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Diatoms as indicators of coseismic, postseismic and interseismic deformation along subduction zones over centennial and millennial timescales

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Diatoms are invaluable to subduction-zone paleoseismic studies due to their ability to provide a continuous record of coseismic, postseismic and interseismic deformation, helping to better define the spatial variability of seismicity over centennial to millennial timescales.

Recent GPS instrumentation and Interferometric Synthetic Aperture Radar (InSAR) observations, coupled with increasingly sophisticated modeling, have identified complex patterns of subduction-zone deformation during earthquakes (coseismic), immediately after earthquakes (postseismic), and in between earthquakes (interseismic) (e.g. Klein et al. 2017). However, GPS and InSAR datasets span only decades, which is a fraction of the hundreds to thousands of years great earthquake cycle. Thus, the degree to which they reflect long-term rates of deformation is widely debated (Sieh et al. 2008). Are modern measurements and observations of subduction-zone earthquakes and tsunamis consistent with past events and, thus, reliable indicators of the future behavior of the subduction zone? Coastal paleoseismic studies that reconstruct rupture histories over multiple earthquake cycles suggest that the answer to this question is no, and that relying on short instrumental and historical earthquake and tsunami observations can lead to devastating societal impacts (Philibosian and Meltzner 2020; Witter et al. 2016).

Coastal paleoseismic studies, which use the methods of coastal stratigraphy, sedimentology, micropaleontology, and geophysical and sediment transport modeling to reconstruct vertical tectonic deformation along subduction zones coasts, have proven to be a powerful tool for examining the earthquake deformation cycle over centennial to millennial timescales. Past earthquakes are expressed in tidal wetland stratigraphy as sharp stratigraphic contacts between organic-rich peat below the contact, and tidal mud above (coseismic subsidence), or between tidal mud below the contact and organic-rich peat above (coseismic uplift) (Atwater 1987; Dura et al. 2017). The stratigraphic transitions captured in between earthquakes reflect the postseismic and interseismic period of the earthquake deformation cycle. Microfossils, such as diatoms, preserved in tidal wetland stratigraphy can provide quantitative estimates of the vertical surface deformation associated with the subduction-zone earthquake cycle (Shennan and Hamilton 2006). Diatom assemblages (groups of diatom species) are particularly useful in paleoseismic studies because their sensitivity to differences in tidal inundation, substrate and salinity can be precisely related to elevation within the tidal frame (Dura et al. 2016). Quantitative models, termed transfer functions, can be constructed from the relative abundance of diatom assemblages at modern tidal-marsh elevations, which can then be applied to diatom assemblages found in cores and/or outcrops, to reconstruct the elevation of a sample when it was deposited. Transfer function analysis can provide a continuous record of coseismic, postseismic and interseismic deformation along subductions zones (e.g. Hawkes et al. 2011; Sawai et al. 2004a).

Here, we provide three examples of the application of diatoms to paleoseismic studies, and the valuable information they provide about the spatial variability of subduction-zone ruptures over centennial to millennial timescales.

Mixed coseismic subsidence and uplift detected with diatoms

Diatom-based paleoseismic work at the Chilean and Alaska–Aleutian subduction zones helped address questions regarding the sources and segmentation of past earthquakes. Stratigraphic, sedimentological and diatom analyses revealed a >1000-year-long mixed record of coseismic subsidence and uplift at a series of coastal sites spanning proposed segment boundaries in south-central Chile (Fig. 1; Dura et al. 2017) and the eastern Aleutian Islands (Briggs et al. 2014), illustrating the variability of coseismic slip on the subduction zone over millennial timescales. At the Tirúa and Quidico coastal sites in south-central Chile, Dura et al. (2017) interpreted the mixed uplift and subsidence record to reflect variability in the rupture depth offshore of the study sites, and concluded that a proposed segment boundary in the region has persisted as a long-term impediment to slip through at least seven of the last subduction-zone earthquakes. At Sitkinak Island in Alaska, Briggs et al. (2014) interpreted the mixed uplift and subsidence record to reflect the location of the study site relative to the edge of past ruptures, concluding that when ruptures stop at Sitkinak, the

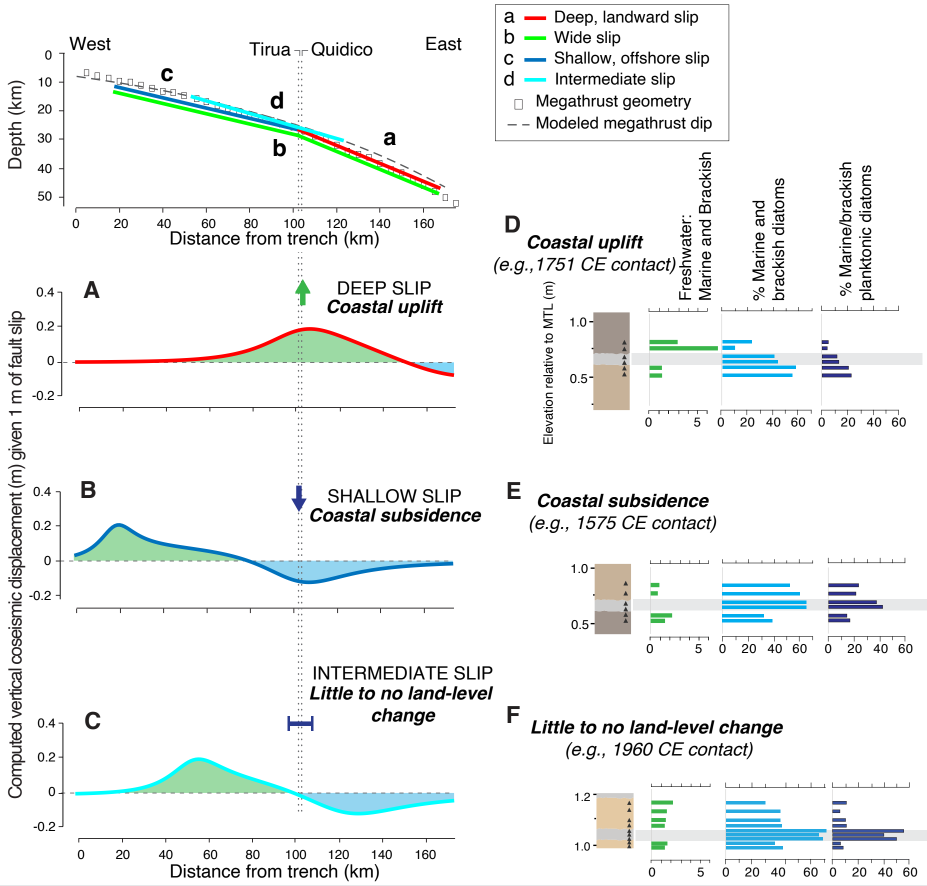

Figure 1: A simple model of constant coseismic slip and corresponding vertical deformation on a subduction zone in which slip is confined to a **(A)** deep; **(B)** shallow; or **(C)** intermediate zone. **(D)** An example of the diatom response to coastal uplift; **(E)** coastal subsidence; and **(F)** little to no coastal deformation. Figure and caption are modified from Dura et al. (2017).

island subsides due to subsidence wrapping around the edges of surface uplift, while ruptures that propagate through the island cause uplift. Because the region east of Sitkinak Island was a proposed segment boundary, the results of Briggs et al. (2014) revealed the potential for multi-segment ruptures in this region, which will be included in future USGS hazards maps.

Diatoms as indicators of coseismic uplift

During the 1964 CE M_w 9.2 Great Alaska Earthquake, the Patton Bay Splay Fault System, a steeply dipping fault system connected to the subduction zone at depth, was activated, contributing to the formation of local tsunamis, and causing significant (4–1 m) uplift of Montague Island in Prince William Sound (PWS; Plafker 1967). Aerial imagery from before and after the 1964 earthquake shows the gradual draining of coastal lagoons along its northwestern coast. DePaolis et al. (2024) investigated the coastal stratigraphy and diatom signature of the 1964 CE earthquake at Hidden Lagoons, Montague Island, and found a distinct silt-peat contact representing the draining of the coastal lagoon system. Diatom analysis showed the pre-earthquake lagoon system was a marine environment with direct tidal communication with the sea, while the post-earthquake diatoms indicated a gradual transition to a brackish, then freshwater lake, then freshwater bog environment, reflecting the gradual freshening and draining of the lagoon (Fig. 2). The ecological changes documented across the 1964 CE contact indicate >3 m of coseismic uplift, exceeding the amount of uplift expected from a subduction-zone-only rupture, and supporting the concurrent rupture of the splay fault system. Further investigation of the subsurface stratigraphy revealed an additional three sharp silt-peat contacts with diatoms displaying similar marine to freshwater ecological shifts across them. The older contacts overlap the timing of three of the seven independently constrained (Shennan and Hamilton 2006) prehistoric subduction zone earthquakes in PWS in 760–870, 2500–2700, and 4120–4500 yr BP. This suggests that the splay fault system may rupture jointly with the subduction zone every other, or every couple of, subduction-zone earthquakes, with a mean recurrence interval of ~1030 years. DePaolis et al. (2024) conclude that future hazard assessments should consider the potential risks of tsunamis associated with combined ruptures of subduction-zone splay fault systems, similar to those observed in historical and prehistoric events.

Post seismic land-level change detected with diatoms

Diatoms have been used to quantify episodic postseismic uplift over the last 3000 years along the Kuril subduction zone in Japan, helping reconcile differences between long-term geologic uplift and shorter-term measurements of interseismic coastal subsidence. Despite no modern earthquake producing more than a few centimeters of uplift along coasts bordering the Kuril Trench, Sawai et al. (2004b) found stratigraphic and diatom evidence of episodic seismically triggered uplift of >1 m that repeatedly changed tidal flats into lowland forests on the island of Hokkaido, Japan, bordering the Kuril Trench. Sawai et al. (2004a, b) developed and applied a diatom-based transfer function to quantify the deformation following one of the events, a significant 17th-century earthquake and resulting tsunami, and found that fossilized diatom assemblages revealed a gradual, rather than sudden, transition from tidal flats into freshwater upland environments in the decades following the earthquake. Due to the gradual nature of the environmental transition, Sawai et al. (2004b) interpreted the 1.5 m of uplift to represent postseismic uplift of the coast. The results suggest that the earthquake ruptured the shallower parts of the subduction zone, triggering a tsunami, but did not produce coseismic uplift along the coast. Instead, Sawai et al. (2004b) attribute the uplift to postseismic slip deep on the plate boundary beneath the island on Hokkaido. Although it is unclear if the episodic uplift events documented by Sawai et al. (2004b) completely account for the long-term net uplift of marine terraces observed in Hokkaido, postseismic and possibly coseismic uplift from large and small earthquakes in the region certainly contribute to the long-term deformation of the coast.

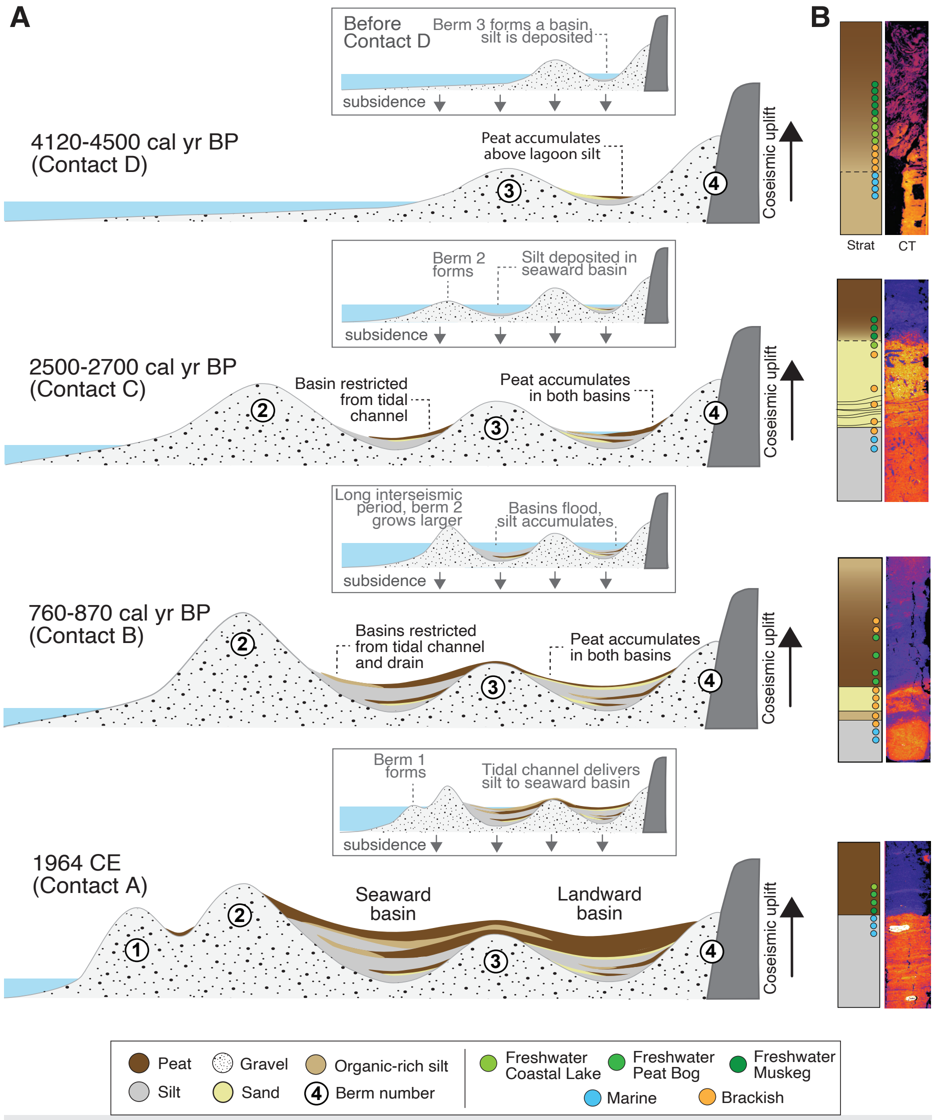

Figure 2: (A) Inferred geomorphological change of the seaward and landward basins during and between major earthquakes (Contacts A-D) recorded at Hidden Lagoons, Montague Island, Alaska. **(B)** Representative stratigraphy and the corresponding Computed Tomography (CT) scan of each major contact are on the far right. Colored circles represent the transitions in diatom ecology at each sample location within the core. Figure and caption are modified from DePaolis et al. (2024).

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