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.

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

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24   sudden land-level change (e.g., Hemphill-Haley et al., 1995a; Cisternas et al., 2005). In

25   addition, trans-oceanic tsunamis produced by the largest subduction zone earthquakes can

26   deposit sediments on coastlines hundreds to thousands of kilometers away from the

27   earthquake source (e.g., Satake et al., 1996; Goff et al., 2006).

28   Microfossils such as diatoms, foraminifera, and pollen that are incorporated into

29   coastal stratigraphy provide qualitative and quantitative estimates of land-level change

30   associated with subduction zone earthquakes (Horton et al., 2013; Fig. 1). In particular,

31   diatoms and foraminifera have been applied to earthquake and tsunami studies around the

32   world (e.g., Darienzo et al., 1994; Hemphill-Haley, 1995a, 1995b, 1996; Sawai et al.,

33   2004a, b; Shennan and Hamilton, 2006; Hawkes et al., 2011; Engelhart et al., 2013;

34   Grand Pre et al., 2012; Clark et al., 2015; Dura et al., 2015). These microfossils have

35   improved upon early coastal studies of subduction-zone earthquake history that estimated

36   the amount of coseismic land-level change with large errors (>1 m) based on the broad

37   elevational ranges of plant macrofossils (Atwater, 1987, 1992; Clague and Bobrowsky,

38   1994). Quantitative diatom and foraminiferal-based reconstructions of land-level change

39   (e.g., transfer functions) can produce substantially smaller (<0.3 m) errors (Guilbault et

40   al., 1995, 1996; Zong et al., 2003; Sawai et al., 2004a,b; Shennan and Hamilton, 2006;

41   Nelson et al., 2008; Hawkes et al., 2011; Engelhart et al., 2013; Watcham et al., 2013).

42   Microfossils are applied to tsunami studies to determine the provenance of tsunami

43   sediments deposited in low-energy coastal environments such as lowlands (Hemphill-

44   Haley, 1995a, 1996; Benson et al., 1997; Nanayama et al. 2007; Sugawara et al., 2009),

45   interdunal depressions (Dawson and Stewart, 2007; Jankaew et al., 2008), lagoons

46   (Minoura and Nakaya, 1991; Nichol et al., 2007; Sawai et al., 2009b; Wilson et al., 2014)

47   and lakes (Hutchinson et al., 1997; Grauert et al., 2001; Kelsey et al., 2005).

48   Allochthonous marine assemblages or a chaotic mix of marine, brackish and freshwater

49   taxa within terrestrial or brackish settings may be indicative of marine incursions from

50   tsunamis (Tuttle et al., 2004; Cochran et al., 2005; Hawkes et al., 2007; Goff et al., 2012;

51   Clark et al., 2015), and the preservation and distribution of diatoms and foraminifera

52   throughout the deposit can be used to infer high-energy transport and provenance

53   (Hemphill-Haley, 1996; Sawai et al., 2002; Pilarczyk et al., 2012a).Tsunamis of the past

54   two decades have provided an opportunity to characterize the microfossil composition of

55   modern deposits (Dawson, 2007; Sawai et al., 2009a; Chagué-Goff et al., 2011;

56   Szczuciński et al., 2012b), improving our ability to identify such characteristics in the

57   fossil record.

58   In this review we explore the application of diatoms to earthquake and tsunami

59   studies (Fig. 2; Table 1). We explain the statistical approaches that use diatoms to

60   estimate earthquake related land-level changes, and assess the utility of diatoms in

61   identifying tsunamis in the stratigraphic record. We also examine the knowledge gaps

62   and limitations of diatom analyses in earthquake and tsunami studies, and make

63   recommendations for future research.

64   **2. Reconstructing coastal environments with diatoms**

65   Diatoms are photosynthetic, unicellular algae that inhabit freshwater, brackish, and

66   marine environments (Round et al., 1990; Jones, 2007). Diatoms are a dominant

67   microphyte in coastal wetland environments and their siliceous valves, ranging in size

68   from ~5 μm to ~200 μm, are resistant to taphonomic degradation (e.g., dissolution,

69   abrasion, bioerosion, oxidation, transport, predation; Admiraal, 1984; Palmer and Abbott,

70   1986; Cooper et al., 2010). As a result, small (1 g wet weight) sample sizes (for example,

71   from narrow-diameter cores 25-50 mm) contain statistically significant (300-600 valves)

72   diatom populations (Birks, 1995; Battarbee et al., 2001; Nelson, 2015).

73   Diatoms have been described and classified for over 200 years based on their shapes,

74   sizes, and the intricate morphological characteristics of their siliceous valves (Round et

75   al., 1990). Diatom taxa are divided into three main classes: the Coscinodiscophyceae

76   (centric taxa); Fragilariophyceae (araphid pennate taxa); and Bacillariophyceae (raphid

77   pennate taxa). Literature on the identification of diatoms to species level includes van der

78   Werff and Huls (1958-1974), Patrick and Reimer (1966, 1975), Krammer and Lange-

79   Bertalot (1986, 1988, 1991a, b), Hartley et al. (1996), Krammer (2000, 2002, 2003),

80   Lange-Bertalot (2000, 2001, 2011), and Levkov (2009).

81   Diatoms are a valuable tool in reconstructing paleoenvironmental changes because

82   of their sensitivity to environmental factors including salinity, tidal exposure, substrate,

83   vegetation, pH, nutrient supply, and temperature found in specific coastal wetland

84   environments (e.g., Zong and Horton, 1998). Over time, diatoms become incorporated in

85   coastal sediments, resulting in buried assemblages that represent an environmental

86   history that can span thousands of years. Literature for the ecological classification of

87   diatoms includes Hustedt (1937, 1939, 1953, 1957), Lowe (1974), Patrick and Williams

88   (1990), Denys (1991-1992), Juggins (1992), Vos and de Wolf (1988; 1993), Van Dam et

89   al. (1994), and Lange-Bertalot (2000).

90   Diatoms' preferences for salinity are valuable for earthquake and tsunami studies.

91   Changes in salinity across the intertidal zone produce vertically zoned diatom

92   assemblages with respect to the tidal frame (Nelson and Kashima, 1993; Hemphill-Haley

93   1995b; Sherrod et al., 1999; Patterson et al., 2005; Horton and Sawai, 2010; Woodroffe

94   and Long, 2010). Establishing the distribution of diatoms across the intertidal zone is a

95   prerequisite for reconstructing paleoenvironmental changes related to earthquakes and

96   tsunamis (e.g., Zong and Horton, 1998). In the halobian classification scheme,

97   polyhalobous and mesohalobous diatom taxa represent the marine and brackish

98   conditions found in tidal flats and lower tidal marshes and mangroves. Oligohalobous-

99   halophile and oligohalobous-indifferent taxa become dominant through the transition

100   from tidal marsh/mangrove to freshwater environments, and halophobous taxa

101   characterize the most landward freshwater communities above the highest tides. The

102   presence of diatoms in freshwater environments is an obvious advantage compared to

103   foraminifera, which are restricted to areas of marine influence (e.g., Murray, 1991).

104   The distribution of diatoms along a modern intertidal transect (Fig. 3) typically

105   shows a clear transition from subtidal, open-water marine diatoms (e.g., *Thalassiosira*

106   *pacifica* and *Odontella aurita*), to marine tidal flat taxa (e.g., *Achnanthes brevipes* and

107   *Tabularia fasciculata*). In the low marsh, where a mixed diatom community is often

108   found, marine–brackish diatoms (e.g., *Planothidium delicatulum* and *Tryblionella*

109   *granulata*) dominate, followed by freshwater taxa that can tolerate low salinities in the

110   high marsh (e.g., *Caloneis bacillum* and *Cosmioneis pusilla*) and freshwater salt-

111   intolerant taxa in the upland environment (e.g., *Eunotia bilunaris* and *Aulacoseira*

112   *crassipunctata*).

113   The distribution of diatoms across the intertidal zone based on their life form is

114   valuable for tsunami studies. The diverse life forms of diatom floras are employed to

115   support the marine provenance of inferred tsunami deposits. Hustedt (1958), Vos (1986),

116 Vos et al. (1988), and Vos and de Wolf (1993) define diatom life forms based on the

117 substrate—or lack thereof—that particular diatom taxa commonly live on. Benthic

118 diatoms are grouped into epipsammic taxa that live attached to sand grains; epipelic taxa

119 that live on or just below the surface of wet muddy sediment; epiphytic taxa that are

120 attached to larger plants or other surfaces; and aerophile taxa that are able to survive

121 subaerial, temporarily dry conditions. Planktonic diatoms float freely in the water column

122 and do not live attached to any substrate; tychoplanktonic diatoms include an array of

123 species that live in the benthos, but are commonly found in the plankton. Based on local

124 conditions, epipsammic, epipelic, planktonic, and tychoplanktonic diatoms may comprise

125 tidal flat populations, whereas epiphytic and epipelic forms are more common on tidal

126 marshes/mangroves. Aerophilous forms are most common within the landward

127 communities above the highest tides (Sherrod, 1999).

128 **3. Application of diatoms to subduction zone paleoseismic cycles**

129 *3.1 Earthquake deformation cycle*

130 On subduction zone coastlines, the land-level changes associated with earthquakes

131 reflect the strain accumulation and release of the earthquake deformation cycle (Burbank

132 and Anderson, 2001; Nelson, 2013). The nature of the interseismic and coseismic motion

133 of the coastline is determined by its proximity to the trench, the geometry of the

134 subduction zone, and where ruptures stop along strike (Plafker, 1965; Plafker and

135 Savage, 1970; Wang et al., 2012). Some subduction zone coastlines (e.g., Cascadia, the

136 Pacific Northwest of North America) lie within a zone that gradually uplifts in between

137 (interseismic) and abruptly subsides during (coesismic) great earthquakes (Plafker, 1972,

138 Atwater 1987). In coastal wetland stratigraphy, the interseismic period is represented by a

139 gradual regression from clastic (e.g., tidal flat or shallow subtidal) to organic-rich (e.g.,

140 marsh or swamp) sediments reflecting land-level uplift (i.e., relative sea-level fall) and a

141 decrease in marine influence. Abrupt coseismic land subsidence creates a sudden change

142 from organic-rich sediments to clastic sediments, reflecting land-level subsidence (i.e.,

143 relative sea-level rise) and an increase in marine influence (Fig. 1).

144   Conversely, some coastal locations bordering subduction zones (e.g., central Chile;

145 Alaska-Aleutian megathrust) lie within a zone that gradually subsides in between and

146 abruptly uplifts during great earthquakes (Shennan et al., 2009; Dura et al., 2015). During

147 the interseismic period, coastal wetland stratigraphy displays a gradual transgression

148 from organic-rich to clastic sediments as land-level subsides and marine influence

149 increases. Abrupt coseismic uplift creates a sudden change from clastic to organic-rich

150 sediments, reflecting land-level uplift and a decrease in marine influence.

151   Coastal wetland stratigraphy can record both coseismic uplift and subsidence at one

152 location (e.g., Hayward et al., 2006; Briggs et al., 2014; Ely et al., 2014), depending on

153 the distribution of slip upon the megathrust surface (Savage and Hastie, 1966) or the

154 interaction with upper plate faults. The possibility of a variable uplift-subsidence history

155 illustrates that the paleoseismic record should not be assumed to record exclusively

156 coseismic uplift or subsidence.

157   Because non-seismic coastal processes can also produce changes in stratigraphy

158 similar to those created by great subduction zone earthquakes, criteria must be considered

159 to support a tectonic origin (Darienzo et al., 1994; Nelson et al., 1996b; Shennan et al.,

160 1996; Dura et al., 2015). The key criteria are the lateral extent of sharp stratigraphic

161 contacts; the suddenness and magnitude of land-level change; the synchroneity of land-

162 level change among regional sites; and the coincidence of tsunami deposits with sudden

163 changes in stratigraphy. No breaks in sedimentation greater than a few weeks are

164 assumed to occur following earthquake-related land-level change and continuous

165 sedimentation is assumed in the interseismic period. Although many paleoseismic studies

166 have relied on stratigraphic investigations to support an earthquake origin (Atwater,

167 1987; Dura et al., 2011), microfossils have been particularly useful in providing

168 supporting evidence of earthquake-related land-level change.

169 *3.2 Diatoms and land-level changes related to the earthquake deformation cycle*

170   Much of the early research using diatoms to reconstruct land-level changes related to

171 the earthquake deformation cycle focused on the Pacific Northwest of North America

172 (Cascadia subduction zone). Regional sea-level rise at rates of up to 2 mm/yr along the

173 central Cascadia subduction zone since 6,000 calibrated years BP (Engelhart et al., 2015)

174 resulted in continuous records of tidal sedimentation that contain evidence of coseismic

175 land-level change and tsunami inundation.

176   Darienzo and Peterson (1990) and Darienzo et al. (1994) employed qualitative

177 diatom analyses to confirm inferences of sudden and widespread coseismic subsidence

178 based on distinctive stratigraphic contacts in Cascadia coastal wetlands. Darienzo et al.

179 (1994) used diatoms to identify broad floral zones (e.g., high marsh, low marsh, tidal flat)

180 in the modern environment and subsequently estimated the magnitude of coseismic

181 subsidence by identifying analogous floral zones from above and below sharp

182 stratigraphic contacts. Because the elevational range of the floral zones was large (0.5-1.0

183 m), errors for subsidence estimates commonly exceeded 1 m (e.g., Nelson and Kashima,

184 1993; Darienzo and Peterson, 1990; Darienzo et al., 1994; Kelsey et al., 2002; Witter et

185 al., 2003).

186   Statistical methods employed the relationship between modern diatom assemblages

187 of known elevation and fossil assemblages to reconstruct land-level changes in

188 stratigraphic sections at Cascadia (Hemphill-Haley, 1995a; Nelson et al., 1996a; Shennan

189 et al., 1996). In southern Washington State, USA, Hemphill-Haley (1995b) used factor

190 analysis to identify the relation of modern diatom distributions to elevation. The result

191 was a list of taxa with dominant occurrences in marsh zones (high marsh, low marsh, and

192 high and low marshes) and three subenvironments of the lower intertidal to shallow

193 subtidal zone (mud flats, sand flats, and *Zostera* (eelgrass) beds). The modern

194 distributions of the same taxa found in the fossil record were used to reconstruct the

195 abrupt changes in environment indicated by stratigraphic contacts spanning the AD 1700

196 subduction zone earthquake (Fig. 4). Distinct changes in diatom assemblages across these

197 sharp contacts confirmed significant, widespread, and lasting change from an upland

198 environment to a tidal-flat or low marsh environment, consistent with coseismic

199 subsidence of 0.8-1.1 m. Shennan et al. (1996, 1998) and Nelson et al. (1996a) employed

200 similar statistical techniques (i.e., ordination and discriminant function analysis,

201 respectively) to quantitatively compare modern diatom assemblages of known elevation

202 with fossil diatom assemblages. Although the statistical techniques of Hemphill-Haley

203 (1995b), Shennan et al. (1996, 1998), and Nelson et al. (1996a) improved the analysis of

204 diatom data, the reconstructions were still based on differences in elevational ranges

205 between pre-earthquake and postearthquake paleoenvironments, resulting in 0.5-1.0 m

206 errors.

207   Fully quantitative, microfossil-based transfer functions used to calculate coseismic

208   land-level change at Cascadia have produced substantially smaller errors (<0.5 m; e.g.,

209   Guilbault et al., 1995, 1996). The transfer function uses multivariate statistical techniques

210   to formalize the relationship between the relative abundance of microfossil species and

211   the environmental variable of interest (in the case of paleoseismic studies, that variable is

212   elevation; e.g., Horton et al., 1999). The transfer function is applied to microfossil

213   assemblages in coastal wetland stratigraphic sequences to calculate changes in paleo-

214   elevation and can provide a continuous record of land-level changes throughout the

215   earthquake deformation cycle. The performance of transfer functions can be measured

216   using multiple techniques to assess the effect of sample design, the goodness-of-fit

217   between microfossil assemblages and elevation, and the statistical significance of each

218   reconstruction (Telford and Birks, 2011a, b). The technique has since been expanded in

219   Cascadia to include extensive modern diatom (Sherrod, 1999, 2000, 2001), foraminifera

220   (Guiltbault et al., 1995, 1996; Hawkes et al., 2010; Engelhart et al., 2013), and pollen

221   (Hughes et al., 2002) datasets, and applied in other geographical locations such as Alaska

222   (e.g., Shennan and Hamilton, 2006), Japan (e.g., Sawai, 2004b), and Chile (e.g., Garrett

223   et al., 2014; Table 1 lists which diatom studies have used quantitative diatom techniques,

224   Fig. 2).

225   Coastal wetland stratigraphy from eastern Hokkaido, Japan contains evidence of

226   preseismic and postseismic land-level change (Atwater et al., 2004; Sawai et al., 2002,

227   2004a, b) associated with subduction zone earthquakes originating from the Kuril Trench

228   (Nanayama et al., 2003). Sawai et al. (2004a) used a diatom-based transfer function

229   (Sawai et al., 2001b, 2004b) to document the land-level change associated with a great

230   17th century earthquake and tsunami (Fig. 6). Fossil diatom assemblages show that tidal

231   flats gradually changed into freshwater upland environments in the decades after the

232   earthquake as a result of up to 1.5 m of postseismic uplift. Sawai et al. (2004a) suggested

233   the large land-level change was the result of a subduction zone earthquake of unusually

234   large size along the Kuril Trench.

235   Diatom data have helped identify coseismic uplift associated with subduction zone

236   earthquakes in Alaska (e.g., Shennan et al., 2009, 2014) and Chile (e.g., Dura et al.,

237   2015). Along the central Chile coast, Dura et al. (2015) used diatoms to identify six

238   instances of cosesimc uplift between 6200 and 3600 calibrated years BP. A repeated

239   influx of freshwater diatoms and other siliceous microfossils above six tsunami sands

240   suggested >1 m of coseismic uplift. The study documented a ~500 year recurrence

241   interval for the earthquakes and accompanying tsunamis in central Chile.

242   Diatom studies have documented evidence of both coseismic subsidence and uplift at

243   the same site. Briggs et al. (2014) used diatoms and foraminifera to identify five instances

244   of sudden uplift and subsidence in the stratigraphy of a coastal marsh on Sitkinak Island

245   bordering the Alaska-Aleutian megathrust. Diatoms showed uplift accompanying

246   earthquakes in 290-0, 520-300, and 1050-790 calibrated years BP, and subsidence in AD

247   1964 and 640-510 calibrated years BP (Briggs et al., 2014). Such studies have

248   implications for seismic hazard analysis, as the mixed uplift and subsidence record shows

249   the variability of slip along the megathrust, suggesting that the segmentation of

250   subduction zones is not fixed (Briggs et al., 2014; Ely et al., 2014).

251   Diatom data have also identified a possible preseismic signal from relatively small

252   amounts of land-level change in the years prior to earthquakes (Bourgeois, 2006;

253   Shennan and Hamilton, 2006). Zong et al. (2003) used detailed modern and fossil diatom

254   analyses from a coastal wetland along the eastern Alaska-Aleutian megathrust to

255   reconstruct preseismic and coseismic land-level changes associated with the AD 1964

256   Alaska earthquake. In the 15 years prior to the AD 1964 earthquake, diatoms showed a

257   gradual shift from a freshwater environment dominated by salt-intolerant taxa (e.g.,

258   *Eunotia exigua, Eunotia pectinales,* and *Achnanthes minutissima*) to salt-tolerant

259   freshwater taxa typical of a high marsh environment (e.g., *Navicula pupula, Nitzschia*

260   *fruticosa,* and *Pinnularia lagerstedtii*). Zong et al. (2003) interpret the shift in diatom

261   assemblages as a phase of gradual land subsidence of ~0.15 m that preceded up to 2 m of

262   coseismic subsidence in the AD 1964 earthquake. If preseismic deformation does occur,

263   the implication is that warning signs may be detectable for several years prior to a great

264   earthquake (Bourgeois, 2006).

265   Hamilton et al. (2005) explored whether the preseismic signal was a result of mixing

266   of diatom assemblages from biological or physical processes. Hamilton et al. (2005)

267   transplanted a block of marsh peat to a lower elevation in the intertidal zone where it

268   would be buried by tidal mud. The results showed that mixing of diatoms did occur, but

269   only in the top ~1 cm of peat, whereas the preseismic signal observed by Zong et al.

270   (2003) and Hamilton and Shennan (2005b) occurred over 2-5 cm. In addition, Shennan

271   and Hamilton (2006) argued that the preseismic signal was not a result of diatoms

272   filtering down from overlying mud because dominant species that reflect subtle

273   preseismic subsidence, such as *Nitzschia obtusa*, *Navicula begeri*, *Navicula brockmanii,*

274   and *Pinnularia lagerstedtii*, do not occur in the overlying mud (Fig. 5). A similar

275   transplant experiment at Cascadia found that mixing of foraminifera did occur up to 3 cm

276   below the transplanted marsh peat surface, mimicking a preseismic signal (Engelhart et

277   al., 2013). Englehart et al. (2013) cautioned against interpreting microfossil assemblages

278   in such mixed layers as a preseismic signal.

279   **4. Application of diatoms to tsunami studies**

280   *4.1 Paleotsunamis*

281   Sequences of tsunami deposits preserved along subduction zone coastlines can be

282   used to estimate recurrence intervals of tsunamigenic earthquakes over centuries to

283   millennia (Nanayama et al., 2003; Cisternas et al., 2005; Jankaew et al., 2008; Sawai et

284   al, 2012). Stratigraphic sequences, supported by diatom studies, reveal repeated tsunamis

285   in numerous locations including Alaska, the Pacific Northwest of North America, Chile,

286   Japan, New Zealand, and locations bordering the North Sea and the Indian Ocean (Table

287   1, Fig. 2).

288   Allochthonous marine and brackish diatoms within tsunami deposits, including

289   benthic and planktonic taxa, can support a seaward provenance of the sediment (e.g.,

290   Hemphill-Haley, 1995a; Sawai, 2002; Dura et al., 2015). Diatom analysis helped identify

291   the provenance of three sand beds recovered from a coastal lake at Suijin-numa, on the

292   subduction zone of the Japan Trench (Sawai et al., 2008). The marine and brackish

293   diatoms (*Diploneis smithii, Delphineis surirella*) within the sand beds contrasted against

294   the freshwater assemblages (*Aulacoseira granulata, A. crassipunctata, Eunotia* spp.) in

295   the under and overlying mud. The middle sand bed at Suijin-numa correlates with the

296   Jogan earthquake in AD 869 (Yoshida, 1906), the presumed predecessor to the 2011

297   Tohoku earthquake. Along the Kuril Trench in northern Japan, Nanayama et al. (2007)

298   used diatoms to identify nine sandy tsunami deposits intercalated with peat. The diatom

299   assemblage within the peats contained freshwater species (e.g., *Eunotia* spp., *Pinnularia*

300   spp.), whereas the sand beds were dominated by marine taxa (e.g., *Delphineis surirella*

301   and *Odontella aurita*). Based on the record of tsunami deposits, the authors estimated a

302   365 – 553 year recurrence interval for large Kuril Trench earthquakes. Later, based on

303   over 60 radiocarbon age estimates, Sawai et al. (2009b) found that the interval between

304   tsunamis on the Kuril Trench ranged from 100 to 800 years, with an average recurrence

305   interval of ~400 years.

306   In the Storegga Slide tsunami[1] deposits in Scotland, Dawson et al. (1996a) found an

307   anomalous marine diatom assemblage with a high occurrence of fragmented diatoms. Up

308   to 90% of valves (60% of which have elongate forms) within the sand bed were

309   fragmented, reflecting the nature of the rapid, turbulent marine incursion of tsunami

310   events (Dawson et al., 1996a; Smith et al., 2004; Fig. 7). Similar preferential

311   fragmentation of diatom valves, in particular elongate forms (>100 μm) has been

312   documented in inferred paleotsunami deposits in the Pacific Northwest of North America

313   (Witter et al., 2009) and Japan (Sawai, 2002). Conversely, anomalously low breakage of

314   diatoms in tsunami deposits has been reported in paleotsunamis from the Pacific coast of

315   Washington State and Puget Sound, USA (Hemphill-Haley, 1996). Hemphill-Haley

316   (1996) suggested that the low breakage of diatoms reflects rapid sedimentation by the

317   tsunamis.

318   Diatoms can be used to estimate tsunami run-up beyond the landward limit of

319   tsunami deposits. Hemphill-Haley (1996) used the distribution of diatoms to show that

320   the inundation area of the tsunami from the AD 1700 Cascadia subduction zone

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

321 earthquake was larger than the distribution inferred from the coarser-grained deposit

322 visible in outcrop. Epipsammic tidal flat diatoms were found about 1 km farther upstream

323 from the landward extent mapped in cores and stream channel outcrops.

324 *4.2 Tsunamis of the past two decades*

325   Diatom analysis of recent tsunami deposits provides modern analogues for

326 reconstructing the fossil record. Recent studies characterized the diatom composition of

327 the 1998 Papua New Guinea (Dawson, 2007), 2004 Indian Ocean (Sawai et al., 2009a;),

328 2009 South Pacific (Chagué-Goff et al., 2011), 2010 Maule Chile (Horton et al., 2011;

329 Garrett et al., 2013), and 2011 Tohoku (Szczuciński et al., 2012b; Sawai et al., 2012)

330 tsunamis. Analyzing the diatom signature of recent tsunamis can be used to infer the

331 sedimentation (e.g., high-energy deposition), sediment provenance, and inundation limits

332 of the events.

333   The taphonomy of diatom valves may indicate the mode of sedimentation of a

334 tsunami. Dawson (2007) explored the condition of diatom valves in the 1998 Papua New

335 Guinea tsunami deposit and found that linear, sigmoid, and clavate diatoms were more

336 readily fragmented during the high-energy tsunami due to their relatively fragile valve

337 structure. In contrast, high abundances of taphonomically unaltered (i.e., pristine) diatom

338 valves were found in tsunami deposits from the 2004 Indian Ocean tsunami in Thailand

339 (Sawai et al., 2009), and the 2010 Maule tsunami in Chile (Horton et al., 2011).

340   The upward fining of grain size observed in tsunami sands may be reflected by

341 similar grading of diatom valves, a result of the variable flow speed of a tsunami

342 (Gelfenbaum and Jaffe, 2003). In Thailand, the 2004 Indian Ocean tsunami deposit

343 consisted of a sand bed with a thin mud cap and contained mostly beach and subtidal

344   diatoms (>80%) and very few freshwater species (Fig. 8; Sawai et al., 2009a). The lower

345   section of the deposit was dominated by larger epipsammic marine diatoms, whereas the

346   middle section contained abundant marine planktonic species, and the mud cap was

347   dominated by a mixture of smaller freshwater, brackish, and marine species. Diatom

348   analysis by Chagué-Goff et al. (2011) following the 2009 South Pacific tsunami deposit

349   in Samoa, Horton et al. (2011) following the 2010 Maule tsunami in Chile, and

350   Szczuciński et al. (2012b) following the 2011 Tohoku-Oki tsunami on the Sendai plain

351   also revealed grading of diatom valves.

352   Diatoms recovered from tsunami deposits perpendicular to the coast show variable

353   concentration, ecology, and taphonomy related to the provenance of material.

354   Szczuciński et al. (2012b) found that within 1 km of the coast, the Tohoku-Oki sand beds

355   were derived mainly from the beach and coastal dunes, and because such sediments were

356   devoid of diatoms, the assemblage within the tsunami sediments was composed of a low

357   concentration of fragmented freshwater and few brackish species sourced from the

358   coastal plain. Further inland the diatom concentration within the tsunami sediments

359   increased, and the assemblage and condition of valves in the deposit (% fragmentation of

360   valves) were very similar to the valves in the underlying soil and nearby freshwater canal,

361   suggesting that the sediment was locally sourced and not transported from the coast

362   (Szczuciński et al., 2012b).

363   Chagué-Goff et al. (2015) used the diatom assemblages of the 2010 Maule Chile

364   tsunami deposit to trace tsunami inundation beyond the limit of sedimentological

365   evidence. Marine diatoms could be traced ~100 m beyond the inundation limit identified

366   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 data sets that include hundreds of samples taken across multiple local coastal wetlands can fail to provide modern analogues for fossil diatom assemblages (Watcham et al., 2013). This non-modern-analogue 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).

388   *5.2 Response of diatoms to coseismic land-level change*

389   When producing diatom-based estimates of earthquake related land-level change

390   across sharp stratigraphic contacts, a possible delay in sediment deposition and diatom

391   response must be considered. If there is a significant (months to years) hiatus in response

392   following an earthquake, estimates of coseismic deformation will include both coseismic

393   and postseismic deformation, thus they will be minimum estimates (Garrett et al., 2013).

394   Shennan et al. (2014a) found that peat formation following the coseismic uplift of an

395   intertidal mudflat along the eastern Alaska-Aleutian megathrust was not instantaneous,

396   resulting in minimum estimates of uplift. The study also found a mixed salinity diatom

397   assemblage in the upper part of the buried silt that formed as a result of ponding and

398   reworking of the uplifted surface before colonization by terrestrial plants, and likely did

399   not represent the pre-earthquake environment and elevation. In Chile, Garrett et al.

400   (2013) found that uplifted marshes had accumulated little to no sediment up to two years

401   after the 2010 earthquake and tsunami, complicating estimates of coseismic uplift.

402   Coseismic subsidence more often results in rapid sedimentation of clastic sediments

403   hours to weeks after an earthquake, due to the accommodation space created in the

404   submerged marsh (Atwater et al., 2001; Hawkes et al., 2011).

405   *5.3 The production and preservation of diatoms*

406   Diatom-based reconstructions of earthquake-related land-level change and tsunami

407   inundation are hindered by variable diatom production and preservation. In the Copper

408   River Delta, Shennan et al. (2014a) found low numbers of diatoms in modern samples

409   taken from tidal flat silts, a result of high sediment accretion of the delta environment.

410   Silts in fossil sequences also contained few diatoms, which complicated quantitative

411 reconstructions of earthquake-related land-level change (Shennan et al., 2014a). In

412 relatively alkaline and warm environments, there are problems with chemical dissolution

413 of diatom valves (Katamani, 1982; Flower, 1993; Barker et al., 1994). Sawai et al.

414 (2009a) found excellent preservation of diatoms in the 2004 Indian Ocean tsunami

415 deposit in Thailand, but three paleotsunami deposits examined at the same site by

416 Jankeaw et al. (2008) contained no fossil diatoms. Dissolution of diatom valves can also

417 make them more susceptible to fragmentation, complicating the use of the fragmentation

418 metric to infer high-energy deposition during a tsunami. Szczuciński et al. (2012b) found

419 a similar degree of fragmentation in diatoms within the soil underlying the 2011 tsunami

420 deposit and within the deposit itself.

421 *5.4 Differentiating autochthonous and allochthonous diatoms*

422 Problems differentiating autochthonous (*in situ*) and allochthonous (transported)

423 diatoms in modern and fossil studies complicate reconstructions. Certain taxa are

424 transported across coastal wetlands and, if included in modern or fossil assemblages,

425 erroneously represent the depositional environment. This problem is common in coastal

426 wetlands where diatom valves are transported from one intertidal floral zone to another

427 by daily tidal currents, or, in colder climates, by ice rafted sediment (Hemphill-Haley et

428 al., 1995a; Hamilton et al., 2005). Hemphill-Haley (1995a) and Sawai (2001b, 2004)

429 suggested several means to distinguish allochthonous diatoms in both modern and fossil

430 assemblages. Planktonic diatoms are considered allochthonous components in modern

431 and fossil coastal wetland assemblages, while benthic taxa (e.g., epiphytic, epipelic and

432 epipsammic types) can be considered as autochthonous (Vos and de Wolf, 1993). Some

433 chain-forming taxa with thickly silicified valves may form prominent allochthonous

434   assemblages. Hemphill-Haley (1995a) excluded the marine tychoplanktonic diatom

435   *Paralia sulcata* from paleoecological interpretations, because its robust valves and long-

436   chained structure allow its valves to be easily floated and transported by tidal currents

437   and deposited far inland in tidal estuaries (Hemphill-Haley, 1995a). Sawai (2001b,

438   2004b) recognized allochthonous distributions of certain epiphytic taxa in the intertidal

439   zone. For example, *Cocconeis scutellum* is an epiphytic species commonly found

440   attached to macrophytes in the intertidal zone. After death, the upper (rapheless) valve

441   that is not attached to the macrophyte may detach and be transported by tidal currents

442   (Sawai, 2004b). As a result, rapheless valves of *C. scutellum* may be found in sediment

443   across the entire intertidal zone, although its habitat is limited to the macrophyte zone

444   (Sawai, 2001b).

445   *5.5 Differentiating tsunami and storm surge deposits*

446   Allochthonous marine and brackish diatoms may be found in storm-surge deposits,

447   making it difficult to differentiate from tsunami deposits in the stratigraphic record (e.g.

448   Liu and Fearn, 2000; Parsons, 1998; Tuttle et al., 2004; Horton et al., 2009). However,

449   coseismic land-level change coincident with anomalous silt and sand beds provides a

450   definitive earthquake source for a tsunami. In Washington State, USA Hemphill-Haley

451   (1995a) identified two coarse-grained silt and sand beds dominated by marine diatoms. A

452   tsunami source was inferred from one bed because it was associated with a sudden

453   change in depositional environment from upland soil to intertidal mud, consistent with

454   coseismic submergence. The other bed within a freshwater upland soil was not associated

455   with a change in stratigraphy and was probably deposited by a storm (Hemphill-Haley,

456   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, 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

480 particular exploring diatoms' relation to salinity and substrate, variable production,

481 preservation, and transport. Examining the response of diatoms to recent earthquake-

482 related land-level change and the character of modern tsunami deposit diatom

483 assemblages will continue to provide analogues for identifying events in the fossil record.

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1370 **Figure captions**

1371 **Figure 1**: Schematic drawing of coseismic uplift (a) and subsidence (b) and

1372 accompanying tsunami inundation.

1373

1374 **Figure 2**: Summary of earthquake and tsunami studies applying diatoms that are

1375 referenced in this paper, and listed in Table 1. (a) In: Indian Ocean; (b) Ja: Japan Trench;

1376 (c) Al: Alaska-Aleutian megathrust; (d) Ca: Cascadia subduction zone; (e) Ch: Chilean

1377 Subduction zone; (f) NZ: New Zealand; NS: North Sea (studies marked with an asterisk

1378 because they are not subduction zone studies); SP: South Pacific; PNG: Papua New

1379 Guinea.

1380

1381 **Figure 3:** Qualitative schematic of the distribution of common diatom species along a

1382 modern salt marsh transect. Typical salinity classes (following the halobian classification

1383 scheme of Hemphill-Haley, 1993) for each environment are shown.

1384

1385 **Figure 4:** Diatoms evaluated relative to modern intertidal zones and stratigraphy at the

1386 Niawiakum River in Washington State, USA. (a) Position of the study area relative to the

1387 Cascadia subduction zone (barbed line), the boundary between North America and Juan

1388 de Fuca/Gorda plates that extends from the northern end of the San Andreas Fault (SAF)

1389 to the southern end of the Queen Charlotte Fault (QCF); (b) Location of the Niawiakum

1390 River Valley, on the eastern side of Willapa Bay; (c) Locations of vertical sections

1391   sampled for diatoms in the Niawiakum River Valley. Sites 1-4 are cutbank outcrops

1392   exposed during low tide; (d) Changes in diatom assemblages within and above a former

1393   upland soil (forming at the transition of extreme high water (EHW) and upland) buried by

1394   coseismic subsidence during a Cascadia subduction zone earthquake in AD 1700.

1395   Changes in diatom assemblages are consistent with an abrupt change from upland forest

1396   to tidal flat or low marsh. (Modified from Hemphill-Haley, 1995a).

1397

1398   **Figure 5:** Diatom analyses during past earthquake cycles on the Alaska-Aleutian

1399   megathrust suggesting preseismic movement. (a) Location of south-central Alaska, USA;

1400   (b) area subsided in the AD 1964 earthquake (Plafker, 1969); (c) Relative sea level (RSL)

1401   changes reconstructed using a diatom-based transfer function; two short periods of

1402   preseismic submergence immediately prior to substantial coseismic subsidence were

1403   recognized at the top of peat units and are highlighted with red arrows. (Modified and

1404   reprinted from Shennan, I., Hamilton, S., Coseismic and preseismic subsidence

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1406   with permission from Elsevier).

1407

1408   **Figure 6:** Example of land-level reconstructions using diatoms in Hokkaido, northern

1409   Japan. (a) Position of study area relative to the Kurile Trench. The solid line with

1410   triangles shows the seaward edge of the subduction zone. The volcanoes responsible for

1411   tephra layers in c and d are shown and rupture areas of instrumentally recorded

1412   earthquakes on the plate boundary off eastern Hokkaido are outlined; (b) Map of

1413   Mochirippu Estuary showing location of stratigraphic cross-section; (c) Stratigraphic

1414   cross-section; (d) Photograph and log of stratigraphy. Example of change from tidal-flat

1415   mud to lowland-forest peat, punctuated by a tsunami deposit and by volcanic ash layers.

1416   (e) Diatom diagram showing the schematic stratigraphy, changes in diatom assemblages,

1417   and the results of diatom-based transfer functions showing the seventeenth-century large

1418   earthquake. Error bars for height estimates span two standard deviations. (Modified and

1419   reprinted from Sawai, Y., Satake, K., Takanobu, K., Nasu, H., Shishikura, M., Atwater,

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1422   with permission from The American Association for the Advancement of Science).

1423

1424   **Figure 7:** Diatom analyses of the Storegga Slide tsunami showing fragmentation of

1425   diatom valves within the high-energy deposit. (a) Location of the Storegga Slides and

1426   sites where evidence for the Holocene Storegga Slide tsunami has been found; (b) Sites in

1427   the United Kingdom where evidence for the Holocene Storegga Slide tsunami may be

1428   found. Numbers correspond to sites discussed in Smith et al., 2004; (c) Diatom summary

1429   diagram from Boreholes 53 and 23 in lower Wick River Valley, Caithness, Scotland

1430   (Dawson et al., 1996). Taxa displayed as % of total valves. (Modified and reprinted from

1431   Smith, D.E., Shi, S., Cullingford, R.A., Dawson, A.G., Dawson, S., Firth, C.R., Foster,

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1437

Figure 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

1460   assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phra

1461   Thong Island, Thailand. Marine Micropaleontology, 73, 70–79, 2009, with permission
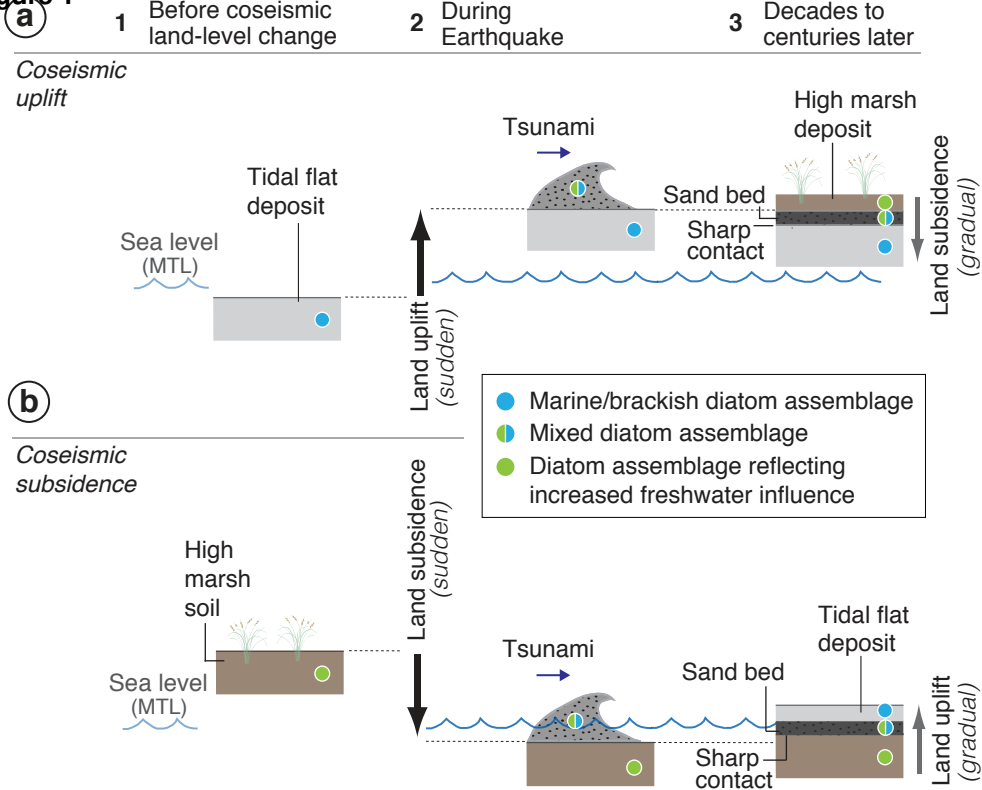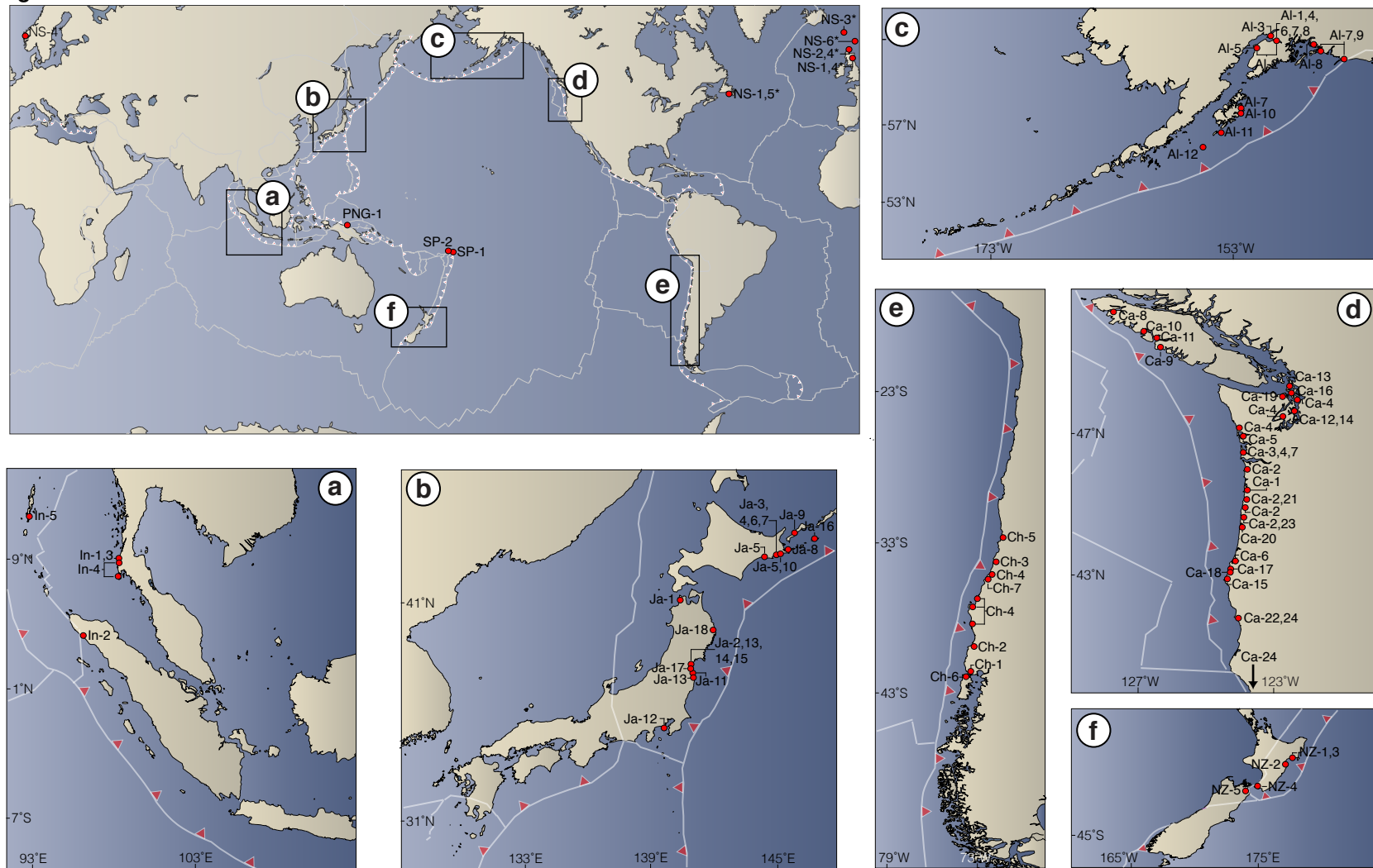
1462   from Elsevier).

1463

Figure 1

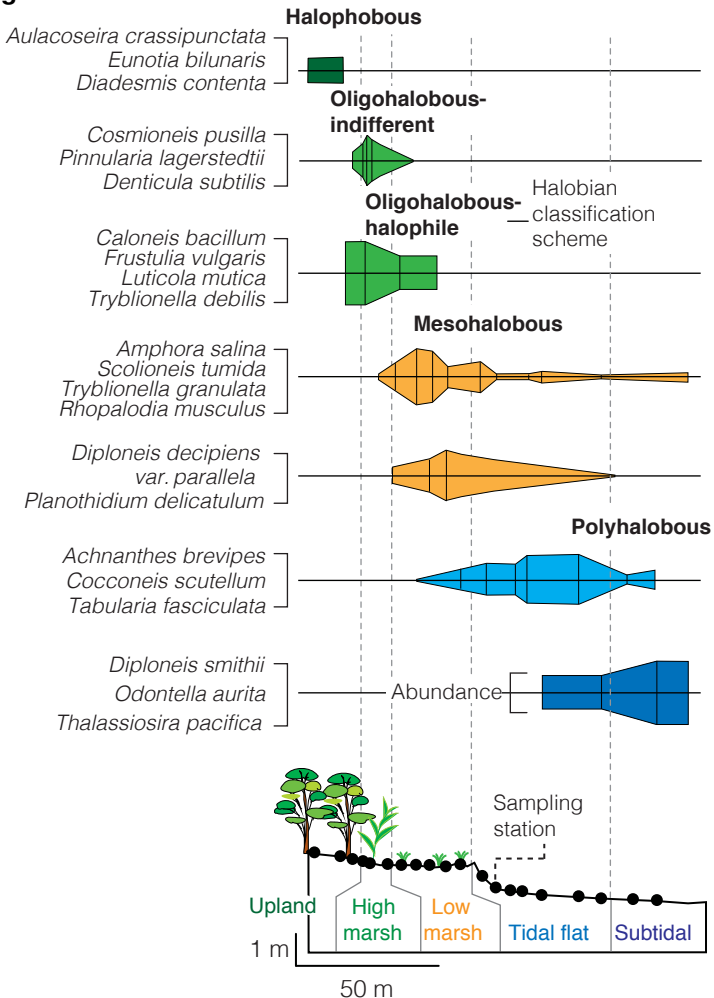**a** | 1 Before coseismic land-level change | 2 During Earthquake | 3 Decades to centuries later

Coseismic uplift

Tsunami
High marsh deposit
Sea level (MTL)
Tidal flat deposit
Sand bed
Sharp contact
Land uplift *(sudden)*
Land subsidence *(gradual)*

b

Coseismic subsidence

Land subsidence *(sudden)*
High marsh soil
Sea level (MTL)
Tsunami
Sand bed
Tidal flat deposit
Sharp contact
Land uplift *(gradual)*

Legend:
- Marine/brackish diatom assemblage
- Mixed diatom assemblage
- Diatom assemblage reflecting increased freshwater influence

Figure 2

Figure 3

Figure 4

Figure panels (a), (b), (c):

(a) **B.C.**, **NAM**, **WA**, *Study Area*, **OR**, **JDF**, **CA**, **PAC**, **GOR**, *Mendocino Fault*, **PAC**, 200 km, 125°W, 50°, 45°, 40°N, SAF, CCF

(b) 123°45'W, *Smith Creek*, 46°45'N, **RAYMOND**, *Willapa R.*, Bone R., **SOUTH BEND**, *Detail in Box c*, **WILLAPA BAY**, North Beach Peninsula, *S. Fork Willapa R.*, 46°30'N, 5 km, N

(c) 123°52.5' W, **Niawiakum River**, Site 1, *Site 2*, Site 3, Site 4, 46°37.5' N, Tidal Flat, Tidal Channel, Marsh, Upland, N, 1 km

(d) Site 2

Columns: Mud flat and *Zostera* beds diatoms; Sand flat diatoms; Low marsh diatoms; Low or high marsh diatoms; High marsh diatoms

Meters above MLLW: 3.1, 3.0, 2.9, 2.8, 2.7, 2.6, 2.5, 2.4, 2.3, 2.2

0   100%   100%   100%   100%   100%

INTERPRETATION

Build up to modern high marsh

Accumulation of deposits at transitional tidal flat to low marsh elevations, with mixed marsh and lower intertidal taxa

Tidal flat deposit (*post-earthquake environment*)

Sand flat diatoms in inferred tsunami sand

Diatoms absent from upland forest soil (*pre-earthquake environment*)

Transition to upland soil; level of paleo-EHW

Diatoms show an abrupt change in environment from upland to tidal flat (minimum change in elevation of ~ 0.8-1.0 m)

Tree root in upland soil

Root

Pre-earthquake EHW based on diatoms
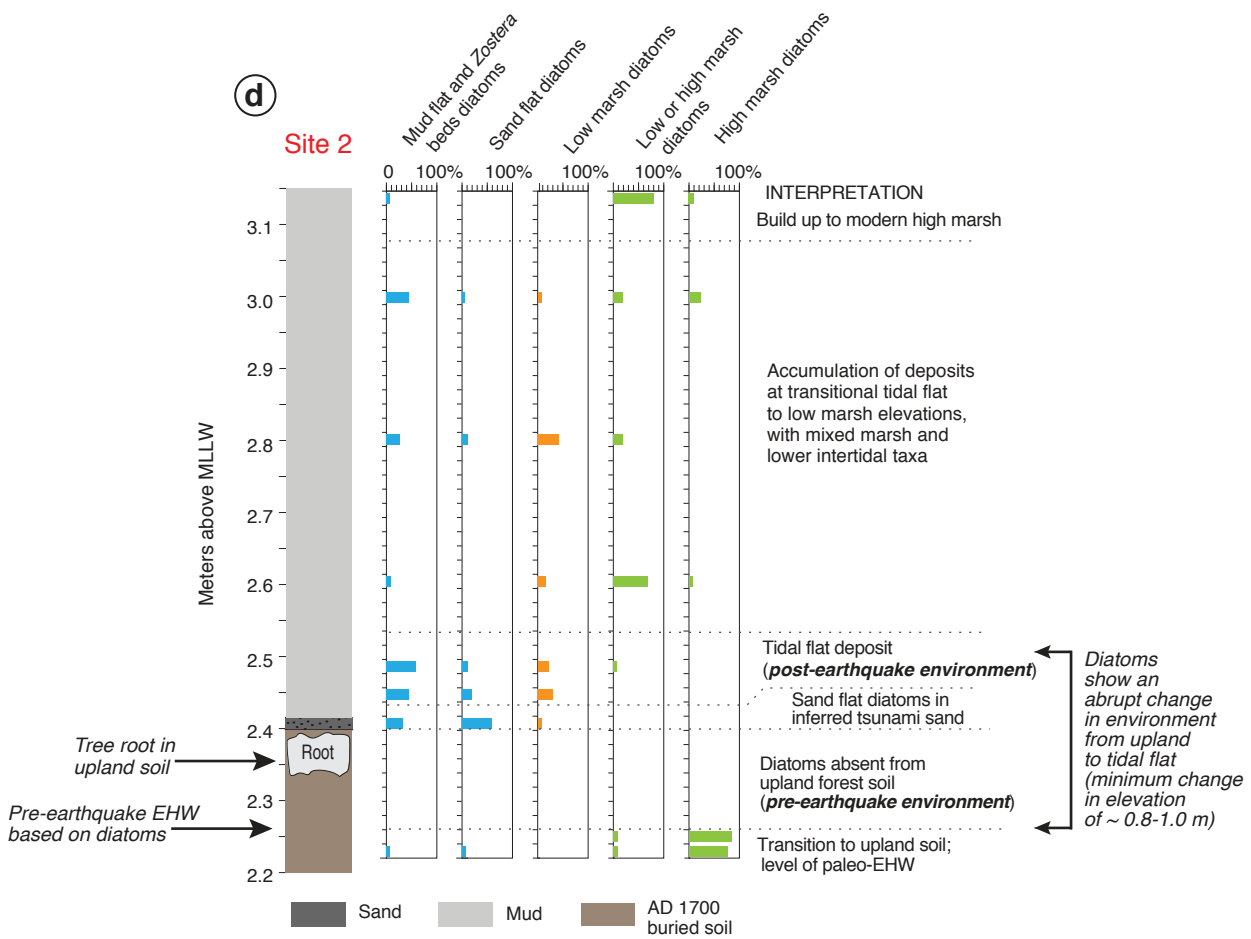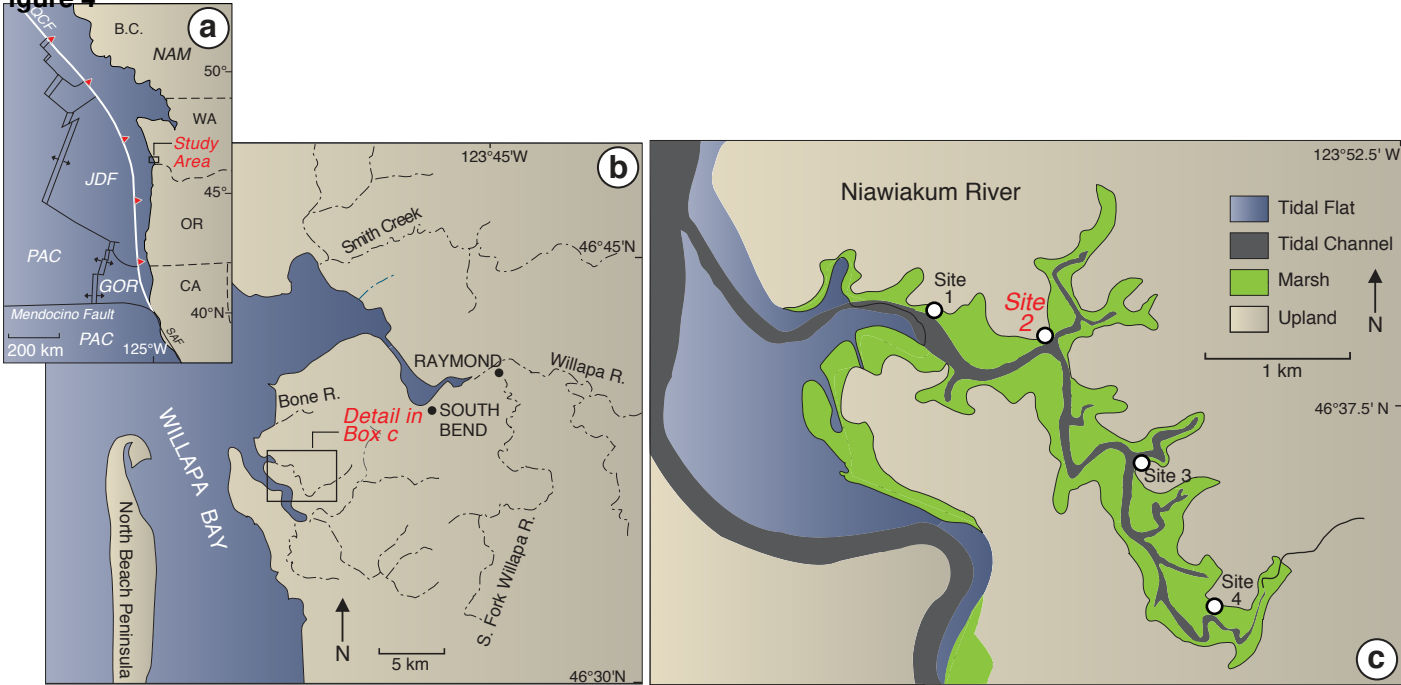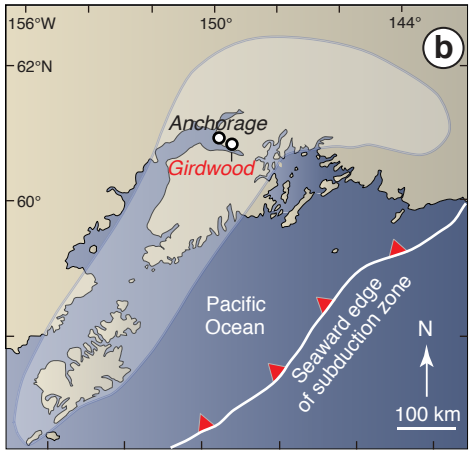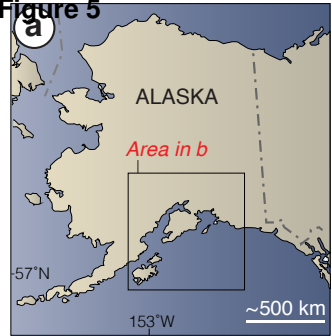
Sand   Mud   AD 1700 buried soil

Figure 5

(a) ALASKA — *Area in b* — ~500 km — 57°N — 153°W

Subsided area in AD 1964 earthquake
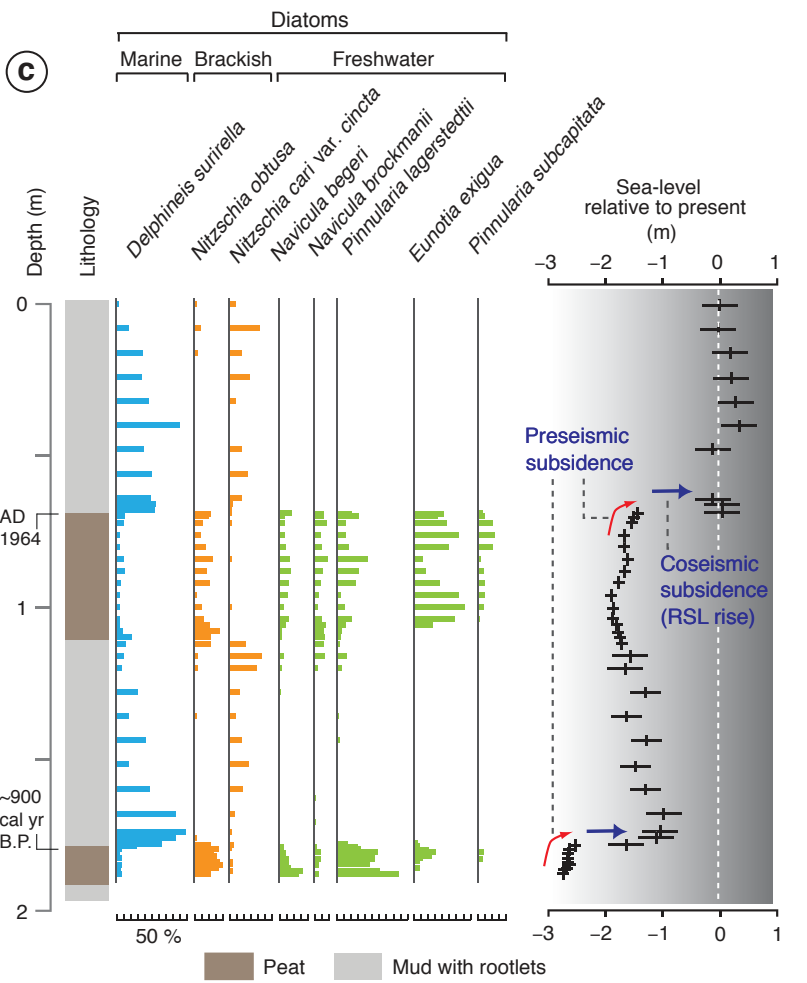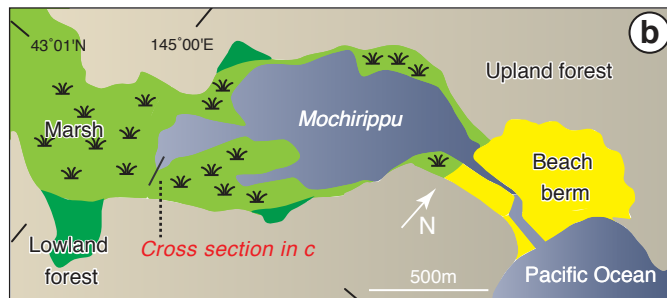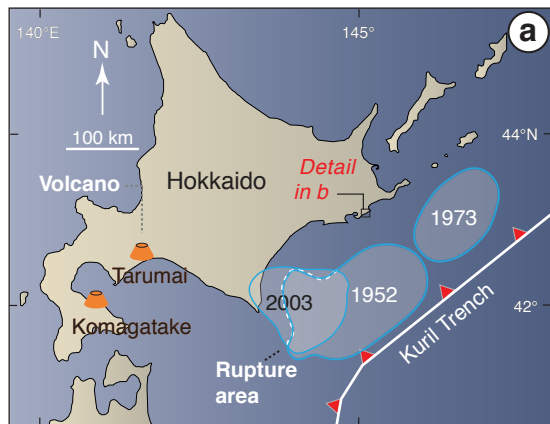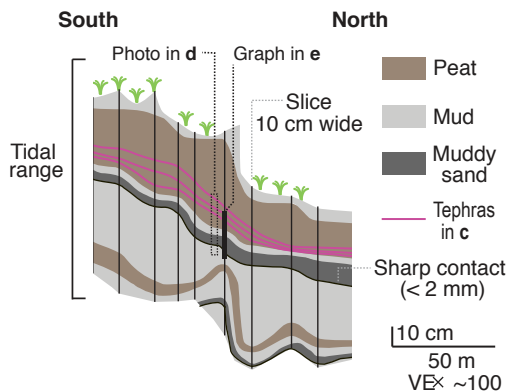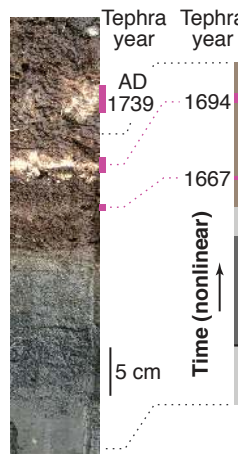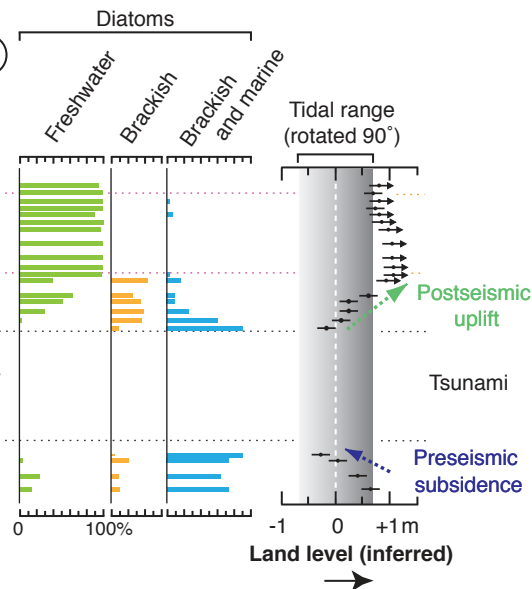
(b) Anchorage — *Girdwood* — Pacific Ocean — Seaward edge of subduction zone — N — 100 km

(c) Diatoms

Marine | Brackish | Freshwater

Delphineis surirella — *Nitzschia obtusa* — *Nitzschia cari var. cincta* — *Navicula begeri* — *Navicula brockmanii* — *Pinnularia lagerstedtii* — *Eunotia exigua* — *Pinnularia subcapitata*

Depth (m) | Lithology

Sea-level relative to present (m)

−3 −2 −1 0 1

AD 1964

Preseismic subsidence

Coseismic subsidence (RSL rise)

~900 cal yr B.P.

50 %

Peat | Mud with rootlets
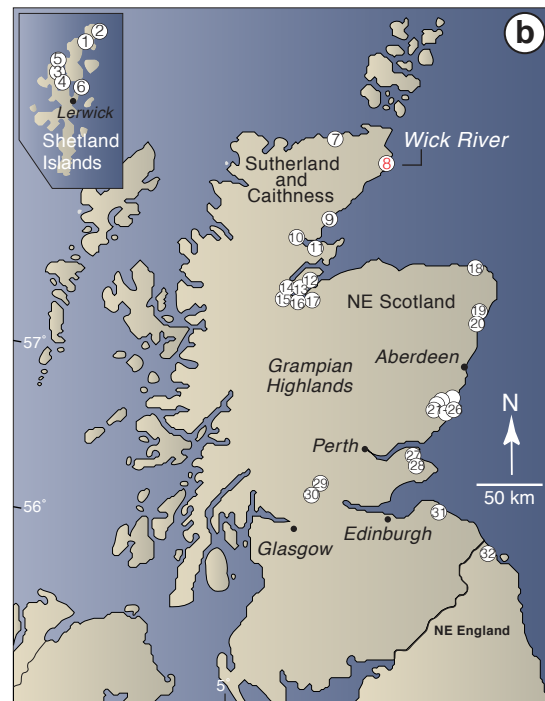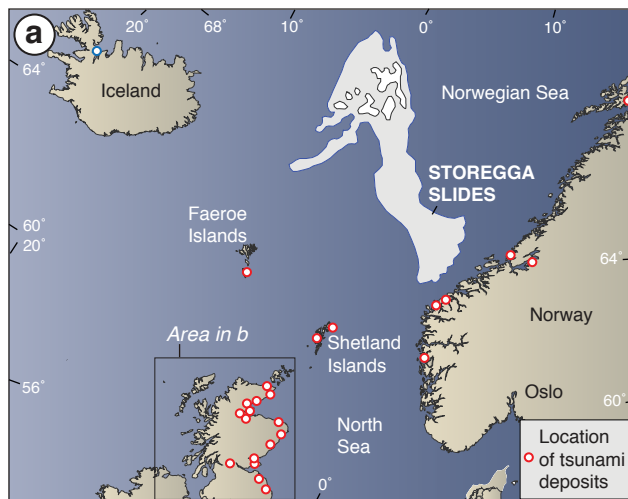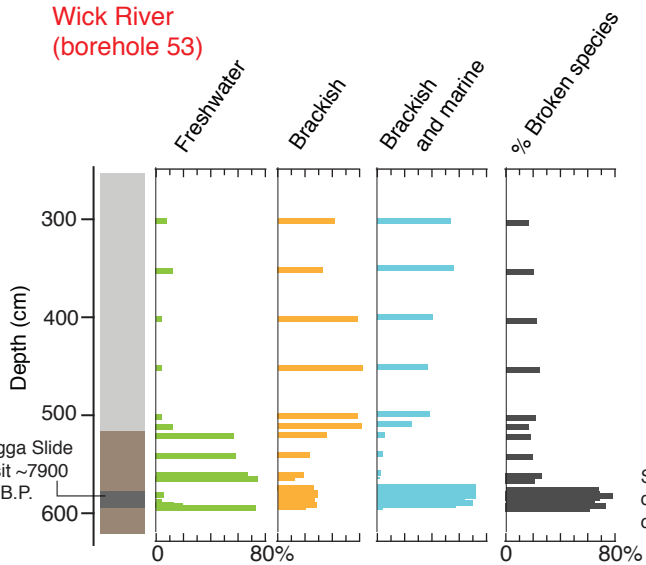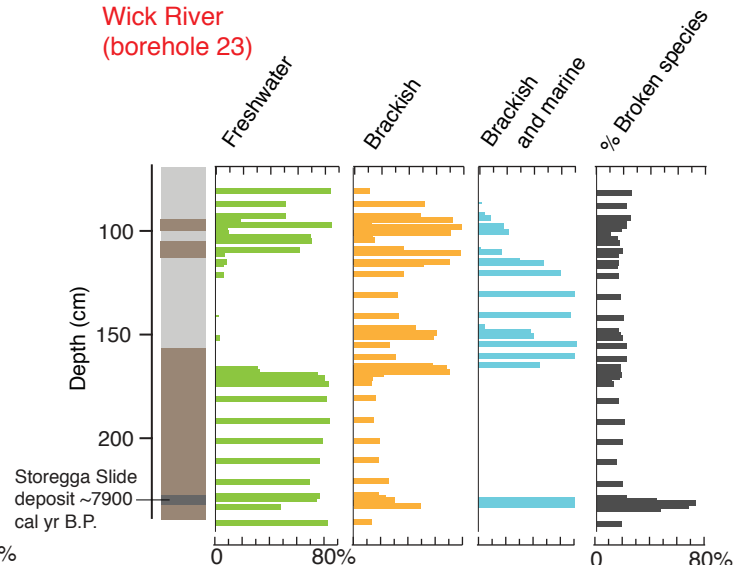
Figure 6

Figure 7

Figure 8

Table

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

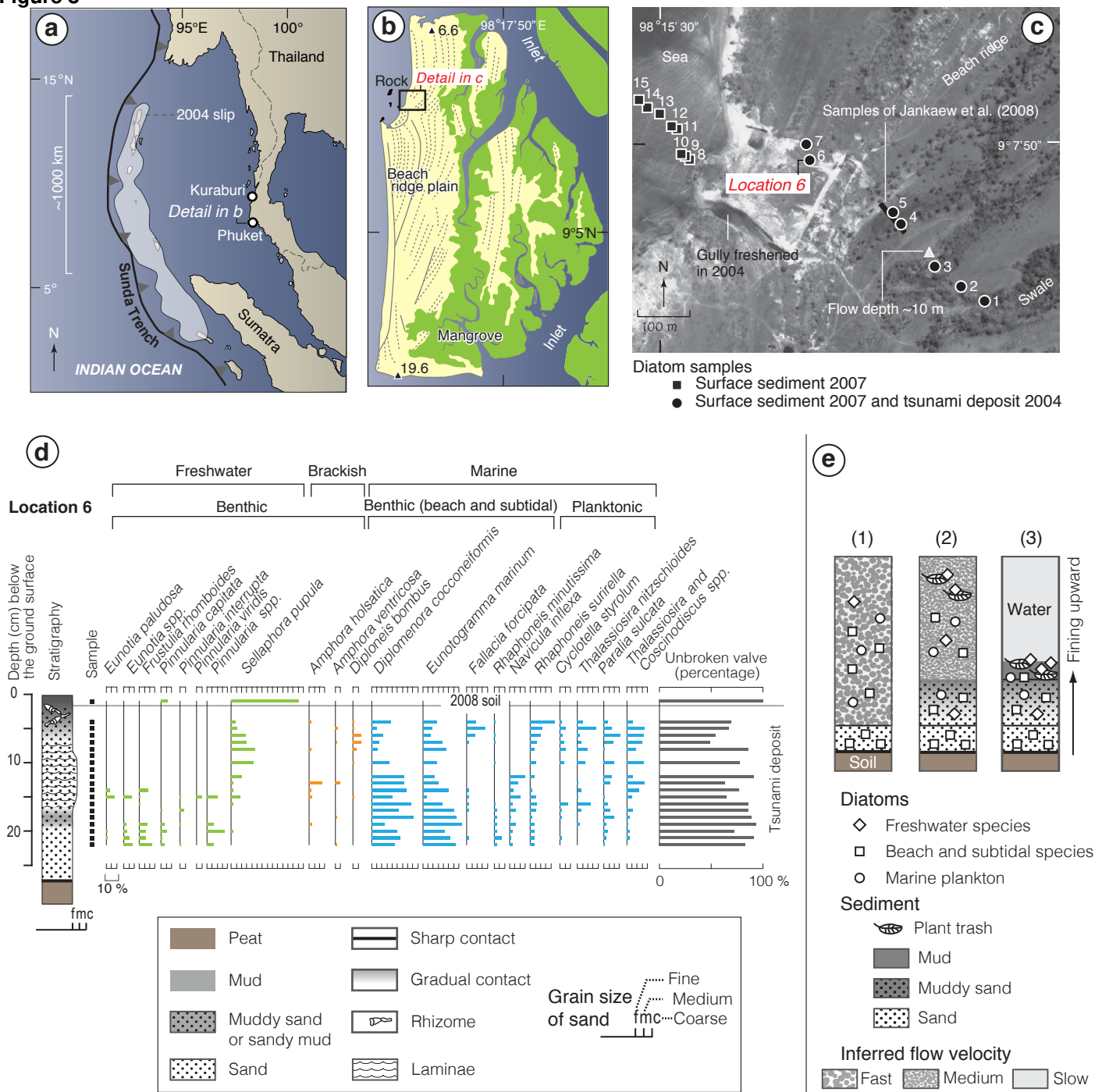| Map code	Earthquake and tsunami studies employing diatoms	Diatom evidence for coseismic land-level change[1]	Accompanying tsunami[2]	Diatom composition of tsunami deposit[3]	Preservation of diatom valves[4]	Concentration of diatom valves[5]
	Alaska					
Al-1	Shennan et al., 1999	Yes (H, Qn)	--	--	--	--
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
	Cascadia					
Ca-1	Darienzo and Peterson, 1990	Yes (P, Ql)	Yes (P)	M&B	--	--
Ca-2	Darienzo 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., 2014	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
	Chile					
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., 2014	Yes (P, Ql)	Yes (P)	M&B (Pl, G)	Poor	Low
Ch-6	Garrett et al., 2014	Yes (H, P, Qn)	Yes (H, P)	M&B (Ep)	--	--
Ch-7	Chagué-Goff et al., 2015	No	Yes (H)	M&B	Poor	Low
	Indian Ocean					
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