal hydrology and salinity of the Ni-les-tun salt marsh was followed

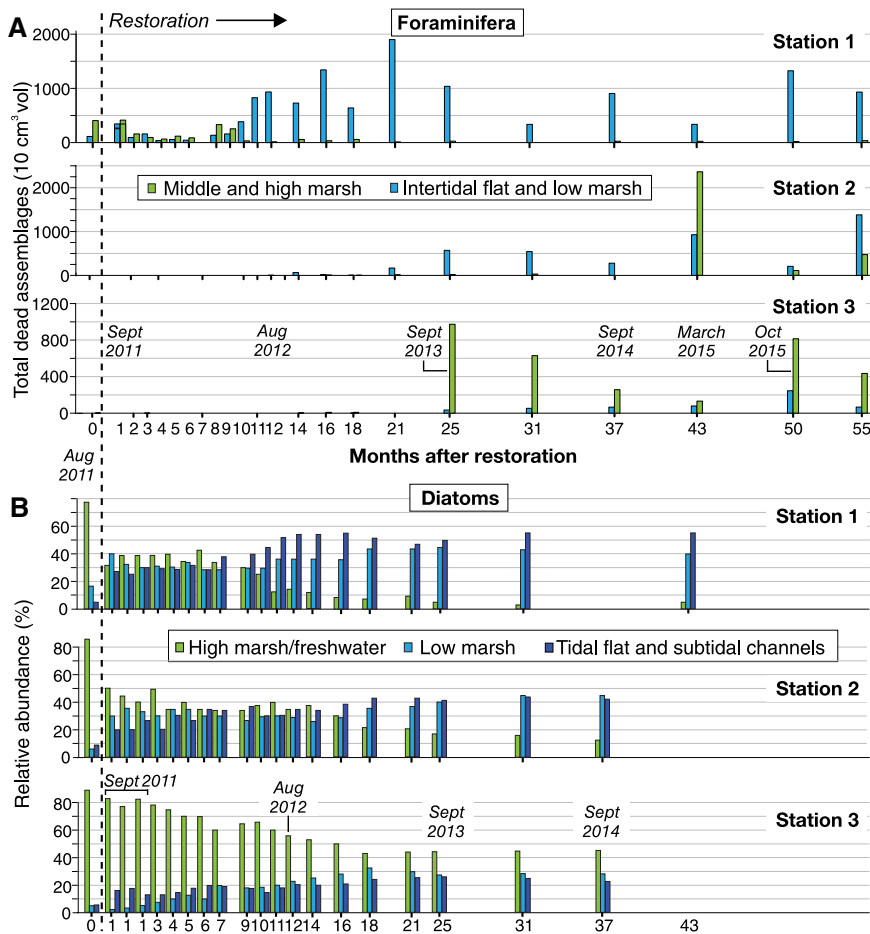


Figure 3. A: Total dead foraminiferal numbers (per 10 cm³ sediment volume). Note different y-axis scales. B: Relative total diatom abundance at stations 1–3, pre-restoration and post-restoration of the marsh.

in less than two weeks by diatom colonization. In contrast, a notable foraminiferal appearance was delayed at least 11 months. Foraminiferal-based reconstructions of vertical motion during past subduction earthquakes may be influenced by months of postseismic deformation, the time-dependent complexity of which is well documented by geodetic measurements at subduction zones. However, the differing response times of diatoms and foraminifera may provide a new means of estimating vertical motion in the months following past earthquakes. Such information could add considerably to our understanding of mantle rheology and fault mechanics (afterslip) at subduction zones.

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