Pacific cod (*Gadus macrocephalus*) as a paleothermometer: otolith oxygen isotope reconstruction

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Journal of Archaeological Science 39 (2012) 3277–3283

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Pacific cod (*Gadus macrocephalus*) as a paleothermometer: otolith oxygen isotope reconstruction

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ARTICLE INFO

Article history:
Received 6 May 2011
Received in revised form
21 May 2012
Accepted 22 May 2012

Keywords:
Stable oxygen isotopes
Pacific cod
Otolith
Kodiak
Alaska
Methods

ABSTRACT

Stable isotope studies are increasingly important for understanding past environmental and cultural developments along the North Pacific Rim. In this paper, we present methods for using Pacific cod (*Gadus macrocephalus*) otoliths as a paleothermometer using a case study from Kodiak Island, Alaska. The results of this study indicate that Pacific cod otoliths record variable paleoenvironmental conditions during the Little Ice Age. The broad distribution of Pacific cod and success in using the otoliths as a paleothermometer makes this method widely applicable to researchers working throughout the northern Pacific Rim.

1. Introduction

Archaeological fish otoliths, or "ear stones", are increasingly used as paleothermometers because the ratio of stable oxygen isotopes deposited in these carbonate structures varies with water temperature (Devereux, 1967; Urey, 1947). This ratio can be used to estimate the environmental conditions where a fish was living. In an archaeological context, otolith stable isotope records have been produced for fish species in several regions (Andrus et al., 2002; Hufthammer et al., 2010; Rowell et al., 2010; Walker and Surge, 2006; West et al., 2011; Wurster and Patterson, 2001). These studies demonstrate that fish otoliths can be used to reconstruct ancient trophic positions, fresh and ocean water temperatures, and as indicators of climate change. Unlike other methods of paleoenvironmental reconstruction, like tree rings or glacial chronologies, archaeological otolith studies provide a direct link among prehistoric fish populations, the environment, and human behavior in the past.

Paleoenvironmental reconstruction based on archaeological material is integral to understanding the past along the Northern Pacific Rim. In particular, stable isotope studies have become important in dietary and climate reconstruction (Byers et al., 2011; Hirons et al., 2001; Misarti et al., 2009; Moss et al., 2006). Despite the recent interest in this methodology, as well as the central role that fish played in prehistoric economies in this region, studies of archaeological otoliths are limited. Previously, West (2009a) and West et al. (2011) used the stable oxygen isotopes in Pacific cod (*Gadus macrocephalus*) otoliths to reconstruct Little Ice Age (LIA) ocean conditions and to assess the relationship among climate, fish biogeography, and human foraging activity in the Gulf of Alaska. In this paper, we focus on the methods for using Pacific cod otoliths as a paleothermometer and suggest that the broad temporal and geographic distribution of this fish species makes their otoliths ideal for paleoenvironmental reconstruction in this region. Here, we outline this analytical method using a case study from Kodiak Island, Alaska.

2. Materials

2.1. Otoliths

Fish have three pair of otoliths (sagittae, asteriscae, and lapillae) that are used for acoustic perception and balance. Among these, the largest and most useful for oxygen isotope analysis in Pacific cod are the sagittae, which are well known to grow in daily, seasonal, and yearly bands (or annuli; Fig. 1). This growth can be seen in cross section as alternating translucent and dark bands: in Pacific cod,

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10.1016/j.jas.2012.05.009

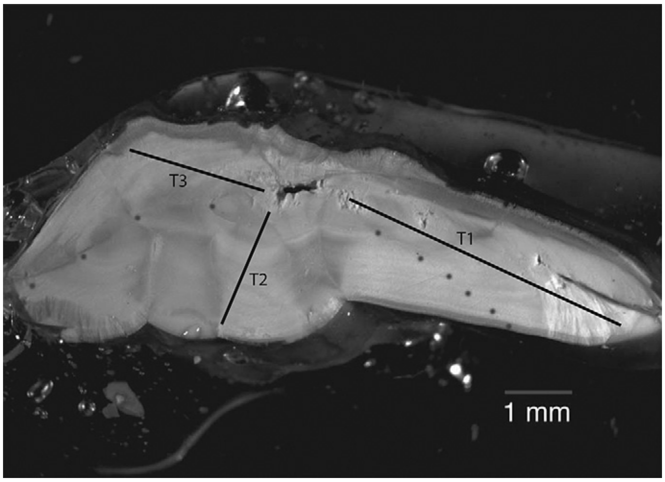

Fig. 1. Cross section of archaeological Pacific cod otolith. Dots indicate growth rings or annuli. Lines indicate location of sampled transects (T1, T2, and T3) from the core to the edges.

these represent periods of fast growth in the summer and slower growth in the winter. These bands are commonly used to age fish, and they have been used to determine the season of capture, though this remains controversial in an archaeological context (Kimura et al., 2007; Van Neer et al., 2004; West et al., 2011).

Otoliths are calcium carbonate ($CaCO_3$) in the form of aragonite, which precipitates in isotopic equilibrium with the surrounding water. Therefore, the annuli can be sampled to understand changes in the environment where the fish are living, migration patterns, and the effects of environmental variables on fish growth (Campana, 1999). In particular, the oxygen isotope ratios (^{18}O:^{16}O) in an otolith's growth bands are determined primarily by water temperature, given constant salinity and minimal influence of biological or metabolic processes (Campana, 1999; Ivany et al., 2000; Thorrold et al., 1997). As temperature decreases, carbonates preferentially uptake ^{18}O; therefore, variations in the ^{18}O:^{16}O in otolith aragonite may be interpreted as changes in ocean temperature.

Despite this well-established relationship, other factors can influence the ^{18}O:^{16}O in otoliths. Salinity is known to affect oxygen isotope ratios in ocean water. For example, fresh water input from glacial melt or seasonal run-off alters the oxygen isotope ratio in marine environments, which can influence fish habitats (Eldson and Gillanders, 2002; Xiong and Royer, 1984). In addition, many fish species migrate following seasonal changes in the North Pacific Ocean. These fish migration patterns may affect the ratio of oxygen isotopes recorded in otolith annuli as fish are exposed to variable environments and fresh water input.

2.2. Pacific cod otoliths

The Pacific cod is a cold-water, demersal fish found throughout the North Pacific Ocean from China's Yellow Sea to Monterey Bay, California (ADFG, 1985; Bakkala et al., 1984; Gustafson et al., 2000; Mecklenburg et al., 2002; Nichol et al., 2007; OCSEAP, 1986; Rovnina et al., 1997, Fig. 2). Cod recorded by the commercial fishery can have a length of up to 120 cm and a weight of 23 kg (Cohen et al., 1990), but are more commonly 70–75 cm with a weight of approximately 4.5 kg (Mecklenburg et al., 2002). Commercially, they are generally 4–6 years old at harvest.

Cod are found from 25 to 550 m deep depending on the season and their age (Gustafson et al., 2000; Shimada and Kimura, 1994). While relatively little is known about their movement, they appear to spend the majority of their time on the sea floor and make few vertical excursions into the water column (Helser, personal communication; Nichol et al., 2007). In many places, these fish spend the winter in deep water where they spawn and stop feeding, and in spring they move to shallower waters near shore to recommence feeding (ADFG, 1985; Savin, 2007; Shimada and Kimura, 1994; Stepanenko, 1995). As a result, Pacific cod are generally thought to have been available to prehistoric fishermen in the spring and summer when they come close to shore, though

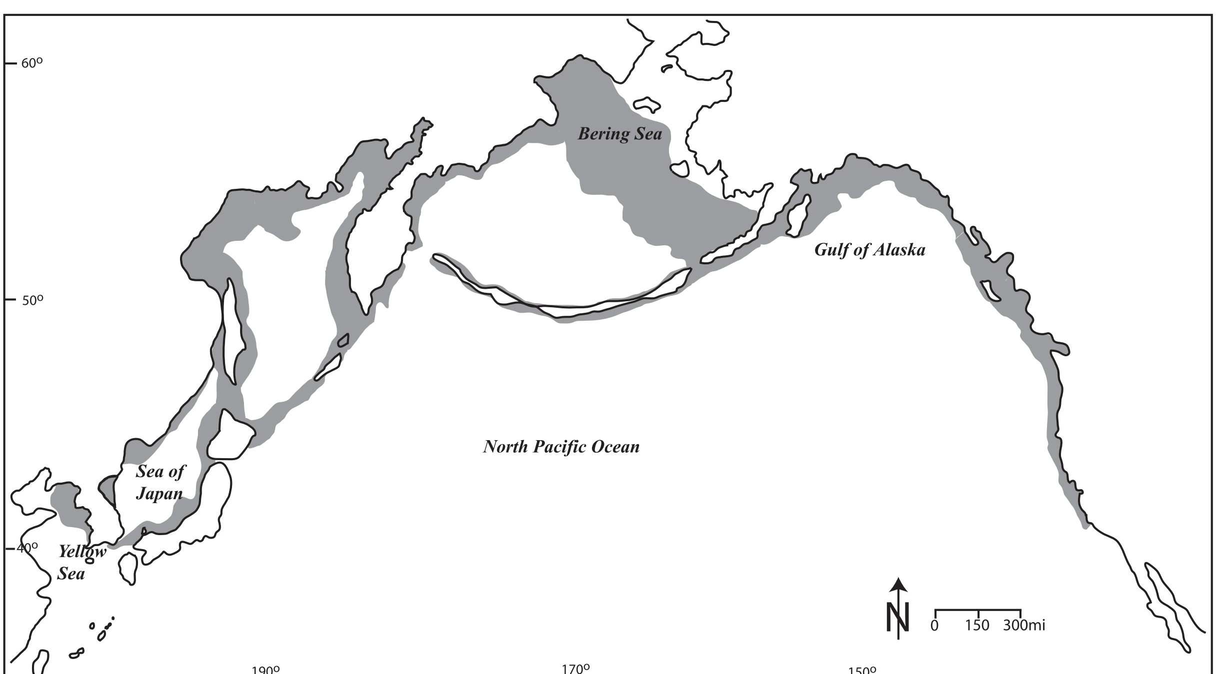

Fig. 2. Map of the distribution of Pacific cod. Redrawn from Gustafson et al. (2000).

they may have been available year-round in some places (ADFG, 1985; Savin, 2007; D. Urban, pers. comm.).

Archaeologically, Pacific cod otoliths are advantageous because of their large size. The relatively large size of the sagittal otoliths (15–20 cm along the frontal axis) increases their chance of preservation in the archaeological record. Archaeological otoliths of this family have been recovered in the North Pacific (e.g. Crockford et al., 2004; Kopperl, 2003; West, 2009a), though it is worth noting that otoliths may be misidentified as shellfish fragments or could have been lost when screens were not used during excavation.

We are unaware of any studies that specifically test the relationship between oxygen isotope fractionation and water temperature in contemporary Pacific cod otoliths; however, previous studies of Atlantic cod (*Gadus morhua*) suggest they are a useful proxy. Research on Atlantic cod confirms that when otoliths are formed, fractionation of oxygen isotopes is temperature-dependent and is in equilibrium with the ambient water (Gao et al., 2001; Hufthammer et al., 2010; Høie et al., 2004; Weidman and Millner, 2000). While there has been some discussion about the potential variations in oxygen isotope fractionation among different species of fish, Campana (1999) argues that this may be due to methodological issues, rather than real biological differences. Several authors demonstrate that the relationship between the oxygen isotope ratio in otoliths and temperature is equivalent to that of inorganic aragonite and appropriate for water temperature calculation (Campana, 1999; Kim and O'Neil, 1997; Kim et al., 2007).

3. Case study: the Karluk-1 site

The otoliths used in this study were sampled from the stratified and well preserved Karluk-1 site on Kodiak Island, Alaska, which has been described in detail elsewhere (Jordan and Knecht, 1988; Knecht, 1995; West, 2009b, 2011, Fig. 3). Kodiak Island is part of the Kodiak archipelago, which is located in the central Gulf of Alaska in the Northeastern Pacific Ocean. The Karluk-1 site is located at the mouth of the Karluk River on the southwest side of Kodiak Island and was excavated by Bryn Mawr College in the 1980s. Radiocarbon dates indicate the site was occupied from 500 $\pm$ 30 BP or 530 cal BP until Russian contact in the eighteenth century (West, 2011, Table 1). The site itself consists of ten discrete house floors and three substantial middens that were preserved in an anaerobic environment, and the house structures, artifacts, and faunal remains are a significant example of late-prehistoric culture (Knecht, 1995).

The Karluk-1 site was occupied during the Little Ice Age (LIA), which began in the Gulf of Alaska approximately 650 years ago (Barclay et al., 1999; Calkin et al., 2001; Grove, 2004; Mann et al., 1998; Wiles and Calkin, 1994; Wiles et al., 1996, 1998). Throughout the northern hemisphere, this period was characterized by cooling of 1–2 °C, colder winters, and glacial advance to Holocene maxima (Mann et al., 1998). This period was not static, however, and both tree rings and glacial records indicate that the Gulf of Alaska experienced periodic cold and warm phases during the LIA (Barclay et al., 1999; Calkin et al., 2001; Wiles et al., 1996).

4. Methods

4.1. Identification and preparation

As described by West (2009a, 2009b) and West et al. (2011), Pacific cod otoliths were recovered from the bulk faunal samples excavated from each stratigraphic layer of the Karluk-1 site (Table 1). Each bulk sample was sifted through 1/8" screen and all otoliths were removed for analysis. The otoliths were graded based

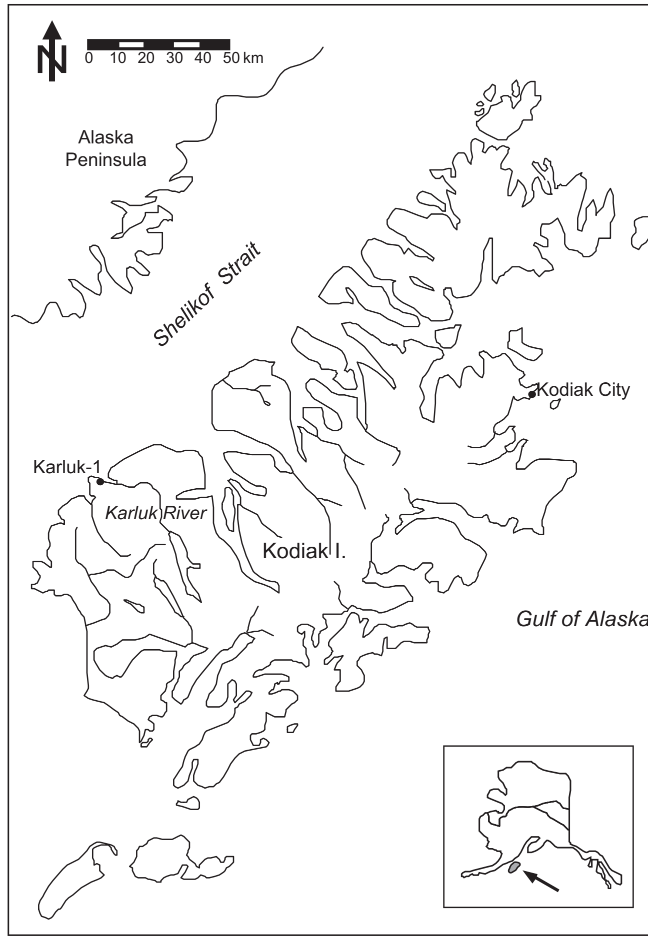

Fig. 3. Map of the Kodiak archipelago showing locations mentioned in the text. Map courtesy of the Alutiiq Museum and Archaeological Repository and Jennie D. Shaw.

on preservation, and a total of 15 whole otoliths were selected from the deposits, representing all layers of the archaeological site over an approximately 500-year time period (Table 1). Spatial patterning was not considered, given the rarity of otoliths among the faunal remains (West, 2009b).

The otoliths pulled from the Karluk-1 collections were identified using Harvey et al.'s (2000) photographic catalog and the protocol outlined by Morrow (1979), as well as comparative specimens. All of the otoliths were identified to the family Gadidae, and only those identified as Pacific cod were employed in this study. The otoliths were cleaned in de-ionized, distilled water in an ultra-sonicator, while those that were too fragile to be cleaned in the sonicator were rinsed in the same water and brushed gently. The otoliths were immersed in Crystal Bond 509, secured to a petrographic slide, and each otolith was cross-sectioned using a Buehler diamond saw fit with a 3.5" blade. The sections were polished gently with 1200-grit waterproof sandpaper to smooth the surface for milling and to remove any Crystal Bond from the cross section.

4.2. Aging

To distinguish between the summer and winter growth rings and target areas for sampling, the otolith sections were aged using the methodology developed by the National Marine Fisheries Service Age and Growth Program in Seattle (Kimura and Anderl, 2005; Roberson et al., 2005, Table 1). This method is based on Roberson et al. (2005), who have tested the relationship among fish

Table 1
Otoliths sampled for this project with their corresponding provenience, AMS date (calibrated and uncalibrated), and age data. A "+" in the age column indicates that the otolith may be older, but was difficult to read because of edge erosion. Those marked with a * were sampled for X-ray diffraction.

Catalog #	Level	NOSAMS accession #	AMS date (BP; 2σ)	Cal BP range (2σ)	Cal yr BP median age	Age
AM193F-01*	House floor 1	OS-58218	130 ± 30	280–10	130	3+ or 4 with growth
AM193F-22	House floor 2	OS-58223	190 ± 25	260–140	180	4+
AM193F-02	House floor 3	OS-58180	295 ± 30	460–290	380	5+
AM193F-03	House floor 3	OS-58180	295 ± 30	460–290	380	4+
AM193F-05	House floor 4	OS-58210	315 ± 30	460–300	390	5+
AM193F-17	House floor 4	OS-58210	315 ± 30	460–300	390	4+
AM193F-16	House floor 6	OS-61045	260 ± 30	430–150	300	3+
AM193F-11	House floor 7	OS-61047	250 ± 30	430–150	300	6+
AM193F-13*	House floor 7	OS-61047	250 ± 30	430–150	300	4+
AM193F-23	House floor 8	OS-58213	405 ± 30	520–330	450	6 with growth
AM193F-24	House floor 8	OS-58213	405 ± 30	520–330	450	5+
AM193F-29	House floor 8	OS-58213	405 ± 30	520–330	450	6+
AM193F-30	Upper Basal Midden	OS-58063	400 ± 30	510–330	470	5+
AM193F-09*	House floor 10	OS-61136	480 ± 30	550–490	520	4+
AM193F-33	House floor 10B	OS-58181	500 ± 30	550–500	530	5+

length, rate of growth, and otolith size in tagged fish to validate the aging methods for Pacific cod, and Kimura and Anderl's (2005) statistical approach to eliminating reader error. More recently, radiometric age validation and stable oxygen isotope data have been used to test the validity of this aging approach (Kastelle, 2009, Kastelle and Helser, 2010). It is notoriously difficult to distinguish between summer and winter growth in Pacific cod because cod tend to develop strong 'checks' in the first 5–6 years of life when the fish is growing rapidly (Ketchen, 1970; Roberson, 2001). Checks, or sub-annular marks, look like the dark winter rings, but are the result of temperature change, trauma, or some other influence during the fish's growing season. A second confounding factor is the annuli themselves: according to Roberson (2001), Pacific cod annuli are often thready and poorly defined, and are commonly miscounted. To confront these issues and to maintain consistency, several experienced readers used the methodology described above to age the archaeological otoliths across a number of axes.

4.3. X-ray diffraction

The interpretation of oxygen isotope data depends on whether the sampled material is in the mineral form calcite or aragonite because the mineral structure influences the relationship between oxygen deposition and temperature. Otoliths in living fish are primarily aragonitic structures, but there is evidence to indicate that there may be small amounts of calcite and vaterite present as well (Campana, 1999). These minerals contribute only minimally to the structure of an otolith, but aragonite can recrystalize into calcite as a result of significant changes in temperature, burial, or through the influence of groundwater (Campana, 1999; Faure and Mensing, 2005).

To determine whether the otoliths recovered from the Karluk-1 collections were aragonitic and appropriate for analysis, several were analyzed through powder X-Ray Diffraction (XRD) in the University of Washington Materials Science and Engineering Department. Otoliths were chosen from the top (house floor 1), middle (house floor 7), and base (house floor 10) of the site to get a representative temporal sample (Table 1). Samples were ground to a 100 μg powder using a mortar and pestle, and secured to glass slides with silicone vacuum grease.

4.4. Oxygen isotope sampling

The otoliths were sampled for oxygen isotope ratios at the Woods Hole Oceanographic Institution (WHOI) using a Merchantek micromilling device with a Leica GZ6 microscope. Drilling locations were chosen based on the annuli identified at NMFS, and each otolith was sampled in three transects (T1, T2, and T3) to get an average sample over the fish's lifetime. As shown in Fig. 1, these transects were taken along the longest axis of growth from the core to the anterior, dorsal, and ventral edges. The summer bands (Year 1, Year 2, etc.) were sampled individually to provide more detailed information, and the central point of each summer band was targeted [Fig. 1]. Summer bands were chosen because Pacific cod were likely harvested by prehistoric fishermen in the spring and summer when these fish came to shore and when the majority of the aragonite is likely deposited. Each locus was drilled to 75 μm deep, and a minimum of 20 μg was collected for isotopic analysis at the WHOI Micropaleontology Mass Spec Facility. The samples were run on a Finnigan MAT253 mass spectrometer system with a Kiel III Carbonate Device with a precision of ±0.1‰.

Oxygen isotope abundances are calculated relative to the international standard Vienna Pee Dee belemnite (VPDB) as a delta value (δ):

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}}\right) \times 1000(‰)$$

where R represents the ^{18}O:^{16}O in the sampled otolith or the international standard (VPDB). The $\delta^{18}O_{VPDB}$ values are expressed as per mil units (‰), and a higher value indicates that the sample is heavier (enriched in ^{18}O) relative to VPDB, while a lower value is lighter (depleted in ^{18}O). Variability in this measure, therefore, indicates changes in the ambient seawater temperature and environmental conditions.

5. Results and discussion

Our analysis suggests that otoliths recorded variable mean environmental conditions over the last 500 years (West, 2009a; West et al., 2011, Fig. 4). Mean $\delta^{18}O$ values range from 0.78‰ to 1.48‰, and the results have been plotted based on the median Accelerator Mass Spectrometry (AMS) date for each stratigraphic layer (Figure 4). There are two periods when $\delta^{18}O$ values are relatively high, meaning ocean conditions were probably cooler: at the onset of occupation at 500 ± 30 BP or 530 cal BP and again after 190 ± 25 BP or 180 cal BP. There is a potentially warmer period at 315 ± 30 BP or 390 cal BP.

XRD analysis demonstrates that the otolith samples did not recrystalize and can be analyzed using the standard methods for aragonite (West, 2009b). While temperature is one influence on the ratio of oxygen isotopes present in a sample, accurate temperature reconstructions are potentially limited by other factors, including metabolic processes, salinity, and ocean water $\delta^{18}O$ values. As mentioned, metabolic processes do not appear to have a significant effect on oxygen isotope fractionation in otoliths (Campana, 1999; Høie et al., 2004; Thorrold et al., 1997). However, mixing of fresh and saltwater is well known to affect oxygen isotope ratios in ocean water, which is reflected in carbonates. Both Gulf of Alaska salinity history and the salinity tolerance of Pacific cod are poorly understood, though studies indicate that Pacific cod are highly demersal

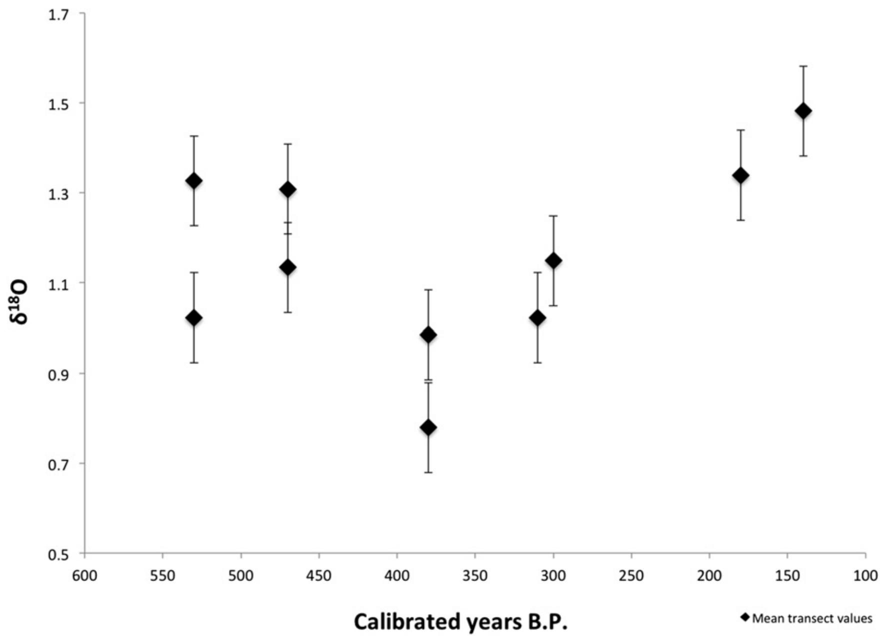

Fig. 4. Results of the Karluk-1 Pacific cod otolith analysis showing changing oxygen isotope ratios ($\delta^{18}O$) through time. The results are based on mean transect values with 0.1‰ error bars, and are plotted through time from 530 cal BP to 130 cal BP.

and spend most of their time close to the sea floor (Nichol et al., 2007). As noted above, they make few vertical excursions into the water column, so it is unlikely these fish experience significant variation in salinity that might be caused by glacial melt, freshwater input, or seasonal mixing (Helser pers. comm.; Nichol et al., 2007). Finally, to calculate ocean temperatures based on $\delta^{18}O_{otolith}$ values, $\delta^{18}O_{water}$ must be known; however, because it is not possible to know prehistoric $\delta^{18}O_{water}$ values, these values must be assumed based on contemporary water conditions. Therefore, temperature calculations of prehistoric ocean water based on $\delta^{18}O_{otolith}$ values are subject to uncertainty (Campana, 1999; Pentecost, 2005). As a result, we present mean $\delta^{18}O_{otolith}$ values, which represent 3–6 years of growth and provide relative changes in environment.

However, using the mean $\delta^{18}O_{otolith}$ values may mask seasonal variability and create ontogenetic biases. To address seasonal variability, we made a graphical assessment of the mean transect and annulus values for the Karluk-1 deposits (Fig. 5). The difference in the transect and annuli mean values is expected to be slight because the wide summer growth rings contribute more material to the isotopic analysis than the very thin winter growth rings.

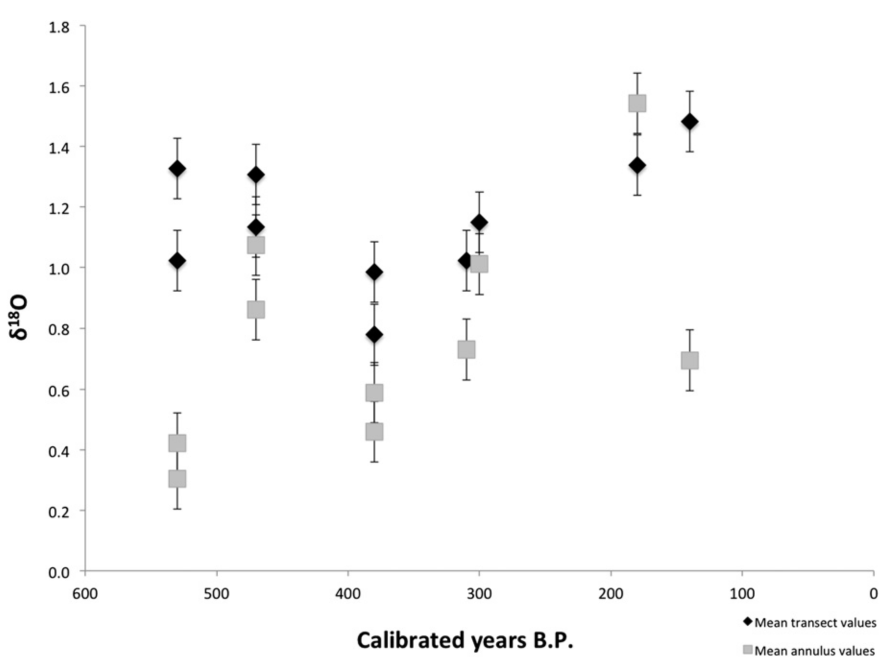

Fig. 5. Comparison of transect mean $\delta^{18}O$ value (squares) and annulus (summer) mean $\delta^{18}O$ value (diamonds) by stratigraphic layer. The results are based on mean transect values with 0.1‰ error bars, and are plotted through time from 530 cal BP to 130 cal BP.

Comparison of these data in Fig. 5 indicates there is little difference in the overall trend for these values among the layers. *T*-tests for each stratigraphic layer reveal there is no significant difference between the annulus mean values and the transect mean values for the majority of the layers (West, 2009b). In addition to seasonal variability, ontogenetic bias may result from slower growth later in the fish's life: as fish grow, less aragonite is deposited in otoliths, potentially biasing mean $\delta^{18}O_{otolith}$ values. This could be solved by taking weighted means or by producing fine-grained, time-series records for Pacific cod otoliths, which do not yet exist. Such fine-grained records are available with detailed milling techniques that could provide an oxygen isotope time series for individual fish (Patterson et al., 1993; Weidman and Millner, 2000; Wurster and Patterson, 2001). This kind of detailed sampling of Pacific cod otoliths will be vital to clarify how seasonal variability and fish growth rate influence aragonite deposition rate.

6. Conclusions

The results presented above indicate that Pacific cod living around the Kodiak archipelago experienced changing environmental conditions during the last 500 years. In West (2009a) and West et al. (2011), we compared these data to other detailed paleoenvironmental records for the Gulf of Alaska, and these comparisons support the suggestion that cod tolerated some fluctuation in ocean temperature during the LIA.

Pacific cod have been recovered from archaeological sites throughout the region, so this methodology is applicable to other faunal collections. The archaeological record indicates cod were a significant resource in many areas over several millennia (e.g. Bowers and Moss, 2001; Huelsbeck, 1983; Kopperl, 2003; Maschner et al., 2008; Partlow, 2000; West, 2009b; Yarborough, 2000; Yesner, 1998), and their significance in human foraging and subsistence activities is increasingly emphasized for the region as a whole (e.g. Moss and Cannon, 2011). In combination with zooarchaeological analyses, otolith datasets may contribute to our understanding of Pacific cod biogeography on a broad geographic and temporal scale, and can offer insight into how fish populations have responded to changes in Holocene climate throughout the North Pacific Ocean.

Further, Pacific cod are currently broadly distributed around the North Pacific Rim and they are a valuable and heavily managed commercial resource. While research on how Pacific cod respond to climate change is limited, several authors argue that an increased abundance of demersal fish, such as Pacific cod, can be loosely tied to positive temperature anomalies in the Pacific Ocean (Bailey, 1981; Hollowed et al., 2001; McFarlane et al., 2000; Stepanenko, 1995). However, this research is limited to current and historical catch records. Given the time depth provided by archaeological otoliths, this methodological approach will provide a long-term record of cod–environmental interaction that may contribute to our understanding of Pacific cod survival in the face of changing climate in the North Pacific Ocean.

Acknowledgments

This research is supported by the Prince William Sound Oil Spill Recovery Institute, the National Science Foundation, the Alaska Anthropological Association, and the University of Washington Quaternary Research Center. Thanks also to Koniag, Inc. and the Alutiiq Museum and Archaeological Repository for facilitating and supporting my use of the archaeological collections, and to Delsa Anderl and Dan Urban at the AFSC, the National Ocean Sciences AMS facility, and Dorinda Ostermann, Benjamin Walther, and Simon Thorrold at the Woods Hole Oceanographic Institute Micropaleontology Lab. Thanks to Torben Rick and two reviewers for their valuable comments on this paper.

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