



Invited review

# The application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis

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## ABSTRACT

Earthquake and tsunami records on centennial and millennial temporal scales are necessary to understanding long-term subduction zone behavior and the occurrences of large, but infrequent events. Microfossils, such as diatoms, incorporated into coastal stratigraphy provide some of the most detailed reconstructions of the history of earthquakes and tsunamis. We explore qualitative and quantitative techniques that employ the relation between diatoms and salinity, tidal elevation, and life form to: (1) reconstruct records of vertical land-level change associated with large earthquakes; and (2) identify anomalous sand and silt beds deposited by tsunamis. A global database shows that diatoms have been successfully employed in the reconstruction of earthquake and tsunami histories in Chile, the Indian Ocean, Japan, New Zealand, the North Sea, the Pacific Northwest of North America, and the South Pacific. We use case studies from some of these locations to highlight advancements in the field and new capabilities that diatoms have enabled. Examples from the Pacific Northwest of North America illustrate the evolution of quantitative diatom-based reconstructions of earthquake-related land-level change. In Alaska and Japan, diatoms have documented land-level changes throughout the earthquake deformation cycle, including possible preseismic land-level change signals and postseismic deformation. Diatoms helped identify coseismic uplift along the central Chile subduction zone coast, and uplift and subsidence along the Alaska–Aleutian megathrust, expanding our knowledge of the variability of slip in megathrust ruptures. In tsunami studies, diatoms help determine the provenance of anomalous sands and silts found in low-energy coastal stratigraphic sequences. In Japan, allochthonous marine and brackish diatoms within sand deposits signaled repeated marine incursions into a coastal lake, helping identify a possible predecessor to the 2011 Tohoku tsunami. In the Pacific Northwest of North America and Chile, diatoms were used to estimate tsunami run-up beyond the landward limit of tsunami sedimentation. Examples from the North Sea, Thailand, and Japan show how the fragmentation and sorting of diatom valves may provide evidence of high-energy transport during the rapid, turbulent flow of a tsunami. To conclude, we emphasize the importance of studying the modern diatom response to changes in land level and/or tsunami inundation to improve diatom-based records of prehistoric earthquakes and tsunamis.

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## Contents

1.	Introduction . . . . .	182
2.	Reconstructing coastal environments with diatoms . . . . .	183
3.	Application of diatoms to subduction zone paleoseismic cycles . . . . .	185
3.1.	Earthquake deformation cycle . . . . .	185
3.2.	Diatoms and land-level changes related to the earthquake deformation cycle . . . . .	186
4.	Application of diatoms to tsunami studies . . . . .	188
4.1.	Paleotsunamis . . . . .	188
4.2.	Tsunamis of the past two decades . . . . .	188

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5.	Knowledge gaps	189
5.1.	Uncertainties in modern diatom distributions	189
5.2.	Response of diatoms to coseismic land-level change	189
5.3.	The production and preservation of diatoms	189
5.4.	Differentiating autochthonous and allochthonous diatoms	189
5.5.	Differentiating tsunami and storm surge deposits	189
6.	Conclusions	191
	Acknowledgments	192
	Appendix A. Supplementary data	192
	References	192

## 1. Introduction

An incomplete understanding of the earthquake and tsunami hazards associated with the Sunda and Japan subduction zones contributed to the devastating societal impacts of the 2004 Indian Ocean and 2011 Tohoku events (Rhodes et al., 2006; Geller, 2011; Stein and Okal, 2011; Heki, 2011). Instrumental records of previous earthquakes and tsunamis proved too short to estimate the potential magnitude and recurrence interval of such great events that recur centuries to millennia apart (Stein and Okal, 2007). With more than a third of the world's coastlines lying adjacent to active plate boundaries (Lajoie, 1986; Stewart and Vita-Finzi, 1998), we must extend earthquake and tsunami histories to adequately assess hazards from subduction zones (Small et al., 2000; Satake and Atwater, 2007; Stein and Okal, 2011).

Stratigraphic evidence of subduction zone earthquakes and tsunamis has been used to extend records over centuries to millennia. Stratigraphic evidence was first described from the coastal wetlands of Alaska (Plafker, 1965; Plafker, 1972; Bartsch-Winkler and Schmoll, 1987; Combellick, 1991, 1994; Combellick and Reger, 1994), the Pacific Northwest of North America (Atwater, 1987; Darienzo and Peterson, 1990; Atwater, 1992; Nelson, 1992; Darienzo et al., 1994; Nelson et al., 1996a), Chile (Wright and Mella, 1963; Bourgeois and Reinhart, 1989; Atwater et al., 1992) and Japan (Kon'no, 1961; Minoura and Nakaya, 1991; Sawai et al., 2002; Nanayama et al., 2003; Sawai et al., 2012, 2015). Subsidence or uplift associated with earthquakes is recorded as a series of sharp stratigraphic contacts that reflect sudden changes in land level (Nelson et al., 1996b; Yeats et al., 1997). Widespread sand beds, rapidly deposited by tsunamis accompanying earthquakes, are often found concomitant with stratigraphic evidence of sudden land-level change (e.g., Hemphill-Haley, 1995a; Cisternas et al., 2005). In addition, trans-oceanic tsunamis produced by the largest subduction zone earthquakes can deposit sediments on coastlines hundreds to thousands of kilometers away from the earthquake source (e.g., Satake et al., 1996; Goff et al., 2006).

Microfossils such as diatoms, foraminifera, and pollen that are incorporated into coastal stratigraphy provide qualitative and quantitative estimates of land-level change associated with subduction zone earthquakes (Horton et al., 2013; Fig. 1). In particular, diatoms and foraminifera have been applied to earthquake and tsunami studies around the world (e.g., Darienzo et al., 1994; Hemphill-Haley, 1995a, 1995b, 1996; Sawai et al., 2004a, 2004b; Shennan and Hamilton, 2006; Hawkes et al., 2011; Engelhart et al., 2013a, 2013b; Grand Pre et al., 2012; Clark et al., 2015; Dura et al., 2015). These microfossils have improved upon early coastal studies of subduction-zone earthquake history that estimated the amount of coseismic land-level change with large errors (>1 m) based on the broad elevational ranges of plant macrofossils (Atwater, 1987, 1992; Clague and Bobrowsky, 1994). Quantitative diatom and foraminiferal-based reconstructions of land-level change (e.g., transfer functions) can produce substantially smaller (<0.3 m) errors (Guilbault et al., 1995, 1996; Zong et al., 2003; Sawai et al., 2004a, 2004b; Shennan and Hamilton, 2006; Nelson et al., 2008;

Hawkes et al., 2011; Engelhart et al., 2013a, 2013b; Watcham et al., 2013).

Microfossils are applied to tsunami studies to determine the provenance of tsunami sediments deposited in low-energy coastal environments such as lowlands (Hemphill-Haley, 1995a, 1996; Benson et al., 1997; Nanayama et al., 2007; Sugawara et al., 2009), interdunal depressions (Dawson and Stewart, 2007; Jankaew et al., 2008), lagoons (Minoura and Nakaya, 1991; Nichol et al., 2007; Sawai et al., 2009b; Wilson et al., 2014) and lakes (Hutchinson et al., 1997; Grauert et al., 2001; Kelsey et al., 2005). Allochthonous marine assemblages or a chaotic mix of marine, brackish and freshwater taxa within terrestrial or brackish settings may be indicative of marine incursions from tsunamis (Tuttle et al., 2004; Cochran et al., 2005; Hawkes et al., 2007; Goff et al., 2012; Clark et al., 2015), and the preservation and distribution of diatoms and foraminifera throughout the deposit can be used to infer high-energy transport and provenance (Hemphill-Haley, 1996; Sawai et al., 2002; Pilarczyk et al., 2012). Tsunamis of the past two decades have provided an opportunity to characterize the microfossil composition of modern deposits (Dawson, 2007; Sawai et al., 2009a; Chagué-Goff et al., 2011; Szczuciński et al., 2012), improving our ability to identify such characteristics in the fossil record.

In this review we explore the application of diatoms to earthquake and tsunami studies (Fig. 2; Table 1). We explain the statistical approaches that use diatoms to estimate earthquake related land-level changes, and assess the utility of diatoms in identifying tsunamis in the stratigraphic record. We also examine the knowledge gaps and limitations of diatom analyses in earthquake and tsunami studies, and make recommendations for future research.

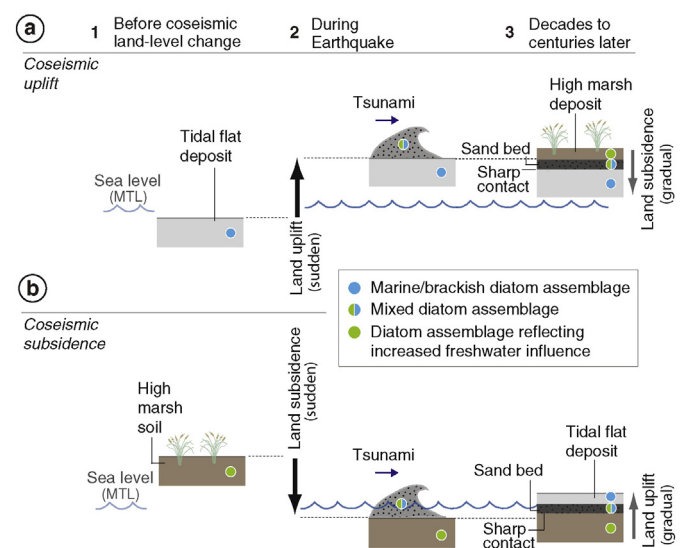
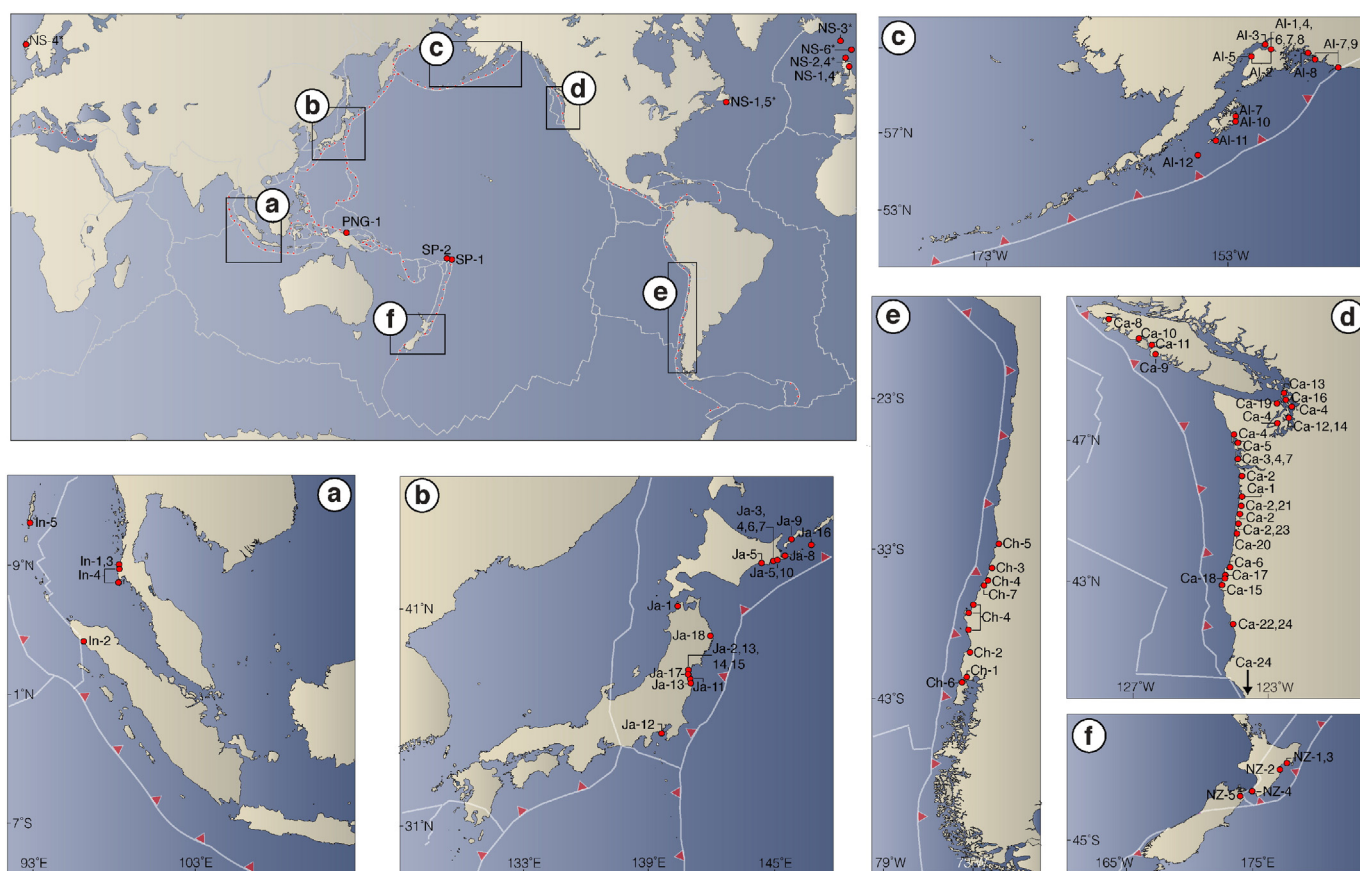


Fig. 1. Schematic drawing of coseismic uplift (a) and subsidence (b) and accompanying tsunami inundation.



**Fig. 2.** Summary of earthquake and tsunami studies applying diatoms that are referenced in this paper, and listed in Table 1. (a) In: Indian Ocean; (b) Ja: Japan Trench; (c) Al: Alaska–Aleutian megathrust; (d) Ca: Cascadia subduction zone; (e) Ch: Chilean Subduction zone; (f) NZ: New Zealand; NS: North Sea (studies marked with an asterisk because they are not subduction zone studies); SP: South Pacific; PNG: Papua New Guinea.

## 2. Reconstructing coastal environments with diatoms

Diatoms are photosynthetic, unicellular algae that inhabit fresh-water, brackish, and marine environments (Round et al., 1990; Jones, 2007). Diatoms are a dominant microphyte in coastal wetland environments and their siliceous valves, ranging in size from  $\sim 5 \mu\text{m}$  to  $\sim 200 \mu\text{m}$ , are resistant to taphonomic degradation (e.g., dissolution, abrasion, bioerosion, oxidation, transport, predation; Admiraal, 1984; Palmer and Abbott, 1986; Cooper et al., 2010). As a result, small (1 g wet weight) sample sizes (for example, from narrow-diameter cores 25–50 mm) contain statistically significant (300–600 valves) diatom populations (Birks, 1995; Battarbee et al., 2001; Nelson, 2015).

Diatoms have been described and classified for over 200 years based on their shapes, sizes, and the intricate morphological characteristics of their siliceous valves (Round et al., 1990). Diatom taxa are divided into three main classes: the Coscinodiscophyceae (centric taxa); Fragilariophyceae (araphid pennate taxa); and Bacillariophyceae (raphid pennate taxa). Literature on the identification of diatoms to species level includes van der Werff and Huls (1958–1974), Patrick and Reimer (1966, 1975), Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b), Hartley et al. (1996), Krammer (2000, 2002, 2003), Lange-Bertalot (2000, 2001, 2011), and Levkov (2009).

Diatoms are a valuable tool in reconstructing paleoenvironmental changes because of their sensitivity to environmental factors including salinity, tidal exposure, substrate, vegetation, pH, nutrient supply, and temperature found in specific coastal wetland environments (e.g., Zong and Horton, 1998). Over time, diatoms become incorporated in coastal sediments, resulting in buried assemblages that represent an environmental history that can span thousands of years. Literature for the ecological classification of diatoms includes Hustedt (1937, 1939,

1953, 1957), Lowe (1974), Patrick and Williams (1990), Denys (1991–1992), Juggins (1992), Vos and de Wolf (1988, 1993), Van Dam et al. (1994), and Lange-Bertalot (2000).

Diatoms' preferences for salinity are valuable for earthquake and tsunami studies. Changes in salinity across the intertidal zone produce vertically zoned diatom assemblages with respect to the tidal frame (Nelson and Kashima, 1993; Hemphill-Haley, 1995b; Sherrod, 1999; Patterson et al., 2005; Horton et al., 2007, 2010; Woodroffe and Long, 2010). Establishing the distribution of diatoms across the intertidal zone is a prerequisite for reconstructing paleoenvironmental changes related to earthquakes and tsunamis (e.g., Zong and Horton, 1998). In the halobion classification scheme, polyhalobous and mesohalobous diatom taxa represent the marine and brackish conditions found in tidal flats and lower tidal marshes and mangroves. Oligohalobous-halophile and oligohalobous-indifferent taxa become dominant through the transition from tidal marsh/mangrove to freshwater environments, and halophobous taxa characterize the most landward freshwater communities above the highest tides. The presence of diatoms in freshwater environments is an obvious advantage compared to foraminifera, which are restricted to areas of marine influence (e.g., Murray, 1991).

The distribution of diatoms along a modern intertidal transect (Fig. 3) typically shows a clear transition from subtidal, open-water marine diatoms (e.g., *Thalassiosira pacifica* and *Odontella aurita*), to marine tidal flat taxa (e.g., *Achnanthes brevipes* and *Tabularia fasciculata*). In the low marsh, where a mixed diatom community is often found, marine-brackish diatoms (e.g., *Planothidium delicatum* and *Tryblionella granulata*) dominate, followed by freshwater taxa that can tolerate low salinities in the high marsh (e.g., *Caloneis bacillum* and *Cosmioneis pusilla*) and freshwater salt-intolerant taxa in the upland environment (e.g., *Eunotia bilunaris* and *Aulacoseira crassipunctata*).

**Table 1**  
A global database of subduction zone earthquake and tsunami studies that have employed diatoms.

Map code	Earthquake and tsunami studies employing diatoms	Diatom evidence for coseismic land-level change <sup>a</sup>	Accompanying tsunami <sup>b</sup>	Diatom composition of tsunami deposit <sup>c</sup>	Preservation of diatom valves <sup>d</sup>	Concentration of diatom valves <sup>e</sup>
<i>Alaska</i>						
Al-1	Shennan et al. (1999)	Yes (H, Qn)	–	–	–	–
Al-2	Zong et al. (2003)	Yes (H, Qn)	–	–	–	–
Al-3	Hamilton et al. (2005)	Yes (H, P, Qn)	–	–	–	–
Al-4	Hamilton and Shennan (2005a)	Yes (H, P, Qn)	–	–	–	–
Al-5	Hamilton and Shennan (2005b)	Yes (H, P, Qn)	–	–	–	–
Al-6	Shennan and Hamilton (2006)	Yes (H, P, Qn)	–	–	–	–
Al-7	Watcham et al. (2013)	Yes (H, P, Qn)	–	–	–	–
Al-8	Shennan et al. (2009)	Yes (H, P, Ql)	–	–	–	–
Al-9	Shennan et al. (2014a)	Yes (H, P, Qn)	–	–	–	–
Al-10	Shennan et al. (2014b)	Yes (H, P, Qn)	–	–	–	–
Al-11	Briggs et al. (2014)	Yes (H, P, Ql)	Yes	Mx	Good	High
Al-12	Nelson et al. (2015)	No	Yes (H, P)	Fw	Poor	Low
<i>Cascadia</i>						
Ca-1	Darizeno and Peterson (1990)	Yes (P, Ql)	Yes (P)	M&B	–	–
Ca-2	Darizeno et al. (1994)	Yes (P, Ql)	Yes (P)	M&B	–	–
Ca-3	Hemphill-Haley (1995a)	Yes (P, Ql)	Yes (P)	M&B (Ep)	Very good	–
Ca-4	Hemphill-Haley (1996)	Yes (P, Ql)	Yes (P)	M&B (Ep, Pl)	Very good	High
Ca-5	Shennan et al. (1996)	Yes (P, Qn)	Yes (P)	M&B (Ep)	–	–
Ca-6	Nelson et al. (1996b)	Yes (P, Qn)	No	–	–	–
Ca-7	Atwater and Hemphill-Haley (1997)	Yes (P, Ql)	Yes (P)	M&B (Ep)	Very good	–
Ca-8	Benson et al. (1997)	No	Yes (H, P)	M	–	–
Ca-9	Hutchinson et al. (1997)	No	Yes (P)	M&B (Ep)	–	–
Ca-10	Clague et al. (1999)	Yes (P, Ql)	Yes (P)	M&B	Good	–
Ca-11	Hutchinson et al. (2000)	Yes (P, Ql)	Yes (P)	Mx	Good	Low
Ca-12	Sherrod et al. (2000)	Yes (P)	No	–	–	–
Ca-13	Williams and Hutchinson (2000)	No	Yes (P)	M&B	Poor	Low
Ca-14	Sherrod (2001)	Yes (P, Ql)	No	–	–	–
Ca-15	Kelsey et al. (2002)	Yes (P, Ql)	Yes (P)	M&B (Ep?)	Good	Low
Ca-16	Kelsey et al. (2004)	Yes (P, Ql)	No	–	–	–
Ca-17	Witter et al. (2003)	Yes (P, Ql)	Yes (P)	M (Ep)	–	Low
Ca-18	Kelsey et al. (2005)	No	Yes (P)	Few M	–	Low
Ca-19	Williams et al. (2005)	Yes (P, Ql)	Yes (P)	M (Ep, Pl)	Good	High
Ca-20	Nelson et al. (2008)	Yes (P, Qn)	Yes (P)	M&B (Ep, Pl)	–	Low
Ca-21	Witter et al. (2009)	Yes (P, Ql)	Yes (P)	M (Ep)	Poor	High
Ca-22	Peterson et al. (2011)	No	Yes (P)	M&B	–	–
Ca-23	Graehl et al. (2015)	Yes (P, Ql)	Yes (P)	M&B (Ep)	Good	Low
Ca-24	Wilson et al. (2014)	Yes (P, Ql)	Yes (H, P)	Mx (Pl, G)	Good	High
<i>Chile</i>						
Ch-1	Cisternas et al. (2005)	Yes (H, P, Ql)	Yes (H, P)	–	–	–
Ch-2	Nelson et al. (2009)	Yes (H, P, Qn)	Yes (P)	Mx	–	–
Ch-3	Horton et al. (2011)	No	Yes (H)	M&B (Ep, Pl)	Selective	High
Ch-4	Garrett et al. (2013)	Yes (H, Qn)	Yes (H)	Mx (Ep)	–	–
Ch-5	Dura et al. (2015)	Yes (P, Ql)	Yes (P)	M&B (Pl, G)	Poor	Low
Ch-6	Garrett et al. (2015)	Yes (H, P, Qn)	Yes (H, P)	M&B (Ep)	–	–
Ch-7	Chagué-Goff et al. (2015)	No	Yes (H)	M&B	Poor	Low
<i>Indian Ocean</i>						
In-1	Jankaew et al. (2008)	No	Yes (H, P)	M&B	Good (H)/Poor (P)	High (H)/Low (P)
In-2	Monecke et al. (2008)	No	Yes (H, P)	Fw&B	Good (H)/Poor (P)	High (H)/Low (P)
In-3	Sawai et al. (2009a)	No	Yes (H)	Mx (Pl, G)	Good	–
In-4	Kokociński et al. (2009)	No	Yes (H)	Mx (Ep, Pl)	Poor	Low
In-5	Malik et al. (2011)	Yes (H, P, Ql)	Yes (H, P)	–	–	–
<i>Japan/Kuril Islands</i>						
Ja-1	Minoura et al. (1994)	No	Yes (H, P)	M&B	–	–
Ja-2	Minoura et al. (2001)	No	Yes (H)	M&B	–	–
Ja-3	Sawai (2001a)	Yes (P, Ql)	No	–	–	–
Ja-4	Sawai et al. (2002)	No	Yes (H)	M&B	Poor	Low
Ja-5	Nanayama et al. (2003)	No	Yes (H, P)	M&B	–	–
Ja-6	Atwater et al. (2004)	Yes (H, Ql)	No	–	–	–
Ja-7	Sawai et al. (2004a)	Yes (H, Qn)	Yes (H)	?	–	–
Ja-8	Sawai et al. (2004b)	Yes (P, Qn)	No	–	–	–
Ja-9	Iliev et al. (2005)	No	Yes (P)	M&B	–	–
Ja-10	Nanayama et al. (2007)	No	Yes (H, P)	M&B (Pl)	–	–
Ja-11	Sawai et al. (2008)	No	Yes (H, P)	Mx	–	–
Ja-12	Shimazaki et al. (2011)	Yes (H, Ql)	Yes (H)	M&B (Pl)	–	–
Ja-13	Sawai et al. (2012)	Yes (H, P, Ql)	Yes (H)	M&B	Moderate	–
Ja-14	Szczuciński et al. (2012)	No	Yes (H)	Fw&B	Poor	Low
Ja-15	Takashimizu et al. (2012)	No	Yes (H)	Mx (Pl)	Poor	Low
Ja-16	Razjigaeva et al. (2013)	No	Yes (H)	Mx (Ep, Pl)	Good	High
Ja-17	Sawai et al. (2015)	No	Yes (H)	M&B	–	–
Ja-18	Goto et al. (2015)	Yes (H, Ql)	Yes (H)	–	–	–

Table 1 (continued)

Map code	Earthquake and tsunami studies employing diatoms	Diatom evidence for coseismic land-level change <sup>a</sup>	Accompanying tsunami <sup>b</sup>	Diatom composition of tsunami deposit <sup>c</sup>	Preservation of diatom valves <sup>d</sup>	Concentration of diatom valves <sup>e</sup>
<i>New Zealand</i>						
NZ-1	Chagué-Goff et al. (2002)	No	Yes (P)	M	Poor	–
NZ-2	Hayward et al. (2006)	Yes (H, P, Qn)	No	–	–	–
NZ-3	Cochran et al. (2006)	Yes (P, Ql)	Yes (P)	M&B	–	–
NZ-4	Clark et al. (2011)	Yes (P, Ql)	Yes (P)	Mx	–	–
NZ-5	Clark et al. (2015)	Yes (P, Ql)	Yes (P)	Mx	–	–
<i>North Sea*</i>						
NS-1	Dawson et al. (1996)	No	Yes (H, P)	M&B	Poor	high
NS-2	Dawson and Smith (2000)	No	Yes (P)	Mx	Poor	Low
NS-3	Grauert et al. (2001)	No	Yes (P)	Mx	Poor	Low
NS-4	Smith et al. (2004)	No	Yes (P)	M&B (Pl)	Poor	Low
NS-5	Tuttle et al. (2004)	No	Yes (H)	M&B (Pl)	Poor	Low
NS-6	Bondevik et al. (2005)	No	Yes (P)	Mx (Pl)	–	–
<i>Papua New Guinea</i>						
PNG-1	Dawson (2007)	No	Yes (H)	M&B (Pl)	Poor	Low
<i>South Pacific</i>						
SP-1	Chague-Goff et al. (2011)	No	Yes (H)	M&B (G)	–	–
SP-2	Goff et al. (2011)	No	Yes (H, P)	M&B (Pl)	Poor	High

<sup>a</sup> H: historical; P: prehistoric; Qn: quantitative; Ql: qualitative.

<sup>b</sup> H: historical; P: prehistoric.

<sup>c</sup> Mx: mixed assemblage (marine/brackish/freshwater diatoms); M: marine diatoms; Fw: freshwater diatoms; M&B: marine and Brackish diatoms; Fw&B: freshwater and brackish diatoms; Ep: sand flat epipsammic diatoms; Pl: marine planktonic diatoms; G: grading of diatom valves.

<sup>d</sup> Metric defined in individual papers.

<sup>e</sup> Metric defined in individual papers.

\* Not subduction zone studies.

The distribution of diatoms across the intertidal zone based on their life form is valuable for tsunami studies. The diverse life forms of diatom floras are employed to support the marine provenance of inferred

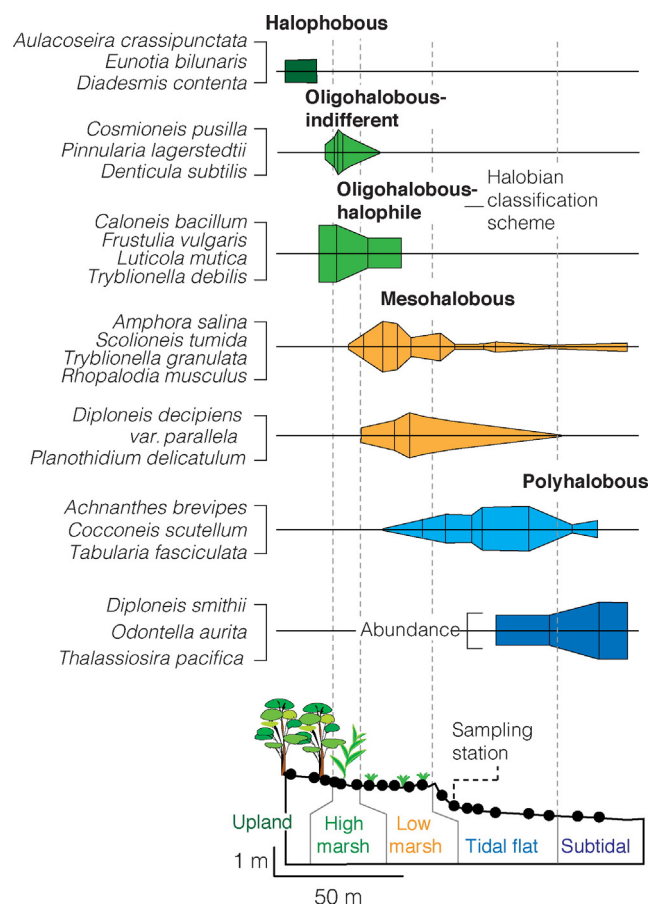


Fig. 3. Qualitative schematic of the distribution of common diatom species along a modern salt marsh transect. Typical salinity classes (following the halobian classification scheme of Hemphill-Haley, 1993) for each environment are shown.

tsunami deposits. Hustedt (1958), Vos (1986), Vos et al. (1988), and Vos and de Wolf (1993) define diatom life forms based on the substrate—or lack thereof—that particular diatom taxa commonly live on. Benthic diatoms are grouped into epipsammic taxa that live attached to sand grains; epipellic taxa that live on or just below the surface of wet muddy sediment; epiphytic taxa that are attached to larger plants or other surfaces; and aerophile taxa that are able to survive subaerial, temporarily dry conditions. Planktonic diatoms float freely in the water column and do not live attached to any substrate; tychoplanktonic diatoms include an array of species that live in the benthos, but are commonly found in the plankton. Based on local conditions, epipsammic, epipellic, planktonic, and tychoplanktonic diatoms may comprise tidal flat populations, whereas epiphytic and epipellic forms are more common on tidal marshes/mangroves. Aerophilous forms are most common within the landward communities above the highest tides (Sherrod, 1999).

### 3. Application of diatoms to subduction zone paleoseismic cycles

#### 3.1. Earthquake deformation cycle

On subduction zone coastlines, the land-level changes associated with earthquakes reflect the strain accumulation and release of the earthquake deformation cycle (Burbank and Anderson, 2011; Nelson, 2013). The nature of the interseismic and coseismic motion of the coastline is determined by its proximity to the trench, the geometry of the subduction zone, and where ruptures stop along strike (Plafker, 1965; Plafker and Savage, 1970; Wang et al., 2012). Some subduction zone coastlines (e.g., Cascadia, the Pacific Northwest of North America) lie within a zone that gradually uplifts in between (interseismic) and abruptly subsides during (coseismic) great earthquakes (Plafker, 1972; Atwater, 1987). In coastal wetland stratigraphy, the interseismic period is represented by a gradual regression from clastic (e.g., tidal flat or shallow subtidal) to organic-rich (e.g., marsh or swamp) sediments reflecting land-level uplift (i.e., relative sea-level fall) and a decrease in marine influence. Abrupt coseismic land subsidence creates a sudden change from organic-rich sediments to clastic sediments, reflecting land-level subsidence (i.e., relative sea-level rise) and an increase in marine influence (Fig. 1).

Conversely, some coastal locations bordering subduction zones (e.g., central Chile; Alaska–Aleutian megathrust) lie within a zone that gradually subsides in between and abruptly uplifts during great earthquakes (Shennan et al., 2009; Dura et al., 2015). During the interseismic period, coastal wetland stratigraphy displays a gradual transgression from organic-rich to clastic sediments as land-level subsides and marine influence increases. Abrupt coseismic uplift creates a sudden change from clastic to organic-rich sediments, reflecting land-level uplift and a decrease in marine influence.

Coastal wetland stratigraphy can record both coseismic uplift and subsidence at one location (e.g., Hayward et al., 2006; Briggs et al., 2014; Ely et al., 2014), depending on the distribution of slip upon the megathrust surface (Savage and Hastie, 1966) or the interaction with upper plate faults. The possibility of a variable uplift-subsidence history illustrates that the paleoseismic record should not be assumed to record exclusively coseismic uplift or subsidence.

Because non-seismic coastal processes can also produce changes in stratigraphy similar to those created by great subduction zone earthquakes, criteria must be considered to support a tectonic origin (Darienzo et al., 1994; Nelson et al., 1996b; Shennan et al., 1996; Dura et al., 2015). The key criteria are the lateral extent of sharp stratigraphic contacts; the suddenness and magnitude of land-level change; the synchronicity of land-level change among regional sites; and the coincidence of tsunami deposits with sudden changes in stratigraphy. No breaks in sedimentation greater than a few weeks are assumed to occur following earthquake-related land-level change and continuous sedimentation is assumed in the interseismic period. Although many paleoseismic studies have relied on stratigraphic investigations to support an earthquake origin (Atwater, 1987; Dura et al., 2011), microfossils have been particularly useful in providing supporting evidence of earthquake-related land-level change.

### 3.2. Diatoms and land-level changes related to the earthquake deformation cycle

Much of the early research using diatoms to reconstruct land-level changes related to the earthquake deformation cycle focused on the Pacific Northwest of North America (Cascadia subduction zone). Regional sea-level rise at rates of up to 2 mm/year along the central Cascadia subduction zone since 6000 calibrated years BP (Engelhart et al., 2015) resulted in continuous records of tidal sedimentation that contain evidence of coseismic land-level change and tsunami inundation.

Darienzo and Peterson (1990) and Darienzo et al. (1994) employed qualitative diatom analyses to confirm inferences of sudden and widespread coseismic subsidence based on distinctive stratigraphic contacts in Cascadia coastal wetlands. Darienzo et al. (1994) used diatoms to identify broad floral zones (e.g., high marsh, low marsh, tidal flat) in the modern environment and subsequently estimated the magnitude of coseismic subsidence by identifying analogous floral zones from above and below sharp stratigraphic contacts. Because the elevational range of the floral zones was large (0.5–1.0 m), errors for subsidence estimates commonly exceeded 1 m (e.g., Nelson and Kashima, 1993; Darienzo and Peterson, 1990; Darienzo et al., 1994; Kelsey et al., 2002; Witter et al., 2003).

Statistical methods employed the relationship between modern diatom assemblages of known elevation and fossil assemblages to reconstruct land-level changes in stratigraphic sections at Cascadia (Hemphill-Haley, 1995a; Nelson et al., 1996a; Shennan et al., 1996). In southern Washington State, USA, Hemphill-Haley (1995b) used factor analysis to identify the relation of modern diatom distributions to elevation. The result was a list of taxa with dominant occurrences in marsh zones (high marsh, low marsh, and high and low marshes) and three subenvironments of the lower intertidal to shallow subtidal zone (mud flats, sand flats, and *Zostera* (eelgrass) beds). The modern distributions of the same taxa found in the fossil record were used to reconstruct the abrupt changes in environment indicated by stratigraphic

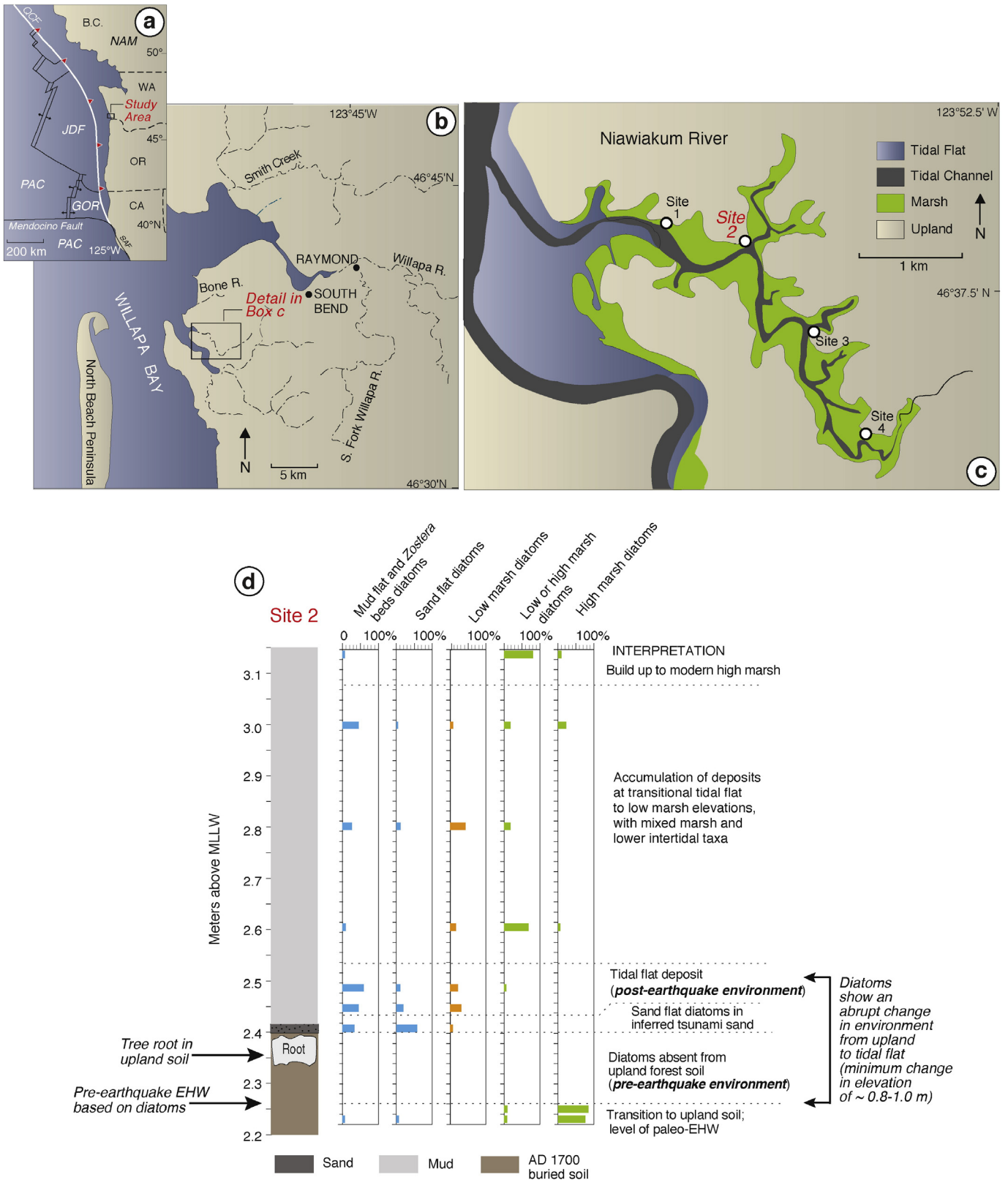
contacts spanning the AD 1700 subduction zone earthquake (Fig. 4). Distinct changes in diatom assemblages across these sharp contacts confirmed significant, widespread, and lasting change from an upland environment to a tidal-flat or low marsh environment, consistent with coseismic subsidence of 0.8–1.1 m. Shennan et al. (1996, 1998) and Nelson et al. (1996a) employed similar statistical techniques (i.e., ordination and discriminant function analysis, respectively) to quantitatively compare modern diatom assemblages of known elevation with fossil diatom assemblages. Although the statistical techniques of Hemphill-Haley (1995b); Shennan et al. (1996, 1998), and Nelson et al. (1996a) improved the analysis of diatom data, the reconstructions were still based on differences in elevational ranges between pre-earthquake and postearthquake paleoenvironments, resulting in 0.5–1.0 m errors.

Fully quantitative, microfossil-based transfer functions used to calculate coseismic land-level change at Cascadia have produced substantially smaller errors (<0.5 m; e.g., Guilbault et al., 1995, 1996). The transfer function uses multivariate statistical techniques to formalize the relationship between the relative abundance of microfossil species and the environmental variable of interest (in the case of paleoseismic studies, that variable is elevation; e.g., Horton, 1999). The transfer function is applied to microfossil assemblages in coastal wetland stratigraphic sequences to calculate changes in paleo-elevation and can provide a continuous record of land-level changes throughout the earthquake deformation cycle. The performance of transfer functions can be measured using multiple techniques to assess the effect of sample design, the goodness-of-fit between microfossil assemblages and elevation, and the statistical significance of each reconstruction (Telford and Birks, 2011a, 2011b). The technique has since been expanded in Cascadia to include extensive modern diatom (Sherrod, 1999, 2001; Sherrod et al., 2000), foraminifera (Guilbault et al., 1995, 1996; Hawkes et al., 2010; Engelhart et al., 2013a, 2013b), and pollen (Hughes et al., 2002) datasets, and applied in other geographical locations such as Alaska (e.g., Shennan and Hamilton, 2006), Japan (e.g., Sawai et al., 2004b), and Chile (e.g., Garrett et al., 2015; Table 1 lists which diatom studies have used quantitative diatom techniques, Fig. 2).

Coastal wetland stratigraphy from eastern Hokkaido, Japan contains evidence of pre-seismic and post-seismic land-level change (Atwater et al., 2004; Sawai et al., 2002, 2004a, 2004b) associated with subduction zone earthquakes originating from the Kuril Trench (Nanayama et al., 2003). Sawai et al. (2004a) used a diatom-based transfer function (Sawai, 2001b; Sawai et al., 2004b) to document the land-level change associated with a great 17th century earthquake and tsunami (Fig. 6). Fossil diatom assemblages show that tidal flats gradually changed into freshwater upland environments in the decades after the earthquake as a result of up to 1.5 m of post-seismic uplift. Sawai et al. (2004a) suggested the large land-level change was the result of a subduction zone earthquake of unusually large size along the Kuril Trench.

Diatom data have helped identify coseismic uplift associated with subduction zone earthquakes in Alaska (e.g., Shennan et al., 2009, 2014a, 2014b) and Chile (e.g., Dura et al., 2015). Along the central Chile coast, Dura et al. (2015) used diatoms to identify six instances of coseismic uplift between 6200 and 3600 calibrated years BP. A repeated influx of freshwater diatoms and other siliceous microfossils above six tsunami sands suggested > 1 m of coseismic uplift. The study documented a ~500 year recurrence interval for the earthquakes and accompanying tsunamis in central Chile.

Diatom studies have documented evidence of both coseismic subsidence and uplift at the same site. Briggs et al. (2014) used diatoms and foraminifera to identify five instances of sudden uplift and subsidence in the stratigraphy of a coastal marsh on Sitkinak Island bordering the Alaska–Aleutian megathrust. Diatoms showed uplift accompanying earthquakes in 290–0, 520–300, and 1050–790 calibrated years BP, and subsidence in AD 1964 and 640–510 calibrated years BP (Briggs et al., 2014). Such studies have implications for seismic hazard analysis,



**Fig. 4.** Diatoms evaluated relative to modern intertidal zones and stratigraphy at the Niawiakum River in Washington State, USA. (a) Position of the study area relative to the Cascadia subduction zone (barbed line), the boundary between North America and Juan de Fuca/Gorda plates that extends from the northern end of the San Andreas Fault (SAF) to the southern end of the Queen Charlotte Fault (QCF); (b) location of the Niawiakum River Valley, on the eastern side of Willapa Bay; (c) locations of vertical sections sampled for diatoms in the Niawiakum River Valley. Sites 1–4 are cutbank outcrops exposed during low tide; (d) changes in diatom assemblages within and above a former upland soil (forming at the transition of extreme high water (EHW) and upland) buried by coseismic subsidence during a Cascadia subduction zone earthquake in AD 1700. Changes in diatom assemblages are consistent with an abrupt change from upland forest to tidal flat or low marsh.

Modified from Hemphill-Haley (1995a).

as the mixed uplift and subsidence record shows the variability of slip along the megathrust, suggesting that the segmentation of subduction zones is not fixed (Briggs et al., 2014; Ely et al., 2014).

Diatom data have also identified a possible pre-seismic signal from relatively small amounts of land-level change in the years prior to earthquakes (Bourgeois, 2006; Shennan and Hamilton, 2006). Zong et al. (2003) used detailed modern and fossil diatom analyses from a coastal wetland along the eastern Alaska–Aleutian megathrust to reconstruct pre-seismic and coseismic land-level changes associated with the AD 1964 Alaska earthquake. In the 15 years prior to the AD 1964 earthquake, diatoms showed a gradual shift from a freshwater environment dominated by salt-intolerant taxa (e.g., *Eunotia exigua*, *Eunotia pectinales*, and *Achnanthes minutissima*) to salt-tolerant freshwater taxa typical of a high marsh environment (e.g., *Navicula pupula*, *Nitzschia fruticosa*, and *Pinnularia lagerstedtii*). Zong et al. (2003) interpret the shift in diatom assemblages as a phase of gradual land subsidence of ~0.15 m that preceded up to 2 m of coseismic subsidence in the AD 1964 earthquake. If pre-seismic deformation does occur, the implication is that warning signs may be detectable for several years prior to a great earthquake (Bourgeois, 2006).

Hamilton et al. (2005) explored whether the pre-seismic signal was a result of mixing of diatom assemblages from biological or physical processes. Hamilton et al. (2005) transplanted a block of marsh peat to a lower elevation in the intertidal zone where it would be buried by tidal mud. The results showed that mixing of diatoms did occur, but only in the top ~1 cm of peat, whereas the pre-seismic signal observed by Zong et al. (2003) and Hamilton and Shennan (2005b) occurred over 2–5 cm. In addition, Shennan and Hamilton (2006) argued that the pre-seismic signal was not a result of diatoms filtering down from overlying mud because dominant species that reflect subtle pre-seismic subsidence, such as *Nitzschia obtusa*, *Navicula begeri*, *Navicula brockmanii*, and *P. lagerstedtii*, do not occur in the overlying mud (Fig. 5). A similar transplant experiment at Cascadia found that mixing of foraminifera did occur up to 3 cm below the transplanted marsh peat surface, mimicking a pre-seismic signal (Engelhart et al., 2013a). Engelhart et al. (2013a) cautioned against interpreting microfossil assemblages in such mixed layers as a pre-seismic signal.

## 4. Application of diatoms to tsunami studies

### 4.1. Paleotsunamis

Sequences of tsunami deposits preserved along subduction zone coastlines can be used to estimate recurrence intervals of tsunamigenic earthquakes over centuries to millennia (Nanayama et al., 2003; Cisternas et al., 2005; Jankaew et al., 2008; Sawai et al., 2012). Stratigraphic sequences, supported by diatom studies, reveal repeated tsunamis in numerous locations including Alaska, the Pacific Northwest of North America, Chile, Japan, New Zealand, and locations bordering the North Sea and the Indian Ocean (Table 1, Fig. 2).

Allochthonous marine and brackish diatoms within tsunami deposits, including benthic and planktonic taxa, can support a seaward provenance of the sediment (e.g., Hemphill-Haley, 1995a; Sawai et al., 2002; Dura et al., 2015). Diatom analysis helped identify the provenance of three sand beds recovered from a coastal lake at Suijin-numa, on the subduction zone of the Japan Trench (Sawai et al., 2008). The marine and brackish diatoms (*Diploneis smithii*, *Delphineis surirella*) within the sand beds contrasted against the freshwater assemblages (*Aulacoseira granulata*, *A. crassipunctata*, *Eunotia* spp.) in the under and overlying mud. The middle sand bed at Suijin-numa correlates with the Jogan earthquake in AD 869 (Yoshida, 1906), the presumed predecessor to the 2011 Tohoku earthquake. Along the Kuril Trench in northern Japan, Nanayama et al. (2007) used diatoms to identify nine sandy tsunami deposits intercalated with peat. The diatom assemblage within the peats contained freshwater species (e.g., *Eunotia* spp., *Pinnularia* spp.), whereas the sand beds were dominated by marine taxa

(e.g., *D. surirella* and *O. aurita*). Based on the record of tsunami deposits, the authors estimated a 365–553 year recurrence interval for large Kuril Trench earthquakes. Later, based on over 60 radiocarbon age estimates, Sawai et al. (2009b) found that the interval between tsunamis on the Kuril Trench ranged from 100 to 800 years, with an average recurrence interval of ~400 years.

In the Storegga Slide tsunami<sup>1</sup> deposits in Scotland, Dawson et al. (1996) found an anomalous marine diatom assemblage with a high occurrence of fragmented diatoms. Up to 90% of valves (60% of which have elongate forms) within the sand bed were fragmented, reflecting the nature of the rapid, turbulent marine incursion of tsunami events (Dawson et al., 1996; Smith et al., 2004; Fig. 7). Similar preferential fragmentation of diatom valves, in particular elongate forms (>100 µm) has been documented in inferred paleotsunami deposits in the Pacific Northwest of North America (Witter et al., 2009) and Japan (Sawai et al., 2002). Conversely, anomalously low breakage of diatoms in tsunami deposits has been reported in paleotsunamis from the Pacific coast of Washington State and Puget Sound, USA (Hemphill-Haley, 1996). Hemphill-Haley (1996) suggested that the low breakage of diatoms reflects rapid sedimentation by the tsunamis.

Diatoms can be used to estimate tsunami run-up beyond the landward limit of tsunami deposits. Hemphill-Haley (1996) used the distribution of diatoms to show that the inundation area of the tsunami from the AD 1700 Cascadia subduction zone earthquake was larger than the distribution inferred from the coarser-grained deposit visible in outcrop. Epipsammic tidal flat diatoms were found about 1 km farther upstream from the landward extent mapped in cores and stream channel outcrops.

### 4.2. Tsunamis of the past two decades

Diatom analysis of recent tsunami deposits provides modern analogs for reconstructing the fossil record. Recent studies characterized the diatom composition of the 1998 Papua New Guinea (Dawson, 2007), 2004 Indian Ocean (Sawai et al., 2009a), 2009 South Pacific (Chagué-Goff et al., 2011), 2010 Maule Chile (Horton et al., 2011; Garrett et al., 2013), and 2011 Tohoku (Szczeniński et al., 2012; Sawai et al., 2012) tsunamis. Analyzing the diatom signature of recent tsunamis can be used to infer the sedimentation (e.g., high-energy deposition), sediment provenance, and inundation limits of the events.

The taphonomy of diatom valves may indicate the mode of sedimentation of a tsunami. Dawson (2007) explored the condition of diatom valves in the 1998 Papua New Guinea tsunami deposit and found that linear, sigmoid, and clavate diatoms were more readily fragmented during the high-energy tsunami due to their relatively fragile valve structure. In contrast, high abundances of taphonomically unaltered (i.e., pristine) diatom valves were found in tsunami deposits from the 2004 Indian Ocean tsunami in Thailand (Sawai et al., 2009a), and the 2010 Maule tsunami in Chile (Horton et al., 2011).

The upward fining of grain size observed in tsunami sands may be reflected by similar grading of diatom valves, a result of the variable flow speed of a tsunami (Gelfenbaum and Jaffe, 2003). In Thailand, the 2004 Indian Ocean tsunami deposit consisted of a sand bed with a thin mud cap and contained mostly beach and subtidal diatoms (>80%) and very few freshwater species (Fig. 8; Sawai et al., 2009a). The lower section of the deposit was dominated by larger epipsammic marine diatoms, whereas the middle section contained abundant marine planktonic species, and the mud cap was dominated by a mixture of smaller freshwater, brackish, and marine species. Diatom analysis by Chagué-Goff et al. (2011) following the 2009 South Pacific tsunami deposit in Samoa, Horton et al. (2011) following the 2010 Maule tsunami in Chile, and Szczeniński et al. (2012) following the

<sup>1</sup> The Storegga Slide tsunami (~7900 calibrated years BP) was produced by a submarine landslide (Bondevik et al., 2005).



2011 Tohoku-Oki tsunami on the Sendai plain also revealed grading of diatom valves.

Diatoms recovered from tsunami deposits perpendicular to the coast show variable concentration, ecology, and taphonomy related to the provenance of material. Szczeniński et al. (2012) found that within 1 km of the coast, the Tohoku-Oki sand beds were derived mainly from the beach and coastal dunes, and because such sediments were devoid of diatoms, the assemblage within the tsunami sediments was composed of a low concentration of fragmented freshwater and few brackish species sourced from the coastal plain. Further inland the diatom concentration within the tsunami sediments increased, and the assemblage and condition of valves in the deposit (% fragmentation of valves) were very similar to the valves in the underlying soil and nearby freshwater canal, suggesting that the sediment was locally sourced and not transported from the coast (Szczeniński et al., 2012).

Chagué-Goff et al. (2015) used the diatom assemblages of the 2010 Maule Chile tsunami deposit to trace tsunami inundation beyond the limit of sedimentological evidence. Marine diatoms could be traced ~100 m beyond the inundation limit identified by the tsunami deposit.

## 5. Knowledge gaps

Diatoms have improved our understanding of the nature of land-level change associated with past earthquakes and have helped define the impacts of past tsunamis. However, when using diatoms for reconstructing earthquake-related land-level change and tsunami inundation, several matters must be kept in mind.

### 5.1. Uncertainties in modern diatom distributions

An absence of local to regional modern diatom datasets from a range of coastal environments restricts the application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis. The relation of diatoms to tidal elevation is unknown in many locations because of a scarcity of modern data (e.g., Dura et al., 2015). However, even modern diatom datasets that include hundreds of samples taken across multiple local coastal wetlands can fail to provide modern analogs for fossil diatom assemblages (Watcham et al., 2013). This non-modern-analog situation (Birks, 1995) is attributed to local environmental conditions having changed significantly over time (Watcham et al., 2013). If this happens, it is not appropriate to apply quantitative reconstruction techniques (e.g., transfer function) using only local modern diatom assemblages (Watcham et al., 2013). Regional modern training sets compiled from a large range of intertidal coastal environments (e.g. marshes with a variety of vegetation zones, substrates, and elevation gradients) can account for such variation in the distribution of diatoms, providing analogs for diatom assemblages found in fossil cores (Zong et al., 2003; Watcham et al., 2013; Shennan et al., 2014a).

### 5.2. Response of diatoms to coseismic land-level change

When producing diatom-based estimates of earthquake related land-level change across sharp stratigraphic contacts, a possible delay in sediment deposition and diatom response must be considered. If there is a significant (months to years) hiatus in response following an earthquake, estimates of coseismic deformation will include both coseismic and postseismic deformation, thus they will be minimum estimates (Garrett et al., 2013). Shennan et al. (2014a) found that peat formation following the coseismic uplift of an intertidal mudflat along the eastern Alaska–Aleutian megathrust was not instantaneous, resulting in minimum estimates of uplift. The study also found a mixed salinity diatom assemblage in the upper part of the buried silt that formed as a result of ponding and reworking of the uplifted surface before colonization by terrestrial plants, and likely did not represent the

pre-earthquake environment and elevation. In Chile, Garrett et al. (2013) found that uplifted marshes had accumulated little to no sediment up to two years after the 2010 earthquake and tsunami, complicating estimates of coseismic uplift. Coseismic subsidence more often results in rapid sedimentation of clastic sediments hours to weeks after an earthquake, due to the accommodation space created in the submerged marsh (Atwater et al., 2001; Hawkes et al., 2011).

### 5.3. The production and preservation of diatoms

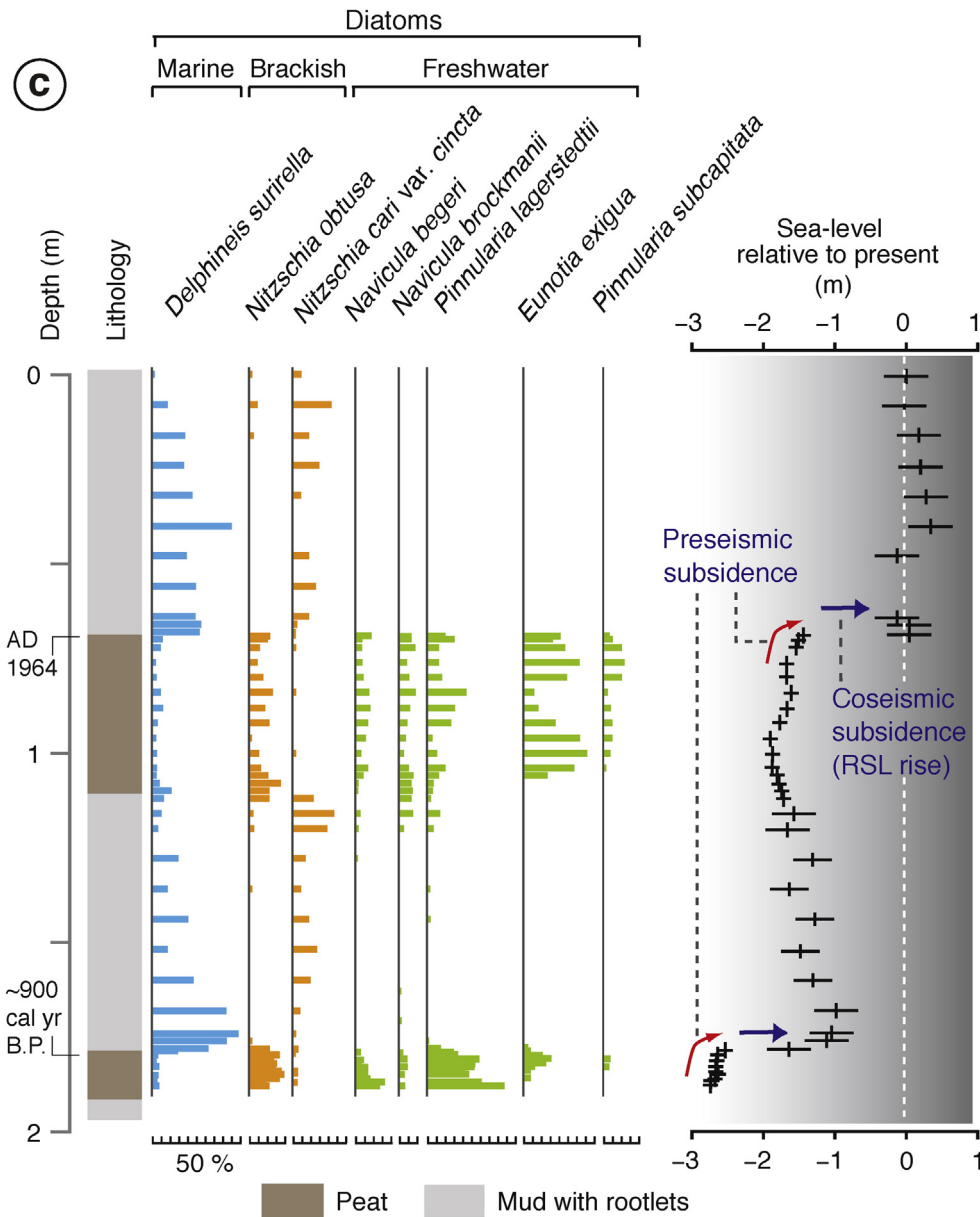
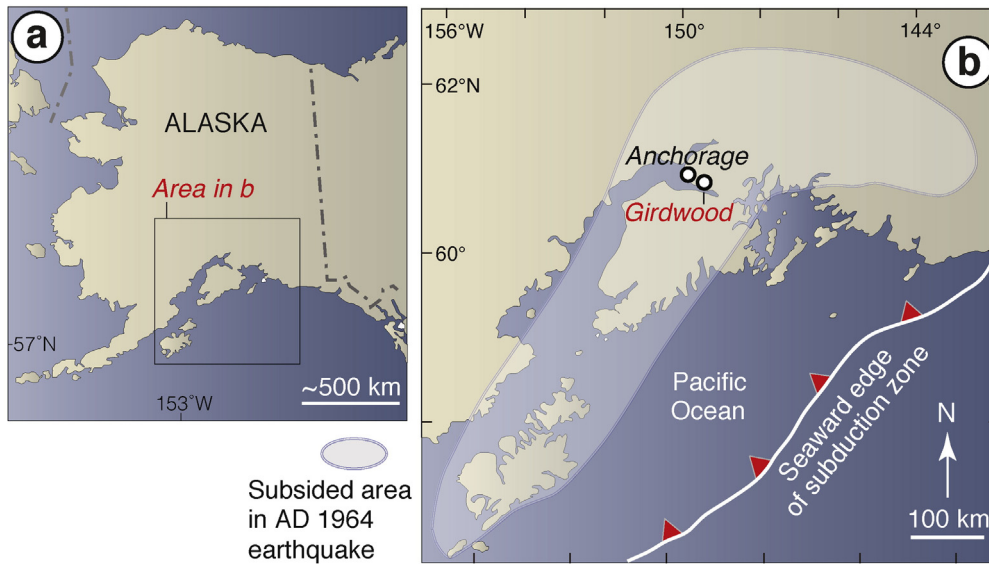
Diatom-based reconstructions of earthquake-related land-level change and tsunami inundation are hindered by variable diatom production and preservation. In the Copper River Delta, Shennan et al. (2014a) found low numbers of diatoms in modern samples taken from tidal flat silts, a result of high sediment accretion of the delta environment. Silts in fossil sequences also contained few diatoms, which complicated quantitative reconstructions of earthquake-related land-level change (Shennan et al., 2014a). In relatively alkaline and warm environments, there are problems with chemical dissolution of diatom valves (Kamatani, 1982; Flower, 1993; Barker et al., 1994). Sawai et al. (2009a) found excellent preservation of diatoms in the 2004 Indian Ocean tsunami deposit in Thailand, but three paleotsunami deposits examined at the same site by Jankaew et al. (2008) contained no fossil diatoms. Dissolution of diatom valves can also make them more susceptible to fragmentation, complicating the use of the fragmentation metric to infer high-energy deposition during a tsunami. Szczeniński et al. (2012) found a similar degree of fragmentation in diatoms within the soil underlying the 2011 tsunami deposit and within the deposit itself.

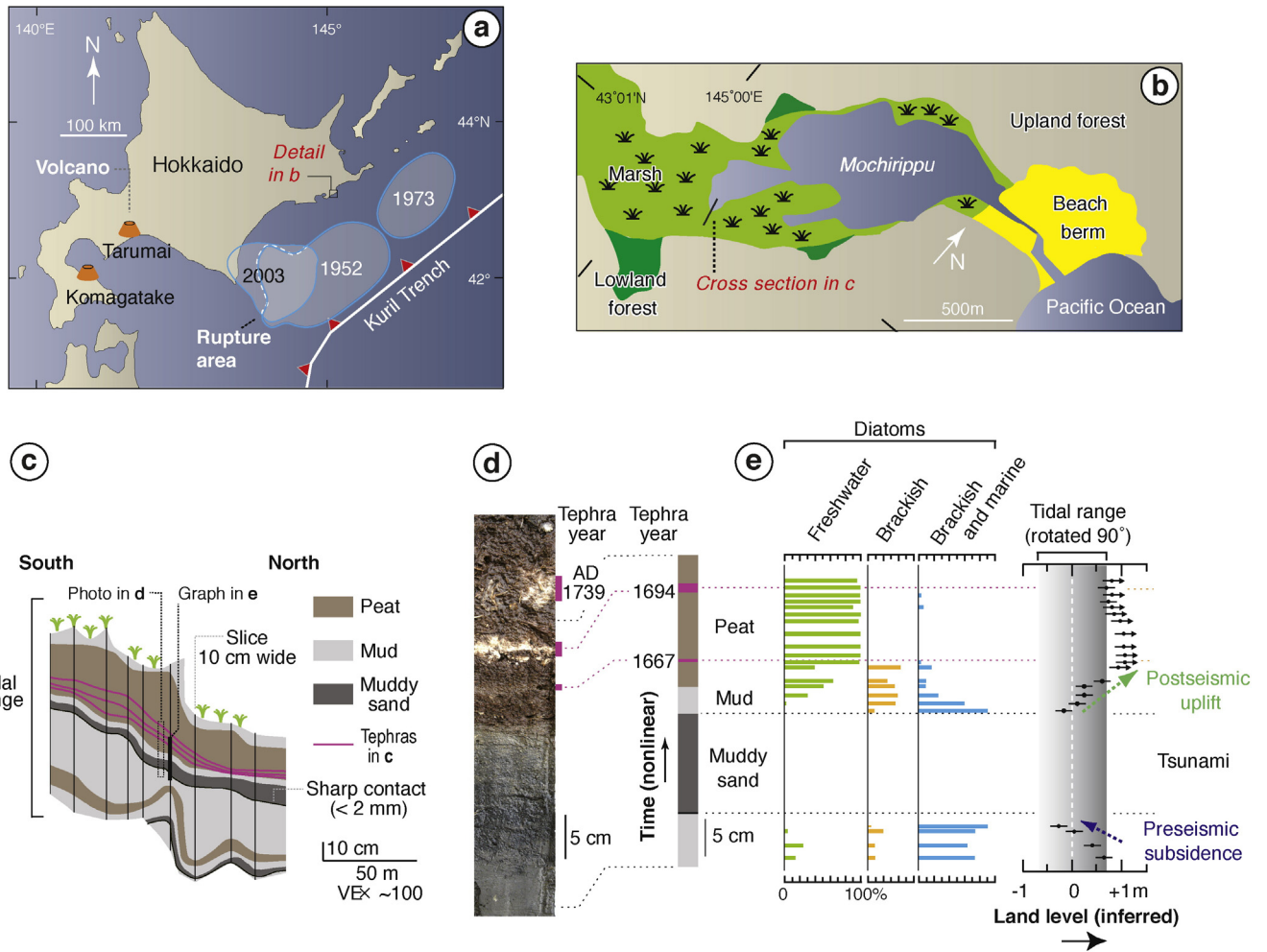
### 5.4. Differentiating autochthonous and allochthonous diatoms

Problems differentiating autochthonous (in situ) and allochthonous (transported) diatoms in modern and fossil studies complicate reconstructions. Certain taxa are transported across coastal wetlands and, if included in modern or fossil assemblages, erroneously represent the depositional environment. This problem is common in coastal wetlands where diatom valves are transported from one intertidal floral zone to another by daily tidal currents, or, in colder climates, by ice rafted sediment (Hemphill-Haley, 1995a; Hamilton et al., 2005). Hemphill-Haley (1995a) and Sawai (2001b, 2004) suggested several means to distinguish allochthonous diatoms in both modern and fossil assemblages. Planktonic diatoms are considered allochthonous components in modern and fossil coastal wetland assemblages, while benthic taxa (e.g., epiphytic, epipellic and epipsammic types) can be considered as autochthonous (Vos and de Wolf, 1993). Some chain-forming taxa with thickly silicified valves may form prominent allochthonous assemblages. Hemphill-Haley (1995a) excluded the marine tycho planktonic diatom *Paralia sulcata* from paleoecological interpretations, because its robust valves and long-chained structure allow its valves to be easily floated and transported by tidal currents and deposited far inland in tidal estuaries (Hemphill-Haley, 1995a). Sawai (2001b, 2004b) recognized allochthonous distributions of certain epiphytic taxa in the intertidal zone. For example, *Cocconeis scutellum* is an epiphytic species commonly found attached to macrophytes in the intertidal zone. After death, the upper (rapheless) valve that is not attached to the macrophyte may detach and be transported by tidal currents (Sawai et al., 2004b). As a result, rapheless valves of *C. scutellum* may be found in sediment across the entire intertidal zone, although its habitat is limited to the macrophyte zone (Sawai, 2001b).

### 5.5. Differentiating tsunami and storm surge deposits

Allochthonous marine and brackish diatoms may be found in storm-surge deposits, making it difficult to differentiate from tsunami deposits in the stratigraphic record (e.g. Liu and Fearn, 2000; Parsons, 1998; Tuttle et al., 2004; Horton et al., 2009). However, coseismic land-level





**Fig. 6.** Example of land-level reconstructions using diatoms in Hokkaido, northern Japan. (a) Position of study area relative to the Kurile Trench. The solid line with triangles shows the seaward edge of the subduction zone. The volcanoes responsible for tephra layers in c and d are shown and rupture areas of instrumentally recorded earthquakes on the plate boundary off eastern Hokkaido are outlined; (b) map of Mochirippu Estuary showing location of stratigraphic cross-section; (c) stratigraphic cross-section; (d) photograph and log of stratigraphy. Example of change from tidal-flat mud to lowland-forest peat, punctuated by a tsunami deposit and by volcanic ash layers. (e) Diatom diagram showing the schematic stratigraphy, changes in diatom assemblages, and the results of diatom-based transfer functions showing the seventeenth-century large earthquake. Error bars for height estimates span two standard deviations.

Modified and reprinted from Sawai, Y., Satake, K., Takanobu, K., Nasu, H., Shishikura, M., Atwater, B.F., Horton, B.P., Kelsey, H.M., Nagumo, T., Yamaguchi, M., Transient uplift after a 17th-century earthquake along the Kuril subduction zone. *Science* 306, 1918–1920, 2006, with permission from The American Association for the Advancement of Science.

change coincident with anomalous silt and sand beds provides a definitive earthquake source for a tsunami. In Washington State, USA [Hemphill-Haley \(1995a\)](#) identified two coarse-grained silt and sand beds dominated by marine diatoms. A tsunami source was inferred from one bed because it was associated with a sudden change in depositional environment from upland soil to intertidal mud, consistent with coseismic submergence. The other bed within a freshwater upland soil was not associated with a change in stratigraphy and was probably deposited by a storm ([Hemphill-Haley, 1995a](#)).

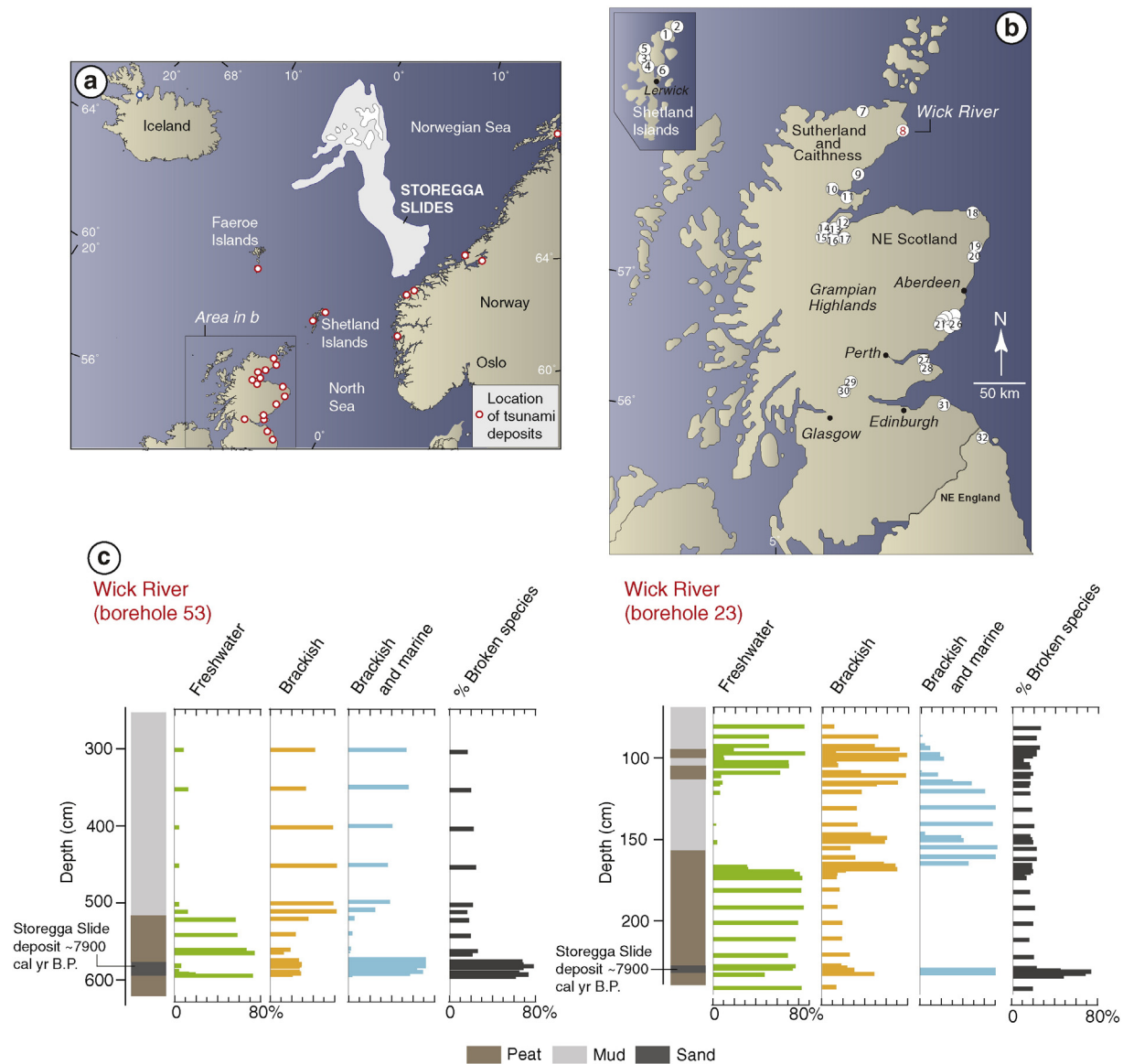
### 6. Conclusions

Using global examples, we illustrated the utility of diatoms in reconstructing land-level change and tsunami inundation histories along subduction zone coastlines on centennial and millennial timescales.

We outlined the evolution of fully quantitative, statistical techniques to estimate coseismic land-level change at the Cascadia subduction zone. Examples from the Alaska–Aleutian megathrust and the Japan trench illustrated the expanded application of the transfer function technique to reconstruct preseismic, coseismic, and postseismic land-level change. In central Chile, diatoms were successfully applied to identify coseismic uplift, and in Alaska, diatoms helped reconstruct a mixed uplift and subsidence record preserved in coastal wetland stratigraphy.

We illustrated the utility of diatoms in inferring the sediment provenance, sedimentation, and inundation limit of tsunamis. Allochthonous marine and brackish diatoms within anomalous sand beds along the coasts of Japan, Scotland, and Thailand indicate a seaward provenance of sediments, supporting a tsunami source. The high fragmentation of diatom valves in sand beds deposited by the Storegga tsunami and the 1998 Papua New Guinea tsunami reflect high-energy sedimentation,

**Fig. 5.** Diatom analyses during past earthquake cycles on the Alaska–Aleutian megathrust suggesting preseismic movement. (a) Location of south-central Alaska, USA; (b) area subsided in the AD 1964 earthquake ([Plafker, 1969](#)); (c) relative sea level (RSL) changes reconstructed using a diatom-based transfer function; two short periods of preseismic submergence immediately prior to substantial coseismic subsidence were recognized at the top of peat units and are highlighted with red arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Modified and reprinted from Shennan, I., Hamilton, S., Coseismic and preseismic subsidence associated with great earthquakes in Alaska. *Quaternary Science Reviews* 25, 1–8, 2006, with permission from Elsevier.



**Fig. 7.** Diatom analyses of the Storegga Slide tsunami showing fragmentation of diatom valves within the high-energy deposit. (a) Location of the Storegga Slides and sites where evidence for the Holocene Storegga Slide tsunami has been found; (b) sites in the United Kingdom where evidence for the Holocene Storegga Slide tsunami may be found. Numbers correspond to sites discussed in Smith et al. (2004); (c) diatom summary diagram from Boreholes 53 and 23 in lower Wick River Valley, Caithness, Scotland (Dawson et al., 1996). Taxa displayed as % of total valves.

Modified and reprinted from Smith, D.E., Shi, S., Cullingford, R.A., Dawson, A.G., Dawson, S., Firth, C.R., Foster, I.D.L., Fretwell, P.T., Haggart, B.A., Holloway, L.K., Long, D., The Holocene Storegga slide tsunami in the United Kingdom. *Quaternary Science Reviews* 23, 2291–2321, 2004, and Dawson, S., Smith, D.E., Ruffman, A., Shi, S., The diatom biostratigraphy of tsunami deposits: Examples from recent and middle Holocene events. *Physics and Chemistry of the Earth*, 21, 87–92, 1996, with permission from Elsevier.

while the upward fining of diatom valves in the 2004 Indian Ocean tsunami reflect the variable flow speed of a tsunami. Examples from the Cascadia subduction zone and the Chile subduction zone showed diatoms how can be used to estimate tsunami run-up beyond the landward limit of tsunami deposits, a powerful tool in estimating paleotsunami inundation.

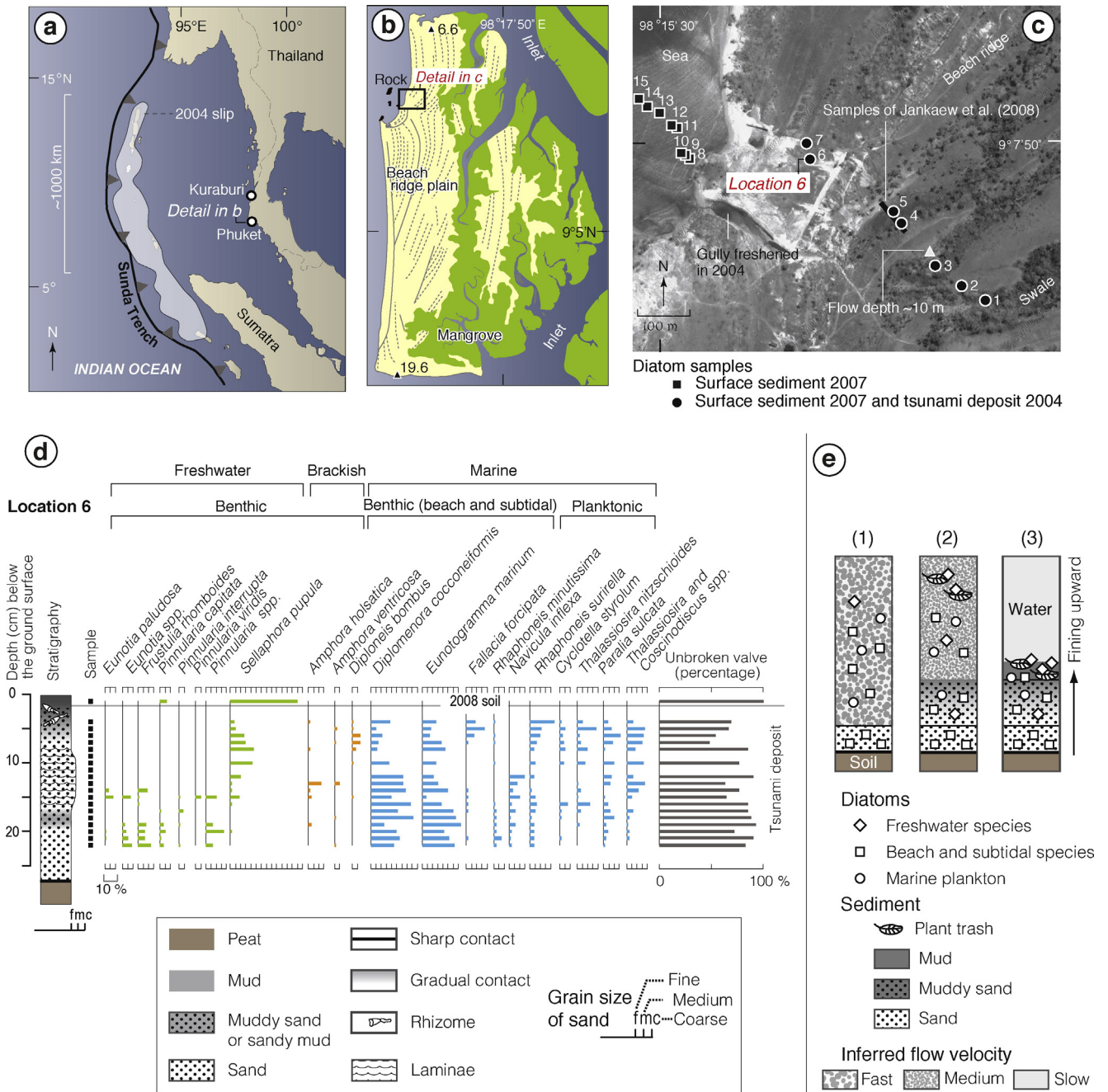
We outlined a series of knowledge gaps that should be considered in future research. Many of the knowledge gaps in the study of diatom-based earthquake and tsunami records can be addressed by continuing to explore the modern diatom environments, in particular exploring diatoms' relation to salinity and substrate, variable production, preservation, and transport. Examining the response of diatoms to recent earthquake-related land-level change and the character of modern tsunami deposit diatom assemblages will continue to provide analogs for identifying events in the fossil record.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: <http://dx.doi.org/10.1016/j.earscirev.2015.11.017>. These data include Google maps of the most important areas described in this article.



**Fig. 8.** Diatom analyses of the 2004 Indian Ocean tsunami deposit showing grading of diatom valves; (a) Position of study area relative to the Sunda Trench. Fault slip during the 2004 Sumatra–Andaman earthquake (Chlieh et al., 2007); (b) Phra Thong Island. The island is isolated from the mainland of Thailand by inlets. Light gray area is grassy beach ridge plains. Dark gray area is mangrove forests. Landforms traced from 1:50,000-scale airphotos taken in 1999 and from post-tsunami satellite images at PointAsia.com (modified from Jankaew et al., 2008); (c) location of pit and modern samples. Satellite image is from PointAsia.com; (d) diatom diagram showing the schematic stratigraphy of location 6 and changes in diatom assemblages throughout the 2004 tsunami deposit. Abundant beach and subtidal species are more abundant in the bottom of the sand bed and freshwater diatoms become more abundant in the top of the sand bed. Diatom valves are relatively pristine in the tsunami deposit as shown by the high percentage of unbroken valves. (e) Simplified process of deposition of diatoms and sediment during tsunami; (1) fast current. Only beach and subtidal species are incorporated with coarse sediment. Because turbulent current can keep a substantial amount of sand fraction in the water column, mixed assemblages of many beach and subtidal, marine plankton are suspended. Freshwater specimens may be included with eroded soil fractions. (2) Current becomes slow. Fine fractions fall onto the ground. Eroded, floated, and transported specimens are also incorporated. (3) Suspension stage (calm current) of tsunami. All floated specimens are allowed to settle down. Many freshwater species incorporated with their substrata (plant trash and eroded soil fractions). Modified and reprinted from Sawai, Y., Jankaew, K., Martin, M.E., Prendergast, A., Choowong, M., Charoentitirat, T., Diatom assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phra Thong Island, Thailand. Marine Micropaleontology, 73, 70–79, 2009, with permission from Elsevier.

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