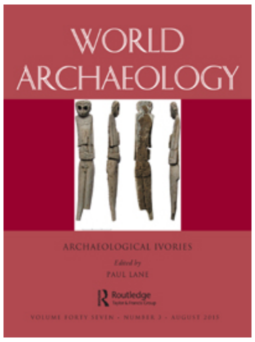

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Abstract

Walrus-tusk ivory and walrus-hide rope were highly desired goods in Viking Age north-west Europe. New finds of walrus bone and ivory in early Viking Age contexts in Iceland are concentrated in the south-west, and suggest extensive exploitation of nearby walrus for meat, hide and ivory during the first century of settlement. In Greenland, archaeofauna suggest a very different specialized long-distance hunting of the much larger walrus populations in the Disko Bay area that brought mainly ivory to the settlement areas and eventually to European markets. New lead isotopic analysis of archaeological walrus ivory and bone from Greenland and Iceland offers a tool for identifying possible source regions of walrus ivory during the early Middle Ages. This opens possibilities for assessing the development and relative importance of hunting grounds from the point of view of exported products.

Keywords

Walrus; Greenland; Iceland; Norse; zooarchaeology; proto-world system; lead (Pb) isotopes.

Introduction: was it for walrus?

The Norse expansion into the North Atlantic is remarkable testimony to the maritime transformation of the early medieval world. Sailing technology and skills developed in the ninth and tenth centuries CE in Scandinavia allowed the settlement of diaspora communities in Iceland and Greenland, with further foraging into the North American continent which had impacts upon

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both human communities and island ecosystems that persist to the present day (Vésteinsson, McGovern and Keller 2002). This diaspora is a legacy of the ‘florescence of piracy, trade, migration, conquest and exploration across much of Europe’ which defines the Viking Age (Barrett et al. 2010, 289). The rising impact of long-range seafaring by the Norse settlers, traders and raiders can be seen as part of a global pattern of the late first millennium CE. Aspects of the maritime expansion that is associated with the Viking Age in the northern seas of Europe are paralleled by developments in other maritime regions of the world in the same period, e.g. in eastern Africa (Sinclair 2007; Sinclair, Ekblom and Wood 2012) and in insular Southeast Asia (Heng 2009; Krahl et al. 2010; Miksic 2013). Seafaring catalysed the creation of new areas of settlement and diaspora communities, and created sustained networks of interaction that introduced new regions and products into existing exchange cycles. As a consequence, the world of the early Middle Ages came to be integrated by flows of material culture that reached almost a global scale, as illustrated for example by the spread of ninth-century Abbasid (Islamic) coins from eastern China (Guy 2010) to Iceland (Blackburn 2005).

The Norse involvement in such networks is evident in the continued relations between the much dispersed North Atlantic settlers and their parent societies after the ninth century AD. Urban centres in Scandinavia and in the British Isles were indispensable to the life-style of the Iceland and Greenland settlers as suppliers of culturally important manufactured products and commodities, including iron. In return, the settlers had access to a range of Arctic products that were prized further south: hides, furs, eider down and, perhaps most notably, tusk ivory from walrus (*Odobenus rosmarus L.*). From the beginning of settlement in Iceland and Greenland, exploitation of natural resources from the Arctic hinterland included walrus hunting (Arneborg 1998; Lucas 2008). Several authors (Vésteinsson et al. 2006; Keller 2010; Einarsson Bjarni 2011) have suggested that the first exploration and settlement of both Iceland (*c*. 850–75 CE) and Greenland (*c*. 980–90 CE) had an initial stimulus from exploiting the walrus, then native to both islands. This is supported by the observation that the use of walrus ivory can be traced archaeologically in finds from Scandinavia, the British Isles and continental Europe, particularly in the eleventh to thirteenth centuries, corresponding to the heyday of Norse settlement in Greenland (Roesdahl 2003). Walrus ivory is recorded as workshop debris in major trading towns such as Dublin, Trondheim, Bergen, Sigtuna, Lund and Schleswig, and in art objects and ornaments (Roesdahl 2005), the most famous in the British Isles being the Lewis chessmen, a group of ninety-three twelfth-century chess pieces discovered in 1831 on the Isle of Lewis in the Outer Hebrides, Scotland (Robinson 2004). Figure 1 provides a location map for place names mentioned in this article.

The extent to which long-distance flows of moveable wealth (such as walrus ivory) had a sufficient scale and intensity in the early Middle Ages to be a potential causal dynamic for major social change (such as the Norse North Atlantic settlement) remains a subject of debate. Critics have downplayed the impact of Viking Age and early medieval long-distance trade and exchange (Wickham 2005, 818ff.; Hodges 2012, 121). In compliance with this view, a traditional assessment (endorsed by medieval saga writers) ascribes the incentive for settlement in Iceland and, by extension, Greenland, to a quest for *landnám* – the search for suitable farmland for a growing population. The issue of Norse trade in walrus ivory brings these matters to a head. On the one hand, the marginal farming potential offered by subarctic Iceland and low arctic Greenland stretches the ‘farming hypothesis’ to its limit. On the other hand, the ‘trade hypothesis’ involves the no less remarkable assumption that societies at the far ecological and

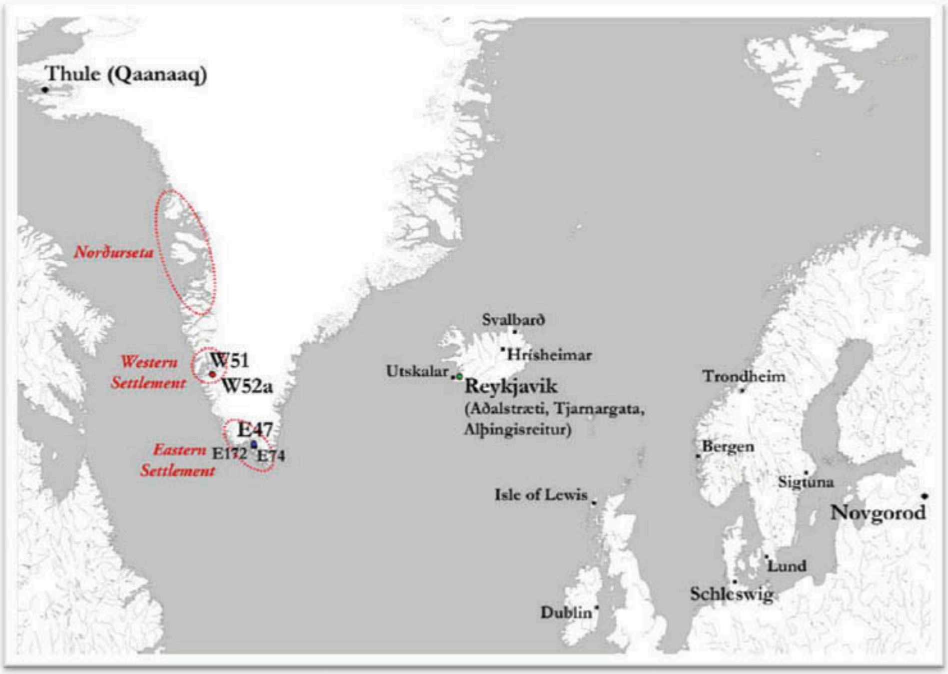

Figure 1 Location map of areas mentioned in the text (courtesy of Christian K Madsen).

cultural margin of Europe were essentially conditioned by exchange cycles involving sea journeys of more than 3,000km – equivalent to the distance from Barcelona to Moscow. Christian Keller recently summed up the puzzle as to why the Norse colonized Greenland and pushed into high arctic Norway in the late tenth century CE: ‘Was it a desperate search for farmland at the margins of the known world, or was it a market-driven economic strategy applied to sub-arctic territory?’ (Keller 2010, 1).

This article presents new evidence and offers a framing interpretation, which outlines a route map for resolving this question. New finds of walrus bone and ivory in early Viking Age contexts in Iceland suggest exploitation of nearby walrus for meat, hide and ivory that appears to have driven local Icelandic walrus populations to extinction. New Greenlandic archaeofauna from both the Eastern and Western Settlements continue to suggest a very different specialized long-distance hunt of the much larger walrus populations in the Disko Bay area that mainly brought ivory and hide rather than meat to the settlement areas and eventually to European markets. New lead isotopic analysis of archaeological walrus ivory and bone from Greenland and Iceland shows distinct and consistent variation in the lead isotope signatures in samples with a different geographical origin, and so offers a tool for identifying different regional sources of walrus ivory during the early Middle Ages. This opens possibilities for assessing the development and relative importance of different hunting grounds from the point of view of exported products. This article thus presents an overview of existing archaeological evidence for Norse North Atlantic walrus hunting and the initial results of lead isotope analyses aimed at sourcing walrus ivory to geographically specific past walrus populations. Collaborative interdisciplinary work is ongoing, so this presentation is necessarily a report of work in progress rather than a final statement.

New field results: Iceland

Walrus bones have been recovered in many parts of Iceland in both archaeological and non-cultural contexts and it appears that walrus have both visited Iceland as single individuals (as they do today) and probably established breeding colonies in several parts of the island in the past (Petersen 1993). Walrus feed on shellfish beds often located on submerged moraines or shallow embayments, and favour rocky ledges for hauling out. In Greenland, the combination of these seascape features is associated with historic records of persistent walrus concentrations, and these conditions are also present in many areas along the coast of Iceland, especially in the north and west. While walrus can be hunted in the water it is far safer and easier to target concentrations of animals on land while sleeping and nursing young. Early modern historical accounts of European walrus hunting in Spitzbergen, Greenland and the Gulf of St. Lawrence emphasize group attacks on hauling out places, and it is likely that Norse hunters followed this pattern (discussion in McGovern 1985a). There are medieval accounts of Icelanders hunting walrus and the medieval law code *Grágás* refers to both walrus meat consumption and hunting (see *Grágás* 29, 32, 354, 355, 366; Kristjánsson 198, 93–7 for a list of walrus hunt accounts). Chance finds of walrus bones during harbour dredging and construction work suggest they lived along the west coast of Iceland, with many finds coming from the embayment of Faxaflói (with a concentration of chance finds around Akranes) and Breiðafjörd to the north. The old place name for the Reykjanes peninsula, Rosmhvalanes ('walrus peninsula'), again suggests early concentrations along the west coast. Significantly, some farm names, Hvallátur and Hvallátrar, indicate hauling out places, where walrus are most vulnerable to human hunters (Kristjánsson 1986, 93; Thorláksson in Orri, Þórláksson and Einarsson 2006, 34–5; Pierce 2009, 57).

In the past decade, zooarchaeological evidence of walrus hunting in Iceland definitely pre-dating the traditional date for first settlement of Greenland (*c.* 985 CE) has accumulated from archaeological excavations in different areas (Einarsson Bjarni 2011). The best-known archaeological walrus-bone finds come from beneath the modern capital city of Reykjavik, which had also seen the chance finds of at least eleven walrus bones in earlier times (Thorláksson in Orri, Þórláksson and Einarsson 2006, 34). Three nearby areas under modern downtown Reykjavik have produced walrus remains, all probably representing elements of the same early settlement. In 1944, construction work at Tjarnargata 4 uncovered a deeply buried concentration of bone which was curated by the Icelandic Natural History Institute and was found to contain three walrus ribs, one of which came from a very young individual (Amorosi 1996). Great auk and pig bones from the same context suggest an early date for this archaeofauna, and it has been used to characterize the initial economy of the early settlers in Reykjavik (Orri, Þórláksson and Einarsson 2006).

Three tusks from at least three different large mature walrus were recovered in 2001 from excavations by the Institute of Archaeology, Iceland (FSÍ), within the hall at Aðalstræti 14–18, a short distance from the 1944 finds (Roberts 2001). This hall is above the 'Landnám' tephra of 871±2 (Grönvold et al. 1995) and is securely radiocarbon dated to the late ninth–early tenth centuries CE (Sveinbjörnsdóttir, Heinemeier and Guðmundsson 2004). These once-complete walrus tusks were very competently extracted from large fully mature walrus skulls and may well represent unused craft material or a deliberate 'closing deposit' on abandonment of the hall sometime in the tenth century. The extraction method is well documented from extensive finds of walrus-skull fragments from Greenland (McGovern 1985b; McGovern et al. 1996).

Immediate post-mortem tusk extraction or sawing at the gum line tends to break the tusk or at least lose a major portion of the roots. Ivory, which is composed of dentine (principally hydroxylapatite $Ca_{10}(PO_4)_6(OH)_{2)}$) is present within the tooth root as well as the supragingival tooth. The more effective extraction method involved the careful breaking out of the deeply rooted tusk from the dense maxillary bone surrounding it. This is best accomplished a few weeks after the walrus has been killed to allow for partial decomposition of soft tissues around the tusk root. Then the extraction was carried out with narrow bladed cutting tools (probably chisels or similar implements), by carefully breaking apart the root cavity to allow full extraction of the undamaged tusk root. The tool marks observed above the gum line of the best preserved specimen (AST 01 SF 355 747 NW) clearly reflect this careful approach, which in this case was completely successful in preserving the large (and potentially valuable) tusk root intact. This competent extraction suggests that the first settlers included craft workers experienced in handling walrus ivory and in walrus butchery (see discussion in Orri, Þórláksson and Einarsson 2006), begging the questions 'When and where did they acquire this knowledge?'.

The most recent archaeofauna containing walrus comes from the multi-period downtown site at Alþingisreitur, close to the lots containing the Aðalstræti 14–18 and Tjarnargata 4 archaeofauna, with the earliest activity phase, Phase IV, dated to 871–1226 CE (Pálsdóttir 2010, 13–15). One walrus cranial fragment and one vertebra were identified from this phase. The results of a later aDNA analysis of the site's marine mammal bones revealed another walrus vertebra from Phase IV and a partial pelvis with cut marks as also from walrus phased to 1226–1500 CE (Buckley et al. 2014, 639). The coarse chronological resolution of the Alþingisreitur excavation and the potential residuality of the late-phase walrus pelvis complicate direct temporal correlation with the nearby early settlement age contexts, but the presence of walrus bone in what seems to have been a combined sheet midden and outdoor activity area is at least suggestive of walrus butchery on site or very nearby.

In 2011, additional walrus-bone elements were identified built into the exterior wall of the Aðalstræti 14–18 Viking Age structure preserved as part of *The Settlement Exhibition Reykjavík 871+/-2* museum built around the excavated structure. These elements comprised a nearly complete walrus vertebral column set into the base of the turf wall and a walrus scapula placed under the corner of the western entry door. Both would have been highly visible from the outside. In neither location would the bone have added structural strength or stability to the wall or door frame (stones such as those used elsewhere in the footings would have been far more durable and effective), and the smaller size and different structure of the walrus skeleton generally make it far less useful for building or tool-making in comparison with whale bone. The potential ritual significance of these walrus bones (whose stratigraphic position in the first stages of construction makes them look like foundation deposits) is apparent, but it is possible that these large bones might equally (or additionally) have served to advertise the walrus-hunting and ivory-preparation skills of the household at Aðalstræti to visitors (Harrison, McGovern and Tinsley in press).

Thus, there are now three collections found in proximity to one another underneath modern Reykjavik that contain walrus remains consisting of both cranial and post-cranial bones of both adults and juveniles. This pattern of bone-element distribution is consistent with predation on walrus hauling out and pupping on beaches fairly close to the point of eventual deposition near the Aðalstræti farm area. The incorporation of walrus bones into the Aðalstræti Viking Age hall and the perhaps deliberate deposition of the three large tusks on abandonment, hints at ritual practices associated with the hunt of these large, dangerous and ivory-bearing sea mammals. Recent excavations at Svalbarð in north-east Iceland, have recovered a very small number of isolated ivory and maxillary fragments in pre-1300 contexts, suggesting that the Icelandic walrus hunt extended beyond the south-west. The early fishing station at Siglunes at the mouth of Siglufjord in northern Iceland has also produced some walrus cranial bones, and this large archaeofauna is still under analysis. The identification of a walrus penis bone (*baculum*) made into a knife handle at the Viking Age site of Hrísheimar in the Mývatn district (datable by tephra to between *c*. 871 and 940 CE) and the find of a heavily worked walrus jaw at the site of Útskálar on the Reykjanes peninsula south of Reykjavik all suggest that much more remains to be learned about early walrus exploitation in Iceland (McGovern et al. 2007; for wider review, see Einarsson Bjarni 2011). Current evidence suggests that walrus hunting and ivory extraction was a significant activity for early settlers in Iceland, and was probably not limited only to the best-known areas of the south-west coast. The downtown Reykjavik archaeofauna all contain substantial amounts of other mammal, bird and fish bone and clearly indicate that the inhabitants were farmers and fishermen as well as hunters of walrus, seals and sea birds, and that the walrus hunt was probably readily integrated into the seasonal subsistence round.

The Icelandic family sagas do not include many references to walrus, although those references that can be found have some interesting implications. A walrus is mentioned in a passage in ‘Kormak’s Saga’ (*Kormáks saga*, early thirteenth century) that tells how the eponymous character Kormak Dolluson set sail, together with his brother Thorgils, from the Miðfjörður region of northern Iceland with merchant wares bound for Norway. As the voyage takes place during the reign of Haakon the Good, the narrative is set not long after the establishment of the Icelandic Free State, *c*. 935–960 CE. The passage in question reports that:

> When the brothers put out from their place of anchorage, a walrus surfaced beside the ship. Kormak fired a weighted staff at it, hitting the animal, so that it sank. People thought they recognised Thorveig’s eyes when they saw it. The animal did not surface from then on; and it was reported of Thorveig that she was dangerously ill, and people say that she died as a result.
>
> (trans. McTurk in Hreinsson 1997)

The walrus here is a conventional figure, a fetch (*fylgja*), in this case of a witch named Thorveig who had cursed the Kormak character, precipitating the central dramatic conflict of the saga. It is clear from this passage that the walrus reference has no real documentary value, as it is a plot device. What is more interesting in this context is the plausibility to the saga’s thirteenth-century audience of a walrus’s appearance in this place and time. The saga does not convey a sense that the animal’s appearance is in any way extraordinary, even though supernatural associations attend it (its specific human eyes identify it with the witch Thorveig). Other references to walrus, or rather walrus-derived goods and commodities, are found in ‘The Saga of Hallfred the Troublesome Poet’ (*Hallfreðar saga Vandræðaskálds*, dating from early thirteenth century), ‘The Saga of the People of Laxardal’ (*Laxdœla saga*, mid-thirteenth century), ‘Bard’s Saga’ (*Bárðar saga Snæfellsáss*, late fourteenth century), ‘The Saga of Ref the Sly’ (*Króka-Refs saga*, late fourteenth century) and ‘The Tale of the Greenlanders’ (*Grænlendinga þáttur*). Nearly all of these references (ed. and trans. in Hreinsson 1997) emphasize the great value of walrus ivory and walrus-hide ship’s ropes and belts as prestige goods, in some cases presented as gifts in order to win the favour of chieftains or royal personages. Reference to a walrus in Iceland (Einarsson 1984) can be found in 'Hrafn Sveinbjarnarson's Saga' (from *Sturlungasaga*, ed. Jóhannesson, Finnbogason and Eldjárn 1946):

> It so happened at Dyrafjord at the spring assembly, when Hrafn was there, that a walrus came on land. People went to attack it, but the whale rushed to the sea and sank, because it was mortally wounded. Later men went in ships and tried to drag the whale on land, but did not succeed. Then Hrafn made a vow to the holy bishop Thomas that if they managed to get the whale he would dedicate the tusks of the whale to him and no sooner had he made this vow that they were able to land the walrus.
>
> (trans. Steven Hartman and Astrid Ogilvie)

After that Hrafn left Iceland and brought the tusks to St Thomas (à Becket) in Canterbury. While memory of this early hunt may be preserved in some place names and scattered saga references indicate occasional encounters with walrus in later medieval times, significant walrus hunting in Iceland was clearly a thing of the past when literacy became widespread in the twelfth–thirteenth centuries.

New field results: Greenland

Greenland was a well-known supplier of walrus tusk from at least the early thirteenth century when ropes made of walrus hide and walrus teeth are mentioned among the commodities traded from Greenland in the Norwegian *Kings Mirror* (*Konungs skuggsjá/Speculum regale*) (Brøgger 1947, trans. Larsen 1918). While individual walrus can be found in many areas in Greenland, the major concentrations of hauling out places are in the north of both the east coast and the west coast of Greenland. On the west coast Disko Bay is thought to be identical with the Norse *Norðurseta* (the 'northern hunting grounds': Arneborg 1993). The Disko Bay area was also the region where eighteenth- and nineteenth-century European hunters took the majority of walrus (often hunted as a by-product of whaling expeditions) and where the twentieth-century Greenlandic Catch Statistics consistently show the greatest kill of walrus by recent Inuit subsistence hunters (discussion in McGovern 1985a). Greenlandic walrus have thus been able to withstand human hunting pressure in historic times but the effect of human hunting on the past distribution of their breeding colonies remains largely unknown. Norse place names supposed to refer to locales north of Disko Bay and archaeological finds, however, show that the Norse hunters went even further north on their hunting trips (Arneborg 1993). As far as the east coast of Greenland is concerned a few place names mentioned in Ívar Bárðarson's *Greenland Description* from the later 1300s indicate that the Norse Greenlanders also went on hunting trips to the southern part of the east coast; how far north is, however, uncertain. Ívar mentions fish, whale, birds, eggs and polar bear among the bag from East Greenland (Jónsson 1930, 19ff.). Walrus are not specially mentioned, and they are not normally known as far south, but of course walrus might have been included in the text as whales.

Christian Keller (2010) makes use of the one surviving record of the size and value of the medieval Greenlandic ivory trade to gain a broad impression of its value to the Norwegian crown:

> In A.D. 1327, a load of walrus tusks from Greenland was sold in Bergen.…This was the Peter's Pence and the six-years tithe, a crusade tax which eventually helped finance King Magnus Eiriksson's 1340ies crusade against Novgorod.…The load of tusks may be estimated to 802 kilograms, suggesting ca 520 tusks representing some 260 animals.…The computed value of the 520 tusks from A.D. 1327 runs into something like 780 cow equivalents, or nearly 60 metric tons of stockfish.…A record from A.D 1311 shows that a total of 3,800 Icelandic farmers paid their (tax of) 20 ells of *vaðmál* (woollen cloth). The value that went to the king has been estimated to 317.5 cow equivalents, making the total (Greenlandic) payment twice as much, i.e. 635 cow equivalents.…Thus the value of the Greenland tusks from A.D. 1327 (representing the six years' tithe) was worth more than the annual tax from nearly four thousand Icelandic farmers.
>
> (Keller 2010, 5–6)

As Keller admits, this is a very broad-brush comparison, but it suggests the value of the export trade from Greenland to the Norwegian kingdom in the early fourteenth century prior to the impacts of the Black Death and increasing availability of White Sea walrus ivory and elephant ivory in the later Middle Ages (Pierce 2009; Seaver 2009).

Zooarchaeology has a long history in Greenland, and walrus bones have been identified in nearly every excavated archaeofauna (Degerbøl 1929, 1936, 1941; McGovern 1985b; Smiarowski et al. 2015). Walrus-bone fragments tend to be found in the greatest numbers in the Western Settlement, and are particularly numerous at the chieftain's farm of W51 Sandnes (Roussell 1936; McGovern et al. 1996; Smiarowski 2014). However, walrus-bone fragments (especially the fragments of maxillary bone produced by tusk extraction work) are also found on most small inland farms in both Western and Eastern Settlements and are numerous at the bishop's manor at Gardar E47 (Smiarowski 2014). The distribution of walrus bones on both coastal and inland farms of all sizes and in both settlement areas underlines the role the Norðurseta hunt must have played in the life of many Greenlandic households, and suggests some sort of share-out of the maxilla/tusk butchery units across the community for final processing and tusk extraction. While specialized hunters may well have been present, this extraction debris distribution suggests that the walrus hunt (like sealing, caribou hunting and probably sea-bird hunting) had a strongly communal character in Norse Greenland. The archaeological record and written accounts indicate that the walrus hunt would have taken many of this small community's active adults and valuable small vessels away from the farming area for much of the summer (e.g. GHM III, 229). One account, *Grœnlandie vetus chorographia 'a afgömlu kveri*, copied in a seventeenth-century Greenland account, even gives the rowing time to the hunting grounds in 'days' row' for a six-oared boat. This record indicates that it took fifteen days' row to reach the northern hunting ground around Disko Bay from the Western Settlement, and twenty-seven days' row from the Eastern Settlement. If hunting parties left the settlements in June (after the main seal hunt) and returned in late August (in time for the hay harvest) this would leave only eleven weeks for the Western Settlement Norðurseta hunters and as little as seven weeks for the Eastern Settlement hunters (McGovern 1985a, 305). These estimates suggest significant problems in allocating boats and human labour in this small society, which also needed to carry out communal seal hunting in the early spring in the outer fjords of the two settlement zones and the vital late summer hay harvest on the home farms. Unlike Icelandic marine fisheries (which, in terms of agricultural labour requirements, could take place during the winter's low season), the Greenlandic long-range walrus hunt imposed serious scheduling conflicts with the hunting/farming subsistence economy (Perdikaris and McGovern 2007). Both Icelandic and Greenlandic maritime adaptations risked regular loss of life at sea, but the far smaller Greenlandic population (perhaps 2,500–3,000 vs. 50,000–80,000) faced disproportionate levels of threat. Loading capacity estimates for similarly sized six-oared modern Nordic wooden boats (*c*. 1.2 metric tons) indicate that hunters would have to choose between transporting one or two walrus carcasses or up to 160 tusk/maxilla butchery units (McGovern 1985a; see also Ljungqvist 2005 for further discussion and alternative calculations). While these are also broad-brush estimates, they may help explain the walrus-element distribution pattern in the later archaeofauna from the settlement areas hundreds of kilometres to the south (McGovern 1985a). Given these loading limits and our single surviving 1327 tax and tithe record discussed above, it seems clear that the transport costs of the long-distance hunt to Disko Bay would tend to restrict cargo options and favour ivory over meat. This was a 'cash' rather than 'subsistence' hunt, and an activity that regularly generated both subsistence scheduling conflicts and considerable hazards. Finds of walrus penis bones in many farm site contexts and the use of walrus post-canine molar teeth as raw material for apparent amulets (bear, walrus and bird) suggest some continued ritual component of the hunt (Ljungqvist 2005).

Key issues for comparing Icelandic and Greenlandic patterns in walrus hunting thus centre on the differences between local and long-distance walrus hunting, and the origins and duration of the specialized Greenlandic *Norðurseta* hunt. The increase in stratigraphic excavations in Norse Greenland since the 1970s has begun to shed light on these questions. Work at W51 Sandnes (Roussell 1936; McGovern et al. 1996) sampled different portions of the deep deposits on the site. Roussell's excavations took place in a significantly cooler climate with lower high-tide levels, allowing for superb organic preservation and access to the earliest phases of settlement near the churchyard boundary. The 1984 project recovered (with sieving) 6,033 identifiable animal bone fragments, of which 1,473 (nearly 30 per cent) were walrus, but the earliest deposits reached were phased (with C14) only to *c*. 1025–150 CE, missing the earlier settlement period. The later 1984 walrus-bone collection contained very few post-cranial elements (and these were nearly all penis-bone fragments). Virtually all the later walrus bones were maxillary fragments and some small chips of tusk ivory accidentally flaked off during extraction. Fragmentation analysis across the five phases (*c*. 1025–350 CE) indicates that the Sandnes householders became more skilled at tusk extraction through time, with the proportion of accidentally chipped ivory dropping progressively (McGovern et al. 1996). This pattern stands in contrast to finds of post-cranial bones (ribs, phalanges, carpals and tarsals) identified from excavations that reached the earlier phases of occupation. These indicate that walruses in the Western Settlement were killed in the immediate vicinity of the farms as well as in the distant hunting grounds (Degerbøl 1929, 183, 1936, 7; Nørlund 1930, 138; Enghoff 2003, 39ff.). According to Degerbøl (1936, 7) walruses 'in former times' used to go ashore at several places in the Nuuk area (i.e. the Norse Western Settlement). By contrast, recent stratified excavations in the Eastern Settlement contain mainly walrus maxillary fragments and penis bones, though again our samples from the first phases of settlement remain limited (Smiarowski et al. 2015; Smiarowski 2012, 2013). In all cases, walrus bones are present from the lowest layers reached to the very last depositional layers. The Norse Greenlanders appear to have focused strongly upon walrus hunting (probably initially locally as well as in the Norðurseta) from the earliest days.

They continued the hunt despite the dangers and scheduling problems of the distant Norðurseta to the very end.

Isotopic sourcing

The early medieval trade in walrus ivory has been confirmed archaeologically through numerous finds in contexts across western and northern Europe. However, the value of these finds as evidence relative to the question of the Norse settlement in the North Atlantic is limited by the fact that until now it has not been possible to source the ivory to any particular geographical region within the vast circumpolar range of walrus. Besides the hunting grounds in Iceland and Greenland, large populations of walrus were also exploited in northern Norway and the White Sea area. Consequently, walrus-ivory artefacts found in archaeological deposits of the early medieval period across Europe may have various geographical origins.

Hence, in order to assess this research question, a pilot project was initiated under the aegis of the ENTREPOT: Maritime Network Urbanism in Global Medieval Archaeology research project, aimed at exploring the potential of biogeochemical methods as a means of determining more precisely the provenance of walrus-ivory artefacts. This pilot project has attempted to identify source regions of walrus ivory using lead isotope analyses (^{208,207,206}Pb/^{204}Pb).

Although this marks the first attempt to source archaeological walrus ivory using the lead-isotope tracing method, there have been recent studies exploring the isotopic heterogeneity in modern walrus populations, focused on stocks hunted in the Canadian Arctic and Greenland. Outridge et al. (2003), whose study inspired our own, demonstrated that it is possible to distinguish the eastern coast of Canada and western coast of Greenland populations by using lead (Pb) isotope analysis. This is possible because walrus feed on sedentary filter-feeders such as clams, and have a localized feeding range. Consequently, as filter-feeders are affected by the local geology, their lead isotope signatures are transferred to the marine animals which feed on them. Since the geological settings of the key source regions of interest during the early medieval period (e.g. Greenland, Iceland and the White Sea) are significantly different, we expected correspondingly that different lead (Pb) isotopic signatures would be reflected in walrus ivory from these different regions. Hence, in order to test the lead (Pb) isotope tracer for this material, we analysed modern and archaeological walrus ivory and bone from Greenland and Iceland as well as one single sample from Russia (Table 1).

The Norse Greenland samples investigated are from Gardar (ruin group E47) in the Eastern Settlement, and from Sandnes (ruin group W51) and ruin group W52a near Sandnes in the Western Settlement. From Gardar, two samples are included in the study; a piece of ivory (EN500) and a piece of bone (EN501) from the jawbone of the same individual. The skull was excavated in 1926 by Poul Nørlund and his team (Nørlund 1930). The find spot is recorded as the cemetery. Between twenty and thirty more-or-less fragmented skulls of walrus and only one post-cranial bone were found in the area, and in his publication Nørlund hints that this may have had ritual significance. However, a more down-to-earth explanation is more likely and indicated by Nørlund's own observations: at some point, the cathedral cemetery was extended southwards into a former midden area and the walrus bones, together with bones from both domesticated and other wild animals, actually derived from midden layers stratigraphically below the

Table 1 Pb isotope data of walrus tusk and bone, and soil leachates

Lab. no.	Sample number	Material	Place	$^{206}Pb/^{204}Pb$	± 2σ	$^{207}Pb/^{204}Pb$	± 2σ	$^{208}Pb/^{204}Pb$	± 2σ	r1**	r2††
P 24, abraded powder	P24/2013KMG (Norse), V51	Tusk ivory	Greenland	18.896	0.068	15.586	0.056	40.498	0.147	0.992	0.993
P 24, piece, acetic acid leach	P24/2013KMG (Norse), V51	Tusk ivory	Greenland	17.758	0.115	15.516	0.102	38.058	0.248	0.991	0.998
P 24, piece, leached	P24/2013KMG (Norse), V51	Tusk ivory	Greenland	20.520	0.040	15.675	0.033	43.979	0.091	0.948	0.977
KF 500, piece, leached	P22/2013KMG (Norse), V51	Bone	Greenland	21.987	0.115	15.901	0.084	44.109	0.236	0.994	0.982
KF 501, piece, leached	P23/2013KMG (Norse), V51	Bone	Greenland	20.428	0.042	15.720	0.033	43.351	0.094	0.988	0.983
KF 502, piece, leached	P25/2013KMG (Norse), V51	Bone	Greenland	21.979	0.045	15.862	0.035	44.227	0.099	0.940	0.942
KF 503, piece, leached	P26/2013KMG (Norse), V51	Bone	Greenland	18.084	0.040	15.544	0.035	38.475	0.089	0.985	0.975
KF 504, piece, leached	P27/2013KMG (Norse), V51	Tusk ivory	Greenland	20.103	0.130	15.671	0.102	41.915	0.273	0.993	0.996
KF 505, piece, leached	P28/2013KMG (Norse), V52a	Tusk ivory	Greenland	17.878	0.033	15.575	0.030	38.207	0.076	0.987	0.960
KF 630, piece, acetic acid leach	V-51 Odobenus Rosmarus. Tusk fragment14.03.201-P14/2014	Tusk ivory	Greenland	17.638	0.092	15.489	0.082	37.557	0.198	0.994	0.994
KF 630, piece, leached	V-51 Odobenus Rosmarus.Tusk fragment14.03.201-P14/2014	Tusk ivory	Greenland	19.692	0.175	15.711	0.140	42.397	0.377	0.997	0.997
KF 630, piece, acetic acid leach	V-51 Odobenus Rosmarus.Tusk fragment14.03.201-P14/2014	Tusk ivory	Greenland	17.962	0.125	15.552	0.109	38.039	0.266	0.995	0.995
KF 630, piece, leached	V-51 Odobenus Rosmarus.Tusk fragment14.03.201-P14/2014	Tusk ivory	Greenland	19.726	0.120	15.616	0.096	42.595	0.261	0.991	0.993
KF 508, abraded powder 1	EN 500 (Norse), Ø47, Igaliku	Tusk ivory	Greenland	18.301	0.050	15.589	0.043	38.717	0.109	0.987	0.974
KF 508, abraded powder 2	EN 500 (Norse), Ø47, Igaliku	Tusk ivory	Greenland	18.358	0.064	15.542	0.056	39.477	0.149	0.979	0.939

(*continued*)

Table 1 (*Continued*)

Lab. no.	Sample number	Material	Place	^{206}Pb/^{204}Pb	± 2σ	^{207}Pb/^{204}Pb	± 2σ	^{208}Pb/^{204}Pb	± 2σ	r1**	r2††
KF 508, piece, acetic acid leach	EN 500 (Norse), Ø47, Igaliku	Tusk ivory	Greenland	18.232	0.083	15.561	0.071	38.754	0.180	0.993	0.984
KF 508, piece, leached	EN 500 (Norse), Ø47, Igaliku	Tusk ivory	Greenland	19.069	0.077	15.506	0.063	41.536	0.238	0.989	0.709
KF 509, piece, leached	EN 501 (Norse) same as EN 500, Ø47, Igaliku	Bone	Greenland	18.577	0.031	15.535	0.027	38.848	0.069	0.982	0.959
KF 510, piece, acetic acid leach	EN 501 (Norse) same as EN 500, Ø47, Igaliku	Bone	Greenland	18.241	0.054	15.568	0.047	38.419	0.117	0.991	0.990
KF 511, piece, leached	AST01-1274, Aðalstræti (Island)	Tusk ivory	Island	18.570	0.075	15.572	0.064	38.379	0.157	0.988	0.995
KF 512, piece, acetic acid leach	AST01-1274 Aðalstræti (Island) leachate	Tusk ivory	Island	18.360	0.089	15.616	0.077	38.216	0.189	0.987	0.979
KF 513, piece, leached	AST01-001 Aðalstræti (Island)	Tusk ivory	Island	18.357	0.117	15.592	0.100	38.282	0.246	0.994	0.994
KF 514, piece, acetic acid leach	AST01-001 Aðalstræti (Island) leachate	Tusk ivory	Island	18.349	0.053	15.605	0.046	38.280	0.113	0.988	0.984
EN 059, piece, untreated	Thule	Tusk ivory, modern	Greenland	18.559	0.128	15.632	0.109	38.485	0.270	0.995	0.989
KF 506, piece, leached	Thule (same as EN 059)	Tusk ivory, modern	Greenland	19.061	0.036	15.676	0.030	41.122	0.083	0.983	0.947
KF 507, piece, leached	Novgrod (White Sea)	Tusk ivory, modern	Russia	18.480	0.146	15.658	0.124	38.490	0.306	0.994	0.993
–	SS 01, V13a	Soil leachate	Greenland	18.111	0.051	14.981	0.043	44.614	0.128	0.989	0.983
–	SS 01, V13a	Soil leachate	Greenland	18.270	0.108	15.039	0.090	44.692	0.268	0.997	0.992
–	SS 02, Umivik	Soil leachate	Greenland	18.399	0.065	14.993	0.054	46.379	0.169	0.988	0.974
–	SS 03, Austmannadalen	Soil leachate	Greenland	21.264	0.089	15.779	0.066	49.061	0.207	0.996	0.995

(*continued*)

Table 1 (*Continued*)

Lab. no.	Sample number	Material	Place	$^{206}Pb/^{204}Pb$	± 2σ	$^{207}Pb/^{204}Pb$	± 2σ	$^{208}Pb/^{204}Pb$	± 2σ	r1**	r2††
–	SS 04, near V51, Sandnæs	Soil leachate	Greenland	21.868	0.089	15.705	0.065	49.182	0.204	0.995	0.994
—	SS 05, V51, Sandnæs	Soil leachate	Greenland	20.130	0.098	15.583	0.077	44.738	0.221	0.994	0.994
—	5, Nuuk/Kobbefjord	Soil leachate	Greenland	20.933	0.016	15.317	0.014	42.022	0.044	0.928	0.858
—	Drill bit 1			17.970	0.048	15.486	0.048	37.870	0.049	0.934	0.965
—	Drill bit 2			17.823	0.026	15.529	0.027	37.523	0.026	0.989	0.992
—	Procedure Pb blank composition 1			17.588	0.163	15.534	0.145	37.191	0.346	0.995	0.997
—	Procedure Pb blank composition 2			18.122	0.138	15.653	0.119	37.826	0.288	0.997	0.998
—	Procedure Pb blank composition 3			17.724	0.080	15.514	0.071	37.424	0.171	0.990	0.992
—	Procedure Pb blank composition 4			17.559	0.108	15.520	0.097	36.656	0.228	0.994	0.995
—	Procedure Pb blank composition 5			17.955	0.044	15.593	0.039	37.491	0.097	0.978	0.952

Notes

Errors are two standard deviations absolute. Fractionation amounted to 0.103±0.011%/AMU (n = 110) on NBS 981 Pb standard.

Total procedure Pb blank <50pg.

** r1 = $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ error correlation.

†† r2 = $^{206}Pb/^{204}Pb$ vs $^{208}Pb/^{204}Pb$ error correlation,

cemetery. Radiocarbon dates from three skulls from the midden layer are: 1) 1030–70 CE (calibrated 1 sigma); 2) 1005–45 CE (1 sigma); and 3) 1010–50 CE (1 sigma) (Arneborg, Lynnerup and Heinemeier 2012). The Sandnes and Austmannadal samples are from Aage Roussell's excavations in 1932 and were collected outside stratigraphic context. From Sandnes, the collection includes both skull fragments and post-cranial bones of walrus (Degerbøl 1936).

The Icelandic ivory samples are from the tusks recovered from the Aðalstræti 14–18 Viking Age hall from Reykjavik described above, and are datable to the tenth century by tephra and radiocarbon on associated deposits (Roberts 2001).

Analytical procedures

Separation of lead (Pb) from tusk and bone pieces

Pieces of 20–30 milligrams were bathed in 1ml of 0.5 M acetic acid for ten minutes in 7ml Savillex Teflon vials in an ultrasonic bath. Then the leachates were pipetted off (and in cases where we analysed these to monitor their lead (Pb) isotopic compositions, they were transferred into separate 7ml Savillex Teflon vials in which these solutions were dried on a hotplate), and the leached pieces were repeatedly washed in ultrapure (MQ system) water with a resistance of 18MΩ. Subsequently, the tusk and bone pieces were dissolved in 300 µlt of 8M HCl, and the solution was then dried on a hotplate. Lead was separated applying a standardized HBr-HCl elution recipe on self-made disposable mini-extraction columns, which consisted of 1ml pipette tips in which we fitted a frit filter to retain 300 µlt of Biorad AG-1x8 100–200 mesh anion resin. The samples were processed twice over these columns to remove disturbing left-over matrix elements which showed problematic (in producing lead beam instabilities) during the measurements of lead fractions on our thermal ionization mass spectrometer (TIMS). Procedural lead blanks remained <50pg (with compositions plotted in Figure 2) and these levels, when compared to 20–30ng of lead from the samples, remain insignificant with respect to changing the isotopic composition measured within the level of external reproducibility.

Separation of lead (Pb) from top soils

In order to gain an understanding of the composition of bio-available lead from site W51 and its nearest surroundings (Sandnes; Western Norse Settlement), we conducted leachates of five soil samples. One gram of soil each was leached for one hour in 10ml 0.1N HNO_3 in centrifuge tubes on a horizontal shaker, after which the samples were centrifuged. One millilitre aliquots of the leachates were pipetted into 7ml Savillex Teflon vials and subsequently dried down on a hotplate. This aliquot was processed over the same ion chromatographic elution scheme for lead (Pb) as the tusk and bone samples describe above.

Mass-spectrometry analyses of sample leads

Samples were loaded in a mixture of 2 µlt 1M H_3PO_4 and 2 µlt of silica emitter (made from the recipe in Gerstenberger and Haase 1997) onto pre-outgassed 20µm thick Re-filaments and

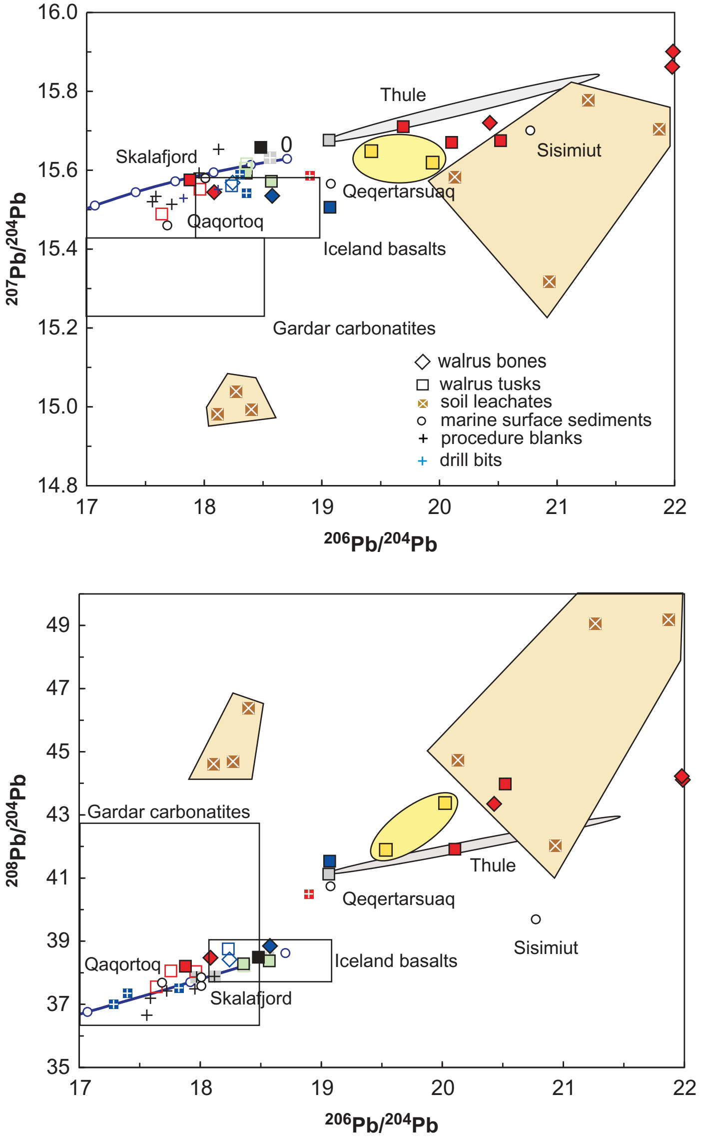

Figure 2 Common lead isotope diagrams (uranogenic; ^{206}Pb/^{204}Pb *vs* ^{207}Pb/^{204}Pb and thorogenic; ^{206}Pb/^{204}Pb *vs* ^{208}Pb/^{204}Pb) plotting the results from Table 1. The colour coding corresponds to the localities of the samples: Symbols in red depict samples from the Western Norse Settlement (sites W51 Sandnes and W52a), symbols in blue are from the Eastern Norse Settlement (site E47; Igaliku) and green symbols are samples from the Aðalstræti site on Iceland. In addition, the grey symbol represents a modern (early twentieth-century) walrus-tusk sample from Thule (north-west Greenland), and the black symbol depicts a medieval tusk fragment from Novgorod (White Sea, Russia). Soil leachate samples mimicking the bio-available signature in the Nuuk fjord area are plotted in brown symbols. These samples define a rude baseline for what can be expected as bioavailable fractions in the Nuuk area.

analysed in static mode on a Micromass VG Sector 54 IT mass spectrometer at the Centre for Isotope Geology, Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark. Lead (Pb) was corrected for thermal mass fractionation by comparison with the long-term reproducibility of the NBS 981 Pb standards under similar conditions and the correction amounted to 0.103%/AMU at average. The external reproducibility of the NBS 981 Pb standard, using a ^{208}Pb beam intensity of 1 volt (10^{-11} amp), is set to +/- 630 ppm (2σ; n > 120) for the ^{206}Pb/^{204}Pb ratio.

Results

The analysis of archaeological (and modern) walrus ivory and bone from Greenland and Iceland seems to show a potential consistent variation in the samples' lead (Pb) isotope signatures. A parallel comparison with the lead isotope compositions of soil samples from some of the likely hunting grounds suggests that this variation is systematically correlated with regional variation in geological bedrock and sediments.

Lead isotope results are presented in Table 1 and plotted in conventional common lead isotope diagrams in Figure 2. The colour coding corresponds to the localities of the samples: symbols in red depict samples from the Western Norse Settlement (sites W51 Sandnes and W52a), symbols in blue are of samples from the Eastern Norse Settlement (site E47; Igaliku) and green symbols are samples from the Aðalstræti site on Iceland. For comparison we have also measured a modern walrus-tusk sample (grey symbol) from Thule (north-west Greenland) and a medieval fragment (black symbol) from Novgorod (White Sea, Russia). Soil leachate samples mimicking the bio-available signature in the Nuuk fjord area are plotted in brown symbols. These samples define a rude baseline for what can be expected as bio-available fractions from the Nuuk area. In the following, we will focus on the lead (Pb) isotope results of the walrus tusk and bone samples, i.e. the residual analyses of pieces which have been leached (deeply pre-cleaned and de-contaminated) prior to dissolution with acetic acid. These correspond to the solid colour filled symbols in Figure 2. In principle, two distinct lead (Pb) isotope signatures can be discriminated based on the combined uranogenic and uranogenic/thorogenic lead (Pb) isotope compositions. Samples from sites W51 and W52a, with two exceptions (sample KF 503, P26/2013KMG, and sample KF 505, P28/2013KMG) are characterized by elevated uranogenic and thorogenic lead (Pb) isotopes, with characteristically high ^{208}Pb/^{204}Pb above 40. The two exceptions (a tusk piece and a bone fragment) in contrast are characterized by non-radiogenic lead (Pb) isotopes which plot close to the Stacey and Kramers (1975) continental crust evolution line in Figure 2.

The samples of tusk and bone (sample EN500) from Igaliku (Eastern Norse settlement; site E47) are comparatively less radiogenic in their lead (Pb) isotope signatures compared to the samples from the Western Norse settlements to the north, and possibly reflect the influence of the local geological range. The area is dominated by carbonatites pertaining to the Precambrian Gardar rift zone (Andersen 1997). Although characterized by relatively heterogeneous bulk rock Pb isotope signatures (Andersen 1997), the majority of carbonatite samples analysed are characterized by non-radiogenic values with average compositions of ^{206}Pb/^{204}Pb = 17.3 +/− 1.2; ^{207}Pb/^{204}Pb = 15.32+/−0.11; ^{208}Pb/^{204}Pb = 39.7+/−3.2 (data field outlined by a black rectangle in Figure 2). If the local basement rocks did in fact contribute to the bio-available lead

(Pb) measured in the two samples from Igaliku, then again we have to postulate that a slightly more radiogenic signature compared to the available bulk rock data entered the walrus food chain. Soil leachates from this rift-related province, which can potentially mimic the range of expected bio-available fractions, are not available and we can therefore not further hypothesize on possible feeding grounds.

For comparison, we also analysed a sample of modern (early twentieth-century) walrus tusk from Thule (north-west Greenland) and a medieval fragment from Novgorod (possibly representing an animal from the White Sea, Russia). The lead (Pb) isotope composition from the Thule sample lies at the lower (non-radiogenic) field of modern tusk samples from Thule (data field outlined by an elongated ellipse in Figure 2) reported by Outridge et al. (2003). This sample also reflects the elevated thorogenic Pb isotope signature which we measured in the W51/W52a samples. This particular characteristic feature is not observed in the Novgorod sample. This sample is instead characterized by non-radiogenic Pb which plots close to the Stacey and Kramers (1975) continental crustal growth curve (Fig. 2) in uranogenic and uranogenic vs. thorogenic Pb isotope space.

Finally, the lead (Pb) isotope signatures of the two samples from Aðalstræti (Iceland) lie close to the Novgorod sample and exhibit non-radiogenic signatures. Given that Icelandic basalts are characterized by relatively non-radiogenic Pb isotope compositions (field of compositions marked with a black rectangle in Figure 2), and that the two tusks from Iceland straddle this compositional field with a tendency again to exhibit slightly elevated compositions (as is the case in the other areas investigated here), we interpret these results as indicating that the tusks originated from local walrus stock. Two marine surface sediments from Skagafjord (Iceland) reported by Larsen et al. (2012) have lead (Pb) isotope compositions that lie close to the field defined by basalts and indicate that the particulate load in the coastal waters around Iceland are dominated by weathered basalt components. In any case, the bio-available lead (Pb) signatures in the walrus tusks from Iceland are clearly distinguishable from those with feeding grounds in Western Greenland and/or the Canadian Arctic (Outridge et al. 2003).

Discussion

Recent archaeological walrus remains from Viking Age sites from Greenland and Iceland revealed different specialization strategies related to walrus ivory exploitation. On the other hand, there is the archaeological evidence of trade as revealed by the objects made of walrus ivory dating from early medieval times across western and northern Europe. In order to connect the archaeofauna evidence from the exploitation sites with the archaeological objects made of walrus ivory, we have investigated the potential of developing a geo-biochemical tracing method for provenancing walrus ivory. For this purpose we have analysed a small data set of archaeological and modern ivory samples from Greenland, Iceland and Russia, supplemented by leachates of soil samples to obtain an idea of the bio-available lead (Pb) isotope signatures from locations close to the retrieval sites. Our pilot study revealed that the elevated thorogenic lead isotope character depicted by most of the W51 site samples (Greenland) is also reflected in the soil leachates. However, these preliminary and reconnaissance soil leachate samples unveil a complexity in the lead (Pb) isotope characteristic of the country rocks, which is attributable to the complex geological terrain assembly involving a composite of Meso/Eoarchean and

Proterozoic granite/gneiss terrains in the Nuuk region. The patch of soil samples with low ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb signatures and elevated ^{208}Pb/^{204}Pb ratios (Fig. 2) from the area north of site W51/W52a is so different from the leads analysed herein, that it can be readily excluded from contributing Pb to the food chain of the walrus species sampled for this study. Leads with elevated ^{208}Pb/^{204}Pb ratios have been described for modern walrus stock from the Canadian Arctic and Greenland (Outridge et al. 2003). These authors report that significant differences between locations in mean Pb isotope ratios and the limited overlap of the ranges of values potentially indicate that each village harvested walrus herds that exploited substantially different geological/geographical habitats. This geographic segregation, based on isotope signature differences, has been interpreted to suggest that most walrus stocks (i.e. the groups of walrus that interact with modern hunters at each community) are more localized in their range than previously thought. Of pertinent importance in the study of Outridge et al. (2003) is that ^{208}Pb/^{207}Pb and ^{208}Pb/^{204}Pb are the most important stock discriminators, reflecting the influence of local geological Th/U composition (i.e. ^{208}Pb) on lead (Pb) isotope composition in walrus teeth. The ^{204}Pb-based isotope ratios in walrus in their study were consistently higher (more radiogenic) and more homogeneous than those in regional terrestrial bedrock, an observation which also holds for our present study. We note that some of the lead (Pb) isotope signatures measured on tusk samples from site W51 (Sandnes) are similar to two values reported for modern walrus from Sisimiut (Outridge et al. 2003; yellow symbols and yellow data field in Figure 2) and correspond to signatures recently measured in marine surface sediments from the Disko Bay area (Sisimiut city and Qeqertarsuaq) in Western Greenland (Larsen et al. 2012). This is in agreement with the zooarchaeological and documentary evidence for long-distance walrus hunting in Greenland. These signatures do not directly mimic the Archaean and Proterozoic basement rocks exposed in this region, which are reported with far fewer radiogenic lead (Pb) isotope signatures (Whitehouse, Kalsbeek and Nutman 1998), particularly with the lack of elevated ^{208}Pb/^{204}Pb ratios. Our first study of soil leachates from the Nuuk region, dominated by Mesoarchaean granite/gneiss terrains, indicates that radiogenic lead (Pb) signatures, with high ^{208}Pb/^{204}Pb signatures, can be mobilized from these archives and that these fractions potentially enter the coastal waters.

Whether or not this lead (Pb) is transported in dissolved form or simply enters the seawater as fine particulate loads that then enter the walrus food chain is not clear. According to studies performed by Kamenov (2008), the Pb budget in humans is dominated by ingestion/inhalation of particle-hosted lead (Pb). In their study of the human uptake of lead (Pb), these authors claim that the isotopic compositions of the local soil labile fractions can be used as approximation of the bio-accessible lead for humans. The study by Kamenov (2008) on human lead uptake in the Sofia area (Bulgaria) also showed that the lead isotope signatures of weak acid leachates (HCl and acetic acid) of soils from this area correspond to the signatures measured in human tooth enamel. Furthermore, *in vitro* soil digestion experiments in humans indicate that lead will be mobilized from the inhaled/ingested soil particles and will become bio-available in the human gastrointestinal tract (Oomen et al. 2002). These human *in vitro* and *in vivo* experiments also showed that the actual process which renders lead mobile/bio-available in the gastrointestinal tract is acid-driven, i.e. low pH increases the soil lead (Pb) bio-accessibility. Hence, in order to mimic the acid-driven gastrointestinal path the pH of such acids is within the range expected for gastric juices (Ruby et al. 1993), making it potentially plausible that lead with elevated radiogenic signatures, relative to bulk rock/or soil signatures, will enter the blood system of humans and animals eventually. These leached fractions of ingested/inhaled soil-born lead will accumulate in the growing teeth and bones, as more than 90 per cent of the blood lead is contributed by the skeleton (Gwiazda, Campbell and Smith 2005). If ingestion/inhalation of airborne dust and/or ingestion of dissolved particulate matter in seawater is the most probable pathway of lead into the blood system of walrus, then it would be tenable to assume that acid-driven mobilization of lead will preferably take place in the gastrointestinal tract of these animals, and this could therefore explain the observation of elevated radiogenic signatures in the tusks/bones relative to the local soils. Consequently, the isotopic compositions of soil leachates should have the potential to be used as an approximation of the bio-available lead.

Nevertheless, the results obtained from archaeological walrus tusk in this study are promising in that the lead isotope tracer system applied to this material has a great potential to narrow down an identification of the geographical origin of walrus ivory. It is thus possible from this pilot study to distinguish walrus ivory of a Greenlandic from an Icelandic and/or from a White Sea provenance. Furthermore, as we observe variations in the isotope composition of Greenlandic tusks, it might be possible to distinguish between different hunting grounds within Greenland itself. In order to verify this, more data and more detailed investigations are needed. Moreover, it is also necessary to gain a better understanding of how bio-available lead is mobilized in walrus in order to correctly interpret the lead isotope signatures of tusk. It is clear that lead is incorporated in tusk mostly via the food chain, but other potentially important sources might include inhalation of airborne particles and ingestion of seawater, where lead occurs both in dissolved form and as fine particulate loads. Hence, isotopic tracing investigations of this type necessitate detailed isotopic baseline data across the Arctic feeding grounds of walrus stocks as well as the land areas where they sleep and nurse. Finally, this pilot dataset provides a platform for futures baseline databases of bio-available lead (Pb) fractions, and it demonstrates the powerful potential of the lead (Pb) isotope system as a tool to identify walrus-hunting grounds in the past.

Conclusion and further perspectives

The combination of zooarchaeology and isotope geochemistry with intensive archaeological fieldwork, environmental history and environmental humanities approaches demonstrates great potential for taking on difficult and controversial problems in world archaeology. In this case we have been able to draw upon a century of interdisciplinary research in both Iceland and Greenland and to benefit from a broad and sustained international collaboration. While a great deal of work surely remains to be done in the field and in the laboratory, this pilot project shows how we may address and connect the classic problem of ‘farming hypothesis’ vs. ‘trading hypothesis’ in explaining the dynamics of Viking Age settlement in the more distant islands of the North Atlantic. The new excavations and zooarchaeological work appear to support the notion of an initial settlement of at least parts of Iceland driven and ‘financed’ by walrus hunting and connections to Viking Age exchange networks. The Icelandic walrus hunt, however, appears to have been part of a broad spectrum farming/hunting tradition that supported a chiefly society with strong interest in continued engagement with the homelands in Scandinavia and the British Isles. In Iceland, walrus hunting rapidly declined as farming expanded and when later medieval trade increased in the thirteenth–fourteenth centuries it was fuelled by the bulk goods of dried fish and woollen cloth (Vésteinsson, McGovern, and Keller 2002; Harrison 2014; McGovern, Harrison, and Smiarowski 2014; Smiarowski et al. 2015). In contrast, in Greenland current evidence suggests that walrus hunting may have always played a central role in economy and society, requiring substantial re-alignment of the subsistence economy to support both local and increasingly distant and large-scale walrus hunting and processing activity. Despite the realities of geography, by the end of the Viking Age *c.* 1050 CE, Greenland may have been paradoxically more tied to distant markets than was Iceland. Continuation of the Viking Age market production strategy of low-bulk/high-value exports in the high Middle Ages is one major point of contrast between the Greenlanders and their Icelandic kin and may well represent a critical point of pathway divergence (Dugmore et al. 2005, 2007, 2009; Harrison 2014).

Lead isotope analyses of walrus ivory show the potential of such a tracing tool that enables the identification of source regions of walrus populations in the wild as well as of archaeological objects. Further lead (Pb) isotope analyses of additional excavated specimens and ivory objects in museum collections will allow testing, revision and refinement of our scenarios of both initial settlement and later economic integration.

As a preliminary conclusion it seems that we can now refine the ‘trading hypothesis’ by verifying or disproving that walrus ivory in north-west European exchange networks may be Icelandic *c.* 850–1000 CE, but increasingly Greenlandic from 1000 CE onwards. Finally, our study might also define a pathway for the investigation of whether or not Greenlandic ivory was increasingly replaced by White Sea walrus ivory or elephant ivory after *c.* 1250–1300 CE. This information will potentially be useful to elucidate on the idea of a plausible scenario of increasing market isolation becoming an ultimately terminal adaptive pathway for Greenlanders.

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Technical appendix

Sample preparation and decontamination procedures

Initially, we extracted material directly from the tusks using a dental drill bit. Upon processing these samples, however, we realized the danger of cross-contamination of the biogenic lead in the ivory samples with the lead contained within the drill bit, which was probably released during abrasion to obtain the sample. We performed an initial experiment on sample P24 (see Table 1) to illustrate the cross-contamination and compare the results of an untreated abraded powder with those from small intact tusk pieces that were pre-treated by a weak (0.5M) acetic acid leaching prior to dissolution of the leached piece in 8N HCl. We compared the results to Pb isotope analyses of concentrated *aqua regia* dissolved drill-bit pieces (two different drill bits were initially used) and to procedural Pb blank compositions measured during the period where we processed our tusk samples. Results in Table 1, plotted in Figure 2, illustrate that direct processing and analysis of sample material collected by drill-bit abrasion techniques is strongly influenced by lead from the tool and Pb isotope compositions are shifted towards less radiogenic values typical of the composition inherent in the tool (drill bits) and towards the compositional field of our Pb blanks. From this initial experiment we learned that sampling had to circumvent using abrasion techniques with drill bits, and instead should be directed towards breaking off small intact pieces of tusk material. Our test of processing pieces directly sampled in this way also revealed that a weak acetic acid leaching of such pieces consistently resulted in a removal of small amounts of Pb with a less radiogenic signature than the leached tusk pieces. The compositions of these acetic acid leachates, which we analysed at the beginning of our investigation to monitor this secondary contamination, tend to show values comparable to the lead directly measured in the drill bits (blue crosses in Figure 2) and/or to the composition of chemical procedure blanks measured along with the samples (black crosses in Figure 2). As a consequence of these tests, we applied an acetic acid leaching to all walrus-tusk and walrus-bone pieces to ensure retrieval of the biogenic lead.