

1     **UTILITY OF SALT-MARSH FORAMINIFERA, TESTATE AMOEBAE AND BULK-SEDIMENT**  
2              **$\delta^{13}\text{C}$  VALUES AS SEA-LEVEL INDICATORS IN NEWFOUNDLAND, CANADA**

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24 **ABSTRACT**

25

26 We investigated the utility of foraminifera, testate amoebae and bulk-sediment  $\delta^{13}\text{C}$  measurements for  
27 reconstructing Holocene relative sea level from sequences of salt-marsh sediment in Newfoundland,  
28 Canada. Modern, surface sediment was collected along transects from low to supra-tidal elevations in  
29 eastern (at Placentia) and western (at Hynes Brook and Big River) Newfoundland. Consistent with  
30 previous work, low-diversity assemblages of foraminifera display an almost binary division into a higher  
31 salt-marsh assemblage dominated by *Jadammina macrescens* and *Balticammina pseudomacrescens* and a  
32 lower salt-marsh assemblage comprised of *Miliammina fusca*. This pattern and composition resembles  
33 those identified at other high latitude sites with cool climates and confirms that foraminifera are sea-level  
34 indicators. The lowest occurrence of testate amoebae was at approximately mean higher high water. The  
35 composition of high salt-marsh testate amoebae assemblages (*Centropyxis cassis* type, *Trinema* spp.,  
36 *Tracheleuglypha dentata* type, and *Euglypha* spp.) in Newfoundland was similar to elsewhere in the  
37 North Atlantic, but preservation bias favors removal of species with idiosomic tests over those with  
38 xenosomic tests. The mixed high salt-marsh plant community in Newfoundland results in bulk  
39 surface-sediment  $\delta^{13}\text{C}$  values that are typical of  $\text{C}_3$  plants, making them indistinguishable from freshwater  
40 sediment. Therefore we propose that the utility of this proxy for reconstructing RSL in eastern North  
41 America is restricted to the coastline between Chesapeake Bay and southern Nova Scotia. Using a simple,  
42 multi-proxy approach to establish that samples in three radiocarbon-dated sediment cores formed between  
43 the lowest occurrence of testate amoebae and the highest occurrence of foraminifera, we generated three  
44 example late Holocene sea-level index points at Hynes Brook.

45           **1. INTRODUCTION**

46 In eastern North America, quiet-water coastal environments are occupied by salt marshes that have a  
47 robust and predictable relationship to tidal datums (e.g., Redfield, 1972). These ecosystems respond to  
48 relative sea-level (RSL) rise by accumulating sediment to ensure that the active salt-marsh surface  
49 maintains its tidal elevation, while increasing in absolute elevation relative to a fixed point of reference on  
50 land. Consequently, buried units or sequences of salt-marsh sediment preserve a history of Holocene RSL  
51 changes (e.g., Bloom and Stuiver, 1963, Stuiver and Daddario, 1963). Interrogating this sedimentary  
52 archive to reconstruct RSL relies on the use of sea-level indicators to accurately establish the elevation of  
53 dated paleomorph surfaces with respect to contemporary and modern tidal datums (e.g., Woodroffe and  
54 Barlow, 2015).

55  
56 Sea-level indicators are biological assemblages, chemical signatures or physical features with a known  
57 relationship to tides. In salt-marshes, the most commonly used sea-level indicators are plants,  
58 assemblages of microfossils such as foraminifera (e.g., Edwards and Wright, 2015, Scott and Medioli,  
59 1978), diatoms (e.g., Zong and Horton, 1999, Zong and Sawai, 2015), or testate amoebae (e.g., Barnett et  
60 al., 2016, Charman, 2015) and bulk-sediment geochemistry (e.g., Kemp et al., 2012b, Lamb et al., 2006).  
61 The analogy between modern sea-level indicators and their paleo counterparts is the basis for estimating  
62 the paleo tidal elevation at which a fossil sample formed and subsequently for reconstructing RSL. This  
63 approach is reliant upon the availability of an empirical modern training set comprised of paired  
64 observations that establish and quantify the relationship between a sea-level indicator and tidal datums.  
65 Due to the influence of secondary environmental variables such as the prevailing climate, oceanographic  
66 and salinity regimes, it is usually necessary to develop a modern training set in the region that will be  
67 targeted for reconstructing RSL.

68  
69 Since deglaciation of the Laurentide Ice Sheet (by ~7000 years before present; BP, 1950 CE), the  
70 principal cause of RSL change along the Atlantic coast of North America was ongoing and  
71 spatially-variable glacio-isostatic adjustment (GIA). Earth-ice models predict that the hinge line between  
72 regions experiencing recent RSL rise/fall from GIA occurs close to the Gulf of St. Lawrence (Figure 1;  
73 e.g., Peltier, 2004). Newfoundland is therefore one of the most northerly regions to preserve a salt-marsh  
74 record of RSL rise since the mid-Holocene, which makes it an important location for investigating drivers  
75 of paleo-RSL change that vary with latitude such as ocean dynamics (Ezer et al., 2013, Levermann et al.,  
76 2005, Yin and Goddard, 2013) and the fingerprint of Greenland Ice-Sheet melt (Mitrovica et al., 2011).  
77 We build on previous investigations of foraminifera (Daly, 2002, Daly et al., 2007) to explore the utility  
78 of foraminifera, testate amoebae and bulk-sediment  $\delta^{13}\text{C}$  values as independent sea-level indicators in

79 Newfoundland and to evaluate their use as part of a multi-proxy approach. This work will support future  
80 efforts to reconstruct RSL using salt-marsh sediment. At three sites (Placentia on the Avalon Peninsula  
81 and Hynes Brook and Big River on the Port-au-Port Peninsula; Figure 1) we collected surface sediment at  
82 regular vertical increments to establish the relationship between each type of potential sea-level indicator  
83 and local tidal datums. We demonstrate that foraminifera and testate amoebae are viable sea-level  
84 indicators (with some limitations), while bulk-sediment  $\delta^{13}\text{C}$  values have little utility in this region. An  
85 example RSL reconstruction is produced by application of these sea-level indicators to three  
86 radiocarbon-dated basal salt-marsh peats from Hynes Brook spanning the last ~2000 years. These  
87 reconstructions demonstrate the utility of using a simple, multi-proxy approach to identify material that  
88 formed between the lowest occurrence of testate amoebae and the highest occurrence of foraminifera.

89

## 90 2. REGIONAL SETTING

91 We studied three sites in Newfoundland (Placentia, Hynes Brook and Big River; Figure 1) that were  
92 identified from existing literature as having well-developed modern salt marshes and being underlain by  
93 sediment (high salt-marsh peat) that was likely to yield a viable RSL reconstruction (e.g., Bell et al.,  
94 2005, Brookes et al., 1985, Daly, 2002, Daly et al., 2007, Wright et al., 2011, Wright and van de Plassche,  
95 2001). In some cases, these earlier studies also included analysis of surface foraminiferal assemblages.  
96 These sites experience a maritime climate characterized by short, cool summers (maximum average  
97 monthly warm temperature of ~20 °C in July) and winters in which the average high temperature for  
98 January is approximately -2 °C (Figure 1). The prevailing oceanographic regime brings cold water (the  
99 Labrador Current) to the sites resulting in an average annual sea-surface temperature of ~1 °C in the open  
100 ocean.

101

102 Placentia is located on the Avalon Peninsula in eastern Newfoundland (Figure 1), where salt marshes are  
103 rare. The study site lies on the protected side of a progradational barrier system comprised of vegetated  
104 ridges and swales. It is indirectly connected to the ocean because the 'south arm' is closed off by a gravel  
105 barrier and marine water reaches the site having first entered the back-barrier lagoon and fluvial system  
106 through the open 'north arm'. This geomorphology results in a great diurnal tidal range (mean lower low  
107 water, MLLW to mean higher high water, MHHW) of 0.91 m. The low gravel barrier directly in front of  
108 the salt marsh is overwashed by high tides. Low salt-marsh environments are absent at the site, although  
109 isolated stands of *Spartina alterniflora* are present and rooted in gravel rather than fine-grained sediment.  
110 The high salt-marsh is a diverse, peat-forming community comprised of *Distichlis spicata*, *Spartina*  
111 *patens*, *Juncus gerardi*, *Potentilla* sp., *Plantago maritima*, *Glaux maritima*, and *Carex glareosa*. Within  
112 the high salt-marsh zone these plants form a mosaic pattern and are frequently intermixed, although some

113 mono-specific stands are present. At the upland edge of the salt marsh is a near-vertical slope of  
114 weathered bedrock that is sparsely vegetated by fir trees, pine trees and brambles. At this site, Daly  
115 (2002) described foraminifera in six surface sediment samples spanning an elevational range of ~0.25 m.

116  
117 On the Port-au-Port Peninsula salt marshes occupy three small incised valleys on the sheltered coast of  
118 West Bay that are protected by a beach barrier/spit formation at their entrance (Figure 1). We recovered  
119 samples from Hynes Brook and Big River, which both display a characteristic division of floral  
120 communities into a low salt-marsh zone dominated by *Spartina alterniflora* (tall form) and a mixed high  
121 salt-marsh mosaic comprised of variable combinations of *Iris versicolor*, *Schoenoplectus* spp., *Spartina*  
122 *patens*, *Distichlis spicata*, *Plantago maritima*, *Triglochin maritima*, *Glyceria borealis*, *Glaux maritima*,  
123 *Agrostis stolonifera*, and *Spartina alterniflora* (short form). These species are frequently intermixed,  
124 although some mono-specific stands are present, for example *Iris versicolor* is often the only plant present  
125 at the upper limits of tidal inundation (e.g., Daly, 2002). The great diurnal tidal range at Hynes Brook and  
126 Big River is 1.06 m. At Hynes Brook, Daly (2002) described foraminifera in twelve surface sediment  
127 samples spanning an elevational range of ~0.70 m. Previous studies demonstrated that Hynes Brook is  
128 underlain by sequences of high salt-marsh peat spanning the last ~3000 years (Bell et al., 2005, Brookes  
129 et al., 1985, Daly, 2002, Daly et al., 2007).

130

### 131 3. MATERIALS AND METHODS

#### 132 3.1 Modern sampling regime

133 We described the modern distribution of foraminifera, testate amoebae and bulk-sediment  $\delta^{13}\text{C}$  values  
134 from surface (0–1 cm) sediment samples collected along transects at each of our three study sites (Table  
135 1). Sampling stations were positioned at regular (~5 cm) vertical intervals spanning the full height range  
136 occupied by salt-marsh vegetation to ensure even sampling of the environmental gradient of interest  
137 (elevation). The uppermost samples of each transect were recovered from supra-tidal environments to  
138 capture the highest occurrence of foraminifera (Wright et al., 2011) and the turnover of testate amoebae  
139 assemblages across the upper limit of marine influence (e.g., Barnett et al., 2016).

140

141 Sample heights at each site were surveyed with a total station and are expressed relative to mean tide level  
142 (MTL). Local tidal datums were determined by comparing data from on-site water-loggers (corrected for  
143 the inverse barometer effect) with the closest tide gauge station operated by Fisheries and Oceans Canada.  
144 At Placentia, two water-loggers were installed to quantify the distortion of the tidal wave as it propagates  
145 into the back-barrier system. One logger measured water depths immediately adjacent to the salt-marsh  
146 site, while a second logger was deployed in the open bay beyond the gravel barrier (Figure 1c, d). High

147 and low tides captured by the water-logger in the bay match those measured by the neighboring tide  
148 gauge at Argentia in timing and amplitude. We used hourly water-level measurements from Argentia  
149 spanning the current tidal epoch (1983–2001) to define tidal datums following the definitions provided by  
150 the National Ocean and Atmospheric Administration (NOAA). We then used the difference in water-level  
151 measurements between the salt-marsh and open-bay water loggers to establish local tidal datums at  
152 Placentia by scaling those previously defined for Argentia. For Hynes Brook and Big River, we used the  
153 tidal datums reported in Wright et al. (2011), who employed a similar approach to the one outlined above  
154 using the long-term tide-gauge measurements from Port aux Basques (Figure 1).

155

### 156 3.2 Processing and analysis of surface sediment samples

157 Samples collected for foraminiferal analysis were placed into vials with buffered ethanol and stained with  
158 rose Bengal to allow identification of individuals that were living at the time of collection (e.g., Figueira  
159 et al., 2012). In the laboratory, each sample was washed over 500  $\mu\text{m}$  and 63  $\mu\text{m}$  sieves to isolate the  
160 foraminifera-bearing fraction, from which a minimum of 100 dead individuals were counted in water  
161 under a binocular microscope. We determined the highest occurrence of foraminifera to occur where the  
162 concentration of dead tests decreased abruptly and above which there were insufficient individuals to  
163 reasonably conclude that they represented a viable and *in situ* population. Species were identified through  
164 comparison to published literature (e.g., Edwards and Wright, 2015, Scott and Medioli, 1980, Scott et al.,  
165 1981, Smith et al., 1984, Wright et al., 2011) and type slides from nearby regions. Different taxonomic  
166 approaches to the classification of salt-marsh foraminifera exist, reflecting the extent to which  
167 morphological variation is viewed as phylogenetic or ecophenotypic. While early work combined a range  
168 of forms within the taxon *Trochammina macrescens*, we differentiate between *Jadammina macrescens*  
169 and *Balticammina pseudomacrescens* following (Daly, 2002), de Rijk (1995), Gehrels and van de  
170 Plassche (1999), Wright et al. (2011), in recognition of their spatially distinctive distributions (see  
171 Edwards and Wright, 2015 for discussion). We also distinguished between *Trochammina inflata* and  
172 *Siphotrochammina lobata*.

173

174 At each sampling station  $\sim 2\text{ cm}^3$  of surface sediment was collected and sealed in a bag for subsequent  
175 analysis of testate amoebae following the protocol developed for salt-marsh environments (Barnett et al.,  
176 2013). For each sample, 1  $\text{cm}^3$  of surface sediment was combined in 100 ml of deionized water with one  
177 tablet of *Lycopodium clavatum* to provide an exotic marker of known concentration during counting  
178 (Stockmarr, 1971). The material was heated at 80  $^{\circ}\text{C}$  for one hour on a hot plate and regularly stirred to  
179 aid disaggregation. After being left to soak for >12 hours, the material was wet sieved and the 300-63  $\mu\text{m}$   
180 fraction retained for counting. Samples were mounted onto glass microscope slides using deionized water

181 and observed under 400x magnification. We counted 100 individual tests per sample. Where test  
182 concentrations were <1500 tests per cm<sup>3</sup>, counting ceased after 100 *Lycopodium* spores were counted.  
183 This point marked the lowest extent of testate amoebae occurrence where counts per *Lycopodium* spore  
184 decreased abruptly and below which there were insufficient individuals to reasonably conclude that they  
185 represented a viable and *in situ* population. Our taxonomy is based on the systematic identification keys  
186 of Charman et al. (2000) and Booth and Sullivan (2007). These keys were supplemented by published  
187 literature pertaining to salt-marsh and littoral taxa (Cash et al., 1905, 1909, 1915, Charman et al., 2002,  
188 Gehrels et al., 2006a, Golemansky, 1974, Golemansky and Todorov, 2004, 2007, Nicholls, 2007, 2009,  
189 Ooms et al., 2015, Todorov et al., 2009).

190  
191 Representative sub samples of the surface material were analyzed in duplicate for  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , total organic  
192 carbon (%), and total nitrogen (%). Sediment samples were treated with 10% HCl to remove carbonate,  
193 rinsed to neutral pH with deionized water, and then dried at 50 °C and ground to a fine, homogenized  
194 powder. The samples were analyzed using a Costech 4010 Elemental Analyzer interfaced with a Thermo  
195 Delta V Plus stable ratio mass spectrometer (EA-IRMS) at the University of North Carolina Wilmington.  
196 Isotopic composition is reported in standard  $\delta$ -per mil notation (‰) relative to the Vienna-Pee Dee  
197 Belemnite (V-PDB) standard. Presented results are the average of the duplicate measurements. Repeated  
198 analyses of USGS 40 and 41 glutamic acid standards indicate that the precision of these analyses is better  
199 than  $\pm 0.5$  ‰.  $\delta^{15}\text{N}$ , total organic carbon (%), and total nitrogen (%)

200

### 201 *3.3 Relative sea-level reconstruction*

202 To investigate the utility of foraminifera, testate amoebae and bulk-sediment  $\delta^{13}\text{C}$  values for  
203 reconstructing RSL in Newfoundland, we collected three cores of basal salt-marsh sediment along  
204 transect HBM-2 at Hynes Brook (Figure 1g). The sediments were recovered using a Russian-type corer to  
205 prevent compaction or contamination, and were stored in rigid plastic sleeves, wrapped in plastic and  
206 refrigerated until processing. Each core comprised a single, 50-cm long sequence that captured the  
207 transition from basal consolidated gray silty clay into an overlying dark-brown to black organic silt. One  
208 half of each core was sliced into 1-cm thick contiguous samples for analysis of foraminifera, testate  
209 amoebae and bulk-sediment  $\delta^{13}\text{C}$ . Processing of these samples followed the methods outlined for surface  
210 samples with the exception of adding rose Bengal to the foraminiferal samples.

211

212 The other half of each core provided material for radiocarbon dating which was extracted from the  
213 sediment matrix and cleaned following Kemp et al. (2013c). We selected only samples that were  
214 deposited on, or close to, a paleo marsh surface such as small, horizontal twigs and the shallow rhizomes

215 of identifiable salt-marsh plants. The samples were analyzed at the National Ocean Sciences Accelerator  
216 Mass Spectrometry facility, where they underwent standard acid-base-acid pretreatment and  $\delta^{13}\text{C}$  was  
217 measured directly on an aliquot of  $\text{CO}_2$  collected during sample combustion. Reported radiocarbon ages  
218 were individually calibrated using the Intcal13 dataset (Reimer et al., 2013) and we used the upper and  
219 lower  $2\sigma$  calibrated ages as the range of possible ages for the dated sample.

220  
221 The lowest depth with a viable assemblage of foraminifera and material suitable for radiocarbon dating  
222 was used to produce a sea-level index point from each core. We counted foraminifera and testate amoebae  
223 and measured bulk-sediment  $\delta^{13}\text{C}$  values in additional core samples surrounding the dated level to ensure  
224 that it was representative of the prevailing environmental conditions at the time of sediment deposition.  
225 Relative sea level was calculated by subtracting reference water level (estimated from foraminifera,  
226 testate amoebae and bulk-sediment  $\delta^{13}\text{C}$  values) from measured sample elevation (e.g., Woodroffe and  
227 Barlow, 2015). Vertical uncertainty for the reconstruction was calculated following Engelhart and Horton  
228 (2012), where sample thickness was 0.01 m and we estimated a leveling error of  $\pm 0.05$  m, a benchmark  
229 error of  $\pm 0.1$  m and an angle of coring error that was 1% of depth. Collectively, these cores record the  
230 time-dependent transgression of the site by late Holocene RSL rise

231

### 232 *3.4 Statistical analysis*

233 To objectively distinguish and describe regional microfossil groups using Partitioning Around Medoids  
234 (PAM; e.g., Kaufman and Rousseeuw, 1990, Kemp et al., 2012a), we combined the results from all sites  
235 into a single dataset of foraminifera and a single dataset of testate amoebae. Species counts were  
236 expressed as percentages and samples that yielded zero or low counts were excluded prior to the analysis.  
237 We determined the number of distinct assemblages within each dataset using the maximum average  
238 silhouette width calculated for 2 to 20 groups. Silhouette widths close to 1 (maximum possible value)  
239 indicate that a sample was classified appropriately, while values close to -1 (minimum possible value)  
240 reflect poor classification. This metric aims to minimize within group variance, while maximizing  
241 differences among groups (Rousseeuw, 1987). To investigate the ecological plausibility of our RSL  
242 reconstructions, we measured the (Bray-Curtis) dissimilarity between each microfossil assemblage in the  
243 core samples to their closest modern analog in the modern training sets of foraminifera and testate  
244 amoebae. If the measured dissimilarity was less than the 20<sup>th</sup> percentile of dissimilarity measured among  
245 all possible pairings of modern samples then we deemed the core sample to have an acceptable modern  
246 analog (e.g., Jackson and Williams, 2004, Watcham et al., 2013). Core samples with a measured  
247 minimum dissimilarity that exceeded this threshold were deemed to lack a modern analog.

248



249 To facilitate comparison among sites with different tidal ranges, we standardized elevation using a variant  
250 of the standardized water level index (SWLI) of Horton (1999). We used MTL as the lower datum (SWLI  
251 = 100) and the highest occurrence of foraminifera as the upper datum (SWLI = 200) because Wright et al.  
252 (2011) demonstrated that this approach improved assemblage alignment in higher marsh settings where  
253 the relationship between elevation and inundation is often nonlinear.

254

#### 255 4. RESULTS

##### 256 4.1 Foraminifera

257 The highest occurrence of foraminifera at Placentia was 0.75 m above MTL (PLA-B station 11) and  
258 samples above this elevation on all three transects were devoid of foraminifera (Figure 2). Each of the  
259 three sampled transects displayed a similar distribution of foraminifera. On transect PLA-A samples from  
260 0.41–0.70 m were dominated by *Jadammina macrescens* and *Balticammina pseudomacrescens* (39–98%  
261 when combined). *Trochammina inflata* was an important part of the assemblage (45–73%) at 0.22–0.46 m  
262 MTL and *Miliammina fusca* characterized samples below 0.30 m MTL (more than 25–50%). On transect  
263 PLA-B *Jadammina macrescens* and *Balticammina pseudomacrescens* were the dominant species above  
264 0.69 m MTL (up to 37% and 62% respectively and up to 96% when combined), while *Trochammina*  
265 *inflata* comprised 62–77% of individuals at 0.51–0.63 m MTL. *Miliammina fusca* was rare (<4%), but the  
266 lowest sample on this transect was above MHHW. On transect PLA-C a single sample at 0.68 m MTL  
267 yielded a foraminiferal assemblage that was 34% *Jadammina macrescens* and 64% *Balticammina*  
268 *pseudomacrescens*. *Trochammina inflata* comprised 32–68% of individuals from 0.34 m to 0.55 m MTL.  
269 Assemblages from 0.22 m to 0.43 m MTL included an average of 28% *Miliammina fusca*.  
270 *Haplophragmoides* spp. were absent on all three transects at Placentia.

271

272 Foraminifera along two transects at Hynes Brook (HBM-0 and HBM-2; Table 1) were described by  
273 Wright et al. (2011). Results from a third transect (HBM-1) described here for the first time show a very  
274 similar distribution of foraminifera. The highest occurrence of foraminifera among all three transects was  
275 at 0.90 m MTL (HBM-1 station 9; Figure 3), which is 0.05 m higher than estimated by Wright et al.  
276 (2011) from the smaller dataset. On transect HBM-1 *Jadammina macrescens* (up to 63%) and  
277 *Balticammina pseudomacrescens* (up to 83%) made up the majority of individuals (57–100% when  
278 combined) at 0.50–0.90 m MTL, while *Miliammina fusca* dominated (44–86%) samples from 0.15 m to  
279 0.45 m MTL. *Tiphotrecha comprimata* and *Haplophragmoides manilaensis* were present on HBM-1.  
280 *Trochammina inflata* was absent or rare (maximum abundance of 7.8%) on the three transects from  
281 Hynes Brook.

282

283 The distribution of foraminifera at Big River is largely consistent among transects and there is also a high  
284 degree of similarity to those at Hynes Brook. The highest occurrence of foraminifera among all three  
285 transects was 0.88 m MTL (BRM-2 station 7; Figure 3). On transect BRM-0 elevations above MHW  
286 (0.31–0.86 m MTL) were dominated by *Jadammina macrescens* (up 93%) and *Balticammina*  
287 *pseudomacrescens* (up to 44%; 58–100% when combined), while *Miliammina fusca* was the characteristic  
288 species (53–82%) in assemblages at -0.09 m to 0.26 m MTL. *Tiphotrocha comprimata* was present on this  
289 transect (up to 39%). On transect BRM-1, assemblages of foraminifera from 0.10 m to 0.85 m MTL were  
290 dominated by *Jadammina macrescens* (up to 40%) and *Balticammina pseudomacrescens* (up to 85%;  
291 49–100% when combined). *Miliammina fusca* made up 31–66% of individuals at 0.05–0.20 m MTL. On  
292 transect BRM-2 elevations from 0.33 m to 0.88 m MTL are characterized by high abundances of  
293 *Jadammina macrescens* (up to 62%) and *Balticammina pseudomacrescens* (up to 60%; 41–86% when  
294 combined). Two samples at 0.23 m and 0.28 m MTL are dominated by *Miliammina fusca* (81% and 66%  
295 respectively). The abundance of *Haplophragmoides manilaensis* at Big River demonstrates variability  
296 among transects (maximum abundance of <5% on BRM-0, but up to 49% on BRM-1 and 37% on  
297 BRM-2) as does *Trochammina inflata* (maximum abundance of 29% on BRM-0, 2.5% of BRM-1 and 6%  
298 on BRM-2), which may reflect a patchy distribution (e.g., Kemp et al., 2011, Swallow, 2000) and/or  
299 within site variability of secondary environmental factors such as salinity or sediment texture that were  
300 not measured. Modern foraminifera data are presented in the supporting appendix.

301

#### 302 4.2 Testate amoebae

303 At Placentia the lowest occurrence of testate amoebae occurred below MHHW at 0.30 m MTL (PLA-A  
304 station 23) with lower samples yielding fewer than 9 individuals after counting a sufficient volume of  
305 material to recognize 100 *Lycopodium* spores (Figure 4). Samples above 0.63 m MTL were dominated by  
306 *Tracheleuglypha dentata* (average 16%) and *Euglypha rotunda* type (average 26%). Because the highest  
307 sample on the transect included abundant testate amoebae, the upper limit of this assemblage cannot be  
308 estimated. At 0.30–0.55 m MTL the most abundant species was *Centropyxiella* type (average 33% and up  
309 to 63%). Other common species on PLA-A included *Pseudocorythion* type (up to 30%) and  
310 *Pseudohyalosphenia* type (up to 22%).

311

312 At Hynes Brook testate amoebae were sparse (fewer than 10 individuals per 100 *Lycopodium* spores) at  
313 stations 10–15 and the lowest occurrence of testate amoebae was established at 0.70 m above MTL  
314 (Figure 4), which is slightly above MHHW. At elevations above 0.98 m above MTL, the most common  
315 species are *Trinema lineare* type (17–26%) and *Trinema enchelys* type (23–34%). The samples between  
316 0.74 m MTL and 0.93 m MTL were characterized by an increased abundance of *Euglypha rotunda* type

317 (20% in each of the three samples). The lowest viable assemblage of testate amoebae includes more than  
318 40% *Centropyxis cassis* type.

319  
320 At Big River, the lowest occurrence of testate amoebae was recorded at 0.52 m above MTL (0.01 m  
321 above MHHW) in the sample from BRM-0b station 11 (Figure 5). At elevations from 0.56 m to 1.51 m  
322 MTL, assemblage composition resembles those identified at Hynes Brook, with the most abundant  
323 species being *Trinema lineare* type (up to 25%), *Trinema enchelys* type (up to 30%), and *Euglypha*  
324 *rotunda* type (up to 27%). The samples at 0.52 m and 0.57 m MTL are characterized by increased  
325 abundance of *Centropyxis cassis* type (>34%) and the appearance of *Arcella catinus* (up to 35%) at the  
326 lower limit of testate occurrence. Modern testate amoebae data are presented in the supporting appendix.

327

#### 328 4.3 Regional-scale microfossil distributions

329 We combined the modern foraminifera results from Placentia, Hynes Brook and Big River into a single  
330 dataset comprised of 134 samples (Figure 5). Analysis of this dataset using PAM indicates two plausible  
331 ways to partition the samples. A maximum average silhouette width is returned by dividing the dataset  
332 into two groups based on the relative abundance of *Miliammina fusca* versus *Jadammina macrescens* and  
333 *Balticammina pseudomacrescens*. This pattern describes the universal distinction between low and high  
334 salt-marsh samples. A more nuanced classification is possible by partitioning the regional-scale dataset  
335 into five groups. Group 1 is dominated by *Jadammina macrescens* with correspondingly low occurrences  
336 of *Balticammina pseudomacrescens*. This group is present at Hynes Brook and Big River, but is absent  
337 from Placentia. Group 2 is dominated by *Jadammina macrescens* and *Balticammina pseudomacrescens*  
338 and was present at all sites. Group 3 is a diverse high salt-marsh assemblage in which *Tiphotrecha*  
339 *comprimata* and *Haplophragmoides manilaensis* occur alongside *Jadammina macrescens* and  
340 *Balticammina pseudomacrescens*. This group was present at each of the three study sites. Group 4 is  
341 comprised of low salt-marsh assemblages characterized by high abundances of *Miliammina fusca* and is  
342 absent from Placentia due to the lack of a well-developed low salt-marsh environment at the site today.  
343 Group 5 is dominated by samples from Placentia and captures the uniquely high relative abundances of  
344 *Trochammina inflata* in these transects.

345

346 We combined the samples from Placentia, Hynes Brook and Big River to create a regional-scale dataset  
347 of testate amoebae from 43 modern samples (Figure 5). Partitioning around medoids showed that the  
348 maximum average silhouette width (0.38) occurred when the dataset was divided into two groups and no  
349 finer-scale sub-division is warranted. Group 1 (30 samples) was represented by *Trinema lineare* type  
350 (13%), *Trinema enchelys* type (18%) and *Euglypha rotunda* type (20%). This group was present at all

351 three sites. In contrast, Group 2 (13 samples) only occurred at Placentia and in a single sample from  
352 Hynes Brook (HBM-0b station 11). It is characterized by *Arecella catinus* (discooides group),  
353 *Centropyxiella* type (25%) and *Pseudohyalosphenia* type (Ooms; 22%).

354

#### 355 4.4 Bulk-sediment $\delta^{13}C$ values

356 Despite differences in floral communities and microfossil assemblages, measured bulk-sediment  $\delta^{13}C$   
357 values from each of the three study sites exhibit no consistent trend with station elevation (Figures 2 & 5)  
358 and largely fall in the range of  $-24\%$  to  $-29\%$  (data are provided in the supporting appendix). The  
359 exceptions to this pattern are three stations from the middle of transect PLA-A at Placentia, which  
360 returned values of  $-21\%$  (the maximum typically associated with  $C_3$  vegetation) and  $-15\%$  to  $-17\%$ ,  
361 which is characteristic of  $C_4$  terrestrial plants and also some marine algae (e.g., Lamb et al., 2006). At the  
362 time of sampling these stations were vegetated predominantly by *Spartina patens* (a  $C_4$  plant) and *Juncus*  
363 *gerardii* (a  $C_3$  plant). Despite the presence of  $C_4$  plant species on the salt marshes at each of our study sites  
364 (e.g. *Spartina patens* and *Distichlis spicata*) the pervasive bulk-sedimentary signatures are those  
365 reflecting  $C_3$  plant material (Lamb et al., 2006).

366

#### 367 4.5 Radiocarbon dates and microfossil assemblages

368 We collected three cores from Hynes Brook that were positioned to capture the transition from  
369 coarse-grained clastic sediment to basal organic sediment at different elevations marking the  
370 time-dependent transgression of RSL during the late Holocene (Figure 6). In core HBM-C102 (48.60133  
371  $^{\circ}N$ ; 58.94578  $^{\circ}W$ ) a radiocarbon date from 2.11 m yielded a calibrated age of 2718–2489 years BP ( $2\sigma$   
372 range; Table 2). Foraminifera from the dated interval are comprised almost exclusively of *Jadammina*  
373 *macrescens* and *Balticammina pseudomacrescens*. The most abundant testate amoebae in these samples  
374 were *Centropyxis cassis* type (63–78%) and *Diffflugla lucida* type (10–12%). In core HBM-C103  
375 (48.60135  $^{\circ}N$ ; 58.94575  $^{\circ}W$ ) a radiocarbon date from 0.99 m yielded a calibrated age of 1825–1713 years  
376 BP ( $2\sigma$  range; Table 2). Foraminifera from the dated interval are comprised almost exclusively of  
377 *Jadammina macrescens* and *Balticammina pseudomacrescens*. The most abundant testate amoebae in  
378 these samples were *Centropyxis cassis* type (64–62%) and *Centropyxis platystoma* type (14–34%). In  
379 core HBM-C104 (48.60133  $^{\circ}N$ ; 58.94584  $^{\circ}W$ ) a radiocarbon date from 1.28 m yielded a calibrated age of  
380 1736–1612 years BP ( $2\sigma$  range; Table 2). Foraminifera from the dated interval are 100% *Jadammina*  
381 *macrescens* and *Balticammina pseudomacrescens*. The most abundant testate amoebae in these samples  
382 were *Centropyxis cassis* (54–70%), *Centropyxis platystoma* (6–14%) and *Centropyxis delicatula-ecornis*  
383 (up to 16%). In each core the consistency of microfossil assemblages indicates that no significant  
384 environmental change took place over the period of time represented by the counted samples.

385 Bulk-sediment  $\delta^{13}\text{C}$  measurements from all of the samples in each core yielded values of approximately –  
386 26 ‰. All assemblages of foraminifera had good modern analogs, while all assemblages of testate  
387 amoebae lacked modern analogs due to the high abundance of *Centropyxis cassis* in core samples (54–  
388 78%) compared to the modern dataset (maximum of 43%).

389

## 390 5. DISCUSSION

### 391 5.1 Distribution of salt-marsh foraminifera

392 Some of the earliest investigations into the use of salt-marsh foraminifera as sea-level indicators were  
393 conducted in Nova Scotia (Scott and Medioli, 1978, 1980), where intertidal transects revealed a  
394 characteristic vertical zonation of distinct assemblages. Shallow sub-tidal environments included large  
395 numbers of calcareous species that became scarce in low salt-marsh assemblages dominated by the  
396 agglutinated species *Miliammina fusca*. High salt-marsh environments were dominated by *Jadammina*  
397 *macrescens* with *Trochammina inflata* and *Tiphotrocha comprimata*. A monospecific zone of *Jadammina*  
398 *macrescens* at the transition from salt marsh to upland occupied the narrowest range of elevation and was  
399 consequently deemed to be the assemblage that could produce the most precise RSL reconstruction. Since  
400 this work, the utility of salt-marsh (and mangrove) foraminifera as sea-level indicators has been  
401 reinforced by recognition of vertically-zoned assemblages at sites around the world under a wide range of  
402 climate, salinity and tidal conditions (e.g., Barbosa et al., 2005, Hayward et al., 1999, Horton and  
403 Edwards, 2006, Horton et al., 2005, Leorri et al., 2008, Patterson et al., 2005, Scott et al., 1996, Spencer,  
404 2000). However, the composition of high salt-marsh assemblages in particular varies among (and within)  
405 regions, as do the specific elevation of boundaries between zones (e.g., Edwards and Wright, 2015, Kemp  
406 et al., 2009, Wright et al., 2011). This pattern necessitates using an appropriate training set to provide  
407 adequate modern analogs for interpreting assemblages preserved in the sedimentary record (e.g., Edwards  
408 et al., 2004). Since surface and sub-surface assemblages at a site may differ due to environmental change  
409 through time, the search for appropriate modern analogs commonly requires compilation of data from  
410 multiple locations (e.g., Horton and Edwards, 2005). As part of this process, new insights into the ecology  
411 of salt-marsh foraminifera can be gained that may, in turn, improve the quality of foraminifera-based RSL  
412 reconstructions.

413

414 To establish the regional-scale relationship between assemblages of salt-marsh foraminifera and tidal  
415 elevation in Newfoundland we identified five distinctive groups of foraminifera using PAM and by  
416 standardizing sample elevations to account for differences in tidal range among sites (Figures 5 and 7).  
417 The major faunal turnover occurs at ~140 SWLI and is characterized by a transition from a low  
418 salt-marsh assemblage dominated by *Miliammina fusca* (Group 4; 86–140 SWLI) to spatially-variable

419 high salt-marsh assemblages in which *Jadammina macrescens* (Group 1; 134–200 SWLI), *Balticammina*  
420 *pseudomacrescens* (Group 2; 133–200 SWLI), or *Trochammina inflata* (Group 5; 129–184 SWLI) is the  
421 dominant species. Group 3 (111–187 SWLI) straddles the boundary between low and high salt-marsh  
422 assemblages and is characterized by greater species diversity including the presence of *Tiphotrocha*  
423 *comprimata* (all three sites) and *Haplophragmoides manilaensis* (absent at Placentia and rare in parts of  
424 Big River).

425

426 Significantly, Groups 1 and 2 extend over the same vertical range and either may characterize the  
427 uppermost salt-marsh samples. Consequently, when considered as tools for RSL reconstruction, the  
428 distinction between *Jadammina macrescens* and *Balticammina pseudomacrescens* provides little or no  
429 improvement of precision or accuracy over the ‘lumping’ of both species into a single taxon. In  
430 Newfoundland, since no other groups extend to the upper limit of marine influence, relative abundances  
431 of *Jadammina macrescens* and/or *Balticammina pseudomacrescens* greater than ~80% are indicative of  
432 accumulation in the highest salt-marsh environment.

433

434 Group 5 is dominated by *Trochammina inflata* and (with the exception of a single sample at Big River) is  
435 only present at Placentia, suggesting particular suitability to environmental conditions at that site. High  
436 abundances of *Trochammina inflata* coincide with an absence or relative scarcity of *Balticammina*  
437 *pseudomacrescens*, which may reflect differing environmental preferences or competitive exclusion.  
438 Since all of our study sites share a similar atmospheric and oceanographic climate (Figure 1), it is  
439 tempting to ascribe the observed distribution of Group 5 to a prevailing regime of lower salinity at  
440 Placentia. The geomorphology at Placentia restricts direct exchange of water with the ocean and the site’s  
441 position in the south arm likely produces a water mass with lower salinity than at Hynes Brook and Big  
442 River where there is direct access to ocean water and little fluvial input. Furthermore, the steep slopes at  
443 the rear of the Placentia salt marsh cause freshwater to drain directly onto the marsh and at the time of  
444 sample collection we observed several springs at the rear of the marsh that serve to further dilute the  
445 salinity at higher tidal elevations. However, *Trochammina inflata* was not noted elsewhere as a  
446 low-salinity indicator. In fact, *Balticammina pseudomacrescens* and *Haplophragmoides* spp. are more  
447 typically linked to low-salinity conditions (de Rijk and Troelstra, 1997, Edwards and Wright, 2015).  
448 Therefore further work is necessary to distinguish the relative importance of secondary environmental  
449 variables as a cause of among-site and among-transect variability in foraminiferal assemblages.

450

451 The pattern of zonation that we observed at Hynes Brook and Placentia is similar to that described by  
452 Daly (2002), who recognized three groups of foraminifera from a total of 29 surface sediment samples

453 collected at four Newfoundland salt marshes (Hynes Brook, St. Paul's Inlet, Village Cove and Placentia;  
454 Figure 1). The three groups of Daly (2002) are all from high salt-marsh environments because sampling  
455 did not extend below mean high water (MHW). The dominant species in these groups were *Jadammina*  
456 *macrescens* with *Balticammina pseudomacrescens*, *Jadammina macrescens* and *Balticammina*  
457 *pseudomacrescens*. Assemblages of salt-marsh foraminifera in Newfoundland closely resemble those  
458 described at sites in the Canadian Maritimes including, Prince Edward Island (Scott et al., 1981), Nova  
459 Scotia (Scott and Medioli, 1978, 1980, Smith et al., 1984), New Brunswick (Patterson et al., 2004) and  
460 the Magdalen Islands (Barnett et al., 2016). A similar distribution is present in Maine, USA (Gehrels,  
461 1994). We conclude that salt-marsh foraminifera from our three study sites (and others; e.g., Daly, 2002,  
462 Daly et al., 2007) in Newfoundland conform to the pattern of vertical zonation observed in surrounding  
463 regions and confirm that they are viable sea-level indicators in this region. A notable characteristic of the  
464 foraminiferal assemblages from Newfoundland is their low species diversity (e.g., Daly, 2002; Figure 7),  
465 which results in bipartite division of the salt marshes into near-monospecific high and low salt-marsh  
466 assemblages. This pattern is also typical at other high latitude sites in the northern hemisphere that  
467 experience a cold maritime climate such as arctic Norway, (Barnett et al., 2015), Iceland (Gehrels et al.,  
468 2006b), the Aleutian Islands of Alaska (Kemp et al., 2013a), Denmark (Gehrels and Newman, 2004) and  
469 the White Sea (Russia; Kemp et al., Submitted). These low-diversity assemblages stand in contrast to  
470 those from warmer climates along the U.S. Atlantic coast where several studies reported a larger diversity  
471 of species at single sites, but also marked variability in the composition of high salt-marsh assemblages  
472 among sites (e.g., Goldstein and Frey, 1986, Kemp et al., 2009, Kemp et al., 2013d, Wright et al., 2011).  
473 We contend that these differences among regions arise from the climate regime, where cold air and ocean  
474 temperatures limit the diversity of high salt-marsh foraminiferal assemblages to a handful of species,  
475 namely *Jadammina macrescens* and *Balticammina pseudomacrescens*. Additional systematic work is  
476 needed to identify the specific ecological conditions (e.g. water temperature, seasonal air temperature,  
477 frequency and duration of freezing) that drive this geographic gradient in species distributions. If it can be  
478 adequately understood then temporal changes in salt-marsh foraminiferal assemblages may yield insight  
479 into past climates as well as RSL change.

480

## 481 5.2 Distribution of testate amoebae

482 Intertidal testate amoebae were initially identified in Atlantic Canada (Medioli and Scott, 1983), often in  
483 samples of salt-marsh sediment being analyzed for foraminifera (Scott et al., 1983, Scott, 1977, Scott and  
484 Martini, 1982), but it was not until the late 1990s that intertidal environments were systematically  
485 sampled for testate amoebae in order to establish their utility as sea-level indicators (Charman et al.,  
486 1998). Subsequent studies demonstrated that the lowest occurrence of testate amoebae in salt marshes

487 typically occurs at, or slightly below, high tidal datums such as mean high water spring tide or MHHW at  
488 mid-latitude sites in the northern hemisphere (Barnett et al., 2013, Gehrels et al., 2006a, Gehrels et al.,  
489 2001). Similarly, the concentration of testate amoebae in surface sediment samples from Newfoundland  
490 decreased abruptly near MHHW. Typical test concentrations above MHHW were ~2000 to ~5000 tests  
491 per cm<sup>3</sup>, but below MHHW counting statistically significant numbers of testate amoebae became  
492 unviable. This pattern occurs because few taxa are tolerant of the increasingly brackish conditions  
493 experienced below MHHW (Patterson and Kumar, 2002). Therefore the presence/absence of viable  
494 testate amoebae populations is a useful paleo-ecological constraint for establishing if sediment samples  
495 from a core accumulated above/below the lowest occurrence of testate amoebae that occurs close to  
496 MHHW, but whose specific elevation must be established from an appropriate modern training set.  
497

498 Using PAM, we identified two distinct groups of testate amoebae in Newfoundland (Figure 5, 7). Group 1  
499 is characterized by high abundances of *Trinema enchelys* type, *Trinema lineare* type, *Euglypha rotunda*  
500 type and *Centropyxis cassis* type (Figure 5). This group occurred at all sampled elevations at Hynes  
501 Brook and Big River and in the uppermost samples at Placentia. Consequently, it spans a minimum  
502 elevational range of 126–269 SWLI because its lower limit is constrained, but its upper limit is not. These  
503 taxa also dominated similar environments from the nearby Magdalen Islands in the Gulf of St Lawrence  
504 (Barnett et al., 2016) and are widespread in salt marshes throughout the North Atlantic (Barnett et al.,  
505 2013, Charman et al., 2002, Gehrels et al., 2006a, Gehrels et al., 2001, Ooms et al., 2015), suggesting that  
506 certain intertidal taxa may be cosmopolitan in and around salt marshes, although a synthesis of existing  
507 studies, datasets and taxonomies would benefit the development of this proxy for future sea-level  
508 research. Group 2 occurs at Placentia, but not Hynes Brook or Big River. It is comprised of  
509 *Centropyxiella* type, *Pseudocorythion* type, *Pseudohyalosphenia* spp. and *Corythionella* type (Figure 5)  
510 and exists at elevations from 140-187 SWLI (its upper and lower limits are constrained by the modern  
511 dataset). *Centropyxiella* type was also common at comparable elevations in the Magdalen Islands  
512 (Barnett et al., 2016), the UK (Charman et al., 2002) and Norway (Barnett et al., 2013), but sometimes  
513 under different names because the nomenclature for salt-marsh testate amoebae is based on a wide  
514 diversity of literature and has evolved over recent decades. Differences in the lowest occurrence of testate  
515 amoebae and assemblage composition between sites in Newfoundland probably occurs in response to  
516 secondary environmental variables such as salinity, pH and sediment composition (Barnett et al., 2016,  
517 Charman et al., 2002). The geomorphological setting and freshwater input to the marsh at Placentia is the  
518 most likely cause of the differences between sites. Lower salinity as a result of runoff and reduced  
519 penetration of ocean waters at Placentia would provide favorable conditions for testate amoebae at lower



520 elevations than at the other sites. Increased runoff can also be an influence on pH and sediment substrate  
521 that may be additional factors influencing the testate amoebae assemblages (e.g., Charman et al., 2002).

522

### 523 5.3 Bulk-sediment $\delta^{13}\text{C}$ values as a sea-level indicator

524 Salt-marsh plants are sea-level indicators because the varied tolerance of species to the frequency and  
525 duration of tidal inundation results in a systematic pattern of zonation, where low and high salt-marsh  
526 communities at the same site are vegetated by different species (e.g., Eleuterius and Eleuterius, 1979,  
527 Johnson and York, 1915, Redfield, 1972). However, the composition of these zones can vary among sites  
528 as a result of secondary environmental factors such as climate and salinity. On the U.S. Atlantic coast for  
529 example, high salt-marsh environments are typically vegetated by *Spartina patens* and *Distichlis spicata*  
530 at locations north of Chesapeake Bay, while *Juncus roemerianus* occupies this ecological position at  
531 locations to the south (Eleuterius, 1976), until mangroves replace salt marshes in southern Florida (Figure  
532 1).

533

534 As an adaptation to regular submergence, some salt-marsh plants (e.g., *Spartina* spp., *Distichlis spicata*)  
535 utilize the  $\text{C}_4$  (Hatch-Slack) photosynthetic pathway in which fractionation against atmospheric  $^{13}\text{CO}_2$  in  
536 favor of  $^{12}\text{CO}_2$  is less pronounced than in  $\text{C}_3$  (Calvin-Benson) plants such as *Juncus* spp. and the majority  
537 of terrestrial species that live above the highest reach of tides. As a result,  $\delta^{13}\text{C}$  values measured in  $\text{C}_4$   
538 plants are usually less depleted/negative than  $-17\text{‰}$  compared to the VPDB standard, while  $\text{C}_3$  plants  
539 return more depleted/negative values between  $-21\text{‰}$  and  $-32\text{‰}$  (e.g., Lamb et al., 2006). In the organic  
540 salt-marshes of eastern North America, the primary source of sediment is the *in situ* accumulation of  
541 above and below ground biomass from the surface plant community and bulk sediment  $\delta^{13}\text{C}$  values reflect  
542 the dominant plant community at the time of deposition (e.g., Chmura and Aharon, 1995).

543 Post-depositional processes (principally preferential biodegradation of cellulose over lignin) cause  
544 bulk-sediment  $\delta^{13}\text{C}$  values to differ slightly, but systematically, from the parent plant material (e.g.,  
545 Benner et al., 1991, Benner et al., 1987, Ember et al., 1987, Haines, 1976), although this change is not  
546 large enough to prevent distinction between  $\text{C}_3$  and  $\text{C}_4$  plants. The use of bulk-sediment  $\delta^{13}\text{C}$  values as a  
547 sea-level indicator is reliant upon salt-marsh environments being dominated by  $\text{C}_4$  plants such as *Spartina*  
548 *patens* and *Spartina alterniflora*, which enables them to be readily and objectively distinguished from the  
549 surrounding  $\text{C}_3$ -dominated freshwater upland environments. For example, peat-forming communities  
550 between MTL and MHHW in New Jersey are vegetated almost exclusively by *Spartina* spp. and  
551 *Distichlis spicata* resulting in bulk-sediment  $\delta^{13}\text{C}$  values that are less depleted than  $-18.9\text{‰}$ , while  
552 elevations above MHHW (including those without marine influence) had bulk-sediment  $\delta^{13}\text{C}$  values more  
553 depleted than  $-22\text{‰}$  (Kemp et al., 2012b). However, sediment more depleted than  $-22\text{‰}$  in which

554 foraminifera are present formed between MHHW and the highest occurrence of foraminifera. This pattern  
555 enabled Kemp et al. (2013b) to reconstruct RSL using bulk-sediment  $\delta^{13}\text{C}$  values, in which the precision  
556 of a multi-proxy approach employing foraminifera and  $\delta^{13}\text{C}$  values was up to 60% better than using  
557 foraminifera alone (Cahill et al., 2016). In contrast, a similar study in North Carolina concluded that  
558 bulk-sediment  $\delta^{13}\text{C}$  values could not be objectively used as a sea-level indicator because the monospecific  
559 high salt-marsh zone is vegetated by the  $\text{C}_3$  species *Juncus roemerianus*, making it indistinguishable from  
560 a freshwater upland (Kemp et al., 2010).

561  
562 In Newfoundland bulk-sediment  $\delta^{13}\text{C}$  values cannot objectively distinguish between material deposited in  
563 a salt-marsh environment and material from the surrounding freshwater uplands that does not have a  
564 systematic relationship to tidal datums (Figures 2 and 4). We therefore conclude that bulk-sediment  $\delta^{13}\text{C}$   
565 values have no utility as sea-level indicators in Newfoundland. Although this is a negative finding for the  
566 potential to reconstruct RSL in our study region, it does help to refine the geographic range of locations  
567 where bulk-sediment  $\delta^{13}\text{C}$  values could be utilized. Eleuterius (1976) found that 49–77% of salt-marsh  
568 area in North Carolina was vegetated by *Juncus roemerianus* ( $\text{C}_3$  species) compared to <10% in Virginia  
569 and Maryland and <0.1% in Delaware, where the high salt-marsh zone is almost exclusively comprised of  
570 *Spartina patens*, *Spartina alterniflora* (short form) and *Distichlis spicata* (all  $\text{C}_4$  species). Therefore we  
571 propose that the southern limit for using bulk-sediment  $\delta^{13}\text{C}$  values as a sea-level indicator on the Atlantic  
572 coast of North America is close to Chesapeake Bay (Figure 1). On the U.S. Atlantic coast most high  
573 salt-marsh environments in New England are solely vegetated by  $\text{C}_4$  plants (e.g., Niering and Warren,  
574 1980, Redfield, 1972). Although *Juncus gerardii* becomes a common occurrence in Maine (e.g., Gehrels,  
575 1994, Johnson et al., 2007) and southern Nova Scotia (e.g., Gordon Jr et al., 1985, Pielou and Routledge,  
576 1976, Scott and Medioli, 1980), large areas of high salt marsh are comprised of *Spartina patens*  
577 meadows, suggesting that bulk-sediment  $\delta^{13}\text{C}$  values are likely to remain useful sea-level indicators in  
578 this region. The increased floral diversity of high salt marshes in New Brunswick (e.g., Gehrels et al.,  
579 2006a, Magenheimer et al., 1996), Prince Edward Island (e.g., Scott et al., 1981) and Newfoundland (e.g.,  
580 Brookes et al., 1985; this study) results in a mosaic structure with increasing contributions to the surface  
581 sediment from  $\text{C}_3$  species such as *Juncus* spp., *Triglochin maritima* and *Plantago maritima*. Despite the  
582 observed presence of *Spartina patens* and *Distichlis spicata*, we conclude that this diversity and structure  
583 results in bulk-sediment  $\delta^{13}\text{C}$  values which are characteristic of  $\text{C}_3$  plants. Occasional samples with less  
584 depleted values (e.g., stations 16 and 17 on PLA-A) likely represent persistent, but patchy stands of  $\text{C}_4$   
585 plants. Therefore the utility of bulk-sediment  $\delta^{13}\text{C}$  values is restricted on the Atlantic coast of North  
586 America to regions from Chesapeake Bay to southern Nova Scotia (Figure 1), although it is necessary to

587 recognize that geographic migration of floral zones may have occurred in response to Holocene climate  
588 changes, which should be considered when choosing whether or not to measure  $\delta^{13}\text{C}$  in core material.

589

#### 590 *5.4 Reconstructing late Holocene relative sea level in Newfoundland*

591 We reconstructed RSL at Hynes Brook from three cores of basal sediment by combining the  
592 radiocarbon-dated age of each sample with an estimate of paleo tidal elevation inferred from microfossil  
593 assemblages preserved in core samples (Figure 8). This approach generated one sea-level index point  
594 from each core. Paleo-tidal elevation was estimated from the combined presence of high salt-marsh  
595 foraminifera (*Jadammina macrescens* and *Balticammina pseudomacrescens*) and testate amoebae. Since  
596 the assemblages of testate amoebae lack modern analogs, we conservatively estimate that the dated  
597 samples formed between the lowest occurrence of testate amoebae (0.52 m MTL at Hynes Brook) and the  
598 highest occurrence of foraminifera (0.90 m MTL at Hynes Brook). Each dated sample came from within 5  
599 cm of the basal contact and therefore experienced no, or minimal, post-depositional lowering due to  
600 sediment compaction (Horton and Shennan, 2009).

601

602 The three new sea-level index points were combined with existing and standardized data from southwest  
603 Newfoundland (Love et al., 2016; Figure 8). There is good agreement between these datasets, which  
604 indicate that RSL rose in this region from approximately  $-3.5$  m at 2900 years BP to present. The average  
605 vertical and chronological uncertainty is smaller for the three new sea-level index points than for those in  
606 the existing database. This pattern occurs because the age of our samples was established by radiocarbon  
607 dating of single macrofossils, while some of the existing dates relied on thick sections of bulk sediment  
608 that inherently included material spanning a range of ages. The vertical uncertainty in some of the  
609 sea-level index points from the database is large because information provided in the original publication  
610 was lacking and the data were standardized in a conservative manner (e.g., Engelhart et al., 2011,  
611 Shennan and Horton, 2002). However, our results indicate that a simple multi-proxy approach using the  
612 presence of high salt-marsh foraminifera and testate amoebae can produce precise RSL reconstructions.

613

614 The ecological plausibility of any paleoenvironmental reconstruction generated through reasoning by  
615 analogy relies on their being an appropriate degree of similarity between modern and fossil assemblages  
616 (e.g., Jackson and Williams, 2004). A long-running debate surrounding the use of microfossil groups to  
617 reconstruct RSL is whether to use a local- or regional-scale modern training set to quantitatively interpret  
618 assemblages preserved core samples (e.g., Horton and Edwards, 2005, Kemp and Telford, 2015,  
619 Watcham et al., 2013). Local-scale datasets typically produce more precise reconstructions since the  
620 effect of secondary environmental variables is minimized, while regional-scale datasets provide a broader

621 suite of analogs for generating reconstructions from sites where environmental conditions in the past may  
622 not be the same as those today. The distribution of foraminifera in Newfoundland highlights the necessity  
623 of compiling a regional-scale training set where the goal is to capture the principal surface assemblages  
624 that are present on salt marshes in the region. For example, Placentia possess distinctive microfossil  
625 assemblages (foraminifera Group 5 and testate amoebae Group 2) that are absent from Hynes Brook and  
626 Big River. Although this diversity of modern assemblages was not necessary to accurately reconstruct  
627 RSL from the Hynes Brook cores, it is likely that investigations spanning longer periods of time (and/or  
628 from other sites) will require that a regional-scale training set be available. We conclude that a  
629 regional-scale training set is necessary to capture the range of assemblages of foraminifera and testate  
630 amoebae that are present on modern Newfoundland salt marshes.

631  
632 All assemblages of testate amoebae in the three cores from Hynes Brook lacked modern analogs (Figure  
633 6). The broad, biogeographical similarities between modern intertidal assemblages found in  
634 Newfoundland (this study) and elsewhere in North America (Barnett et al., 2016, Gehrels et al., 2006a)  
635 and Europe (Barnett et al., 2013, Charman et al., 2002, Ooms et al., 2015) suggests that this dissimilarity  
636 between modern and fossil assemblages did not arise from temporal changes in the testate amoebae  
637 population at the study site, unless ecological conditions differed so significantly in the past that Hynes  
638 Brook supported an assemblage that is yet to be observed in modern North Atlantic salt marshes.  
639 Alternatively, the lack of analogy between core and modern samples was caused by preferential  
640 preservation where certain taxa are more or less likely to be lost through time due to differences in test  
641 composition. This hypothesis is supported by comparison of the contemporary and fossil assemblages  
642 from Newfoundland (Figure 9). The modern data contains an abundance of idiosomic genera (tests  
643 composed of proteinaceous secretion and siliceous plates) such as *Arcella*, *Euglypha*, *Pseudocorythion*,  
644 *Pseudohyalosphenia*, *Tracheleuglypha* and *Trinema*. In contrast, these genera are rarely encountered in  
645 the fossil samples, where xenosomic genera (tests formed from agglutinated particles) represent the vast  
646 majority of taxa (e.g., *Centropyxis*, *Cyclopyxis* and *Diffflugia*). Ratios of idiosomic : xenosomic tests are  
647 consistently two or three orders of magnitude greater in the surface assemblages than in fossil  
648 assemblages (Figure 9), suggesting that idiosomic taxa were preferentially lost over time as evidenced  
649 (for example) by the uncharacteristically extreme dominance of *Centropyxis cassis* type (xenosomic test)  
650 in the core samples. Analyses of coastal sediments from the UK reported good preservation of testate  
651 amoebae in supratidal deposits (e.g., raised bogs and lakes), but poor preservation in mid-Holocene  
652 salt-marsh sediments, including a lack of idiosomic genera (Lloyd, 2000, Roe et al., 2002). In contrast,  
653 two short (~100 year) cores of salt-marsh sediment collected in Maine and Nova Scotia to reconstruct  
654 RSL contained preserved idiosomic genera such as *Arcella*, *Euglypha*, *Tracheleuglypha* and *Trinema*

655 (Charman et al., 2010). Conditions in organic salt marshes (e.g., dissolved oxygen concentrations and pH)  
656 are likely to promote loss of idiosomic tests (e.g. through dissolution). For example, Swindles and Roe  
657 (2007) demonstrated experimentally that idiosomic tests were preferentially removed from testate  
658 amoebae assemblages in low pH environments. While idiosomic tests may be preserved for several  
659 hundred years, they can decay over longer time periods. Systematic studies that encompass a  
660 comprehensive range of salt marsh and estuarine environments will greatly elucidate the viability of  
661 testate amoebae as sea-level indicators from a preservation potential perspective. However, the simple  
662 classification of presence or absence used in this study is unlikely to be unduly influenced by preservation  
663 bias between idiosomic and xenosomic tests.

664

## 665 6. CONCLUSIONS

666 Newfoundland is one of the most northern sites at which cores of salt-marsh sediment can yield detailed  
667 RSL reconstructions to investigate physical processes that vary by latitude such as ocean circulation  
668 changes (e.g., Levermann et al., 2005) and the fingerprint of Greenland Ice Sheet melt (Mitrovica et al.,  
669 2011). In support of this work we investigated the utility of foraminifera, testate amoebae and  
670 bulk-sediment  $\delta^{13}\text{C}$  values as sea-level indicators in Newfoundland using modern (surface) sediment  
671 samples collected along intertidal transects at Placentia (eastern Newfoundland) and Hynes Brook/Big  
672 River (western Newfoundland).

673

674 Foraminifera are divided into five distinct groups which primarily discriminate low salt-marsh  
675 environments dominated by *Miliammina fusca* (Group 4) from more diverse high salt-marsh zones with  
676 assemblages dominated by *Jadammina macrescens* (Group 1), *Balticammina pseudomacrescens* (Group  
677 2), or *Trochammina inflata* (Group 5). Group 3 spans the transition between the high and low marsh  
678 groupings and comprises variable abundances of the secondary salt marsh taxa *Tiphotrecha comprimata*  
679 and *Haplophragmoides manilaensis*. Group 5 is only present at Placentia, indicating the potential need to  
680 compile regional-scale modern training sets to capture natural variability within a study region and  
681 maximize the analogy between modern and fossil assemblages. Overall, the distribution of foraminifera  
682 that we observed is similar to previous results from Newfoundland (e.g., Daly, 2002) and more generally  
683 to other sites in the Canadian Maritimes and other high-latitude regions.

684

685 The lowest occurrence of testate amoebae at Hynes Brook and Big River occurs close to MHHW, but is  
686 slightly lower at Placentia reflecting local environmental or taphonomic influences. Idiosomic taxa (e.g.,  
687 *Trinema* spp., *Tracheleuglypha dentate* type, and *Euglypha* spp.), which characterize upper salt-marsh  
688 environments along the east coast of North America were abundant in Newfoundland. However, the

689 difference in the ratio of idisomic and xenomic tests between modern and fossil samples suggests  
690 assemblages of testate amoebae in salt marshes experience preservation bias in which idisomic tests are  
691 preferentially removed. This preservation bias results in a lack of analogy between modern and fossil  
692 assemblages.

693  
694 Bulk-sediment  $\delta^{13}\text{C}$  values cannot be used as sea-level indicators in Newfoundland because salt marsh and  
695 freshwater upland environments yield values that are characteristic of  $\text{C}_3$  plants and that cannot be  
696 objectively distinguished from one another. We propose that the utility of this proxy for reconstructing  
697 RSL in eastern North America is restricted to the coastline between Chesapeake Bay and southern Nova  
698 Scotia.

699  
700 We further tested the utility of these sea-level indicators by applying them to three radiocarbon-dated  
701 cores of basal sediment from Hynes Brook. A simple, multi-proxy classification approach recognized this  
702 sediment as having been deposited between the lowest occurrence of testate amoebae and the highest  
703 occurrence of foraminifera. This interpretation is not effected by possible preservation bias of testate  
704 amoebae in salt marshes. The three new sea-level index points are in agreement with those in an existing  
705 database, but have smaller vertical ( $\pm 0.22$  m) and temporal uncertainties ( $\sim\pm 80$  years).

706

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718 *millennia*”.

719 **Table 1:** Details of modern transects used to characterize the distribution of foraminifera, testate and  
 720 bulk-sediment  $\delta^{13}\text{C}$  values in Newfoundland.

Site	Transect	Year	Analysis	No. S	Range (m MTL)	Reference
Placentia	PLA-A	2015	F, T, $\delta^{13}\text{C}$	25	0.30 to 1.22	This study
Placentia	PLA-B	2015	F, $\delta^{13}\text{C}$	15	0.51 to 1.26	This study
Placentia	PLA-C	2015	F, $\delta^{13}\text{C}$	10	0.23 to 1.21	This study
Hynes Brook	HBM-0	1999	F	25	-0.13 to 0.83	Wright et al. (2011)
Hynes Brook	HBM-0b	2015	T, $\delta^{13}\text{C}$	15	0.24 to 2.16	This study
Hynes Brook	HBM-1	2001	F	24	0.15 to 1.28	This study
Hynes Brook	HBM-2	2001	F	22	0.12 to 1.15	Wright et al. (2011)
Big River	BRM-0	1999	F	25	-0.14 to 1.04	This study
Big River	BRM-1	2001	F	25	0.05 to 1.23	This study
Big River	BRM-1b	2015	T, $\delta^{13}\text{C}$	13	0.42 to 1.51	This study
Big River	BRM-2	2001	F	20	0.23 to 1.16	This study

721  
 722 F = samples analyzed for foraminifera; T = samples analyzed for testate amoebae;  $\delta^{13}\text{C}$  = samples  
 723 analyzed for bulk-sediment  $\delta^{13}\text{C}$  values. No. S = total number of samples on transect (including those in  
 724 which foraminifera were absent).

725 **Table 2:** Radiocarbon ages and relative sea level (RSL) reconstruction from three cores of basal organic  
 726 sediment at Hynes Brook.

Core	Sample Elevation (m, MTL)	Sample ID	<sup>14</sup> C Age	<sup>14</sup> C Error	Indicative Meaning	Sampling Error (m)	RSL (m)
HBM C102	-1.38	OS-123524	2,490	20	LOT-HOF	0.17	-2.09 ± 0.22
HBM C103	-0.25	OS-123656	1,840	20	LOT-HOF	0.17	-0.96 ± 0.22
HBM C104	-0.55	OS-123525	1,770	20	LOT-HOF	0.17	-1.26 ± 0.22

727  
 728 Sample ID is the unique identifier assigned to each reported radiocarbon age by the National Ocean  
 729 Sciences Accelerator Mass Spectrometry facility. Indicative meaning is the tidal elevation at which each  
 730 sample was judged to have formed at based on the presence of both foraminifera (HOF = highest  
 731 occurrence of foraminifera) and testate amoebae (LOT = lowest occurrence of testate amoebae) in and  
 732 around the dated sample. At Hynes Brook and Big River, HOF is at 0.90 m MTL and LOT is at 0.52 m  
 733 MTL, resulting in a reference water level of 0.71 m above mean tide level and an indicative range of ±  
 734 0.19 m. The sampling error for each sea-level index point is the sum of estimated uncertainties for  
 735 leveling (± 0.05 m), benchmarks (± 0.1 m), sample thickness (± 0.01 m) and core angle (1% of depth  
 736 equating to ± 0.01 m for these samples). The RSL error was calculated following Engelhart and Horton  
 737 (2012).



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## FIGURE CAPTIONS

**Figure 1:** Location of study sites in Newfoundland, Canada. (A) Approximate geographic boundaries between regions on the Atlantic coast of North America where high salt-marsh environments are vegetated predominately by C<sub>3</sub> (e.g. *Juncus* spp.) and C<sub>4</sub> species (e.g. *Spartina patens*, *Distichlis spicata*), where salt marshes replace mangroves and regions experiencing uplift or subsidence as a consequence of ongoing glacio-isostatic adjustment. Number sites are locations discussed in text (Daly, 2002; 1 = St. Paul's Inlet, 2 = Village Cove) (B-D) Study site at Placentia, close to the Argentia tide gauge. The site experiences tidal inundation because the open North Arm is connected to the South Arm at the eastern edge of the Placentia peninsula. The gravel barrier in front of the salt marsh is overwashed by high tides. (E-H) Study sites at Hynes Brook and Big River. The location of the Port aux Basques tide gauge is shown. Foraminifera from transects HBM-0 and HBM-2 were originally presented by Wright et al. (2011). Three cores of basal sediment were collected along HBM-2. (I) Monthly average high (H) and low (L) air temperature at Stephenville (1942–2014) and Argentia (1945–2007), calculated from Government of Canada historic climate data.

**Figure 2:** Distribution of foraminifera and  $\delta^{13}\text{C}$  values measured in samples of modern salt-marsh sediment collected along three transects at Placentia, Newfoundland. HOF = highest occurrence of foraminifera, which is the single highest sample from all three modern transects at Placentia to provide a robust and *in situ* assemblage of foraminifera. MHHW = mean higher high water; MHW = mean high water; MTL = mean tide level. Measured, bulk-sediment  $\delta^{13}\text{C}$  values are expressed relative to the Vienna Pee Dee Belemnite (VPDB) standard. Shaded intervals represent values that are typical of salt-marsh sediment from floral zones dominated by C<sub>3</sub> and C<sub>4</sub> plant species.

**Figure 3:** Distribution of foraminifera in samples of modern salt-marsh sediment collected along three transects at Big River and one transect at Hynes Brook in Newfoundland. Foraminifera along two other transects at Hynes Brook (HBM-T0 and HBM-T2) were published by Wright et al. (2011) and are used in our regional compilation of data, but are not presented in detail here. HOF = highest occurrence of foraminifera, which is the single highest sample from the six modern transects at Big River and Hynes Brook to provide a robust and *in situ* assemblage of foraminifera. MHHW = mean higher high water; MHW = mean high water; MTL = mean tide level.

**Figure 4:** Distribution of testate amoebae in samples of modern salt-marsh sediment collected along transect HBM-0b at Hynes Brook, BRM-1b at Big River and PLA-A at Placentia. Panels in the top row

773 show the position of sampling stations along each transect; note that the elevation axes differ among sites.  
774 HOF = highest occurrence of foraminifera; LOT = lowest occurrence of testate amoebae (the sample  
775 below which test abundance was insufficient to represent a viable and *in-situ* assemblage); MHHW =  
776 mean higher high water; MTL = mean tide level. The concentration of testate amoebae per counted spore  
777 of the exotic pollen *Lycopodium clavatum* (row 2) was used to determine LOT. Typically there was an  
778 easily recognizable and abrupt decrease in test concentration at this point from ~0.2 to <0.1. Rows 3–6  
779 show the distribution of the five most abundant species of testate amoebae on each transect, note that the  
780 abundance axes are the same within each transect, but differ among them. The lowest row of panels  
781 presents measurements of bulk-sediment  $\delta^{13}\text{C}$  values. The profile for Placentia is presented in Figure 2.  
782

783 **Figure 5:** Regional-scale modern datasets of foraminifera and testate amoebae from Hynes Brook, Big  
784 River and Placentia in Newfoundland, Canada. **(A)** Average silhouette width calculated by partitioning  
785 around medoids of the foraminifera dataset from which we recognized five distinct groups. **(B)**  
786 Foraminifera dataset divided into five groups and colored by site. Hm = *Haplophragmoides manilaensis*;  
787 Tc = *Tiphotrocha comprimata*. **(C)** Average silhouette width calculated by partitioning around medoids  
788 of the testate amoebae dataset. These results demonstrated that two distinct groups should be recognized.  
789 **(D)** Testate amoebae dataset divided into two groups and colored by site. Po = *Pseudohyalosphenia* type  
790 (Ooms).  
791

792 **Figure 6:** Samples of basal salt-marsh sediment from Hynes Brook that were analyzed to reconstruct late  
793 Holocene relative sea-level. For each of the three cores (C102, top row; C103, middle row; C104 bottom  
794 row), a lithology column shows the position of the basal contact and radiocarbon date with its unique  
795 identifier from the National Ocean Sciences Accelerator Mass Spectrometry facility. Core top elevations  
796 with respect to modern, local mean tide level (MTL) are listed. Abundance of *Jadammina macrescens*  
797 (Jm) and *Balticammina pseudomacrescens* (Bp) are shown in the first column of panels (blue bars).  
798 Dissimilarity between each core sample and its closest modern analog based on foraminifera are shown in  
799 the second column of panels (dashed lines represent values for percentiles of dissimilarity measured in  
800 pairings of modern samples). Abundance of the two most common species of testate amoebae are shown  
801 in the third and fourth columns (red bars; DL = *Diffflugia lucida* type; CP = *Centropyxis platystoma* type;  
802 CD = *Centropyxis delicatula-ecornis* type). Note that the second most abundant species (after *Centropyxis*  
803 *cassis* type) varies among cores. The concentration of testate amoebae is expressed relative to the  
804 frequency of *Lycopodium* spores in the fifth column of panels. The dashed line represents the lowest  
805 concentration in a modern sample that was considered to have a viable and *in-situ* assemblage. Values  
806 exceeding this threshold indicate deposition above the lowest occurrence of testate amoebae.

807 Dissimilarity between each core sample and its closest modern analog based on testate amoebae are  
808 shown in the fifth column of panels (dashed lines represent values for percentiles of dissimilarity  
809 measured in pairings of modern samples). Measured, bulk-sediment  $\delta^{13}\text{C}$  values with respect to the  
810 Vienna Pee Dee Belemnite (VPDB) standard are presented in the final column and the shaded regions  
811 denote the approximate range of  $\text{C}_3$  and  $\text{C}_4$  plants.

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813 **Figure 7:** Relationship between species of modern (A) foraminifera and (B) testate amoebae and tidal  
814 elevation in Newfoundland. Symbol color denotes group membership established by partitioning around  
815 medoids applied separately to the regional modern datasets of each microfossil group. Colored bars at  
816 right show the range of elevations over which each group was found. Arrows indicate groups for which  
817 upper and/or lower limits could not be reliably established. Note that an anomalously low sample from  
818 foraminifera group 5 was discounted in estimating the range of this group. Elevation is expressed as a  
819 standardized water level index (SWLI), where a value of 200 is the highest occurrence of foraminifera  
820 and 100 is mean tide level.

821

822 **Figure 8:** Late Holocene relative sea-level history of southwestern Newfoundland produced using a  
823 standardized database of sea-level index points (Love et al., 2016; open rectangles) and the three new  
824 basal sea-level index points from Hynes Brook (this study; filled rectangles labeled to denote the core  
825 from which each new index point was produced). The study of Love et al. (2016) utilized several earlier  
826 datasets to produce standardized sea-level index points (see references therein).

827

828 **Figure 9:** Ratio of testate amoebae with idiosomic (composed of proteinaceous secretion and siliceous  
829 plates) and xenosomic (formed from agglutinated particles) tests in modern and fossil sediment samples  
830 in Newfoundland. Bars represent modern samples (colored by site), while the blue, shaded region  
831 represents the range of values encountered in core samples from Hynes Brook. The apparent loss of  
832 idiosomic tests is interpreted as preservation bias.

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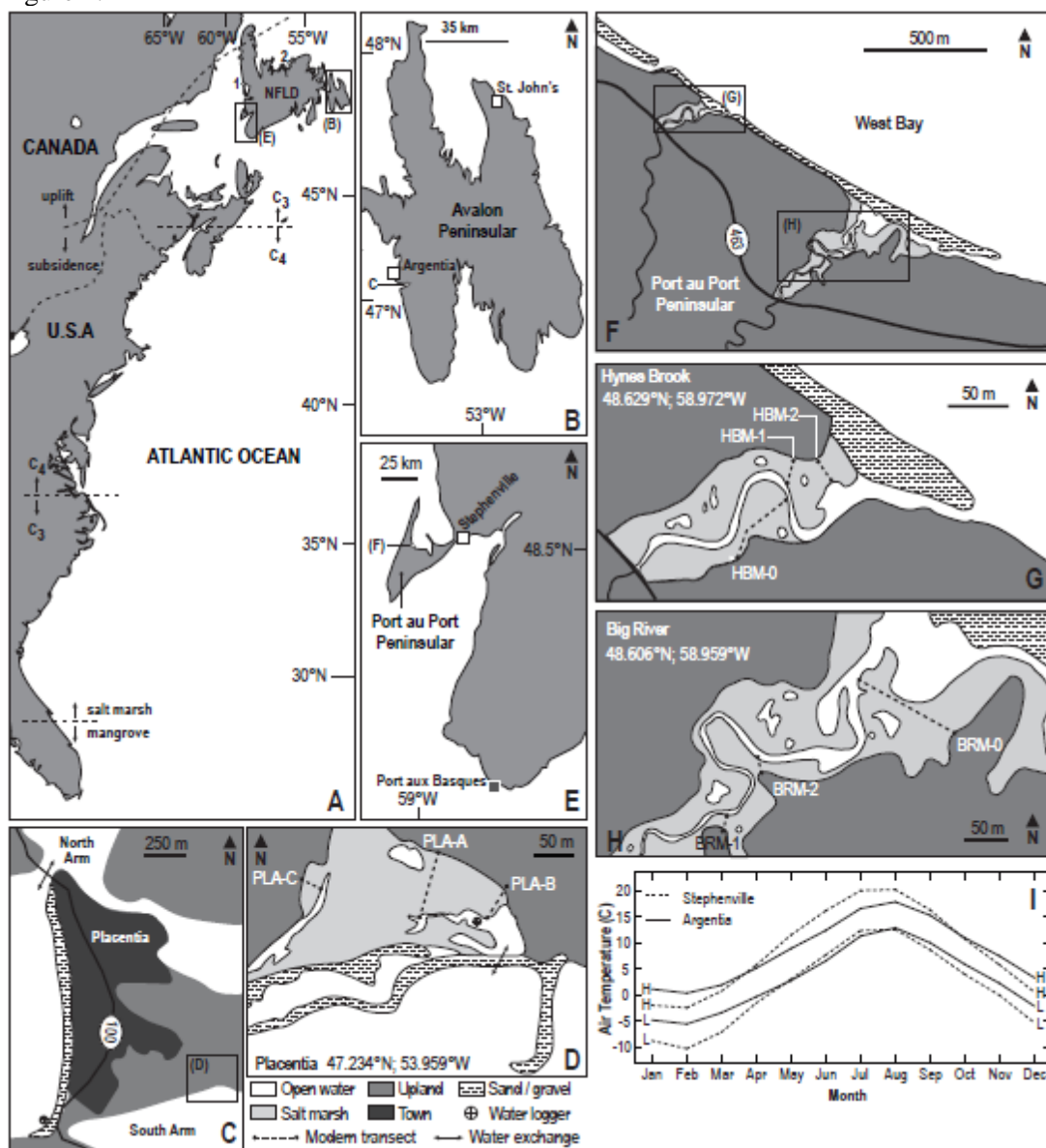


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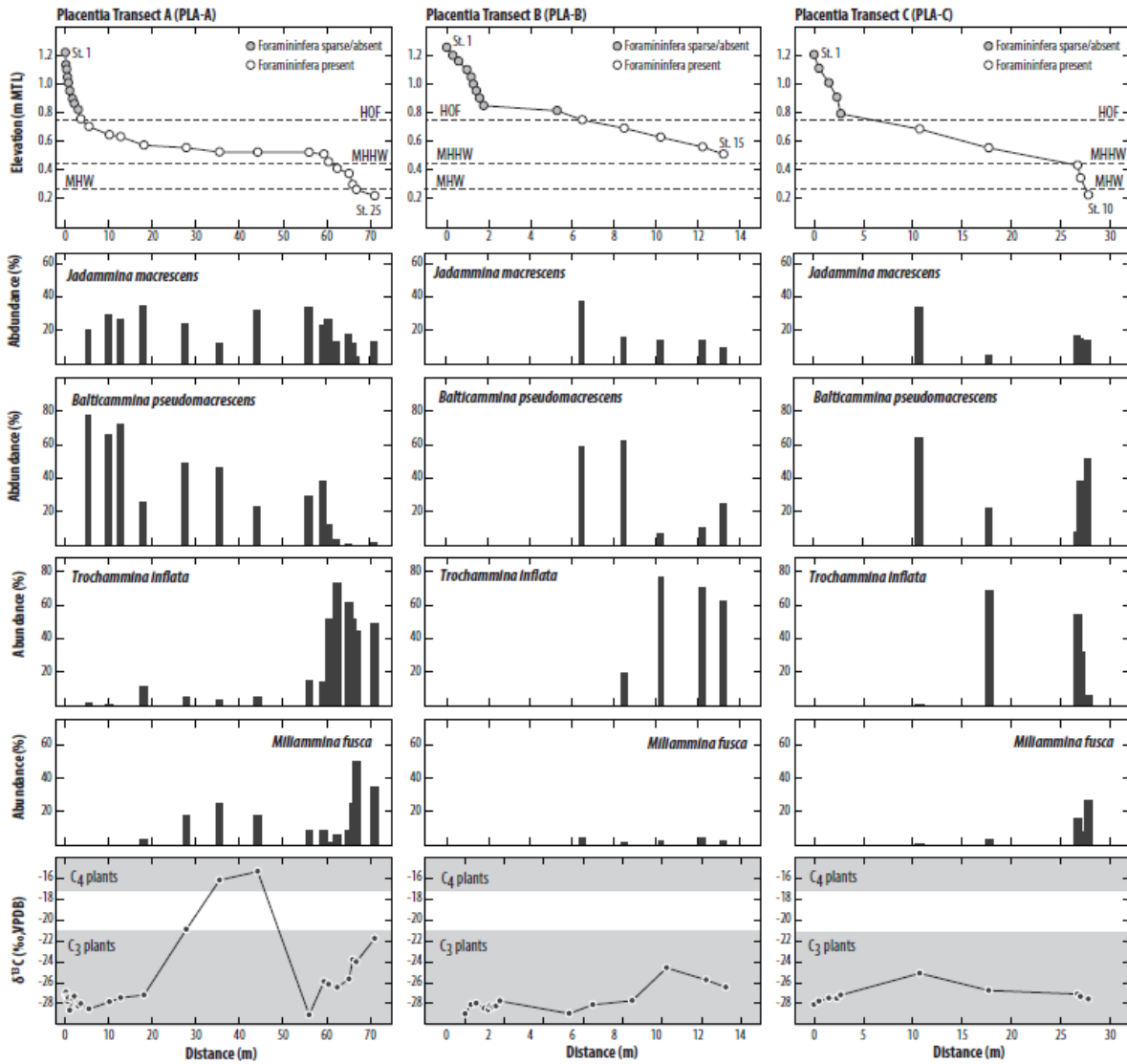
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1091 Figure 1.



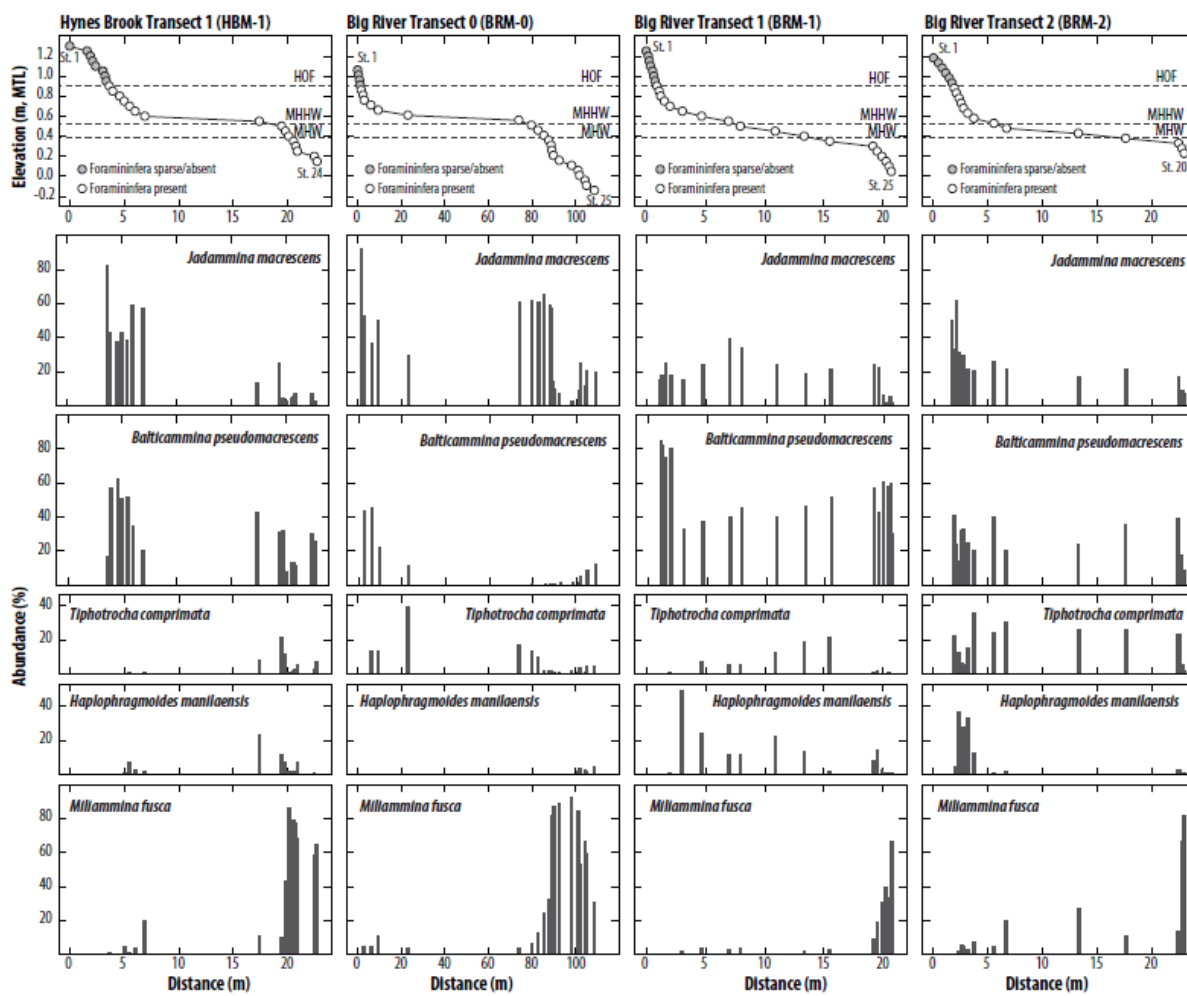
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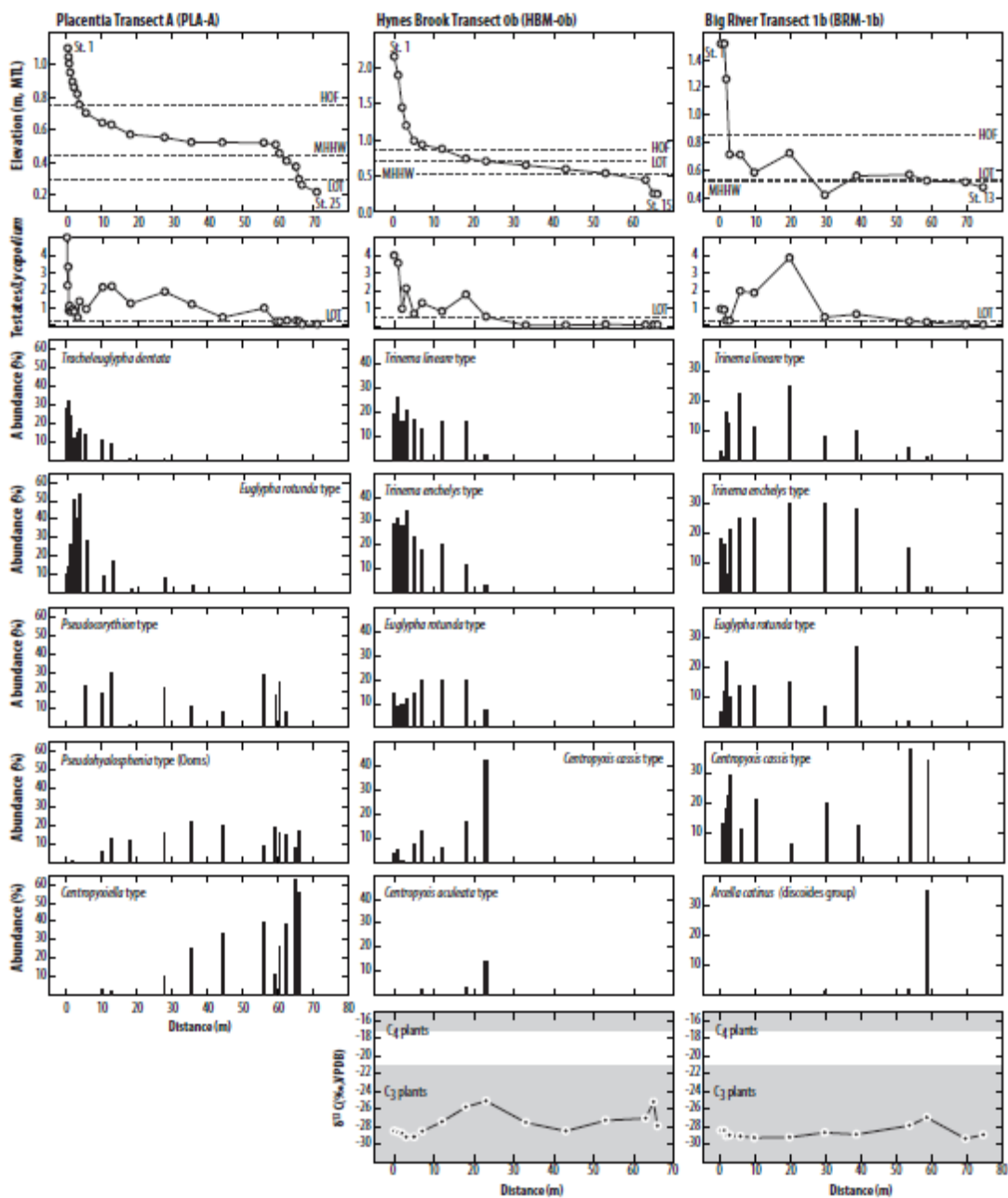
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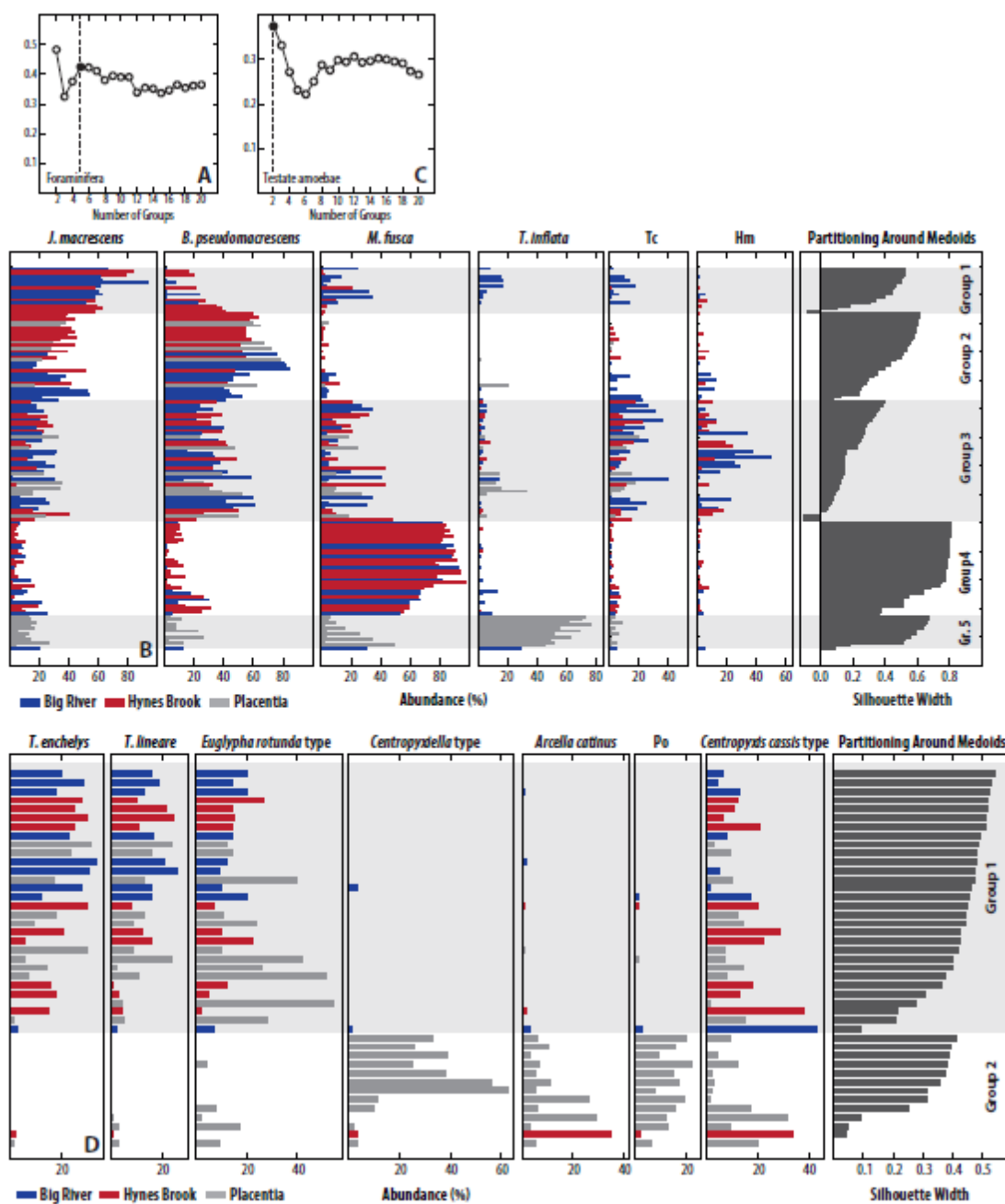
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1100 Figure 4.



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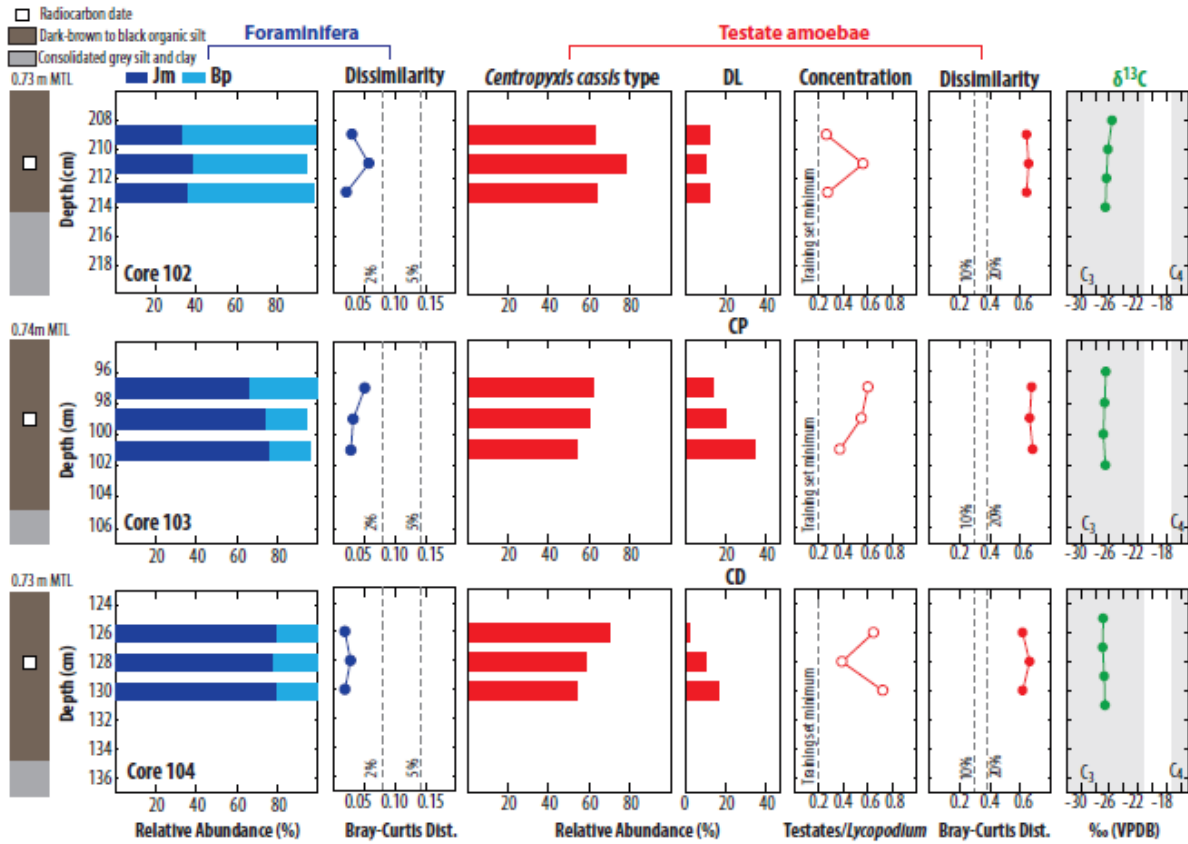
1103 Figure 5.



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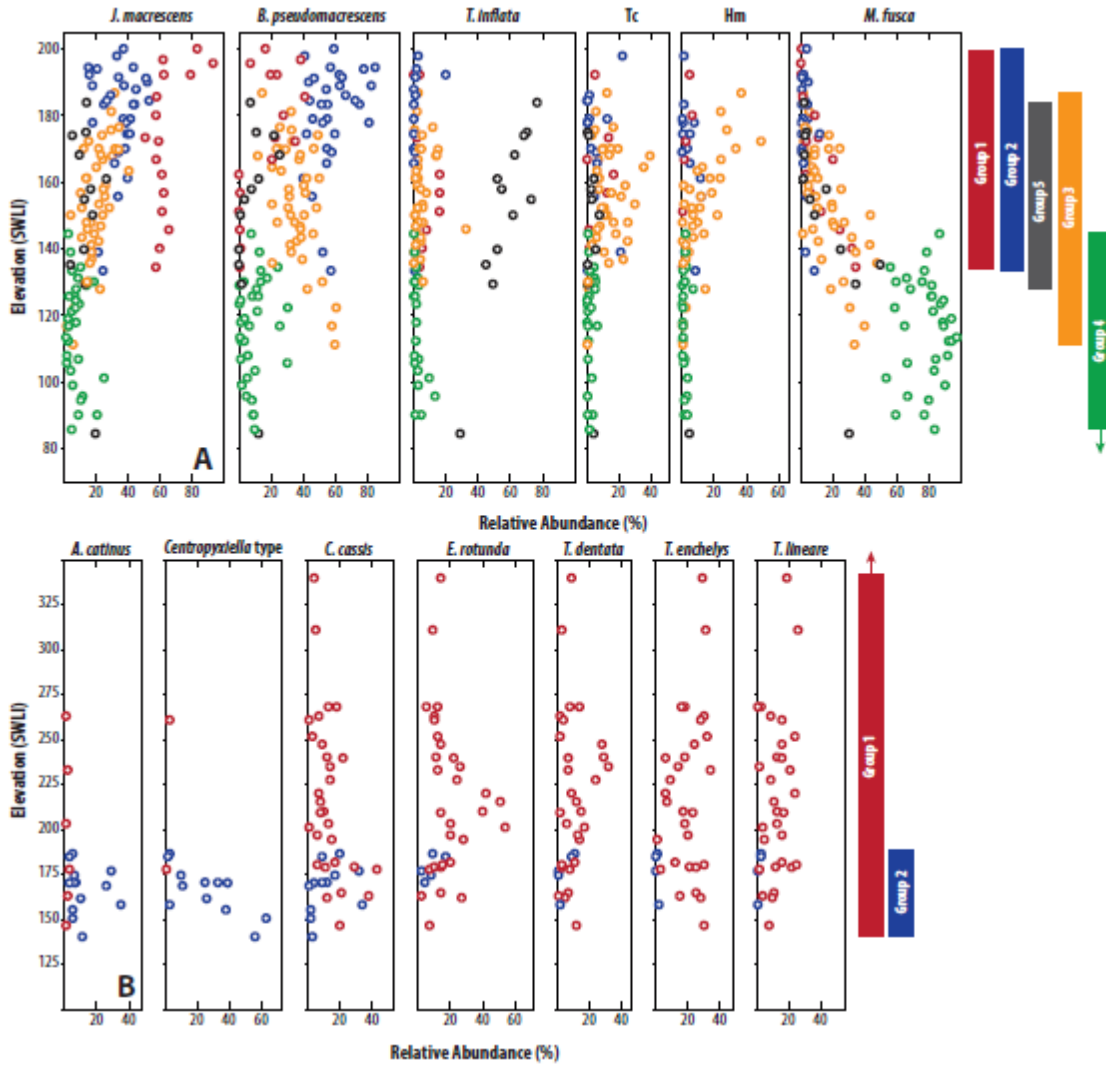


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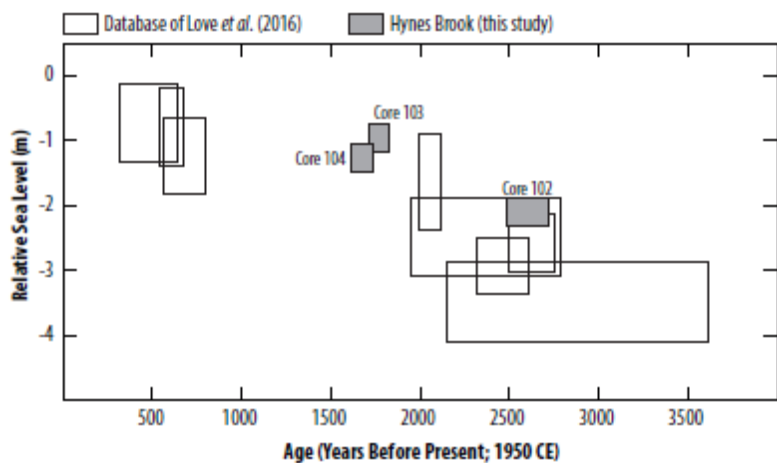
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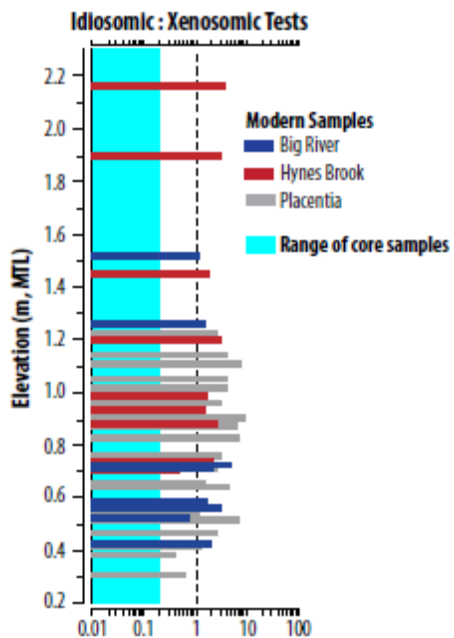
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1112 Figure 8.



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Figure 9.



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