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The role of salmon fishing in the adoption of pottery technology in subarctic Alaska

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ABSTRACT

Ceramic technology makes an abrupt appearance in the New World Arctic at circa 2800 cal BP. While there is general consensus that the ultimate source of these Alaskan pottery traditions lay in continental NE Asia, the motivations for the adoption of pottery in Alaska have remained unclear. Through organic residue analysis we investigated the function of Norton pottery in Southwest Alaska, and the extent to which its function changed in later periods under the increasing northern influence of Thule culture in the region (from ca. 1000 cal BP). Our results show clear evidence of aquatic resource processing in all pottery vessels. Regional variability due to environmental and ecological differences are apparent in the pottery. The majority of Norton pottery was from inland riverine locations and the function of this early pottery was to process anadromous fish, with only limited evidence of other resources. After 1000 cal BP more sites appear on the coast, and while pottery technology changes dramatically at this time, this is not as clear in pottery function which remains aimed at local abundant aquatic resources. We hypothesize that pottery was adopted into Alaska as part of a riverine adaptation and suggest that targeted human exploitation of large riverine systems may have facilitated its expansion into Southwest Alaska. Furthermore, we suggest that this pattern might extend back into Siberia where Alaskan pottery originates.

Author contributions

M.A. and P.D.J. designed the research; M.A., H.M.T., M.V.T., M.B., A. S., K.M.G. and A.L. did lipid residue analysis; M.A., J.H., O.E.C., and A.L. analyzed the data; M.A., P.D.J., O.E.C., and A.L. wrote the article.

1. Introduction

The arrival of pottery in the New World Arctic around 2800 years ago represents a remarkable new technological development (Fig. 1a). The tundral landscape is ill-suited to pyrotechnology, with limited supplies of fuel, and cold winters and damp summers limiting the manufacture and maintenance of ceramic vessels (Harry and Frink, 2009; Jordan and Gibbs, 2019a). Nonetheless, pottery was used by hunter-gatherer groups in Alaska for nearly 3 millennia (Anderson et al., 2017; Heizer, 1949). Before arriving in Alaska, pottery flourished in Northeast Siberia amongst the Late Neolithic (~3000 cal BP) and Ust' Belaia (3500 - 2500 cal BP) cultures of Northern Chukotka (Jordan et al., 2022; Kuzmin, 2014; Ponkratova, 2006). From a possible origin in the ceramic Ymyiakhtakh culture (4200 - 2500 cal BP) of Yakutia (Ackerman, 1982;

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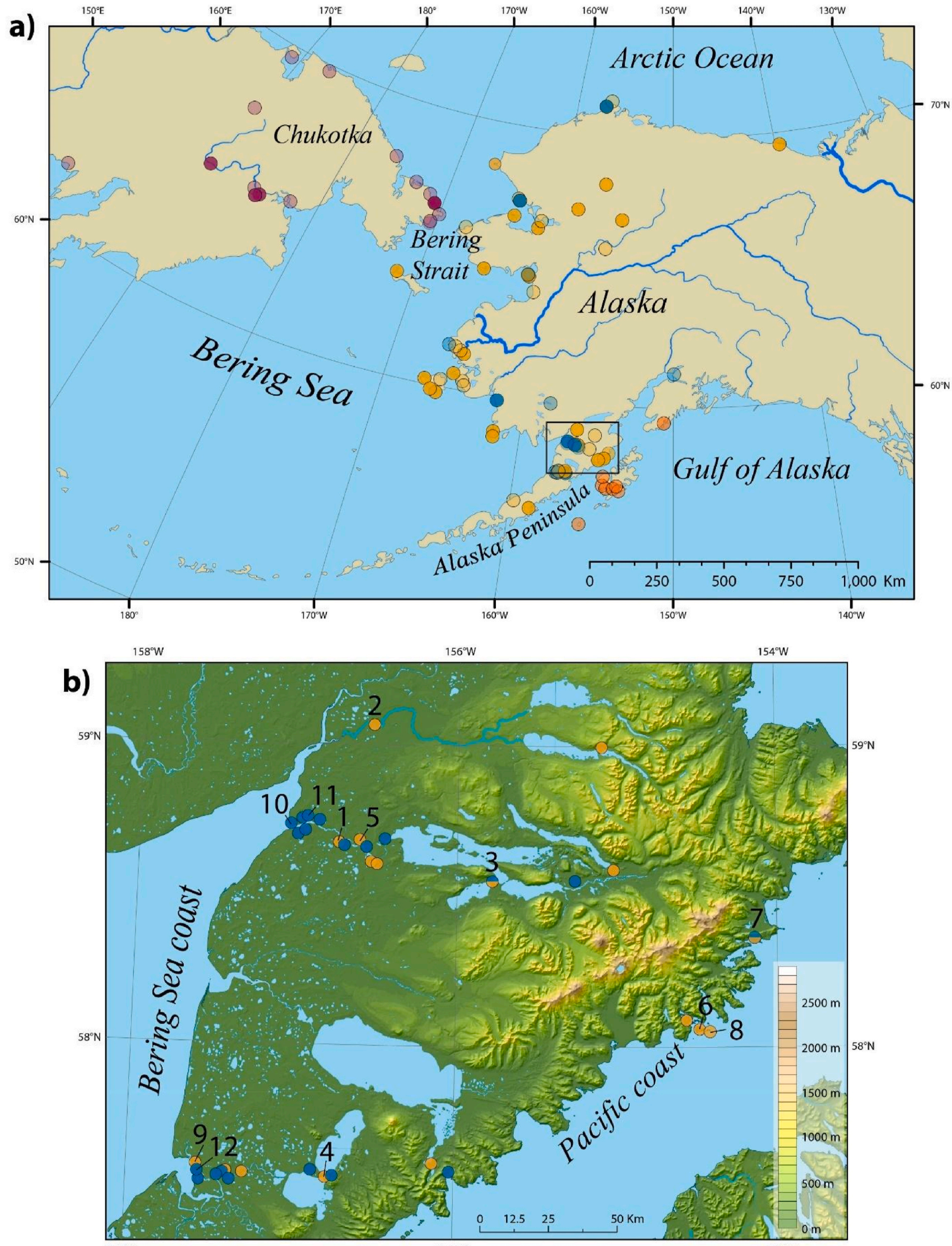

Fig. 1. Map of a) Alaska showing pottery sites of the Norton (ca. 2800-1000 cal BP, yellow), late prehistoric (including Thule and ancestral Yup'ik from ca. 1000 cal BP to contact, blue), and Koniag (ca. 500 cal BP to contact, orange) traditions, and post-3000 cal BP sites across the Bering Strait in Northeast Siberia (maroon) (a list of sites is available in Appendix Table B1. Translucent markers refer to sites that were not radiocarbon dated. The research area is marked by a rectangle corresponding to the outline of map b) showing the Alaska Peninsula and Norton (yellow) and ancestral Yup'ik (blue) sites. Sites sampled for this study are marked with a number: (1) NAK-3, (2) DIL-161, (3) the Brooks River sites (n = 7), (4) Ugashik River 1 and 2, (5) NAK-10, (6) AK-3, (7) Kukak 1, (8) Mink Island, (9) UGA-29, (10) NAK-2, (11) Leader Creek, (12) UGA-28, see Table 1 and Appendix Table B2. Images reproduced from (Admiraal, 2020) and designed by Frits Steenhuisen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Site and sample information. For more detailed information see Appendix B.

Fig. 1 #	Culture/site	Environment	Calendar date (cal BP)	Sampled sherds	Reference
	Norton				
1	Naknek River 3	Inland	2310–1848	8	Dumond (2011)
2	DIL-161		2130–2060	3	Bundy (2007)
			1500–1300	3	
3	Brooks River 10		*undated*	1	Dumond (1981)
4	Brooks River 14		1854	1	Dumond (2011)
5	Brooks River 7		1850	2	
6	Brooks River 8		1230	1	
7	Brooks River 5		1136	4	
10	Ugashik River 1		1871	5	Henn (1978)
11	Ugashik River 2		*undated*	2	
12	Naknek River 10		1685	1	Dumond (1981)
13	AK-3/MK-14	Pacific coast	1680	1	Clark (1977)
14	Kukak 1		1450	2	
15	Mink Island		1620–1360	1	Hilton (2002)
			960–755	1	
16	Ugashik River 29	Bering Sea coast	896	1	Henn (1978)
	Ancestral Yup'ik				
8	Brooks River 1	Inland	767–662	1	Dumond (2011)
9	Brooks River 20C		673	2	
14	Kukak 1	Pacific coast	775	1	Clark (1977)
17	Naknek River 2	Bering Sea coast	667	1	Dumond (2011)
18	Leader Creek (Naknek River 8)	Bering Sea coast	290–240	2	Dumond (2003)
			295	3	
19	Ugashik River 28	Bering Sea coast	*undated*	1	Henn (1978)

Dikov, 1979; Dumond and Bland, 1995), it entered the American continent at the Bering Strait and spread rapidly along Alaska's coastal margins with the Norton tradition (2800 - 1000 cal BP) (Anderson et al., 2017; Dumond, 2016; Oswalt, 1955). Pottery remained restricted to the broader coastal areas (Oswalt, 1955: pp. 40–41), and never truly spread further into the Alaskan hinterland (Fig. 1a). It first appeared after a pan-Alaskan occupation hiatus that followed the disappearance of the Arctic Small Tool tradition (ASTt) (Barton et al., 2018; Dumond, 2016; Tremayne and Brown, 2017). In the Northwest an early shift towards the exploitation of marine mammals occurred already among the ASTt (Buonasera et al., 2015) but this only intensified with the local Choris and Norton stages (Britton et al., 2013; Tremayne et al., 2018). This was possibly the result of the nearly year-round presence of sea-ice in the north, which was absent for several months of the year further to the south. These pronounced environmental differences have major effects on species distribution (e.g. salmon runs were much more abundant in Southwest Alaska) and helped shape subsistence strategies and likely also determined variation in pottery technology and function (Admiraal and Knecht, 2019; Dumond, 2016; Frink and Harry, 2019). .

Norton subsistence practices on the Southwest Alaskan mainland, especially on the Alaska Peninsula, encompassed a diversity of resources reflecting the different environmental zones of the area. The Alaska Peninsula is made up of an extensive coastal plain (the Bering Sea coast), a well-forested inland with abundant lakes and large rivers that drain into the Bering Sea, and a substantial mountain range (the Aleutian Range) that creates a barrier between the Pacific coast and the rest of the peninsula. The substantial runs of anadromous fish that occur from spring to autumn in the many rivers south of the Bering Strait played a significant role in Norton subsistence in Southwest Alaska (Dumond, 2016; Lutz, 1982). Anadromous fish in the region include Pacific salmon (*Oncorhynchus* sp., i.e. Chinook: *O. tshawytscha*; Sockeye: *O. nerka*; Coho: *O. kisutch*; Pink: *O. gorbuscha*; and Chum salmon: *O. keta*), but also other species such as trout (e.g. Dolly Varden: *Salvelinus malma*) and whitefish (e.g. *Coregonae* sp.). Caribou was also an important part of the Norton diet, further supplemented by marine species, waterfowl and shellfish depending on site location and the geographic distribution of prey-species (Casperson, 2018; Coltrain, 2010; Dumond, 2016; Frink and Harry, 2019; Miszaniec et al., 2021). In Northern Alaska salmon runs were less abundant and marine mammals played a more important role in coastal Norton sites, also south of the Seward Peninsula (Bockstoce, 1979; Britton et al., 2013; Tremayne et al., 2018). At around 1000 cal BP influences originating from the Thule tradition further to the north reached across Alaska and brought change (Britton et al., 2013; Dumond, 2003; Farrell et al., 2014). In Southwest Alaska more sites appeared on the Bering Sea coast, and while anadromous fish and caribou remained an important part of the diet, subsistence practices shifted more towards the marine environment. This change is best witnessed by the increased appearance of technologies for the open water hunt of large marine mammals (e.g. toggling harpoons), but also in more abundant sites on the Bering Sea coast and in the transformation of pottery technology. These late prehistoric ancestral Yup'ik groups experienced varying levels of Thule influence throughout the region. The pottery of these late prehistoric groups was tempered with crude mineral material, it was fragile, thick, and not as well-fired as that of the Norton tradition, which was often tempered with organic material (Figs. C1 and C2). These new traits likely originated in the northern Arctic where local climate further complicated the manufacture of pottery (Frink and Harry, 2008).

While the archaeological record testifies to the importance of pottery to the coastal peoples of Alaska, the reasons for investment in ceramic technology at this juncture in prehistory, and in such an extreme environment, remain poorly understood (Anderson et al., 2017; Jordan and Gibbs, 2019a). What drove the adoption of pottery technology in Alaska? What was pottery used for? How did it evolve throughout Alaskan prehistory? The dispersal of pottery on the Alaska Peninsula encompassed different environmental and climate trajectories including the distinct coastlines of the Subarctic Bering Sea and the more maritime climate of the Pacific coast. The large rivers and lakes of the Alaska Peninsula support major salmon runs from spring to autumn. In contrast, the Pacific coast is isolated from the inland peninsula by the Aleutian Range and lacks large river systems (Fig. 1b). This, and the divergence between the two chronological ceramic traditions (before and after 1000 cal BP) makes the region an interesting case study to investigate questions concerning pottery adoption drivers, functional patterns and changes throughout time and space.

Recent efforts to answer similar questions have focused primarily on late prehistoric pottery (e.g. Western Thule) (Anderson et al., 2017; Farrell et al., 2014; Harry and Frink, 2009; Solazzo et al., 2008; Solazzo and Erhardt, 2007). A common assumption is that the adoption of coastal pottery was strongly connected to a maritime adaptation (Jordan and Gibbs, 2019b). Indeed, the earliest pottery in Alaska is found around the Bering Strait where a maritime adaptation is more apparent than in the southwest (Tremayne et al., 2018). Pottery may have been an indispensable tool used for processing marine resources, particularly rendering marine mammal fats, an idea supported by ethnographic literature and Alaska Native oral histories (Anderson, 2019; Khvostof and Davydov, 1810; De Laguna, 2000; Heizer, 1949) and results from other regions (Admiraal et al., 2019, Admiraal et al., 2020a,b; Farrell, 2013; Farrell et al., 2014). We aim to test this hypothesis through the characterization of organic residues left in the pottery vessels themselves. We apply a combined approach of lipid residue analysis, compound specific isotope analysis and proteomics that can provide a unique insight into past culinary practices and human diet (Evershed, 2008a; Heron and Craig, 2015; Solazzo et al., 2008). While lipid residue analysis and compound specific isotope analysis are routinely applied to pottery, the study of proteins preserved in pottery is still in its infancy (Hendy et al., 2018; Solazzo et al., 2008). As the preservation of faunal remains in Alaska Peninsula Norton and ancestral Yup'ik sites is limited, this approach is especially valuable. Indeed, by applying lipid residue analysis and compound specific isotope analysis to pottery Anderson et al. (2017) found that Thule pottery, as well as two Norton vessels at the Cape Krusenstern site in Northwest Alaska, was predominantly used to process freshwater fish or anadromous fish. The site is located in an estuary setting on the Arctic Ocean. This result illustrates that long-standing assumptions regarding the reasons for pottery adoption in Alaska, may be wrong. There is a significant gap in research regarding early Alaskan pottery function, and its role in the adoption of the technology. Alternative drivers, deviating from a model of maritime adaptations, need to be explored. Norton and the later ancestral Yup'ik peoples of the Alaska Peninsula were known to exploit a diversity of resources over a variety of environmental settings including marine mammals and fish on the Pacific and Bering Sea coasts, anadromous fish on rivers, lakes and river mouths, and caribou in the interior (Bundy, 2007; Casperson, 2018; Dumond, 2016). Here we investigate the function of pottery with respect to these different subsistence foci. Our approach to explore spatial and temporal differences in pottery function on the Alaska Peninsula could shed new light on our understanding of prehistoric lifeways in this region and may reveal whether pottery was indeed used as part of a maritime adaptation.

2. Materials and methods

2.1. Sample selection

This represents the first large-scale organic residue study of Norton pottery and includes some of the earliest pottery from the North American Subarctic. Pottery of the Norton tradition is generally low in frequency, and the number of vessels per site is often unidentifiable due to the fragmented nature of the material which also limits the potential to reconstruct vessel form (Anderson et al., 2017). We aimed to explore wider trends in Alaska Peninsula pottery use and extracted lipid residues from a limited number of sherds per site, in addition to a small number of late prehistoric pottery samples of ancestral Yup'ik sites to explore regional temporal change in pottery function (see Appendix B Tables B2 and B3). A total of 37 Norton pottery sherds and 11 late prehistoric/ancestral Yup'ik sherds from 19 sites on the Alaska Peninsula (Fig. 1b, Table 1 and Appendix Table B2) were sampled, covering a wide variety of landscapes ranging from the Bering Sea coast to the interior river systems and the Pacific coast (Fig. 1). We targeted a variety of sites, regions and ecological zones to allow for comparison of organic residue data with spatial analysis of site distributions in Southwest Alaska to further explore patterns in the occurrence of pottery in these different environmental settings. Norton pottery is more often found in inland settings while ancestral Yup'ik pottery is more frequent at the coast. This is reflected in our sample selection with 81% of Norton vessels coming from the interior Alaska Peninsula, while 66% of ancestral Yup'ik samples come from the coast. Norton sites on the interior river systems have often been interpreted as fishing camps with semi-subterranean houses and abundant net-sinkers present (Dumond, 1981, 2003, 2011). While ancestral Yup'ik sites are often found on the coast it is important to note that such sites are often located near river mouths that were also excellent strategic locations for the interception of anadromous fish (Dumond, 2003). To investigate potential differences between the interior and exterior of the vessels, both in ceramic and carbonized surface residues we collected several samples per sherd: in total 46 ceramic samples and 56 carbonized surface residue samples, and one carbonized surface residue sample of a stone lamp from an earlier period as a reference (see Appendix Table B3). Additionally, lipids from faunal remains (bone) of several archaeological sites in Southwest Alaska and the Aleutian Islands were analyzed as reference materials.

2.2. Lipid extraction and analysis

Lipids were extracted using acidified methanol and following established protocols (Craig et al., 2013; Papakosta et al., 2015a; Colonese et al., 2015). In short, pottery samples were obtained by either scraping off carbonized crusts with a sterile scalpel, or by drilling into the surface of the sherd (3–5 mm depth) after removal of a 1 mm surface layer to avoid contamination. Bone samples were obtained by removing a mechanically cleaned section of bone that was then crushed to a homogenized powder (1 g) and solvent washed (3 × 2 mL dichloromethane/methanol 2:1 v/v wash) before extraction. Methanol was added to the homogenized samples (4 mL–1 g of ceramic powder/bone, 1 mL to 20 mg foodcrust) and the samples were sonicated for 15 min after which sulphuric acid was added (800 μL to ceramic powder/bone, 200 μL to foodcrust). Subsequently the acidified methanol mixture was heated for 4 h at 70 °C. After cooling and centrifugation, the supernatant was transferred to a sterile vial and extracted using hexane (3 × 2 mL). To test for the presence of triacylglycerols and wax esters a selection of 10 samples were also subjected to solvent extraction (Evershed et al., 1990). Briefly, a mixture of dichloromethane/methanol 2:1 v/v wash was used to extract 1 g of ceramic powder (3 × 2 mL). All acid and solvent extracted samples were finally also derivatized using N,O-Bis (trimethylsilyl)trifluoroacetamide (BSTFA). All samples were analyzed by gas chromatography-mass spectrometry (GC-MS) and GC-combustion-isotope ratio MS (GC-c-IRMS). Carbon and nitrogen values of bulk foodcrust samples were obtained by elemental analysis-IRMS (EA-IRMS) according to existing protocols (Craig et al., 2013; Lucquin et al., 2016b; see Appendix A for further information on methodology).

2.3. Proteomics

A selection of 11 ceramic samples was analyzed by proteomics in order to supplement lipid-based organic residue analysis and provide further insight into processed foodstuffs. Protein extractions were performed on 100 mg of powdered ceramic material. Proteins were extracted using Gel-Aided Sample Preparation, previously described in Hendy et al. (2018). Extracts were analyzed using LC-MS/MS at the Target Discovery Institute using the parameters previously described in Hendy et al. (2018). Samples were searched semi-tryptically using Mascot (Matrix Science) against the Swiss-Prot database (d.o.a.: 01-05-2017) with the following propionamide (C) as a fixed modification and deamidated (NQ), oxidation (M), propionamide (K), and propionamide (N-term) as variable modifications. Peptide mass tolerance was set at 10 pm m and fragment mass tolerance at 0.5 Da. Samples were searched using a decoy strategy and an FDR correction of <1% of all peptide spectral matches above the homology threshold was applied. Proteins were considered confident identifications when matching the criteria above, as well as being represented by at least two peptides.

Table 2
Lipid concentrations (expressed in mg g^{-1}) of ceramic and foodcrust (FC) samples on the Alaska Peninsula.

	Inland (ceramic)	Inland (FC)	Pacific coast (ceramic)	Pacific coast (FC)	Bering Sea coast (ceramic)	Bering Sea coast (FC)
range	0.028–4.3	0.7–10.4	0.4–4.4	0.5–16.6	1.2–11.1	1.1–37.8
mean	1.2	3.2	2.3	8.0	6.8	14.5
st dev	1.2	2.9	2.1	6.5	3.6	11.9

3. Results and interpretation

Lipid concentrations are generally high, ranging from 0.028 mg g^{-1} to 37.8 mg g^{-1} with a mean of 1.4 mg g^{-1} for Norton ceramic samples, and 5.6 mg g^{-1} for the late prehistoric ceramic samples. These values greatly exceed the minimum amount required for interpretation (>5 μg g^{-1} for ceramic, and >100 μg g^{-1} for charred deposits) and indicate excellent preservation (Craig et al., 2013; Evershed, 2008b). In one sherd (NAK8-13) extractable lipids accounted for almost 4% by total mass, the highest recorded in an archaeological sample. Interestingly, variability in lipid concentration is observed between samples from three defined regions: the inland (34 sherds, >15 km from the coast), Pacific Coast (6 sherds) and Bering Sea coast (8 sherds), with higher lipid concentrations from the coastal regions than from the inland, and especially high lipid concentrations on the Bering Sea coast irrespective of site. Lipid concentrations from foodcrusts are generally higher than ceramic powder concentrations (see Table 2 and Appendix Table B3). Norton samples (n = 75) have considerably lower lipid concentrations than those of later ancestral Yup'ik samples (n = 27) (Mann Whitney $U = 263$, $z = 5.681$ $p = < 0.05$), a trend likely also connected to geographic site distribution.

While protein analysis had been successful before on Arctic pottery (Solazzo et al., 2008), our material did not yield any ancient proteins that could be confidently assigned to a dietary source (Appendix Table B4). Identified proteins were from human keratin, most likely derived from contamination with skin and dust, and common laboratory reagents (e.g. trypsin). It is possible that the absence of proteins is due to the high lipid content and low protein content of the original content which may have lowered the extraction efficiency.

3.1. Molecular analysis

Several samples (n = 55) contain compounds that may have been formed during the firing of the pottery or during cooking on a coniferous wood-fueled fire (polycyclic aromatic hydrocarbons (PAH), benzene-polycarboxylic acids (BPCA) and abietic acid derivatives). Resinous compounds may also have been used to waterproof the pottery (Simoneit et al., 2000; Oras et al., 2017). Non-specific plant biomarkers such as sterols (β-sitosterol) and terpenes (α-amyrin) were identified in four carbonized food crust samples. It is possible that the presence of plants is underestimated in our samples as the presence of lipid-rich aquatic oils may obscure the plant derived lipids that usually occur at low abundance. Contamination by migration of lipids from the burial environment to the carbonized crusts must also be considered here (van Bergen et al., 1998). Seven samples have trace amounts of *n*-alkanes (C_{15}–C_{29}) and long-chain *n*-alkanols (C_{16}–C_{30}), identified in acidified methanol extracts following conversion to their TMS esters (Appendix Table B3). While this may hint at the processing of plants, abundances were too low to properly assess this. A selection of samples (n = 10) was subjected to solvent extraction and silylation to further explore the presence of plant biomarkers that may be lost by acidified-methanol extraction. Eight samples out of ten contained mono- and di-acylglycerols but no further diagnostic compounds were detected.

Most ceramic vessels presented strong molecular evidence for the processing of aquatic resources. The presence and high relative abundance of monounsaturated ($C_{16:1}$ to $C_{26:1}$) and polyunsaturated ($C_{18:2}$, $C_{20:2}$, and $C_{22:2}$) fatty acids, in addition to more common medium and long-chain saturated (C_9 to C_{32}), and dicarboxylic (C_7–C_{15}) fatty acids in nearly all samples, make up a lipid profile comparable to that of degraded aquatic products (Appendix Table B3). Aquatic biomarkers were identified by GC-MS in nearly every sample and include ω-(o-alkylphenyl) alkanoic acids (APAAs) with carbon length 16 to 22, and isoprenoid acids: TMTD (4,8,12- trimethyltridecanoic acid), pristanic acid (2,6,10,14- tetramethylpentadecanoic acid), and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid). APAAs are formed during the prolonged heating of mono-, di- and tri-unsaturated fatty acids at a temperature of 200 °C and higher, and therefore likely derive from cooking activities (Bondetti et al., 2021b; Evershed et al., 2008; Hansel et al., 2004). APAA C_{20}/C_{18} ratios are above the threshold of 0.06 (0.09–0.76 in our samples) as defined by Bondetti et al., 2021b, further supporting the presence of aquatic resources. Additionally, dihydroxy acids such as 11,12-dihydroxydocosanoic acid were identified in 17 out of 43 samples in the acidified methanol extracts following conversion to their TMS esters, confirming the aquatic origin of the vessel contents (Hansel et al., 2011; Hansel and Evershed, 2009).

The ratio of branched fatty acid ($C15_{br}$ and $C17_{br}$) further supports the aquatic nature of these samples (Appendix Table B3). Iso-branched fatty acids predominate in aquatic products (Demirci et al., 2021; Garnier et al., 2018; Hauff and Vetter, 2010), while anteiso-branched fatty acids are present in higher quantities in ruminants (Dudd et al., 1999; Hauff and Vetter, 2010), and even more so in beaver tissue (Demirci et al., 2021; Käkelä et al., 1996). The majority of our pottery samples show high percentages of iso-branched fatty acids and are comparable to aquatic species. However, seven of the Norton samples also show values more comparable to ruminants. While these samples also exhibit aquatic biomarkers, it is interesting to note the possibility that several foodstuffs, including caribou, may have been mixed in these ceramic vessels, either at the same time or in separate cooking events.

Isoprenoid acids are abundantly present in the samples and are degradation products of phytol, a constituent of chlorophyll which occurs widely in plants and algae. In the freshwater and marine food web phytanic acid is formed from phytol through the digestion of phytoplankton chlorophyll by invertebrates such as zooplankton (Avigan and Blumer, 1968). Phytanic acid becomes integrated in the marine food web where it may accumulate and where catabolic processes may also form other isoprenoid acids such as pristanic acid and the relatively stable TMTD (Ackman and Hooper, 1968). While in lesser abundances, phytanic acid also occurs in ruminant animal tissues. In the rumen it is formed by bacterial oxidation and hydrogenation of phytol. We discriminate between these sources by comparing the abundance of SRR and RRR diastereomers of phytanic acid (SRR%) (Lucquin et al., 2016a). All SRR% pottery values plot within the aquatic range as compared to modern references (Fig. 2a), although two outliers of Norton pottery (NAK3-1 and AK3-16) also are withing the range of ruminant values and may represent the processing of caribou in these pots.

That Alaskan coastal pottery was used to process aquatic species comes as no surprise. However, the aquatic spectrum encompasses a huge variety of species and accompanying human subsistence strategies. Indeed, it takes a completely different strategy to fish for salmon than it does to hunt marine mammals on the open water. The ratio of isoprenoid acids TMTD and phytanic acid may be of further interpretational value and could offer a potential means to discriminate between (groups of) marine species (Ackman and Hansen, 1967; Ackman and Hooper, 1968; Cox et al., 1972; Ratnayake et al., 1989). We observed differences between modern anadromous fish and other aquatic species including seal and shellfish, where anadromous fish has low quantities of TMTD and

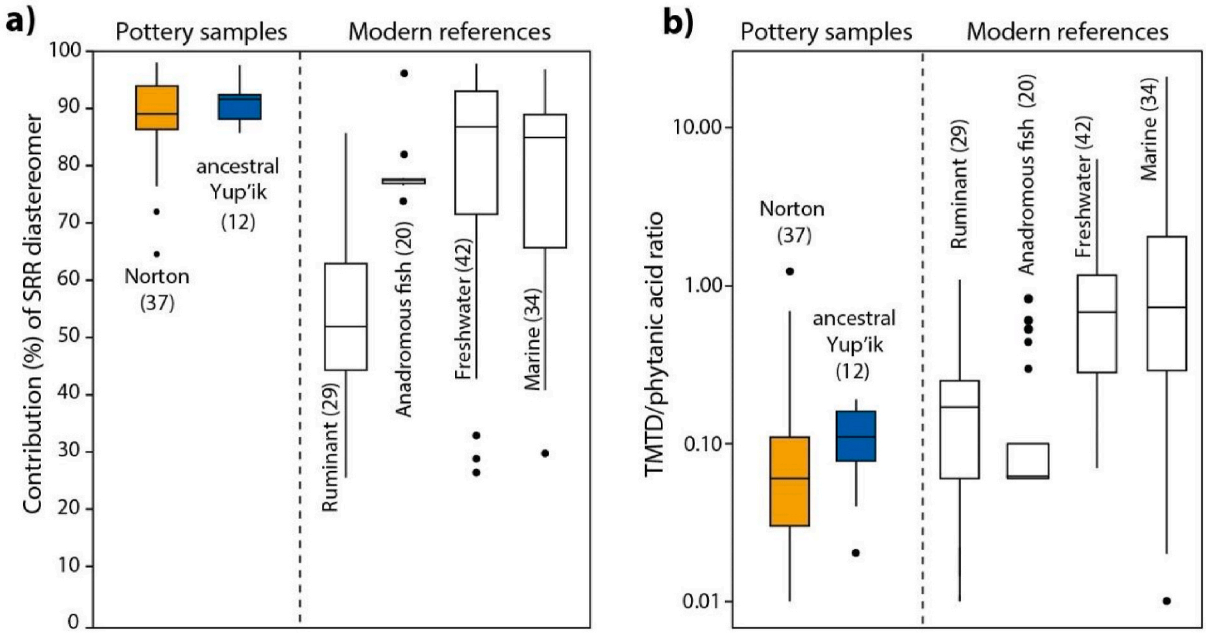

Fig. 2. A) Percentage of SRR diastereomer in total phytanic acid in Norton (yellow) and ancestral Yup'ik (blue) pottery, compared with modern ruminant and aquatic resources; and b) ratios of 4,8,12-TMTD and phytanic acid (logarithmic scale) in Norton and ancestral Yup'ik pottery and modern references (see Appendix Table B3 and Table B5). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

high phytanic acid quantities (t (2.19), $p = 0.03$) compared to other aquatic species, especially seal (see Ackman and Hooper, 1968). Our pottery data exhibits low TMTD/phytanic acid ratios similar to anadromous fish (Fig. 2b). To fully explore the potential of the TMTD/phytanic acid ratio further research is necessary. The influence of metabolic processes and the position of the species in the marine food web, as well as post-depositional and degradation processes are currently poorly understood.

3.2. Isotopic analysis

3.2.1. Compound specific isotopes of individual fatty acids

To further distinguish between potential sources of the residues we measured the carbon isotope values ($\delta^{13}C$) of individual fatty acids $C_{16:0}$ and $C_{18:0}$ using GC-combustion-isotope ratio MS (GC-C-IRMS). These compound specific isotopes further corroborate that the majority of samples are aquatic in origin (Appendix Table B6). Modern reference values of known origin in three different aquatic groups (marine species, anadromous fish and freshwater fish) allow for further differentiation within the aquatic spectrum after correction to account for recent changes in the isotopic content of atmospheric CO_2. Marine organisms are generally more enriched in ^{13}C than other aquatic species such as anadromous fish and freshwater fish, although variation exists depending on feeding habits. Seventy percent of Norton pottery (28/40) values plot within the range of anadromous fish species (Fig. 3). Some outliers have fatty acids less enriched in ^{13}C that may indicate the processing of freshwater fish, and two early Norton samples (i.e. DIL161-1004; NAK3-1) plot towards ruminant values. Seven Norton samples (of which four are from the Pacific coast) show a stronger marine signature with more enriched values. Compared to Norton (n =

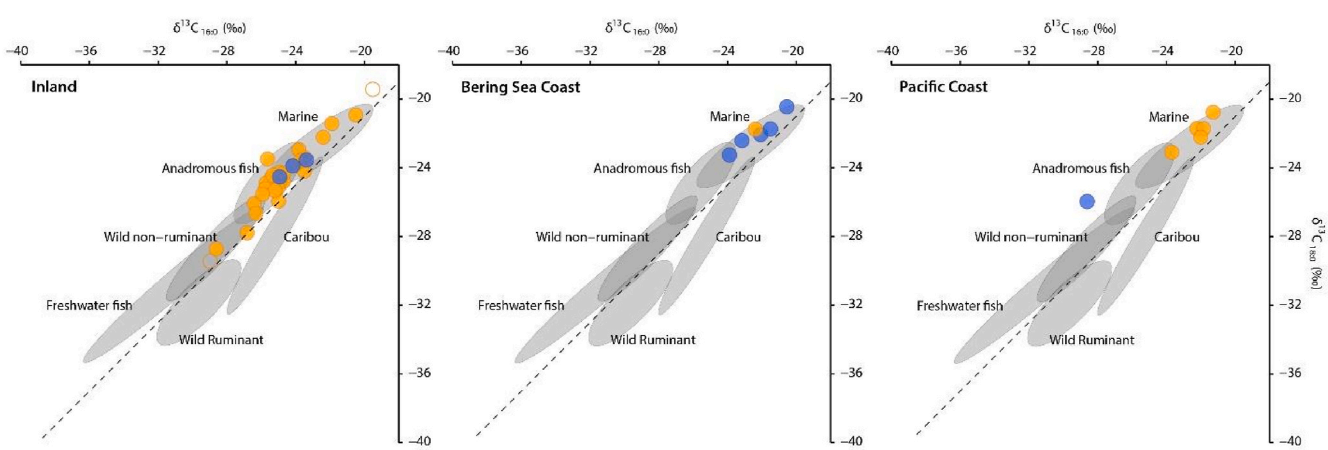

Fig. 3. Carbon isotope measurements of individual fatty acids $C_{16:0}$ and $C_{18:0}$ for the three distinct regions: the Alaska Peninsula inland, the Bering Sea coast, and the Pacific Coast (Appendix Table B6). Norton samples are in yellow ancestral Yup'ik in Blue. Shapes refer to the presence (filled circles) and absence (open circles) of aquatic biomarkers. The data are compared to reference values of modern tissue and bone from the Northern Hemisphere plotted in 66,8% confidence ellipses, the dotted diagonal line represents the ruminant offset boundary of $\Delta^{13}C = -1$ (Appendix Table B7; Bondetti et al., 2021a; Choy et al., 2016; Courel et al., 2020; Craig et al., 2011; Cramp et al., 2014; Horiuchi et al., 2015; Lucquin et al., 2016b; Pääkkönen et al., 2020; Taché and Craig, 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

36), pottery of the ancestral Yup'ik (n = 9) does not show statistically significant differences in isotopic values of fatty acid $C_{16:0}$ (Mann-Whitney $U = 123$, $z = 1.092$, $p = 0.274$) but do show slightly more enriched values (late prehistoric mean $C_{16:0} = -23.9$; Norton mean $C_{16:0} = -24.3$). Samples from the late prehistoric period are mainly from the coast, except for two samples from the Brooks River (BR20) that are indeed less enriched than the other late prehistoric samples, likely reflecting the processing of anadromous fish (Appendix Table B3). This data is further corroborated by carbon and nitrogen stable isotope values of human remains from the interior Brooks River area (BR5) (Coltrain, 2010). Coltrain's results indicate that late prehistoric ancestral Yup'ik people in this area subsided on a diet of terrestrial animals and anadromous fish such as salmon, with the possible addition of marine animal products from the coast.

3.2.2. Carbon and nitrogen analysis of foodcrusts

The bulk carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), %C and %N values of charred deposits from the surface of 38 pottery vessels were determined by EA-IRMS (Appendix Table B6). This approach is complicated both by the charring process and the different quantities of proteins, lipids and carbohydrates in the vessel contents prior to charring (Heron and Craig, 2015), but has been shown to be effective at distinguishing different sources and substances (e.g. oil vs protein-rich foodstuffs; Gibbs et al., 2017). In Fig. 4, the $\delta^{15}N$ values obtained from the foodcrusts are compared with archaeological bone collagen values from Alaska and Canada, adjusted to consider the tissue to collagen offset (ca.+ 2‰; Fernandes et al., 2014). Thirty-three of 38 (87%) foodcrust samples had $\delta^{15}N$ values between 10‰ and 15‰, within the lower range expected for aquatic organisms and closer to the range of anadromous fish and freshwater fish than to marine organisms (Knudson and Frink, 2011), but also in the range of wild non-ruminants such as bear, fox and small game. The $\delta^{13}C$ values of the charred deposits are harder to compare with bone collagen measurement as their value depends on their lipid content, which is relatively depleted in ^{13}C. Nevertheless, there is a positive correlation between $\delta^{13}C$ and $\delta^{15}N$ (Pearson $r = 0.92$, $df = 8$, $p \leq 0.005$) for the late prehistoric ancestral Yup'ik samples (mainly coastal), as may be expected for mixtures of marine resources at different trophic levels (fish, marine mammals). The Norton foodcrusts, mainly from riverine sites, show no correlation between $\delta^{13}C$ and $\delta^{15}N$ (Pearson $r = 0.30$, $df = 24$, $p = 0.143$), indicating a more varied source of carbon, that could reflect freshwater or anadromous fish but may also be the result of mixtures with plants and terrestrial animals (Fig. 4).

3.2.3. Elemental composition of charred surface deposits

The atomic C:N ratio of foodcrust samples and the $\Delta^{13}C$ offset between compound specific and bulk data can crudely inform on the composition of the charred deposits (Robson et al., 2022). High C:N ratios indicate a lipid rich sample (Admiraal et al., 2019), or a sample rich in carbohydrates from plants (Bondetti et al., 2020). A low C:N ratio shows a greater proportion of nitrogenous compounds such as proteins (Gibbs et al., 2017). Most of our foodcrust samples have intermediate atomic C:N ratio values (n = 31/37 = 6.24–14.10), reflecting lipid-rich, but not pure lipid products (Admiraal et al., 2019; Heron et al., 2013). This is supported by the positive correlation (Pearson $R = 0.625$, $df = 34$, $p = < 0.05$) between the C:N ratio and the lipid concentrations of the lipid extract of the same sample. The offset of compound specific $\delta^{13}C$ values (average $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$, measured on the lipid extract) and the foodcrust bulk ^{13}C value, is of interest because it can show whether the two techniques are essentially measuring the same component (i.e. lipids: exhibiting a minimal offset), or if the bulk analysis is picking up on other components such as proteins and carbohydrates, resulting in a larger offset due to the isotopic difference between fats, proteins and carbohydrates (Admiraal et al., 2020b; Post et al., 2007; Robson et al., 2022). The $\Delta^{13}C$ offsets ($\Delta^{13}C$ FA_{mean}- $\delta^{13}C_{bulk}$) show marginally greater range (−8.23 to 2.26) in Norton pottery, than in the ancestral Yup'ik pottery (−4.47 to 1.72), indicating that the late prehistoric ancestral Yup'ik pottery may have been used to process slightly more lipid-rich substances. There is no statistically significant difference between C:N ratios of Norton (n = 26) and ancestral Yup'ik pottery (n = 11) (Mann-Whitney $U = 136$, $z = 0.216$, $p = 0.828$) nor between coastal (n = 11) and inland (n = 26) samples (Mann Whitney $U = 113$, $z = 0.980$, $p = 0.327$). However, when comparing the pottery data to Aleutian stone bowls, previously interpreted to have been used for oil rendering purposes (Admiraal et al., 2019), the lower C:N ratios (Mann Whitney $U = 306$, $z = 3.288$, $p = < 0.05$, stone bowls n = 31, pottery n = 37) and smaller $\Delta^{13}C$ offsets in the pottery samples (n = 32) versus the stone

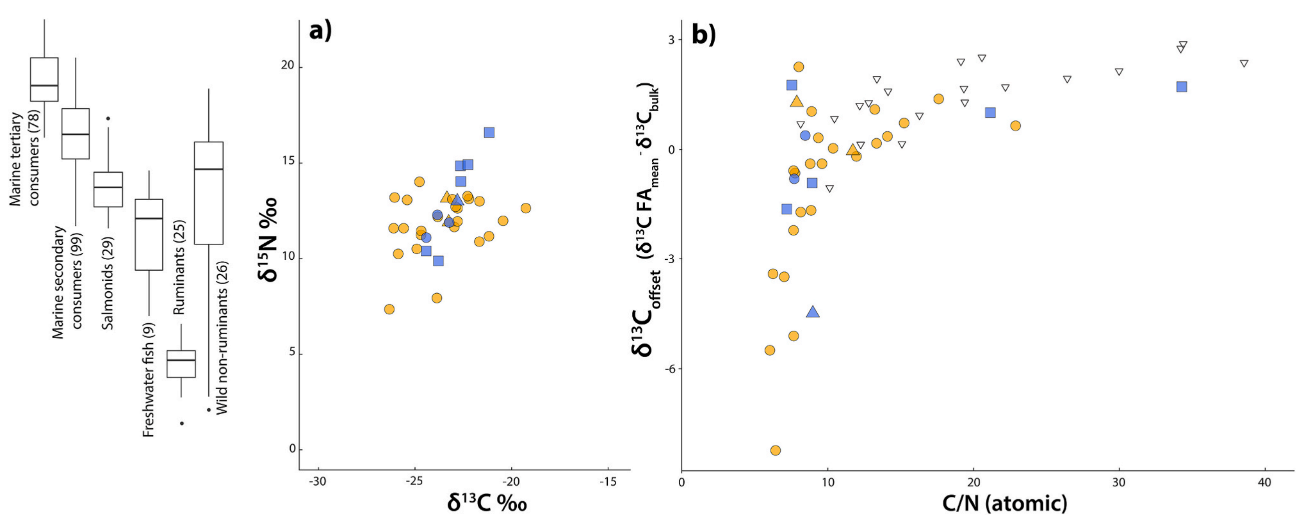

Fig. 4. A) carbon and nitrogen values of bulk carbonized residues of Norton (yellow) and ancestral Yup'ik (blue, Appendix Table B6), against $\delta^{15}N$ values of modern references on the left (Admiraal et al., 2019; Britton et al., 2013; Byers et al., 2011; Choy et al., 2016; Coltrain et al., 2016, 2004; Knudson and Frink, 2011; Marsh et al., 2017; Misarti et al., 2009; Pauly et al., 1998; West and France, 2015, see Appendix Table B8). $\delta^{15}N$ values of collagen were corrected to allow comparison to carbonized surface residues by assuming that the δ15 N in the surface residues are derived from protein in animal tissue and the $\Delta^{15}N_{tissue\text{–}collagen} = \sim+2‰$ (Fernandes et al., 2014); b) $\Delta^{13}C_{offset}$ ($\delta^{13}C$ FA_{mean}- $\delta^{13}C_{bulk}$) of Norton (yellow) and ancestral Yup'ik (blue) inland sites (circles); sites on the Pacific coast (triangles); and sites on the Bering Sea coast (squares), Aleutian stone bowl values are shown for reference (downward triangles, Admiraal et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bowls (n = 19) (Mann Whitney $U = 95$, z = 4.222, p = < 0.05) may indicate that the pottery of the Alaska Peninsula was not a specialized tool used for the rendering of oil, but had a more diverse use in general.

4. Discussion

4.1. The function of Norton and ancestral Yup'Ik pottery

Organic residue analysis of Norton and late prehistoric ancestral Yup'ik pottery from the Alaska Peninsula provided unambiguous evidence for the processing of aquatic resources in all the ceramic vessels tested here (n = 49). Our main finding is that the vast majority of the Norton pottery we tested from the interior Alaska Peninsula was used to process salmonids or other anadromous fish while coastal resources were present in the pottery from coastal sites. We found limited evidence of the addition of other resources, such as caribou and plants. However, we caution that this may be the result of masking of less lipid-rich resources (e.g. from plants) by lipid-rich aquatic oils. Interestingly, some of the earliest pots in the region, from inland site locations on the Naknek River (NAK-3) and Alagnak River (DIL-161), have yielded clear marine values beyond the range of anadromous fish (Appendix Table B6). These sites are located 20 and 38 km from the coast respectively, indicating the transport of coastal resources inland over distances of more than a day's walk (~15 km) as early as 2120 cal BP (Bundy, 2007; Dumond, 2011). This suggests that marine resources were still of importance to these early settlers of the Alaska Peninsula.

The ancestral Yup'ik pottery tested in this study (n = 11) mainly originates from Bering Sea coastal sites and yielded abundant marine lipids. Some late prehistoric pottery from the Alaska Peninsula inland (i.e. Brooks River sites, n = 2) was used to cook anadromous fish, a result further corroborated by human isotope data (Coltrain, 2010). Based on our limited sample of ancestral Yup'ik pottery we cannot confidently suggest a major change in pottery function from 1000 cal BP. High lipid concentrations, a few high C:N ratios and smaller $\Delta^{13}C$ offsets between lipid and total carbon in foodcrusts may indicate the processing of more lipid-rich species, likely marine mammals. While this interpretation is in line with ethnohistoric information about pottery use in Alaska (Anderson, 2019; Heizer, 1949), we stress that further research is necessary to confirm such patterns. Indeed, pottery data from the Cape Krusenstern site (900–300 cal BP) indicates that anadromous and freshwater fish remained important among the late prehistoric inhabitants of this site (Anderson et al., 2017). Perhaps the connection of pottery technology to the processing of riverine resources lingered longer than expected, even within the strongly maritime-adapted tradition of the Western Thule.

4.2. Geographically dependent pottery use

The direct evidence for pottery function we have generated through organic residue analysis is in line with suggested subsistence strategies of the Norton and ancestral Yup'ik traditions in Southwest Alaska (Dumond, 2016; Shaw, 1998), and supports the notion that differences in subsistence are specific to the geographically dependent distribution of prey-species (Miszaniec et al., 2021, p. 19; Moss, 2012). Indeed, the strongest differences in pottery use on the Alaska Peninsula are observed on a geographic scale between three defined regions (Pacific coast (PC), Bering Sea coast (BSC), and inland (I) locations). The differences between the three regions are apparent in compound specific isotopes (Mann Whitney $U = 0$, z = 8.378, p = < 0.05, PC = 6, BSC = 6, I = 33) with more depleted values at inland sites, likely reflecting the processing of anadromous fish versus marine species on the coast. TMTD/phytanic acid ratios (Mann Whitney $U = 37$, z = 8.762, p = < 0.05; PC = 7, BSC = 8, I = 37) are higher on the coasts than in the inland. This is in line with our analysis of modern reference data which shows lower TMTD/phytanic acid ratios in anadromous fish. In turn, lipid concentrations are highest on the Bering Sea coast as opposed to the Pacific coast and inland (Mann Whitney $U = 0$, z = 12.636, p = < 0.05; PC = 12, BSC = 17, I = 73). This supports the notion that more lipid-rich species were processed in the pottery there (e.g. seal). This might reflect the processing of different species in these areas. Interestingly, while marine resources were processed on both the Pacific and Bering Sea coasts, the prey-species between these marine regions may have differed as well. This argument is supported by faunal assemblages (where preserved) (Dumond, 2003, 2016), human isotope data from the Pacific coast and the Brooks River (Coltrain, 2010) and other inferences on subsistence focus in these areas (e.g. the presence of harpoons, net sinkers, etc.) (Dumond, 2003; Schaaf, 2008). The Pacific coast is isolated from the rest of the Alaska Peninsula by the Aleutian Range and lacks large salmon rivers. It is possible that, while contemporary with other Norton sites, the early ceramic presence on the Pacific coast may actually be culturally distinct from the Norton on the Bering Sea coast and in the Alaska Peninsula interior (Clark, 1977: p. 82).

4.3. The drivers of pottery adoption in Southwest Alaska

Our results indicate that the tested Norton pottery from Southwest Alaska was used for a variety of cooking purposes: pottery from the interior was mainly used to process anadromous fish, with the possible addition of terrestrial game like caribou, and plant resources (which are likely underrepresented in our samples due to masking by the lipid-rich aquatic oils), and even some marine species both at coastal and inland locations. The use of the pottery for cooking, as opposed to cold storage, is evidenced by the presence of heating biomarkers such as APAAs, BPCA's and PAH's (see Appendix Table B3). Pottery was likely a household item and used on a daily basis to cook meals. However, pottery function may not have been limited to household use and could also have played an important role in the seasonal processing of vast amounts of salmon throughout the ceramic period. Highly productive salmon runs in Southwest Alaska occur from spring to autumn, allowing for the mass harvesting of fish during this time. These large surplus catches would have demanded a rapid turnover to preserve the fish for winter (Tushingham and Bettinger, 2013). The drying and smoking of salmon is a well-known practice in Alaska and around the world (Fienup-Riordan, 2007; Henry et al., 2018). But fish could also be preserved through cooking. Pottery would have provided a controlled way to process these resources quickly and efficiently for long-term storage (Jordan and Gibbs, 2019b). Subsequently, these pots could have been used to rehydrate and cook dried fish in the winter season. Our data shows that while Norton pottery seems to have been predominantly used to process aquatic resources, it did not seem to have a very specialist function (e.g. for rendering oil). Instead it was likely used as a cooking vessel to prepare dishes in which fish was the main ingredient.

4.4. Implications for the origins of alaskan pottery traditions

As the function of early pottery in Alaska is becoming clearer, further questions now arise in relation to ancestral pottery traditions of Northeast Siberia (Yakutia, Kamchatka and Chukotka), thought to be the ultimate source of the Alaskan ceramic traditions. While technological comparisons between pottery from Alaska and Siberia have been drawn before (Ackerman, 1982; Oswalt, 1953), reconstructing pottery function can shed new light on this question. The abundant presence of Norton sites on interior riverine locations and the predominant use of the pottery at those sites to process anadromous resources is interesting. We have analyzed some of the earliest pottery in Alaska, albeit not the oldest which occurs in Northwest Alaska (Anderson et al., 2017; Dumond, 2016; Tremayne et al., 2018) and remains untested. The main use of these pots to process riverine fish raises the question whether pottery entered the New World Arctic as part of a riverine adaptation (Admiraal, 2020; Jordan et al., 2022). Pottery sites in Eastern Siberia are often located along large river systems (e.g. the Lena, Kolyma and Anadyr rivers, see Fig. 1a). Pottery in this area may have been used in the same way as in Alaska. Especially the environments of Southwest Alaska with its major river drainage systems (e.g. the Yukon-Kuskokwim, Ayukalik, and Naknek rivers) could have reflected origin regions in interior Northeast Siberia. Organic residue analysis of Northeast Siberian pottery (Admiraal et al. forthcoming) and further work on early Alaskan pottery assemblages will help resolve this question.

5. Conclusions

Here we examined the function of pottery in Southwest Alaska to better understand the adoption of ceramic technology in this sub-Arctic environment. Through lipid residue and stable isotope analysis we presented unequivocal evidence that Southwest Alaskan pottery was used to process aquatic resources. Norton sites are predominantly present at inland locations along major rivers and the pottery at these sites was predominantly used to process anadromous fish, although there is some variation with contributions of caribou and potentially plant products. Interestingly, we also found evidence for the presence of marine resources at some of the earliest inland sites of the Alaska Peninsula (NAK-3 and DIL-161), as well as on the Pacific coast. We observe that pottery function may have included daily cooking practices, but we infer that pottery could also have been a valuable tool to process fish during seasonal mass harvests, although likely not for the rendering of oil. Although pottery technology drastically changes under the influence of the Western Thule from Northern Alaska at around 1000 cal BP, this transition is not as clear in pottery function. Instead, differences in pottery function seem to be linked to shifting site locations with environmental differences that deviate from the generally occupied range of environments by Norton and ancestral Yup'ik groups (i.e. riverine vs. coastal subsistence foci; Dumond, 2000; Shaw, 1998). Indeed, this geographically-dependent function of pottery is also observed during the Norton period with results pointing to marine resource processing on the Pacific coast.

We have also explored the potential implications of our results for the adoption of pottery in this part of the world. While pottery technology first entered Alaska among maritime adapted groups (i.e. Choris/Norton in Northwest Alaska) organic residue analysis studies on early Alaskan pottery so far indicates its main function was aimed at anadromous and freshwater fish rather than marine resources. While sampling strategies may play a role in this conclusion, this is also supported by organic residue analysis at the estuary Cape Krusenstern site in Northwest Alaska (Anderson et al., 2017). We hypothesize that anadromous and freshwater fish played an important role in the expansion of pottery in Alaska. It is possible that inland routes along large rivers could have been feasible for the spread of this technology. This idea has implications for the dispersal of pottery in Siberia, where early pottery sites are often found along large rivers and only appear on the coast with the rise of maritime adaptations in the area (Jordan et al., 2022). The function of these Siberian pottery vessels remains unclear and further research is now underway to clarify this important issue (Admiraal et al. forthcoming). Additionally, more research into the variability and changing function of pottery in the different Alaskan environments is needed to better understand spatiotemporal patterns of adoption and transformation, and to close gaps in knowledge.

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.

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Supplementary data

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