Quaternary Science Reviews 299 (2023) 107825

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Source-sink dynamics drove punctuated adoption of early pottery in Arctic Europe under diverging socioecological conditions

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A R T I C L E I N F O

Article history:
Received 24 February 2022
Received in revised form
30 August 2022
Accepted 11 October 2022
Available online xxx

Handling Editor: Danielle Schreve

Keywords:
Early pottery
Hunter-gatherers
Arctic maritime Europe
Early northern comb ware
Asbestos tempered ware
Organic residue analysis
Source-sink dynamics
Human ecodynamics

A B S T R A C T

What drives the adoption of pottery amongst prehistoric foragers in high-latitude environments? Following the long-running interests of archaeology in explaining the origin and dispersal of new technologies, recent years have seen growing efforts to understand what drove the emergence and expansion of early hunter-gatherer pottery use across northern Eurasia. However, many regional dimensions to this continental-scale phenomenon remain poorly understood. Initial pottery adoption has often been explained as a generic cultural response to warming climates and the growing diversity of food resources, yet resolving challenges of food security during seasonal shortfalls or general climatic downturns may have provided alternative motivations. It is also becoming clear that many regions experienced more complex patterns of pottery adoption and that many resist simplistic monocausal interpretations. In this paper we deploy a Human Ecodynamics framework to examine what drove the punctuated adoption of two early pottery traditions into Arctic Maritime Europe, which were separated by a multi-millennial ceramic hiatus — Early Northern Comb Ware (ENCW) and Asbestos Tempered Ware (ATW). Our multi-proxy approach involves the revision of pottery chronologies to clarify the timing and ecological context for each dispersal, combined with analysis of technological and functional dimensions of the ceramic traditions to understand the contrasting social organization of these technologies. Our results confirm that ENCW expanded at a time of increased locational investment and ecological abundance in the region, while ATW spread in a series of smaller and more intermittent waves in the context of a major ecological downturn and alongside a return to a high-mobility lifestyle. Finally, we use the concept of "source-sink dynamics" to suggest that both dispersals were driven by the same underlying process. This involved major climatic fluctuations triggering small-scale population transfers from lake and riverine settings of western Russia, Finland and the Eastern Baltic region via interior areas and through to the Arctic Norwegian coastline, a persistent process that is also well-documented in later historical periods. Our results highlight the crucial importance of bridging-scale case studies as these have the "unsettling" potential to highlight deeper problems of equifinality. In this case, they reveal that two broadly similar material traditions spread into the same regions, albeit in the context of strikingly different environmental and behavioural conditions.

1. Introduction

Archaeologists have long sought to explain the innovation and long-range dispersal of major technological innovations. Recent

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https://doi.org/10.1016/j.quascirev.2022.107825

years have seen growing international interest in understanding the emergence of early pottery by hunter-gatherers. It is now well-established that the world's oldest fired-clay cooking vessels emerged independently around and slightly after ca 20.000 years ago among Late Glacial hunther-gatherer communities in several different parts of East Asia (Hommel, 2014; Iizuka, 2018; Kuzmin, 2017; Wu et al., 2012; Yanshina, 2017). This was followed by appearance of several further independent innovation center across North Africa ca. 12.000 cal BP (Jordan et al., 2016). A growing body of research has attempted to trace the character and timing of a potential continental-scale dispersal of early ceramic traditions across Eurasia. This may form a general east-to-west pattern, following the waterways of the Eurasian plain during the warmer conditions of the Holocene (Courel et al., 2020, 2021; Jordan et al., 2016; Papakosta et al., 2019; Piezonka et al., 2020). However, poor data coverage and limited chronological resolution render many aspects of this model rather speculative. While some progress has been made in exploring these continental-scale distribution patterns, as well as in local, site-level typochronologies, the refinement of intra and inter regional-scale chronological frameworks are citical to enable more “meso” scale insights to emerge. These studies have the potential to connect analytical scales, and to highlight more complex and context-specific factors that can drive both pottery adoption and rejection. Our goal in this paper is to highlight the potentials of regional-scale studies that focus on identifying how particular - rather than generalized – factors drove the adoption of early pottery traditions into new areas, crucial for sorting out the reasons why pottery appears in some places and at some times, but not others.

We present an in-depth case-study from “Arctic Maritime Europe”, defined in this paper as “northernmost Norway” which forms the northern margin of European mainland, interfacing the Barents Sea at 71° north. In the Holocene, this region experienced two separate waves of early pottery expansion, interspaced by a multi-millennia ceramic hiatus (Fig. 1). The local archaeological record contains an unbroken record of these developments due to the series of raised paleo-shorelines and unprecedented level of archaeological investigations in the high latitudes. While coastal Northeast Eurasia primarily has been subject to major sea level rise obscuring early patterns of pottery adoption, the Norwegian coastline is characterized by significant isostatic uplift, thus providing a rare window into deep-time sequences of socio-ecological change in the Arctic (Damm et al., 2019).

The earliest pottery tradition in the area belongs to the Early Northern Comb Ware (ENCW), dispersing ca. 7500 cal BP and disappearing ca. 6500 cal BP (Skandfer, 2003, 2005). After a ceramic hiatus of ca. Two millennia, the Asbestos Tempered Ware (ATW) eventually expanded into the same area. The exact timing of this second ceramic dispersal remains unclear, but has been assumed to start at ca. 4200 cal BP (Jørgensen and Olsen, 1988). The ATW tradition went on to have a much wider geographical distribution than the ENCW, but eventually discontinued around 1500 cal BP.

Importantly, both these early pottery traditions dispersed into the Arctic coast from the Baltic region and western Russia. Here, the two constitute a mostly continuous ceramic technological sequence of evolution (Seitsonen et al., 2012; cf. Nordqvist, 2018; Pesonen, 2021; Piezonka, 2015), although discontinuities are becoming more apparent also here (Pesonen, 2021), particularly in northern Fennoscandia. As such, Arctic Maritime Europe can be viewed as a “periphery” into which a series of macro-scale pottery traditions dispersed at different times from outside “core” areas, pinpointing general properties of the processes responsible for inter-regional pottery dispersal mechanics. While a plethora of local sub-types and associated chronologies have been a major topic of research in the area, we here focus on regional dispersal patterns of ceramic technologies. This is particularly valuable, as we argue that underlaying processes of ceramic dispersals may best be studied at distributional margins where cultural event horizons are particularly pronounced, providing “laboratories” for dissecting deeper contextual processes driving adoption and “resistance” to technological innovations in deep time. This, combined with a wealth of new archaeological, chronological and palaeoenvironment evidence from northern Norway offers rich scope for an updated analysis.

2. Alternative adoption (and abandonment) scenarios

To establish a series of models about the factors driving pottery adoption we examined recent work on the emergence of pottery across northern Eurasia and the circumpolar regions more generally. Various hypothesis have been proposed to account for the spread and uptake of ceramic technology amongst prehistoric hunter-gatherers (Jordan and Zvelebil, 2010a:59), as well as for the non-adoption amongst contemporary, and geographically adjacent aceramic groups (Admiraal et al., 2020; Demirci et al., 2021; Elliott et al., 2020). Production of ceramic technologies and the high-mobility lifestyle led by many hunter-gatherer (HG) populations are often seen as mutually exclusive characteristics due to the high investment requirements and stationary production sequence of pottery production – an idea of deep intellectual roots and engrained in cultural evolutionary thought (Arnold, 1985:109). Among the plethora of ideas, arguments and overlapping assumptions, two salient lines of enquiry emerge and are summarized in (Table 1).

2.1. Model 1: ecological surplus drives adoption

Most commonly, early pottery has been assumed to offer Holocene hunter-gatherers an effective means for processing “surplus” production in the context of warming climates and increasing ecological productivity. The emergence of ceramic technologies has been strongly linked to processing and storage of surplus production in high-yielding, coastal/aquatic ecotones – most explicitly formulated in a series of publications by (Hayden, 1995). According to this scenario, pottery use spreads as part of a wider suite of Holocene technologies offering more effective harvesting, mass capture and processing capabilities. These, in turn, support economic diversification and intensified exploitation of particular food types, ranging from nuts and plants, through to ungulates, freshwater fish and diverse coastal resources (Hayden, 2010, 2019) – with one of the major benefits being the increased nutritional output from lower-ranked resources for lower work-effort. Due to latitudinal gradients in terrestrial biomass, aquatic and maritime resources tend to play a more central role in explaining pottery adoption into higher-latitude environments (Jordan and Gibbs, 2019), though interception of game and especially migrating herds was important in certain regions. Over time, this constellation of cultural and ecological factors is assumed to converge into growing sedentism and increased social complexity (Admiraal et al., 2020; Hayden, 2014). Views on the role of pottery within such communities range from vessels being used on a more routine household basis to expand the range of foodstuffs, improve nutrition or experiment with new cuisines (Jordan and Zvelebil, 2010:54–55), through to the use of pottery by ambitious individuals and households to expand production of prestigious foods that can be used in competitive cycles of feasting within and between communities (Hayden, 2014, 2019).

Overall, the ultimate driving force for this kind of pottery-

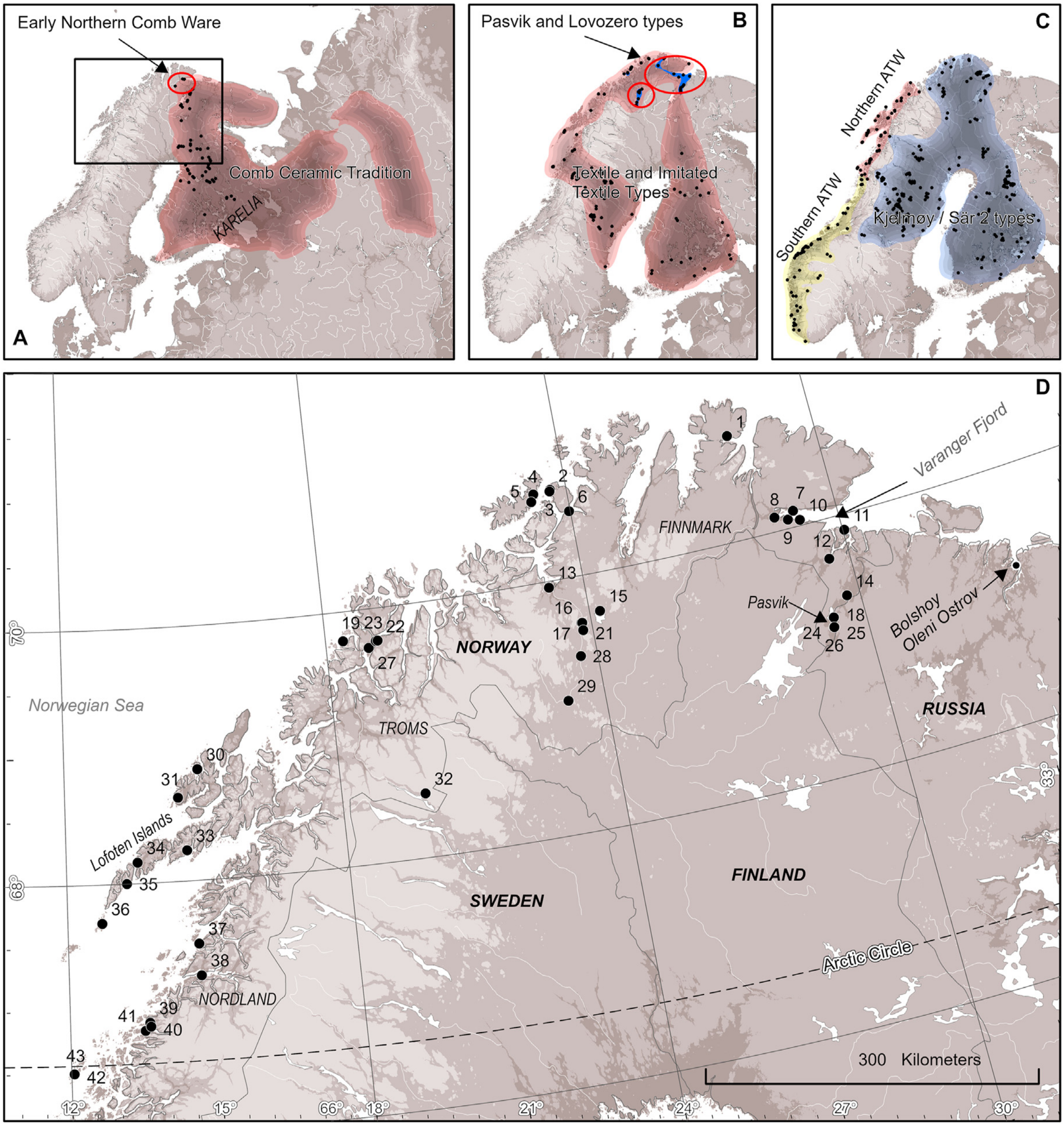

Fig. 1. Location maps showing (a) study region and the extent of the Comb Ware pottery tradition and the ENCW off-shot in northern Norway, after (Pesonen 2021: Fig 2.1; Piezonka 2012: Fig. 22; Skandfer 2005: Fig. 1); (b) the distribution of Textile and imitated Textile ATW-types in Norway, Sweden and Finland including Pasvik and Lovozero types in northern Norway, after (Forsberg 2001: Fig. 2; Huurre 1986:54; Jørgensen and Olsen 1988: Fig. 14–17); (c) the distribution of northern («Risvik) and southern ATW types in Norway and Kjelmøy/Sär 2 ATW-types in Norway, Sweden and Finland, after (Arntzen in prep; Forsberg 2001: Fig. 1; Hop 2011: Fig. 3; Huurre 1986:54; Jørgensen and Olsen 1988: Fig. 12); (d) study region with sampled sites (key in SI:Table 1) and important place names marked.

adoption scenario is the “surplus” offered by growing ecological productivity, combined with the need for cheap container technologies, which together become entangled in a transition towards sedentism and storage. This, in turn, supports growing population and further fuels the social motivations to maintain the delayed-return investments that are central to maintaining pottery traditions. Conversely, the abandonment of early ceramic traditions would require a decline in ecological productivity, in turn, triggering population decline, combined with growing mobility to resolve seasonal shortfalls. In short, phases of pottery adoption should coincide with improving environmental productivity, whereas downturns should trigger the collapse of pottery traditions and the opening of ceramic hiatus periods.

2.2. Model 2: ecological risk drives adoption

An alternative scenario has also been presented, revolving around an inverse “deficit” relationship as the main driver of technological innovation. The deficit model argues that stress/risk, such as more challenging environmental conditions, can stimulate populations to invest in new technological traditions to resolve food security (Fitzhugh, 2001). Examples include micro-blades, plant grinding stones and early pottery traditions that seem to appear across northern China during the return to cold and arid conditions during the Younger Dryas (Elston et al., 2011). The motivation in the case of pottery is to maximize overall calory extraction from seasonally scarce or unpredictable resources in

Table 1
Contrasting "surplus" and "deficit" pottery-adoption scenarios: environment, food security, mobility and technology.

Main Driver	Motivating Factor	Environmental Conditions (Palaeo-Demography)	Target Resources	Food Security	Settlement / Mobility	Organisation of Technology (Social Dynamics)
"Surplus"	**Maximise production** (predictable seasonal abundance)	**Improving / Stable** (increasing population / density)	**Planned** - marine fish, salmon runs, seals, migrating reindeer herds	**Low Risk** Archaeological Correlate: minimal evidence for intensified calory extraction (e.g. long bones discarded intact)	**Logistic mobility** (storage) with base camps and seasonal extraction points (pottery used at both / either)	**Large-scale pottery usage** at specific extraction / processing sites; local raw materials; local production, use, discard. Status-driven feasting and social competition (?)
"Deficit"	**Maximise calory-capture** (unpredictable seasonal shortages)	**Challenging / Declining** (small / declining populations)	**Opportunistic** – seasonal game, salmon runs; marine fish, seals.	**High Risk** Archaeological Correlate: evidence for intensified calory extraction practices (e.g. highly fragmented bone – grease rendering, etc.)	**"Serial Specialists"** – high mobility targeting dispersed seasonal resources.	**Small-scale usage** at many temporary camps; small, light and portable vessels; curation of pots and (re)use of optimal raw materials (grog / temper); communal feasts to maintain fragile social networks.

times of shortage (Terry, 2022). One possible example is the use of Late Glacial pottery to extract marrow and bone grease, with pottery used in the rendering process (Elston et al., 2011; Shoda et al., 2020). Although not widely applied in early pottery research, this scenario offers an interesting alternative to the "surplus" model outlined previously.

To resolve these relationships, much more contextual work is needed to explain why pottery traditions expand from one region to another under particular environmental conditions – this important factor is often glossed over via reference to more generic processes of knowledge transmission, supported by open social networks and generalized group exogamy (Jordan et al., 2016). In our case, Arctic Maritime Europe forms the outer edges of the wider Fennoscandian landmass, including Finland and NW Russia. The two early pottery traditions that expanded into northern Norway crossed significant ecological and climatic gradients, spreading from the milder, more productive south-eastern Fennoscandia and into northern coastal settings. Importantly, such coastal and inland ecosystems can respond quite differently to climatic shifts, with terrestrial ecosystems being subject to higher amplitude changes, whereas marine productivity changes tend to occur as gradual trends due to the greater potential for geographical shifting as a mitigation response by marine species.

Thus, investigating the drivers of punctuated pottery adoptions into Arctic Maritime Europe can offer useful regional-scale insights into more general processes of cultural evolution and human-environment interactions. To evaluate the competing "surplus" versus "deficit" scenarios we deploy a multi-scalar and multi-disciplinary approach to tackle four overarching research questions:

a) precisely when did the two pottery horizons start and stop?
b) to what extent di these dispersal horizons correlate with other climatic, environmental, demographic, and human behavioural trends?
c) did the design and function of the two technological traditions differ significantly from one another?
d) what processes drove the punctuated expansion of these traditions from inland into coastal zones?

We start with a short review of current knowledge to highlight knowledge gaps and research opportunities.

3. Research context: early pottery adoptions in Arctic maritime Europe

Two distinct early pottery traditions are adopted into what is a highly dynamic cultural trajectory (context of the dispersals presented in; SI text). While each has distinct spatiotemporal distribution, technological and stylistic features, both originate in, and disperse from core areas located significantly further to the Southeast (the Baltics and W Russia). The main types are illustrated in (Fig. 2).

3.1. Pottery tradition 1: Early Northern Comb Ware (ENCW)

ENCW is an umbrella term for a variety of local sub-variants of Early Comb Ware (ECW) in northern Fennoscandia of the mid-Holocene (Skandfer, 2003, 2005). Although the ENCW and Early Comb Ware (with a plethora of local variants (see Nordqvist and Mökkönen, 2015; Pesonen, 2021; Piezonka, 2015; Torvinen, 2000) - traditions predominantly have been considered separate ceramic traditions in previous research, here they are treated as part of the same general technocomplex on the basis of shared production sequence, temporal contemporaneity and geographic interaction - trumping stylistic variation (following (Skandfer, 2010:348–9).

At this macro scale, we are interested in understanding how this general ceramic tradition dispersed into Arctic maritime Europe. The ENCW tradition is united by several key features: large, thick-walled pots with pointed or rounded bottoms, tempered with crushed minerals, mostly quartz. Specifically, the most definitive trait of ENCW's is the full exterior decoration with horizontally organized combinations of comb and pit stamps (Fig. 2a). The tradition's many variants, form geographically specific stylistic groupings, down to site-scale and individually decorated pots. In northern Norway, the ENCW pottery horizon is sharply restricted to coastal sites in the Varanger fjord and upper Pasvik river, which drain into it, all now located on the Norwegian – Russian – Finnish border (Simonsen, 1963; Skandfer, 2010). Most of the Norwegian ENCW assemblages have been securely dated, resulting in a 7500-6500 cal BP (2σ) range from direct dates, accounting for possible reservoir effects, supported by contextual radiocarbon dates (Skandfer, 2003:233, 2005:5–6, 2010). The ENCW tradition forms a northwestern outlier to the much larger and expansive Early Comb Ware (ECW) pottery horizon. More generally, the ultimate origins of the greater ECW tradition may be in the Upper Volga region of Russia, though improved dating of many continental assemblages is required to confirm this interpretation (Piezonka, 2012). The ECW consists of several local styles, including Säräisniemi-1 (Sär-1) in northern Finland, Early Comb Ware (Ka I:1) in southern and central Finland, and Sperrings-1 in Karelia (Nordqvist and Mökkönen, 2015; Pesonen, 2021; Torvinen, 2000), plus much of the eastern Baltic. Mid- and South Finland regions together with Karelia and the Baltic form the "core" area of the larger ECW pottery tradition in

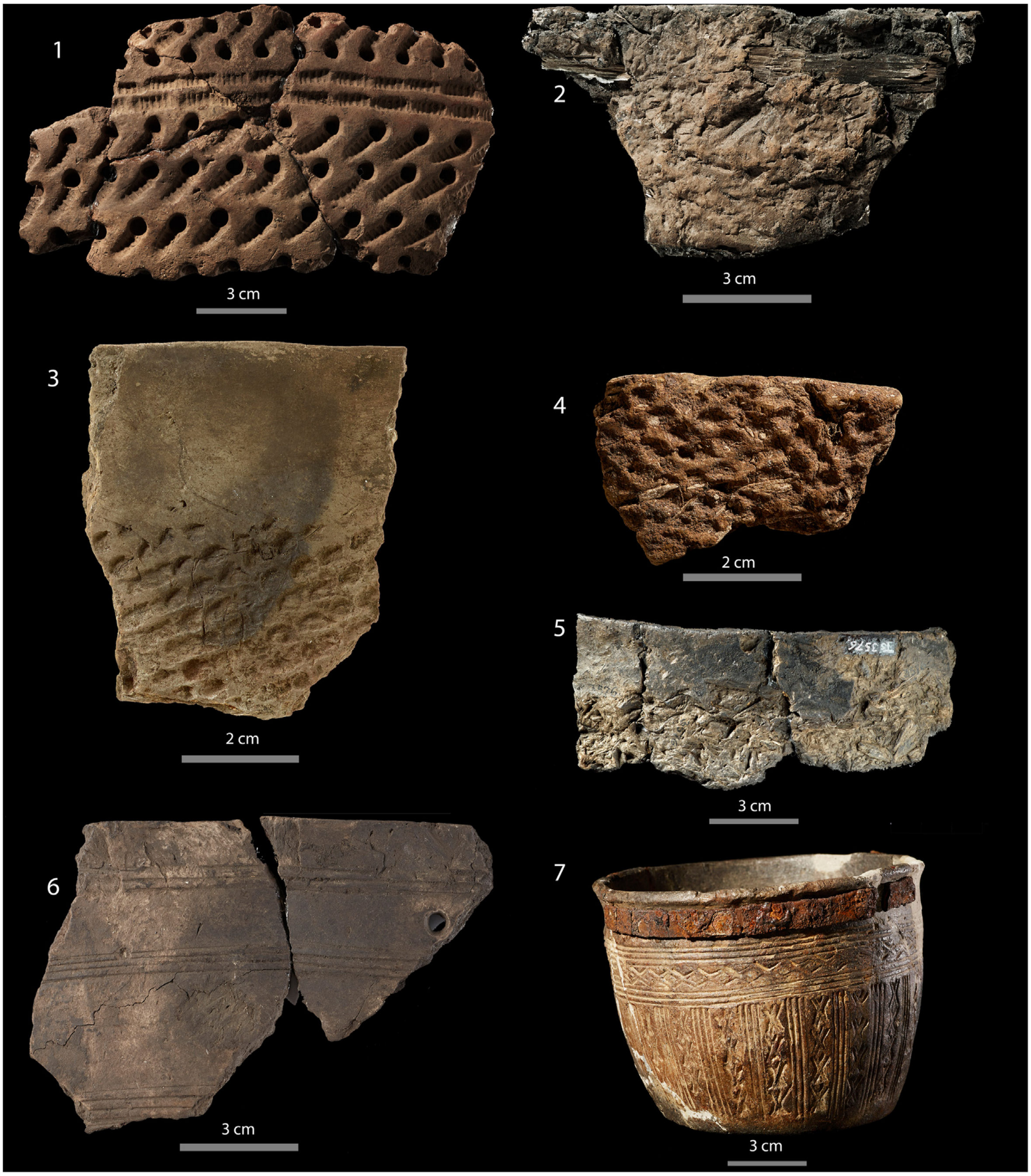

Fig. 2. The two pottery traditions and types discussed in the paper. All specimens from the Arctic region. 1.ENCW (Ts6128, Noatun Neset Vest site). 2.ATW, undecorated Pasvik/Lovozero type (Ts5895, Gasadaknes site). Note intense tempering and use of larger, finger-sized asbestos fibers. 3.ATW, textile-imprinted type (Ts3867, Kirkhellaren site). 4.ATW, imitated textile-imprinted type (Ts8226.bz, Sandbukt House 21 site). 5.ATW, Risvik type (Ts3576, Solheim site). 6.ATW, Kjelmøy type (C2946, Mestersanden site). 7.ATW, "Bucket-shaped pot" type (Ts1432, Mjønes burial mound).

Fennoscandia. Whereas pottery is given up in the "peripheral" northern region after c. 6500 cal BP, Northern Norway Comb Ware is here developed into later variants.

3.2. Pottery tradition 2: Asbestos Tempered Ware (ATW)

After a 2000-year ceramic hiatus, the next tradition to expand into northern Norway was Asbestos Tempered Ware (ATW). The ATW tradition can also be classed as a single unified technocomplex, albeit with local variants. has received disproportionately little attention across its entire distributive area in the northern parts of Norway, Sweden, Finland and NW Russia. The focal point of previous research has been the great typological variation within the ATW tradition (Lavento, 2001), used to argue for multifaceted introduction of the various types across the Scandinavian peninsula (Forsberg, 2012:38).

The intra- and inter-regional chronology of ATW is less well understood and it has remained a somewhat enigmatic phenomenon in Norway (Andreassen, 2002; Bakka, 1976:29–38; Jørgensen and Olsen, 1988; Pääkkönen et al., 2018). In contrast to the compact distribution pattern of the ENCW, the ATW tradition spreads much more widely with small quantities of ATW being found all along the western Norwegian coast to the southernmost tip (Ågotnes, 1986; Hop, 2016), and in the inland south to Lesja in central-south Norway (Bergstøl and Reitan, 2008). However, the primary area of use was among foragers in northern Norway.

ATW is an umbrella term, which covers a great diversity of forms, types and decorations. Functional differences therefore seem likely. The single unifying trait linking this diversity is the copious addition of asbestos strands as temper. Unfortunately, our understanding of ATW pottery is underdeveloped – likely resulting from the highly fragmented state of most ATW sherds. What few larger diagnostic examples exist seem to confirm major variability in decoration, including textile-imprints, through to geometric shapes and lines, and plain vessels with smoothed surfaces.

The general ATW pottery horizon in northern Norway had long been assumed to start at ca. 4200 cal BP, and persist through to ca. 1500 cal BP (Helskog, 1983:74; Jørgensen and Olsen, 1988). This particular adoption date has been understood to correlate with a much-discussed trend towards renewed sedentism and growing social complexity during the 4200-3600 cal BP "Gressbakken phase", with aggregations of large multi-room houses and extensive middens in the coastal areas of eastern Finnmark (Olsen, 1994; Schanche, 1994). In turn, the presence of pottery reinforce the circular "social complexity" argument, with pottery indicating the presence of sedentary communities that had evolved affluent lifeways and were exhibiting new levels of technological achievement (cf. Skandfer, 2012:137). Together, the dating and context of the ATW expansion should align closely with the surplus model, though these interpretations have been increasingly questioned.

One major problem is that the ATW assemblages have never been systematically dated. As a result, the chronology for pottery adoption is only supported by contextual dates with large STD and insufficiently controlled association with the house features. For example, the "Early ATW Phase" in northern Norway is thought to date between ca. 4200-3900 cal BP and consists of the Pasvik and Lovozero ATW types (Fig. 2b). These wares - like the ENCW tradition – are restricted to coastal and lower river settings in easternmost Finnmark. Somewhat later, Textile-Imprinted and Imitated Textile-Imprinted ATW (Fig. 2c–d) variants expand across coastal and inland areas of northern Norway. Based on the current chronology, all these variants fade ca. 3800–2900/2500 cal BP. The "Middle ATW Phase" is then marked by the appearance of the Risvik Type (Fig. 2e), with a wide distribution along the NW coast, which starts to emerge from ca. 3700 cal BP, though most dates fall after this (Jørgensen and Olsen, 1988; Skandfer, 2012:130–131).

The "Late ATW Phase", dated to ca. 3000-2000 cal BP, is marked by the appearance of the Kjelmøy Type (Fig. 2f) across all areas. In particular, the vessels have extremely thin walls and occasionally, elaborate decoration. In this final part of the ATW tradition, pots can alternatively be tempered with mica or shell, and others with asbestos, yet all are still grouped as ATW variants due to the obvious stylistic affinity. The ATW tradition ends with the short effervescence of "bucket-shaped pots" (Fig. 2g) (350–550 AD) stemming from burial contexts as opposed to the earlier ATW types association with settlement sites, tentatively ending with the collapse of artistic ceramic production knowledge of Late Iron Age aristocracy – potentially disrupted by the 536/537 AD Fimbulwinter and Justinian plague (Kristoffersen and Magnus, 2010:82; cf. Fredriksen et al., 2014). Its distribution in northern Norway is strongly associated with coastal sites, and argued to be a continuation and final stage of the northern Fennoscandian ATW tradition (Jørgensen, 1988:52; countering, Bøe 1931:165; see also Breivik, 2006; Engevik, 2008).

3.3. Summary: knowledge gaps and research questions

While northern Norway has an exceptionally rich and continuous archaeological record making it an ideal location for investigating punctuated adoptions of early pottery, the uncertain dating of the ATW tradition, and especially its first appearance, emerge as a major obstacle. In contrast, the ENCW tradition is well dated, though the timing of its expansion and disappearance has yet to be properly correlated with the new suite of high-resolution culture-environmental proxies that now exist. Finally, the function of these two traditions has yet to be examined with organic residue analysis – this would offer useful insights into why the traditions may have been adopted, as well as how pottery use was embedded into locally, and potentially varied, adaptive strategies. Addressing these gaps and generating a more holistic understand of punctuated dispersal dynamics emerges as the overarching goal of this paper.

4. Materials and methods

Our analysis started with conducting a site-based inventory of all the significant ENCW and ATW assemblages and radiocarbon dates in northernmost Norway (See: SI Table 6 and SI data). With the exception of a stray-find in the 1980s, the ENCW assemblages were all excavated prior to 1960 (Simonsen, 1961, 1963), and have been subject to a re-evaluation and direct-dating program covering all Norwegian assemblages (Skandfer, 2003). Considering the many large-scale rescue excavations undertaken and research-led investigations (Skandfer, 2003) targeted specifically at identifying ENCW sites in the region since 1990, the almost non-existent addition of new ENCW assemblages seem to underline the geographically bounded distribution.

A comparable dataset did not exist for the ATW prior to this study. Therefore, our first priority was to refine and improve the ATW chronology for Northern Norway. We targeted key ATW sites and sherds that would enable us to assess key dates for the existing chronology, plus new material to add extra dates. As ATW sherds are typically highly fragmented, this reduced the range of material open for dating and our sampling strategy had to accommodate this issue. In total, 25 potentially dateable new sherds were selected, curated by the Arctic University of Norway, which yielded 24 extra AMS dates. To these were added all the existing dates to create a total dataset of 74 dates derived directly from the Northern Norway ATW horizon. All these dates were carefully evaluated against the earlier contextual dates, to control for likely reservoir and depositional biases in either direction (i.e. younger/older adjustments). Particular attention was directed at critically evaluating the veracity of earlier estimations about the assumed arrival and disappearance dates for the ATW tradition (See: SI text). Again, these older estimations were primarily based on contextual rather than direct dates on the pottery itself (Jørgensen and Olsen, 1988). Finally, renewed scrutiny was directed to the existing ENCW chronology, so that all dates on both traditions have been screened according to standardized protocols. This exercise generated updated chronologies for the two pottery traditions based on an updated set of dates (ENCW, $n = 10$. ATW, $n = 74$).

The refined chronologies for both pottery traditions created a more robust foundation for a multi-proxy analysis of the main contextual patterns of pottery adoption. To facilitate correlation with a wide range of proxies we converted the refined dating of the ENCW and ATW traditions into Summed Probability Distributions. We then targeted proxy datasets best placed to elucidate the socioecological contexts into which early pottery was adopted, including the environmental factors that would have exerted the most direct influence on human subsistence and food security. These data included: prime paleoenvironmental records pertaining to climate, ecology and maritime versus terrestrial productivity (SI Table 5). In all cases, our selection criteria were: close geographical proximity, highest possible resolution, and coverage of both terrestrial and marine environmental systems. In addition, we added published paleodemographic models for interior and coastal regions of northern Norway (Jørgensen, 2018; Jørgensen and Riede, 2019), plus chronologies of other selected cultural traditions including well-dated examples of the large houses (i.e. from the Gressbakken phase, that purport to provide evidence for peaking sedentism and social complexity), plus various lithic traditions including slate and bifacial technologies. Finally, all the chrono-referenced data were compiled into a single figure to support careful analysis of potential correlation between the various cultural and environmental parameters (Fig. 3).

To better understand potential variability in the scale-of-use, function, and design features of the two early pottery traditions, MNI of ATW vessels per site were calculated across northern Norway using data in the inventory of pottery assemblages and compared to existing calculations of ENCW (Skandfer, 2003:120–122) (SI Table 6). Second, we conducted a targeted program of organic residue analysis (ORA) to clarify variability in function within and between the ENCW and ATW traditions. These efforts focused on sites within the restricted ENCW distribution. This strategy was devised as ENCW vessels from the area have never been subject to organic residue analysis. Secondly, sampling ATW vessels from inside the same sites and region enabled us to assess whether patterns of pottery use had varied within and between the two traditions. We studied absorbed lipid residues and biomarkers embedded, using established protocols (see SI for sampling strategy, methods, and detailed summary of results). Finally, these new results could be used to complement recent residue studies on the wider ATW tradition in surrounding parts of northern Fennoscandia (Pääkkönen et al., 2018).

5. Results

5.1. Revised pottery chronologies

Our review of the ENCW chronology confirmed its veracity (7500-6500 cal BP). In contrast, our re-dating of the ATW tradition in northern Norway indicates that adoption had started significantly later – between 200 and 500 years – than had been assumed, thus certainly not before 4000 cal BP (Fig. 3). In addition, the main corpus of dates on the ATW tradition also fall within a younger time range, that is, 3000-2000 cal BP range. This adjustment in the pottery chronology has significant consequences for our understanding of the timing of the ATW horizon in northern Norway – it now indicates that the tradition was being adopted under worsening environmental conditions. Moreover, the assumed association between pottery and the Gressbakken houses is called into question – the revised chronology indicates that ceramics were being adopted *after* the peak of sedentism and social complexity in the Gressbakken phase, (see SI Table 3).

Other significant patterns in the revised ATW chronology include: (a) the presence of a bimodal distribution in dates, divided by a potential hiatus within the broader ATW pottery tradition, which falls at 3100 cal BP; (b) a heavy tail of dates towards the end of the tradition, which may include further brief ceramic hiatus periods within the 2000-1500 cal BP interval. Overall, these patterns may potentially indicate a series of separate, small-scale and somewhat ephemeral dispersals into northern Norway. The outlier dates from the Iversfjord site that have formed the lower limit of ATW reintroduction at least from 4200 cal BP (Jørgensen and Olsen, 1988) have been subjected to new evaluation and controlled against new dates from the assemblage, with the new results falling in line with the overall chronological span of the entire dataset of direct ceramic dates (discussed in detail in SI).

5.2. Human Ecodynamics: Multi-Proxy Synthesis

The emergence of Human Ecodynamics (Fitzhugh et al., 2019) as a multi-disciplinary research field involves the integration of multiple lines of evidence to understand the long-term interactions between people, technology and environments within particular regional trajectories. In our case, the establishment of secure chronologies for both the ENCW and ATW traditions enable the timing of the expansions to be directly correlated with a wide range of other parameters that provided the wider ecological context for human decisions and strategies. Inspection of (Fig. 4) indicates that all the chosen parameters are highly dynamic, and that the

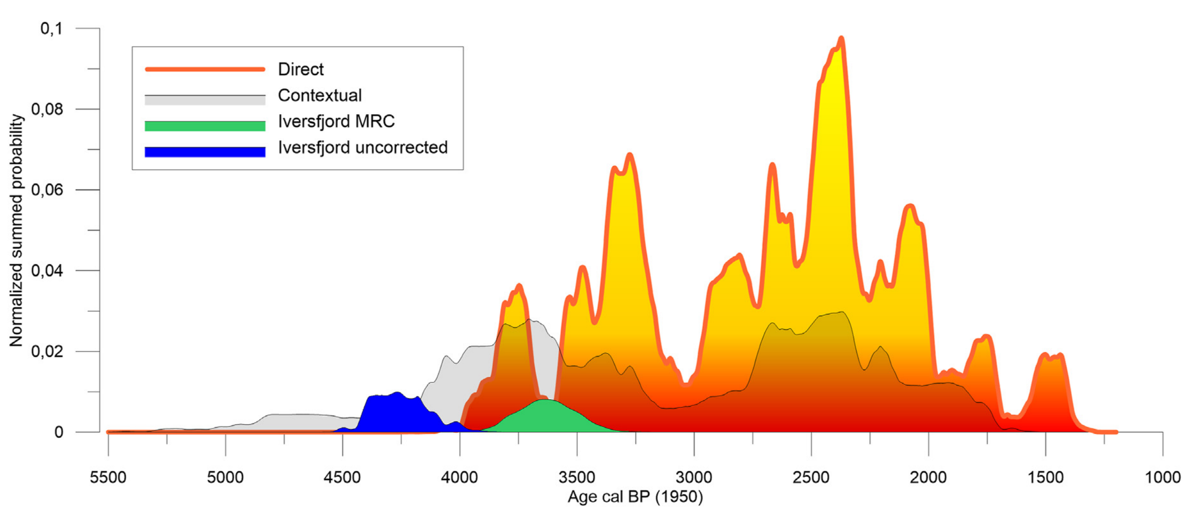

Fig. 3. Comparison of new and existing chronological framework for the ATW tradition. High precision, direct dating exclusively of ceramic vessels result in a significant young-shift of the lower age range of the ATW tradition compared to the existing framework based on direct dates with substantial errors and uncertain association. The outlier dates from Iversfjord are displayed in original format (blue),and corrected for MRE (green) which aligns with the new dates from the same assemblage.

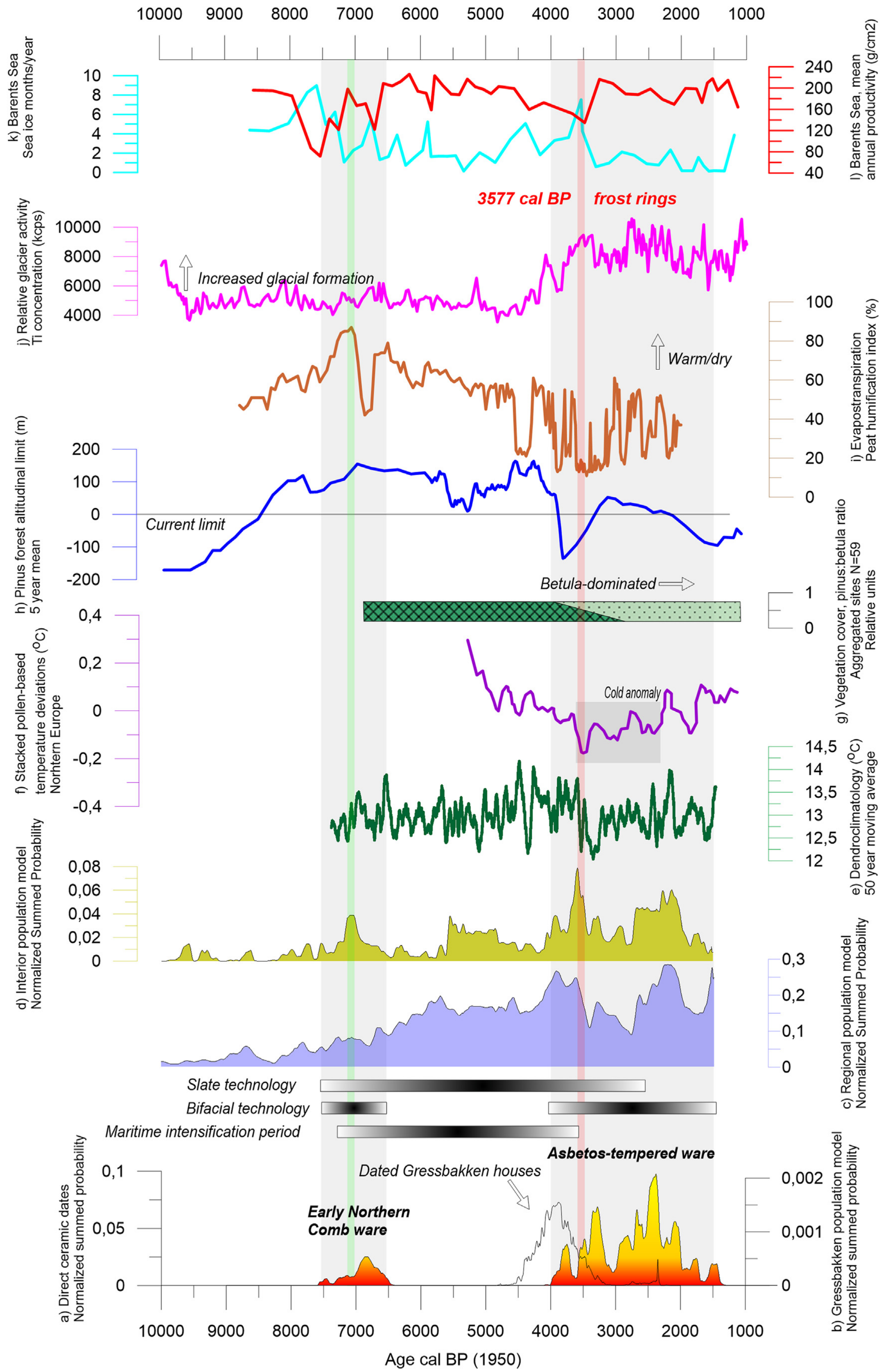

Fig. 4. Multi-Proxy Synthesis: Environmental and Cultural Contexts for the Expansions of ENCW and ATW Traditions into Northern Norway. For data sources: see SI.

expansion of each early pottery tradition appears to correlate with significant shifts in other sets of variables. However, contradictory patterns emerge:

- First, the ENCW expansion correlates with increasing ecological productivity, including marine productivity (Fig. 4 l), plus indications of growing population levels (Fig. 4c), correlating especially with a pulse of heightened inland human activity (Fig. 4d). Thus, the ENCW adoption patterns align well with the "surplus" model (Table 1). This is evident across the set of proxies all reflecting the general trend of the Holocene Thermal Maximum, with the ENCW dispersing along with peaking evapotranspiration (Fig. 4i), maximum forest cover and altitudinal extent of pine (Fig. 4g,h), as well as the complete disappearance of local mountain glaciers (Fig. 4j).
- Second, the ATW tradition is adopted under completely different environmental conditions. Arriving at a time of diametrically opposing characteristics. The ATW dispersal corresponds with a drastically different environmental regime compared to the more productive, warmer, drier and stable conditions during the ENCW period to cold, wet and volatile conditions witnessed across proxies: collapsing forest ecosystems with rapid forest cover retreat and altitudinal drop of several 100 m (Fig. 4g,h), volatile, low-state evapotranspiration and reformation of glaciers showcase wet and cold conditions (Fig. 4i,j), also backed by Holocene-low temperatures (Fig. 4e,f). In turn, these combined developments align with the "deficit" adoption model – employing new ceramic technologies at a time of heightened food insecurity and increased mobility (Table 1). This impression is reinforced by the fact that ATW was expanding during the collapse phase of the Gressbakken house pits aggregations with comprehensive middens phenomenon assumed to represent sedentary societies, and the entire regional social-ecological system was tipping into a new mode of existence. These ecologically stressful times provide the ecological backdrop to the intermittent and often faltering dispersal of the general ATW tradition into northern Norway.

5.3. Tracking variability in the scale and function of early pottery traditions

Our calculation of the scales at which ENCW versus ATW pottery was used may indicate interesting contrasts in the mode of pottery usage (SI Table 6). Overall, ENCW sites, restricted to one compact area of Eastern Finnmark, generally contain high numbers of vessels per site (MNI of 1–154, typically between 5 and 20) (Skandfer, 2003:120–122). These figures may indicate production and use of pottery at particular sites (Skandfer, 2003:342–8; Skandfer and Høeg 2012). In contrast, the ATW tradition has a much wider geographic extent, but very few pots appear to have been used at each site (MNI of just 1–2 vessels per site). The fragmentary nature of asbestos-tempered pottery may add a preservation bias here, though the scale of the contrast remains striking. Overall, the impression is that while ATW pottery is in use over a larger geographic range, it remained a "low-intensity" tradition, with a few pots used on a more occasional basis across different sites. This may be coupled to the movement of pots around the landscape, or deliberate breakage and recycling of older vessels to recover valuable asbestos temper.

The organic residue analysis generated interpretable results from 21 ceramic sherds and two food-crusts. The combination of compound-specific and molecular analyses indicated the processing of aquatic resources dominate across both traditions (Fig. 5). Moreover, the main variability in usage patterns was not between ENCW and ATW vessels, but between coastal sites (used for processing marine mammals and marine fish), and inland sites (used to process mainly salmonids). However, a greater proportion of terrestrial resources was contained in ATW pottery at inland sites. Thus, while the general coastal-inland patterns of pottery use persist across both traditions, there may be some expansion in the range of resources processed in later periods. In addition, the very different scales of pottery use noted above may suggest that the precise ways in which resources were processed may have changed over time, including the role of these activities in wider subsistence and mobility strategies.

Looking at the wider ATW tradition, some of the earliest dated assemblages in northern Norway have been recovered from interior sites such as Virdnejavri 112 and Gasadaknes. Despite these being located on major waterways in the interior, intensive terrestrial resource exploitation is evidenced by lithic tool assemblages dominated by hide scrapers and projectile points (Hood and Olsen, 1988). As such, Virdnejavri 112 has been interpreted as a specialized ceramic production site, and forms the second richest assemblage both ranked by ceramic fragments and weight (Hood and Olsen, 1988). This more intense local use of pottery may be linked to site function, likely the interception and mass-processing of seasonal migrating reindeer. The importance of terrestrial resources is further corroborated by lipid analysis demonstrating processing of ruminant fats in ATW vessels from interior sites in northern Norway and adjacent areas of Finland (Pääkkönen et al., 2018).

Overall, it appears that the expansion of ENCW into northern Norway correlated closely with peaking environmental conditions of the Holocene Thermal Maximum (HTM). This was a global-scale phenomenon and led to the maximum northern expansion of pine forest into northern Fennoscandia (Heikki Seppä et al., 2009; Sjögren and Damm, 2019), as well as maximum evapotranspiration (Vorren et al., 2012) and minimal extent of local glaciers (Wittmeier et al., 2015). Concurrently, the waters of the Barents Sea underwent rapid productivity boost, combined with retraction of sea ice cover (de Vernal et al., 2013; Voronina et al., 2001), coupled with very high North Atlantic SST (Calvo et al., 2002). At the same time, core areas of Comb Ware use in Finland, the Baltics and W Russia also experienced higher levels of ecological productivity (Ojala et al., 2008; H. Seppä et al., 2009). In northern Norway, these environmental developments correlate with the appearance of a wide range of new cultural traits, including the emergence of numerous house pit clusters pointing to seasonal sedentism combined with increasing socio-technological complexity, and growing population densities. All these parameters align well with the "surplus" scenario of pottery adoption outlined in Table 1.

The later onset of the ATW tradition (4000-3000 cal BP interval) now places its dispersal precisely within the "collapsing" final phases of the Gressbakken phenomenon, which correspond to an enduring Holocene cold anomaly that is evidenced in the dendrochronology as a rapid and sustained decline in temperatures (Helama et al., 2013). Moreover, this cold anomaly impacted across northern Europe, and has been identified in the meta-analysis of stacked pollen cores (H. Seppä et al., 2009). It is also reflected in an abrupt and dramatic drop in the altitudinal limit of pine (Karlsson et al., 2007; Sjögren et al., 2015), and also includes frost rings in local dendrochronological records that date to 3577 cal BP, which indicates onset of sub-zero temperatures during the primary growth season of July – potentially driven by the "volcanic winter" impacts of the Thera eruption (Helama et al., 2019). Reviewing the Human Ecodynamic results for this tumultuous period suggest dramatic population decline, likely abandonment of the semi-sedentary and high-investment coastal settlements, a shift

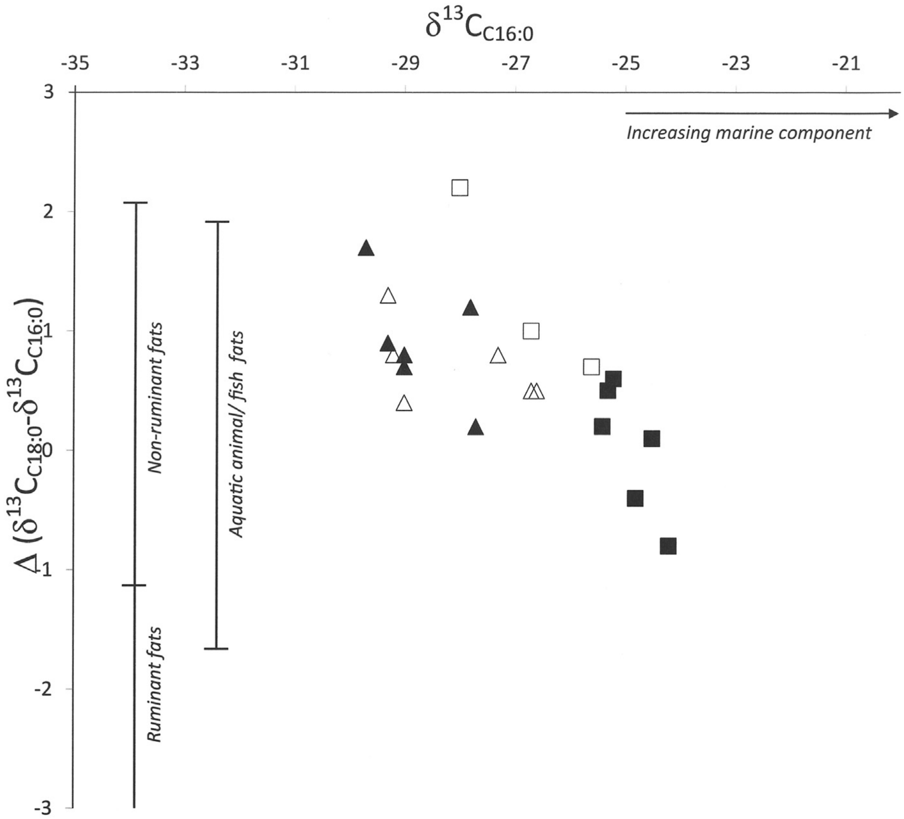

Fig. 5. Organic residue analysis of the ENCW and ATW traditions in Eastern Finnmark. Values of the twenty-one samples, separated by geographic location and ceramic tradition: Squares=Coastal. Triangles=Inland. Filled=ATW. Unfilled=ENCW.

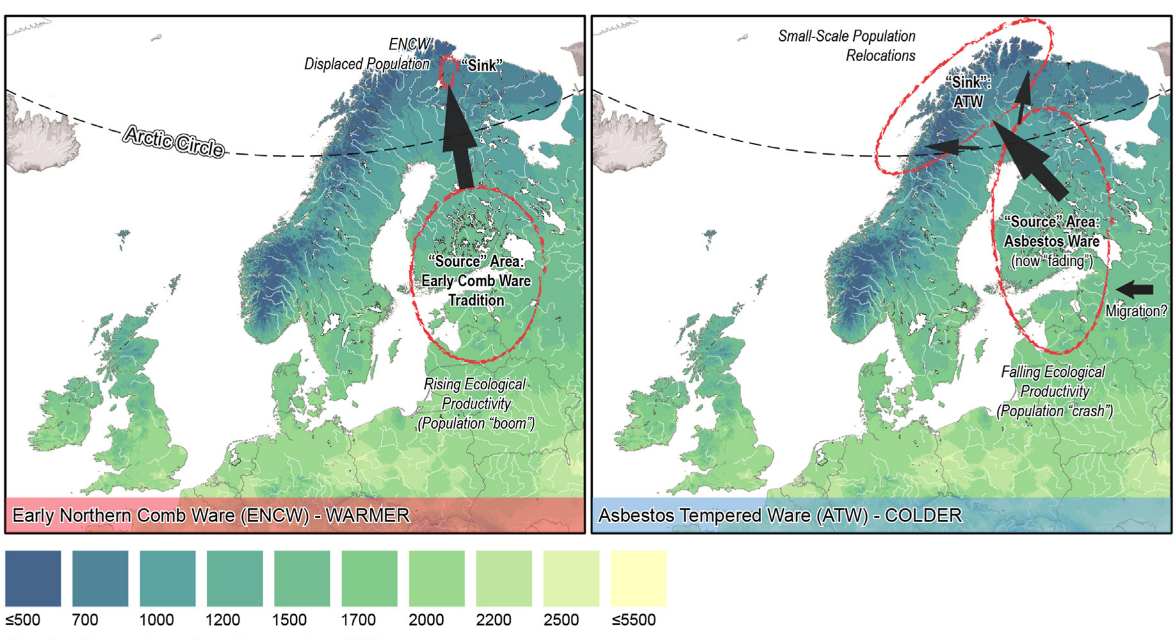

Fig. 6. Schematic illustration of how "source-sink" dynamics resulted in population movements and the expansion of ENCW and ATW traditions to northern coasts in very different environmental settings. The base map shows calculated growing degree days (GDD, 5 °C base temperature) based on the 1961–1990 normal period (Marchi et al., 2020).

towards increased residential mobility (Jørgensen and Riede, 2019) - all suggesting that the ATW was adopted into a "deficit" scenario (Table 1) – introduced from southeastern regions also impacted by a climatic downturn with critical impacts on food security.

5.4. Comparative analysis of the technological organization of the ceramic traditions

In northern Norway, the ENCW tradition typically consists of large vessels (up to c. 40 cm tall), which are coil built with mouth diameters ranging from 13 up to 36 cm. The pots are heavily built, with relatively thick walls between 7 and 13 mm thick. Most vessels are large, but some assemblages contain smaller cup-sized vessels, with mouths of up to 8 cm. Such solidly constructed earthenware requires careful firing to maintain even temperatures and avoid heat fracture. ENCW vessels are typically tempered with crushed quartz of heterogenous sizes, as well as local sand. Such opportunistic and locally variable choices of temper, combined with great diversity in clay coloration are generally regarded as an expression of pragmatically sourced local materials, combined with local production, use and discard. (Skandfer, 2003; Skandfer and Høeg, 2012). This suggests that the pots were intended for performing local, site-based processing tasks, with large numbers of pots made at specific sites. Interestingly, the 13 ENCW pottery bearing sites of northern Norway consist of surface scatters that lack associated dwelling structures (cf. Sohlström, 1992). This may indicate that demand for vessels was concentrated at seasonal harvesting sites, perhaps during the warmer months, and judging by the residue results, could include coastal fishing and sealing sites, plus harvesting of river salmon runs. It remains a conundrum why pottery use did not expand into surrounding areas, where communities essentially maintained very similar lifeways.

The organization of the ATW tradition is again quite different. ATW assemblages seem to be associated with former house structures, suggesting that older sites were being revisited, though possibly now being integrated differently into the seasonal round with what seems as shorter-term and lower investment stops. ATW pots are abundantly tempered with raw and/or crushed asbestos fibers. The dense and often thread like tempering enabled production of vessels with much thinner walls, ranging from as little as 3 through to 10 mm. The vessels are also significantly smaller than the ENCW pots – the largest known ATW vessel is Norway has an estimated diameter of ca. 30 cm (Sundquist, 2009:479) – pointing to potential functional differences. However, much larger ATW vessels (30–50 cm diameter) have been recorded in Finland and northern Sweden (Bergman, 1995; Lavento, 2001:64–75). The persistent use of asbestos tempering is instructive of the technological organization as sources of this raw material appears to have a wide spatial distribution. Initial petrographic analysis of archaeological asbestos tempering suggest main use of local occurrences, yet also showcase examples of non-local minerals in line with an apparent preference for iron-rich asbestos (Hood et al., 2022), possibly implying exchange of particular tempering agents, probably via open social and kinship networks, combined with higher general levels of mobility.

The time and energy invested in obtaining asbestos from distant sources, combined with it generous use for tempering of the clay paste point to some kind of powerful motivation for making this very deliberate technological choice (Ikäheimo and Panttila, 2002). This is substantiated by the set of physical properties which distinguish asbestos minerals as a ceramic temper: low thermal conductivity, non-flammable, high melting point [up to 1500 °C], chemically non-reactive with most caustic and oxidizing minerals, and neutral electric conductivity (ideal isolator) and thus high insulation capacity. The tempering of ceramic vessels with high densities of asbestos mineral result in vessels that are slow to heat (energy demanding) yet retain acquired heat well. This is highly unusual for cooking ware and rather a sought-after property in heat containers. It is not known whether asbestos was intentionally used as tempering to obtain this property or if it rather reflected a preference for the fibrous properties of asbestos in pot production.

Regardless, it would reduce heat transfer and require more fuel for external heating of the contents, though there may have been vital trade-offs between lightness, portability and local fuel efficiency, especially when considering the great variability in wall-thickness amongst ATW ware. Alternatively, the insulating properties of asbestos were a deliberate design feature and could have reflected a "return" to other cooking methods such as hot stone boiling, typically used in combination with wooden or bark boxes, woven baskets or skin bags. Finally, the smaller and thinner-walled ATW vessels compared to ENCW vessels may also have been lighter and more portable. Thus while the individual pots may have been "immobile", their material elements may have been recycled and recombined in different locales (contra (Ikäheimo and Panttila, 2002:3). This may account for the smaller scale of pottery use in the ATW horizon and its divergence from surplus scenario ceramic traditions. Instead, it seems to be a response to challenging socio-ecological conditions, including higher mobility, regular reuse of recycled materials, by communities investing in the combined reproduction of social and material relationships to maintain more fragile social networks at a time of lower population levels.

In support of this adaptive shift, other "embedded" technologies change in synchrony: the highly curated ground slate complex - which was the dominant lithic technology at coastal sites in the preceding millennia - is replaced by a more expedient quartz technology (Jørgensen, 2020), combined with the renewed uptake of bifacial technology, considered a predominantly terrestrial technology for ungulate hunting (Blankholm, 2011). Both may be linked to growing mobility and a growing contribution from hunting of terrestrial game as indicated by the ORA results, part of a wider set of responses to declining environmental conditions across all of Fennoscandia (Forsberg, 1989; Halinen, 2005; Holm, 1991; Jørgensen and Riede, 2019; Larsson et al., 2012). While use of marine resources persisted at coastal sites, as evidence by our ORA results, there is indication of a broader array of resources being processed in ATW pots at the inland sites, following resource diversification as a risk management response to environmental decline at the time.

In sum, many intriguing features of the ATW tradition deviate from several common assumptions in early-pottery research and align more closely with the adoption scenario of ecological "deficit" (Table 1). Given the poor preservation of faunal material across northern Norway, it is difficult to properly assess whether these later communities were suffering from declining food security and were adopting and investing in pottery technologies to maximize calory capture from a declining resource base. We assembled some limited available information on bone breakage patterns from coastal and inland sites during the ENCW and ATW. The earlier coastal assemblages were more intact, with limited evidence for deliberate bone fragmentation (Hodgetts, 2000), whereas bones at ATW sites had been heavily broken, rich in cut marks and mostly burnt (Simonsen, 2001:32–33).

Finally, ATW likely had health risks. Fine-grained asbestos fibers constitute a hazardous substance even classified as a carcinogen, causing various forms of cellular damage to both the respiratory, digestive, and reproductive organs through the asbestos-related and highly aggressive cancer form of mesothelioma (O'Reilly et al. 2007). As such, there has been some speculation over the potential negative health impacts from the prehistoric use of asbestos as a tempering agent, both through inhaling dust during the production stage of grounding and working asbestos fibers, as well as intake through seepage but also from ingesting microfibers released into foods cooked in asbestos and soapstone vessels (Rolfsen, 1985). However, no empirical or experimental studies have mapped potential exposure rates and/or health risks of this technology.

6. Discussion

6.1. Inter-regional dispersal mechanisms: two traditions, one process?

Our results indicate that two very different pottery technologies expanded into northern Norway during diametrically opposed Human Ecodynamic regimes. Yet, both dispersal events share a common origin in "core" areas of southeastern Fennoscandia. This realization opens to investigating the processes of dispersal into northern Norway.

Most studies of early pottery expansions avoid overt reference to demic diffusion, highlighting instead the likely role of knowledge transmission via open social networks, often combined with generalized exogamy (Jordan et al., 2016), though there are occasional exceptions, including the brief Late Glacial appearance of pottery into Hokkaido, which is assumed to reflect some kind of small-scale migration from northern Honshu (Fukuda et al., 2022; Robson et al., 2020). However, this assumption increasingly sits at odds with the expanding field of aDNA research, showcasing the frequency of wide-scale and often abrupt population movements, displacements and admixtures throughout human prehistory. While the integration of aDNA with archaeology have confirmed that demic diffusion did play a major role in the expansion of farming into Europe (Shennan, 2018), archaeologists have been more reticent about directly linking migration and replacement to expansion of hunter-gatherer innovations like early pottery.

Returning to Arctic Europe, there is compelling empirical evidence that the ENCW tradition dispersed as a multi-faceted techno-complex including ground slate and bifacial technology (Fig. 3), while also correlating with major social changes, as seen in an explosion of rock art and intensified long-range exchange and followed by increased sedentism – possibly hinting at a densely-connected social world spanning northern Fennoscandia, population growth and possibly people movements (Gjerde 2010:400; Skandfer, 2005; Niemi et al. 2019:200). These, in turn, were supported by highly productive ecological conditions and growing population trends. These factors do not directly showcase that the ENCW expansion was driven by a population migration. However, multi-component changes occurring in synchrony are less likely to occur through diffusive process given the limitations of successful knowledge transfer and maintenance of skills. Considering the amount and scale of changes co-occurring at the time, in-migration of groups/communities already familiar with these technologies and practices seems reasonable to assume.

While lithic technologies evidently can be transmitted through diffusive processes, ceramic technology on the other hand introduces a completely new concept and a pyrotechnical operational chain not related to the existing (container) technologies in the area, resulting in a relatively high threshold for transmitting the know-how of ceramic production. This should be in favor of the dispersal of at least some people over ideas.

Also, the ENCW horizon remains tightly restricted to an ecotone very similar to adjacent areas of Finland, through which the ENCW tradition dispersed. The maximum expansion of forest cover marks this period of the HTM, equating to the expansion of inland-like ecological conditions to the gentle coastal topography of Varanger fjord, and may have supported the expansion of communities/People originating from the region around the Bothnian Gulf and adjacent inland, to the Barents coast exclusively along the major Pasvik river waterway. Likewise, the ENCW pottery did not expand into the more maritime ecotone of Western Finnmark – primarily a rugged archipelago with minimal terrestrial productivity. The fact that the ENCW expansion correlates with a pulse of heightened activity levels in interior areas (Fig. 3) (cf. Hood, 2012) may suggest that increased ecological productivity encouraged the "shedding" of people and traditions to the less densely settled Arctic coast providing a more stable oceanic ecotone, with the expansion of southeastern groups following the northward expansion of the boreal niche. This may also account for the restricted presence of the ENCW in northern Norway – whose timing corresponds to the peak in terrestrial productivity and the limited window of when the boreal taiga extensively interfaced with the Barents Sea.

Our revised chronology for the ATW expansion in northern Norway has implications for the likely origin and dispersal process for the wider Fennoscandian asbestos pottery phenomenon. Now that the ATW expansion into northern Norway is chronologically shifted to a later date, these northern assemblages become contemporary with a general dispersal and uptake of ATW across the majority of northern Fennoscandia. The revised spatiotemporal patterning therefore points to a rapid East-to-West pottery expansion, uniting developments in Finland and Sweden with the final "pulse" that reaches the northern and western sections of the Norwegian coast.

Also for ATW, this east-west direction of movement is again supported by analysis of other material traditions. Most notably, the ATW tradition appears to disperse in tandem with a new kind of bifacial lithic technology (see, Fig. 4), and seems to suggest a joint dispersal of multi-technology toolkits and associated know-how. We therefore suggest these technologies belong to the same technocomplex. As opposed to the ENCW period, there is strong distribution correspondence between these technologies in the ATW period, with Northern Fennoscandic bifacial types (the main distributive area of ATW) differing from the contemporary south Scandinavian bifacial technology present in southern Norway (Apel, 2012).

As with the ENCW, the ultimate "source" area for the ATW was the more productive environment of W. Russia and the Baltic Region. This is illustrated by the fact that southeastern Fennoscandia, Karelia, western Russia and the eastern Baltic region display continuous use of ceramic technologies and significantly greater antiquity of asbestos-tempering vessels (Lavento, 2001). The pottery traditions of eastern Fennoscandia generate an unbroken sequence from the Early Comb Ware, via local transitions and intermediate forms into the eventual coalescence of the ATW and also later wares (Kulkova et al., 2012:1057) – which also find their way to the Norwegian coast. The dates for the arrival of the ATW wares across Fennoscandia and Karelia now cluster within the 3900-3500 cal BP span (Bergman, 2007; Forsberg, 2001; Hulthén, 1991; Kosmenko, 1996; Linder, 1966; Seitsonen et al., 2012) – Lavento (2001:102) presenting the only significant exception to our knowledge. This points to a rapid long-range dispersal process. It is, however, worth noting that asbestos-tempering originated already around 6500 cal BP in interior Finland and around Lake Saimaa where asbestos deposits are readily available, in both Kaunissaari Ware and interior variants of Sperrings 2 Ware (Nordqvist, 2018:63; Pesonen, 1996, 2021:24,26), however seems to have gone out of use after approx. 500 years (Oinonen et al., 2014:1421). Yet this remained an eastern Fennoscandic phenomenon until a rapid and widespread dispersal of asbestos-tempering across north and central Fennoscandia.

Again, this raises questions about the likely socio-cultural processes involved. Traditionally, evidence for a large-scale migration involving expansion of specific populations and their technocomplexes into northern Norway has been regarded as lacking beyond the early Holocene colonization event. Instead, the ATW phenomenon has often been understood as slow, steady and essentially localized indigenous transformation (Gjessing, 1953, 1955; Jørgensen and Olsen, 1988; Simonsen, 1976, 1979) (critics (Johansen 1979; Skandfer, 2012:136–7):). Viewed against the palaeoecological context of these cultural changes, this period now seems to undergo radical turmoil, with the end result being the eventual emergence of new adaptive strategies and communal structures exhibiting higher levels of mobility and expansive social networks, forming the potential vacancy for ATW to successfully expand and get adopted – aligning with the "deficit" scenario.

Intriguingly, paleogenomic studies from adjacent areas of Finland and Russia now demonstrate influx and admixture of eastern steppe genetic material to these areas by ca. 3500 cal BP (Lamnidis et al. 2018; Sarkissian et al. 2013). These include individuals sampled at the NW Russian site of Bolshoy Oleni Ostrov on the Kola peninsula bordering Norway, which contained multiple finds of ATW pottery (Murashkin et al., 2016). This truly constitutes a smoking gun, further substantiated by additional indications of major population shifts and replacements reported in Finland (Sundell et al., 2014; Tallavaara et al., 2014; cf. Sajantila et al., 1996).

Also significant is that the original ATW tradition was fading in its original source areas while expanding into northern Norway and remained in use in northern Finland (Lovozero ware). This cultural shift within Finland has been explained by a migration into this area by external populations brining new ideas and practices (Lavento, 2001:176); this may also have triggered displacement of population to areas further north, until ATW-using groups eventually reached northern Norway. This scenario is potentially supported by recent palaeodemographic modelling of population levels across Finland – these suggest a population decline across all areas, centering on 3800 cal BP, which aligns well with the pattern from northern Norway. However, there are marked latitudinal differences, with populations in southern and central Finland remaining very low until ca. 2500 cal BP, while the northern regions fluctuate around a higher and more stable mean level (Tallavaara et al., 2010:255), potentially suggesting population relocations into a northern refugium.

6.2. Underlying processes: Human Ecodynamics and "source-sink" dynamics

The *pattern* we have identified of repeated movements of people and ideas from a population and innovation core area in SE Fennoscandia to the periphery of the northern Norwegian coast, closely aligns with the *process* conceptualized by "source-sink" dynamics. The S/S framework is increasingly being used to understand the biogeography of human dispersals, typically a slow and intermittent process – the dynamic involves a population in a patch of mean surplus productivity growing until it eventually spills out individuals who move into empty or less densely packed regions with lower productivity (Dennell, 2017, 2020; Dennell et al., 2011; Lamb et al., 2017; Robertson and Hutto, 2006).

Such slow and intermittent population expansions are also structured by ecological and isothermal constraints, resulting in latitudinal gradients and longitudinal zonation in later patterns of genetic similarity (Fine, 2015; Mittelbach et al., 2007). In the case of these two early pottery expansions, it is clear that they occurred in different environmental settings, and had divergent internal characteristics (technological choices, etc.), though what certainly unites them is the underlying process of origin in (the same) external "source" area, and their expansion into the "sink" area of northern Norway. This may involve large scale migrations, but more commonly the cumulative small-scale movements of groups and individuals, often via established networks, into remoter areas.

Although Maritime Arctic Europe is typically considered exceptionally productive in terms of potential human food resources, and thus a prime patch for human exploitation/occupation, the highest potential for prehistoric population growth was actually located in the terrestrial lake-river-forest ecosystems of south-central Finland (Jørgensen et al., 2020). However, the average ecological characteristics of the two regions differ in other vital ways, including resource abundance, species diversity and trophic chain length/complexity but especially in the potential magnitude of responses to different climatic conditions. In other words, the Norwegian coastal ecotone likely facilitated greater opportunities for resource diversification and risk reduction under reduced terrestrial productivity regimes despite lower overall productivity. In contrast, the terrestrial ecosystems of the Boreal zone are ecologically simpler/more uniform, and its human inhabitants are therefore more susceptible to unpredictable cycles of deep long-term risk given the higher amplitude of resource variability and consequently a more limited range of fallback strategies such as extensive resource diversification during prolonged resource depletion.

While source-sink dynamics assume *senso stricto* that the habitat quality of the sink area is too low to sustain a local population without access to resources and genetic mixing with the richer source area (Pulliam, 1988), northern Norway may have functioned as a "pseudo-sink". Such remain ecologically rich, but continue to receive migration of individuals and groups from the richer source areas (Watkinson and Sutherland, 1995). Shifting productivity between resource patches - or indeed large ecotonal changes on the scale of interior/coastal environments - may provide the incentive to relocate between resource patches. Importantly, the environmental pressures that encourage major population movement in the area operate equally during both elevated and lower ecological productivity regimes. For example, in the case of the ENCW expansion, increased environmental productivity and consequent niche expansion may have caused population increase in the source areas of the Baltics and W Russia, resulting in the overflow of population and their traditions being pushed into the northern areas. In contrast, the ATW expansion into northern Norway, may have been driven by the reverse process, including drastic terrestrial niche retraction in source areas of Finland and NW Russia, followed by abandonment and the movement of small pulses of "refugees" into Arctic Maritime Europe (Fig. 6). This latter dimension may help account for the great typological variability within the ATW tradition in northern Norway, plus the suggestion of small intermittent waves of the new tradition being spread in small pulses, leading to small breaks and even hiatus periods within the main ATW horizon.

While these "source-sink" interpretations of the archaeological record remain somewhat speculative at this stage, it is supported by direct historical analogies within the same region, which may indicate the deeper persistence of the same process. Archival records document frequent population movements from areas of south and central Fennoscandia into coastal northern Norway. Furthermore, they generally correlate with prolonged cold and wet conditions which depressed interior resources yields (by this time agricultural harvest of mono crops), dating at least as far back as the 13–15th century (Holopainen and Helama, 2009; Huhtamaa and Helama, 2017). Some climatic events such as the late 17th CE worsening of the Little Ice Age in Finland led to widespread famine and a 30% population decline in 1696 alone (Neumann and Lindgrén, 1979). Such events were important drivers in the "Forrest Finn" migration and the expansion of the particular rye slash-and-burn agriculture (so-called "Huuhta") from central/east Finland (Savolax and Karelia) into the southern Swedish-

Norwegian forested borderland. Similarly, this also involved displacement of survivors into northern Norwegian areas, who generally reestablished themselves with more diversified economies including farming and fishing along the coast and river valleys, yet retained ancestral linguistic and other cultural and material traditions, to the extent that they became known as “Kven People” (i.e. Finnish settlers) (Niemi, 2010). Older events are highly likely, but their positive identification is restricted by the limited time-depth of historic, demographic and tax records.

We suggest that the bursts of ceramic dispersals into northern Norway may have taken place under analogous conditions, with the repeated and historically documented migration dynamics between North Finland and coastal Arctic Norway indicative of deep-time human responses to the inherent instability of the northern Fennoscandian climate. As such, the source-sink framework may offer a novel and more interconnected way of understanding the punctuated pattern of distinct cultural traditions reaching prehistoric northern Norway. Such processes also highlight the structured ecological diversity of costal versus interior ecotones, and the combined socioecological responses to major shifts in climate and environment. In contrast, archaeologists have tended to focus on local sequences, but may need to start thinking across broader and more connected range of cultural and ecological scales. Finally, these kinds of “deep” yet structured Human Ecodynamics may explain some of the intriguing dynamism that is increasingly being detected by a growing suite of aDNA studies, with admixture, migration, but also population displacement and relocation being a common feature of the human genetic past (Allentoft et al., 2015; Sikora et al. 2019).

Yet the result that two opposing processes (surplus and deficit scenarios) both can produce seemingly similar results (people movements) is slightly worrying, showcasing the limited options available to us for reconstructing past processes based on empirical patterns. How can we separate the underlying mechanics given identical outcomes? We suggest that our approach in this paper demonstrates the need to apply multi-scale and multi-proxy frameworks that consider patterns of pottery dispersal within broader contexts of chronology, environment, and material culture to facilitate more accurate pinpointing of what are inherently complex, humanecodynamic processes (as opposed to single-proxy views of ceramic dispersals as “pots with legs”).

7. Conclusions

Growing archaeological efforts to understand the emergence and long-range dispersal of early hunter-gatherer pottery traditions across northern Eurasia have yet to address more punctuated patterns of adoption, abandonment, and secondary uptake. Arctic Maritime Europe offers an excellent setting in which to investigate these processes, given the arrival of two different early pottery traditions – ENCW and ATW, which are divided by a two-millennium hiatus – plus a wealth of contextual, chronological and palaeoecological data. As such, northern Norway offers scope for testing alternative adoption scenarios of early ceramic technologies, ranging from “surplus” to “deficit” models, as well as investigating inter-regional dispersal mechanisms, since both traditions emerged elsewhere.

Systematic re-dating of the ATW tradition, combined with the multi-proxy correlation of both ENCW and ATW traditions with a range of paleoenvironmental variables indicates that the ENCW expansion provides a “classic” example of pottery being adopted during “surplus” ecological conditions by communities demonstrating growing sedentism underpinned by exploitation of coastal and riverine resources and signs of expanding social complexity. In contrast, our refined dating of the ATW tradition indicates that it expanded much later than previously assumed, and consisted of multiple, yet discontinuous, dispersal events that correlated with a major environmental downturn, population decline, and an adaptive shift following ecological restructuring. In particular, the opening millennium of the ATW horizon does not appear to hold a widespread and generalized process of pottery adoption, but instead a scattered, low-magnitude process that appears to have involved high mobility, growing use of terrestrial resources can be suggested, combined with the steady in-flow of small-scale pottery-using individuals/groups from older core areas of the pottery tradition in eastern Fennoscandia.

Finally, we invoke the concept of “source-sink” dynamics to explain what appears to be repeated shedding of population from these core areas during opposing ecological settings, resulting in punctuations of groups relocating to the northwestern coasts and river valleys in prehistoric through to historic times. This is linked to the spatial structuring and strong zonation of Fennoscandia's ecotones, combined with their differing response mechanisms to major climatic shifts, with the northern coast providing incentives to relocate during instances of both surplus and deficit.

A striking and slightingly “unsettling” result from our case-study is that two opposing processes (surplus and deficit scenarios) both can produce seemingly similar results (people movements). Such process identification would not have been possible without applying a multi-scale and multi-proxy framework that consider patterns of pottery dispersal within broader contexts of chronology, environment, and material culture and such facilitate more accurate pinpointing of what are inherently complex, humanecodynamic processes. Our case-study of punctuated ceramic dispersals under diverging human-ecodynamic settings, likely reflect real, on-the-ground variability in the driving motivations for ceramic uptake as well as functional variability through time. This again, creates fascinating new avenues for early pottery research that have so far been only minimally explored.

One such avenue is the need to consider multi-scalar behavioural patterns inherently embedded in both ecological, economical, logistical, ritual, social and organizational considerations – analysing pottery not as a single phenomenon but as a highly flexible element in wider technological system where it can used for quite different reasons.

A second avenue is that of improving the chronological resolution of spatiotemporal dynamics in ceramic technologies particularly in interior northern Sweden and Finland, as well as NW Russia in general, which will greatly improve our ability to evaluate hypotheses of source-sink dynamics in Arctic Europe. Current data suggest a source area in southeastern Fennoscandia for most Fennoscandic pottery types, yet geographical variation is also implied by the mostly Arctic phenomena of the ATW ware. Linking this to other, and so far, less well studied object classes of punctuated appearance, such as bifacial lithic technology, could provide instructive parallels. Increased chronological resolution will aid in mapping and separating source from sink regions, with greater antiquity/continuity being expected of the source areas and later/discontinuous dispersals into sink regions. That being said, we highlight the need to consider that the direction of movement of both people and technologies appears to vary though time, as evidenced by the results presented here.

Author contribution

Erlend Kirkeng Jørgensen: Conceived and designed the analysis, Collected the data, Contributed data or analysis tools, Performed the analysis, Wrote the paper. Johan Eilertsen Arntzen: Collected the data, Contributed data or analysis tools, Wrote the paper. Marianne Skandfer: Contributed data or analysis tools, Wrote the paper. Madison Llewellin: Collected the data, Performed the analysis. Sven Isaksson: Collected the data, Performed the analysis. Peter Jordan: Contributed data or analysis tools, Wrote the paper.

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

Data is available in the SI.

Acknowledgements

The radiocarbon dating program was funded through a joint effort by the Stone Age Demographics project at UiT – The Arctic University of Norway as funded by the Research Council of Norway Grant No. 261760, and research funds of MS and EKJ.

Contributions by ML, SI and PJ were supported by the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Marie Curie Actions, Grant Agreement No. 676154. Sampling was conducted by ML under supervision of MS, and the ORA was conducted in Stockholm by ML under supervison of SI.

Financial support was also provided for EKJ through NIKU research funds.

We are grateful for the kind support provided by the staff at the Arctic University Museum of Norway curating the ceramic materials.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2022.107825.

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