



Using Radiocarbon Dates and Tool Design Principles to Assess the Role of Composite Slotted Bone Tool Technology at the Intersection of Adaptation and Culture-History

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Abstract

Slotted bone tools are an iconic example of composite tool technology in which change in one of the components does not require changing the design of the other parts. Commonly, slotted bone tools are seen through the lens of lithic technology, highlighting organizational aspects related to serial production of insets, reliability and maintainability. In this framework, slotted bone tool technology is associated with risk aversion in demanding environmental settings. Here, we provide the first overview of radiocarbon-dated slotted bone tools in northernmost Europe and the East European Plain, including 17 new direct dates on pitch glue, and show that the Late Pleistocene to Middle Holocene period of inset slotted bone tool use in this area shows marked variation and idiosyncrasy in associated lithic technology against a trend of continuously warming climate. We suggest that historical specificity and path-dependence, rather than convergent evolution, best explain the variability seen in slotted bone tool technology in the studied case, and that slotted bone tools in general formed an organizationally flexible, adaptable and hence likely adaptive technological solution that met a wide variety of cultural and technological demands.

Keywords Slotted bone tools · Europe · East European Plain · Mesolithic · Composite tools · Organization of technology

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Introduction

Technologies that combine small replaceable lithic insets, slotted bone shafts and wooden hafts into composite tools and weapons were produced in many parts of the world up until the Late Holocene. Microliths appear fairly early in prehistory (cf. Burdukiewicz, 2005; Elston & Kuhn, 2002; Lewis et al., 2014) are strongly associated, for instance, with early modern humans in the African Middle Stone Age (e.g. Wadley, 2015), but evolve repeatedly in different parts of the globe in a process that converges on similar design principles (Clarkson et al., 2018). The patchy geography, repeated appearance and episodic disappearance of microlithic technology and the complex composite tools it implies suggest that this technology cannot be seen as the endpoint of a preordained modal development, nor can it readily be seen as a global adaptive optimum.

In an influential paper on microblade and slotted bone point technology in Late Pleistocene northern Asia, Elston and Brantingham (2002) suggested a strong link between an efficient risk-minimizing microlithic technology and composite slotted bone tool technology. Although Elston and Brantingham noted that the use of bone tools with inset microblades in their area of study was contingent and situational, the occurrence of inset technology in the northern latitudes has since often been regarded as evidence of design choices rooted in risk-minimization in cold and harsh environmental conditions (e.g. Elston et al., 2011; Graf, 2010; Rabett & Piper, 2011; Qu et al., 2012). Other researchers have suggested links between production of microblades, inset bone tools and high residential mobility, as raw material efficiency and serial production reduce tool-stone carrying costs and provide a means of reducing the risk of ending up with no suitable tool-stone when mobility is high and the foraging range large (e.g. Goebel et al., 2000; Hartz et al., 2010; Yi et al., 2013). Barton et al. (2007) also note that there is evidence suggesting a continuous use of composite tool technology over the Late Glacial Maximum (LGM) in northern China, and that the expansion of microblade technology after the LGM was based on a substrate of composite tool technology employing bipolar-on-anvil reduction on various materials in pebble form (see also Brantingham et al., 2004; Madsen et al., 2001).

In northern Europe and on the East European Plain (Fig. 1), slotted bone tools have a long history of research as parts of Mesolithic hunter-gatherer-fisher tool inventories (e.g. Clark, 1936; Gurina, 1956; Indreko, 1948; Lidén, 1942; Pälsi, 1920; Sarauw, 1904). The Early and Middle Holocene in this region was a time of rapid climatic warming interrupted only by short cooling events (e.g. Feurdean et al., 2014; Fleitmann et al., 2008; Seppä et al., 2002, 2009; Veski et al., 2015); the climatic and environmental settings thus differing considerably from the cold, dry and variable Late Pleistocene conditions of northern Asia.

A scenario purporting a connection between inset tool technology of the Mesolithic East European Plain and South Scandinavian Maglemose and Kongemose (ca. 11,800–7400 BP) cultures has gained support in recent years from studies indicating Postglacial dispersal of bone tool and lithic pressure blade production technologies—probably alongside an influx of people—in the Scandinavian Peninsula from the east (Bergsvik & David, 2015; Damlien, 2016; David, 2009; Sørensen et al., 2013). The same culture-historical connection across the Baltic Sea, based on similarities in slotted bone tool technology and other typo-technological details, was suggested already by precocious synthesizers such as Clark (1936) and Lidén (1942). Fundamentally, however, research



Fig. 1 a The Northern Hemisphere and the area discussed in the paper. b Sites and locations: 1. Karacharovo; 2. Minino 2; 3. Zamoštje 2; 4. Zamoštje 5; 5. Sakhtysh 14; 6. Ivanovskoje 7; 7. Stanovoje 4; 8. Aziarmoje 2B; 9. Michnievičy; 10. Vaikantonys; 11. Obšrūtai; 12. Tłokowo; 13. Zvejnieki II; 14. Pāmu River; 15. Ulbi; 16. Kunda Lammasmägi; 17. Muilamäki; 18. Antrea Korpilahti; 19. Yuzhniy Oleni Ostrov; 20. Groß Fredenwalde; 21. Tuse Hauge; 22. Vedbæk; 23. Tågerup; 24. Rönneholms Mosse; 25. Barum Grave; 26. Norje Sunnansund; 27. Stora Bjers; 28. Motala Kanaljorden; 29. Motala Strandvägen; 30. Prestemoen 1; 31. Viste cave; 32. Åflo. The dotted line indicates the border between North European (D-method) and North-East European (Z-method) bone technology for slotted bone tool production ca. 9500–8000 cal BP according to Bergsvik and David (2015)

related to the composite slotted bone tool technology in northern Europe and the East European Plain is strongly hampered by the suboptimal preservation of organic material, as well as a preference to date layers instead of implements, which has resulted in a scarcity of well-dated inset bone tools.

Until recently, a very limited number of sites with more or less securely dated inset bone tool contexts has been reported from the vast area stretching from the Scandinavian Peninsula to the Moscow region in the east (Knutsson et al., 2016). However, with the addition of 13 slotted tools from Strandvägen and Kanaljorden sites in Motala, Sweden (Gummesson & Molin, 2019), as well as direct dates on the slotted points from Vaikantonys and Obšrūtai in Lithuania (Ivanovaitė et al., 2018), the slotted knife from Ulbi, Estonia (Bjørnevad et al., 2019) and a slotted point from an unknown location in the southeastern Baltic (Philippsen et al., 2019), the chronological position of inset bone tool technology in the area is becoming more robustly constrained, yet even this

improved chronological lattice makes it difficult to evaluate whether slotted bone technology using standardized microliths should be seen as an adaptive response to specific climatic/environmental conditions, or whether it is carried to Northern Europe as part of a demic diffusion, or possibly both.

In this paper, we present a set of additional direct dates from slotted tools deriving from Central Russia, Belarus, Estonia and Poland. We combine the new information with previous, secure dates of composite slotted tools in the area to arrive at a better understanding of the timeframe within which the technology was in use, and on this basis to discuss aspects related to the organization of slotted inset bone tool technology vis-à-vis culture-historical, climatic and environmental drivers. Against this dramatically improved empirical backdrop, we suggest that neither single environmental drivers nor cultural preferences explain the use of slotted bone tool technology alone. Instead, the composite nature of slotted bone tool technology means that it is affected by a diverse suite of organizational and cultural drivers, the strength and downstream correlates of which may be strongly situational and therefore not duplicated in other regions even if seemingly similar composite technologies were in use.

Material and Methods

All dates in our ^{14}C dating program were obtained on pitch glue sampled from slots of inset tools or, in two cases, from pitch glue on the distal end of the implement where a haft was originally attached. Pitch glue was considered a better material for dating than bone collagen for two reasons:

- 1) The less than 10 mg sample required in dating pitch glue (equivalent in dimensions to the ball head of a common sewing pin) is considerably smaller than the up to 1000 mg of bone needed for dating bone collagen. This makes dating pitch glue a markedly less intrusive method.
- 2) Analyses conducted on the black substance used to glue insets to slotted points, as well as for other purposes in northern Europe during the Mesolithic, suggest the use of birch bark pitch (Bjørnevad et al., 2019; Edgren, 1997; Vahur et al., 2011), while the osseous material used to produce slotted bone tools in the area seems to derive from large terrestrial ungulates (David, 2009), for which a reservoir effect may in some cases be possible (Philippsen, 2019), birch bark pitch, with tar produced from the outer layer of short-lived *Betula* ssp. as its main component, can be expected to have a very limited age of its own.

We had the possibility to sample and date 17 previously undated inset bone tools from the study area for this study (Table 1, Fig. 2). All samples were dated in the Aarhus AMS Centre (Department of Physics and Astronomy, Aarhus University) and the results calibrated using the OxCal 4.4.2 program (base year 1950; Bronk & Ramsey, 2020) and the IntCal 20 calibration curve (Reimer et al., 2020). We targeted specimens with enough preserved pitch glue to enable sampling without depletion, targeting sites and areas from which no dates of inset tools existed. For the purpose of comparison, we also dated one bone harpoon from Zamośćje 5, layer IX, where lithics belonging to the

Table 1 The sampled implements. The measurements indicate the size of the osseous part of the inset tools and harpoon in their present state. See Fig. 2 and SI 1 for photographs of all the artefacts in the table

Country	Location	Nr.	L (mm)	W (mm)	T (mm)	Slotting
Russia	Karacharovo		102	10	5	Unilateral
Russia	Minino 2	Y2: 1	98	29	10	Bilateral
Russia	Minino 2	Y5: 114	85	18	8	Bilateral
Russia	Minino 2	Y5: 123	108	23	7	Bilateral
Russia	Minino 2	Y5: 152	64	19	10	Bilateral
Russia	Minino 2	Y5: 172	202	25	15	Unilateral
Russia	Minino 2	Y5: 193	295	32	11	Bilateral
Belarus	Aziamoje 2B	KP 5773: VP 373	93	6	4	Bilateral
Belarus	Aziamoje 2B	KP 5788: VP 399	214	8	6	Bilateral
Belarus	Aziamoje 2B	KP 5788: VP 403	171	12	7	Bilateral
Belarus	Michnievičy		145	30	18	Unilateral
Estonia	Lammasmägi	AI 3359: 172	90	33	7	Bilateral
Estonia	Lammasmägi	AI 3359: 189	125	25	7	Bilateral
Estonia	Lammasmägi	AI 3410: 561	117	23	5	Bilateral
Estonia	Pärnu River	AI 2761: 5	128	10	7	Unilateral
Estonia	Pärnu River	AI 2761: 6	151	11	8	Unilateral
Poland	Tłokowo	MMA 1730	186	13	5	Bilateral
Russia	Zamoštje 5	Zam 5: 74	222	10	7	No slot

Resseta culture suggested an early context with good preservation of organic material but devoid of slotted bone tool technology. To test the reliability of pitch glue in radiocarbon dating, in one case (Minino 2, Y5: 193; Fig. 2h), two separate samples were dated from the same implement, one from a slot and a second from the hafting glue.

Sites and Sampled Tools

Karacharovo (Vladimirskaja Oblast, Murom, Russia) The Karacharovo sample derives from a fragment of a unilaterally slotted bone point with flint insets. The point is a stray find made by a resident of the village of Karacharovo in 2016 and brought to the Murom Regional Museum of Local Lore, from which it was delivered to the Institute of Archaeology (Moscow) by V.V. Beylekchi. It originates from the mouth of the Karacharov ravine, in the upper part of which was located the Terminal Paleolithic Karacharov site, excavated in the late nineteenth century by Count A.S. Uvarov (1881). The site appears to have been lost to time as recent surveys have not been able to locate it (Trusov, 2011). It was nevertheless considered probable that the slotted point originally derived from the Paleolithic site.

Minino 2 and Zamoštje 5 (Moscowskaja Oblast, Sergievo-Posad Region, Russia) The complex geo-archaeological site Minino 2 is located adjacent to the Dubna River in the area of the Zabolotsky peat bog. The site consists of multiple



Fig. 2 Examples of slotted bone tools dated in our dating program to ca. 15700–7300 calBP. **a** Aziamoje 2B/KP 5773: VP373; **b** Karacharovo; **c** Minino 2/Y2:1; **d** Tlokowo/MMA 1730; **e** Pärnu River/AI 2761:6; **f** Minino 2/Y5:152; **g** Kunda Lammasmägi/AI 3410:561; **h** Minino 2/Y5:193. See Supplementary information 1 for photographs of all the implements dated for this study. Photo D courtesy of J. Orłowska

layers of Stone Age occupation and a set of burials, forming a complex palimpsest that has evidently been conditioned by various natural and cultural processes affecting the soil profile from the Late Pleistocene onwards, as well as the digging of burials through earlier layers. In addition, processes related to modern peat extraction in the Zabolotsky bog area have also significantly altered the site.

Excavations at Minino 2 have been conducted during ten field seasons in the years 1997–2019 in a total area of about 600 m² (Gracheva et al., 2006; Nikolaev et al., 2002; Sorokin, 2000, 2007, 2009, 2010, 2011, 2013, 2016; Sorokin & Hamakawa, 2014; Sorokin et al., 2018). The finds consist of ca. 25,000 lithic items, of which approximately 4000 show secondary processing, ca. 8500 fragments of osseous material including over 600 bone and antler implements and fragments thereof, as well as other finds including small fragments of Neolithic-Bronze Age pottery in the upper cultural layer.

The lower cultural layer in the main occupation area of the site consists of two horizons. In the upper horizon, there are artefacts of the Zadnepilevo Mesolithic culture (ca. 10,000–8500 cal BP), while the lower horizon contains artefacts of the long-lived Resseta culture generally considered a Terminal Paleolithic archaeological culture (ca. 15,800–12,000/11,500 cal BP; Sorokin et al., 2018). On the shore slope and in river sediments in front of the site, finds of diverse cultural and chronological settings were found in water-deposited layers rich in organic matter separated by sterile strata (Sorokin, 2009, 2010, 2011; Sorokin & Hamakawa, 2014; Sorokin et al., 2018, 2019). Two of the slotted implements selected for this study originate from the lower occupation layer of the site (Y2: 1 and Y5: 123) and four from the sloping shore layers (Y5: 114, :152, :172 and :193).

Zamoštje 5 is also a site with well-preserved organic material. It is located ca. 50–100 m from Minino 2 on the opposite bank of the Dubna River. Zamoštje 5 has yielded no finds of inset bone tools, although a rich assemblage of artefacts made of organic material has been retrieved. The site has a stratigraphy consisting of nine cultural layers and burials (Sidorov & Sorokin, 1997, 1998, 2000, 2001; Sorokin, 2000, 2009; Sorokin & Hamakawa, 2014; Sorokin et al., 2018). A harpoon head of osseous material found in the stratigraphically lowest layer (layer IX, nr. 74) containing also lithic implements of the Terminal Paleolithic Resseta culture was selected for dating.

Aziarnoje 2B (Liubań District, Belarus) An assemblage of more than 120 bone and antler artefacts was salvaged from the underwater site Aziarnoje 2B located in Lake Viačera, central Belarus. The artefacts were lifted up from the lakebed in the course of commercial saptopel extraction and collected by archaeologist Mikalai Kryvaltsevich in 1985–1991 (Kryvaltsevich, 1996, 2008; Kryvaltsevich & Simakova, 2004). A number of prehistoric sites are known around Lake Viačera. The rich Stone and Bronze Age site Aziarnoje 2A is located on the shore next to the underwater area Aziarnoje 2B. In addition, the Aziarnoje 1 site is located on a sandy promontory a few hundred meters to the northwest of Aziarnoje 2B. Excavation and controlled surface collection at Aziarnoje 1 yielded evidence of activity beginning in the Terminal Paleolithic and continuing all the way through the Iron Age (Kryvaltsevich, 1999). Alongside with finds from other periods, a representative lithic assemblage of the Mesolithic Kudlavka culture, as well as some flint finds associated with the Terminal Paleolithic Swiderian culture, derives from here (Kudrashou & Kryvaltsevich, 1994; Kudrashou, 1997).

The lakebed assemblage from Aziarnoje 2B includes items of various morphological and functional types such as points, arrowheads, harpoons, daggers, adzes and mattocks. On typological grounds, Kryvaltsevich (1996) associates the finds with various cultural units of the Mesolithic and Neolithic. In addition to the osseous material, nearly 1150 other archaeological finds were collected: ca. 1100 potsherds of

the Neolithic and Early Bronze Age, a small flint inventory including two Swiderian tanged points and a number of non-worked animal bones and pieces of osseous material. Kryvaltsevich suggests that the Mesolithic implements made their way into the lakebed in the course of hunting, fishing or other activities by the lakeside, whereas the later artefacts may derive from pile-dwellings or possibly from a site submerged during a later transgression. Three bilaterally slotted points kept at the Liubań Museum of People's Glory (KP 5773: VP 373, KP 5788: VP 399 and KP 5788: VP 403) were dated from the Aziarnoje 2B assemblage.

Michnievičy (Smarhoń District, Belarus) From the 1970s through the 1990s, a rich paleontological and archaeological collection was recovered from the site of Michnievičy (also known as Smarhoń quarry) near the town of Smarhoń in the middle reaches of the Vilija River. Nearly 7000 animal bones and antlers, including more than 100 worked pieces and implements, were collected from floodplain deposits in the course of sand and gravel quarrying. On typological grounds, the finds date from the Mesolithic and the Neolithic (Charniauski, 1992, 2006; Charniauski & Kalinouski, 1972; Kalinouski, 1983, 1995; Malyutina et al., 2019). A flat unilaterally slotted bone spearhead from Michnievičy, kept in the Institute of History of the National Academy of Sciences of Belarus, was sampled for this study.

Kunda Lammasmägi (Estonia) The iconic settlement site of Kunda Lammasmägi is located on a small hilltop in northeastern Estonia, a location that during the Mesolithic was an island in the Kunda paleolake (Sander & Kriiska, 2018). Following the discovery of the site in 1886, numerous archaeological excavations have taken place and a large number of artefacts, including multiple items made of bone and antler, have been found (Åkerlund et al., 1996; Grewingk, 1882, 1887; Indreko, 1936, 1948; Jaanits, 1965; Sander & Kriiska, 2015). Some items of osseous material have also been collected from the sediments of the ancient lake that surround the settlement.

The cultural layer of the settlement that in places reaches a thickness of approximately 1 m developed over a long period of time and has been extensively mixed by various natural and cultural processes. It contains finds from a timespan extending from the Early Mesolithic to the end of the Neolithic, with twelve radiocarbon dates between 10,700 and 3700 calBP (Sander & Kriiska, 2018). In addition, a small number of loose human bones have been found from the Kunda Lammasmägi site (Tõrv, 2018). Three bilaterally slotted implements (fragmented knives/daggers) stored at the Archaeological Research Collections of the Tallinn University (AI 3359: 173, AI 3359: 189 and AI 3410: 561) were dated from the site in this study.

Pärnu River (the Lower Reaches of River Pärnu, Estonia) During the first decades of the twentieth century, nearly 2000 archaeological finds, mostly objects of bone and antler, were collected from the lower reaches of River Pärnu, southwestern Estonia (Bliebernicht, 1924; Glück, 1906; Indreko, 1926). All artefacts derive from a 1.5 km-long stretch of the river and were salvaged in the course of sand and gravel quarrying. No in situ finds or cultural layers were reported. Two antler objects from this collection have previously been dated—a sculpture of a bird to ca. 7880 cal BP (Jonuks, 2013) and a human figurine to ca. 7990 cal BP (Jonuks, 2016). On typological grounds, most finds from the riverbed would be expected to date from the Early Mesolithic to the Neolithic, while the youngest finds are from the Middle Ages.

It is probable that the finds from Pärnu River derive from several Stone Age sites originally located on the banks of the River Pärnu but inundated and buried under marine sediments by the rising transgressive Littorina Sea around 7500–7300 cal BP (Nirgi et al., 2019; Rosentau et al., 2011). On the basis of reported human bones (Glück, 1906, 275), a cemetery may also have been buried under the sediments (Tõrv, 2018, 242). Unfortunately, the human bones that were collected during the sand and gravel quarrying in the early twentieth century can no longer be located. Two broken unilaterally slotted points/knives from the Pärnu River collection stored at the Archaeological Research Collections of the Tallinn University (AI 2761: 5 and AI 2761: 6) were dated.

Tłokowo (Poland) The Tłokowo slotted bone point was found accidentally in 1989 while digging a cattle pond in the village of Tłokowo (north-east part of Poland). It was retrieved from a depth of approximately 0.8–1 m below the present-day ground level, in the bottom part of a layer of brown peat (Sulgostowska & Hoffman, 1993). The discovery of the artefact resulted in six seasons of excavation at the site, managed by Romuald Schild of the Archaeology and Ethnology Institute of the Polish Academy of Sciences (PAN) in Warsaw (Schild et al., 2003). Several settlement horizons were distinguished at the site, although in strata assigned to the Horizon IV, which yielded the point selected for dating in this study, only a limited number of finds were present (Schild et al., 2003).

The bilaterally slotted Tłokowo point was made using a piece of radial bone from a large herbivore, most likely a red deer or European elk (*Alces alces*). The 16 preserved flint insets are made of chalk flint, and using an X-ray image, typologically classified as 4 Borki-type blades, 8 triangles and 4 likely triangles (Sulgostowska & Hoffman, 1993).

The chronological position of the Tłokowo point was earlier determined on the basis of contextual analyses, typological inference vis-à-vis the flint insets and direct radiocarbon dates obtained from peat layers. As a result, the artefact was assigned to the Kunda complex and dated to the Preboreal (Schild et al., 2003; Sulgostowska & Hoffman, 1993). Based on the same premises, some researchers shifted the relative age forward to the Boreal period, dating it to ca. 9300 cal BP (Hartz et al., 2010). Currently, the point is in the collection of the Archaeology Department of the Museum of Warmia and Mazury in Olsztyn (inv. no. MMA 1730). Recently, a separate paper on the Tłokowo point, including the radiocarbon date from this dating program, has already been published (Osipowicz et al., 2020).

Other Radiocarbon Dates and Summed Probability Distributions

In order to draft a more comprehensive picture, we also gathered all readily available radiocarbon dates from the study area with a secure connection to slotted bone tools (closed contexts, see SI 2). We divided the dates into three classes according to their evidential strength in relation to dating inset bone tools: (1) direct date of pitch or collagen, (2) date from a closed context (burials) and (3) short-term site contexts *i.e.* contextual dates from excavation units that suggest a relatively short period of formation. Contexts containing only microliths/microblades were consequently left outside of this study, as were dates from slotted bone tool-bearing horizons/layers showing long

accumulation spans. Corrections for reservoir effect were applied according to the original publications, and where possible, dates on terrestrial animal bone and bast were preferred over dates on human bone and pine bark from the same context. We then used the radiocarbon data to interrogate the temporal distribution of slotted bone tool use in the study area by calculating three summed probability distributions (SPD) based on the radiocarbon date classification (SPD-A: classes 1, 2 & 3, SPD-B: classes 1 & 2, and SPD-C: class 1) employing the *Sum* function in OxCal 4.4.2 (Bronk & Ramsey, 2020). Dates for SPD-A and SPD-B were aggregated per context using a 200-year bin size combining all dates within a bin with the *R_Combine* function of the same program, to represent a single date in the SPD. Finally, we visually compared the SPD:s to the NGRIP $\delta^{18}\text{O}$ data and local temperature proxy curves from the studied region to detect possible correlations between temperature and slotted bone tool use (Fig. 3).

Results

Radiocarbon dating results are presented in Table 2. The success rate of pitch dating was high with 18 of the 19 samples sent for dating yielding results deemed reliable based on the find context. The two dates made separately on pitch deriving from the hafting mechanism and the slot of Minino 2 Y5: 193 are near-identical, suggesting that birch bark pitch samples give consistent and reliable results.

The summed probability distributions SPD-A, SPD-B and SPD-C are plotted in Fig. 3 together with four temperature reconstructions: the NGRIP $\delta^{18}\text{O}$ temperature proxy data and three pollen-based reconstructions from the study area. The radiocarbon dataset resulted in 61 dates in 45 bins from 31 sites in SPD-A and 47 dates in 36 bins from 22 sites in SPD-B. In SPD-C, every date represents a single directly dated artefact, with two dates from the same artefact combined in only one case, resulting in 38 cases from 39 dates. In Fig. 4, the dates are represented in a geographical (west-east) order to illustrate their spatio-temporal positioning.

Discussion

Some of the earlier assumptions concerning the chronological position of the sampled implements were shown to be questionable by the radiocarbon dates presented here (Table 3). Most markedly, the Karacharovo point and the harpoon from Zamoštje 5, assumed to date to the Late Pleistocene, turned out to date to the Early Holocene, while the Tłokowo point, earlier assigned to the Early Holocene, turned out to belong to the Late Holocene. These results are not contradicted by the find contexts, as the Karacharovo point is a stray find and the discrepancies between contextual and radiocarbon dates in the case of Zamoštje 5 and Tłokowo are easily explained by later deposition into lacustrine/riverine sediments.

Together with the other radiocarbon dates on inset bone tool technology in the studied area (our categories 1–3, SI 2), the new dates demonstrate substantial longevity of the technological concept in northern Europe and the East European Plain. The Late Pleistocene dates from Minino 2 are the earliest for inset bone implements in this part of Europe, but in the same broad timeframe as the inset technology of the Eastern

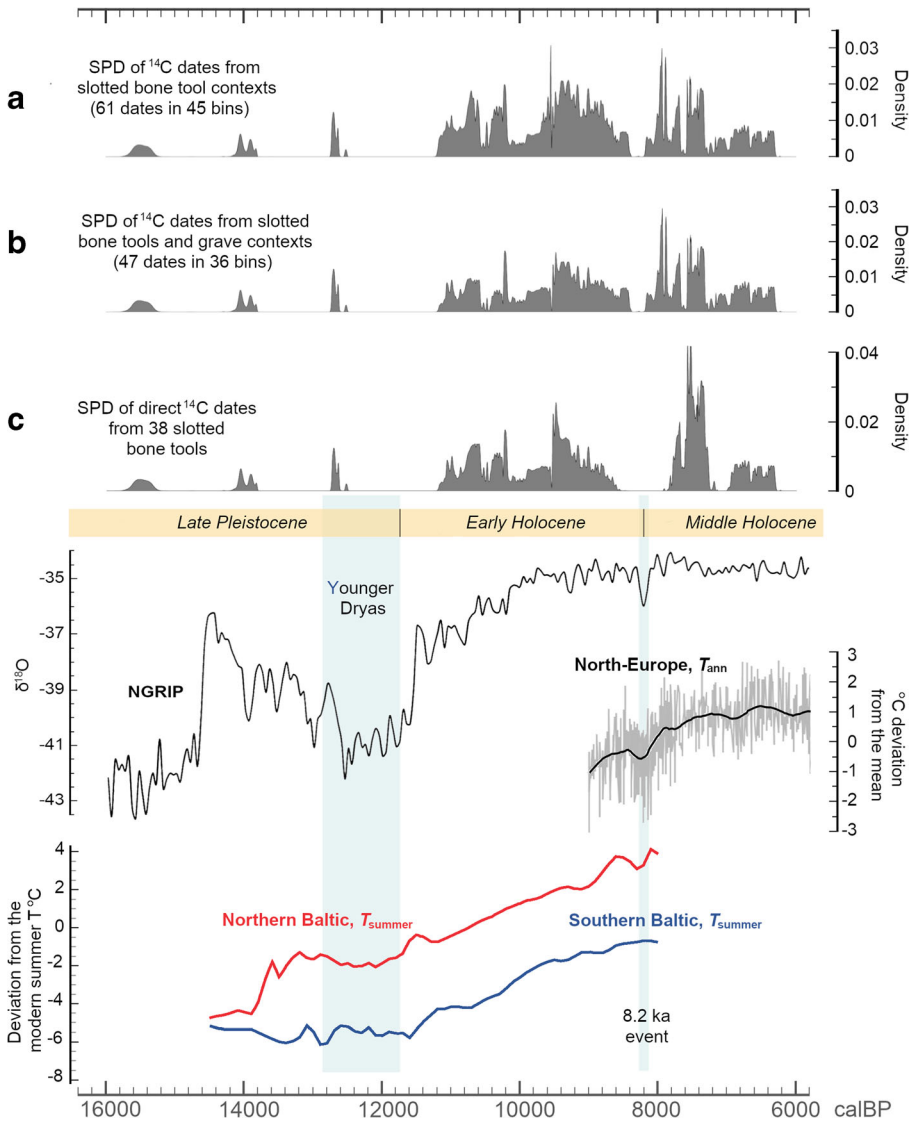


Fig. 3 Top, summed probability distributions of radiocarbon dates from the study area: **a** directly radiocarbon-dated slotted bone tools and radiocarbon-dated slotted point contexts aggregated per context using a 200-year bin size (SPD-A); **b** directly dated slotted points and grave contexts aggregated per context using a 200-year bin size (SPD-B); and **c** directly dated (pitch or collagen) slotted bone tools. Bottom: NGRIP $\delta^{18}\text{O}$ variation (Rasmussen et al., 2006), North-European pollen-based stacked annual mean temperature (Seppä et al., 2009), and pooled-based reconstructions of summer temperatures in the Northern Baltic (Estonia & Latvia) and Southern Baltic (Belarus & Lithuania) regions (Veski et al., 2015). The borders between Late Pleistocene and Early and Middle Holocene are indicated according to the International Commission of Stratigraphy Chronostratigraphic Chart (www.stratigraphy.org). See SI 2 for data used to form the SPDs

Gravettian of the Russian Plain (Amirkhanov, 1998; Amirkhanov et al., 2009; Praslov & Rogachev, 1982), early finds of slotted bone tools from western Siberia (e.g. Abramova, 1984; Abramova et al., 1991; see also Knutsson et al., 2016), and

Table 2 The radiocarbon dating results. Map = site number in Fig. 1

Country	Site	Number	Lab. code	Date	±	cal BP	Median	Map
Slotted (inset) bone tools								
Russia	Minino 2	Y2: 1	AAR-27604	12946	61	15721-15250	15473	2
Russia	Minino 2	Y5: 123	AAR-27607	12115	58	14135-13782	13997	2
Russia	Minino 2	Y5: 114	AAR-27603	10653	47	12708-12553	12631	2
Russia	Minino 2	Y5: 172	AAR-26567	9613	50	11169-10768	10944	2
Belarus	Aziarnoje 2B	KP 5773: VP 373	AAR-28506	9545	37	11086-10710	10926	9
Russia	Karacharovo	-	AAR-26569	9485	35	11068-10590	10734	1
Russia	Minino 2	Y5: 193 (slot)	AAR-26568	9206	35	10491-10253	10358	2
Russia	Minino 2	Y5: 193 (handle)	AAR-27606	9173	43	10486-10237	10333	2
Russia	Minino 2	Y5: 152	AAR-27605	9200	45	10496-10247	10357	2
Belarus	Aziarnoje 2B	KP 5788: VP 399	AAR-28507	9026	41	10251-9972	10209	9
Estonia	Lammasmägi	AI 3359: 173	AAR-26570	8789	50	10146-9601	9814	15
Estonia	Lammasmägi	AI 3359: 189	AAR-27602	8455	40	9532-9429	9483	15
Estonia	Lammasmägi	AI 3410: 561	AAR-26571	8446	48	9537-9325	9475	15
Belarus	Aziarnoje 2B	KP 5788: VP 403	AAR-28508	8255	42	9405-9090	9235	9
Estonia	Pämu river	AI 2761: 5	AAR-26573	8252	41	9404-9040	9229	14
Estonia	Pämu river	AI 2761: 6	AAR-26572	8018	49	9023-8662	8881	14
Poland	Tłokowo	MMA 1730	AAR-27601	6492	38	7472-7320	7397	11
Belarus	Michnievičy	-	Unsuccessful					10
Harpoon head								
Russia	Zamoštje 5	Zam 5: 74	AAR-27608	8724	52	9890-9550	9690	4

Magdalenian sites characterised by composite tools with insets in western Europe (*e.g.* Langlais et al., 2015), as well as the Asian microblade industries associated with slotted bone tools (*e.g.* Elston & Brantingham, 2002).

The results also lend strength to the notion that most of the slotted points from northern Europe and the East European Plain are linked to the rapid Early Holocene climatic warming and its downstream environmental correlates. This result warns against causally linking microblade use and slotted inset bone tools to increased environmental pressure from climatic cooling without closer analysis. In fact, the broad correlation of the dates with the haphazard warming trend beginning at around 16,000 cal BP after the end of the Last Glacial Maximum would instead suggest that this kind of technological constellation may be linked to warmer, wetter and more forested environments, or to risks generated by changing environmental regimes independently of whether such change is towards colder or warmer situations. By the same token, do note also the clear gap in the SPDs coinciding with the 8.2 ka cold event that caused a ~200 year-long cold snap in the study area and beyond (*e.g.* Seppä et al., 2009), although at this point, any possible causal relationship between the lack of dates and the cold event remains to be demonstrated.

The early dates from Minino 2 indicate that inset bone tools were already in use in the Moscow region when Norway, Finland, most of Sweden and Estonia were still covered by the Scandinavian Ice Sheet. Their use continued in this region at least into

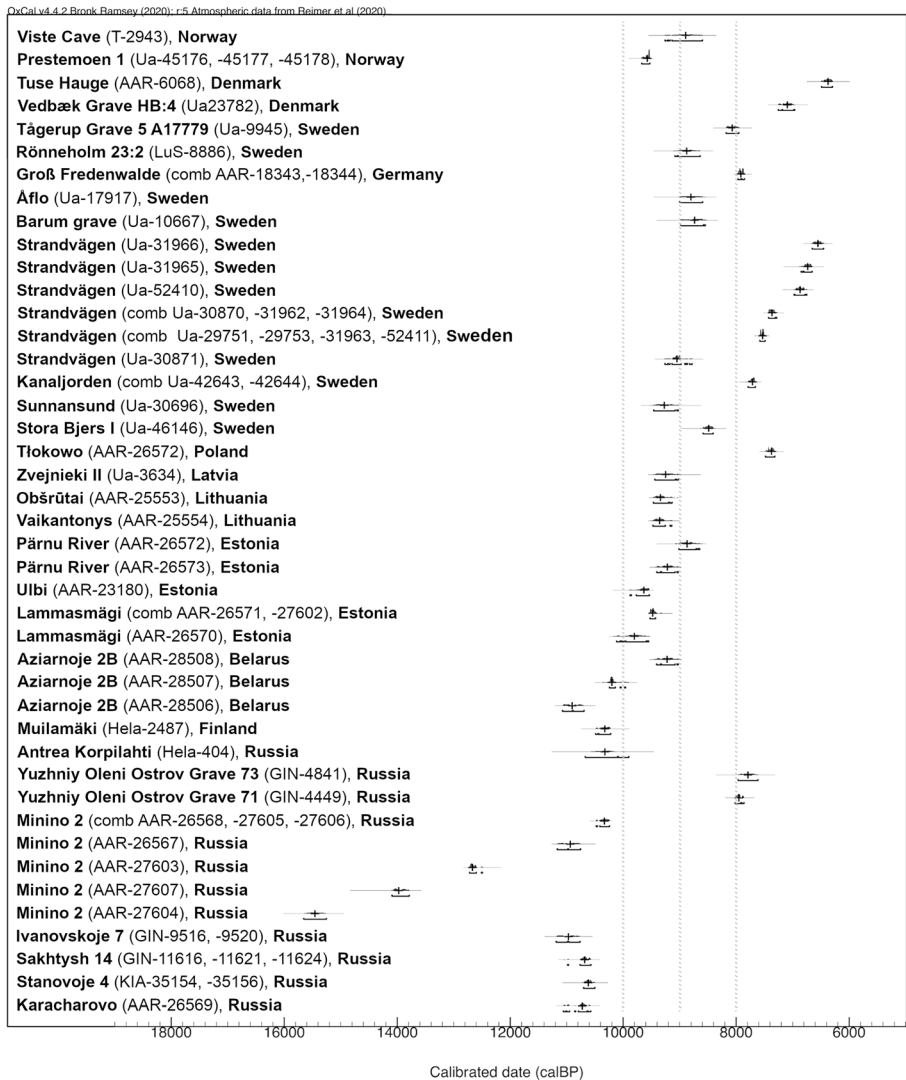


Fig. 4 Calibrated radiocarbon date plots (normalized areas) of slotted point contexts and stray find slotted points in the study area ordered according to the longitudinal coordinate of the find location. Data from Apel et al. (2017), Bergsvik & David (2015), Børnevad et al. (2019), Brinch Petersen (2015), Edgren (1997), Eriksson et al. (2003), Gummesson & Molin (2019), Gurina (1956), Hartz et al. (2010), Ivanovaitė et al. (2018), Jungklaus et al. (2016), Jussila et al. (2012), Kjällquist (2001), Kjällquist et al. (2016), Larsson (2005), Miettinen et al. (2008), Oshibkina (1989), Persson (2014), Philippsen et al. (2019), Sjöström & Hammarstrand Dehman (2010), Skakun et al. (2011), Sten et al. (2000), Vang Petersen (2001), Zaretskaya et al. (2005), and this study. See SI 2 for radiocarbon dates and coordinates

the local Final Mesolithic period (ca. 7900–7700 cal BP) that marks the end of inset bone tool use at the Zamoštje 2 site, located in the vicinity of Minino 2 and Zamoštje 5 (Lozovskaya & Lozovski, 2013).

In light of earlier data and the new radiocarbon dates, and despite the mostly unfavorable soil conditions for the preservation of osseous materials, slotted point

Table 3 The expected chronological position (CP) of the radiocarbon-dated slotted tools against their verified chronological position according to the radiocarbon dates. LP= Late Pleistocene, EH= Early Holocene, MH=Middle Holocene. See Fig. 3 for chronological division

Site	Number	Expected CP	C14 / cal BP	CP after C14
Karacharovo	-	LP	11068–10583	EH
Minino 2	Y2: 1	LP/EH	15679–15274	LP
Minino 2	Y5: 114	LP/EH	12734–12505	LP
Minino 2	Y5: 123	LP/EH	14135–13782	LP
Minino 2	Y5: 152	LP/EH	10496–10247	EH
Minino 2	Y5: 172	LP/EH	11177–10765	EH
Minino 2	Y5: 193	LP/EH	10487–10248	EH
Zamošnje 5	Zam 5: 74	LP	9893–9546	EH
Aziarnoje 2B	KP 5773: VP 373	EH/MH	11084–10701	EH
Aziarnoje 2B	KP 5788: VP 399	EH/MH	10250–9965	EH
Aziarnoje 2B	KP 5788: VP 403	EH/MH	9414–9031	EH
Lammasmägi	AI 3359: 173	EH	10124–9557	EH
Lammasmägi	AI 3359: 189	EH	9537–9421	EH
Lammasmägi	AI 3410: 561	EH	9538–9321	EH
Pärnu river	AI 2761: 5	EH	9410–9031	EH
Pärnu river	AI 2761: 6	EH	9019–8650	EH
Tłokowo	MMA 1730	EH	7481–7316	MH

use is now detected in the Eastern Baltic region and Belarus almost throughout the Early Holocene, ca. 11,000–8000 calBP, with the earliest slotted tools in Russian and Finnish Karelia contextually dated to ca. 10,800–10,400 cal BP, *i.e.* to the Early Holocene pioneer colonisation phase in Karelia (Kriiska et al., 2016; Rostedt & Kriiska, 2019). Later use is indicated by the two points dated to Middle Holocene from south-eastern Baltic, as well as slotted implements found in graves in Yuzhniy Oleni Ostrov (Russian Karelia), dated to ca. 8000–7600 cal BP (see also Schulz, 1996 for a possible late find from Finland).

In southern Scandinavia, the use of slotted bone tools seems to peak late, in the local Middle Mesolithic Kongemose culture, ca. 8400–7400 cal BP (Sørensen, 2017). To this period belong also three other slotted tools from southern and south-eastern Baltic, the Tłokowo point, a contextually dated dagger from Groß Fredenwalde (Germany) and a directly dated slotted point from an unknown find location in S-E Baltic. An exception to the relatively late dates is the stray find point reported by a seller of antiquities in the early 1800s to have been found near Wiesbaden in Germany, and dated to the Early Holocene (10,180–9690 cal BP, see SI 2). Unfortunately, the other slotted implements found in Poland and Germany *i.e.* slotted tools reported from German museum collections in the late nineteenth century and linked by Friedel (1872) to the Swedish and Danish Kongemose finds, and the ten slotted points found prior to WW2 from Poland but destroyed during the war remain undated.

The earliest dates of slotted inset artefacts thus are from the eastern part of the study area, corresponding to the model that people and technological concepts dispersed from

the East European Plain—perhaps ultimately from the Far East—towards the west in the early Postglacial, and that this dispersal had a major influence on the tool-kit composition of the northern European Early/Middle Mesolithic (e.g. Bergsvik & David, 2015; Damlén, 2016; Günther et al., 2018; Kashuba et al., 2019; Knutsson et al., 2016; Manninen et al., 2021; Sørensen et al., 2013). However, resolving the issue of whether composite inset technology should primarily be seen as a local adaptive response to changing environmental conditions or as a culture-historically contingent marker of particular communities or constellations of practice (cf. Stahl & Roddick, 2016) demands a consideration of the wider technological context of their production and use.

Despite the long period of occurrence, *chaîne opératoire* analyses of Early and Middle Mesolithic bone tool technology in Europe indicate rather uniform ways (the so-called Z-method, Bergsvik & David, 2015) of bone tool production, including slotted points, in most of the area discussed here ca. 9500–8000 cal BP. This suggests a shared ancestry in production methods, although such a perspective would also delineate a break or border in such traditions between the north-eastern sections of the study area and the area covering present-day Denmark and northern Germany (where the so-called D-method was in use; see Fig. 1; Bergsvik & David, 2015; David, 2009). In marked contrast to the homogeneity suggested for technologies used to manufacture the osseous part of inset tools, the lithic blade and flake production technology that was used in the area during the Early Holocene was diverse, up to the point that, on the basis of lithic artefact typology, the record has been divided into a heterogeneous suite of archaeological cultures that supposedly occupied and evolved across northern Europe and the East European Plain (but see Reynolds & Riede, 2019 for a recent critique of such definitions).

On a more general level, the insets used in slotted bone tools varied from backed blade segments and microblades on microcrystalline raw materials of good flakeability to macrocrystalline quartz flake fragments, the latter strategy considered advantageous when moving into regions scarce in tool-stone of suitable quality (e.g. Knutsson et al., 2016; Kriiska et al., 2016; Tsvetkova, 2017; see also Manninen & Knutsson, 2014). However, core treatment practices show that on the eastern side of the Baltic Sea, Early Mesolithic reduction of flint and other high-workability tool-stone can be divided into three main strategies, consisting of conical or sub-conical blade core, narrow-face blade core and irregular core reduction (Hertell & Tallavaara, 2011 and references therein). The conical blade core concept included intensive rejuvenation of the core platform, which resulted in constant reduction of blade length and width during the core reduction process and consequently to from up to 20 cm long blades to what can be called microblades (Sørensen et al., 2013). Its use seems to correlate with high mobility (Hertell & Tallavaara, 2011). The narrow-face cores yielded blades of more uniform dimensions and can be considered a standardized serial production strategy suited especially for inset production (Hartz et al., 2010). The dataset analysed by Hertell and Tallavaara (2011) shows a rising trend for narrow-face core use between ca. 10,600 and 9600 cal BP in north-eastern Europe, after which the use of both conical and narrow-face blade reduction strategies seems to have markedly diminished in favour of flake production from irregular cores.

In Scandinavia and other parts of north-western Europe, the handle-core concept, dating to ca. 9000–7400 cal BP (Olofsson, 2002; Söderlind, 2018), is a reduction

concept in many ways reminiscent of the serial bladelet production from narrow-face cores. Handle-core technology is also strongly linked to the use of inset bone tool technology (Larsson, 1990; Hartz et al., 2010). In this context, it is noteworthy that especially in Middle and Northern Sweden, the raw material for handle-cores was often macrocrystalline vein quartz (e.g. Molin & Wikell, 2009), a raw material known to produce a large proportion of waste compared to, for instance, chert or flint (Tallavaara et al., 2010). Moreover, finds of slotted bone points with inset flakes and flake fragments of vein quartz in Sweden and Finland (Knutsson et al., 2016; Manninen et al., 2018; Pälvi, 1920) indicate that also a strategy utilizing insets produced as a part of flake core reduction was employed. Evidently, the inset raw material or the reduction methods used to produce the insets were not decisive elements in this technology in our study area, although future experimental work could substantiate to what degree inset standardization impacts function and re-tooling costs.

Tool and weapon systems in principle are costlier to produce the more parts and raw materials they require. It is often assumed, therefore, that in addition to durability provided by the osseous part of the composite tool, lithic organizational dimensions such as reliability (*sensu* Bleed, 1986) and efficiency through standardization, as well as intensification of lithic raw material use as a response to high mobility, were the main drivers for the adoption of inset bone tool technology (cf. Elston & Brantingham, 2002). However, the variety of ways Early Holocene slotted bone tool technology and associated lithic technology was organized in northern Europe and the East European Plain suggests a much wider set of organizational and other dimensions linked to inset bone tool technology. Intensification of raw material use may very well have been one important dimension in serial production of blades, but the presence of the much more wasteful and generalized conical blade production, employing the same high-quality raw materials at the same sites, suggests that at least in these cases, the scarcity of raw material cannot be considered the main reason for inset production from narrow-face cores.

The rapidly warming Postglacial climate and the colonisation of previously uninhabited areas at the margins of the retreating Scandinavian Ice Sheet offer in our case the possibility to study the use and cultural evolution of a multicomponent technology in variable environments within a comparatively large area, and with an, at the time, shared history of material culture traits. Chatters (1987) regards human adaptation as a multidimensional mesh in which adaptive choices form separate axes intersecting in ways affected by a variety of interdependent choices. In such a view, the variability detected in lithic technology related to slotted implements on the one hand, and the relative uniformity of the slotted osseous parts of the composite tools on the other, can be considered adaptive choices operating within a framework of broadly shared cultural history.

The use of vein quartz for microblade production from handle-cores, as well as flake fragments of the same material, emphasises that although in many cases, probably interconnected, inset bone tool use, raw material selection and microblade production are components positioned on different axes of the mesh of organizational choices—and that these components, and the drivers for their combination in different situations, may have differed substantially between communities and even community members (Fig. 5). Organizational dimensions affecting the non-lithic parts of a composite tool affect also its lithic components. A composite tool therefore also implies a composition

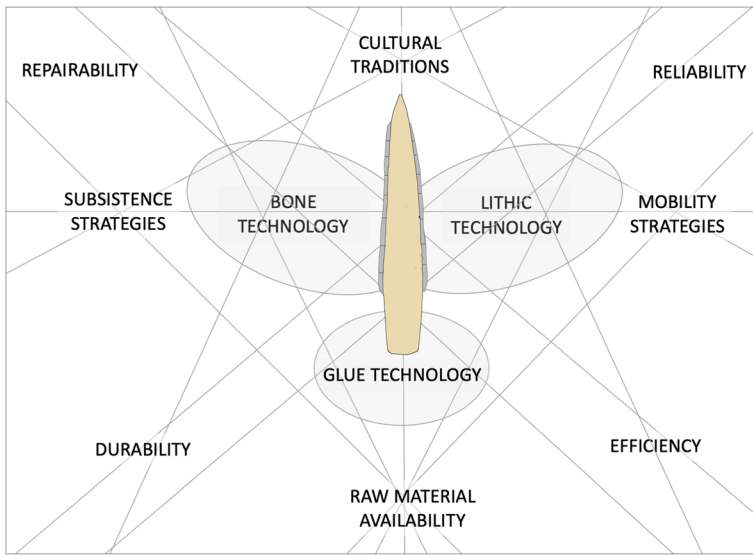


Fig. 5 Some dimensions in the n -dimensional mesh of technological choices affecting the use and manufacture of slotted bone tools in any given prehistoric situation. Many of these dimensions intersect separately in the different components of the composite tool, while at the same time, the locus of intersection in these separate technologies is also situational and affected by the whole

of organizational dimensions that are not necessarily in unison and that are not directly comparable to single-raw-material technologies. Such dimensions affecting the manufacture, use and repair of slotted bone tools are to be found, for example, in the restrictions affecting the design of the osseous part of the implement, the availability of suitable osseous raw materials and the availability and workability of adhesive materials, but also in the flexibility provided by the osseous support when selecting suitable lithic edge components.

We therefore argue that there is no one-to-one mechanistic link between microblade technology and slotted bone tools, suggesting that inset bone tool technology is a technological strategy that should not be considered an *a priori* extension of microblade technology, but rather as a technology in its own right, susceptible to situational variation, modification and evolution. Accepting this, its occurrence in diverse temporal and spatial settings (*e.g.* Abramova et al., 1991; Buvit & Terry, 2011; Fedje et al., 2008; Helvig et al. 2008; Langlais et al., 2015; Okladniukov, 1950; Pétilion et al., 2011; Savchenko & Zhilin, 2018; Tomasso et al., 2018; Tsvetkova, 2017; Zhilin, 2019) does not imply similarity in the associated lithic technology or environmental drivers.

Conclusions

In northernmost Europe and the East European Plain, the available data does not reveal a clearly defined trajectory leading to a superficially similar slotted bone tool technology. In fact, what the data suggest is that no single trajectory is there to be found, not in our study area, nor for the use of slotted tool technology in general.

On the basis of our dating program and other radiocarbon dates, the earliest inset tools in our study area are of Late Pleistocene date, and a more or less continuous use can be tracked through the rapidly warming Early and Middle Holocene. During this time period, slotted bone tool technology is associated with a variable set of lithic core treatment practices and ways of inset production. Hence, explanations for the use of inset bone tools based on monolithic models of reliability, efficiency and the like ultimately fail. They do serve as robust starting points and end-members along the spectrum of technological choices that are actually faced and taken by prehistoric groups, but the pattern we see in our study area reveals historical specificity and path-dependence rather than clear patterns of selective or convergent evolution.

Although the data at hand do not allow tracing cultural transmission of the technology or continuity of cultural traditions, the spread of the technology to the west following the retreat of Scandinavian Ice Sheet, and its occurrence in the same area where also eastern Early Mesolithic blade production technology and lithic tool types spread during early Postglacial pioneer colonisation (Manninen et al., 2021; Sørensen et al., 2013) do suggest that knowledge of the technological concept in the area first arrived in the footsteps of the first pioneers from the east and was later transmitted and adopted with modifications in favourable circumstances, rather than re-invented multiple times.

Our results additionally suggest that a bottom-up approach is needed in order to understand why slotted bone technology and related microlith technology were used in different parts of the study area and beyond, as the reasons behind their use seem to be contingent, situational and variable. That said, evolutionary models and methods that seek to use the specific technological traits in parallel with notions of adaption (the tools of the so-called comparative method *e.g.* Collard & Shennan, 2008; Mace & Pagel, 1994; Manem, 2020; O'Brien et al., 2008) could be helpful in eventually more fully understanding the processes that shaped this technology.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10816-021-09517-7>.

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