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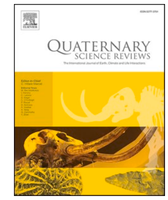

Freshwater exploitation at Ajvide - Pitted ware culture fishing practises investigated through laser ablation facilitated strontium isotope analyses

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A R T I C L E I N F O

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A B S T R A C T

The importance of marine resources for the Neolithic hunter-fisher-gathers of the Pitted Ware Culture of Gotland, Sweden, is well documented through zooarchaeological analyses and diet studies of human remains. Terrestrial areas were important for living and supplementing the diet but the extent of the terrestrial territories and regions of land use for different groups is largely unknown. The presence of euryhaline species in recovered zooarchaeological assemblages indicates that freshwater fishing or fishing in the brackish estuaries of the Baltic Sea was part of the subsistence practises. To explore if the inland freshwaters of Gotland were used and, if exploited, where they were located, 18 teeth from euryhaline fish from the Pitted Ware Culture site Ajvide on Gotland were selected. The $^{87}Sr/^{86}Sr$ isotope ratios in the fish teeth were analysed using laser ablation-multi collector-inductively coupled plasma-mass spectrometry and correlated with an updated bioavailable baseline of Gotlandic water sources. Through this approach, the habitational origin of the fish was shown to primarily stem from at least six freshwater sources located in the west-central area of Gotland, in close relation to the site, with a few individuals originating from within the Baltic Sea. The study highlights the significance of ichthyoarchaeological analysis in understanding the territorial practice of past foraging societies and recommends further studies on euryhaline species to expand our knowledge of fish habitat, human resource utilization and land use.

1. Introduction

The Pitted Ware Culture (PWC) was situated in a Neolithic context a millennia after farming and agriculture were introduced to Scandinavia and was the last outpost of foragers in southern Scandinavia. The PWC foragers lived alongside contemporaneous agricultural groups (the Funnel Beaker Culture and, later, the Scandinavian branch of the Corded Ware Culture - The Battle Axe Culture), who had replaced the Mesolithic groups in the area (Allentoft et al., 2024; Skoglund et al., 2014). The PWC is generally considered a repopulation of hunter-gatherers-fishers to areas of Northern Europe previously "abandoned" by earlier Mesolithic foraging societies. Based on aDNA data the PWC is not an adaptation to a foraging lifestyle by Neolithic farmers (Skoglund et al., 2012; Skoglund et al., 2014). The PWC genetic signature is, instead, largely consistent with the genetic profile of the older Mesolithic Scandinavian societies (Günther et al., 2018; Malmström et al., 2015; Skoglund et al., 2014). There is also a limited, albeit present, genetic admixture from Neolithic farmers in the genetic profile of the PWC (Günther et al., 2018; Mittnik et al., 2018; Malmström et al., 2019), which suggests some level of contact between the different groups of people.

PWC sites are found along the Scandinavian coastline from the northernmost parts of the Swedish west coast, to Denmark, Scania, the islands of Bornholm, Öland, Gotland and Åland up to the Swedish east coast in the Gävle area (Klassen, 2020; Nordqvist and Jonsson, 2009; Björck, 2011; Papmehl-Dufay, 2006; Janzon, 1974; Stenbäck, 2003). The PWC ability to maintain a functional foraging society alongside and in contact with agricultural groups is often connected to their ability to exploit the marine/brackish aquatic systems of the Baltic Sea and the marine waters of the Scandinavian west coast (Artursson et al., 2023), i.e. occupying an ecological niche which was under-exploited by their agricultural neighbours.

Stable isotope dietary data ($\delta^{13}C$ and $\delta^{15}N$) from PWC foragers agree with this generic view of the PWC society by suggesting a strong dependence on marine resources (Eriksson, 2004; Eriksson and Lidén, 2013; Fornander et al., 2008; Howcroft et al., 2014). The coastal location of the known PWC sites and zooarchaeological assemblages often dominated by seal bones and fish offers further evidence for their strong marine dependence (Lindqvist and Possnert, 1997; Olson, 2008; Sjöstrand, 2022;

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Storå, 2001). On the island of Åland, in the Baltic Sea, mobility patterns among both humans and dogs have, through analyses of strontium isotope ratios ($^{87}Sr/^{86}Sr$), further increased the perception of strong marine orientation. Here, the inferred mobility patterns have linked both humans and dogs from the Ålandic archipelago to the island of Gotland, and possibly also to Öland and mainland Sweden – highlighting various levels of mobility within the Baltic Sea (Boethius et al., 2024), see Supplementary data (SI) for a description of the premises related to mobility and provenience studies based on the interpretation of Sr isotope ratios.

Although the strong marine association is evident, PWC societies are also connected to terrestrial areas. This includes various terrestrial wild game species in the faunal assemblages on current-day mainland Sweden (Aaris-Sørensen, 1978; Lepiksaar, 1974; Magnell, 2019) and large numbers of pig/wild boar bones on Gotlandic sites (Ekman, 1974; Stenberger et al., 1943; Sjöstrand, 2022). The recovery of charred seeds on PWC sites (Edenmo and Heimdahl, 2012; Vanhanen et al., 2019) offers further dietary connection to terrestrial areas and although it occurs in small amounts, it suggests that the PWC foragers had some form of access to cereals.

Furthermore, while aquatic $^{87}Sr/^{86}Sr$ ratios have a clear impact on the human Sr ratios, evidence from the PWC site Västerbjers on eastern Gotland suggests there is also a terrestrial component to their Sr ratios, indicating Sr from a limited part of the landscape is also present in the enamel (Boethius et al., 2022). This may, to some extent, be caused by dietary inclusions of pig and terrestrial plants, despite stable isotope data suggesting limited inclusion to the protein diet (Eriksson, 2004; Eriksson and Lidén, 2013; Fornander et al., 2008; Howcroft et al., 2014). Furthermore, while plants are recognised for having a strong impact on the Sr isotope ratios in omnivorous species, meat from terrestrial animals has low Sr concentrations and does not affect the ratios of the end consumer unless ca. 70 %, or more, of the diet is based on terrestrial meat (Bentley, 2006). The strontium pathway in fish differs from that among terrestrial species where fish mainly obtain their Sr via the water through the gills (Schiffman, 1961) whereas mammals obtain their Sr through their diet (Bentley, 2006). Through a biopurification process, there is a significant reduction in Sr/Ca ratio, with reduced Sr concentrations, when moving up the trophic level in the food chain, whereby plants have significantly higher concentrations of Sr compared to meat from mammals (Bentley, 2006). Since fish have a different Sr pathway the same principle does not apply to them, which allows fish to have Sr concentration equalling or, if the bones are also considered, surpassing that of plants (Boethius et al., 2024 Supplementary Material Fig. S16 & Table S19). Thereby, a strong dependence on aquatic resources suggests fish consumption may influence human Sr isotope ratios.

1.1. *The PWC site Ajvide, Gotland*

On Gotland, many of the PWC sites were found and excavated in the early 20th century and no sieving was implemented during excavation –

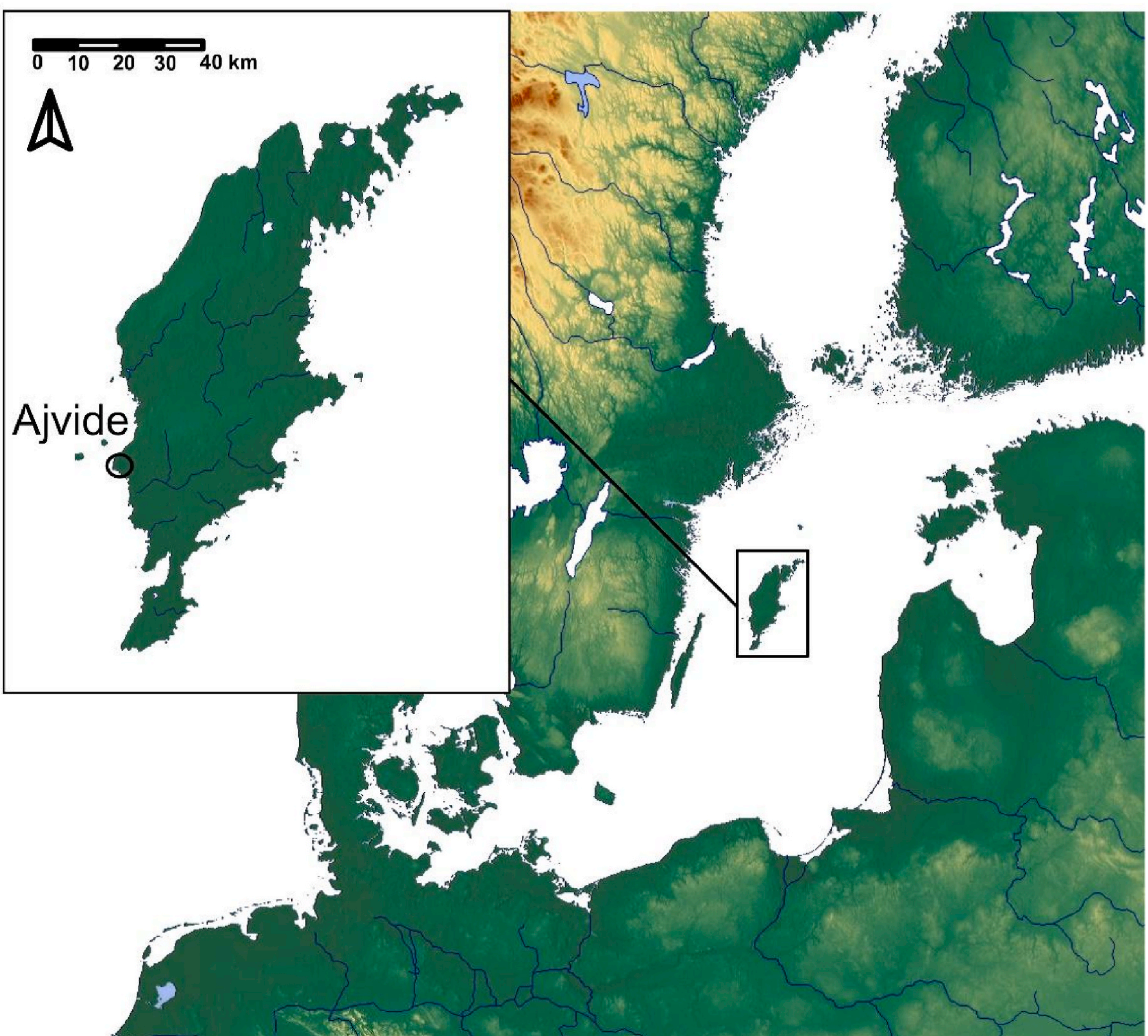

Fig. 1. Location of Gotland and Ajvide in the Baltic sea. Map from https://maps-for-free.com/.

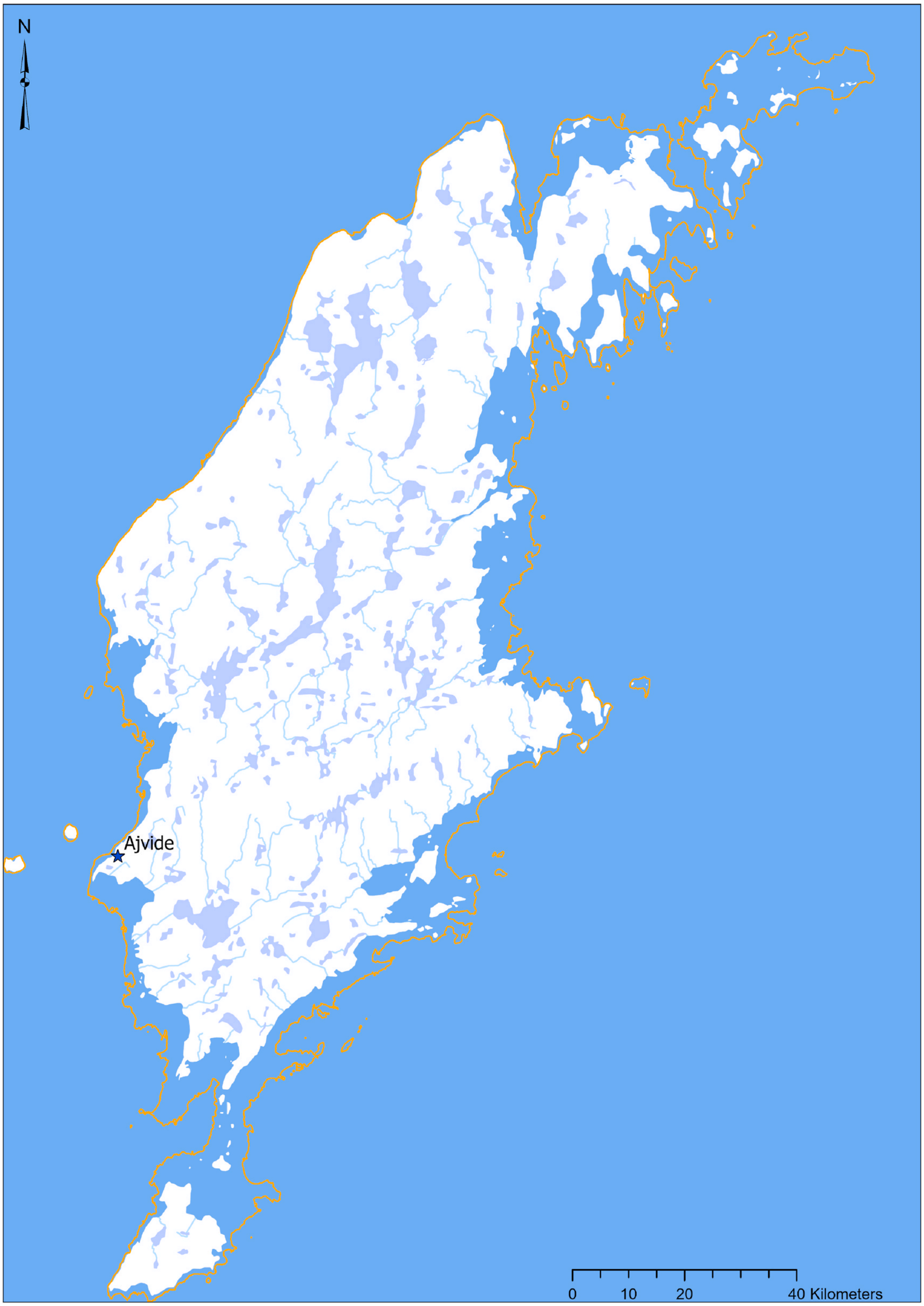

Fig. 2. Modelled freshwater systems and Gotlandic shoreline around 5000 years ago, with the modern shoreline marked in yellow (for pre-drainage ca 19th century and modern freshwater distribution se Fig. S1). Freshwater distribution and modelled coastline of Gotland around 5 Ka (based on data from SGU: Strandförskjutningsmodell, using the shoreline and lake model for the period 5000 years ago and Gotlandic streams (SMHI_ Vattendragslinjer_nätverk_2016). Maps generated in ArcGIS Pro version 3.2.

leading to an almost complete lack of recovered fish bones, as there is a strong correlation between sieving, mesh size, and fishbone recovering rates (Boethius, 2016; Payne, 1975; Segerberg, 1999). The PWC site Ajvide, on the island of Gotland (Figs. 1 and 2), is an exception. Ajvide has been excavated during several different excavation campaigns reaching from 1923 until 2017 (Österholm, 2002, 2008; Norderäng, 2001a, 2001b, 2003, 2004, 2006a, 2006b, 2007, 2009, 2010; Sjöstrand and Wallin, 2017). The excavations have been carried out in four areas: A, B, C and D, of which area D is the most extensively excavated area connected to PWC activities and contains two so-called *Dark areas* (DA) and the Post Hole area (PH) (Fig. 3). Large amounts of both terrestrial and aquatic faunal remains and 85 human burials have been recovered; however, only parts of the recovered material have been analysed (Storå, 2001; Mannermaa, 2008; Molnar, 2008; Olson, 2008; Sjöstrand, 2022).

Sieving was implemented during several of the excavation campaigns (4 mm mesh between 1983 and 1987 and 7 mm from 1992 and onwards (Sjöstrand, 2022), which has facilitated the recovery of fish bones. Unfortunately, the fishbone assemblages from Ajvide remain mostly unidentified despite dominating many of the sieved layers and assemblages (cf. e.g. Sjöstrand, 2022: Fig 4.122). Although from a limited area of Ajvide, one exception to the general lack of fish species identification from PWC Gotland is the work of Carina Olson, who sieved (using stepwise 8, 4, 2 and 1 mm mesh sizes) and analysed a small amount of soil from a limited area on Ajvide D-Upper (Olson, 2008). Interestingly, while cod (*Gadus morhua*) and herring (*Clupea harengus*) dominate the assemblage there is also a distinct presence of fish species that can live and thrive in both fresh- and brackish waters, e.g. pike (*Esox lucius*), cyprinids (Cyprinidae), perch (*Perca fluviatilis*), zander (*Sander lucioperca*) etc. (Kullander et al., 2012). In general, zooarchaeological assemblages from PWC sites on Gotland contain euryhaline fish species (i.e. able to adapt to different salinities), albeit in unknown quantities (Bägerfeldt, 1992; Ekman, 1974; Lidström, 2012; Nihlén, 1923, 1927; Rundkvist et al., 2004; Wallin, 1984; Österholm, 1989). In the Ajvide material, due to their limited numbers, the inclusion of euryhaline species has generally been interpreted as a by-catch when fishing for cod and herring, implying that these species were caught in the Baltic Sea when residing in the littoral waters close to Gotland (Olson and Walther, 2007). This assumption had probably been enhanced by the strong marine connection of the PWC, whereby terrestrial regions and freshwater systems have often been considered of lesser societal relevance. However, recently, when the whole diet, and not only the protein part, was studied through analyses of $\delta^{13}C$ in human enamel from the Gotlandic PWC site Västerbjers, terrestrial components of the diet were highlighted (Ahlström and Price, 2021). Considering that the PWC foragers from Gotland have Sr ratios affiliated with limited terrestrial regions and elevated $\delta^{15}N$ (indicating the consumption of high trophic level species - i.e., aquatic resources), inland freshwaters may also have been exploited. Isotope studies on archaeological fishbones on Gotland are limited, two studies contain $\delta^{13}C$ data for Middle Neolithic fish indicating that fishing took place in both the Baltic Sea and freshwater sources (Eriksson, 2004; Widerström and Norderäng, 2020). The inclusion of euryhaline species in the Ajvide assemblages is thereby important as they may provide information about fishing practices and possible use of freshwater systems (Fig. 2), which, considering our limited knowledge about how the PWC foragers on Gotland utilised terrestrial areas and freshwater lakes, is of great importance for our understanding of Gotlandic PWC societies.

To expand our understanding of if/how the PWC societies utilised inland freshwater systems on Gotland and if there may be temporal or contextual differences related to these practises, we sequentially analysed the $^{87}Sr/^{86}Sr$ ratios of pike and cyprinid teeth (i.e. euryhaline species) from three different contexts from Ajvide. To contextualise the fish tooth data, water samples from various freshwater bodies on

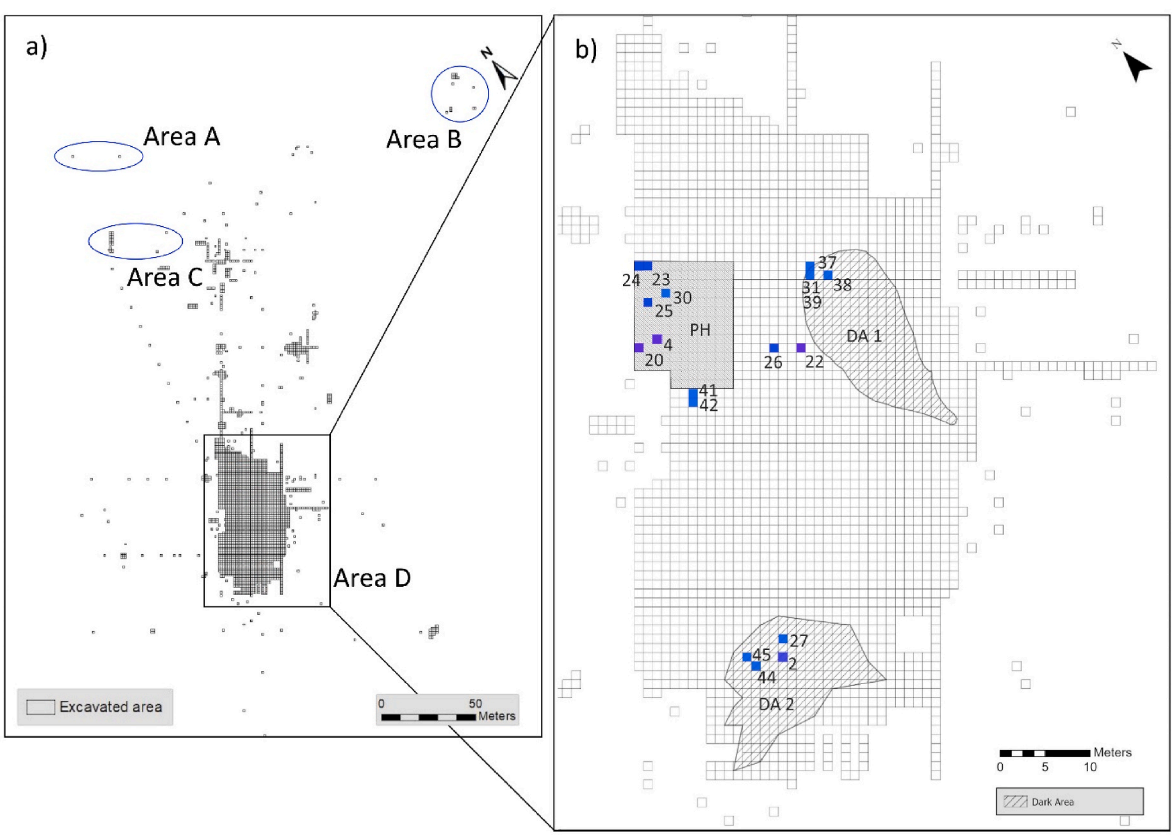

Fig. 3. a). Excavated area at Ajvide (based on Sjöstrand, 2022). b) Location of the sampled teeth, blue squares indicate sample and associated sample number, in Dark area 1 and 2 (DA 1, 2) and the Posthole area (PH) at Ajvide.

Gotland were sampled for bioavailable Sr ratios, which was complemented with previously published data to create a bioavailable Sr map of the inland freshwater lake regions of Gotland and the surrounding Baltic Sea. The combined data was used to study fish catchment areas, the possible use of freshwater aquatic systems, in contrast to fishing in the Baltic Sea, and how fishing activities may be related to potential land use.

2. Materials

2.1. Archaeological fish teeth

The fishbone material from the years 1987, 1993, 1998 and 2001 excavation of Ajvide was extensively analysed, using the comparative collections at the Department of Archaeology and Ancient History at Uppsala University and the Osteological Research laboratory at Stockholm University, to locate teeth from euryhaline species. Following the osteological identification, the teeth from 12 cyprinid pharyngeal bones and six pike dentaries were selected for sequential Sr analysis using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). The teeth originate from three separate contexts in area D, with known chronology – "Dark area" 1 and 2 and the posthole area (Fig. 3), for radiocarbon dates, Fig. 8c, and Supplementary Information Tables S1 and S2).

In total, 166 data points ranging between 6 and 12 Sr measurements per tooth were analysed (Table 1). Due to a thin and inconsistent enamel (in fish referred to as enameloid) cover on fish teeth, 99 of the measurements were partly (or in some cases fully) targeting dentine, resulting in them being discarded from further use due to suspected contamination from the soil (see methods section and SI, Tables S3–S20 and Figs. S2–S19 for detailed information and close-up photographs of both valid and invalid measurements). On all but one individual, at least one valid measurement was obtainable. The one individual without valid measurements (pike T4) was not further included in the analyses. The fish teeth were sampled with permission from the Museum of Gotland (Dnr. 2023-14-2).

2.2. Water samples

To contextualise the Ajvide fish ^{87}Sr/^{86}Sr data, 14 water sources from Gotland and one source in the brackish estuary outside the coast of Gotland were sampled and subsequently analysed using Thermal Ionization Mass Spectrometry (TIMS). The obtained data was connected to previously existing Gotlandic Sr data (Boethius et al., 2022) and data from the Baltic Sea (Åberg and Wickman, 1987; Andersson et al., 1992) to establish the bioavailable baseline of the water bodies of the region (Fig. 4; see Tables S21–23 for detailed information).

3. Method

3.1. LA-MC-ICP-MS analysis on teeth

The Ajvide fish teeth were washed in distilled water and cleaned with a soft brush. After cleaning the teeth were brought to the Vegacenter, Museum of Natural History, Stockholm, Sweden, and mounted in a movable sampling cell. The ^{87}Sr/^{86}Sr isotope ratios were analysed through LA-MC-ICP-MS using an NWR193 excimer laser ablation system, Elemental Scientific Lasers, Bozeman, USA, connected to a Nu Plasma II multi-collector ICP mass spectrometer, Nu Instruments Ltd, Wrexham, UK. Before the Sr ratios were measured, each tooth was pre-ablated using a laser spot size of 150 μm of ca. 400 μm length. This was done to reduce the risk of measuring surface contaminated enamel and remove the outer−10 μm of the surface. Each tooth was then analysed in the pre-ablated tracks with a 130 μm spot size, which was measured in subsequent order from the tip to the cementum-enameloid junction.

The laser beam targeted the enameloid at an equal depth. Cyprinid and pike teeth form similarly to mammal teeth (Albertson and Yelick, 2004; Herold, 1974). This suggests it is possible to obtain ordinal scale measurements, as proven obtainable for mammal enamel (Boethius et al., 2022). However, fish are polyphodont, and generate new teeth throughout life, whereby it is not possible to establish the age of the fish corresponding to the measurement. Furthermore, fish enameloid is thin and the laser beam passed through the enameloid and included dentine on almost 60% of the individual measurements. Dentine has a more porous structure and a lower density than enamel (Montgomery, 2010) and is more easily contaminated by the depositional environment (Hoppe et al., 2003). Sr data from unburnt bone or dentine of archaeological specimens tend to absorb Sr from the soil and is not considered to provide reliable results (Snoeck et al., 2015). Thus, all fish tooth measurements including dentine were deemed contaminated and

Table 1
Tooth-specific information for the studied fish teeth from Ajvide. DA = Dark Area, PH= Posthole area.

ID	Species	Family	Context	Valid measurements	Discarded measurements	Other information
T22	Cyprinid (cyprinidae indet.)	Cyprinidae	DA1-outside	6	2	
T26	Northern pike (*Esox lucius*)	Esocidae	DA1-outside	7	5	
T31	Tench (*Tinca tinca*)	Cyprinidae	DA1-inside	5	3	
T37	Pike (*Esox lucius*)	Esocidae	DA1-inside	3	9	
T38	Roach (*Rutilus rutilus*)	Cyprinidae	DA1-inside	1	11	
T39	Tench (*Tinca tinca*)	Cyprinidae	DA1-inside	8	0	Data not sequential
T2	Cyprinid (cyprinidae indet.)	Cyprinidae	DA2	7	1	
T27	Roach (*Rutilus rutilus*)	Cyprinidae	DA2-inside	1	7	
T44	Pike (*Esox lucius*)	Esocidae	DA2-inside	5	5	
T45	Pike (*Esox lucius*)	Esocidae	DA2-inside	1	11	
T20	Bream (*Abramis brama*)	Cyprinidae	PH	1	9	
T23	Bream (*Abramis brama*)	Cyprinidae	PH	6	2	
T24	Rudd (*Scardinius erythrophthalmus*)	Cyprinidae	PH-periphery	2	4	
T25	Bream (*Abramis brama*)	Cyprinidae	PH	2	8	
T30	Pike (*Esox lucius*)	Esocidae	PH	6	4	
T41	Roach (*Rutilus rutilus*)	Cyprinidae	PH- periphery	3	5	
T42	Roach (*Rutilus rutilus*)	Cyprinidae	PH- periphery	3	5	
T4	Pike (*Esox lucius*)	Esocidae		0	8	discarded

excluded from further analysis and interpretation. The dentine inclusions were detected visually, by studying close-up photographs, taken with a Nikon stereomicroscope SMZ800N mounted to a DFK 33UX264 33U Series camera using the program IC Measure 2.0.0.286, of each ablated tooth (Figs. S2–S19). Dentine contamination was further observed through divergence in $^{87}Rb/^{86}Sr$ ratios (Tables S6–S23), and confirmed by observable changes in $^{87}Sr/^{86}Sr$ ratios when dentine was struck. Enamel contamination is more difficult to identify, but the results do not show an increased concentration of Rubidium or Ytterbium, which could have indicated contamination, whereby ablations targeting pure enameloid were considered valid.

The teeth were measured in June 2023. Instrument operating conditions are listed in SI Table S24 and information on a primary standard (spine from a velvet belly lantern shark (Etmopterus spinax)), used for normalisation, and secondary standard (tooth from a mountain hare (Lepus timidus)), used to verify that all interferences had been successfully removed are listed in SI Table S25.

Isobaric interferences were corrected by subtracting a gas blank (^{84}Kr) and peak stripping (doubly charged REE, Ca-dimers/argides, ^{87}Rb). The corrections were applied online and resulted in interference-free $^{87}Sr/^{86}Sr$ ratios. Polyatomic interference (Ca/Ar)$^{31}P^{16}O^{+}$) on m/z 87 may introduce a significant offset in $^{87}Sr/^{86}Sr$ in samples with low strontium concentrations (Horstwood et al., 2008), resulting in inaccurate LA-MC-ICP-MS results (Simonetti et al., 2008). This interference was reduced by low oxide tuning of the gases as suggested by (Willmes et al., 2016) and, accurate $^{87}Sr/^{86}Sr$ ratios have been demonstrated at low concentrations, down to $C_{Sr} \sim 7$ ppm (Boethius et al., 2021).

3.2. TIMS analyses on water

The water samples used to establish the bioavailable Sr ratios in the Gotlandic waters were collected between April and June 2022. A minimum of three weeks without precipitation was maintained throughout the sampling period, to avoid rainwater or runoff contamination, and a zone of a minimum of 100 m from the closest potential source of contamination was also established, including farmland (fertilisers) and mining operations etc.

The water analyses were made using the Thermal Ionization Mass Spectrometer (TIMS) at the Museum of Natural History, Stockholm, Sweden implementing a Thermo Scientific TRITON TIMS using a load of purified samples mixed with silicotungstic activator on a single rhenium filament. Two hundred 8-s integrations were recorded in multi-collector static mode, applying a rotating gain compensation. The measured ^{87}Sr intensities were corrected for Rb interferences using $^{87}Rb/^{85}Rb = 0.38600$ and ratios were reduced using the exponential fractionation law and $^{88}Sr/^{86}Sr = 8.375209$. The external precision for $^{87}Sr/^{86}Sr$ as judged from running 987 standards was 28 ppm (n = 20). Accuracy correction was applied, while the $^{87}Sr/^{86}Sr$ ratio for the NBS 987 standard was 0.710214 ± 13 (n = 36). When accuracy correction was applied the $^{87}Sr/^{86}Sr$ ratio for the NBS 987 standard was 0.710214 ± 13 (n = 36), which was normalised to an NBS987 $^{87}Sr/^{86}Sr$ ratio of 0.710248 following McArthur (2010).

4. Results

4.1. Bioavailable baseline

The established bioavailable baseline for Gotlandlandic freshwater systems includes the 14 lakes and small streams sampled and subsequently analysed for Sr isotope ratios in this study (See SI Table S21 and S22). This data was complemented with one sample from the Baltic Sea coastal zone and previously existing bioavailable water and plant Sr data from the island and water data from the Baltic Sea. When visualised on a map of the local geology, showing the slight variations in the otherwise homogenous Neoproterozoic and Phanerozoic bedrock unit, it allowed us to create a bioavailable map of Gotland and the surrounding Baltic Sea (Fig. 4a). Further division of the Sr ratios according to their geological sub-units, bioavailable ranges for different areas on Gotland was also established (Fig. 4b).

The sedimentary limestone bedrock of Gotland is homogenous, and as seen in the bioavailable baseline, not perfectly aligned with the minor changes in the bedrock. Some patterns are observable in the data, with a slight elevation in Sr ratios on the Northwestern coast and in the marl areas of the Central-North and Central-South. Thereby, while the baseline is overlapping it mainly follows the geological formations of the island with a clear distinction from the bioavailable Sr ratios of the Baltic Sea. These geographical zones form the basis for discussions on terrestrial mobility of the PWC when related to the Sr data of the euryhaline fish teeth from Ajvide.

4.2. Euryhaline fish at Ajvide

67 valid Sr measurements from 17 individuals were used in the study. All individuals have Sr ratios related to the general area but with slightly different ratios, suggesting an origin and mobility within different water bodies (Fig. 5). Three pike individuals have Sr-ratios corresponding with the Baltic Sea (cf. Figs. 4b and 5), whereas the rest show Sr values coherent with the bioavailable baseline from Gotland. The three Baltic Sea pikes have high estimated Sr concentration (see Table S10, S12 and S19). Fish with $^{87}Sr/^{86}Sr$ ratios corresponding to the Baltic Sea, in general, tend to have somewhat elevated estimated Sr concentrations. However, the pattern is unclear, and the differences between inter-tooth ablations targeting pure enameloid and ablations including parts of the dentine are more pronounced. Thereby, since the LA-MC-ICP-MS only provides Sr concentration estimates and because there tends to be both an intra-species and intra-individual variation in Sr concentrations (when obtained through TIMS, see Boethius et al., 2024 Fig. S16 and Table S19), it makes using Sr concentrations obtained through LA-MC-ICP-MS for studying provenance an interesting albeit a somewhat blunt tool.

Due to many ablations failing to target only enameloid, a large number of measurements had to be discarded for further use. This limits the amount of available mobility information for each individual, whereby the inferred intra-individual mobility pattern is derived from less data and as a consequence of lower resolution than if more ablations had been valid. Nevertheless, despite four individuals being represented with only one measurement - whereby no mobility signals can be obtained from them, there is a discernible pattern when comparing the mobility of pike with cyprinids. If individuals with only one data point are discarded, the pike appears more sedentary than the cyprinids (Fig. 6).

To further contextualise the Sr ratios of the euryhaline fish at Ajvide the Sr ratios of the cyprinids and pikes were related to the bioavailable baseline of the geological zones on Gotland and the surrounding Baltic Sea proper (Fig. 4). This approach allows the assessment of an estimated region of catch, i.e. which Gotlandic region the fish originated from (Fig. 7).

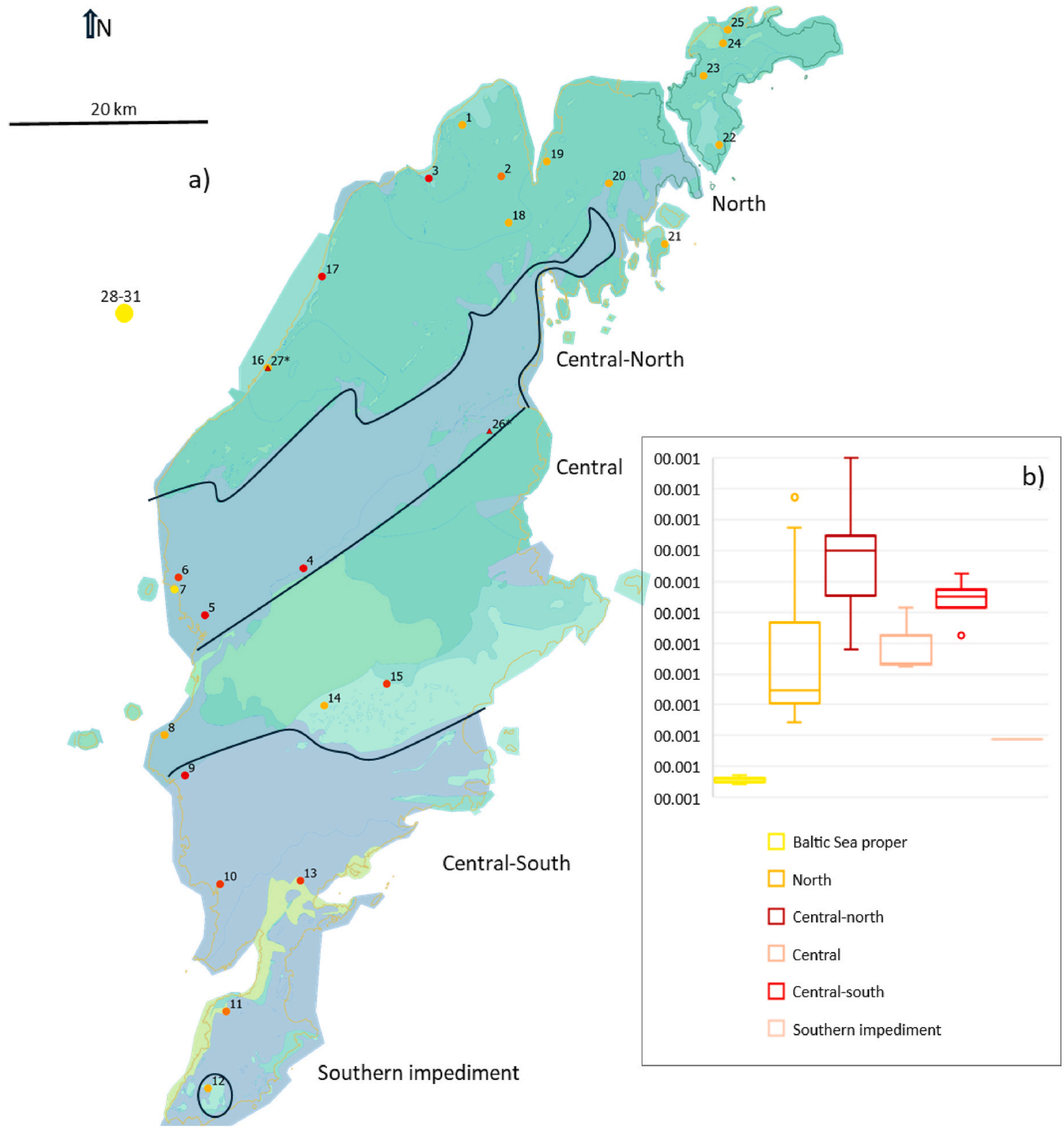

Fig. 4. a. Bioavailable Sr ratios on the island of Gotland (1–6; 8–27) and in the Baltic Sea proper (7; 28–31 (generic, sampling location not shown on map). Data points 26* and 27* marked with triangles represent Sr values obtained from plant samples. Bedrock data based on data from SGU (1:50000–1:250000 bedrock information). Where the North, Central, and Southern impediment consist of bioherm limestone and marl (Wenlock) and Central-North and Central-South of Marl (Ludlow). 4b. Boxplots showing the Sr ratios divided by bedrock unit using an inclusive median. See Table S23 for specifics.

5. Discussion

The bioavailable baseline indicates some, albeit low, Sr variability in the five geographical zones (Fig. 4). These zones largely correlate with the bedrock of the island, the two marl strokes; Central-North and Central-South show higher Sr values than the bioherm limestone of the other zones. Areas with the same bedrock (i.e. Central-north and Central-south on the one hand and North, Central and South on the other) show overlapping values. The overlapping baselines suggest that the Sr values can be used to delimit the likely origin of fish to the different zones, but, if using the measurement data only, not to one specific area.

5.1. Origin of pike and cyprinids on Ajvide

The tooth enameloid Sr ratios indicate that the fish in the Dark areas I and II and the Posthole area originate from at least six different water bodies and that euryhaline fish were caught in both freshwater lakes and the Baltic Sea (Fig. 7). Despite limited ^{14}C dates from the context and layers sampled for this study (see SI, Tables S1 and S2), there is some chronological variability in the sampled fish teeth. Correlated to the Sr data, the spatial-temporal trends indicate a slightly shifting fishing practice between different areas, with a slight narrowing of represented Sr ratios between the post hole area and the dark areas, which, if temporally dependent, could indicate increasing access to freshwater lakes over time (Fig. 8). The sample size is, however, limited, and interpretations of intra-site specific fishing practices should be done with caution.

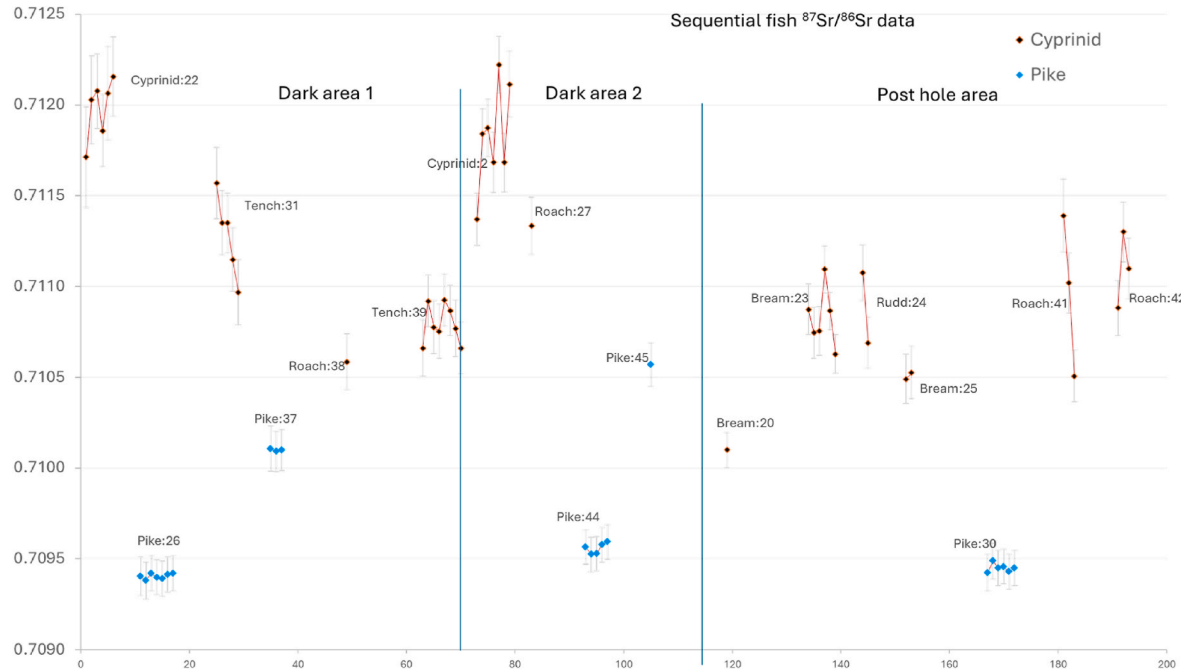

Fig. 5. Sequential fish data showing all valid Sr measurements.

Pike and cyprinids have varied mobility patterns, with both sedentary and migrating populations (Westin and Limburg, 2002; Rohtla et al., 2015). Seasonal fishing practices for different species have been shown in other Scandinavian foraging contexts, albeit several millennia older (Boethius et al., 2021), highlighting prehistoric foragers' ability to exploit different fish species based on their ecological-behavioural prerequisites optimally. From Ajvide, the comparably limited intra-individual mobility signal thus indicates that the sampled fish were relatively sedentary within their specific aquatic systems. Pike can be caught all year round, but can more easily be targeted during spawning (water temperatures above 9 °C) when they move to shallow waters. The comparably low number of pike bones, in relation to bones from cod and herring at Ajvide, does, however, suggest that although the season of catch may correlate with the spawning period pike fishing was most likely done sporadically and not specifically during natural agglomeration events. This assessment is further strengthened by the sequential Sr

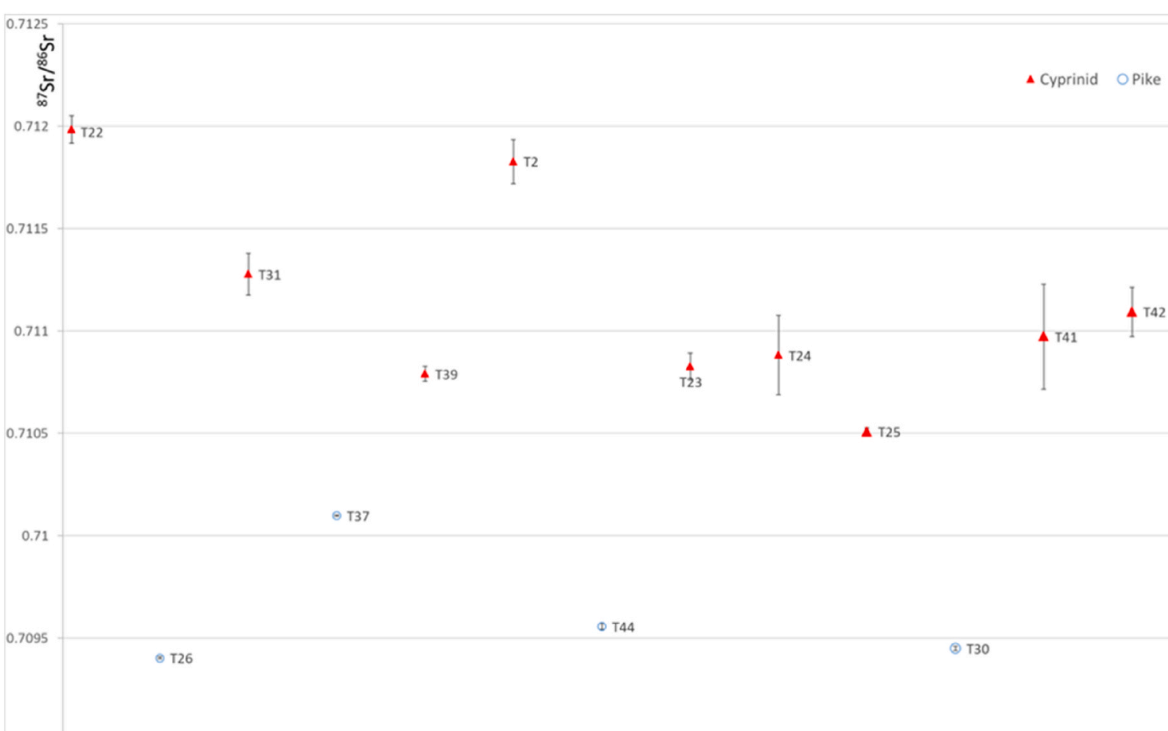

Fig. 6. Intra-individual mobility signals (range of Sr-ratios) for the cyprinids and pike with more than one data point illustrated as the mean and standard error of the mean for the combined enameloid ablations from each tooth.

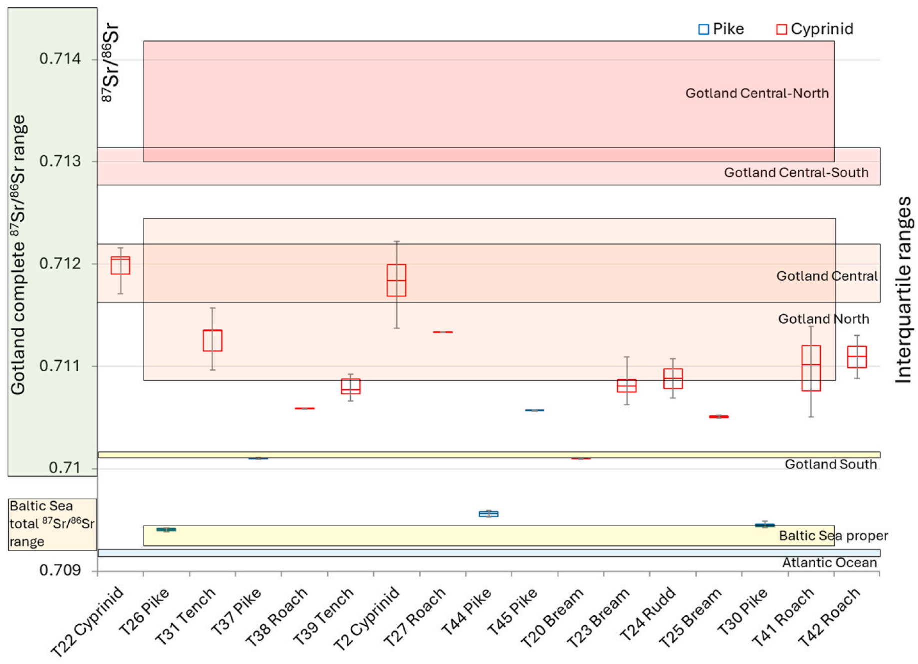

Fig. 7. Boxplots showing the measurement distribution of the ablations from the fish related to the Sr ranges from the Gotlandic zones established in Fig. 3b. Left shows the complete Sr ranges of both Gotland and the Baltic Sea, right shows the interquartile limited zones, i.e. the most likely occurring Sr ranges in the different zones.

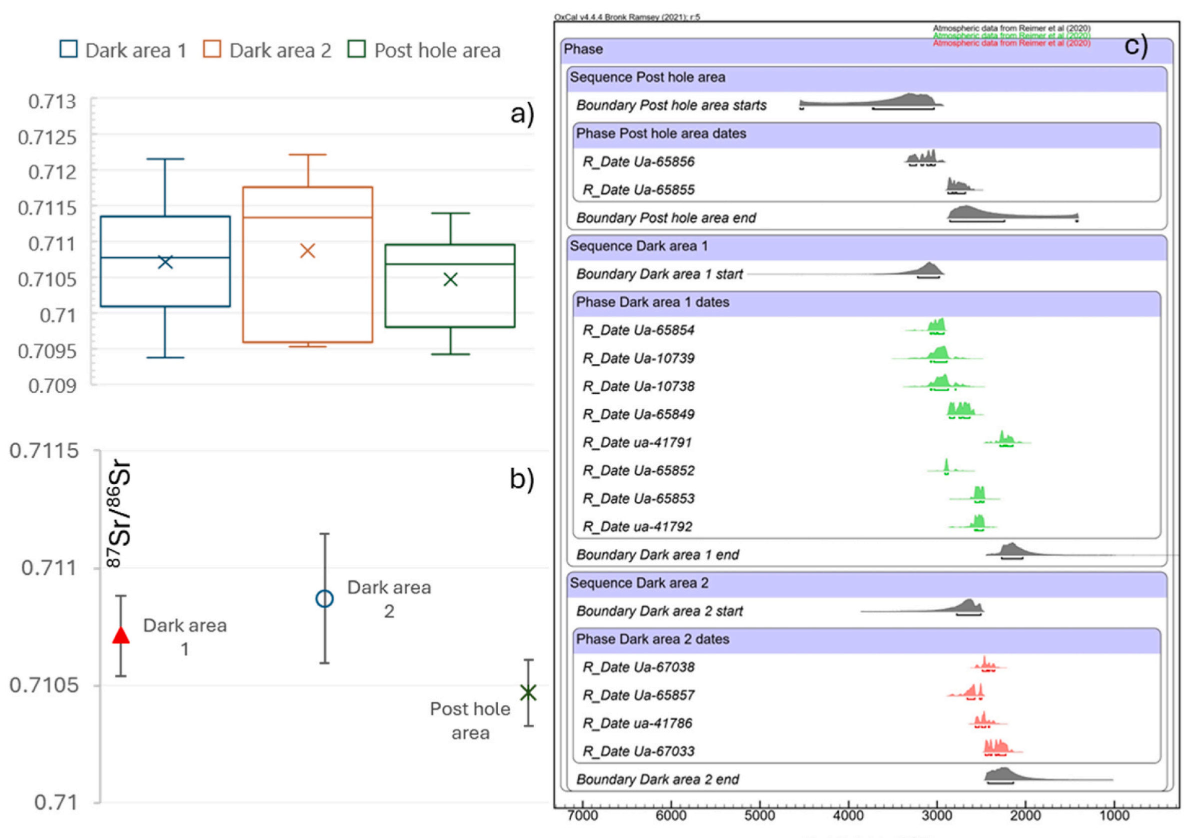

Fig. 8. a) total range of Sr ratios in the different areas of Ajvide. b) group mobility ranges in the three areas. c) Bayesian chronological model of ^{14}C Cal BCE from the Post hole area, Dark area 1 and 2 (Data from Wallin and Martinson-Wallin, 2016; Sjöstrand, 2022; Norderäng, 2008) (see SI Tabell S2 for ^{14}C data). The ^{14}C ages were calibrated using OxCal v.4.4.4. For all but one sample (Ua-65856 a dog/fox with a marine δ^{13}C value of −14.4‰) the Northern Hemisphere atmospheric calibration curve, IntCal20 (Reimer et al., 2020) was applied. For Ua-65856 calibration were done using the Mix_Curves function (i.e. the global marine calibration curve, Marine20 (Heaton et al., 2020) and IntCal20 offset by 380 ± 30 years (Kashuba et al., 2019; Günther et al., 2018)).

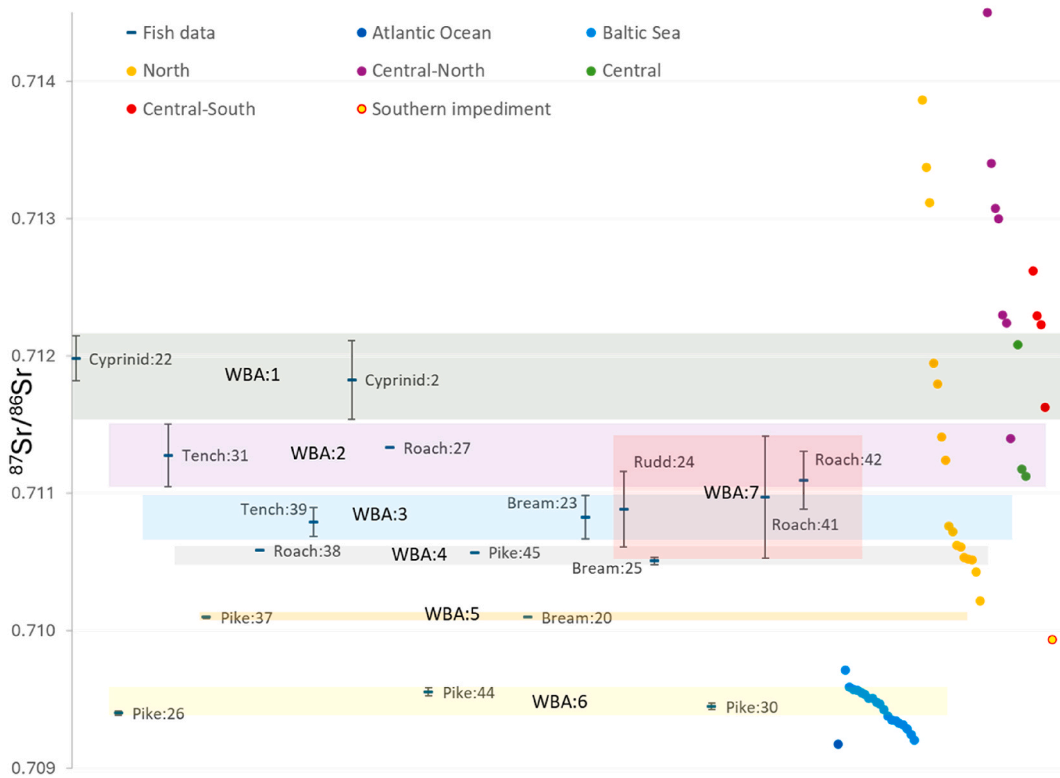

Fig. 9. Water Body Alignment derived from non-overlapping average Sr ratios, with added standard deviation to account for the intra-individual measurement discrepancies from each fish (WBA 1–6) and fish with Sr signals overlapping with the other WBAs (WBA 7). Data plotted against the bioavailable baseline sources on Gotland, the Atlantic Ocean and the Baltic Sea (see Table S23 for baseline data specifics) to illustrate the minimum number of different exploited water bodies.

analyses (Figs. 5 and 6), where the intra-individual measurements show low data variability, regardless of whether the pike originated within a Gotlandic lake or from the Baltic Sea, indicating that the exploited pike populations did not move between fresh and brackish habitats. This, in addition to the $\delta^{13}C$ signature of pike bones from Västerbjers (Eriksson, 2004), supports the interpretation that PWC pike fishing was not limited to fresh or brackish waters.

In contrast to the pikes, cyprinid Sr values only show ratios related to freshwater sources. Previous interpretations of the cyprinid catchment areas place them in the littoral zone or estuaries (Olson and Walther, 2007). Today, the cyprinid populations living in the coastal waters around Gotland migrate upstream in the spring to spawn. If the same were true during the Middle Neolithic period, this would have enabled large catches in nets or traps placed across/in the streams. However, the Sr data does not support the seasonal-specific utilization of cyprinid spawning activity-related mobility as no cyprinid measurements are related to Baltic Sea Sr ratios. Instead, the sequential cyprinid data indicate moderate mobility patterns (Figs. 5 and 6), where the targeted cyprinid populations were mostly sedentary and lived and moved within the Gotlandic freshwater systems.

If the average Sr ratio measurements from each individual, with added standard deviation to account for the intra-individual measurement discrepancies, are plotted against the bioavailable baseline sources, the fish data aligns six times into different non-overlapping Sr ratios (Fig. 9). Because fish mainly obtain their Sr from the water, and not their diet (see discussions in Boethius et al., 2024), this may be suggested to represent several different water bodies. The ancient water bodies that existed during the PWC occupation of Ajvide are not similar to the modern-day layout of freshwater systems on Gotland (see Fig. 2 for estimation on the freshwater systems on Gotland, and Fig. S1 for comparison between Neolithic, pre- and post-drainage). This is mainly due to extensive drainage where, at least, 211 km^2 of shallow lakes and wetlands have been drained since the 19th century (Sernander, 1941). This recent intense drainage implies that the Gotlandic terrestrial areas had larger and more numerous freshwater systems during the Middle Neolithic period, making it impossible to trace the exact water bodies used by the Ajvide foragers. To enable interpretation despite the differences in the layout of modern and prehistoric freshwater systems we constructed water body alignments (WBA) consisting of non-overlapping intraspecific average Sr ratios (including the standard deviation). When the WBA was correlated with the bioavailable signals from Gotland, it suggested the use of several different water bodies for euryhaline fishing activities (WBA 1–6 in Fig. 9), where, in some cases, the caught fish appears to have been mobile between different lakes/-streams (e.g. WBA 7 in Fig. 9).

If the fish data are related to the bioavailable Sr ratios, most of the fish Sr ratios can be found in the water bodies from the bioherm limestone areas (North, Central and South). The most elevated Sr ratios, found in the marly areas of Central-North and Central-South, are not reflected in the fish data. Ajvide is located in the Central zone and although the bioavailable Sr ratios of both the northern and southern zones correspond with the fish data, the absence of data in the zones between Ajvide and the outer zones may suggest that the caught fish came from the central zone only. This suggests that the terrestrial areas used by the foragers at Ajvide may have been limited to the areas closest to the settlement. Based on the landscape model (Fig. 2) and the WBAs (Fig. 9), access to the five non-overlapping water sources would require a minimum travelling distance of 15 km. If freshwater fishing was only done in the local lakes closest to the settlement, it may imply either freshwater fishing by convenience, i.e. in the lakes where they lived, or it may imply restrictions from fishing elsewhere. The latter possible interpretation thus suggests that Middle Neolithic period Gotland may have been divided into distinct territories.

5.2. Exploring the possibility and extent of PWC territories on Gotland

Gotland was one of the main areas for PWC occupation, as evidenced by a large number of cemeteries, large settlement sites and rich material known from the island (cf. e.g. Janzon, 1974; Österholm, 1989; Andersson, 2016). The known PWC sites are spread throughout the island, with settlements located at even distances from each other in sheltered areas along the coast (Österholm, 1989). Cemeteries are known from around the island and are often located in exposed areas, where they would have been visible from the water. The placement of the cemeteries thus fits with known ethnographic sources, where visible cemeteries are often placed along trading routes and at special locations in the group territory (Conolly, 2018; Grøn, 2015) and may under the right circumstances, following the so-called Saxe-Goldstein hypothesis (cf. Saxe, 1970; Goldstein, 1981), be connected to an ancestral claim to the area (Rowley-Conwy and Piper, 2016 and references therein). This type of ancestral claim could, potentially, have been practised among PWC societies on Gotland. Such decent lineage claims to a specific area are also further highlighted by a high prevalence of interpersonal violence noted on the human remains from Västerbjers (Ahlström and Molnar, 2012); which, if occurring on a large scale among indigenous foraging societies, may be connected to territorial disputes or even warfare (Kelly, 2013). The large amount of evidenced violence could, however, have other explanations, whereby further considerations must be made. For a society to develop territorial tendencies several factors and criteria are often met. For example, ethnographic forager data suggest territorial practices are more common among aquatic-dependent societies (Binford, 2001), especially if they live in regions where resources are seasonally abundant but otherwise more limited (Rowley-Conwy and Piper, 2016). In addition, one of the most significant factors related to violent behaviour and territorial practices is population pressure (Keeley, 1988), especially if it leads to resource limitations/scarcity (Allen et al., 2016; Nolan, 2003) and a pronounced need to exploit a particular area by different groups of people.

As previously discussed, the PWC is considered to have a subsistence base primarily depending on aquatic resources. In addition, the limited size of Gotland and the relatively large number of PWC settlements located at regular intervals along the coast suggest Middle Neolithic Gotland could have experienced intensified population pressure (cf. Apel et al., 2018). Furthermore, access to inland regions would have been needed to access the terrestrial resources. This is particularly highlighted by the abundantly occurring, sometimes even dominating, pig/boar bones on the Gotlandic PWC sites (Lindqvist and Possnert, 1997; Ekman, 1974; Sjöstrand, 2022; Stenberger et al., 1943). Although the importance of pigs/boars may have been limited in the daily diet, as suggested by human stable isotope data (cf. e.g. Eriksson, 2004; Eriksson and Lidén, 2013; Fornander et al., 2008; Howcroft et al., 2014; Boethius et al., 2024), seasonality information and age-of-death patterns have been studied to assess the reason for their abundance. This has resulted in suggestions of hunting and/or slaughter having been done to facilitate ritualised feasting events (Rowley-Conwy and Storå, 1997; Wallin and Martinsson-Wallin, 2016), whereby access to inland Gotland regions may not only be viewed as directly related to survival, as it may also have had a more sacral relevance. It may even be that freshwater exploitation should be seen in this context, i.e. as an addition to seasonal pig/boar hunting/slaughtering. Opportunistic fishing could explain the limited amount of euryhaline species in the assemblage, where the different waterbodies (Fig. 9) were located in the same areas used for hunting boar. Strontium values from boar teeth from Ajvide (Fraser et al., 2018 supplementary information) are consistent with the North, Central and Southern-impediment strontium baselines.

Additional competition for resources could, during the early period of the PWC occupation on Gotland, be related to the FBC presence on the island. Known FBC sites are located in the central areas of the island, and overlapping radiocarbon dates indicate a brief coexistence of the two cultures (c.f. Apel et al., 2018, Lindquist, 1997; Fraser et al., 2018). The exact timeframe for PWC and FBC coexisting on Gotland is, however, somewhat difficult to assess, as the freshwater radiocarbon reservoir effect is particularly pronounced on, and around, Gotland (Lougheed et al., 2016), and thus difficult to correct for (cf. e.g. radiocarbon data and discussions in Fraser et al., 2018; Philippsen, 2013, 2018; Iversen et al., 2021). Given the available radiocarbon dates it does, however, appear as if the PWC and the FBC coexisted on Gotland, at least partly. Human FBC δ^{13}C and δ^{15}N data indicate a primarily terrestrial diet, with a few individuals with elevated δ^{15}N values suggesting dietary input from freshwater fish (cf. e.g. Fraser et al., 2018). This means that terrestrial inland regions may be exposed to competition from the FBC as well.

Considering the ethnographic foraging data connected to violence and territoriality, the circumstantial evidence related to the PWC occupation of Gotland is interesting. In this context, the observed frequency of interpersonal violence and the territorial displays suggested by PWC cemeteries located in exposed and visible locations along the travelling routes could signal the practice of territorial limitations and terrestrial mobility restrictions. If the Västerbjers human Sr mobility patterns, their main affinity to the areas closest to the cemetery, and the homogenized inter-individual mobility patterns are also considered (Boethius et al., 2022), access to Middle Neolithic Gotland may have been restricted. This means that the PWC foragers were possibly unable to freely, and without limitations, exploit the inland regions of the island without inflicting aggression from neighbouring groups. The slight temporal diversification of freshwater sources (Fig. 8), could be an expression of slightly increasing terrestrial mobility as FBC presence decreases on the island, suggesting access to freshwater bodies, over time, became less restricted by other groups. All considered, it may, thus, be suggested that the Ajvide freshwater fish data correspond to the bioherm limestone areas of northern, central and southern Gotland is, in fact, only showing the use of Central Gotland, and potentially, only the areas of the western part closest to Ajvide.

6. Conclusion

The PWC population on Ajvide had a multi-resource utilization pattern where the regional availability of foodstuff was integrated into the dietary practices. The Sr values of the euryhaline species at Ajvide show that PWC fishing was not limited to the Baltic Sea, and correlates to at least five Gotlandic freshwater systems. Pike fishing was conducted both in the Baltic Sea and in Gotlandic freshwater systems, whereas cyprinids were only caught in freshwaters on Gotland. Furthermore, pikes showed lower mobility in the sequential Sr values indicating that the pike caught did not move between fresh and brackish water habitats. Cyprinids show higher mobility within different freshwater systems and a complete lack of Sr ratios related to coastal brackish estuaries or the Baltic Sea. When related to the bioavailable baseline, the Sr data from the fish teeth, suggests that the PWC population on Ajvide utilised freshwater systems located in the central zone, possibly in close relation to the settlement.

Albeit based on limited data, it may be possible to suggest a slight temporal shift related to freshwater utilization. The data suggest a slight increase in the variability of exploited freshwater systems in the Dark areas 1 and 2 compared to the posthole area. Considering the slight temporal differences, this may correlate with the decrease of FBC on the Island. However, given the limited amount of data, this needs further investigation as the observed trend may also be related to differences in deposition patterns.

This study highlights the importance of fish bone analyses to discuss the sustenance strategies and social structures of past societies. Our results highlight that the PWC terrestrial resource utilization on Gotland was more diverse than previously assumed. Lastly, this study demonstrates that conducting Sr analyses on euryhaline species found at Gotlandic archaeological sites with access to both the Baltic Sea and freshwater bodies is crucial for understanding sustenance procurement strategies and aquatic resource utilization.

Ethics

The archaeological tooth specimens included in this study were obtained with permission from Gotlands museum (Dnr. 2023-14-2) and will be returned to the museum. All analyses of archaeological specimens have been conducted by laser ablations. This causes minimal damage to the investigated specimens, the ablations are ca 400 µm long and 150 µm wide cut in the enameloid, which is barely visible to the naked eye.

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CRediT authorship contribution statement

Beatrice Krooks: Conceptualization, Funding acquisition, Resources, Data curation, Formal analysis, Visualization, Project administration, Writing – original draft, review, and editing. **Adam Boethius:** Data curation, Formal analysis, Visualization, Writing – original draft, review, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is available in the main document, in the Supplementary Information or in referenced publications

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108967.

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