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# Detecting the medieval cod trade: a new method and first results

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## Abstract

This paper explores the potential of stable isotope analysis to identify the approximate region of catch of cod by analysing bones from medieval settlements in northern and western Europe. It measures the $\delta^{13}$C and $\delta^{15}$N values of cod bone collagen from medieval control samples collected from sites around Arctic Norway, the North Sea, the Kattegat and the Baltic Sea. These data were considered likely to differ by region due to, for example, variation in the length of the food chain, water temperature and salinity. We find that geographical structuring is indeed evident, making it possible to identify bones from cod caught in distant waters. These results provide a new methodology for studying the growth of long-range trade in dried cod and the related expansion of fishing effort—important aspects of the development of commercialisation in medieval Europe. As a first test of the method, we analyse three collections of cod bones tentatively interpreted as imported dried fish based on *a priori* zooarchaeological criteria. The results tentatively suggest that cod were being transported or traded over very long distances since the end of the first millennium AD.

*Keywords:* Fish trade; Cod; Middle Ages; Europe; Stable isotopes; Zooarchaeology; Provenance

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## 1. Introduction

Past research has shown that the consumption of marine fish such as cod increased abruptly around the end of the first millennium AD in parts of northern and western Europe (e.g. Barrett et al., 2004a; Enghoff, 2000). However, it remains to be determined whether this phenomenon involved only relatively local fishing or the development of long-range trade and the expansion of fishing effort to more and more distant grounds—two inter-related facets of commercialisation. To do so is important because the emergence of commercial fishing represents a watershed in the intensity of human use of the sea. It is central to an understanding of economic history and represents the earliest date at which large-scale and sustained human impacts on northern marine ecosystems might be expected (Barrett et al., 2004b; cf. Pandolfi et al., 2003). To address these issues, this paper begins to map the ancient $\delta^{13}C$ and $\delta^{15}N$ ratios of collagen from archaeological cod bones recovered in medieval settlements around Arctic Norway, the North Sea, the Kattegat and the Baltic Sea (Fig. 1). By demonstrating geographical structuring within these data, this research opens the possibility of identifying the approximate region of catch of remains found in archaeological settlements, and thus of tracking fish trade and/or expanding fishing effort. The method is then tested by applying it to three collections of cod bones tentatively interpreted as imported dried fish based on *a priori* zooarchaeological criteria.

## 2. Materials and background

Three categories of cod bones were collected from 15 archaeological sites of medieval date from Arctic Norway, the Orkney Islands in northern Scotland, England, Belgium, Denmark, Germany and Poland: control samples, target samples and unclassified samples (Fig. 1). Control samples are skull bones (jaw bones such as premaxillae and dentaries where available). In medieval Europe, cod were often decapitated prior to drying (or salting and drying) for long-range trade (Barrett, 1997). Thus control samples are likely to be from relatively local catches, although exceptions where fish were

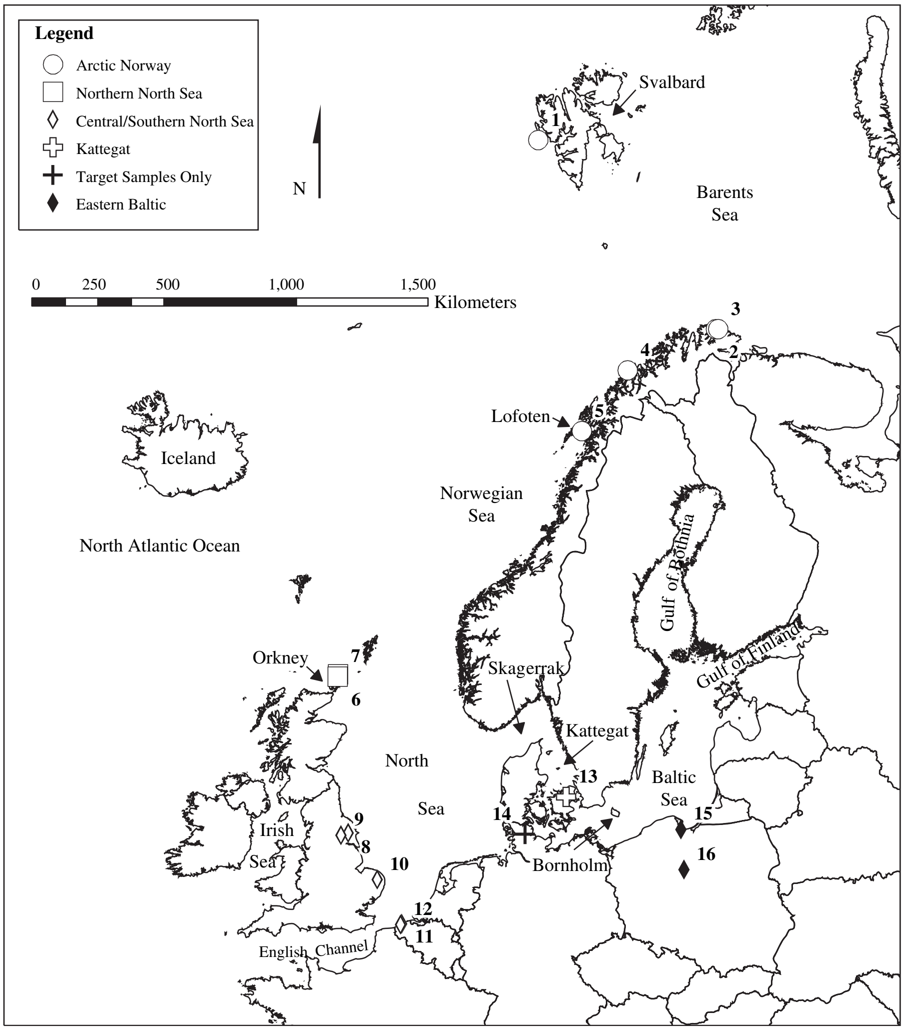

Fig. 1. Location of the main archaeological sites (and the modern Barents Sea sampling location) considered in this study. The analytical region to which each belongs is indicated. 1, Svalbard; 2, Skonsvika; 3, Kongshavn; 4, Helgøygården; 5, Storvågan; 6, Quoygrew; 7, Knowe of Skea; 8, Wharram Percy; 9, Coppergate; 10, Castle Mall; 11, Oostende Mijnplein; 12, Raversijde; 13, Selsø-Vestby; 14, Haithabu/Hedeby; 15, Gdańsk Olejarna Street; 16, Mała Nieszawka.

probably traded with heads attached do exist (e.g. Jonsson, 1986). Target samples are bones that have a higher probability of being from traded fish. They were chosen to maximise the likelihood of detecting imported cod in assemblages that might also include locally caught fish—and thus to reduce the problem of potentially 'looking for a needle in a haystack'. Targets include skeletal elements such as vertebrae with butchery marks known to be characteristic of processing cod for drying (Fig. 2) and cleithra (paired bones from behind the skull often left in dried cod products such as stockfish) (Barrett, 1997). Unclassified samples, which were included to augment sample sizes, are bones such as vertebrae without distinctive cut marks, which could occur in either locally caught or traded fish. In practice, the very few unclassified samples in this study (three from Oostende in Belgium and one from Selsø-Vestby in Denmark) fall within the range of the skull bone isotope values from the same region and have thus been treated as controls themselves.

The study's main chronological range is from the 9th to 15th centuries AD, in order to include the earliest period when cod trade may have been practiced in medieval Europe (Barrett et al., 2004a; Enghoff, 2000) and to exclude the complication of fish traded from the western North Atlantic after the European 'discovery' of North America. The date range for the Knowe of Skea, Orkney, may extend into the 16th century, but this site is unlikely to have imported any New World fish as it was a local fishing station (Kilroy, 2006). A few specimens predating the 9th century have also been included from the Danish site of Selsø-Vestby.

The regions for study were chosen to include both potential sources and recipients of traded cod in the Middle Ages. Based on the historical record, Arctic Norway was one of Europe's most important exporters of preserved cod (in the form of air-dried stockfish) from at least the 12th century (Christensen and Nielssen, 1996; Urbanczyk, 1992). Iceland began to export stockfish as well by the end of the 13th century (Thor, 2002). Dried cod were also traded from the far north of Scotland (including Orkney), by the 15th century based on historical records and possibly from the 11th century based on the zooarchaeological record (Barrett, 1997, 2005a; Barrett et al., 1999; Harland, 2006). Cod bones first became common in English archaeological sites within a few decades of AD 1000 (Barrett et al., 2004a). However, a commercial fishery for cod and related species is not fully documented in England until the 12th to 14th centuries (Childs and Kowaleski, 2000; Kowaleski, 2003). England was also an importer of Norwegian stockfish at this time (Nedkvitne, 1976). Zooarchaeological data from Belgium suggest that fishermen exploited offshore fishing grounds from AD 1000, but cod bones only became common from the 13th century (Ervynck et al., 2004).

Zooarchaeological evidence indicates that some settlements around the Skagerrak and Kattegat were fishing for cod from the very beginning of the period covered by this study. For example, all parts of cod skeletons were found at sites such as Selsø-Vestby in Denmark (Enghoff, 1999) and Kaupang in southern Norway (Barrett et al., 2007), in phases of 8–9th century and 9th century date, respectively. In fact the history of cod fishing stretches all the way back to the Mesolithic around these bodies of water (Enghoff, 1994; Rosenlund, 1976).

The medieval Baltic is well known for its herring production (Holm, 1996), and as an importer of North Atlantic stockfish (Heinrich, 1983; Meier, 2006). However, early

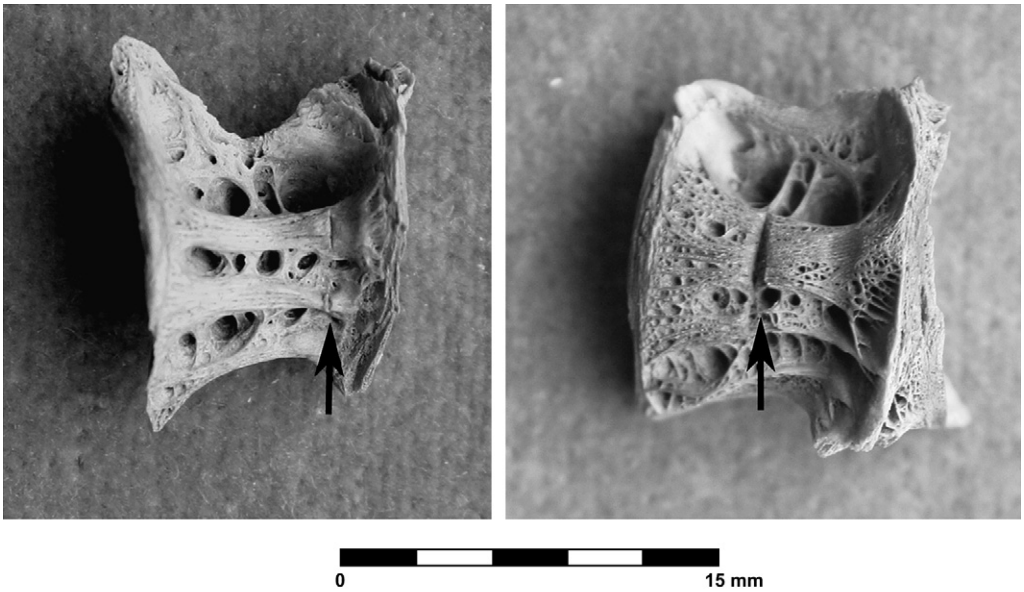

Fig. 2. Butchery marks on caudal vertebrae of cod from Wharram Percy in eastern England dating to the 13th or 14th century AD. Cut marks like these were produced when removing anterior vertebrae during the preparation of some dried cod products. Bones cut in this way are occasionally found at production sites (e.g. Barrett, 1997). Sometimes, however, they appear to have remained with the caudal vertebrae left in dried cod destined for long-range trade (e.g. Barrett, 2005b). These Wharram Percy specimens are thought to represent such imports.

prehistory aside, local cod fishing may only have begun on any meaningful scale from the 13–14th centuries (Jonsson, 1981, 1986; Lõugas, 2001; Makowiecki, 2003; Makowiecki, unpublished data). Prior to this date, small collections of cod bones from the Baltic region, at settlements such as Groß Strömkendorf (Schmölcke, 2004), Birka (Lõugas, 2001), Haithabu/Hedeby (Heinrich, 2006; Lepiksaar and Heinrich, 1977) and Schleswig (Heinrich, 1983, 1986, 1987) for example, are treated as anomalies and/or possible imports (see below).

This brief overview of historical and zooarchaeological evidence provides a qualitative sampling frame for the present study. As dried fish exporters, Arctic Norway and Orkney will provide only control samples, whereas the other regions considered have the potential to produce both control samples (probably from local fishing) and target samples (possibly from imported dried cod). Iceland has not yet been included in our study due to its late entry into the stockfish trade and the present unavailability of appropriate control samples. The Skagerrak is also unrepresented at present due to poor collagen preservation in the material available (from Kaupang). However, archaeological control samples have been analysed for all the other regions considered above. As an additional set of control data, premaxillae have also been extracted from a group of 12 modern cod caught around Svalbard in the northern Barents Sea. The role of these last specimens is explained in Section 3.

As a first test of the use of $\delta^{15}$N and $\delta^{13}$C to recognise traded fish, target samples have also been selected from three sites: one in England near the North Sea coast (Wharram Percy; Barrett, 2005b), one in Germany on a fjord off the western Baltic (Haithabu/Hedeby; Heinrich, 2006) and one in Poland upriver from the eastern Baltic coast (Mała Nieszawka, Makowiecki, 2003) (Fig. 1). In each case there was *a priori* evidence suggesting that traded fish might be represented (see below).

## 3. Methods

Our sample sizes were sometimes limited by the availability of appropriate specimens (skull bones for control samples and cleithra or butchered vertebrae for target samples) from fish of appropriate total length (see below) and by collagen preservation. Nevertheless, the collections analysed reach or exceed the number of specimens typically used in modern studies of spatial variation in stable isotope values of fishes (e.g. Bösl et al., 2006; Deutsch and Berth, 2006; Fredriksen, 2003; Jennings and Warr, 2003). The bones were identified to species and classified into fish size groups by comparison with an extensive reference collection of skeletons from individuals of known total length (Table 1, Table 4). They were also measured where practicable, facilitating more precise comparisons of size and the calculation of total length estimates using allometric regression equations (Jones, 1991; Watt et al., 1997). Ideally these equations would be based on fish of the same biological population as the analysed material, but this is not strictly practicable when considering ancient archaeological specimens. Regressions based on modern North Sea cod have thus been used throughout for the sake of consistency. Cut marks from butchery, which can indicate the preparation of a dried product, were recorded.

Isotopic measurements of fish tissues expressed as $\delta^{13}$C and $\delta^{15}$N have well established relationships with environment, diet and trophic level (Fredriksen, 2003; Jennings and Warr, 2003; Sweeting et al., 2007; Weidman and Millner, 2000). Thus, they have also been shown to spatially differentiate modern fish populations (e.g. Deutsch and Berth, 2006). The analysis of bone collagen was chosen for this study because it is frequently preserved in archaeological contexts and accepted measures exist to exclude poor quality samples that may yield spurious results (e.g. C:N ratio: DeNiro, 1985; Ambrose, 1990). This is in contrast with otolith aragonite, for example, which can be subject to chemical alteration in

Table 1
The archaeological and modern control cod bone samples analysed in the present study

| Site | Date | Total length 500–800 mm | Total length 800–1000 mm | Number of specimens | Area | Reference |
|---|---|---|---|---|---|---|
| Svalbard | August 2004 | 7 | 5 | 12 | Arctic Norway | This study |
| Skonsvika | c. 1240–1390 AD | 2 | 2 | 4 | Arctic Norway | Olsen and Urbanzcyk, in press |
| Kongshavn | c. 1300–1400 AD | 3 | 3 | 6 | Arctic Norway | Olsen and Urbanzcyk, in press |
| Helgøygården | c. 1300–1400 AD | 6 | 3 | 9 | Arctic Norway | Holm-Olsen, 1981 |
| Storvågan | c. 12–15th C | 2 | 4 | 6 | Arctic Norway | Bertelsen et al., 1987 |
| Quoygrew | 11–12th C | 4 | 9 | 13 | N. North Sea | Harland, 2006 |
| Knowe of Skea | 15–16th C | 3 | – | 3 | N. North Sea | Kilroy, 2006 |
| Wharram Percy | Late 13–14th C | – | 2 | 2 | Cent./S. North Sea | Barrett, 2005b |
| Coppergate | Late 10–13th C | – | 2 | 2 | Cent./S. North Sea | Jones, unpublished data |
| Castle Mall | 11–12th C | 5 | – | 5 | Cent./S. North Sea | Locker, 1997 |
| Oostende Mijnplein | 15th C | 3 | – | 3 | Cent./S. North Sea | Pieters et al., 2005 |
| Raversijde | 15th C | – | 2 | 2 | Cent./S. North Sea | Ervynck et al., in press |
| Selsø-Vestby | 8–9th C | 4 | – | 4 | Kattegat | Enghoff, 1999 |
| Selsø-Vestby | 10–11th C | 6 | – | 6 | Kattegat | Enghoff, 1999 |
| Gdańsk Olejarna Street | 1295–1350 AD | – | 2 | 2 | E. Baltic | Makowiecki, 2003 |
| Mała Nieszawka | 14–15th C | 4 | 3 | 7 | E. Baltic | Makowiecki, 2003 |
| Total | | 49 | 37 | 86 | | |

the ground (Fred et al., 2002) and is only rarely preserved in archaeological deposits. Therefore research on sourcing the origin of fish otoliths (Campana et al., 1994; Gao et al., 2005; Swan et al., 2006) is of limited archaeological utility—a problem exacerbated by the fact that in the Middle Ages cod were often decapitated prior to trade (see above). Some otolith provenancing research involves trace element analysis that could be applied to bone mineral, but diagenetic changes in the burial environment make this an unreliable approach for archaeological material (e.g. Radosevich, 1993; Fabig and Herrmann, 2002). Ancient DNA could theoretically also be used to identify region of catch (Arndt et al., 2003), but most population structuring in cod has been studied using microsatellite genetic markers which are very difficult to recover from archaeological material (Nielsen et al., 2001).

Sample preparation was carried out in the following way. Specimens greater than 1 g in mass were sawn in two, with one subsample archived for further study. The second subsample (or whole specimen if under 1 g) was then processed for stable isotope analysis by drilling a cross-section of each bone. Given the incremental growth characteristic of fish bone (Van Neer et al., 1999), this procedure is likely to approximate lifetime average isotope values. Bone collagen was then extracted from 100 to 200 mg of whole bone following standard procedures outlined in Richards and Hedges (1999), with the addition of an ultrafiltration step (Brown et al., 1988). For modern samples the bone was pre-treated with chloroform/methanol to remove lipids. Additionally, the use of ultrafiltration also removes lipids from the collagen extract. Samples were analysed using a ThermoFinnigan Flash EA coupled to a Delta Plus XP mass spectrometer. The $\delta^{13}$C values are reported relative to the V-PDB standard, and $\delta^{15}$N values relative to the AIR standard. Errors on both the $\delta^{13}$C and $\delta^{15}$N measurements are better than 0.2‰. Amounts of carbon and nitrogen in the collagen extract were measured, and we only report isotope values from those samples with acceptable C:N ratios (DeNiro, 1985).

All the bone collagen data reported here are directly comparable. Similar methods have been used for analysis of archaeological material from Haithabu/Hedeby and Schleswig (Germany) published by von Steinsdorff and Grupe (2006) to be discussed below. However, comparison of our data (all from bone collagen) with published modern evidence (typically from muscle tissue) is more problematic. The offsets between fish muscle and bone collagen stable isotope values remain to be thoroughly studied. The tissues are likely to have different values due to differing amino acid compositions and the presence of ($\delta^{13}$C depleted) lipids in muscle. Variability will also exist due to changes in diet, differences in turnover rate between tissues and differences in sample preparation methods (Perga and Gerdeaux, 2005; Phillips and Eldridge, 2006; Sweeting et al., 2006, 2007). Nevertheless, present evidence suggests that muscle-collagen offsets are close to nil for $\delta^{15}$N (Richards and Hedges, 1999) and are approximately 4.0 for $\delta^{13}$C values (Barrett et al., 2000). Direct comparisons between bone collagen and fish muscle data will not be attempted in this study, but relative differences in muscle $\delta^{13}$C and $\delta^{15}$N values will inform our interpretation of both spatial structuring and potential confounding variables such as size effects.

Before using isotope values to differentiate cod populations one must address three potential confounding variables: fish size, fish migration and change through time. Each will be addressed in turn. Based on data from muscle samples of 121 modern cod from the northern North Sea (caught between 57.5° and 61.5° N and between 1° W and 4° E) there is no significant correlation between $\delta^{13}$C and fish size in cod ($r = 0.02$, $p = 0.85$) (data from Jennings, personal communication; see Jennings et al., 2007 for collection protocols). Conversely, a positive correlation between total length and $\delta^{15}$N of cod muscle has been established (Jennings et al., 2002). This is to be expected as larger cod (which can be piscivorous and cannibalistic) are likely to be of a higher trophic level than small ones which feed on plankton and benthic invertebrates as well. However, the slope of the appropriate regression is low (3.17), meaning that a predicted enrichment of only c.0.95‰ would be expected between fish with lengths from 500 mm to 1000 mm. The $r^2$ value is also low (0.18). Other sources of variation will therefore often overwhelm size-related patterning. Moreover, the analysis of complete archaeological bone cross-sections in the present study is likely to dampen this ontogenetic effect, given that fish bone grows incrementally and will have a much slower turnover rate than muscle.

The relationship between $\delta^{15}$N and size in very large fish has not been studied by fisheries biologists because cod of greater than a metre in length are very rarely caught today (although they are common in archaeological collections). Therefore our study will only use bones from fish with predicted total lengths of between 500 and 1000 mm. This range is appropriate in historical terms as it includes the sizes of fish used in many traditional dried cod products (Amundsen et al., 2005; Perdikaris, 1999). If sufficient archaeological samples become available, future work could improve on this approach by subdividing all analyses by total length categories.

Fish migration is a critical variable in any attempt to evaluate spatial structuring in isotopic data. Experimental (Neat and Righton, 2006), morphological (Galleya et al., 2006), genetic (Hutchinson et al., 2001) and isotopic (Jennings and Warr, 2003) evidence all suggest that the mobility of populations of cod and related species in the North Sea is relatively limited. Wright et al. (2006) found that most adult cod remain within 100 km of their spawning area throughout the year in the North Sea and north-west Scotland. The arbitrary division of the North Sea into northern (between 57.5° and 61.5° N) and central/southern (below 55° N) regions in the present study is thus expected to separate two groups of cod populations. More lengthy spawning migrations do occur in the Baltic. However, there is little overlap between the eastern and western Baltic cod populations, with a narrow transitional zone west of the island of Bornholm (Bagge et al., 1994). Cod in the Kattegat and Skagerrak may have more mobile life histories. The Skagerrak in particular is characterised by the exchange of current-transported larvae and migrating adults with both the eastern North Sea and the Kattegat (Knutsen et al., 2004; Pihl and Ulmestrand, 1993). No Skagerrak samples have been analysed in the present study, but in light of these observations it is not surprising that our Kattegat results demonstrate wide dispersion (see below).

There are two genetically distinct populations of cod in Norwegian waters: the coastal cod complex and the migratory Barents Sea cod, also named Northeast Arctic cod (Sarvas and Fevolden, 2005 and references therein). Norwegian stockfish were traditionally made from fish of the migratory population (Christensen and Nielssen, 1996), but it is likely that some coastal cod were caught, dried and traded at the same time. The Norwegian coastal cod complex is probably composed of several local stocks along the coast and in the fjords of mainland Norway and it may be more or less stationary. In contrast, the Barents Sea cod undertake a long migration (over 700 km at approximately 20 km per day) from the northern and central Barents Sea down to mainland Norway. There is a migration of mature cod (older than 7 years) to the main spawning sites in the Lofoten area (and in some years, probably as far south as Møre-Romsdal near Ålesund) in January–April. The possibility of differing isotope signatures between these groups is addressed in our study below, by comparing data from Arctic Norwegian archaeological specimens with analyses of premaxillae from twelve modern cod caught in the northern Barents Sea (Svalbard area). These fish have been genetically typed as migratory following the methods outlined in Fevolden and Pogson (1997) and Sarvas and Fevolden (2005).

Inter-annual fluctuations in the isotope values of cod tissues (for individuals of the same size) are known to occur (Jennings, personal communication). This variability will be reduced in the present study by the use of complete cross-sections of bone (which approximate lifetime averages). It will also be reflected in the dispersions of each archaeological data set or group of related data (each of which will have accumulated over many years, decades or centuries). The possibility of longer-term temporal variation in baseline isotope values (due to modern eutrophication, for example), which could be a confounding influence on spatial differences in $\delta^{15}$N and $\delta^{13}$C, has been addressed by using medieval archaeological specimens rather than modern bones as controls. In future work it may be possible to evaluate century-scale variation within the Middle Ages, but this is not realistic on the basis of present sample sizes. Previously published data from von Steinsdorff and Grupe (2006) regarding 9–10th century Haithabu/Hedeby and 11–12th century Schleswig (both in the western Baltic area) could be taken to imply a temporal shift in cod $\delta^{15}$N values within the Middle Ages. However, the variability in their data is more likely to be due to comparison of imported and local fish as will be discussed below.

## 4. Results and discussion

The archaeological control samples from settlements along the coast of Arctic Norway (including Storvågan from the main spawning area around Lofoten) do not statistically differ ($\delta^{13}$C: Kruskal–Wallis chi-squared = 3.43, df = 3, $p = 0.34$, $n = 25$; $\delta^{15}$N: Kruskal–Wallis chi-squared = 4.10, df = 3, $p = 0.25$, $n = 25$) and can thus be combined for the purposes of this study. They are all likely to contain a mixture of migratory and coastal fish given that subsistence fishing will have occurred outside the spawning season of the Barents Sea cod. This cannot be tested directly as routine genetic typing of archaeological specimens is not possible. However, the modern genetically typed migratory cod have more depleted $\delta^{13}$C values than many of the archaeological samples from Arctic Norway (Fig. 3). This difference may relate partly to location of catch and/or long-term temporal change, but it also implies that the most enriched archaeological $\delta^{13}$C values are characteristic of coastal Norwegian cod. If so, and stockfish were typically prepared from the migratory population, the Norwegian archaeological data will provide a conservative control for dried cod traded further south. Their $\delta^{13}$C values overlap with the northern North Sea data (Fig. 4, see below), whereas the more depleted (genetically 'migratory') modern fish from the Barents Sea do not.

Two of the outliers in the Norwegian dataset have enriched $\delta^{13}$C and exceptionally high $\delta^{15}$N values. There is one example each from the Skonsvika ($\delta^{13}C = -14.05$, $\delta^{15}N = 15.75$) and Storvågan ($\delta^{13}C = -13.59$, $\delta^{15}N = 15.82$) collections (Fig. 3). It is not possible to infer causation from our present evidence, but clearly occasional fish from Arctic Norway will exhibit this pattern creating an overlap with the central/southern North Sea data (Fig. 4). As a working hypothesis these individuals may have adopted a particularly piscivorous and/or cannibalistic feeding strategy, increasing their trophic level and thus their $\delta^{15}$N and (to a lesser degree) $\delta^{13}$C values.

Fig. 4 is a plot of individual data points, means and two standard deviation ranges for archaeological control specimens combined into the groups Arctic Norway, northern North Sea, central/southern North Sea, Kattegat and eastern Baltic Sea. Summary statistics for the individual collections within each group are provided in Table 2. There are many

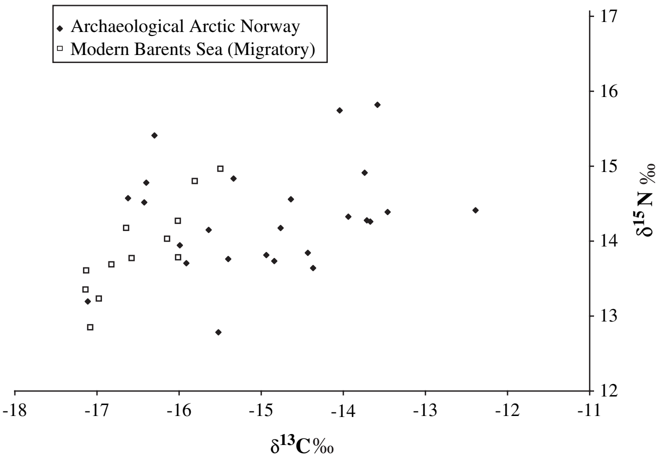

Fig. 3. The distribution of $\delta^{13}$C and $\delta^{15}$N values for cod bone collagen from four Arctic Norwegian medieval settlements and from modern cod of the migratory genetic type caught in the Barents Sea.

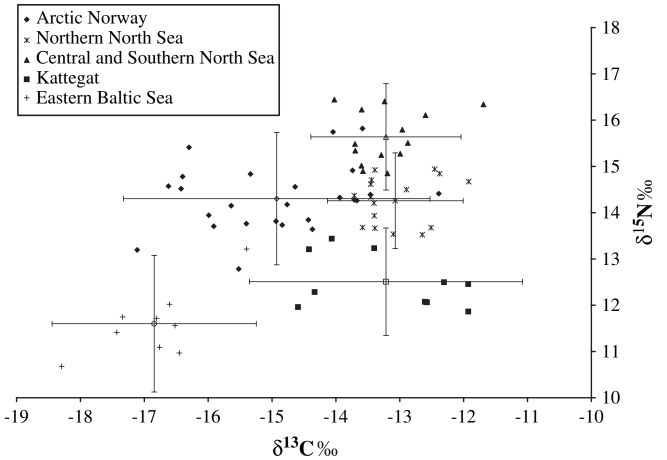

Fig. 4. $\delta^{13}C$ and $\delta^{15}N$ values, including means ± two standard deviations, for medieval control samples of cod bone collagen from Arctic Norway, the northern North Sea, the central/southern North Sea, the Kattegat and the eastern Baltic Sea.

geographical gaps to be filled by future work and much intra-regional variability is evident. Nevertheless, inter-regional variability is greater than intra-regional variability. Distinct isotopic structuring exists. Arctic Norwegian samples have depleted $\delta^{13}C$ values on average, central/southern North Sea samples have enriched $\delta^{15}N$ values on average and eastern Baltic samples have depleted $\delta^{13}C$ and $\delta^{15}N$ values. The Kattegat and northern North Sea values are intermediate, with the former showing much variability (particularly in $\delta^{13}C$) as anticipated in Section 3.

It is not possible to directly infer causal variables. Nevertheless, based on studies of modern material these patterns are likely to be at least partly due to inter-regional differences originating from a combination of:

- the structure of the food web, given that $\delta^{15}N$ is enriched by 3–5‰ (Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984) and $\delta^{13}C$ by c. 1‰ (DeNiro and Epstein, 1978) per trophic level,
- water temperature, given that the $\delta^{13}C$ of particulate organic matter at the base of the food chain is positively correlated with this variable (Goericke and Fry, 1994; Weidman and Millner, 2000) and
- salinity, given that the $\delta^{13}C$ of estuarine water is typically depleted (Guelinckx et al., 2006) and that areas of sea with freshwater river input can have enriched $\delta^{15}N$ values (Jennings and Warr, 2003).

Discriminant function analysis (DFA) of these data produces reclassification success rates of 60% for Arctic Norway, 94% for the northern North Sea, 93% for the central/southern North Sea, 90% for the Kattegat and 89% for the eastern Baltic Sea (Table 3). Apart from the Arctic Norway group, these statistics are very good. The reason for the lower reclassification rate for the Arctic Norwegian material is the greater range of values, possibly as a result of the group containing a mixture of migratory and coastal cod. This may underestimate the potential discrimination between Arctic Norwegian stockfish and northern North Sea catches for the reasons outlined above (i.e. most Norwegian stockfish were probably produced from migratory Barents Sea cod which have particularly depleted

Table 2
Summary $\delta^{13}C$ and $\delta^{15}N$ data for collagen from the control cod bone samples analysed in the present study

| Area | Site | Date | *n* | $\delta^{13}C$ | | | | $\delta^{15}N$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Minimum | Maximum | Mean | SD | Minimum | Maximum | Mean | SD |
| Arctic Norway | Svalbard | August 2004 | 12 | −17.1 | −15.5 | −16.6 | 0.6 | 12.9 | 15.0 | 13.9 | 0.6 |
| Arctic Norway | Skonsvika | c. 1240–1390 AD | 4 | −14.8 | −13.7 | −14.2 | 0.5 | 13.6 | 15.7 | 14.5 | 0.9 |
| | Kongshavn | c. 1300–1400 AD | 6 | −17.1 | −14.4 | −15.5 | 0.9 | 13.2 | 14.8 | 13.9 | 0.5 |
| | Helgøygården | c. 1300–1400 AD | 9 | −16.6 | −12.4 | −14.7 | 1.5 | 12.8 | 14.9 | 14.3 | 0.6 |
| | Storvågan | c. 12–15th C | 6 | −16.4 | −13.6 | −15.1 | 1.2 | 13.7 | 15.8 | 14.7 | 0.8 |
| All | | | 25 | −17.1 | −14.4 | −14.9 | 1.2 | 12.8 | 15.8 | 14.3 | 0.7 |
| N. North Sea | Quoygrew | 11–12th C | 13 | −13.7 | −11.9 | −13.0 | 0.6 | 13.5 | 14.9 | 14.2 | 0.5 |
| | Knowe of Skea | 15–16th C | 3 | −13.5 | −13.4 | −13.4 | 0.0 | 14.2 | 14.9 | 14.6 | 0.4 |
| All | | | 16 | −13.7 | −11.9 | −13.1 | 0.5 | 13.5 | 14.9 | 14.3 | 0.5 |
| Cent./S. North Sea | Wharram Percy | Late 13–14th C | 2 | −13.2 | −12.9 | | | 14.9 | 15.5 | | |
| | Coppergate | Late 10–13th C | 2 | −14.0 | −13.6 | | | 16.2 | 16.4 | | |
| | Castle Mall | 11–12th C | 5 | −13.7 | −11.7 | −13.0 | 0.8 | 15.3 | 16.3 | 15.8 | 0.6 |
| | Oostende Mijnplein | 15th C | 3 | −13.6 | −13.0 | −13.3 | 0.3 | 15.0 | 15.3 | 15.2 | 0.1 |
| | Raversijde | 15th C | 2 | −13.7 | −12.6 | | | 15.5 | 16.1 | | |
| All | | | 14 | −13.7 | −11.7 | −13.2 | 0.6 | 14.9 | 16.4 | 15.6 | 0.6 |
| Kattegat | Selsø-Vestby | 8–9th C | 4 | −14.3 | −11.9 | −12.9 | 1.0 | 11.9 | 12.3 | 12.1 | 0.2 |
| | | 10–11th C | 6 | −14.6 | −11.9 | −13.5 | 1.1 | 12.0 | 13.4 | 12.8 | 0.6 |
| All | | | 10 | −14.6 | −11.9 | −13.2 | 1.1 | 11.9 | 13.4 | 12.5 | 0.6 |
| E. Baltic | Gdansk Olejarna Street | 1295–1350 AD | 2 | −16.8 | −16.6 | | | 11.1 | 12.0 | | |
| | Mała Nieszawka | 14–15th C | 7 | −18.3 | −15.4 | −16.9 | 0.9 | 10.7 | 13.2 | 11.6 | 0.8 |
| All | | | 9 | −18.3 | −15.4 | −16.8 | 0.8 | 10.7 | 13.2 | 11.6 | 0.7 |

Table 3
Discriminant function analysis results based on the $\delta^{13}$C and $\delta^{15}$N data from the archaeological control cod samples

| Group | No. in group | No. correctly reclassified | % correctly reclassified | Group to which others reclassified |
|---|---|---|---|---|
| Arctic Norway | 25 | 15 | 60.0 | All, but mostly N. North Sea |
| N. North Sea | 16 | 15 | 93.8 | Cent./S. North Sea |
| Cent./S. North Sea | 14 | 13 | 92.9 | N. North Sea |
| Kattegat | 10 | 9 | 90.0 | N. North Sea |
| E. Baltic Sea | 9 | 8 | 88.9 | Arctic Norway |

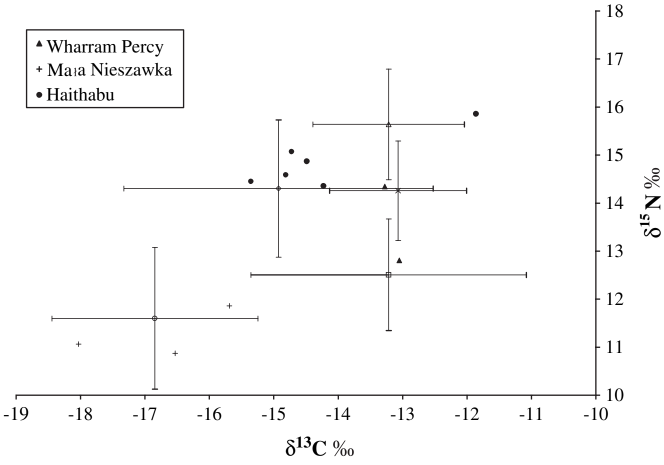

Fig. 5. $\delta^{13}$C and $\delta^{15}$N values for target cod bones from Wharram Percy, Haithabu/Hedeby and Mała Nieszawka superimposed on the means and two standard deviations from Fig. 4.

$\delta^{13}$C values). The observation that imported fish (or ones caught in distant fishing grounds) are likely to be recognized as particularly obvious outliers in some regions, the eastern Baltic for example, is supported by this analysis.

In some instances the degree of discrimination will facilitate the attribution of single specimens to a probable source, and in many more cases it will at least allow recognition of non-local catches (given the present lack of control data from Iceland, the western Baltic, the Skagerrak, the English Channel, the Irish Sea and other locations). Where distributions overlap, analysis may need to proceed at the collection level, evaluating changes in sample dispersion, skewing of sample distributions and changes in sample central tendency. For example, on average one might expect south-east English cod bone assemblages to include more specimens with depleted $\delta^{13}$C and $\delta^{15}$N values in cases where stockfish from Arctic Norway were imported.

These results open the possibility of detailed future work on the origin and development of the European cod trade (and the related expansion of fishing effort to ever more distant grounds). As a brief illustration of this potential, Fig. 5 provides the $\delta^{15}$N and $\delta^{13}$C values for a small selection of "target" samples (bones thought likely to represent traded fish on *a priori* criteria) superimposed on the means and standard deviations from Fig. 4. The stable isotope data and DFA classifications for each specimen are provided in Table 4.

The potential for differentiating 'imported' and 'local' fish is clear in the case of the 14–15th century Mała Nieszawka specimens from Poland (Makowiecki, 2003), which were probably caught in the eastern Baltic Sea despite our original judgement that they might be from North Sea or North Atlantic cod. The basis of the initial hypothesis was the style of butchery (cutting through the ventral portion of the cleithrum), which is known from stored cod found in the Mary Rose shipwreck (Coy and Hamilton-Dyer, 2005) and a dried fish production site at Knowe of Skea in Orkney (Kilroy, 2006). In hindsight, however, the stable isotope results and cut mark evidence are not as contradictory as they first appear. The severed cleithra from the Mary Rose include only the dorsal part of the bone (the ventral portion having remained at the original processing site). Conversely, at Mała Nieszawka both the ventral and dorsal portions of this element are present. In this context the distinctive cut marks may simply result from decapitating fish during local processing.

Whilst the isotope values of the Mała Nieszawka target specimens show the distinctive signature of the eastern Baltic, the DFA results gave relatively low probability values (Table 4). This is because the Baltic control data are quite widely dispersed (Fig. 4) and the target samples plot some distance from the DFA group centroid (and the raw data mean). Nevertheless, the statistical probability of these specimens belonging to the eastern Baltic is higher than for any of the other control

Table 4
Summary data, $\delta^{13}$C and $\delta^{15}$N results and discriminant function analysis results for the archaeological target cod bone samples analysed in the present study

| Site | Date | Element | Size class (mm) | $\delta^{13}$C | $\delta^{15}$N | Predicted group | Probability | Mahalanobis distance |
|---|---|---|---|---|---|---|---|---|
| Mała Nieszawka | 14–15th C | Cleithrum | 500–800 | −18.0 | 11.1 | E. Baltic Sea | 0.37 | 2.01 |
| Mała Nieszawka | 14–15th C | Cleithrum | 500–800 | −16.5 | 10.9 | E. Baltic Sea | 0.44 | 1.65 |
| Mała Nieszawka | 14–15th C | Cleithrum | 500–800 | −15.7 | 11.9 | E. Baltic Sea | 0.45 | 1.59 |
| Wharram Percy | Late 13–14th C | Caudal vertebra | 800–1000 | −13.0 | 12.8 | Kattegat | 0.89 | 0.23 |
| Wharram Percy | Late 13–14th C | Caudal vertebra | 800–1000 | −13.3 | 14.3 | N. North Sea | 0.96 | 0.08 |
| Haithabu/Hedeby | 9–11th C | Cleithrum | 800–1000 | −15.4 | 14.5 | Arctic Norway | 0.85 | 0.33 |
| Haithabu/Hedeby | 9–11th C | Caudal vertebra | 800–1000 | −14.7 | 15.1 | Arctic Norway | 0.48 | 1.46 |
| Haithabu/Hedeby | 9–11th C | Cleithrum | 800–1000 | −14.2 | 14.4 | Arctic Norway | 0.75 | 0.58 |
| Haithabu/Hedeby | 9–11th C | Cleithrum | 800–1000 | −14.5 | 14.9 | Arctic Norway | 0.64 | 0.88 |
| Haithabu/Hedeby | 9–11th C | Cleithrum | 800–1000 | −11.9 | 15.9 | Cent./S. North Sea | 0.34 | 2.16 |
| Haithabu/Hedeby | 9–11th C | Cleithrum | 800–1000 | −14.8 | 14.6 | Arctic Norway | 0.91 | 0.20 |

groups considered. There is no reason to argue that they were imported as dried fish from the North Sea or North Atlantic.

At the opposite end of the spectrum, two caudal vertebrae from 13–14th century Wharram Percy in eastern England do appear to have been imported as dried fish, as originally hypothesized on the basis of distinctive butchery marks. These are transverse cuts on the centra characteristic of severing the vertebral column to remove anterior vertebrae prior to drying (Barrett, 1997, 2005b; see Fig. 2). One of the vertebrae falls within the range of isotope values for the northern North Sea or Arctic Norway. The other has a slightly low $\delta^{15}$N value for these sources and is thus attributed to the Kattegat by DFA (Table 4). Although possibly from this area, both specimens have similar cut marks and cod export from the Kattegat is not documented in the Middle Ages. Thus this second bone may alternatively represent an outlier within the distribution of northern values. Regardless, both specimens show isotope values that are unlikely to represent a local central/southern North Sea catch.

Five cod cleithra and a single caudal vertebra from the harbour of the Viking Age (9–11th century) town of Haithabu/Hedeby on the Schlei Fjord off the western Baltic Sea require more lengthy discussion. They were originally interpreted as possibly deriving from imported ship provisions based on finds of ling (*Molva molva*), saithe (*Pollachius virens*) and halibut (*Hippoglossus hippoglossus*) at the same settlement (Enghoff, 1999; Heinrich, 2006; Lepiksaar and Heinrich, 1977). These species are not characteristic of the Baltic, but are common in the North Sea and North Atlantic (Froese and Pauly, 2007). Five of the archaeological cod samples from Haithabu/Hedeby plot within the main range of the Arctic Norwegian control data. A single specimen with enriched $\delta^{13}$C and $\delta^{15}$N values is more consistent with a fish transported across the Jutland peninsula from the central/southern North Sea, but could also be a Norwegian outlier (see above). Most or all of the analysed Haithabu/Hedeby bones may thus represent fish transported from Arctic Norway. This possibility is conceivable as a trading voyage from the Lofoten area to Haithabu/Hedeby, by a Norwegian known as Ohthere or Ottar, is recorded in a rare late 9th century source (Fell, 1984). These specimens may only have been from ship provisions as originally suggested (Heinrich, 2006; Lepiksaar and Heinrich, 1977). However, they could alternatively have formed cargoes intended for long-range market trade—if transported from the Arctic region later known for its stockfish exports as the stable isotope evidence implies. A time-lag between the origin of the Arctic Norwegian stockfish trade and its earliest medieval historical documentation in the 12th century is not improbable (Barrett et al., 2004a).

The importation of cod to Haithabu/Hedeby would help explain previously published isotope analyses by von Steinsdorff and Grupe (2006) conducted as part of a food-web study. They found the median $\delta^{15}$N for five cod specimens from this settlement to be higher than the comparable value for seals from the same site, despite the observation that seals should be of a higher trophic level. Trade would also make sense of the fact that the $\delta^{15}$N values for cod from Haithabu/Hedeby (range 13.68–17.37) were much more enriched than for bones of the same species from the nearby, but slightly later, town of Schleswig (range 11.99–12.24) (von Steinsdorff and Grupe, 2006). Heinrich (1983, 1987) argues that at least partly locally caught Baltic cod were probably eaten in Schleswig by the 13–14th centuries, based on zooarchaeological criteria, and von Steinsdorff and Grupe's isotope values from this town match our (eastern) Baltic control samples (Fig. 4).

Having suggested that most or all of the Haithabu/Hedeby specimens were imports from the far north, a possible alternative interpretation must also be considered. Like Arctic Norway, the western Baltic food-web could conceivably have been characterised by depleted $\delta^{13}$C and moderately enriched $\delta^{15}$N values in the Middle Ages. Archaeological control data are not yet available from the *western* Baltic and modern evidence based on analysis of muscle tissue shows that western Baltic cod have higher $\delta^{15}$N values than eastern Baltic cod (Deutsch and Berth, 2006). If this was also the case in medieval times, most of the Haithabu/Hedeby cod could be local catches. The outlying specimen with highly enriched $\delta^{13}$C and $\delta^{15}$N values would then be most easily explained as a central/southern North Sea fish.

Of these two alternative hypotheses, an origin in Arctic Norway is considered more probable. Isotopic studies of seafloor sediment cores demonstrate that highly enriched $\delta^{15}$N values became characteristic of shallow areas of the Baltic only in the 20th century, particularly after increases in the use of mineral fertilizers (Struck et al., 2000; Voss et al., 2000). Voss et al. (2000) found that enrichment over pre-industrial levels could reach 10‰ in organic sediments. This recent eutrophication is the most likely explanation for elevated $\delta^{15}$N values in modern cod from the shallow waters of the western Baltic Sea.

## 5. Conclusions

To conclude, this study has illustrated that it is possible to attribute archaeological cod bones to their approximate region of catch using measurements of $\delta^{13}$C and $\delta^{15}$N on bone collagen. Further sampling is needed to address variation by space, time and fish size. In due course, however, this method has the potential to revolutionise our understanding of the origins and growth of commercial fishing in Northern Europe—freeing it from the limits of an incomplete historical record. Based on present results, it is already possible to hypothesise (although not yet to prove) that dried cod may have been transported over vast distances—from Arctic Norway to Haithabu/Hedeby in the Baltic—from the very beginning of northern Europe's sea fishing revolution at the end of the first millennium AD. Future research will seek to corroborate these results at other settlements and to explore their wider archaeological and ecological implications.

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