Testing precise foraminiferal reconstructions of upper plate deformation during Earth's greatest earthquakes

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Abstract

The recent magnitude-9 (M9) earthquakes at subduction zones in Sumatra and Japan are focusing efforts to learn the history of infrequent earthquakes that are commonly accompanied by devastating tsunamis. The Pacific Northwest coastline along the

Cascadia subduction zone contains a sedimentary archive of past megathrust earthquakes. Where coastal stratigraphy records sudden subsidence due to relaxation of the overriding plate during rupture of the subduction fault, transfer functions can convert microfossil data into estimates of the amount of coseismic subsidence. Subsidence is then used in 3D elastic models of subduction-zone deformation to calculate earthquake magnitude. We tested this method with a simulated earthquake by "transplanting" a bed of modern high salt-marsh sediment into the low marsh, a vertical elevation change equivalent to coseismic subsidence of 0.62m. The transplanted bed was quickly buried by sediment and sampled for microfossils after five years. Our reconstruction of this simulated "coseismic" subsidence using our foraminiferal transfer function was 0.61m, which yields the same magnitude in deformation models. Our analyses also showed that sediment mixing could explain some occurrences of the "pre-seismic" microfossil signal inferred from prehistoric records in Cascadia and presented further evidence for sediment mixing from a record of the AD 1700 earthquake at the Coquille River, Oregon.

1. Introduction

Coastal paleoseismology addresses the timing, amounts, and rates of deformation on Cascadia's megathrust throughout complete earthquake cycles over periods of hundreds to thousands of years (e.g., Shennan et al., 1996; Atwater and Hemphill-Haley, 1997; Witter et al., 2003). We measure subduction-zone strain accumulation and release indirectly by inferring coastal land-level changes from small (< 2 m) changes in relative sea level that occur instantaneously (coseismic) and gradually (interseismic). Measuring how and when the Cascadia plate boundary deforms helps us understand subduction at other plate boundaries and improves assessments of earthquake and tsunami hazards in western North America. Except for Japanese records of the most recent great earthquake's tsunami (26 Jan AD1700, Satake et al., 2003), at Cascadia, coastal stratigraphy is the sole archive of evidence for the magnitude of past great earthquakes.

In its first decades, Cascadia paleoseismology understandably focused on mapping coastal stratigraphy and radiocarbon dating buried peat inferred to record the sudden

subsidence of wetlands during great earthquakes (e.g., Atwater, 1992; Darienzo and Peterson, 1995). A common approach was to describe the stratigraphic evidence of the AD 1700 earthquake, now estimated at magnitude M8.8-9.2, and assume that earlier earthquakes were similar (e.g., Nelson et al., 1996). The amount of subsidence during earthquakes (an indirect measure of earthquake magnitude) was estimated from differences in lithology and plant macrofossils across contacts inferred to mark coseismic subsidence. Errors generally >±0.5 m were too large to distinguish differences in amounts of subsidence from one earthquake cycle to the next (e.g., Nelson et al., 2008).

The study of Cascadia's modern counterparts to fossil intertidal foraminiferal, diatom, and pollen assemblages (e.g., Nelson et al., 1996; Shennan et al., 1996) provides the basis for more precise reconstructions of coseismic subsidence using statistical transfer functions (e.g., Guilbault et al., 1996; Hawkes et al., 2011). Similar transfer functions applied to climate related sea-level rise yield estimates with vertical resolutions of $< \pm 0.2$ m and are validated against instrumental records (e.g. Kemp et al., 2011). At Cascadia, however, questions concerning the use of microfossils including the rate of post-earthquake colonization and the effects of bioturbation and infaunal migration of near subsidence contacts (e.g., Hemphill-Haley, 1995), add unassessed uncertainty to transfer function estimates of coseismic subsidence. Below we test the accuracy of the seismic application of foraminiferal transfer functions.

Our test also partially answers questions about postulated gradual coastal subsidence just prior to coseismic subsidence. In models of the earthquake cycle, strain accumulation due to plate convergence above locked portions of the megathrust is expressed as gradual interseismic coastal uplift that continues with decreasing rate until coseismic subsidence during a megathrust earthquake. Studies from Hokkaido, 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 small, pre-seismic reversal of motion from uplift to subsidence might be explained by slow precursory slip along the locked part of the megathrust. Tilt of the ground to a maximum $1/180^{th}$ of degree was measured in the week prior to the 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, to simulate coseismic subsidence of a southern Oregon high marsh during the AD 1700 earthquake followed by burial by intertidal mud, we transferred a block of the modern high marsh soil to a shallow pit about 0.6 m lower in the muddy low marsh (e.g., Hamilton et al., 2005). By analyzing foraminifera and sediment geochemical data from this 'transplant' experiment, we examined the potential for sediment mixing to 'blur' foraminiferal assemblages above and below the buried soil–mud contact; an alternative explanation to pre-seismic motion reversal. And we tested a foraminiferal-based transfer function by comparing its calculated lowering of the high marsh peat block against the actual surveyed lowering. Finally, we investigated a stratigraphic record of the AD 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.

2. Reconstructing land-level change

South Slough, the location of the transplant experiment, is a 5,000-acre preserve in the western part of the Coos Bay estuary, Oregon (Figure 1B). Great diurnal tidal range determined by the NOAA tide gauge at Charleston (9432780) is 2.32 m. Transplant methodology broadly followed Hamilton et al. (2005). Two stations (one high marsh and one low marsh) were chosen along a transect at South Slough previously analyzed for modern foraminifera (Hawkes et al., 2011). At the high marsh station (0.24 m above Mean High Water (MHW), a block of peaty high-marsh soil (O horizon; 0.35x0.35x0.1m) was removed and transplanted to a pit of the same area at the low marsh site (-0.38 m MHW). The low marsh pit was 0.02 m deeper than the block height to promote initial sediment accumulation; although this may induce a local hydraulic gradient. Short cores (20 cm long) were collected across the transplant contact after 12 months and five years, and revealed the transplanted soil overlain by 1 and 7 cm of mud, respectively. Such sediment thicknesses are comparable with a surface-elevation table

estimate of annual sediment accretion (6.6 mm a^{-1}) in South Slough marshes (REF FROM CRAIG CORNU).

To use core fossil assemblages to reconstruct sea-level change, transfer function methods require an extensive modern dataset of foraminiferal assemblages along elevational gradients spanning the full range of tidal environments (e.g., Horton et al., 1999). Preparation and analysis of foraminifera from the transplant cores followed Horton and Edwards (2006). The transfer function was developed using the modern dataset of Hawkes et al. (2011) and Engelhart et al. (accepted). The dataset contained 152 samples from six intertidal zones at northern to southern Oregon estuaries. To develop the transfer function we used weighted averaging partial least squares with component one, which had an r^2_{boot} of 0.85. The reconstruction error (±7% of the great diurnal tidal range) is comparable to transfer functions from other temperate marshes (e.g., Horton and Edwards, 2006; Callard et al., 2011). We applied the transfer function to assemblages from the core that included five years of post-transplant sediment.

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

3. Simulation of coseismic subsidence

To model coseismic deformation from the transplant experiment and AD 1700 fossil sequence, we used a 3-D elastic dislocation model that allows the slip to vary both along strike and in the dip direction (Wang et al., in revision). But elastic models of upper plate deformation during subduction (e.g., Wang et al., in revision) depend on the accuracy of

paleoseismic estimates of subsidence during megathrust earthquakes. Our analyses show that the low marsh species *Miliammina fusca* from the recently deposited mud is incorporated into the underlying transplanted block. The foraminiferal assemblages (Figure 2) within the lower section of the buried high-marsh soil (13 to 10 cm) were dominated by agglutinated species *Haplophragmoides* spp., *Jadammina macrescens* and *Trochammina inflata*, found today in the high marshes of South Slough and elsewhere in Oregon (Hawkes et al., 2011; Engelhart et al., accepted). Predicted elevations from the transfer function in the lower section (13 to 10 cm) of the soil were ~ 0.12 ± 0.03 m MHW, which is comparable to the elevation of the original sample block (0.24 m MHW). In the upper section (10 to 7 cm) of the buried soil, the presence of *M. fusca* caused the transfer function to predict a much lower elevation of -0.35m MHW. *M. fusca* dominated (>70%) the newly deposited mud overlying the buried soil with predictions (~ -0.45 ± 0.06 MHW) consistent with the observed elevation of the low marsh site (-0.38 m MHW).

We calculate the simulated coseismic subsidence (CS) and error (CS$_{error}$) using the following equations (Preuss, 1979):

$$CS = E_{pre} - E_{post} \qquad\qquad\qquad\qquad\qquad\qquad (Eq. 1)$$

where E$_{pre}$ is the elevation of the preseismic buried soil and (E$_{post}$) is the elevation of the post-seismic overlying mud.

$$CS_{error} = \sqrt{[(E_{pre\ error})^2 + (E_{post\ error})^2]} \qquad\qquad\qquad (Eq. 2)$$

where the sample-specific E$_{pre\ error}$ and E$_{post\ error}$ 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 0.62 m.

Our finding of low marsh foraminifera within the transplanted high-marsh soil mimics the pre-seismic signal. This must be the result of either infaunal *M. fusca* burrowing (e.g.,

Patterson et al., 2005) or sediment mixing at the high-marsh peat-mud contact (e.g., Hamilton et al., 2005). 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. Assuming ecological inferences from microfossil assemblages are correct, geochemical measures of bulk sediment (e.g., TOC and S1/S2 hydrocarbons) that parallel gradual changes in assemblages across a sharp contact (Figure 2) may provide a simple means of identifying whether or not sediment above and below the contact has been mixed and allow for a correction.

To remove the effect of mixing we changed the *M. fusca* abundances (Figure 3) in the upper section of the transplant block to the background level found in its lower section (~7%). This raises the transfer-function predicted elevation from -0.35 to 0.09 m MHW and so changes the estimate of block lowering to 0.61 ± 0.24 m, a value matching the surveyed lowering of the transplanted block. Upper plate deformation models explained elsewhere (Wang et al., in revision) suggest that a similar amount of coseismic subsidence might be the result of an earthquake of M 8.1 to M8.8 with rupture lengths of 200 to 1000 km, respectively.

4. Coseismic subsidence during the AD 1700 earthquake

At Coquille River (Figure 1) we sampled a dark brown peaty soil that occurs from 0.94 to 0.74 m depth beneath the modern middle marsh. Stable carbon isotopes including $\delta^{13}C$ (-26.1 to -27.8‰), high percentages of TOC (8.9 to 44.6%), total nitrogen (0.6 to 1.5%), and wood fragments within the soil 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 a grey mud from 0.74 to 0.58 m depth (Figure 4). Witter et al. (2003) attributed the burial of the soil to subsidence during the AD 1700 earthquake. At the base of the soil foraminifera are absent, but from assemblages dominated by *M. fusca* in the upper section of the soil and

overlying mud, we infer sediment mixing across the upper contact of the soil. In prior studies of modern assemblages (Hawkes et al., 2011; Engelhart et al., accepted), high abundances of *M. fusca* (>80%) have not been found in sediment with TOC greater than 10%. The mixing interpretation is also supported by decreasing TOC values at the top of the soil; similar to the pattern identified in the transplant cores (Figure 2) and supports of our hypothesis that geochemical measures of bulk sediment may allow for recognition of mixing. A pre-seismic signal cannot explain the change in foraminiferal assemblage as a gradual switch from a forest soil to a *M. fusca* dominated assemblage is missing the high marsh deposit that separates these two environments.

Because *M. fusca* dominates the assemblage above and below the AD 1700 contact at Coquille River, failing to consider mixing across the contact results in an estimate of coseismic subsidence of zero meters during this best-known great Cascadia earthquake. Conversely, correcting assemblage percentages as we did at our transplant site yields a transfer function estimate for coseismic subsidence of >0.81 m. This is a minimum subsidence value because the buried forest AO horizon represents an upland environment too high to host foraminifera. Similar minimum estimates of AD 1700 subsidence have been obtained 20 km to the north at Crown Point in South Slough (0.67 m; Hawkes et al., 2011) and at Sixes River (range of 0.7 to 2.2 m; Kelsey et al., 1998), 35 km to the south.

Conclusions

Three findings impact the quantitative, microfossil-based reconstruction of upper plate deformation during megathrust earthquakes. First, along subsided coasts sediment mixing introduces foraminiferal species living in lower intertidal environments into the buried soils of higher intertidal environments and, if unrecognized, results in significant underestimates of coseismic subsidence. To help identify mixed assemblages we recommend analyzing samples more than 5 cm below contacts inferred to mark earthquake subsidence, especially in the absence of a tsunami-deposited sand bed on contacts. Depending on bed thickness, such sand beds greatly reduce the mixing of foraminifera across contacts. Second, identification of mixing as an important process in

our transplant experiment and for the AD 1700 earthquake contact at Coquille River suggest that sediment mixing may explain assemblage changes previously interpreted as recording pre-seismic land-level change in some earlier studies (e.g., Hawkes et al., 2005). Mixing, however, is not necessarily the explanation for all such inferred changes (e.g., Shennan and Hamilton, 2006). Geochemical signatures show potential for identifying subsidence contacts where sediment has been mixed requiring corrections to be applied. Third, we interpret from transplant test of simulated coseismic subsidence that a foraminiferal-based transfer function 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 (e.g., Wang et al., in revision).

Acknowledgements

Figure Caption

Figure 1. Map of (A) The Cascadia subduction zone (USA) showing the location of South Slough and Coquille River, (B) the location of the marsh transplant in Hidden Creek, South Slough that was sampled for foraminifera and geochemical analyses, and (C) the location of the core taken at Osprey Marsh, Coquille River that contained a record of subsidence associated with the AD 1700 earthquake.

Figure 2. Stratigraphy, foraminiferal assemblages, transfer function reconstructions of elevation, and total organic carbon and hydrocarbon analyses for samples above and below the contact between the transplanted block of high-marsh peat and five year's accumulation of overlying low marsh mud. The calculated subsidence with the error in

meters is marked on the reconstruction. MHW = mean high water; Mf = *Milliammina fusca*; Jm = *Jadammina macrescens*; Ti = *Trochammina inflat*a; Hs = *Haplophragmoides* spp.; Tr = *Trochamminita irregularis.*

Figure 3. Stratigraphy, modified foraminiferal assemblages and transfer function reconstructions of elevation for samples above and below the contact between the transplanted high marsh peat and the overlying clastics that accumulated in the five years since emplacement. The calculated subsidence with the error in meters is marked on the reconstruction. MHW = mean high water; Mf = *Milliammina fusca*; Jm = *Jadammina macrescen*s; Ti = *Trochammina inflata*; Hs = *Haplophragmoides* spp.; Tr = *Trochamminita irregulari*s.

Figure 4. Stratigraphy, foraminiferal assemblages and total organic carbon (TOC) values for samples above and below the contact recording the AD 1700 earthquake at Osprey Marsh, Coquille River. Mf = *Milliammina fusca*; Jm = *Jadammina macrescens*; Ti = *Trochammina inflata*; Hs = *Haplophragmoides* spp.

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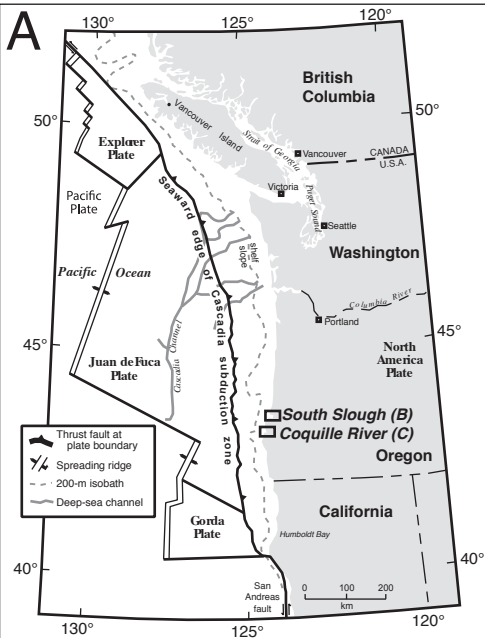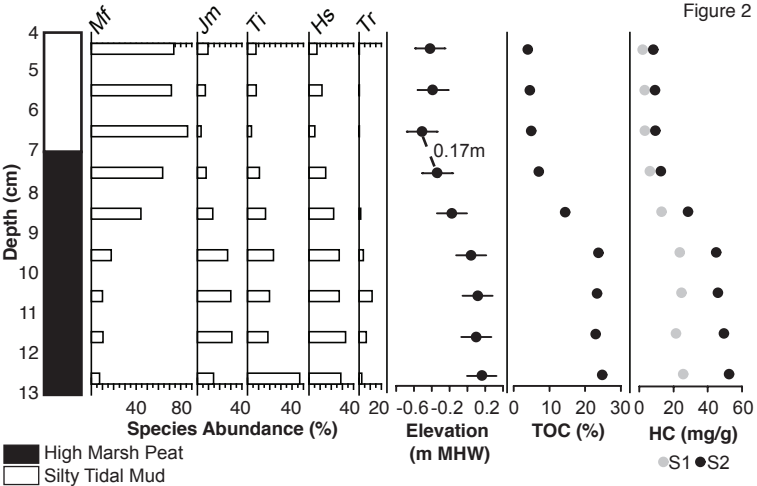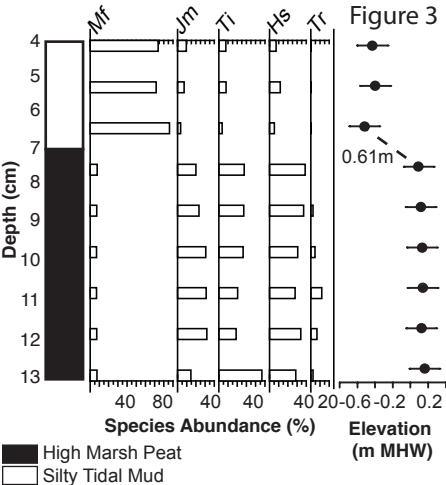
Figure 1

Salt Marsh · Tidal Flat ▦ Upland ★ Transplant ● Core OSP2 ▬ Road

Figure 2

Figure 3

Figure 4