

Testing the use of microfossils to reconstruct great earthquakes at Cascadia

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ABSTRACT

Coastal stratigraphy from the Pacific Northwest of the United States contains evidence of sudden subsidence during ruptures of the Cascadia subduction zone. Transfer functions (empirical relationships between assemblages and elevation) can convert microfossil data into coastal subsidence estimates. Coseismic deformation models use the subsidence values to constrain earthquake magnitudes. To test the response of foraminifera, the accuracy of the transfer function method, and the presence of a pre-seismic signal, we simulated a great earthquake near Coos Bay, Oregon, by transplanting a bed of modern high salt-marsh sediment into the tidal flat, an elevation change that mimics a coseismic subsidence of 0.64 m. The transplanted bed was quickly buried by mud; after 12 mo and 5 yr, we sampled it for foraminifera. Reconstruction of the simulated coseismic subsidence using our transfer function was 0.61 m, nearly identical to the actual elevation change. Our transplant experiment, and additional analyses spanning the A.D. 1700 earthquake contact at the nearby Coquille River 15 km to the south, show that sediment mixing may explain assemblage changes previously interpreted as evidence of pre-seismic land-level change in Cascadia and elsewhere.

INTRODUCTION

At the Cascadia subduction zone (Pacific Northwest coastline of the United States), study of coastal stratigraphy and fossils has helped in reconstructing the timing and magnitude of past great (magnitude >8) earthquakes and provided estimates of the rate of upper-plate deformation during complete earthquake cycles of the past 3000–7000 yr (e.g., Shennan et al., 1996; Atwater and Hemphill-Haley, 1997; Witter et al., 2003). Using tidally sensitive microfossils, such as foraminifera and diatoms, we estimate strain accumulation and release above the subduction megathrust indirectly by inferring coastal land-level changes that occur instantaneously (coseismic) and gradually (interseismic). Measuring amounts and rates of the deformation of Cascadia's coast helps us understand subduction earthquakes at other plate boundaries and improves assessments of earthquake and tsunami hazards in western North America (Fig. 1A).

In its first decades, Cascadia paleoseismology focused on mapping coastal stratigraphy and radiocarbon dating fossils inferred to record the sudden subsidence of coastal wetlands during great earthquakes (e.g., Atwater, 1992; Nelson, 1992; Darienzo and Peterson, 1995). A common approach was to describe the stratigraphic

evidence of the A.D. 1700 earthquake, now estimated at magnitude 8.8–9.2, and assume that earlier earthquakes were similar (e.g., Nelson et al., 1996a). The amount of subsidence during earthquakes (an indirect measure of megathrust slip) was estimated from differences in lithology and plant macrofossil, foraminiferal, diatom, and pollen assemblages across contacts inferred to mark coseismic subsidence (e.g., Shennan et al., 1996; Atwater and Hemphill-Haley, 1997). Errors generally larger than ± 0.5 m were too large to distinguish differences in amounts of subsidence from one earthquake cycle to the next.

Recent reconstructions of coseismic subsidence using microfossil-based statistical transfer

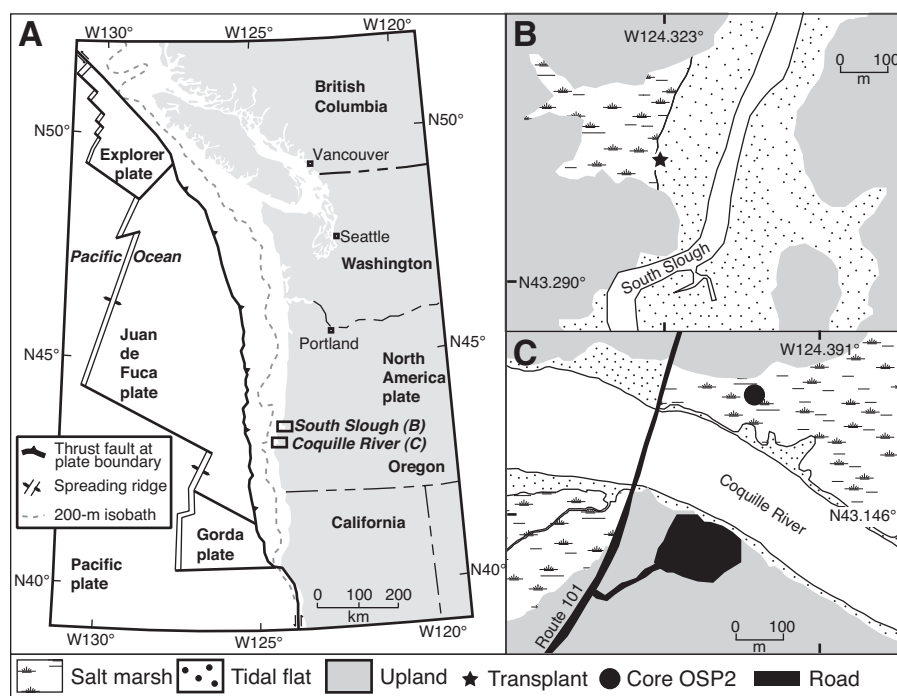


Figure 1. A: Map of Cascadia subduction zone of western North America showing location of South Slough (an arm of Coos Bay) and Coquille River, Oregon. **B:** Location of marsh transplant in Hidden Creek, South Slough, that was sampled for foraminifera and geochemical analyses. **C:** Location of core at Osprey Marsh, Coquille River, that shows evidence of subsidence during the A.D. 1700 earthquake.

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functions (e.g., Guilbault et al., 1996; Hawkes et al., 2011) have improved upon initial estimates. Transfer functions express elevation as a function of microfossil assemblages. Using empirical relationships developed from modern samples, transfer functions convert the fossil assemblages into quantitative estimates of the past elevation (see the GSA Data Repository¹). Transfer functions applied to climate-related sea-level rise yield estimates with vertical resolutions of $< \pm 0.2$ m and have been validated against instrumental records (e.g., Kemp et al., 2011). At Cascadia, however, questions about the rate of post-earthquake microfossil colonization (e.g., Hawkes et al., 2011) and the effects of bioturbation and infaunal migration near subsidence contacts (e.g., Hemphill-Haley, 1995; Nelson et al., 1996b) add unassessed uncertainty to microfossil-based estimates of coseismic subsidence. Elastic models of overriding-plate deformation during megathrust earthquakes (e.g., Wang et al., 2013) depend on the accuracy of paleoseismic estimates of coseismic subsidence.

In models of the earthquake cycle, strain accumulation due to locking at the start of the interseismic period features monotonic gradual coastal uplift or subsidence that continues with decreasing rate until a megathrust earthquake (Yeats et al., 1997). Studies from Hokkaido (Japan), Cascadia, and Alaska used small changes in microfossil assemblages to infer modest subsidence prior to coseismic rupture (Sawai et al., 2004; Hawkes et al., 2005; Shennan and Hamilton, 2006). If real, this subsidence implies that warning signs are detectable as much as decades before an earthquake occurs (Bourgeois, 2006). This small, pre-seismic signal of uplift changing to subsidence might be explained by transient precursory slip along an offshore part of the megathrust. Tilt of the ground to a maximum of $1/180^{\text{th}}$ of a degree was measured in the week prior to the A.D. 1923 Kanto earthquake (Hough and Bilham, 2005), but no near-field, continuous geodetic monitoring prior to a great earthquake supports or negates the postulated pre-seismic subsidence as a common feature of subduction zone earthquake cycles.

Here we transferred a block of modern high-marsh peat of South Slough, southern Oregon (United States) to a shallow pit ~0.6 m lower in the tidal flat (e.g., Hamilton et al., 2005) to simulate coseismic subsidence of a salt marsh and subsequent burial by tidal flat mud. By analyzing foraminifera and geochemical data from this “transplant” experiment, we examined the

potential for sediment mixing to blur foraminiferal assemblages below the buried peat-mud contact, an alternative explanation to pre-seismic motion reversal (e.g., Roeloffs, 2006). We tested a foraminifera-based transfer function by comparing its estimated subsidence of the high-marsh peat block against the surveyed subsidence. Finally, we investigated a stratigraphic record of the A.D. 1700 earthquake at the Coquille River, 15 km to the south, and demonstrated that the mixing signal identified in the transplant experiment is also found in the fossil record.

RECONSTRUCTING LAND-LEVEL CHANGE

South Slough, the location of the transplant experiment, is a 5000 acre preserve in the western arm of the Coos Bay estuary, Oregon (Fig. 1B). Great diurnal tidal range at Charleston (National Oceanic and Atmospheric Administration ID: 9432780), near the mouth of South Slough, is 2.32 m. Transplant methodology broadly followed Hamilton et al. (2005). One high-marsh and one tidal-flat station were chosen near a transect at South Slough previously analyzed for modern foraminifera (Hawkes et al., 2011). At the high-marsh station (2.36 m above mean lower low water; MLLW), a block ($0.35 \times 0.35 \times 0.1$ m) of peaty high-marsh sediment was removed and transplanted to a pit of the same area at the tidal-flat station (1.74 m MLLW). The tidal flat pit was 0.02 m deeper than the block height to promote sedimentation. In total, we vertically lowered the high-marsh block's surface by 0.64 m (28% of tidal range), similar to subsidence values estimated for the A.D. 1700 earthquake (e.g., Hawkes et al., 2011). Short cores were collected across the transplant contact 12 mo and 5 yr later, and revealed a similar stratigraphy of transplanted peat overlain by 1 and 7 cm of mud, respectively. These sediment thicknesses are comparable with a surface elevation table estimate of annual sediment accretion (6.6 mm/

yr) in South Slough marshes (C. Cornu, 2012, personal commun.).

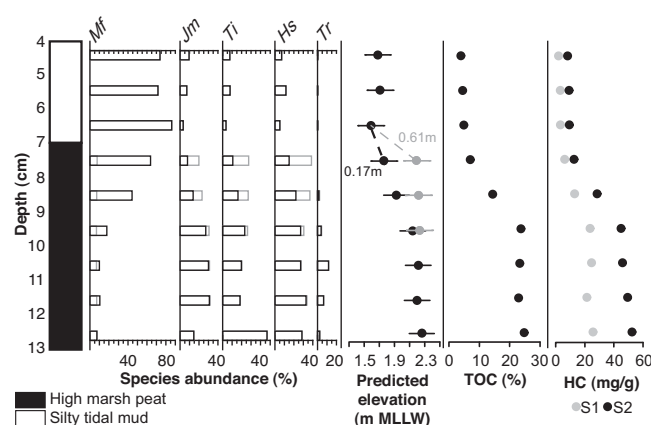
To use fossil assemblages to reconstruct land-level change, transfer function methods require a modern data set of foraminiferal assemblages from environments spanning the full range of tidal elevations (e.g., Horton et al., 1999). Preparation and analysis of foraminifera from the transplant cores followed Horton and Edwards (2006). The transfer function uses the modern data set of Hawkes et al. (2011) and Engelhart et al. (2013). It contains 152 samples from intertidal zones of six estuaries from northern to southern Oregon. We used a weighted averaging partial least squares transfer function, which had an r^2_{boot} of 0.85 and a reconstruction error of $\pm 7\%$ of the great diurnal tidal range (see the Data Repository). We applied the transfer function to assemblages from centimeter-thick slices of the core that included 5 yr of post-transplant sediment.

Stable carbon isotopes and hydrocarbon concentrations yield clues to the botanical and environmental origin of organic material preserved in coastal sediment (e.g., Kemp et al., 2012). For measurement of $\delta^{13}\text{C}$, total organic carbon (TOC), and total nitrogen, a Costech Elemental Analyzer coupled online to an Optima dual-inlet mass spectrometer was used (Lamb et al., 2007). Hydrocarbon concentrations were measured using pyrolysis on 60 mg of powdered sediment (dry/weight) using a Rock-Eval 6 analyzer (Vinci Technologies) following Behar et al. (2001).

SIMULATION OF COSEISMIC SUBSIDENCE

Sediment mixing evident across the peat-mud contact in our transplant test challenges efforts to accurately estimate coseismic subsidence. Our analyses show that the low marsh–tidal flat species *Miliammina fusca* from the recently deposited mud is incorporated into the underlying transplanted block. The foraminiferal assemblages (Fig. 2) within the lower section of the

Figure 2. Lithology, initial (black bars) and modified (gray bars) foraminiferal assemblages, transfer function reconstructions of elevation for initial (black) and modified (gray) assemblages, and total organic carbon (TOC) and hydrocarbon (HC) analyses for samples above and below contact between transplanted block of high-marsh peat and 5 yr accumulation of overlying tidal flat mud. Calculated subsidence with error in meters is marked on the reconstruction. MLLW—mean lower low water; Mf—*Miliammina fusca*; Jm—*Jadammina macrescens*; Ti—*Trochammina inflata*; Hs—*Haplophragmoides* spp.; Tr—*Trochammina irregularis*.



¹GSA Data Repository item 2013295, foraminiferal transfer function methods, Figures DR1 and DR2, and data presented in this study (including modern and transplant foraminiferal abundances, and elevations for modern samples), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

buried high-marsh peat (13–10 cm depth) were dominated by agglutinated species *Haplophragmoides* spp., *Jadammina macrescens*, and *Trochammina inflata*, found today in the high marshes of South Slough and other Oregon estuaries. Predicted elevations from the transfer function in the lower section (13–10 cm depth) of the peat were between 2.22 and 2.28 m MLLW, consistent with the elevation of the transplanted block (2.36 m MLLW). In the upper section (10–7 cm depth) of the buried peat, the presence of *M. fusca* caused the transfer function to predict lower elevations (between 1.77 and 2.16 m MLLW). The prediction for the sample at the top of the peat (8–7 cm depth) is 1.77 ± 0.17 m MLLW, which is considerably different from the elevation of the original sample block (2.36 m MLLW). *M. fusca* dominated (>70%) the newly deposited mud overlying the buried soil with predictions (1.60 ± 0.17 m MLLW at 7–6 cm depth) consistent with the observed elevation of the tidal flat site (1.74 m MLLW).

We calculate the simulated coseismic subsidence (CS) and error (CS_{error}) using the following equations (Hawkes et al., 2011):

$$CS = E_{\text{pre}} - E_{\text{post}} \quad (1)$$

where E_{pre} is the elevation of the pre-seismic buried peat and E_{post} is the elevation of the post-seismic overlying mud, and,

$$CS_{\text{error}} = \sqrt{\left[\left(E_{\text{pre error}} \right)^2 + \left(E_{\text{post error}} \right)^2 \right]}, \quad (2)$$

where the sample-specific $E_{\text{pre error}}$ and $E_{\text{post error}}$ are provided by the transfer function. From the samples just above and just below the top of the buried soil, the transfer function gives an estimate of block lowering of 0.17 ± 0.24 m, a significant underestimate compared to the actual value of 0.64 m.

Our finding of low marsh–tidal flat foraminifera within the transplanted high-marsh soil mimics a pre-seismic signal (e.g., Hamilton et al., 2005). This must be the result of either infaunal *M. fusca* burrowing (e.g., Patterson et al., 2005) or sediment mixing at the peat–mud contact (e.g., Hemphill-Haley, 1995; Nelson et al., 1996b; Hamilton et al., 2005). While live foraminifera were found in core samples, only five live *M. fusca* were noted in either the 12 mo or 5 yr samples. Geochemical data show a decrease in TOC (23.7%–7.0%), S1 hydrocarbon (23.6–6.2 mg/g), and S2 hydrocarbon (45.0–12.7 mg/g) between 10 and 7 cm depth. It is improbable that infaunal burrowing would introduce the allochthonous sediment required to alter the geochemical signature of the peat, suggesting that sediment mixing is responsible. However, Shennan and Hamilton (2006) concluded that sediment mixing is not necessarily the explanation for all such assemblage changes. Using diatoms, they found that the species indicating

pre-seismic subsidence were not present in the overlying sediment. Geochemical measures of bulk sediment that parallel gradual changes in assemblages across a sharp contact (Fig. 2) may provide a means of identifying whether or not sediment above and below the contact has been mixed. Also, tsunami-deposited beds of sand that overlie high-marsh deposits may reduce the mixing of foraminifera across high-marsh contacts (Hawkes et al., 2011).

The geochemical profiles suggest little mixing below 10 cm depth (3 cm below the contact), where *M. fusca* abundances are ~7%. Therefore, to remove the effect of mixing in the upper block we adjusted the *M. fusca* abundances (Fig. 2) in the upper section of the transplant block to 7% (i.e., background level). This raises the transfer function–predicted elevation from 1.77 ± 0.17 m to 2.21 ± 0.17 m MLLW and so changes the estimate of block lowering to 0.61 ± 0.24 m, a value matching the surveyed lowering of the transplanted block (0.64 m). Models of overriding-plate deformation (e.g., Wang et al., 2013) suggest that a similar amount of coseismic subsidence might be the result of an earthquake of M 8.1 to M 8.8 with megathrust rupture lengths of 200–1000 km, respectively.

COSEISMIC SUBSIDENCE DURING THE A.D. 1700 EARTHQUAKE

At Coquille River (Fig. 1) we sampled a dark-brown peat that occurs from 0.94 to 0.74 m depth beneath the modern middle marsh. Measured $\delta^{13}\text{C}$ values (–26.1‰ to –27.8‰), high percentages of TOC (8.9%–44.6%), total nitrogen (0.6%–1.5%), and wood fragments within the peat suggest it is the AO horizon of an upland forest soil (e.g., Lamb et al., 2007; Hawkes et al., 2011). The soil is overlain by gray mud from 0.74 to 0.58 m depth (Fig. 3). Witter et al. (2003) attributed the burial of the soil to subsidence during the A.D. 1700 earthquake. Foraminifera are absent at the base of the unit, as expected for a forest soil, but from assemblages dominated by *M. fusca* in the upper section of the soil (0.78–0.74 cm) and overlying mud, we infer sediment mixing across the contact. In prior studies of modern assemblages, high abundances of *M. fusca* (>80%) have not been found in sediment with TOC/LOI (loss on ignition) greater than 10% (Hawkes et al., 2011; Engelhart et al., 2013). The mixing interpretation is also supported by generally decreasing TOC values at the top of the AO horizon—similar to the pattern identified in the transplant cores (Fig. 2)—and is consistent with our premise that geochemical measures of bulk sediment may allow for recognition of mixing. A gradual pre-seismic signal cannot explain the change in foraminiferal assemblages, because a gradual shift from a forested upland to a tidal flat dominated by *M. fusca* skips the intervening high-marsh environment between the forest and tidal flats, violating Walther’s law.

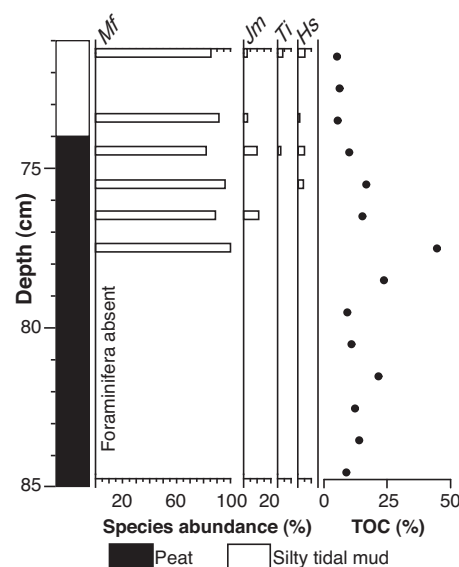


Figure 3. Lithology, foraminiferal assemblages, and total organic carbon (TOC) values for samples above and below the A.D. 1700 earthquake contact at Osprey Marsh, Coquille River, Oregon. Abbreviations as in Figure 2.

Because *M. fusca* dominates the assemblage above and below the A.D. 1700 contact at Coquille River, failing to consider mixing across the contact results in an estimate of coseismic subsidence of 0 m during this well-known great Cascadia earthquake. Conversely, correcting assemblage percentages, as we did at our transplant site, yields an estimate for coseismic subsidence of >0.81 m. This is a minimum value because the buried AO horizon represents a forest environment too high to host foraminifera. Similar estimates of A.D. 1700 subsidence have been obtained 20 km to the north at Crown Point in South Slough (>0.67 m; Hawkes et al., 2011).

CONCLUSIONS

Three findings impact the quantitative microfossil reconstruction of overriding-plate deformation during megathrust earthquakes. First, sediment mixing may introduce foraminiferal species living in lower intertidal environments into the buried marsh soils of higher intertidal environments and, if unrecognized, results in different ecologic interpretations and significant underestimates of coseismic subsidence. To help identify mixed assemblages we recommend analyzing samples at least 3 cm below contacts inferred to mark earthquake subsidence. Second, identification of sediment mixing as an important process in our transplant experiment and for the A.D. 1700 earthquake contact at Coquille River suggests that mixing may explain assemblage changes previously interpreted as evidence of pre-seismic land-level change. Mixing, however, is not necessarily the explanation for all such inferred changes (e.g., Shennan and Hamilton, 2006). Geochemical signatures

show potential for identifying contacts where sediment has been mixed and corrections are required to estimate subsidence. Third, our transplant simulation shows that foraminiferal transfer functions can accurately reconstruct subsidence during a great earthquake. This result gives us confidence in using such estimates to constrain elastic models of deformation during prehistoric megathrust earthquakes.

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