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# The importance of diatoms for understanding subduction-zone earthquakes in Alaska

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**Past earthquakes have left geological imprints, and microfossil approaches using coastal sediments offer ways to constrain rupture characteristics over centennial to millennial timescales. New approaches may provide a means to reconstruct smaller earthquakes and improve our understanding of seismic hazards.**

Great subduction-zone earthquakes (moment magnitude [$M_w$] >8) pose a significant threat to human populations, the environment and infrastructure, yet the spatial and temporal patterns of these hazards before the 20th century are often poorly constrained. Limited instrumental data (~100 years) offer only partial information on the potential magnitude, recurrence intervals and spatial variability of rupture area for past earthquakes due to infrequent occurrence (typically multi-centennial recurrence intervals) of great earthquakes. Impacts from the 2004 Sumatra and 2011 Japan earthquakes demonstrate the dangers of heavy reliance on temporally limited records (Dura et al. 2016). Great earthquakes can also trigger tsunamis that impact coastlines far from the rupture area and necessitate a better understanding of the hazard.

Paleoseismology, in general, can extend and constrain earthquake records beyond instrumental and historical data. Coastal sediments from low-energy environments contain valuable archives of past relative sea-level (RSL) changes and have been utilized globally (Dura et al. 2016). Sharp lithological contacts of alternating organic (peat) and minerogenic (silt) sediments often indicate abrupt vertical land-level changes associated with an earthquake. In Alaska, diatoms are the most common microfossil used to reconstruct RSL changes associated with great earthquakes due to their preservation potential, high abundance and ecological niches with respect to elevation within the tidal frame.

### Use of diatoms in Alaskan paleoseismology

Alaska has played a pioneering role in our understanding of plate tectonics with the demonstration via multiple lines of evidence that the $M_w$ 9.2 1964 CE earthquake was caused by a megathrust (e.g. Plafker 1965). Observations of land-level changes during this earthquake provided a framework for subduction-zone paleoseismology both in Alaska and globally. Initial studies focused on radiocarbon dating to understand the chronology of past events and used plants and lithology to estimate the magnitude of deformation (e.g. Combellick 1991). However, such approaches have limited vertical resolution with errors typically >0.5 m and, therefore, limit the ability to differentiate between different magnitudes of events. One approach to increasing the precision is to utilize microfossils such as diatoms (e.g. Hemphill-Haley 1995).

Diatoms are a group of photosynthetic, single-celled algae that are highly resistant to degradation due to their siliceous valves, allowing them to be incorporated into coastal sedimentary sequences, and preserved. Individual diatom taxa possess optima and tolerances to various environmental factors such as temperature, salinity and pH, making them highly sensitive to environmental change. The use of diatoms within Alaskan paleoseismology began through research conducted by Shennan et al. (1999) who examined the utility of diatoms to reconstruct the magnitude of land-level change at Girdwood. Since then, diatoms have been the most commonly utilized microfossil in Alaskan paleoseismology. Diatoms can be used in paleotsunami identification, with common characteristics of tsunami deposits including mixtures of fresh, brackish and marine diatoms (e.g. Fig. 1c), as well as broken and abraded valves (e.g. Dura et al. 2016; Hemphill-Haley 1995).

Paleoseismic evidence from coastal sediments currently provides a good understanding of great earthquakes in south-central Alaska, with records of approximately seven great earthquakes in the past 4000 years and 10 in the last 6000 years (Shennan et al. 2014). However, absolute correlations between sites are limited by uncertainties in radiocarbon chronologies (Barclay et al. 2024). Detailed diatom studies in this region from Cook Inlet, Cape Suckling and Cape Yakataga reveal two additional great earthquakes, in addition to the 1964 CE event, radiocarbon-dated to ~900 and ~1500 cal yr BP (Shennan et al. 2009, 2014). At the stratigraphic contact (peat-silt), diatoms display an increased abundance of marine taxa, indicating coseismic subsidence (Fig. 1b-c).

At the southwestern termination of the 1964 CE rupture, diatom analysis has also documented evidence of both uplift and subsidence at Sitkinak Island with five instances of vertical land-level motion over ~1200 years (Briggs et al. 2014). For example, coseismic subsidence is recorded in 1964 CE where diatom taxa show a shift from a freshwater and brackish assemblage to a brackish and marine assemblage. This is interpreted as indicative of the arrest of

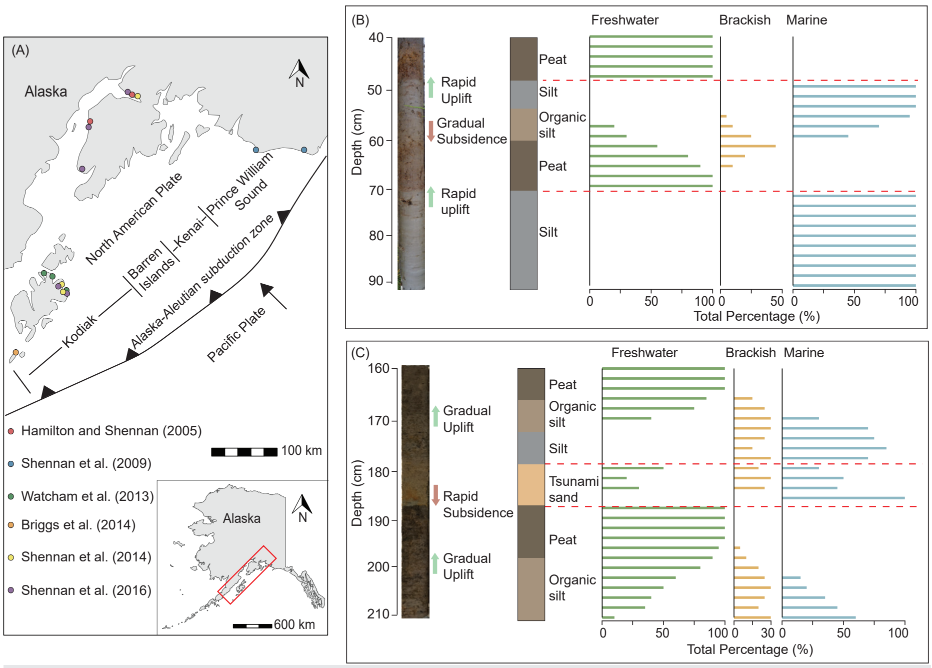


**Figure 1: (A)** Location of Alaskan diatom research discussed within this article. For detailed information on diatom analysis for each site see the reference list. **(B)** Schematic showing simplified stratigraphy and theoretical diatom assemblages representing coseismic uplift and gradual interseismic subsidence. Photo credit: Dr. Rich Briggs. **(C)** Schematic showing simplified stratigraphy and theoretical diatom assemblages representing coseismic subsidence, a tsunami deposit and gradual interseismic uplift.

 

rupture at, or near, the island. In contrast, coseismic uplift, potentially related to a historically documented earthquake in 1788 CE, is identifiable by a change from a marine-dominated to freshwater-dominated assemblage. This variability in uplift and subsidence is also found for three older earthquakes. This finding of mixed uplift and subsidence suggests that rupture boundaries in the Alaskan–Aleutian subduction zone are not persistent. Similar conclusions regarding rupture variability were reached by Shennan et al. (2014) who, utilizing diatoms, inferred the possibility of both multi-section (rupture spanning the Kodiak section) and at least one other section (e.g. at 1964 CE) and single section (Individual section rupture where only the Kodiak section ruptured e.g. at 1440–1620 CE) ruptures. These results suggest shorter recurrence intervals within the Kodiak section, impacting hazard analysis.

**Application of transfer functions**

In paleoseismology, transfer functions quantify the relationship between modern diatom taxa and elevation. They can produce precise estimates of RSL change and have been tested against known amounts of subsidence, and shown to produce accurate results (e.g. Hamilton and Shennan 2005). The known contemporary relationship between modern diatom taxa and elevation (modern training set) can be applied to fossil assemblages within coastal stratigraphic sequences, to calculate the RSL changes throughout an earthquake cycle (Dura et al. 2016). However, diatom assemblages are very diverse and can result in challenges where the fossil diatom assemblage is not well represented in the modern training set; a no-modern analog situation (Watcham et al. 2013). When this occurs, quantitative reconstructions may not be reliable. Regional modern diatom datasets are more appropriate given the high diversity of diatom assemblages. They encompass modern taxa from a wide range of intertidal environments providing analogs for fossil diatom assemblages (Watcham et al. 2013). Further, Watcham et al. (2013) demonstrated that regional modern training sets with good modern analogs most closely matched observed subsidence when available.

**Future directions**

The methods used to study and identify great earthquakes within paleorecords are well-established. However, there remains a significant gap in our knowledge of the detection limit for smaller earthquakes. In November 2018 a $M_w$ 7.1 earthquake occurred near Anchorage and produced land-level changes ranging from +2 to -5 cm (West et al. 2020), lying below our current estimates for detection within coastal sediments (0.1–0.2 m; Shennan et al. 2016). This earthquake had significant impacts on society, emphasizing the importance of a better understanding of the recurrence intervals of smaller earthquakes. Therefore, improving our understanding about the range of earthquake sizes which can be identified in coastal sediments is an important research objective.

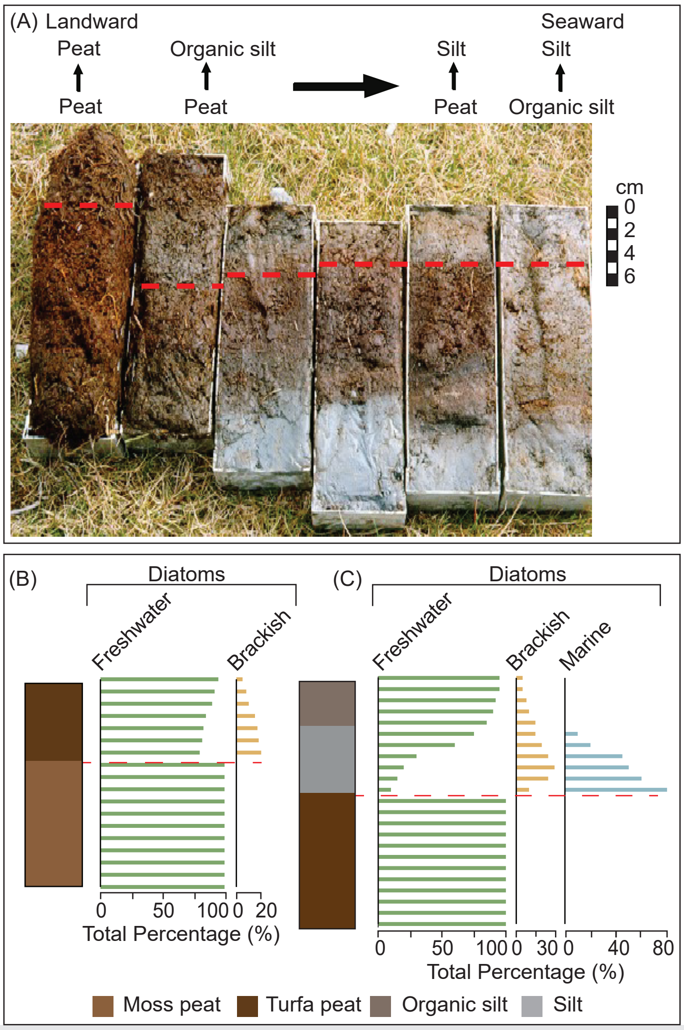


**Figure 2: (A)** Sediment cores from near the city of Kenai demonstrating how the peat-silt subsidence contact from the great $M_w$ 9.2 1964 CE earthquake (red dashed line) can be traced landward (from right to left) until the subsidence is expressed as a peat-to-peat contact. Photo credit: Prof. Ian Shennan. **(B)** Theoretical diatom assemblage for a peat-peat couplet. **(C)** Theoretical diatom assemblage for a peat-silt couplet.

Detection limits of coastal sediments are dependent on the tidal range, stratigraphy and choice of transfer function. Current criteria used to identify land-level change in coastal sediments rely heavily on clear and abrupt changes in sediment stratigraphy (peat-silt or silt-peat couplets) indicative of larger changes in RSL. However, the long interval between the penultimate earthquake, (1169–1189 CE; Barclay et al. 2024) and the great 1964 CE earthquake may require either significant strain to be carried to a future great earthquake, or to have been released by aseismic creep (steady fault movement generally without an associated earthquake), or smaller earthquakes in the intervening time period (Barclay et al. 2024). Diatom assemblages at Kenai and Shuyak Island identify coseismic subsidence associated with the 1964 CE earthquake within peat-peat couplets that are associated with the most precise transfer function estimates (Fig. 2a-c; Hamilton and Shennan 2005; Shennan et al. 2018; Watcham et al. 2013). Identifying peat-peat couplets associated with land-level change opens the possibility for detecting smaller earthquakes in coastal sediment sequences and is a topic of current and future research. New data generated from peat-peat couplets could also be correlated to recent lake paleoseismology research in south-central Alaska (e.g. Praet et al. 2017). The combination of these two techniques would allow for an integrated investigation into paleoseismic events.

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