Journal of Archaeological Science 37 (2010) 78–83

Contents lists available at ScienceDirect

Journal of Archaeological Science

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

Seasonality of human site occupation based on stable oxygen isotope ratios of cod otoliths

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ARTICLE INFO

Article history:
Received 18 December 2008
Accepted 1 September 2009

Keywords:
Gadus morhua
Norway
$\delta^{18}O$
Carbonate
Micromilling
Temperature

ABSTRACT

Oxygen isotope ratios ($\delta^{18}O$) were measured in micromilled samples of cod otoliths recovered from two Stone Age sites, one from Skoklefald, southeastern Norway and five from Skipshelleren, southwestern Norway. Discrete samples of otolith material were milled from the edge of the otolith towards the centre, each sample representing 3–4 weeks of growth. The $\delta^{18}O$ values showed seasonal signals, covering a period 1–2 years prior to the time of capture. Isotope ratios at the edge of the otoliths, which is the material deposited at the time of fish capture, corresponded to the coldest seasonal water temperatures, in late winter or early spring. These data provide independent evidence for the season of use of the Skoklefald and Skipshelleren sites.

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1. Introduction

The Mesolithic inhabitants of Norway were hunters, fishers and gatherers, with a predominantly coastal mobile settlement pattern. The settlement system probably consisted of a combination of smaller, short-term occupation sites, either hunting camps or activity sites (Indrelid, 1978; Mikkelsen, 1978; Skar and Coulson, 1986) and, mainly in the Late Mesolithic, larger sites that were used repeatedly or for longer duration (Bergsvik, 2001; Olsen, 1992). To understand the settlement sites and their role in subsistence strategy it is essential to determine the seasonal timing of their occupation.

In western Norway there are also numerous caves and rock-shelter sites that provide excellent preservation conditions for unburnt bones (Hufthammer, 2006). Studies of seasonal occupation have been made for a few of these sites, limited to archaeological methods, i.e. based on artifacts and settlement extension.

The analysis of vertebrate remains, i.e. teeth, bones and fish otoliths has been the principle tool for the interpretation of seasonality in archaeology. Most methods, such as interpretation of tooth replacement and wear and reading of incremental zones in mammal teeth and fish vertebrae and otoliths, rely on validation by comparisons with modern control samples as well as large sub-fossil vertebrate samples (Van Neer et al., 2004).

Fish remains are abundant among the bones preserved in Stone Age coastal sites in Norway. Although fish otoliths (ear stones) are fairly rare in the prehistoric settlement sites in southern Norway, they are frequently found in Northern Norway sites, in particular in farm middens dated to Historical times.

Both annual and daily growth structures are identifiable in fish otoliths, and analysis of these growth zones has been used to determine season of occupation or fishery, i.e. at the Mesolithic sites Ertebølle and Bjørnsholm in Denmark (Enghoff, 1995) and at the Medieval site Raversijde in Belgium (Van Neer et al., 1999). The method relies on the assumption that the opaque and translucent growth increments are formed seasonally and therefore that the type and size of the outermost zone will indicate the time of fish capture. However, the seasonal timing of opaque and translucent zone formation varies between individuals, populations and species (Beckman and Wilson, 1995; Pilling et al., 2007). For example, cod in northern Norway deposit translucent zones from December to April, while cod in southern Norway deposit translucent zones from July to October (Dannevig, 1933; Høie et al., 2009). This variation leads to uncertainty in determining the time of capture for individual fish.

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0305-4403/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.jas.2009.09.001

The chemical composition of carbonate material can be measured and the information used in conjunction with growth zones for a more precise estimation of seasonality. Stable isotope ratios can provide valuable insights in paleoenvironment studies (Hedges et al., 2005; Patterson et al., 1993). Shackleton (1973) measured the $\delta^{18}O$ values of carbonate material sampled along a transect crossing the growth increments of mollusc shells and reconstructed annual seasonal cycles from the estimated temperatures. The temperature cycle was used to determine the time of death and infer the season of harvest by site occupantion. The methodology employed large amounts of sampled carbonate material, both because of the drills used to extract the samples from the shells and because of the limits of the analytical instrumentation. For this reason the analysis of seasonality from $\delta^{18}O$ measurements was difficult to apply to smaller objects like fish otoliths.

The oxygen isotope ratio in the apatite and carbonate tissues of bones, otoliths, and shells is determined by ambient temperatures as well as by the isotope ratios of local water masses. Often biological processes, or "vital effects", are also involved. The calculation of accurate temperature from measured carbonate (or apatite) $\delta^{18}O$ values requires incorporation of the $\delta^{18}O$ values of the surrounding water mass at the time of carbonate precipitation. Recent methodological developments have enabled the determination of variations in $\delta^{18}O$ from material sampled at discreet intervals through the growth zones of fish otoliths (Høie et al., 2004a). Using experimentally determined relationships (Høie et al., 2004b), and information about water $\delta^{18}O$ values (Hoefs, 1997), the temperature experienced by an individual fish can be reconstructed for studies of growth and ecology in modern fish (Weidman and Millner, 2000). However, the challenge in applying this technique to archaeological samples stems from the lack of corresponding water $\delta^{18}O$ values for calculation of accurate temperature.

Even without accurate temperature values, the cycle of variation carbonate $\delta^{18}O$ values will mirror seasonal changes, and provide evidence for the seasonality of capture and site occupancy. The interval of the individual samples along the time transect must be at a fine scale to avoid masking the temperature minima and maxima. The ability to extract and analyze small sample volumes provides a high-resolution series of $\delta^{18}O$ values, resulting in realistic reconstruction of seasonal temperature cycles (Høie et al., 2004a; Wurster et al., 1999). Seasonal variations in $\delta^{18}O$ values have been measured in fish otoliths as old as the Jurassic period (Patterson, 1999), and have been used to study past climate and fish behaviour (Andrus et al., 2002; Carpenter et al., 2003; Patterson, 1998). Thus, even if data of water $\delta^{18}O$ are lacking, the season of fish capture can still be obtained from otolith $\delta^{18}O$ values as long as the fish experience seasonal temperature fluctuations. The outermost samples, which reflect the time of capture, can be positioned relative to the seasonal temperature fluctuation (Høie and Folkvord, 2006). The technique uses a high-resolution series of $\delta^{18}O$ estimates to follow seasonal variations and provide a more accurate method to determine season of occupation than single edge estimates or by reading of incremental zones of the otoliths.

We used high-resolution micromilling to obtain discreet samples of otolith material to reconstruct the annual temperature cycles from fossil otoliths and to estimate the season of capture. These data can be used to infer the seasonality of occupation for the archaeological sites where the remains were recovered. This micromilling technique provides high spatial resolution otolith carbonate samples corresponding to high temporal resolution of the fish's life, resulting in a well defined pattern of seasonal temperature fluctuations. The method has been validated experimentally for cod in Norwegian waters (Høie et al., 2004a).

2. Material

We measured seasonal otolith signals from six cod otoliths: five from the Mesolithic and one from the Neolithic (Table 1). One otolith originates from Skoklefald, an assumed short-term occupation site in Eastern Norway (Jaksland, 2001). The other otoliths are from Skipshelleren, a presumed seasonally occupied rock-shelter in western Norway (Indrelid, 1978). Skipshelleren has occupation faces from the Mesolithic, the Neolithic as well as the older Iron Ages (Haakon Olsen, pers. comm.; Hufthammer, 1994).

The Skoklefald locality is an open air site on the eastern side of the Oslofjord (Fig. 1). According to Jaksland (2001) the site is a kitchen midden, so far the only one of its kind found in Eastern Norway. The site is dated to ca. 6000 BC based on typology and shore line displacements curves. The small extension and thickness of the culture layer, as well as the lack of separate layering, events or faces observed in the profile indicate that it most probably is a short term site and occupied only once (Jaksland, 2001). The excavation produced 633 bones, most of them unburnt, along with 6–7 kg of shells. At least 11 vertebrate species are represented in the sample and fish remains, including 3 otoliths, dominate.

Skipshelleren is a rock-shelter site in Western Norway, ca. 50 km from the sea coast (Fig. 1). Archaeological typology (Bøe, 1934; Indrelid, 1978; Bergsvik, 2001) and radiocarbon dates indicate that the site was mainly in use in the late Older- and Younger-Stone Age and Bronze Age. Skipshelleren was probably a short term settlement, most likely utilized seasonally (Bergsvik, 2001). More than 24,000 bones (including 230 otoliths) have been identified to the level of species; a total of 23 mammal species, 22 fish species and 48 bird species.

All six otoliths were well preserved, with their outer edges intact (Fig. 2). When sectioned, the growth increments were clearly visible in the five otoliths from Skipshelleren, while it was difficult to detect any growth zones in the otolith from Skoklefald. However, based on size, morphology and some visible growth features, we judge the Skoklefald cod to have been two years old when captured. The Skipshelleren otoliths were estimated to come from fish captured at 4–7 years of age (Table 1).

Between 29 and 53 mg of material was sampled from the anti-rostrum of the Skipshelleren otoliths for radiocarbon dating. Otoliths SH1, SH2, SH3 and SH5 were dated to the Mesolithic, ca. 6000 BP, and otolith SH4 was date to the Late Neolithic (Table 1).

Table 1
Overview of otolith samples used for oxygen isotope analysis of season of capture giving otolith size, estimated fish length, fish age and radiocarbon dating results.

Otolith	Otolith weight, mg	Otolith length, mm	Estimated fish length, cm	Fish age	Age
SK 1	129.8	8.0	18.5	2	≈6000 BC
SH 1	487.2	16.6	60.3	7	Poz 11990 6420 ± 40 BP
SH 2	443.9	16.6	60.3	4	Poz 11991 6440 ± 35 BP
SH 3	516.8	17.5	64.3	6	Poz 11992 6420 ± 40 BP
SH 4	678.8	19.5	74.1	7	Poz 11993 3860 ± 35 BP
SH 5	540.0	17.0	61.9	7	Poz 11994 6630 ± 40 BP

SK = Skoklefald, SH = Skipshelleren. Fish lengths were estimated from otolith length by the linear equation of Härkonen (1986).

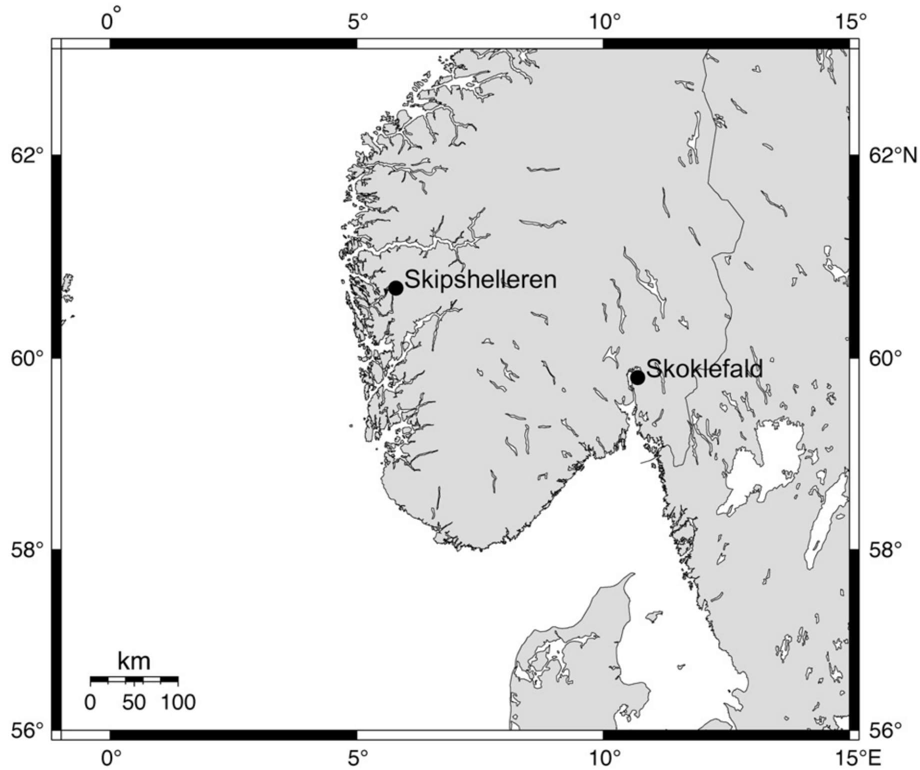

Fig. 1. Locations of Skoklefald in eastern Norway and Skipshelleren in western Norway.

3. Methods

The seasonality of human occupation at these two sites was estimated by analysis of the seasonal variations in fish otolith oxygen isotope ratios, as sampled with high-resolution micromilling and analyzed with high precision, low sample volume mass spectrometry (Høie et al., 2004a; Kleiven et al., 2008). The six selected otoliths were embedded in Epofix resin and two or three 500 μm sections were cut in the transverse plane close to the core, using a Buehler low speed saw with diamond blade. The sections were polished until the growth increments were visible, and the sections were photographed using reflected and transmitted light (Fig. 2).

The Skoklefald otolith was sampled from otolith edge to close to the core. The two outermost annuli, representing the last two years of the fish's life, were sampled from the Skipshelleren otoliths. Lines following the otolith growth increments were traced on the digitized otolith images using ImageJ software (Abramoff et al., 2004, Fig. 2c). The line coordinates were imported to the computer-controlled micromill (NewWave Research), which consists of an adjustable-speed drill and a sample stage that moves in sub-micron step resolution along the *X*, *Y* and *Z* axes. Scan lines were interpolated based on the imported coordinates to give 10–12 samples within each otolith annulus.

Discrete samples were milled from the otolith edge and inwards, using the edge of the drill bit. In this manner the sampling resolution is independent of the drill size since the samples are shaved off using the drill bit edge. Sample depth was set to 150 μm, and sample width varied from 24 to 45 μm resulting in carbonate samples of approximately 25–45 μg. Fourteen samples were collected from the Skoklefald otolith (a young fish), and 17–23 samples from each of the five Skipshelleren otoliths. Some samples near the edge of otolith SH1 and SH5 were lost during sampling and analyses. Four new samples from the edge and inwards were milled from a second section of the same otoliths to supplement the lost samples.

The milled otolith carbonate was transferred to glass vials and analysed on a Finnigan MAT 253 mass spectrometer (Kleiven et al., 2008). The long term reproducibility of the MAT 253 is ±0.1‰ for $\delta^{18}O$ (standard deviation) for sample sizes between 6 and 90 μg based on replicate measurements of an internal carbonate standard over a period of months, corresponding to ±0.5 °C when converted to a temperature estimate based on the temperature – $\delta^{18}O$ relationship for cod (Høie et al., 2004b).

4. Results

An annual cycle of seasonal temperature change was revealed from the 14 measurements of the Skoklefald otolith (Fig. 3a). In coastal Norwegian waters maximum temperatures occur in July/August and minimum temperatures in February/March (Høie and Folkvord, 2006). The edge sample has the highest $\delta^{18}O$ value, indicating that the edge of the otolith was deposited when waters were coldest; i.e. in late winter or early spring. The edge is the last material to be deposited on the otolith and marks the time of fish capture, leading to the conclusion that the Skoklefald site was in use in late winter or early spring.

The $\delta^{18}O$ curves of the 5 Skipshelleren otoliths are based on 17–23 microsamples (Fig. 3b–f). The $\delta^{18}O$ values from SH1 to SH4 all show clear seasonal cycles, ending with high values at the otolith edge. Therefore these four fishes were caught at time of the lowest sea temperature; in early spring.

The pattern of the $\delta^{18}O$ cycle in SH5 is different, with generally lower values. These could result from either warmer waters or less saline conditions. Also the outermost sample was lost during sampling, and replaced with samples milled from a parallel section. The data cannot be interpreted to indicate at what time of the year this fish was caught.

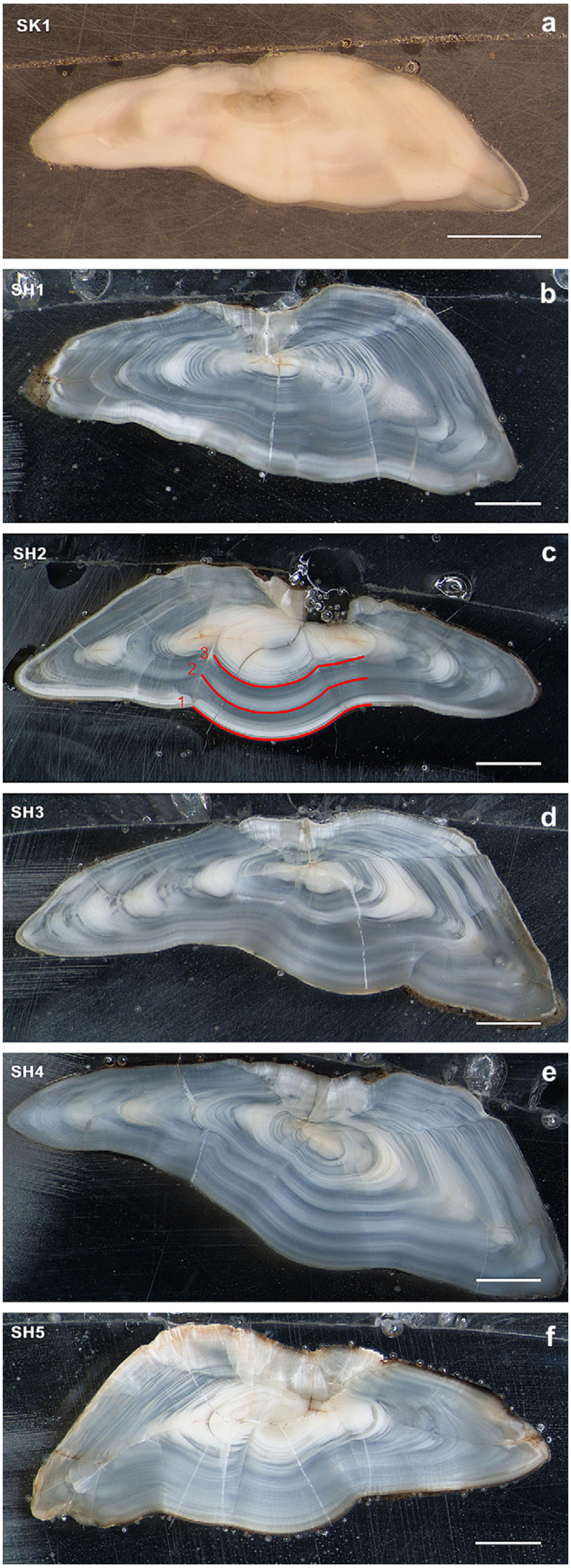

Fig. 2. Pictures of the sectioned otoliths. (a) SK1 is the otolith from Skoklefald, (b–f) SH1–SH5 are the five otoliths from Skipshelleren. (c) Otolith SH2 also shows the lines used for defining the carbonate sampling areas. Nine samples were milled following paths interpolated between lines 1 and 2. Ten samples were milled following paths interpolated between lines 2 and 3. Horizontal scale bars in each picture represent 1 mm.

5. Discussion

The reconstruction of seasonal cycles using stable isotope analysis of otolith material sampled by the micromilling technique is one of the most accurate methods available for assigning time of death of fish from archaeological sites. This analysis offers a great potential in identifying season of occupation, because it relies on inferring the edge from a long term pattern rather than an exact temperature estimate. The condition of the preserved material is an important consideration, and it is critical that the outer surface of the otolith is intact and well preserved. All six otoliths in our investigation were intact, and showed no visual signs of chemical diagenesis/alteration.

$\delta^{18}O$ values in fish otolith carbonate are inversely related to water temperature because more of the heavier ^{18}O isotopes are incorporated into the precipitating otolith as temperature decreases. Otoliths continue to grow throughout a fish's life and the otolith material is not reabsorbed or remolded after deposition (Campana and Neilson, 1985). The calcium carbonate found at the outer surface of the otolith has been deposited most recently, and represents the environment experienced by the fish just prior to capture or death. The micromilling technique removed samples beginning at the outer edge of the otolith, each sample representing 3–4 weeks of growth (Høie et al., 2004a). As demonstrated using modern cod samples, the micromilling techniques produces a high-resolution record of the seasonal temperature cycle experienced by an individual (Høie et al., 2004a; Weidman and Millner, 2000; Wurster et al., 1999).

If fish migrate between areas with different water masses with varying $\delta^{18}O$, this may confound the seasonal temperature signal. This is especially the case for marine fish living in water masses of high and variable freshwater influence, where the $\delta^{18}O$ of water will be more negative and can vary considerably as an effect of local freshwater runoff from land (Hoefs, 1997; Punning et al., 1991). Otolith $\delta^{18}O$ values decrease by approximately 1‰ for every 5 °C increase in temperature (Høie et al., 2004b; Weidman and Millner, 2000). In comparison, otolith $\delta^{18}O$ decreases by approximately 1‰ for every 4 psu reduction in salinity, based on isotope mixing lines for the northeast Atlantic (Israelson and Buchardt, 1999; Punning et al., 1991). Fish that migrate between estuarine areas with low salinity and offshore areas with high salinity will therefore have otolith $\delta^{18}O$ values that incorporate the $\delta^{18}O$ values of the different water masses, which can mask the temperature effect. However, when fish enter very low salinity areas, like the waters in some areas close to Skipshelleren, which is situated by a fjord at the mouth of the river Vosso, this incursion into lower salinity water can be recognised in the otolith $\delta^{18}O$ signals. These values would be much more negative than values found in typical marine environments, even at warmer temperatures. We suggest that this might be the case in one of the otoliths (SH5) due to the generally lower $\delta^{18}O$ values. That might indicate that this fish spent more time at low salinities and this masks the seasonal temperature signal.

The $\delta^{18}O$ values of the Skoklefald otolith reflect a seasonal cycle, with increasing values at the otolith edge. The edge is the last material deposited on the otolith and marks the time of fish capture, leading to the conclusion that the Skoklefald site was in use in late winter or early spring. This does not exclude the

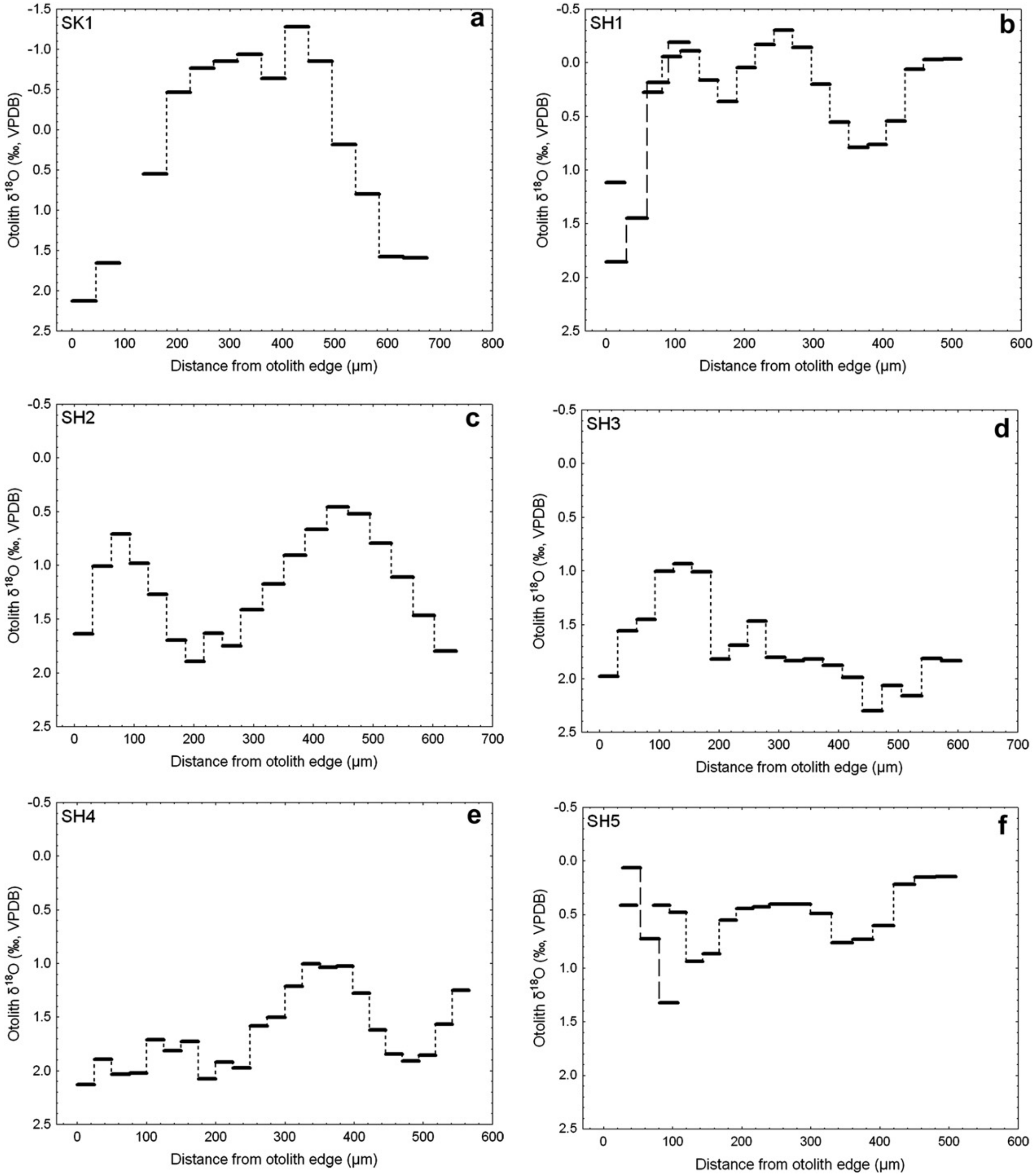

Fig. 3. Stable oxygen isotope values ($\delta^{18}O$) of the six cod otoliths. Note the different *Y*-axis scale for otolith SK1 (a), and that the *Y*-axes are reversed so that smaller values corresponding to higher temperatures are toward the top of each graph and larger values corresponding to colder temperatures are toward the bottom of each graph. Four and three extra samples from a second otolith section were analysed from otoliths (a) SH1 and (f) SH5 respectively.

possibility that the site was also occupied during the summer, as postulated by Jaksland (2001). Numerous single structures and clearly defined deposits are present in the cultural deposits of the Skoklefald site, but heavy compression, mix up or layers are not observed. This evidence, together with the scarcity of artefacts that have been found suggested that the site was used infrequently (Jaksland, 2001). In fact the thickness and extension of the culture layer and the significant amount of shell fragments as well as bones suggest that the duration of occupation was longer than a few weeks. Although no actual ''season indicators'' have been found, the high frequency of herring, and the presence of species like pollock and small saithe, which are most frequently encountered along the coast in the summertime, indicates occupation beyond late winter/early spring.

The cultural deposits of the Skipshelleren rock-shelter are 50–170 cm thick, with seven distinct cultural layers. 90–100 m^2 of the ca. 200 m^2 ''dry'' settlement area (the area sheltered by the overhanging bedrock) have been excavated (Bøe, 1934). Radiocarbon analysis of recovered bones dates the site from Late Mesolithic to older Iron Age. Based on the lithic inventory, Skipshelleren most likely was a short-term occupation camp, used repeatedly in seasonal cycles in the Mesolithic as well as the Neolithic (Bergsvik, 2001; Bjørgo, University of Bergen, pers comm.). Haakon Olsen (University of Bergen, pers comm.) identified seasonal indicators such as salmon (*Salmo trutta*), mackerel (*Scomber scombrus*), bluefin tuna (*Thynnus thynnus*) and eel (*Anguilla anguilla*) which all indicate summer and autumn occupation. But he also makes clear that many of the identified species can be found in the area during the winter.

Among the 48 bird species that have been identified from Skipshelleren, there were no little auk (*Alle alle*) remains. The little auk is a seasonal indicator species for winter occupation; it is quite common along the coast of southern Norway from October/November to January, and is present in many Stone Age sites, in Eastern Norway as well. However this "winter indicator" is quite common at other Stone Age settlement from the area, sites that have been regarded as long term settlement sites (Hufthammer, 2006). No other Stone Age material has been analysed for seasonality, but the age distribution of sheep and goat bones in Bronze Age and Older Iron Age indicates that Skipshelleren was probably occupied in early spring (Hufthammer, 1994).

6. Conclusions

δ^{18}O signals measured from otoliths were useful to interpret the season of settlement in archaeological studies. We have determined the time of the year these fish were captured which corresponds to when the water was at the coldest, i.e. in late winter or early spring. This may indicate an enhanced availability of fish resources through seasonal spawning aggregation. A high precision micromill technique coupled with small sample volume mass spectrometry analyses provided a method of determining season of capture without the assumptions needed for direct calculations of actual temperature values. The minimum requirement for this technique is being able to sample a full year's cycle of carbonate that was deposited over seasonally varying conditions.

Acknowledgements

Funding for this project "High latitude climate variability and its effect on human settlement and fishery resources as revealed by fossil otoliths" was made available through support from the Meltzer Foundation (L. Meltzers Høyskolefond). The authors thank Julie Skadal, Ståle Kolbeinson, Olaug Flatnes Bratbak, Lasse Jaksland, and Kjell Nedreaas for their help in various aspects of this work, and the research institute Monrepos for providing excellent working facilities for the preparation of the manuscript.

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