

1 **A 200-year archaeozoological record of Pacific cod (*Gadus macrocephalus*) life history as**  
2 **revealed through ion microprobe oxygen isotope ratios in otoliths**

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25

26 **Abstract**

27 We measured  $\delta^{18}\text{O}$  values in modern and archaeological Pacific cod (*Gadus macrocephalus*)  
28 otoliths recovered from Aialik Bay on the Pacific coast of the Kenai Peninsula, Alaska, using a  
29 high precision ion microprobe. Values of  $\delta^{18}\text{O}$  were measured in as many as sixty 10-micron  
30 spots along 2-3 mm transects from the otolith core to its margin with high spot-to-spot analytical  
31 precision ( $\delta^{18}\text{O} \pm 0.3\text{‰}$ ). We obtained sample densities along a linear transect that were at least 2  
32 to 3 times greater than micromilling/conventional mass spectrometry techniques. From modern  
33 Pacific cod otoliths (using *in situ* temperatures from electronic archive tags) we calibrated an  
34 empirical fractionation equation of aragonite  $\delta^{18}\text{O}$  to sea water temperature ( $r^2 = 0.75$ ,  $p < 0.001$ ,  
35  $\delta^{18}\text{O}_A = 2.13 - 0.25T$  °C) and from which we predicted the thermography of fish life history and  
36 historic nearshore water temperature in the Gulf of Alaska (GOA). Sinuous variability of  $\delta^{18}\text{O}$   
37 values along core-to-margin transects likely reflect seasonal temperature changes and suggest  
38 similar longevity between modern and archaeological cod. Generally increasing  $\delta^{18}\text{O}$  values  
39 from the otolith core region to the margin revealed an ontogenetic migration from warmer  
40 nearshore habitat during the first year of life to cooler deeper waters at later ages, a behavior that  
41 has not changed over the past 200 years. A decline in the average  $\delta^{18}\text{O}$  of otolith cores from  
42 archaeological (~200+, ~100+ years before present, YBP) to modern otoliths suggest increasing  
43 sea surface temperatures from the late Little Ice Age to present. Temperatures calculated from  
44 the  $\delta^{18}\text{O}$  in aragonite suggest a 2-3 °C rise in coastal marine sea surface temperatures in the GOA  
45 over the last 200 years. Implications of indigenous subsistence resource use and settlement  
46 patterns are discussed in light of major shifts in GOA water temperatures and biological regimes.

47

48 Key Words: Little Ice Age, Pacific Cod, Climate Change, Gulf of Alaska, Ion Microprobe,  
49 Oxygen Isotopes

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51

## 52 **1. Introduction**

53 Pacific cod (*Gadus macrocephalus*) is a demersal marine fish species that has a pan-Pacific  
54 distribution with abundances concentrated over continental shelves and slopes to 500 m and  
55 marginal seas in the northern hemisphere (Allen and Smith, 1988). Recent genetic studies point  
56 to contemporary population structure of Pacific cod that has been shaped by genetic divergences  
57 from ice-age isolations and postglacial colonization (Canino et al., 2010). In the Gulf of Alaska  
58 and Bering Sea, where present day Pacific cod are most abundant in the Northeast Pacific,  
59 populations originated from a southern refuge population from colonizations as late as 14,000-  
60 15,000 YBP (Canino et al., 2010). Subsequent to the ice-age maxima, interglacial periods would  
61 have been favorable for reconnection of divergent populations and increased gene flow resulting  
62 in gradients of genetic subdivision which is observed today in the Gulf of Alaska (GOA) and  
63 Aleutian Islands (Cunningham et al., 2009; Canino et al., 2010; Spies, 2012). Since the  
64 “Medieval Warm period” (MWP) ca. A.D. 900-1350 and subsequent Little Ice Age ca. A.D.  
65 1350-1900 (Mann et al., 1988), climate system changes, particularly in the North Pacific Ocean  
66 circulation patterns and coast thermal structure, probably had a substantial impact on how these  
67 genetic subdivisions interacted and adapted to local environmental processes.

68 All life stages of Pacific cod have unique geographic area, depth, and temperature regimes,  
69 which may have been affected by ice-age reorganizations. For instance, adults generally spawn  
70 widely over the continental shelf in water up to about 200 m with eggs loosely adhering to  
71 benthic habitat. After hatching larvae are carried into the upper layers of the water column where  
72 they are transported shoreward and then westward by the Alaska Coastal Current (Matarese et  
73 al., 2003; Hurst et al., 2009; Rugen and Matarese, 1988). Juvenile Pacific cod in their first year  
74 of life (age-0) are thought to settle into shallow coastal areas and embayments where they are  
75 associated with seagrass, kelp and other structure for nursery habitat (Abookire et al., 2007;  
76 Laurel et al., 2007; Stoner et al., 2008). Following the early juvenile stage, age-1 Pacific cod are  
77 still found near coastal margins (Laurel et al., 2009). As they mature to sub-adult and adult life  
78 stages they go through an ontogenetic offshore migration to cooler continental shelf waters  
79 (Nichol et al., 2007). Thus, habitat requirements for reproduction, rearing, growth, and survival  
80 are on a continuum of habitat type from nearshore to deeper offshore continental shelf waters.

81 In ecological time scales, distribution and life history characteristics of contemporary  
82 populations responded to historic changes in temperatures. Pacific cod have been found to  
83 actively avoid the summer ‘cold’ pool (0–2 °C), a reoccurring cool dense water mass in the  
84 Bering Sea (Ciannelli & Bailey, 2005). During recent climatic warming events in the Bering Sea,  
85 Pacific cod have followed northward ice retreat (Mueter and Litzow, 2008) and in some years  
86 have been found as far north as the Bering Strait (Lauth, 2011). Pacific cod have high fecundity,  
87 fast growth rates, and planktonic larval stages (Paul et al., 1990; Ormseth and Norcross, 2009)  
88 which can facilitate high levels of gene flow between populations, swift colonization, and rapid  
89 population growth. Despite the large potential for gene flow, several discrete populations have  
90 been identified on relatively small geographical scales (Canino et al., 2010) from the Gulf of  
91 Alaska to the Aleutian Islands and Bering Sea (Spies, 2012).

92 Pacific cod have been an important food source in the GOA for centuries, utilized by modern  
93 industrial fisheries and indigenous Alutiiq (Sugpiaq) residents (Birket-Smith, 1953; Davydov,  
94 1977; Steffian et al., 2015). As reported by 18<sup>th</sup> and 19<sup>th</sup> century observers and written historical  
95 accounts (Holmberg in 1851), Alutiiq fishers in kayaks took adult cod in water depths of 85-128  
96 m using a bottom-fishing rig made up of a dried kelp line, bone hooks suspended from a wooden  
97 spreader, and a grooved anchor stone (Birket-Smith, 1941; Heizer, 1952; Holmberg, 1985;  
98 Korsun, 2012; Shelikhov, 1981; Steffian et al., 2015). Russian naval officer Gavriil Davydov,  
99 who was stationed on Kodiak Island in 1802-03, wrote that in spring, cod arrived “off the shore  
100 in great shoals” and that Alutiiq residents harvested them until the first salmon became available  
101 (Davydov, 1977).

102  
103 Pacific cod otoliths for the present study were collected at two historic village sites in Aialik Bay  
104 on the GOA coast of the Kenai Peninsula (Fig. 1). The Early Contact Village site (XBS-029)  
105 includes pit houses and a stratified shell/bone midden (Fig. 2). It was occupied in ~A.D. 1790-  
106 1820 based on the predominance of bone and stone artifacts combined with trade artifacts (glass  
107 beads, pieces of iron and copper, a 1748 ½ kopek coin) indicative of early Russian contact  
108 (Crowell et al., 2008; Crowell and Mann, 1998). A single radiocarbon date on a wood charcoal  
109 (species unidentified) from the base of the stratified midden 25 cm below surface was 180 +/- 60  
110 RCYBP (Beta 74860), which most likely falls within the calibrated interval A.D. 1720-1820  
111 ( $p=36.4\%$  at 2 SD). During the archaeological excavations at this site 12,709 fish bones were

112 recovered, of which 2,620 were taxonomically identifiable to at least the family level (Hanson,  
113 2007). Of the identifiable bones, 1,815 (69.3%) of these were cod (Gadidae) followed by  
114 rockfish (Scorpaenidae), flatfish (Paralichthyidae, Pleuronectidae), greenlings (Hexagrammidae),  
115 sculpins (Cottidae), salmon (Salmonidae), and herring (Clupeidae). Most gadid bones were  
116 presumed to be Pacific cod although walleye pollock (*Gadus chalcogrammus*), saffron cod  
117 (*Eleginus gracilis*), and Pacific tom cod (*Microgadus proximus*) could also have been  
118 represented. The faunal assemblage included 31 otoliths identified as Pacific cod. The adjacent  
119 Denton Site (XBS-014) includes seven debris mounds left nearby former log cabins (Figure 2)  
120 and was occupied during ~A.D. 1850-1920 based on the range of manufacturing dates for more  
121 than 700 glass, ceramic, and metal trade artifacts, with a mean date of A.D. 1880 (Crowell, 2006;  
122 Crowell and Mann, 1998). Of 12,800 fish bones recovered during Denton Site excavations, 2,243  
123 were identifiable to family and of these 1349 (60%) were cod (Gadidae), followed by rockfish  
124 and other minor taxa (Hanson, 2009). Six otoliths from the Denton site were identified as *Gadus*  
125 *macrocephalus*, of which three were selected for the present study. Four additional otoliths were  
126 of the family Gadidae.

127  
128 Otoliths are calcium carbonate structures found in the inner ear of teleost fish. In most fish,  
129 including Pacific cod, a new layer of calcium carbonate (in the form of aragonite) is deposited  
130 over the course of each year forming annual growth zones (Matta and Kimura, 2012; Kestelle et  
131 al., 2017). Calcium carbonate is usually precipitated in isotopic equilibrium with the surrounding  
132 seawater (Campana, 1999; Thorrold et al., 1997). In otoliths, and other marine carbonates, the  
133 oxygen isotope fractionation,  $^{18}\text{O}/^{16}\text{O}$ , (measured as  $\delta^{18}\text{O}$ ) is dependent on temperature and has  
134 been shown to decline as water temperature increases (Hoie et al., 2004a; Kestelle et al., 2017).  
135 The otolith's  $\delta^{18}\text{O}$  is also a function of  $\delta^{18}\text{O}$  in the surrounding seawater, which varies due to  
136 such things as continental freshwater runoff and atmospheric inputs. Salinity is often used as a  
137 predictor of the water  $\delta^{18}\text{O}$  and the relationship between salinity and  $\delta^{18}\text{O}$  has been reported in  
138 numerous studies (Grossman and Ku, 1986; Jones and Campana, 2009; Lécuyer et al., 2004;  
139 Campana, 1999), implications regarding this are discussed later in this paper. Otoliths are  
140 metabolically stable throughout the life of the fish. Therefore, they provide a recording  
141 mechanism and a way to reconstruct temperature over the fish's life history (Hoie and Folkvord,  
142 2006; Darnaude et al., 2014; Thorrold et al., 1997). Indeed, this relationship between temperature

143 and  $\delta^{18}\text{O}$  has been used in a range of marine carbonates including corals and shells (Grossman  
144 and Ku, 1986; Culleton et al., 2009; Nielsen and Nielsen, 2009; Lopez Correa et al., 2010) and  
145 also in fish otoliths (Weidman and Millner, 2000; Hoie et al., 2004a; Hoie et al., 2004b; Kastle  
146 et al., 2017). Further, some studies have investigated oxygen isotopes in Pacific cod otoliths as  
147 paleothermometers (West et al., 2012) and Atlantic cod (*Gadus morhua*) otoliths found at  
148 archaeological sites as a record of historical interactions between climate, fish populations, and  
149 early coastal inhabitants (Geffen et al., 2011).

150 Our goal was to reconstruct the nearshore temperature regime and ontogenetic Pacific cod  
151 habitat use in the GOA since the Little Ice Age. Intact Pacific cod otoliths found at the ~200+  
152 (YBP) Early Contact Village and the ~100+ YBP Denton site provided a unique opportunity to  
153 explore interactions between climate and fish populations on temporal scales not typically  
154 available to modern ecologists. By using a high-resolution sampling method and applying an  
155 empirical oxygen-temperature fractionation curve, we analyzed oxygen isotope ratios ( $\delta^{18}\text{O}$ ) for  
156 otoliths from each of the two sites and from modern (2004) Aialik Bay fish. We anticipated that  
157 isotopically derived water temperatures for the ~200+ YBP samples should be significantly  
158 colder than present since they derive from the late Little Ice Age (LIA). During the final cooling  
159 phase of the LIA from A.D. 1810 to 1880 the mean air temperature from February to August on  
160 the GOA coast has been reconstructed from tree ring data to have been 6.7 °C, compared to a  
161 mean of 7.7 °C from A.D. 1880 to 2010 (Wiles et al., 2014). Therefore, the  $\delta^{18}\text{O}$  values from the  
162 ~200+ and ~100+ YBP and modern otoliths should reflect this post-LIA warming trend.  
163 Cultural transitions and altered settlement patterns in relation to possible shifts in GOA water  
164 temperatures and biological regimes were also examined.

## 165 **2. Material and Methods**

166 Nine Pacific cod otoliths were chosen, 3 from each of the two sites described above (representing  
167 ~200+ YBP from XBS-029 and ~100+ YBP from XBS-014) and 3 recently collected  
168 (modern) otoliths. The modern otoliths were from adult fish captured in 2004 near the entrance  
169 of Aialik Bay. These were processed and analyzed in 2007 (Table 1). Another set of 7 otoliths  
170 which came from adult Pacific cod tagged with archival recoding tags (*in situ* bihourly  
171 measurements of depth and water temperature were recorded) and at liberty for 1-2 years (Nichol  
172 et al., 2007) were analyzed in 2011-2012. Otoliths were sonically cleaned, dried, weighed, and

173 embedded in polyester resin. Fish lengths were estimated by using a relationship between otolith  
174 weight and fish length established by the International Pacific Halibut Commission (Kastelle,  
175 unpublished data). The embedded otoliths were thin sectioned on a high speed IsoMet 5000 saw.  
176 Three parallel cuts were made, and two transverse thin sections centered on the otolith's focus  
177 were extracted. The thin sections were mounted on glass slides and polished on an EcoMet 3  
178 (Buehler Inc.) polishing wheel with 1200 grit which produced thin sections about 0.75 mm thick.  
179 Annual growth zones, which consist of paired opaque and translucent zones, were examined  
180 using reflected light under a Leica stereomicroscope. Ages of the Pacific cod were determined by  
181 counting the translucent zones (Matta and Kimura, 2012) from high-resolution digital images of  
182 the sectioned otoliths, and the innermost growth zone was identified. This innermost growth  
183 zone represents the first year of life, a stage when Pacific cod are using nearshore coastal areas as  
184 nursery habitat. Thin sections were remounted in epoxy disks (2.5 cm diameter and 4 mm thick),  
185 such that the polished side of the thin section was exposed on one surface of the disk, along with  
186 small crystals of a calcite standard. The disks and thin sections were finely polished using an  
187 EcoMet grinder/polisher (Buehler Inc.) with sequentially higher grits (600, 800, 1200), followed  
188 by a final 0.05  $\mu\text{m}$  diamond polishing compound. Next, they were cleaned in a sonic cleaner after  
189 which they were dried in a vacuum oven at 40 °C for 2.5 hours. Finally, prior to instrumental  
190 sampling, the epoxy plugs with embedded otolith thin sections were sputter coated with an even  
191 layer gold ~ 60 nm thick.

192

193 *In situ* oxygen isotope ratios were obtained using a CAMECA IMS-1280 large radius, multi-  
194 collector ion microprobe at the WiscSIMS Laboratory, University of Wisconsin-Madison  
195 (Valley and Kita, 2009). In the ion microprobe sampling, transects of 10  $\mu\text{m}$  diameter spots were  
196 made from otolith core region to edge (Fig. 3); this ensured sample coverage for the entire life  
197 history. Generally, transects were approximately 3-4 mm long in either a dorsal or ventral axis;  
198 the choice of axis depended on the clarity of annual growth zones and avoidance of cracks and  
199 occlusions. The sampling strategy consisted of equally spaced spots with higher density near the  
200 otolith core. This was intended to provide good sub-annual resolution for pre-adult and adult life  
201 stages, including inside of the first translucent growth zone (i.e., the first year of life).

202

203 The ion microprobe (secondary ion mass spectrometer, SIMS) parameters (settings) we used for  
204  $\delta^{18}\text{O}$  analysis are the same as in Matta et al. (2013) who sampled otoliths from yellowfin sole  
205 (*Limanda aspera*), which are similar in composition to the Pacific cod otoliths analyzed here.  
206 The relevant parameters and a description of analytical conditions for our study are summarized  
207 in the following description, and more detail can be found in Matta et al. (2013) and Ferry et al.  
208 (2010). The primary beam of  $^{133}\text{Cs}^+$  ions was focused a spot diameter of  $\sim 10\ \mu\text{m}$  on the surface  
209 of the thin section. The analysis of each sample spot took 4 minutes and resulted in a pit  $\sim 1\ \mu\text{m}$   
210 deep. For carbon isotope analysis, a  $^{133}\text{Cs}^+$  ion beam with a diameter of  $\sim 7\ \mu\text{m}$  was used, with a  
211 total analysis time of 6 minutes per spot. The secondary ions were analyzed in the mass  
212 spectrometer set up for high secondary-ion transmission (Kita et al., 2009). Groups of 10 to 15  
213 sample spots were bracketed, before and after, by 4-5 analyses of the calcite standards. In 2007  
214 the standard was UWC-1 ( $\delta^{18}\text{O} = 23.36\text{‰}$  Vienna Standard Mean Ocean Water (VSMOW) and  
215  $\delta^{13}\text{C} = 2.03\text{‰}$  Vienna Pee Dee Belemnite standard (VPDB)) and in 2011 and 2012 the standard  
216 was UWC-3 ( $\delta^{18}\text{O} = 12.49\text{‰}$  VSMOW,  $\delta^{13}\text{C} = -0.91\text{‰}$  VPDB) (Bowman et al., 2009; Kozdon  
217 et al., 2009). Analysis of the standard was used to correct for instrumental bias and to estimate  
218 precision in spot sampling (Kita et al., 2009, Valley and Kita, 2009, Kozdon et al., 2009, Matta  
219 et al., 2013, Orland et al., 2009). After the ion microprobe analyses, we imaged each spot by  
220 scanning electron microscopy to be sure that the pits did not include otolith irregularities or  
221 contaminants. In two otoliths, one from  $\sim 100$  YBP (XBS-014-5) and the other 0 YBP (MOD-14)  
222 a full life history transect was measured for both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  to evaluate the relationship  
223 between these isotopes and possibly infer potential differences in coastal productivity.  
224 Variability in  $\delta^{13}\text{C}$  is can be related to marine productivity, fish metabolic rates, fish diet, and  
225 fish growth rate. Results from both measurement methods are reported in  $\delta^{13}\text{C}\ \text{‰}$  and  $\delta^{18}\text{O}\ \text{‰}$   
226 VPDB. To check for diagenesis, the sample spot analyses were evaluated using the ion yield ( $^{16}\text{O}$   
227 or  $^{12}\text{C}$  count rates/primary beam intensity) to recognize irregular data. Based on dispersion of ion  
228 yields of the standard calcite in the same session, irregular (altered) data were defined if the C  
229 ion yield is 10% higher than average value or if the O ion yield is 5% lower than the  
230 average value, and omitted from analysis.  
231  
232 We developed an empirical fractionation equation between  $\delta^{18}\text{O}$  and temperature from the 7  
233 electronic archival tagged Pacific cod (Nichol et al., 2007). Each time series of instrumental



234 temperatures was divided into quarters and averaged. The re-captures occurred during the winter  
235 or spring, and most fish were at liberty for nearly a year. Quarterly average  $\delta^{18}\text{O}$  values were  
236 then obtained using a rough proportional distance between the otolith margin and inner annulus;  
237 which we took to represent the period the fish was at liberty. Ion microprobe samples at the  
238 margin spanned the most recent winter period. As such, if a Pacific cod was at liberty for 1 year,  
239 then we obtained 4 averaged data points of  $\delta^{18}\text{O}$  and temperature. One Pacific cod (sample 1169)  
240 was at liberty for 716 days and given roughly 8 data points. Then the average quarterly  $\delta^{18}\text{O}$   
241 representing the aragonite material accreted during the period at liberty were regressed with  
242 average quarterly *in situ* instrumental temperatures;  $\delta^{18}\text{O} = \alpha + \beta T^{\circ}\text{C}$ , where  $\alpha$  and  $\beta$  is the  
243 intercept and slope of the linear response of  $\delta^{18}\text{O}$  to temperature ( $T$ ). However, we regressed  
244 temperature on  $\delta^{18}\text{O}$  to derive a predictive equation ( $T^{\circ}\text{C} = \alpha' + \beta' \delta^{18}\text{O}$ ), and then applied that to  
245 estimate the thermography of Pacific cod's life history from ion probe spot samples over the  
246 entire transect, shown as a loess smoothed time series. We also reconstructed the presumed  
247 average nearshore Gulf of Alaska surface temperatures from spot samples taken within the 1<sup>st</sup>  
248 growth zone near the otolith core of archaeological and modern samples. *In situ* nearshore  
249 temperature data (2000-2006) from an oceanographic monitoring mooring station, GAK1, at  
250 59°50.7' N, 149°28.0' W (<http://www.ims.uaf.edu/gak1/>) was used to ground truth the surface  
251 (<25 m) water temperature with those inferred from  $\delta^{18}\text{O}$  measured in the contemporary Pacific  
252 cod otoliths.

253

### 254 **3. Results**

255 Archaeological Pacific cod annual growth zones, visible from stereomicroscopic examination of  
256 otoliths were sufficiently preserved for analysts to assign age within +/- 1 year (Table 1, Fig. 3).  
257 Ages ranged between 4 and 7 years of age (Table 1). In selected samples shown in Figures 3A-  
258 3B (XBS-014-4) and 3C-3D (XBS-029-11), the otolith core was generally apparent as an ellipse  
259 within the first year's growth, followed by a number of concentric wide opaque and thin  
260 translucent material identified as annual growth zones from which age (count of translucent  
261 zones) was estimated. Based on our knowledge of contemporary Pacific cod growth, the opaque,  
262 material represents aragonite accretion during fast summer growth periods and translucent  
263 material forms during slower winter growth periods. The fish lengths, estimated with the

264 relationship between Pacific cod fish length and otolith weight, ranged from 562 to 782 mm  
265 (Table 1). In general, lengths and ages of Pacific cod inferred through otoliths did not show  
266 differences between archaeological recovered and contemporary specimens.

267 While maximization was not a goal, the number of spots from the ion microprobe varied between  
268 22 and 58 per otolith, with the greatest density made in or near the otolith core in the first year of  
269 the animal's life (Table.1, Fig. 3). This was largely because the aragonite linear accretion rate is  
270 greatest during the first year allowing for a greater sampling density. The greatest number of  
271 analyses ( $n=58$ ) were taken in specimen XBS-029-11 with about sixteen 10  $\mu\text{m}$  -diameter spots  
272 within each of the first and second years of life, followed by approximately 8-10 samples in each  
273 of the remaining growth zones (Fig. 3D). Transect lengths ranged from about 3 to 4.9 mm with  
274 sample densities ranging from 5 to 19 spots per mm (Table 1). This provided multiple spots per  
275 annulus which allowed an assessment of seasonal trends in the  $\delta^{18}\text{O}$  values.

276 In all otoliths, the lowest  $\delta^{18}\text{O}$  value was generally observed within or near the core, which is  
277 considered the early juvenile stage of life (Fig. 4). Depending upon the era from which otoliths  
278 were recovered the  $\delta^{18}\text{O}$  value ranged from a low of approximately -2.0 ‰ to a high of 1.5 ‰  
279 (XBS-029-10) among the 200 YBP group, -3.0 ‰ to 1.0 ‰ (XBS-014-4) among the 100 YBP  
280 group, and -3.5 ‰ to 1.0 ‰ (MOD-18) in the 0 YBP group. In most samples, the  $\delta^{18}\text{O}$  value  
281 increased considerably during the first or second year and showed a sinuous pattern of peaks and  
282 troughs. The observed sinuous pattern indicated a strong seasonal variation in temperature.  
283 Given the inverse relationship between  $\delta^{18}\text{O}$  values and temperature, the increase in  $^{18}\text{O}$  during  
284 the first 1 or 2 years indicated that individual Pacific cod in the Gulf of Alaska experienced an  
285 overall decrease in water temperature through their life. This possibly reflects an ontogenetic  
286 migration from warmer nearshore costal water to cooler deeper shelf water. Another interesting  
287 feature, particularly for otoliths with high sampling density such as XBS-014-4, is that the 5  
288 peaks in  $\delta^{18}\text{O}$  are consistent with the estimated age of the fish (Table 1, Fig. 4).

289 We found that water temperature was a dominant factor affecting the  $\delta^{18}\text{O}$  (aragonite) of Pacific  
290 cod otoliths (Fig. 5). The estimated functional relationship between Pacific cod otolith aragonite  
291 ( $\delta^{18}\text{O}$ ) and water temperature showed a statistically significant inverse linear relationship ( $\delta^{18}\text{O}$   
292 =  $2.13-0.25T^{\circ}\text{C}$ ,  $r^2 = 0.75$ ,  $p < 0.001$ ). This was based on the 7 Pacific cod which had instrumental  
293 temperature measured during the time at liberty with archival tags and the corresponding otolith

294  $\delta^{18}\text{O}$  measured with ion microprobe analyses. The estimated regression from all 7 fish shows  
295 that there is approximately a 3-4 °C temperature change for each per mil change in the  $\delta^{18}\text{O}$   
296 concentration. This is also demonstrated with sample 1169 where the *in situ* bi-hourly  
297 temperature sequence, over the 716 day period at liberty, corresponds in an inverse relationship  
298 to the ion microprobe samples of  $\delta^{18}\text{O}$  (Fig. 5). This relationship (reanalyzed for temperature as  
299 the response variable and  $\delta^{18}\text{O}$  as the independent variable, Table 1) was used to reconstruct the  
300 life history temperature profile in the archaeological and contemporary Pacific cod (Fig. 6). For  
301 selected specimens, Figure 6 shows the general and consistent pattern where Pacific cod  
302 experience higher thermal habitat in nearshore areas as early stage juveniles, but as they grow  
303 into later stages of development the temperature experienced or preferred becomes gradually  
304 cooler as they move to deeper depths.

305 Ion microprobe analyses taken within the first growth zone near the otolith's core, were used to  
306 reconstruct nearshore Gulf of Alaska temperatures experience by Pacific cod during ~200+,  
307 ~100+ and 0 YBP. Here we assumed that the average of these near-core  $\delta^{18}\text{O}$  samples represent  
308 the first summer of life when the Pacific cod were in nearshore coastal water and most affected  
309 by surface temperature changes. A decline in average  $\delta^{18}\text{O}$  from otolith cores in archaeological  
310 (~200+, ~100+ YBP) to modern samples suggest increasing sea surface temperatures from the  
311 late Little Ice Age to present. Predicted average sea surface temperatures from  $\delta^{18}\text{O}$  in Pacific  
312 cod otoliths was roughly 8.5 °C during the ~200 YBP period with a slight temperature increase to  
313 9.0 °C in the ~100 YBP period (Fig. 6). The  $\delta^{18}\text{O}$  in otoliths from contemporary Pacific cod  
314 suggest an average 2-3 °C rise over the last 100 years in coastal sea surface temperatures in the  
315 Gulf of Alaska (Fig. 6). Two of the modern Pacific cod otoliths indicated a nearshore summer  
316 temperature of ~13 °C (Figure 7). Normally, when making such a prediction, an estimate of water  
317  $\delta^{18}\text{O}$  (itself a function of salinity) is necessary (Hoie et al., 2004a). We do not have an estimate  
318 of surface water  $\delta^{18}\text{O}$ , however, the GAK1 mooring surface temperature consistently reached 11-  
319 13 °C during the early to mid-2000s. This agreement provided a way to ground truth the  $\delta^{18}\text{O}$   
320 based temperature estimates. In one Pacific cod otolith (MOD-18) the average near-core  $\delta^{18}\text{O}$  (-  
321 1.29 ‰) was considerably higher, and hence predicted lower temperature than the other two  
322 contemporary fish (Fig. 7).

323 Average values of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  from sample XBS-014-5 (100 YBP) were  $-2.87\text{‰}$ , and  $-0.35$   
324  $\text{‰}$ , respectively (Fig. 8A). For sample MOD-14 (0 YBP),  $\delta^{13}\text{C}$  was similar with an average of  $-$   
325  $2.77\text{‰}$ , but by comparison,  $\delta^{18}\text{O}$  had a substantially more negative concentration of  $-1.69\text{‰}$   
326 (Fig. 8A). Both samples show a measure of linear relationship between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$   
327 concentrations, however, sample XBS-014-5 (100 YBP) has a much stronger correlation  
328 between the two isotopes ( $r = 0.77$ ). Variability in  $\delta^{13}\text{C}$  from XBS-014-5 was also observed to be  
329 greater than in MOD-14. Both otolith chronologies of  $\delta^{13}\text{C}$ , over the entire life history transects,  
330 appear on the whole to show similar increasing trends (Fig. 8B). One principal difference is the  
331 average  $\delta^{13}\text{C}$  values in the core areas; XBS-014-5 is significantly lower than in MOD-14.

#### 332 4. Discussion

333 High resolution sampling for  $\delta^{18}\text{O}$ , using tools such as the ion microprobe, provides a unique  
334 perspective on Pacific cod biogeography and migratory behavior, showing habitat preference for  
335 warmer nearshore water during early life stages followed by migration to cooler deeper water.  
336 First year juvenile Pacific cod (age 0 years) have been documented to exhibit associations with  
337 shallow, nearshore coastal areas in the Gulf of Alaska (Laurel et al., 2007; Stoner et al., 2008).  
338 As the juveniles grow they move gradually to offshore cooler coastal water as sub-adult and  
339 adults (Laurel et al., 2009). These movement patterns are confirmed by population level research  
340 survey data which shows the greatest concentration of juvenile Pacific cod are in shallower,  
341 warmer shelf water until 4 years old (Nichol et al., 2007; Nichol et al., 2013). During the  
342 transition to maturity, between ages 4-5 years (Stark, 2007), there is a tendency for animals to  
343 move toward deeper cooler waters of the continental shelf where they find suitable habitat for  
344 spawning. Matta et al. (2013) conducted a similar high-resolution ion microprobe study of  
345 yellowfin sole in the Eastern Bering Sea and found  $\delta^{18}\text{O}$  chronologies reflecting similar seasonal  
346 and biogeographic movements. Similar patterns in the  $\delta^{18}\text{O}$  chronologies in the archaeologically  
347 obtained otoliths and those of contemporary Pacific cod point to an ontogenetic migratory life  
348 history strategy that does not appear to have changed over the past 200 years. Migratory behavior  
349 such as this could be an adaptive response to advance and retreat of glacial reorganizations  
350 throughout evolutionary time scales.

351 The Pacific cod ages estimated from archaeologically obtained otoliths in this study (4-6 years)  
352 are indeed consistent with the most numerous age classes in the Gulf of Alaska population

353 (A'mar et al., 2012). Fish lengths predicted from otoliths are also consistent with typical sizes of  
354 Gulf of Alaska Pacific cod taken in recent fishery-independent resource surveys, and there is also  
355 no indication that the length estimated from the archaeological specimens are any different from  
356 those of contemporary fish. Ethnohistoric descriptions of Alutiiq fishing technology, presented in  
357 the Introduction, indicate a focus on larger fish taken near bottom depths, often over 100 m.  
358 Based on current information such fish could clearly be fully grown adult Pacific cod.  
359 Interestingly, in some specimens the number of  $\delta^{18}\text{O}$  concentration peaks roughly correspond to  
360 the estimated fish age based on visual interpretations of otolith growth zone counts. Several  
361 recent studies of  $\delta^{18}\text{O}$  signatures in otoliths have been used to age both Pacific cod (Kastelle et  
362 al., 2017) and Atlantic cod (Weidman and Millner, 2000). Kastelle et al. (2017) found that from  
363 a sample of 40 Pacific cod otoliths aged by growth zone counts, nearly 70% were assigned the  
364 same age or 90% were assigned an age +/- 1 year different from estimates derived from counts of  
365  $\delta^{18}\text{O}$  peaks. In both the above studies, the goal was to use  $\delta^{18}\text{O}$  chronologies in fish otoliths to  
366 validate ages estimated by interpreting and counting growth zones. These studies relied on the  
367 well-established relationship between an otolith's oxygen isotopic fractionation and water  
368 temperature (Valley and Kita, 2009; Hoie et al., 2004a; Thorrold et al., 1997). The study by  
369 Kastelle et al., (2017) was the first to give a  $\delta^{18}\text{O}$  – temperature fractionation relationship based  
370 on Pacific cod otoliths from the North Pacific Ocean. The fractionation relationship reported here  
371 (Fig. 5) is consistent with that reported in Kastelle et al., (2017); we found a both a comparable  
372 slope and intercept. Similar studies on otoliths from other regions and species report consistent  
373 expected temperature-driven variation in  $\delta^{18}\text{O}$  of aragonite, close to  $0.2\text{‰}/\text{C}$  (Hoie et al., 2004a;  
374 Grossman and Ku, 1986; Thorrold et al., 1997; Kim et al., 2007; Wang et al., 2013). Not  
375 surprisingly, this well studied property has led investigators to use  $\delta^{18}\text{O}$  in biogenic structures as  
376 a proxy for reconstructing palaeotemperatures (Wierzbowski and Rogov, 2011; West et al.,  
377 2012), and examining seasonal fluctuations of  $\delta^{18}\text{O}$  signatures in otoliths (Thorrold et al., 1997;  
378 Matta et al., 2013).

379 Nearshore surface temperatures in the Gulf of Alaska, estimated here using the  $\delta^{18}\text{O}$  of otolith  
380 core regions from archaeological and modern Pacific cod, appears to have increased 2-3 °C since  
381 the late Little Ice Age. We only sampled three fish from each era, although many ion probe  
382 analyses were taken in the core, nevertheless we emphasize that this estimate represents an  
383 implied average sea surface temperature. Nor do the results of this analysis provide a large

384 geographical inference because Pacific cod inhabit a diversity of nearshore habitat during their  
385 first year of life throughout the Gulf of Alaska. West et al. (2012) found a period of ocean  
386 warming around 400+ YBP in the Gulf of Alaska, with a gradual decrease in temperature to  
387 about 190+ YBP based on archaeological recovered Pacific cod otoliths from archaeological  
388 sites on Kodiak Island, AK; West et al. (2012) did not analyze modern otoliths. Similar findings  
389 from  $\delta^{18}\text{O}$  chronologies of Atlantic cod otoliths show cooler ocean water temperatures during the  
390 Late Little Ice Age (Geffen et al., 2011). Samples in West et al. (2012) were obtained partly by  
391 micro-drilling and averaging  $^{18}\text{O}$  measurements (from conventional acid digestion/gas-source  
392 mass spectrometry) across the entire life history transect. This method of sampling would  
393 obscure both seasonal and age-related ontogenetic movements. Further, they used a different  
394 analytic technique of measuring  $\delta^{18}\text{O}$ , which may make comparisons with our study difficult.  
395 Nevertheless, a difference of about 2-3 °C cooler around the decade of A.D. 1800 from otolith  
396  $\delta^{18}\text{O}$  demonstrated in these multiple studies are consistent with tree-ring derived estimates of  
397 cooler summer air temperatures during the same period (Barkley et al., 1999, D'Arrigo et al.,  
398 2005, Wiles et al., 2014). We “ground truthed” contemporary temperatures estimated from  
399 otolith core  $\delta^{18}\text{O}$ . The temperature-  $\delta^{18}\text{O}$  curve was used to generate predictions of nearshore  
400 temperatures from the cores of modern Pacific cod otoliths which were consistent with <25m  
401 surface water temperatures from the GAK1 mooring during the early 2000s. Both indicated  
402 temperatures up to about 13 °C during summer months within nearshore habitat. Other recent  
403 studies have corroborated these temperature estimates; high densities of age-0 and age-1 Pacific  
404 cod occupy a diversity of nearshore embayments in the Gulf of Alaska where annual summer  
405 water temperatures reach 13-15 °C (Ormseth et al., 2016), and are important nursery areas during  
406 the early juvenile stage (Abookire et al., 2007, Laurel et al., 2007, Stoner et al., 2008). Further,  
407 Pacific cod growth and activity is maximized at 12 to 15 °C (Laurel et al., 2016); so this temp  
408 range is reasonable.

409 Carbon isotope chemistry in fish otoliths is complex and the fractionation in precipitated  
410 aragonite is thought to be mediated possibly by biological, diet, and kinetic effects (Thorrold et  
411 al., 1997; Weidel et al., 2007). Isotopes of carbon  $^{13}\text{C}/^{12}\text{C}$  and oxygen  $^{18}\text{O}/^{16}\text{O}$  have commonly  
412 been reported to be highly correlated in numerous animal taxa (Patterson et al., 1993; Thorrold et  
413 al., 1997; Vanhove et al., 2011). Kalish (1991) also reported a positive correlation between  $\delta^{13}\text{C}$   
414 and  $\delta^{18}\text{O}$  in marine fish otoliths and proposed that  $\delta^{13}\text{C}$  levels are a function of metabolic rates

415 increasing with temperature. Considering a freshwater fish species, Wurster and Patterson (2003)  
416 similarly suggested that  $\delta^{13}\text{C}$  levels are controlled by changes in metabolic rates. Since aragonitic  
417  $\delta^{13}\text{C}$  has been shown to be inversely related to water temperature across different taxa of  
418 biogenic carbonates (Kalish, 1991; Grossman and Ku, 1986; Wurster and Patterson, 2003), the  
419 positive relationship between  $\delta^{13}\text{C}$  and oxygen  $\delta^{18}\text{O}$  is not at all surprising. While the precise  
420 mechanism is unknown, evidence from laboratory and field studies point to diet and metabolic  
421 effects rather than physical temperature dependence of  $\delta^{13}\text{C}$  in otolith aragonite precipitation  
422 (Thorrold et al., 1997; Romanek et al., 1992). In our study only two otoliths were analyzed for  
423  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  so proposing a mechanism for their relationship is not possible. However, roughly  
424 similar trends between  $\delta^{13}\text{C}$  over the life history transects in these otoliths might suggest the  $\delta^{13}\text{C}$   
425 disequilibria is associated with temperature related increased metabolic activity, which is  
426 accompanied by enhanced demands for growth and reproduction (Thorrold et al., 1997).

427 We found the core region of specimen XBS-014-5 (~100 YBP) to be lower in  $\delta^{13}\text{C}$  relative to  
428 MOD-14 (0 YBP). Assuming somewhat similar metabolic functioning of these two Pacific cod  
429 in their first year of life, it might be postulated that concentrations of inorganic carbon (DIC) in  
430 the nearshore marine waters in the Gulf of Alaska were lower during 100 YBP period compared  
431 to the present. Depletion of DIC could be attributed to lower marine productivity associated with  
432 advancing glaciers into nearshore Pacific cod habitat as well as overall lower water temperatures  
433 limiting plankton production. Growth of juvenile Pacific cod in laboratory studies is shown to be  
434 depressed in ambient water temperatures of less than the optimum of 11.5 °C (Laurel et al.,  
435 2016). Based on  $\delta^{18}\text{O}$  predicted historic temperatures of 8-9 °C in our study, metabolic  
436 limitations of carbon incorporation into otoliths from either poor growth or reduced marine  
437 productivity seem within the realm of plausibility. We should caution that predicted temperature  
438 histories from otolith  $\delta^{18}\text{O}$  aragonite from archaeological specimens assumes that the  $\delta^{18}\text{O}$  of the  
439 water (hence salinity) has remained unchanged, which is a difficult assumption to verify. Other  
440 factors can also affect the  $\delta^{18}\text{O}$  fractionation seen in otoliths (Campana, 1999; Horn et al., 2012)  
441 such as changes in seawater  $\delta^{18}\text{O}$  due to glacier ice melt and river runoff (Coachman, 1986;  
442 Stabeno et al., 2005). These geophysical processes must have undoubtedly changed over the past  
443 200 years affecting coastal glacier retreated and freshening of the continental shelf waters, so it is  
444 difficult to ascertain the extent to which they have affected our temperature reconstructions.  
445 Further research is needed to understand and correct for the  $\delta^{18}\text{O}$  concentration of coastal waters.

446 Despite these uncertainties, the fact that  $\delta^{18}\text{O}$  predicted nearshore temperatures from  
447 contemporary otoliths are quite reasonable based on real time mooring data and other studies,  
448 including ones that use tree rings, and suggest a similar finding of increased coastal temperatures  
449 lends credence to the findings presented in this study.

450 Colder SSTs during the late LIA are likely to have affected the abundance of Pacific cod and  
451 other fish species in the GOA, necessitating adjustments in the subsistence economies and  
452 settlement patterns of human coastal populations. Considering modern short-cycle climate data  
453 first, commercial catches and recruitment of GOA Pacific cod rose (although with high annual  
454 variability) during the strong warm phase of the Pacific Decadal Oscillation (PDO) from 1977 to  
455 1988 and declined during the weaker cooling phase from 1989 to 1998, as did flatfish and other  
456 gadids including walleye pollock and hake (A'mar et al. 2014; Benson and Trites 2002; Hare and  
457 Mantua 2000; McGowan et al. 1998; Overland et al. 2008). Catches of all salmon stocks and  
458 species increased, in some cases substantially, during 1977-1988, and most increased again or  
459 showed weak declines after 1989 (Hare and Mantua 2000: Table 1).

460 Because gadids and/or salmonids are the numerically predominant fish in most GOA  
461 archaeofaunal assemblages (based on the number of identified specimens), the present discussion  
462 focuses on the relative abundance of these two important taxa during the Neoglacial interval  
463 (5000 B.C. - A.D. 900), the Medieval Warm Period (A.D. 900-1350), and the Little Ice Age  
464 (A.D. 1350-1900). Over this span Pacific cod and salmon populations appear to have decreased  
465 and increased in response to climate changes but in opposing directions rather than in phase as  
466 during recent PDO regimes. In the examples below, archaeological abundance (high numbers of  
467 bones in middens) serves as a proxy for species abundance in the natural environment, although  
468 this relationship is indirect and mediated by human behavior.

469 On Sanak Island in the western GOA, Pacific cod were the dominant species harvested at eight  
470 archaeological sites from 2550 B.C. through A.D. 520 (Neoglacial), then declined in dominance  
471 relative to other species (salmon, flatfish, greenlings, sculpins) during the MWP (sample date =  
472 A.D. 1030) and increased again during the LIA (sample date = A.D. 1540) (Maschner et al.  
473 2008). At four sites in the Kodiak archipelago (Rice Ridge, Uyak, Crag Point, and Settlement  
474 Point), Pacific cod were the dominant fish species during the Neoglacial from 5000 B.C. through  
475 about A.D. 1100, but were superseded by salmon at about A.D. 1300 in the late MWP (Kopperl



476 2003). Pacific cod and other marine species exceeded salmon in some stratigraphic levels at  
477 Karluk-1 on Kodiak Island, an LIA site dated to about A.D. 1400-1750, despite the site's  
478 location at the mouth of one of the GOA's most productive salmon rivers, suggesting salmon  
479 decline during the LIA (West 2012). This is confirmed by a study of oceanic <sup>15</sup>N sampled from  
480 2,200 years of bottom sediments in Karluk Lake, a sockeye salmon spawning site at the head of  
481 the Karluk River (Finney et al. 2002). Spawning in the lake was at low levels from 100 B.C. to  
482 A.D. 800 during the Neoglacial, increased to high levels during the MWP and early LIA, and  
483 dropped sharply in A.D. 1700-1850 during the late LIA. The two Kenai Peninsula LIA sites  
484 discussed in the present paper – the Early Contact Village (A.D. 1790-1820) and the Denton Site  
485 (A.D. 1850-1920) – are dominated by Pacific cod with only minor representation of salmon, and  
486 so conform to the regional trend. In southeastern Alaska, gadids (primarily Pacific cod) alternate  
487 with salmonids as the dominant taxon in 26 archaeological sites ranging in age from 6200 B.C.  
488 to A.D. 1900, but clear temporal trends or association with climatic cycles have not been  
489 discerned (Moss 2011). Overall, the GOA archaeological record suggests that cod were most  
490 abundant and important to subsistence during the Neoglacial and LIA, while salmon peaked  
491 during the MWP.

492 Major shifts in GOA water temperatures and biological regimes have been correlated with  
493 cultural transitions and altered settlement patterns. With the onset of the MWP, interior Dena'ina  
494 groups migrated to the coast of Cook Inlet and initiated a subsistence economy based on  
495 intensive salmon harvesting (Reger, 2013). On Kodiak Island, the Late Kachemak phase with its  
496 emphasis on Pacific cod and other pelagic fish gave way at the start of the MWP to the Koniag  
497 phase when large salmon fishing villages were established on the Karluk, Ayakulik and other  
498 rivers along the southwestern side of the island (Finney et al. 2002; Knecht 1985; Kopperl 2003;  
499 Steffian et al. 2015). During the late LIA but before Russian contact in the late 18<sup>th</sup> century,  
500 many of the western Kodiak villages were abandoned and the Koniag population shifted to the  
501 northern and eastern coasts of the island where cod and other offshore resources are more  
502 abundant (Clark 1987).

503 A GIS-based factor analysis of all known archaeological sites (n=1,959) along 17,000 km of  
504 coastline in the central GOA demonstrated that sites cluster in areas of highest food resource  
505 diversity and that two factors – Factor 1 indicating access to cod, halibut, herring, and sea lions

506 and Factor 4 to salmon – together explain over 60% of the variance in site count per 2.5 km  
507 shoreline segment (Crowell et al., 2013). In part, this result is likely to reflect seasonal rotation  
508 between fall-winter-spring villages and summer salmon camps, but on a larger scale Factor 1  
509 may represent subsistence emphasis and corresponding site choice during cooler phases when  
510 salmon were reduced but gadids, flatfish, forage fish, and sea mammals increased, whereas  
511 Factor 4 represents the alternative warm phase strategy when coastal residents moved to major  
512 salmon rivers and relied on mass production of this resource. Of the 1,959 GOA sites in the  
513 sample, 41% were estimated from radiocarbon dates, artifacts, and features to have been  
514 occupied since A.D. 900; 10% were older than A.D. 900; and 49% were of indeterminate age but  
515 likely to be post-A.D. 900 in the same proportion. Therefore, the analysis primarily represents  
516 changes in settlement patterns and resource use during the MWP and LIA.

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842 Oceanic and Atmospheric Administration, National Marine Fisheries Service.

843

#### 844 Figure Captions

845 Figure 1. Recovery location (yellow arrow) of Pacific cod (*Gadus macrocephalus*) otoliths from  
846 archaeological sites in Aialik Bay, Alaska. The location of the GAK1 oceanographic mooring is  
847 shown (red star) which is at 59° 50.7' N, 149°28.0'W, within the Alaska Coastal Current.

848 Figure 2. Feature and topographic map of the Early Contact Village Site (XBS-029) and Denton  
849 Site (XBS-014) in Verdant Cove on the west side of Aialik Bay, Kenai Fjords National Park,  
850 Alaska. Pacific cod (*Gadus macrocephalus*) otolith samples were taken from the midden area  
851 at XBS-029, and from cabin mounds M-2 and M-3 at XBS-014. Excavations at the two sites  
852 were conducted in 2003-2004. Both x- and y-label axes are in meters.

853 Figure 3. Images of transverse thin sections from Pacific cod (*Gadus macrocephalus*) otoliths  
854 recovered from the archaeological sites in Aialik Bay, Alaska. Panels A and B are ~200 year  
855 before present (from XBS-029-11) and panels C and D are ~100 year before present (from XBS-  
856 014-4). Panels A and C show locations of the core and the approximate region of translucent  
857 annual winter growth zones (black dots). Panels B and D show the ion microprobe spot samples  
858 along dorsal-oriented (B) and ventral-oriented (D) transects from otolith core to edge. White bars  
859 represent 1 mm.

860 Figure 4. Sequences of measured  $\delta^{18}\text{O}$  (‰ VPDB,  $\pm 2$  S.D.) in Pacific cod (*Gadus*  
861 *macrocephalus*) otoliths, in  $\mu\text{m}$  from the core region to the margin. The left column is samples  
862 with a calibrated age of ~200+ years before present (YBP), the middle column is samples with  
863 an age of ~100+ YBP, and the right column is samples with an age of 0 YBP.

864 Figure 5. A) Temperature recorded by an archival recording tag on Pacific cod (*Gadus*  
865 *macrocephalus*) ID 1169 during the time at liberty, 716 days. C) Image of a Pacific cod otolith  
866 thin section showing the location of ion microprobe spot samples which were near the outer edge  
867 of the otolith in material representing time at liberty. B) The  $\delta^{18}\text{O}$  (‰ VPDB,  $\pm 2$  S.D.) values  
868 measured as distance ( $\mu\text{m}$ ) from the otolith edge. D) Empirical fractionation equation of otolith  
869 aragonite ( $\delta^{18}\text{O}$ ) to water temperature from 7 archival tagged Pacific cod, showing a statistically  
870 significant inverse linear relationship ( $r=0.75$ ,  $p<0.001$ ).

871 Figure 6. Left column: Three example sequences of ion microprobe spot samples measuring  $\delta^{18}\text{O}$   
872 (‰ VPDB,  $\pm 2$  S.D.) from the otolith core to edge. The right column shows the temperatures  
873 estimated from the equation,  $T^{\circ}\text{C} = 6.198 - 2.195 * \delta^{18}\text{O}$  (Fig 5) shown as Loess smoothed time

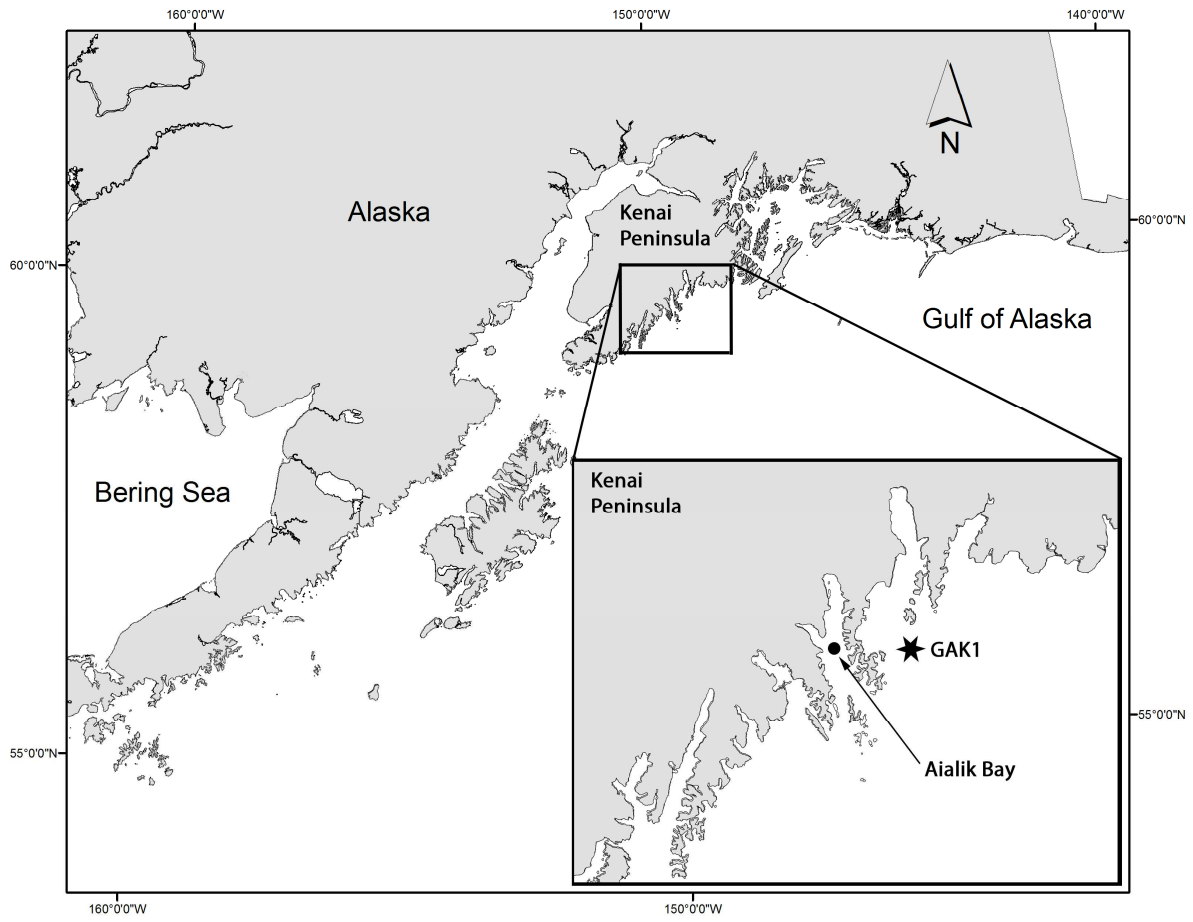
874 series. The large circles in the  $\delta^{18}\text{O}$  sequences indicate spot samples which were in the otolith  
875 core region and used to reconstruct nearshore surface temperature change since Little Ice Age.

876 Figure 7. Average predicted nearshore surface water temperature since the Little Ice Age, 200+  
877 years before present (YBP), to modern times, 0 YBP. The predictions were from 9 Pacific cod  
878 otoliths (*Gadus macrocephalus*) (6 recovered from archaeological sites dated to ~200+ and  
879 ~100+ YBP, and 3 from 0 YBP) sampled for stable oxygen isotopes  $\delta^{18}\text{O}$  in the core of the  
880 otolith (refer to Fig. 6). Ion probe spot-specific temperatures were predicted from  $T^{\circ}\text{C} = 6.198 -$   
881  $2.195 * \delta^{18}\text{O}$ , and averaged. Error bars show 2SD of the mean.

882 Figure 8. Upper panel: Relationship between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (‰ VPDB,  $\pm 2$  S.D.) measured by  
883 ion microprobe at WiscSIMS, in two specimens. Lower panel: Sequences from the otolith's core  
884 to its margin of measured  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (‰ VPDB,  $\pm 2$  S.D.) in the same two specimens as  
885 above.

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889 Figure 1.

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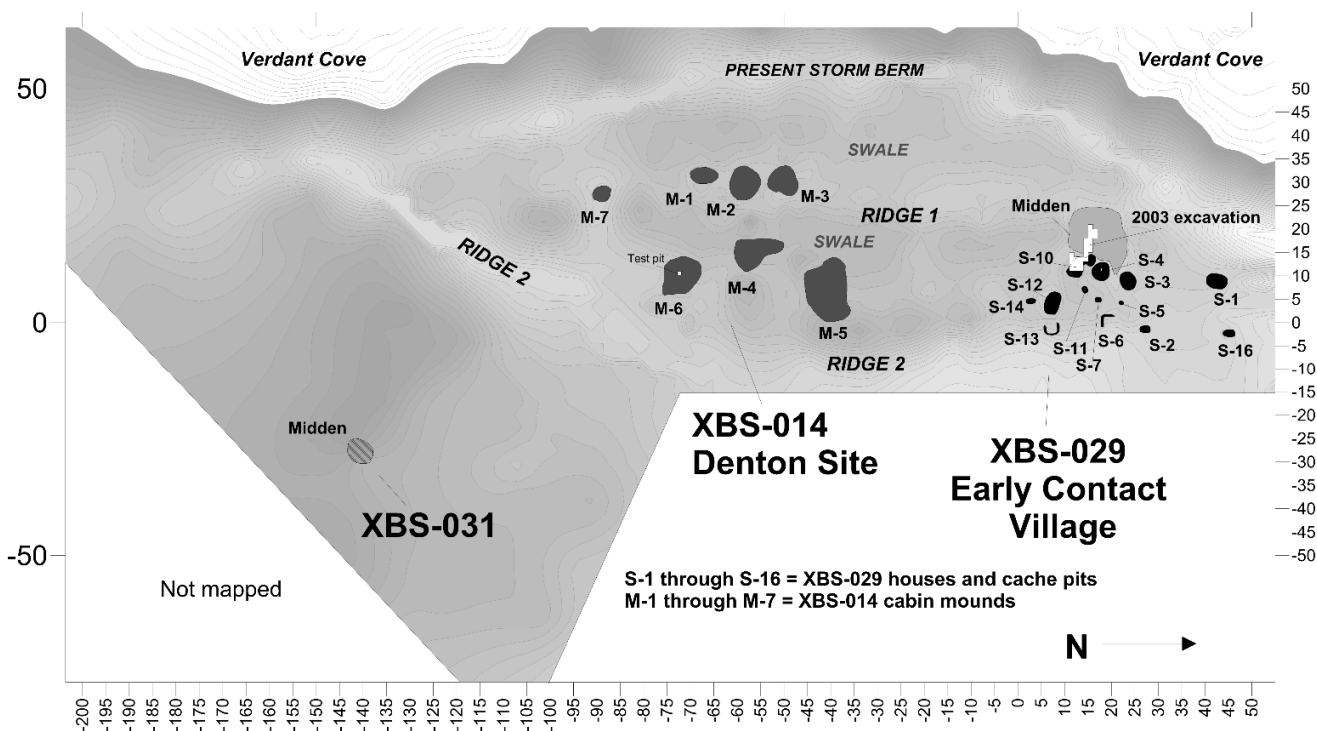
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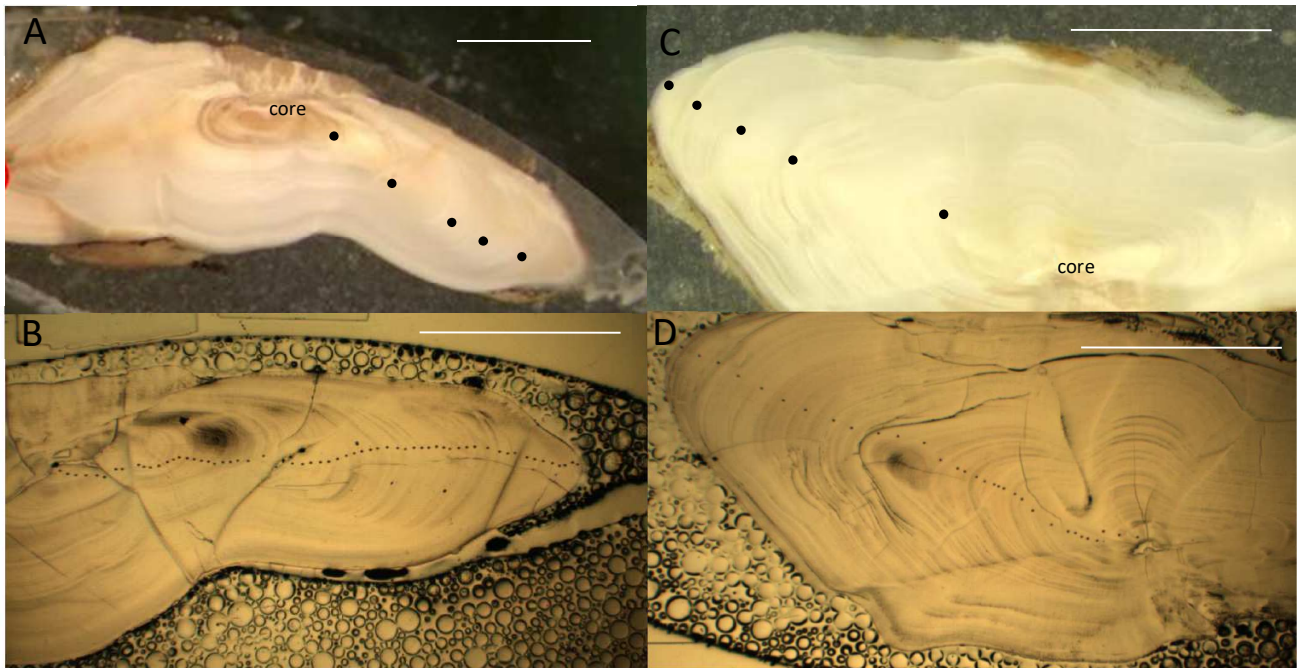
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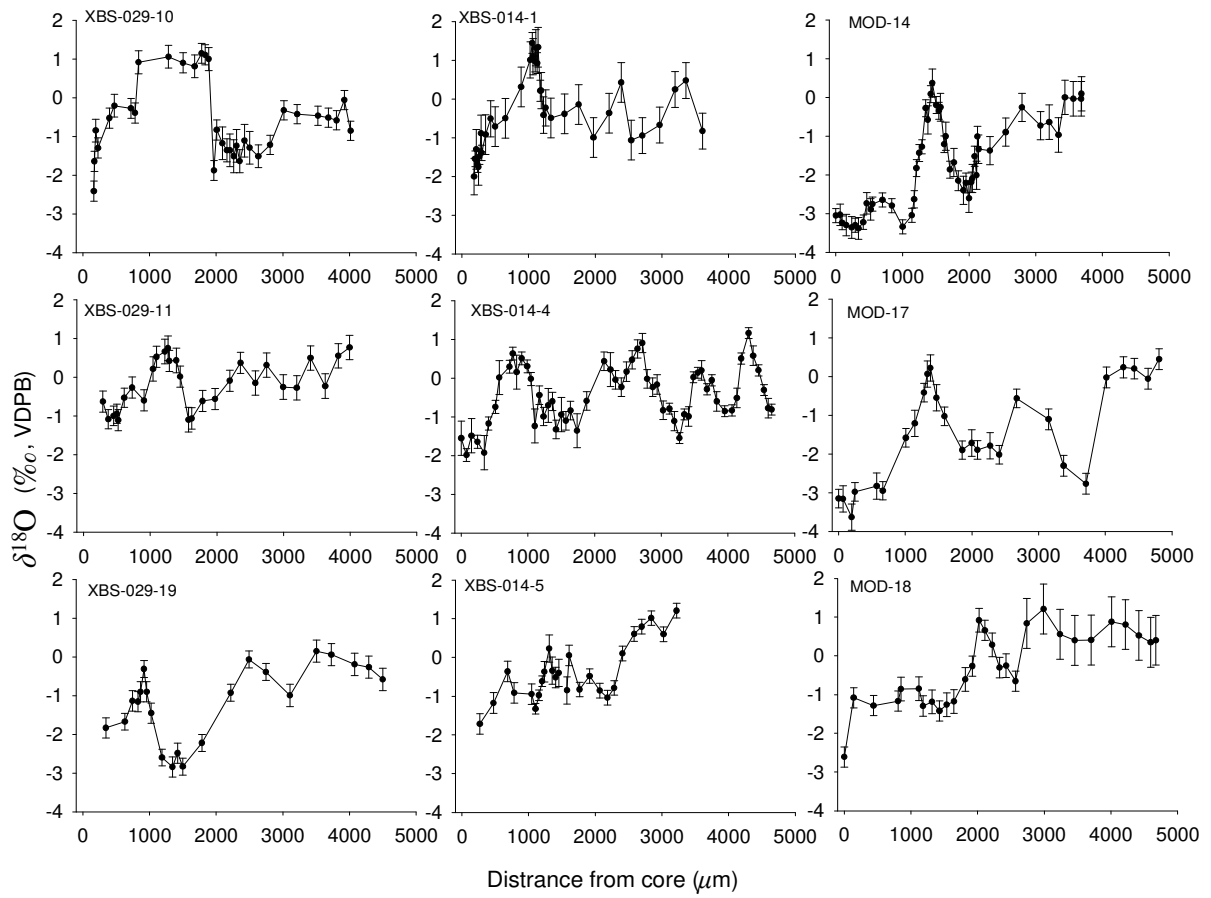
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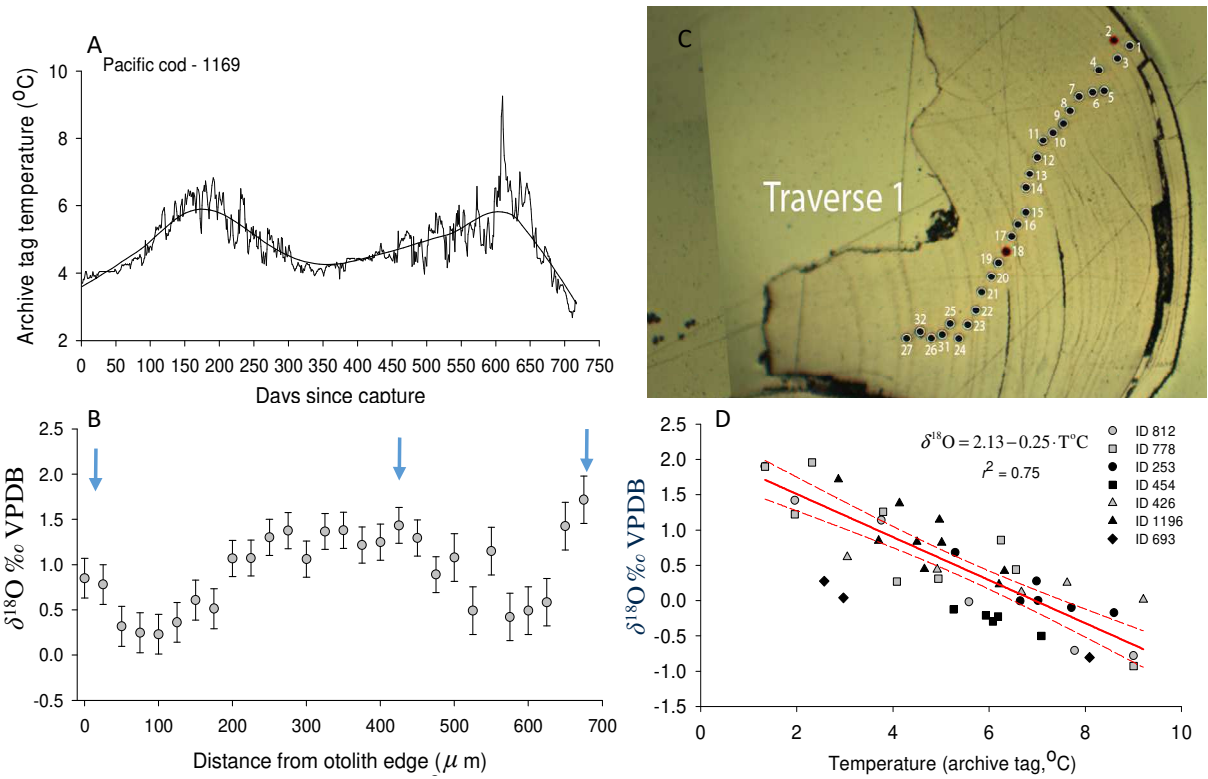
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933 Figure 5.

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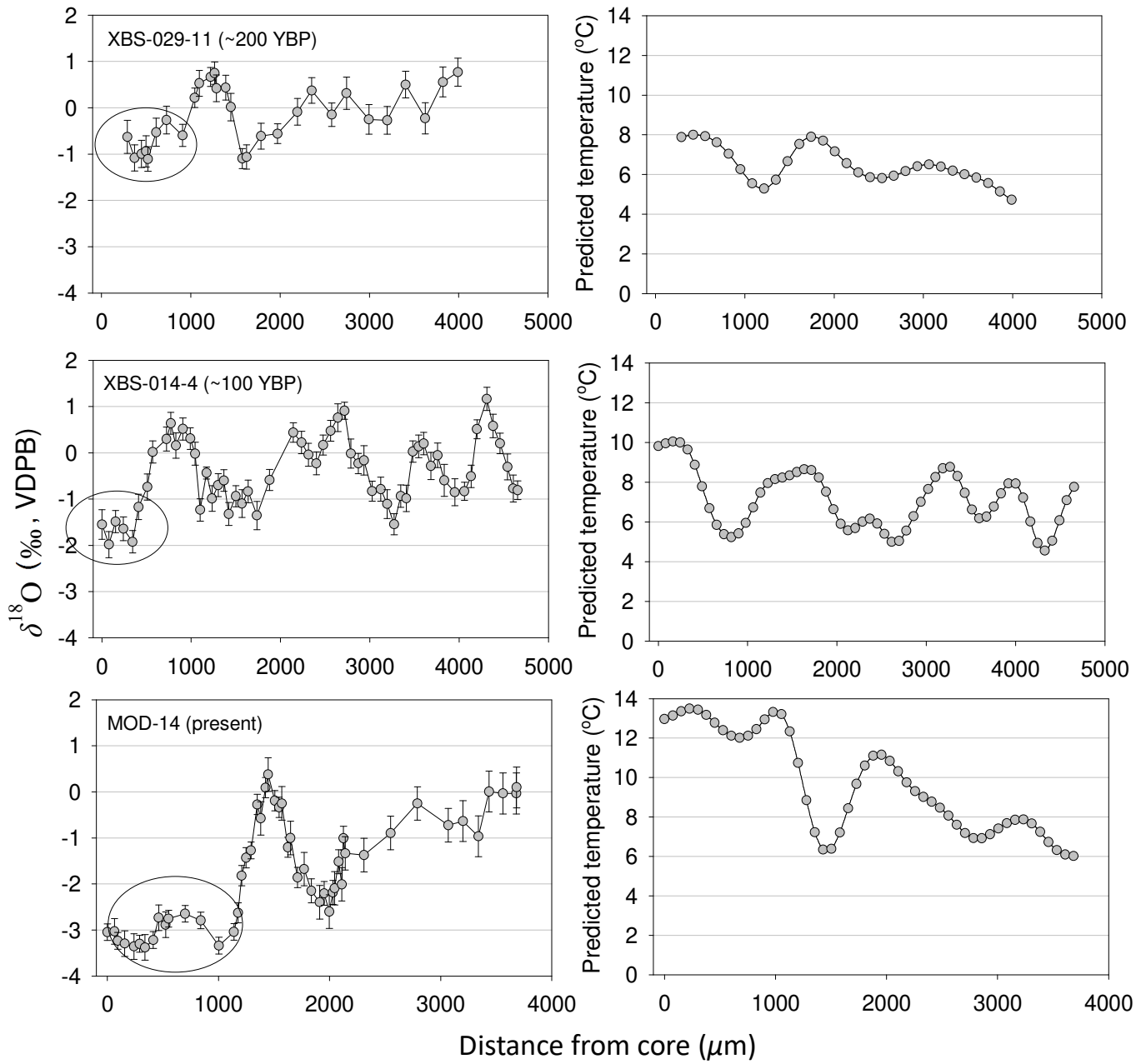
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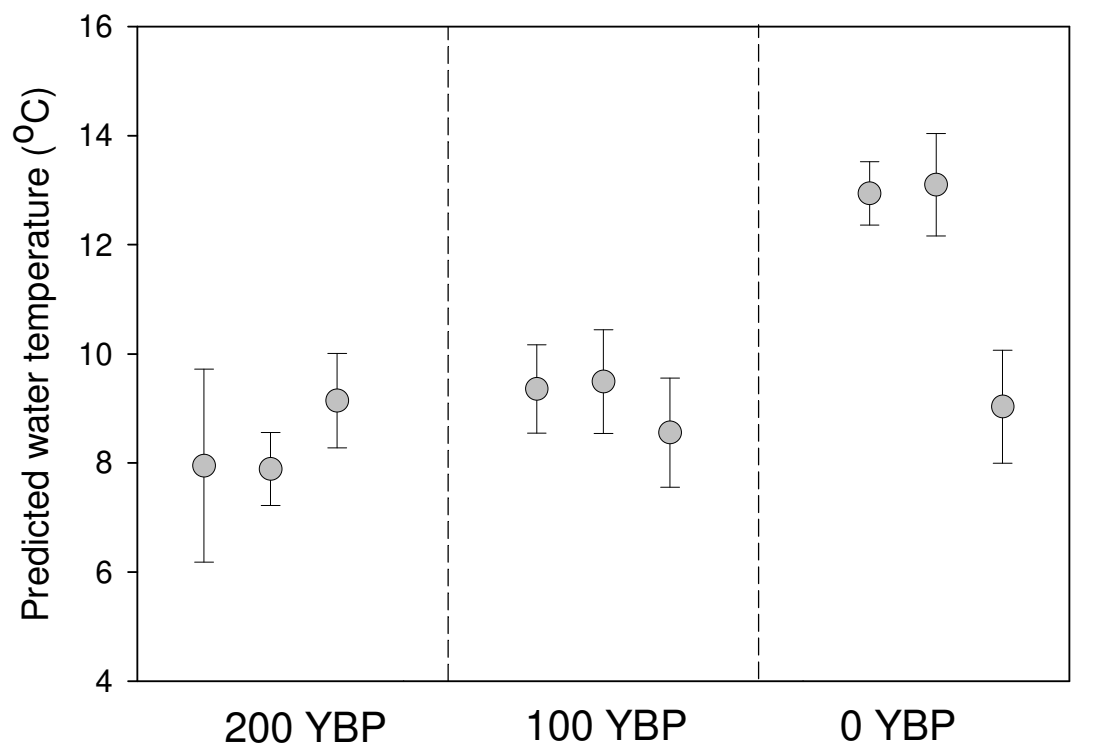
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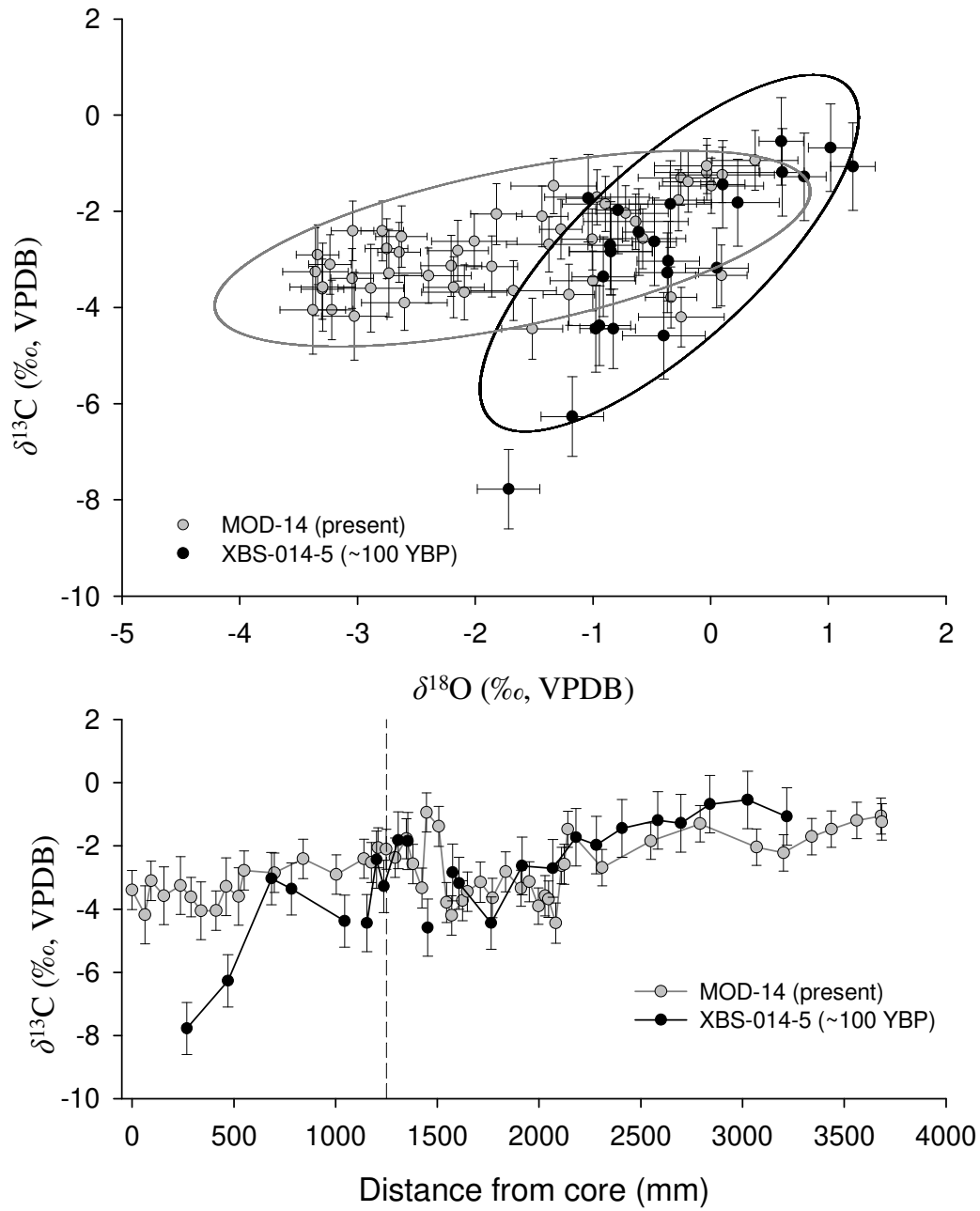


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958 Figure 7.

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982 Figure 8.

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985 Table 1. Modern and archaeological Pacific cod (*Gadus macrocephalus*) otoliths recovered from  
 986 the Early Contact village (~200 YBP) and Denton (~100 YBP) sites on Kenai Peninsula.  
 987 Summary data include sample age (YBP), fish ages estimated from growth zone counts, otolith  
 988 weight, fish length, details of the ion probe SIMS analyses, core region  $\delta^{18}\text{O}$ , and average  
 989 nearshore surface water temperatures predicted from  $\delta^{18}\text{O}$  values (Ion probe spot-specific  
 990 temperatures were predicted from  $T^{\circ}\text{C} = 6.198 - 2.195 * \delta^{18}\text{O}$ , and averaged).

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Sample ID <sup>3</sup>	Calibrated Age (YBP)	Estimated Age (years)	Otolith weight (g)	Fish length (mm) <sup>1</sup>	Number SIMS spots	Transect orientation	Transect		Core $\delta^{18}\text{O}$		Ave. water temp ( $^{\circ}\text{C}$ ) <sup>2</sup>
							Distance (mm)	Core $\delta^{18}\text{O}$			
								mean	SD		
XBS-029-10	200	5 - 6	0.445	564	37	Dorsal	4.43	-0.80	0.806	7.95	
XBS-029-11	200	4 - 5	0.454	571	32	Dorsal	3.03	-0.66	0.436	7.89	
XBS-029-19	200	6 - 7	0.529	629	25	Proximal	3.49	-1.34	0.394	9.14	
XBS-014-1	100	6 - 7	0.537	635	44	Dorsal	4.43	-1.44	0.370	9.36	
XBS-014-4	100	4 - 5	0.728	782	60	Ventral	4.15	-1.50	0.432	9.49	
XBS-014-5	100	5 - 6	0.534	633	31	Dorsal	4.72	-1.07	0.455	8.55	
MOD-14	present	4 - 5	0.531	630	50	Dorsal	3.68	-3.07	0.265	12.94	
MOD-17	present	5 - 6	0.482	593	28	Dorsal	4.94	-3.11	0.283	13.10	
MOD-18	present	5 - 6	0.679	744	32	Ventral	4.67	-1.29	0.472	9.03	

<sup>1</sup> Pacific cod length is predicted from:  $L = 221.5 + 769.97 * \text{Otolith\_weight}$ ,  $r^2 = 0.91$  (IPHC trawl data from Gulf of Alaska, 1964)

<sup>2</sup> Temperature predicted from:  $T^{\circ}\text{C} = 6.198 - 2.195 * \delta^{18}\text{O}$ .

<sup>3</sup> XBS-029 refers to the Early Contact Village site, XBS-014 refers to the Denton Site.

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