Reconstructing coastal evidence for earthquakes and tsunamis using elemental (XRF) geochemistry

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X-ray fluorescence (XRF) analysis is a geochemical technique that reveals subtle environmental changes over sub-annual to millennial timescales. Elemental geochemistry of salt-marsh sediments responds to tidal frequency similar to microfossil distributions, which are used to reconstruct sea- and land-level change.

Subduction zones are known to generate some of the largest magnitude earthquakes and their subsequent tsunamis are capable of inundating local and distant coastlines. The recurrence interval of large earthquakes rupturing along a subduction interface are generally on the order of hundreds to thousands of years, making risk assessment challenging because the observational records do not fully capture these larger timescales (e.g. Sawai et al. 2012). Therefore, we must rely on the geologic record to extend our understanding of earthquake-rupture mechanisms, magnitudes, and frequencies (e.g. Atwater et al. 2003; Nelson et al. 2021).

Salt-marsh archives
In salt marshes, tides result in distinct environmental zones that are controlled by the frequency and duration of tidal inundation. Tidal inundation in salt marshes is controlled by the elevation gradient relative to sea level; where lower elevations are inundated more frequently and for longer durations than sections of the marsh situated at higher elevations. The predictable response of salt-marsh sediments to tidal inundation forms the basis for applying proxies (i.e. microfossils, XRF-elemental geochemistry) to reconstruct sea-level change, and in doing so, identifying paleoearthquakes and tsunamis in the geologic record (Atwater and Hemphill-Haley 1997).

In salt marshes, megathrust earthquakes may result in coseismic subsidence (instantaneous land-level lowering during the earthquake), which is analogous to instantaneous local sea-level rise. Stratigraphically, coseismic subsidence is identified as peat-mud couplets where pre-earthquake intertidal peat is suddenly lowered further into the intertidal and subtidal zone, where mud is subsequently deposited, resulting in a distinctive mud-over-peat contact (Atwater 1987). The tsunami generated from the earthquake can also inundate local coastlines, and the resulting overwash sediments can be preserved within salt-marsh stratigraphy as a thin marine sand sheet between the peat (pre-earthquake) and mud (post-earthquake) units (Hemphill-Haley 1995).

XRF as a tool for recognizing paleoearthquakes and tsunamis
Although intertidal microfossils (e.g. fora-minifera and diatoms) are among the most

widely used proxies for reconstructing paleoearthquakes and tsunamis (Pilarczyk et al. 2014), elemental geochemistry obtained through XRF-core scanning (XRF-CS) is a promising technique for reconstructing long term records of coastal change because of its rapidness and ability to detect even subtle environmental changes preserved within sediment cores (Giang et al. 2023).

XRF-CS offers rapid, continuous and non-destructive analysis of elemental composition for a wide range of geologic materials, including core samples. In XRF analysis, samples are irradiated with X-rays which induce the atoms from the samples to emit characteristic fluorescence photons. Detectors measure the energies of fluorescence photons which, in turn, identify the element and the number of fluorescence photons of that energy, to determine the abundance of a particular element in a given substance.

In theory, XRF analysis identifies all elements based on their characteristic fluorescence emissions, but in practice, XRF is incapable

of detecting low atomic number elements (Z <11; e.g. H, C, N, O). Instead, XRF can indirectly measure these elements based on the X-ray scatter measured simultaneously with elemental data. X-ray scatter occurs when an incident X-ray is redirected or changes direction due to an interaction with an electron. Incoherent scattering occurs when the X-ray loses energy to the electron and is more prevalent with lower atomic number elements, while coherent scattering involves no change in X-ray energy and is more common with higher atomic number elements. The incoherent/coherent scattering ratio (ICR) provides insights into the average atomic mass of the total elemental composition.

Along salt-marsh coastlines, the elemental composition of modern marsh sediments shows a consistent relationship with tidal elevation, and is in agreement with marsh zones that are derived from intertidal microfossil assemblages (Giang et al. 2023; Pilarczyk et al. 2014). Generally, tidal flat and low marsh sediments from lower elevations are dominated
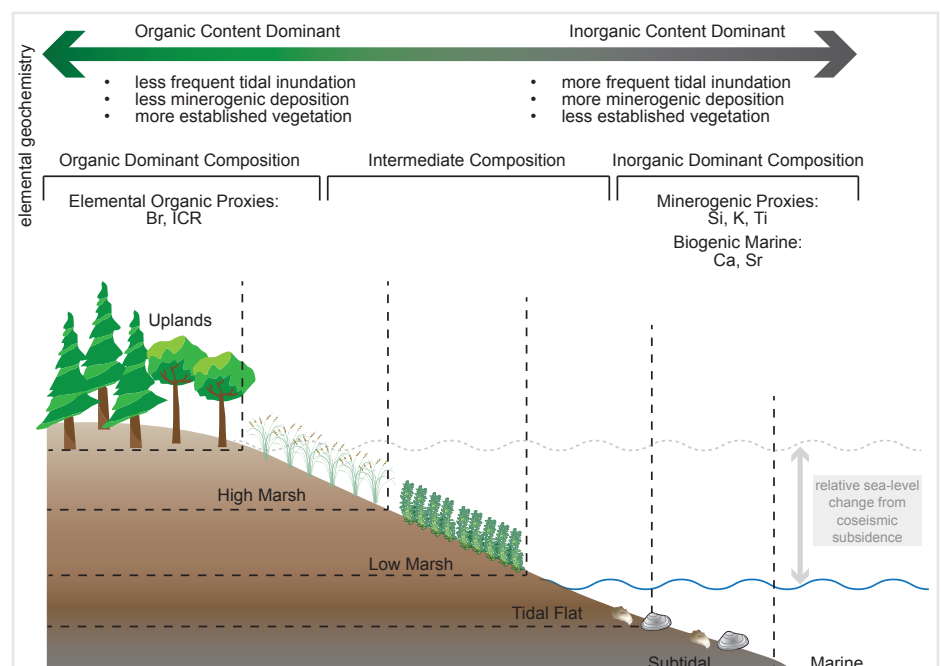
Figure 1: Conceptual model of elemental geochemistry zonation within Cascadia salt marshes. The elemental composition of low elevation (i.e. tidal flat) sediments is dominated by lithogenic (Si, K, Ti, Fe) and biogenic (Ca, Sr) elements, while the composition at high elevations (i.e. high marsh/uplands) is dominated by organic indicators, such as Br and ICR (incoherent/coherent scattering ratio). Relative sea-level change associated with coseismic subsidence is shown in gray, and results in the deposition of tidal flat muds on top of salt-marsh peats.
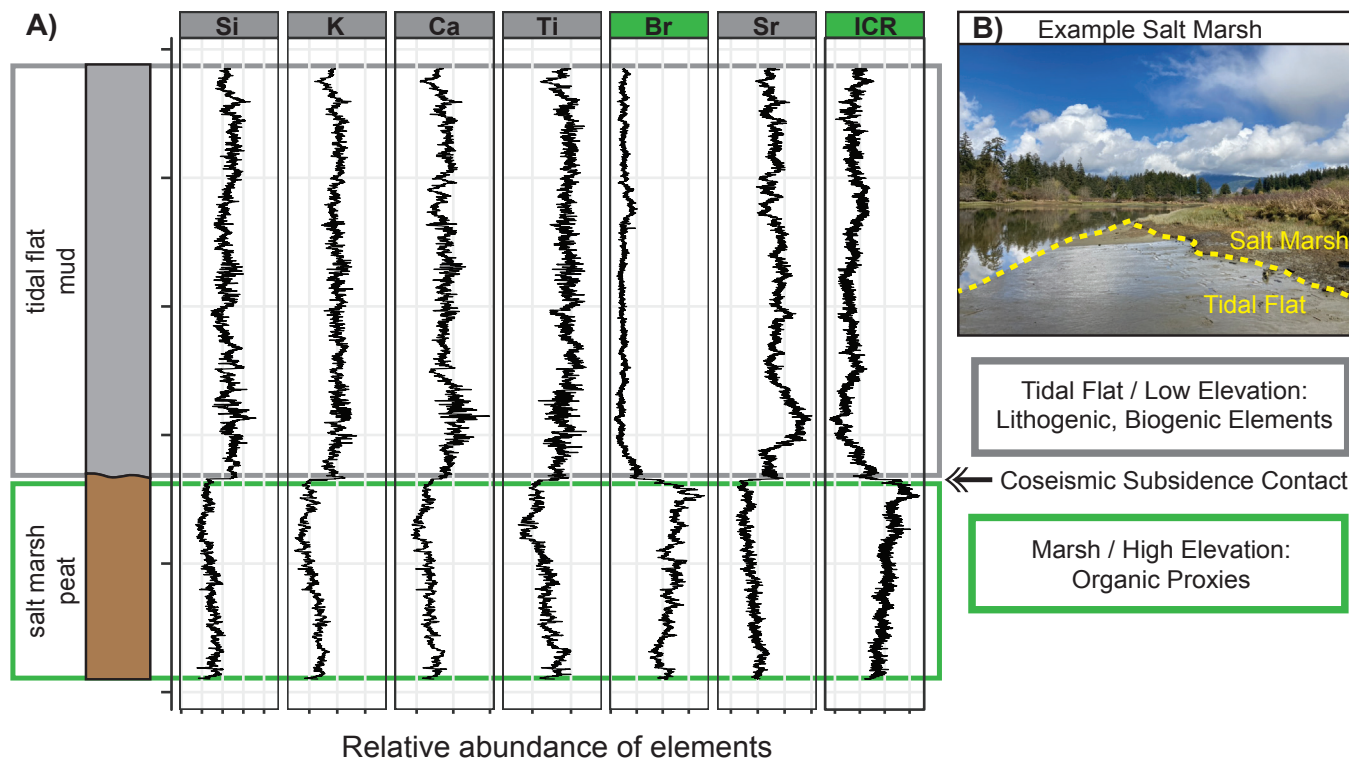
Figure 2: (A) Idealized sediment core collected from a salt marsh and associated conceptual elemental data illustrating stratigraphic evidence for coseismic subsidence. The subsidence contact is recognized by a sharp and abrupt change in lithology and elemental composition. Lithogenic (Si, K, Ti,) and biogenic (Ca, Sr) elements dominant at low elevations are highlighted in gray, while organic elements (Br, ICR), dominant at high elevations, are highlighted in green. **(B)** Typical Cascadia salt marsh where evidence for earthquakes and tsunamis can be found. The tidal flat and salt marsh subenvironments are delineated with the dashed line.

by lithogenic (Si, K, Fe, Ti) and biogenic (Ca, Sr) elements (Fig. 1). At low elevations, frequent tidal inundation remobilizes detrital sediment from the subtidal basin into the intertidal salt marsh. At higher elevations, the elemental composition is dominated by Br (high marsh; Fig. 1); however, despite its high abundance in seawater, Br in marshes is not as dominant at low elevations, but rather at high elevations where tidal inundation is less. This may be the result of Br's involvement in biogeochemical processes that transform mobile Br ions into immobile species within peats and soils (e.g. Keppler et al. 2000).

The ICR is applied as a proxy for organic content because organic forming elements (e.g. H, C, O, N) tend to have lower atomic numbers, while clastic sediments tend to be composed of higher atomic number elements (e.g. Si, Fe) (Woodward and Gadd 2019). The ICR also follows the same trend as Br, where highest values are found at high elevations where vegetation is most established within the intertidal range (Fig. 1). The elemental composition can distinguish subtle differences in the inorganic and organic content of salt-marsh sediments, which is predominantly controlled by tidal inundation.

Elemental geochemistry, obtained through XRF analysis, can resolve continuous, high-resolution elemental variation within sediment cores (Fig. 2). The relationship between modern salt-marsh sediments and elemental geochemistry can be applied downcore to resolve changes in paleoenvironmental conditions, including sudden, high-magnitude changes, such as coseismic subsidence associated with large earthquakes as shown conceptually in figure 2. Coseismic subsidence may be recognized by a dramatic and sharp

change in geochemistry from an organic dominated composition (i.e. Br-rich peats, soils) to a lithogenic and biogenic dominated one (i.e. Si, K, Fe, Ti, Ca, and Sr-rich tidal flat mud; Fig. 2). Elemental geochemistry may be especially useful for recognizing smaller amounts of coseismic subsidence when stratigraphic evidence is not obvious. Data derived from XRF analysis may also be applied as a supplemental proxy in microfossil-based sea- and land-level reconstructions to increase precision (e.g. Cahill et al. 2016). The down-core applications of elemental geochemistry for reconstructing coseismic subsidence still requires ground truthing, but shows promising potential based on the modern relationship between elemental composition and tidal elevation of salt-marsh sediments (Giang et al. 2023).

In addition to delineating the occurrence of coseismic subsidence in marsh stratigraphy, elemental geochemistry can also be used to identify tsunamis. Tsunami sediments preserved in salt marshes are often characterized by high concentrations of seawater ions (e.g. Na^+, Cl^-) and heavy elements from the offshore environment (e.g. Zn, Pb) (Chagué-Goff et al. 2017). In this way, XRF data can identify a marine origin for the anomolous sands, and may provide better estimates of marine inundation limits and lateral extensiveness of these deposits.

Advantages of elemental geochemistry
XRF-CS analysis simultaneously measures a wide suite of elements (Al to U), each with the potential to bolster paleoenvironmental and sea-level reconstructions. The rapid and high resolution (up to 100 μm) capability of the XRF-CS, in particular, enhances our ability to detect subtle changes occurring

over very short timescales. Similarly, XRF-CS offers non-destructive analysis of sediment cores, allowing for flexibility in subsampling strategies where elemental geochemistry can help guide subsequent destructive analyses (e.g. microfossil and grain-size analysis). Elemental geochemistry has many unexplored, but promising, applications that can be applied to the study of paleoearthquakes and tsunamis.

REFERENCES

Atwater BF et al. (2003) In: Developments in Quaternary Sciences. Elsevier, 331-350

Atwater BF (1987) Science 236 (4804): 942-944

Atwater BF, Hemphill-Haley E (1997) US Geol Surv Prof Pap 1576, 108 pp

Cahill N et al. (2016) Clim Past 12: 525-542

Chagué-Goff C et al. (2017) Earth-Sci Rev 165: 203-244

Giang A et al. (2023) MSc Thesis, Simon Fraser University, 63 pp

Hemphill-Haley E (1995) Geol Soc Am Bull 107: 367-378

Keppler F et al. (2000) Nature 403: 298-301

Nelson AR et al. (2021) Quat Sci Rev 261: 106922

Pilarczyk JE et al. (2014) Palaeogeogr Palaeoclimatol Palaeoecol 413: 144-157

Sawai Y et al. (2012) Geophys Res Lett 39: L21309

Woodward CA, Gadd PS (2019) Quat Int 514: 30-43