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## **Provenancing wood used in the Norse Greenlandic settlements: a biogeochemical study using hydrogen, oxygen, and strontium isotopes.**

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### **Abstract**

A growing number of studies strive to examine wooden archaeological remains recovered from Norse sites in the North Atlantic, contributing to a better understanding of patterns in both wood exploitation and woodland management. Despite the limited diversity and abundance of trees in the North Atlantic islands, the Medieval Norse kept using wood in most everyday activities including the construction and repair of buildings and boats, the production of artefacts and tools, and as a source of fuel. The proximity of the Greenland settlements with the northeastern American coast, puts them at the forefront in the exploration and exploitation of remote resource regions. While some species may have arrived both as driftwood or imported material, there is currently no method to conclusively identify archaeological wood remains as driftwood. Here, we use biogeochemical analysis of stable hydrogen ( $\delta^2\text{H}$ ), stable oxygen ( $\delta^{18}\text{O}$ ), and radiogenic strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotopes in soil, water, and modern plant samples from various sites in Greenland and Canada to characterize expected local isotopic baselines. While  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios do not provide a clear distinction between the regions of interest,  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  ratios appear to help discriminate not only between regions but also specific sites. In addition, we completed a pilot study of archaeological wood samples obtained in Greenland to test the effectiveness of the  $^{87}\text{Sr}/^{86}\text{Sr}$  biogeochemical baseline. Results demonstrate that at least in some cases, diagenetic processes were not sufficient to mask a non-local  $^{87}\text{Sr}/^{86}\text{Sr}$  signature.

### **Keywords**

Norse Greenland; Wood resource exploitation; Newfoundland and Labrador; Driftwood; Isotopes; Biogeochemical baselines

### **1. Introduction**

One of the main drivers for the Norse colonization of Greenland and their subsequent exploratory journeys along the North American Atlantic coast is believed to have been the search for Arctic commodities such as furs and ivory (Roesdahl 2003; Arneborg 2008; Dugmore et al. 2009; Keller 2010). The settlement of Greenland represents the last steppingstone of the Norse expansion in the North Atlantic during which populations from Scandinavia and the British Isles were attracted by new opportunities and/or driven out their homelands, while keeping strong

cultural, economic, and political relationships with mainland Europe (Vésteinsson et al. 2002; Barrett 2003; Dugmore et al. 2007; Sigurðsson 2008). Norse settlers originated from regions where trees and timber were essential parts of their landscape and material culture (McGrail 1982; Ljungkvist 2008, 188). In colonizing the North Atlantic islands, they successfully adapted their craft processes and exploitation strategies to the limited wood resources of these new environments. Archaeologists are continuously unraveling the ways in which the Norse maintained a reliance on wood and timber as a fuel source, a construction material for homes and boats, and in the production of everyday tools and objects (e.g. Larsen 1991; Andersen and Malmros 1993; Malmros 1994; Bishop et al. 2013; Christensen 2013; Guðmundsdóttir 2013a; Mooney 2016a; Pinta 2018).

In addition to using locally available timber - either native species or driftwood – these studies have proven that the Greenland Norse also relied on imported materials, although it is difficult to assess to what extent, or how to identify precise areas of origin for these resources (Mooney 2017; Pinta 2018). Wood provenancing in the North Atlantic and beyond has been assessed using different methods such as taxonomical identification (e.g. Andersen and Malmros 1993; Malmros 1994; Guðmundsdóttir 2013a; Mooney 2016a; Pinta 2018), dendrochronology (Mehler and Eggertsson 2006), or chemical analyses (e.g. Alix and Stimmel 1996; Caruso Fermé et al. 2014; Steelandt et al. 2016; Mooney 2017). Each method has proven useful to some extent, helping to identify clear trends in wood exploitation, but none offers a clear way to differentiate between native, drifted, and imported timber (Mooney et al. 2021).

This paper generates isotopic baselines in stable hydrogen ( $\delta^2\text{H}$ ), stable oxygen ( $\delta^{18}\text{O}$ ), and radiogenic strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotopes, obtained at different locations in southwestern Greenland and eastern Canada to determine if these regions are biogeochemically distinct. We then use radiogenic strontium isotope analysis to conduct a pilot provenance study of Norse Greenlandic wood artifacts.

## **2. Historical background**

Historical, archaeological and isotopic data attest of the colonization of Greenland by Norse people from Iceland and the British Isles between 985 AD to the mid-fifteenth century. They settled in two main areas along the southwestern part of the island known as the Eystribyggð - the Eastern Settlement - and the Vestribyggð - the Western Settlement (ÍF IV 1985; Arneborg 2004, 2008; Arneborg et al. 2012; Price and Arneborg 2014) (Figure 1). The establishment of the Norse Greenlandic settlements should be considered as part of a broader cultural complex of Medieval North Atlantic societies, interrelated by strong social, political, and economic ties (Arneborg 2008; Keller 2010). Norse Greenlanders were involved in North Atlantic trade routes through which they exported Arctic goods obtained in Norðrsetr and other hunting grounds, from walrus, polar bears, and seals, to Scandinavia and the British Isles and Central Europe (Keller 2010; Frei et al. 2015; Star et al. 2018). In return, as suggested by archaeological, historical, and literary sources, commodities such as iron, timber, grain, and other luxury items were imported to Greenland (Seaver 1996; Arneborg 2000, 2004, 2008; Wallace 2005; Nedkvitne 2019).

Around AD 1000, as stated in the so called *Vínland Sagas* (Hreinsson 1997), the Greenland Norse explored part of the North American Atlantic coast, naming the regions they encountered for what they had to offer. It has been demonstrated that the main purpose of these expeditions was to identify new resource regions – also referred as the *óbyggðir*, the “wilderness” far from the settlements (e.g. Grove 2009; Madsen 2019) –, including sources of lumber (Wallace 2005; Ljungqvist 2005). Based on the literary descriptions (Hreinsson 1997), Markland has been interpreted as the forested region of the Labrador coast – possibly centered on the Hamilton Inlet area –, while *Vínland*, named after wild grapes and vines, usually refers to the entire region of the Gulf of St Lawrence – and perhaps more precisely the New Brunswick area (Wallace 2003a). Archaeological research revealed that a Norse settlement, probably used as a the “gateway to *Vínland*” (Wallace 1991) was established at L’Anse aux Meadows in northern Newfoundland (e.g. Ingstad 1971; Lewis-Simpson 2003; Wallace 2003b, 2005, 2009). Originally interpreted as a short-lived, seasonal outpost, recent investigation indicates the site may have been occupied significantly longer (Ledger et al. 2019), which could have had considerable implications for the Greenlandic settlements.

Under immense pressure due to climate change and population loss that impacted the Norse agro-pastoralism economy, the settlements in Greenland declined and were ultimately abandoned – the Vestribyggð during the 14<sup>th</sup> century, and the Eystribyggð by AD 1450 (Arneborg 2008; Arneborg et al. 2012).

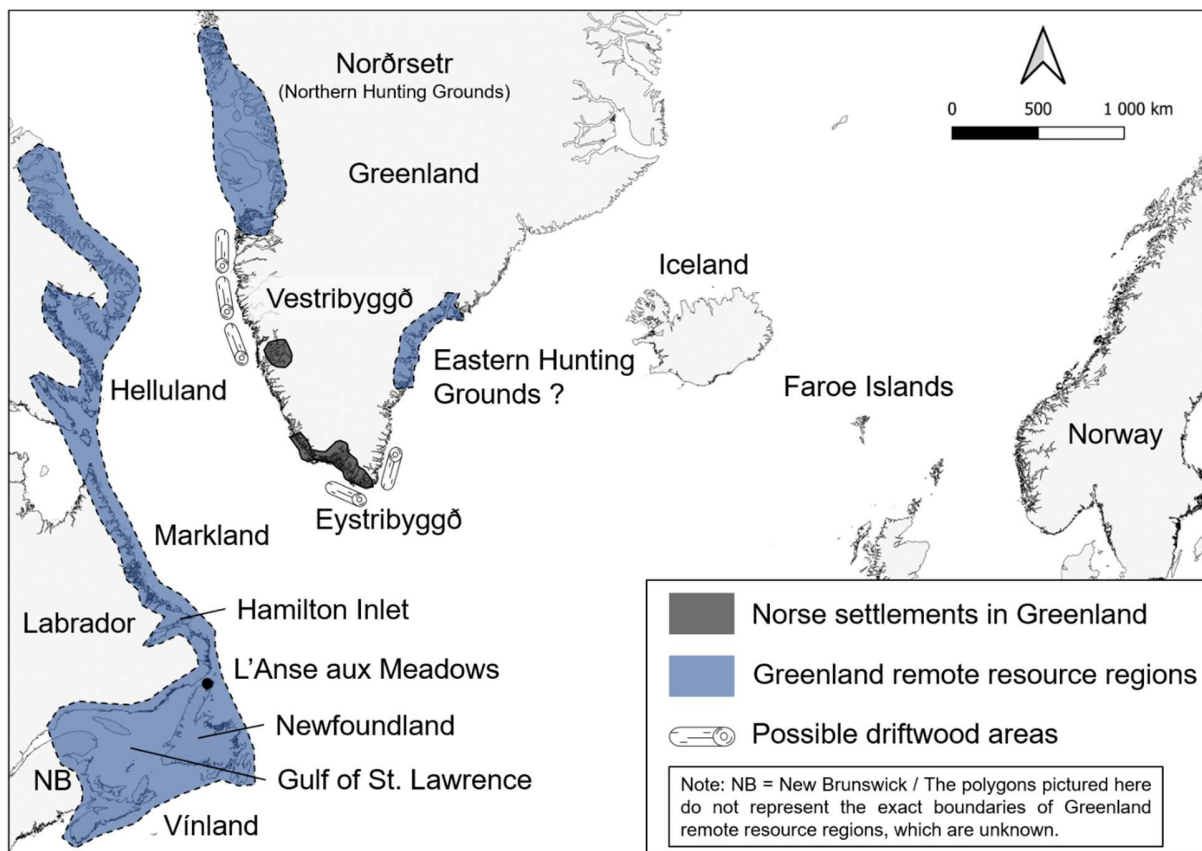


Figure 1. Map showing the locations of the Norse settlements and resource regions in the North Atlantic and North America. After Madsen 2019; Mooney et al. 2020.

### 3. Availability of wooden materials in the Norse Greenlandic settlements

The flora of Greenland is rather limited, both in terms of species diversity and distribution, because of its northerly latitude, harsh climate, and low nutrient availability (Olson et al. 2001; Andersen et al. 2020) (Table 1). Although most native woody taxa are low-growing shrubs rather than trees suitable for construction, some like the downy birch (*Betula pubescens* Ehrh), the mountain alder (*Alnus viridis* subsp. *Crispa* (Ait.) Pursh.) and the Greenland mountain ash (*Sorbus groenlandica* (Schneid.) Löve & Löve) tend to form small areas of open woodland or copses, especially in sheltered subcontinental regions towards the heads of the fjords (Böcher et al. 1968; Fredskild 1973; Böcher 1979; Feilberg 1984; Ledger et al. 2016). Several studies have shown that in the Eystribyggð especially, some regions were - and still are - particularly lush, with individual trees growing up to 10 m high (Feilberg and Folving 1990; Ledger et al. 2014). The tree line is traditionally located at approximately 67°N in the Kangerlussuaq Fjord, above the most northern main Norse settlement area (Ødum 1979).

| Binomial name  | English common name    | Greenlandic common name   | Habitat   |
|--|------------------------|---------------------------|---|
| <i>Alnus alnobetula</i> subsp. <i>crispa</i> (Aiton) Raus.<br>(synonym: <i>Alnus viridis</i> subsp. <i>Crispa</i> (Ait.) Pursh.) | (American) green alder | Pelleq                    | Tree (up to 3 meters high) that can be found in the Vestribyggð and a few sheltered valleys of the Eystribyggð. Grow in humid areas alongside willows and birches |
| <i>Betula pubescens</i> Ehrh.  | Downy birch            | Orpik                     | Tree (from 3 to 10 meters high) that can be found in sheltered valleys of the southwestern regions of Greenland, both the Eystribyggð and Vestribyggð             |
| <i>Juniperus communis</i> var. <i>saxatilis</i> Pall.<br>(synonym: subsp. <i>alpina</i> )  | Alpine juniper         | Kakillarnaq, Paarnaqulluk | Shrub (up to 1 meter high) that can be found mostly in high elevation areas (plateau and mountains)   |
| <i>Salix glauca</i> L.   | Gray willow            | Orpigaq                   | Shrub or small tree (up to 2.5 meters high) that can be found mostly in high elevation areas (plateau and mountains)  |
| <i>Sorbus decora</i> (Sargent) C.K. Schneider<br>(synonym: <i>Sorbus groenlandica</i> (C.K. Schneider) Á. Löve & D. Löve)        | Greenland mountain ash | Napaartoq                 | Tree (up to 4 meters high) that can be found only in the Eystribyggð area, mostly alongside the willow and birche copses  |

Table 1. Table displaying the main native woody taxa (except dwarf shrubs) recorded in the western and southern botanical provinces of Greenland. After Böcher et al. 1968; Böcher 1979; Feilberg 1984; Fredskild 1996; Holt and Johansson 2020; VASCAN [online, accessed 13 January 2021]; ASIMI [online, accessed 13 January 2021].

In addition to native taxa, driftwood was a key source material. This wood originates in Siberia and North America, where trees growing on riverbanks are washed out by erosion and carried out to sea (e.g. Eggertsson 1993; Alix 2005; Hellmann et al. 2013) (Figure 2). Current driftwood circulation patterns in the Arctic and North Atlantic oceans are thought to have originated some 12.000 years ago (Tremblay et al. 1997; Hole and Macias-Fauria 2017), consisting mostly of conifer taxa, especially pine (*Pinus* sp.) - although its presence is mostly due to modern logging activities and it is believed to have been much rarer in old assemblages (Hellmann et al. 2016) – as well as larch (*Larix* sp.) and spruce (*Picea* sp.). This partly reflects the forest composition of source areas (Eggertsson 1993; Hellmann et al. 2013, 2017), but also that conifer wood is more buoyant than wood of broadleaf trees (Häggbloom 1982) and can float long enough to be incorporated into the sea ice. In contrast to the native trees of the North Atlantic islands, driftwood logs can often be long and straight, hence their importance in activities such as construction and shipbuilding. Having spent a considerable amount of time immersed in seawater, drift timbers often bear evidence of marine fungi, insects, or mollusks (e.g. Blanchette et al. 2016; Steelandt et al. 2016; Mooney 2017). At the macroscopic scale, one of the most common features are boreholes drilled by shipworms (*Teredinae*) which tend to weaken the wood structure. However, damaged layers would most certainly be removed during the woodworking process to ensure the reliability of the material. Such features could also be erased during the diagenetic processes affecting the archaeological wood. Therefore, even if the traces left by marine woodborers are a positive proof of a stay in seawater, the absence of such traces does not mean the timber has not been drifted (Alix 2001, 114; Caruso-Fermé et al. 2014, 176). Furthermore, driftwood as well as ship timbers can be affected by shipworms, making it difficult to differentiate between them two.

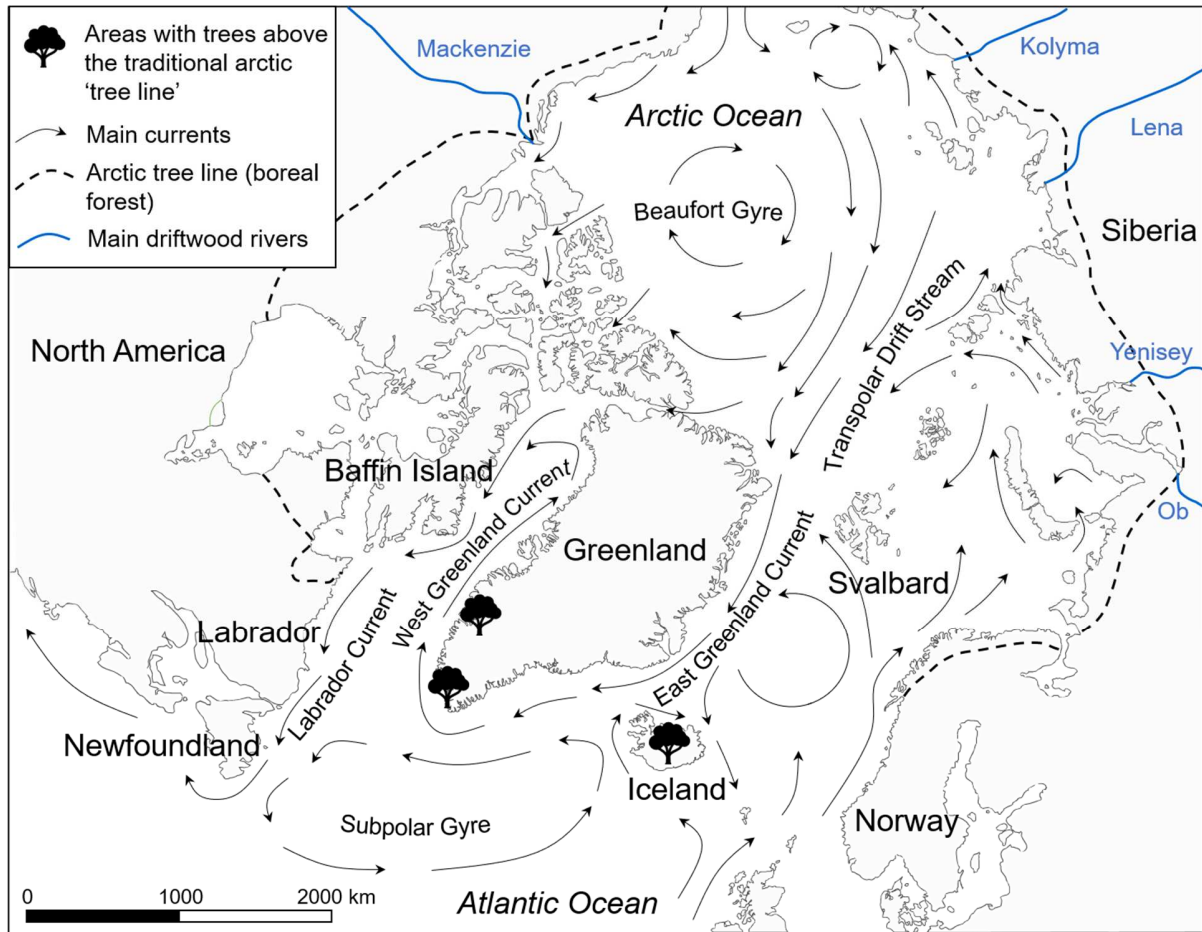


Figure 2. Map showing the main surface currents affecting the circulation of driftwood in the Arctic and North Atlantic oceans. The ‘Arctic tree line’ (CAVM Team 2003) and ‘Main driftwood rivers’ (Hellmann et al. 2013) are approximate locations. Also note that in some regions in Southwestern Greenland and Iceland, *Betula pubescens* Ehrh. is the only forest-forming tree-species to be found naturally (Ødum 1979). After Häggblom 1982; Eggertsson 1993; Alix 2005; Mooney et al. 2021.

The *Vínland Sagas* (Hreinsson 1997) as well as contemporaneous medieval sources (ÍF IV 1985; Storm 1888; Larson 1917) suggest the Norse could rely, to some extent, on timber imported from Europe and the North American coast to supplement their resource deficit (Andersen and Malmros 1993; Wallace 2005; Ljungqvist 2005; Nedkvitne 2019). More specifically for the Greenlandic settlements, Pilgrim (2004, 33) emphasizes that forested regions along the North American coast may have played a significant role in the Norse “timber hunting expeditions”. Such voyages probably relied on various types of peripheral outposts – or shielings (Madsen 2019) –, like L’Anse aux Meadows, for the exploration and exploitation of the adjacent regions and the resources they had to offer (Wallace 2005; Ljungqvist 2005; Madsen 2019).

This suggests a rather intricate resource acquisition pattern, for which multiple sources of raw materials or finished products must be considered. Several studies conducted in the North

Atlantic islands (Andersen and Malmros 1993; Malmros 1990, 1994; Guðmundsdóttir 2013a, 2013b; Mooney 2016a, 2016b; Pinta 2018) have demonstrated the use of a majority of drifted or imported materials for making artefacts and in construction, rather than native species. This can be explained in terms of woodcraft, because native trees and shrubs are generally rather small and twisted and thus not suitable for use in construction and boatbuilding. Norse communities could rely on imported timber and finished items from Europe, but also on other “remote resource regions” (Ljungqvist 2005, 16) such as Markland and Vínland. All previous studies focused on wood provenancing have reached the limits of data interpretation due to the complex differentiation between the species of wood within the same genus, or the locations where trees grew, thus often creating an overlap between drifted and imported taxa (Mooney 2017; Pinta 2018). The difficulty in differentiating between spruce (*Picea* sp.) and larch (*Larix* sp.) is well documented in wood anatomical studies (Bartholin 1979; Anagnost et al. 1994). Given that Norse Greenlanders established an outpost in Newfoundland and likely exploited North American resources, it remains essential to establish some means of identifying these resources among materials excavated in Norse sites across the North Atlantic.

#### 4. Biogeochemical approaches to wood provenance

A promising avenue in identifying such materials is biogeochemical analysis of  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , and  $^{87}\text{Sr}/^{86}\text{Sr}$ . Hydrogen and oxygen isotopes ratios in environmental waters reflect local hydrologic cycles and vary according to climatic factors such as mean annual temperature, amount of local precipitation, elevation, humidity, latitude, and distance from the sea (Craig 1961; Dansgaard 1964; Gat 1996; Bowen et al. 2005; Knudson 2009). Additionally, environmental water carries measurable  $^{87}\text{Sr}/^{86}\text{Sr}$  concentrations as suspended and dissolved sediments reflective of localized erosion processes (e.g. Stewart et al. 1998; Tricca et al. 1999; Aubert et al. 2002; Négrel et al. 2003; Bentley 2006; Bataille and Bowen 2012).

Soils generally share similar  $^{87}\text{Sr}/^{86}\text{Sr}$  values with their substrate. However, minerals within the rock weather at different rates and therefore contribute unevenly to bioavailable strontium in soil (Dasch 1969). As such, soil can exhibit a huge amount of variability within a given geologic zone. Other major sources of variation in bioavailable strontium in soil are ground and stream waters, as discussed above, as well as wind-transported dust deposits (loess) in arid areas. In West Greenland especially, the dry and warm foehn wind may blow at extremely high speed (e.g. Cappelen 2015). Similarly, sea spray in coastal zones as well as rainfall can skew strontium isotope ratios to seawater values of  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$  (e.g. Spooner 1976; Burke et al. 1982; Veizer 1989; Chadwick et al. 2009; Alonzi et al. 2020). Finally, it is speculated that glacial melt can be a contributor to the local bioavailable strontium. Because glaciers in large part form out of frozen precipitation, glacial melt is thought to introduce the rainfall strontium signature into an ecosystem (Israelson and Buchardt 1999). The effects of sea spray, rainfall, and glacial melt are particularly relevant to this work. In Greenland, which is the world’s highest contribution to glacial melt (King et al. 2020), the interaction of these three factors may heavily influence the modern observable local strontium values.



In comparison to soils,  $^{87}\text{Sr}/^{86}\text{Sr}$  values in plants are more uniform within geologic zones. Most strontium present in plants is taken up through shallow root systems, rather than deep roots (Blum et al. 2012). As such, plant  $^{87}\text{Sr}/^{86}\text{Sr}$  values typically reflect topsoil and groundwater strontium. However, plant rooting depth can impact the Sr pool plants take up: deeper rooting plants will more closely reflect bedrock  $^{87}\text{Sr}/^{86}\text{Sr}$ , while shallow rooting plants are more likely to be impacted by environmental sources of strontium, including atmospheric dust, the use of non-local fertilizers and irrigation water, and sea spray (e.g., Frei and Frei 2011; Frei and Price 2012; Reynolds et al. 2012; Alonzi et al. 2020). Hydrogen and oxygen isotopes in plants are taken up from the soil water plants use to synthesize their cellulose (Epstein et al. 1977; Gat 1996). Thus while  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  ratios in plants typically reflect the same climatological variables affecting these isotopes in environmental waters (temperature, elevation, humidity, etc.), oxygen isotope ratios can also be affected by plants' incorporation of atmospheric  $\text{CO}_2$  during carbon fixation (Epstein et al. 1977).

Although numerous biogeochemical analyses of  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopes have been used for investigating places of origin for archaeological human or animal skeletal remains (e.g. Longinelli 1984; Luz et al. 1984; Ericson 1985; Ehleringer et al. 2008; Price et al. 2012), fewer studies have addressed the provenance of archaeological woods. Researchers have illustrated that radiogenic strontium can be used to determine the provenance of wooden materials like construction timbers (English et al. 2001; Reynolds et al. 2005), miscellaneous artefacts (Stanish et al. 2018) or shipwrecks (although these are complicated by the impact of the timbers' immersion in seawater; see Rich et al. 2012, 2016; Hajj et al. 2017). Similarly, while analyses of stable hydrogen and oxygen isotopes in wood have been used primarily as proxies for paleoclimate reconstruction (e.g. Epstein et al. 1977), recent forensic studies have focused on using oxygen isotopes to establish the geographic origins of wood samples (Farmer et al. 2005; Horacek et al. 2009).

However, because timber is fairly porous, it is highly susceptible to diagenetic alteration of its original isotopic signatures from groundwater, seawater, and the depositional environment (Van Ham-Meert et al. 2020). While timber does take on a marine isotopic signal after being immersed, the soluble compounds taken up in timber during immersion in seawater are leached out by taphonomic processes following the timber's deposition (Alix and Stimmell 1996; Caruso Fermé et al. 2014; Steelandt et al. 2016; Mooney 2017). This diagenesis from the burial environment affects not only the marine chemical signature of driftwood, but also the 'native' chemical signature of the wood, thus complicating the identification of driftwood and non-local timbers in archaeological contexts.

## 5. Sampled sites and materials

Water, soil, and modern plant samples were collected to characterize biogeochemical variability in  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic systems across southwest Greenland, northern Newfoundland, and the southeastern Labrador coast (Figure 3).

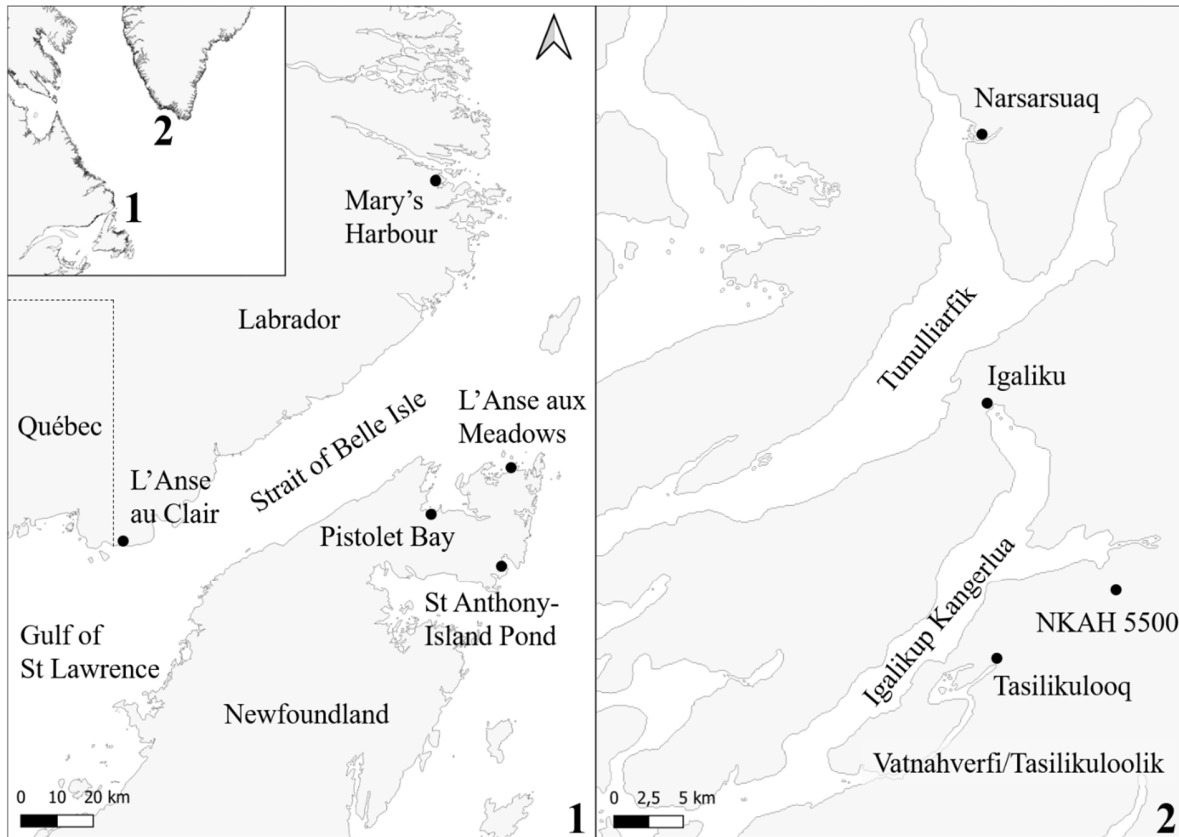


Figure 3. Map showing the general location of the sampled sites in Newfoundland, Labrador, and Greenland.

Sampling locations in Greenland were primarily chosen because of their proximity to previously recorded Norse archaeological sites. The overall sampling region is relatively small, comprising a roughly 35-kilometer radius that, nonetheless, includes two compositionally distinct geologic formations: the Ketilidian and Gardar provinces (Garde et al. 2002; Sørensen 2006). While the Ketilidian province (ca. 1850-1720 Ma) consists primarily of granites and similar rocks, the Gardar province (ca. 1300-1120 Ma) incorporates a wider mineralogical diversity largely dominated by sandstones (Sørensen 2006). The vegetation in southwest Greenland can be particularly lush inland, near the head of the fjords as well as in the sheltered valleys such as the Vatnahverfi/Tasilikuloolik region where woody taxa are dominated by the downy birch (*Betula pubescens* Ehrh) creating small areas of open woodland or copses (Böcher et al. 1968; Feilberg 1984; Fredskild 1996; Ledger et al. 2014) (Table 2).

| Site | Location | Archaeological overview | Simplified geological composition | Simplified vegetation types | Sampled water source |
|------|----------|-------------------------|-----------------------------------|-----------------------------|----------------------|
|------|----------|-------------------------|-----------------------------------|-----------------------------|----------------------|

|                     |                          |  |   |   |                        |
|---------------------|--------------------------|--|---|---|------------------------|
| Narsarsuaq          | N61°10.00'<br>W45°26.00' | The sampled area is not located directly next to a Norse archaeological site | Julianehåb Ketilidian granite and associated moraine deposits/<br>Eriksfjord Formation sandstone and basalt | Mostly willow-birch and juniper scrubs with individual taller birch | Brook/Stream/<br>River |
| NKAH 5500           | N60°52.21'<br>W45°14.56' | Madsen (unpublished data)  | Julianehåb Ketilidian granite/occasional diorite and gabbro inclusions                                      | Mostly birch with patches of willow                                 | Brook/Stream/<br>River |
| Tasilikuloq<br>Ø171 | N60°50.01'<br>W45°24.24' | Madsen 2014  | Julianehåb Ketilidian granite   | Mostly willow-birch scrubs  | Lake/pond              |
| Igaliku<br>Ø47      | N60°59.27'<br>W45°25.09' | Arneborg 2006  | Eriksfjord Formation sandstone and basalt/<br>Julianehåb Ketilidian granite                                 | A few willow-birch and juniper patches                              | Brook/Stream/<br>River |

Table 2. Table displaying a general overview of each of the sampled sites in Greenland. Geological data obtained from (Garde et al. 2002; Sørensen 2006). Vegetation data obtained from (Böcher et al. 1968; Böcher 1979; Feilberg 1984; Fredskild 1996; Ledger et al. 2014; Holt and Johansson 2020). Note: the Eriksfjord Formation is a component of the Gardar Province.

A different approach to methodology was used when sampling in Newfoundland and Labrador. Beyond L'Anse aux Meadows, there is no conclusive archaeological evidence of Norse activity in the area. Thus, the other sampling sites were chosen on the basis of five criteria:

- 1) Proximity to L'Anse aux Meadows, so that a round trip would not have exceeded a few days travel.
- 2) Proximity to the coast, assuming the Norse would have favored fairly quick and easy access to the timber.
- 3) Quantity and quality of timber available. While the extent and structure of the forest ecosystems since the Norse expeditions have profoundly been altered by successive human land use (Kaplan 2009; Lemus-Lauzon et al. 2018), there have not been major changes in the last 5000 years in terms of species composition (see Drushka 2003).
- 4) Proximity to a body of fresh, running water, to obtain the water samples needed to characterize the biogeochemical variability of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values.
- 5) Geological and environmental variability to maximize the potential for distinguishing local isotopic signatures.

The Great Northern Peninsula of Newfoundland is located in the Humber zone, one of the main tectonic divisions of Newfoundland. Deposits in this region are mostly sandstone, limestone, shale, and conglomerates, formed ca. 541-443 Ma, as well as intrusive igneous rocks like basalt and granites (Coleman-Sadd et al. 2000). Southern Labrador is part of the Greenville Province.

More specifically, the rocks along the southeastern coastal region were mostly formed ca. 1650-1450 Ma, with more recent intrusions dated ca. 1080-540 Ma. Most deposits are igneous dominated by granites, as well as localized sedimentary rocks such as sandstone and limestone (Wardle et al. 1997). The vegetation in the region is similar across the Labrador Coastal Barrens and the Forteau Barrens in Labrador, and the Strait of Belle Isle Barrens and Northern Peninsula Forest in Newfoundland (Boland 2011). Near the shores, one can find tuckamore – rather small and twisted coniferous trees such as white spruce (*Picea glauca* (Moench) Voss) or balsam fir (*Abies balsamea* (L.) Mill.), as well as shrubs of deciduous species – along with heath barrens. More sheltered and further inland, on higher elevation and along the riverbanks, stunted trees eventually give way to thicker coniferous woodlands mainly composed of black spruce (*Picea mariana* Mill.), balsam fir and white spruce (Boland 2011) (Table 3).

| Site                   | Location                 | Simplified geological composition      | Simplified vegetation types  | Sampled water source |
|------------------------|--------------------------|--|--|----------------------|
| L'Anse aux Meadows     | N51°35.44'<br>W55°32.00' | Shale/Basalt/Gabbro                    | Willow shrubs/Scattered spruces and firs                                   | Brook/Stream/River   |
| Pistolet Bay           | N51°32.00'<br>W55°39.00' | Sandstone/Shale/Basalt                 | Stunted deciduous trees/Coniferous (mostly spruces) the farther inland     | Brook/Stream/River   |
| St Anthony-Island Pond | N51°22.21'<br>W55°35.41' | Sandstone/Shale/Basalt/Gabbro          | Stunted deciduous trees/Thick coniferous woodlands (balsam fir) inland     | Lake/Pond            |
| L'Anse au Clair        | N51°25.57'<br>W57°03.51' | Sandstone/Limestone/Basalt occurrences | Short coniferous trees (balsam fir and spruces) in the upland              | Brook/Stream/River   |
| Mary's Harbour         | N52°18.55'<br>W55°50.01' | Mostly Granite/Granitoids occurrences  | Scrubby white spruces along the coast/White spruce forests along the river | Brook/Stream/River   |

Table 3. Table displaying a general overview of the sampled sites in Newfoundland and Labrador. Geological data are obtained from (Wardle et al. 1997; Coleman-Sadd et al. 2000). Vegetation data are obtained from (Boland 2011).

## 6. Archaeological pilot study

To test the effectiveness of the  $^{87}\text{Sr}/^{86}\text{Sr}$  biogeochemical baseline, we analyzed a small sample ( $n = 20$ ) of wood artifacts from the archaeological site Ø171-Tasilikuloq, Greenland alongside the baseline samples. Ideally, the pilot study would have included analyses of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopes as well, but limited remaining funds made this impossible. Additionally due to time constraints, archaeological samples were prepared and analyzed prior to having baseline results. Despite not

having baseline data, we elected to analyze  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopes in the archaeological samples because of the geologic diversity of the regions of interest (Tables 2-3).

Ø171 is a medium farmstead “that could have been [a] cottage under [a] major farmstead” established in the central Vatnahverfi area in the Eystribyggð, occupied between the early 11th to the mid-13th century (Madsen 2014, 216). A midden associated with the site was investigated in 2011 and more recently in 2016, revealing good preservation of organic materials. Samples selected for the pilot study include worked wooden debris and woodchips, as well as unworked twigs and small branches from two distinct stratigraphic units.

Although Ø171 is not interpreted as a political or economic center, imported wooden materials might have found their way to it, an assumption that is supported by the discovery of a few ceramic sherds during the 2016 investigation of the midden. To date, there is no evidence for locally made ceramic containers in Norse Greenland, implying that these items were imported (Høgsberg 2017). The foreign and presumably expensive ceramic items likely would have been considered an exclusive goods reserved only for those having the right economic, cultural, and social connections.

## 7. Biogeochemical methods

Water, soil, and modern plant samples, as well as archaeological wood samples were prepared at Arizona State University’s (ASU) Archaeological Chemistry Laboratory. Water samples ( $n = 27$ ) were sent to the Colorado Plateau Stable Isotope Laboratory (CPSIL) at Northern Arizona University for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  analysis on the LGR Liquid Water Isotope Analyzer DLT-100. Typical internal CPSIL secondary check standard error precision was 0.02 for  $\delta^2\text{H}$ , and 0.03 for  $\delta^{18}\text{O}$ .

Remaining water and plant baseline samples ( $n = 72$ ) and archaeological samples ( $n = 20$ ) were prepared for  $^{87}\text{Sr}/^{86}\text{Sr}$  analysis following standard laboratory procedures described in Pacheco-Forés et al. (2020) that prioritize the release of bioavailable strontium in plants. Soil samples ( $n = 27$ ) were dried for 48 hours at  $120^\circ\text{C}$ . They were then partially dissolved in 10 mL of 1 M ammonium acetate ( $\text{CH}_3\text{COONH}_4$ ) at room temperature for 24 hours and decanted, following procedures established in Blum (2000). This method maximizes the release of bioavailable strontium while minimizing the release of strontium that is tightly bound in the mineral crystal lattices of the soil and thus not bioavailable.

Water, soil, and plant samples being analyzed for  $^{87}\text{Sr}/^{86}\text{Sr}$  were digested in concentrated nitric acid and diluted to a 2 M stock solution at the Metals, Environmental, and Terrestrial Analytical Laboratory (METAL) at ASU. A small subsample, or aliquot, of each sample was taken for elemental concentration characterization by a Thermo Fisher Scientific iCAP quadrupole inductively coupled plasma mass spectrometer (Q-ICP-MS). Strontium was isolated from the sample matrix on a PrepFAST automated low-pressure ion exchange chromatography system (Romaniello et al. 2015) using Elemental Scientific, Inc. supplied Sr-Ca ion exchange resin and ultrapure 5 M  $\text{HNO}_3$ . Strontium cuts from the PrepFAST were dried down in Teflon beakers and digested with concentration nitric acid and 30%  $\text{H}_2\text{O}_2$  to remove organics from the resin. Once

digested, samples were again dried down and reconstituted with 0.32 M HNO<sub>3</sub>. Aliquots from approximately 14% of samples were measured on the Q-ICP-MS before and after chemical purification to determine chemical recovery. Average chemistry yield was 78% ± 0.19 (n = 18). Using elemental concentration information from the Q-ICP-MS, the samples were diluted with 0.32 M HNO<sub>3</sub> to a calculated constant concentration of 50 ppb Sr. <sup>87</sup>Sr/<sup>86</sup>Sr ratios were measured on a Thermo-Finnigan Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS).

Data were collected over two analytical sessions by measuring 60 simultaneous ratios integrating 4.194 seconds each. Samples were corrected for on-peak blanks, and in-line correction of the contributions of <sup>84</sup>Kr on <sup>84</sup>Sr and <sup>86</sup>Kr on <sup>86</sup>Sr using <sup>83</sup>Kr/<sup>84</sup>Kr ratio of 0.201750 and <sup>83</sup>Kr/<sup>86</sup>Kr ratio of 0.664533, after instrumental mass bias correction using a normalizing <sup>88</sup>Sr/<sup>86</sup>Sr ratio of 8.375209. Average sensitivity was 18 V on <sup>88</sup>Sr with a 50 ppb Sr solution, with <sup>83</sup>Kr values <0.0001 V. <sup>85</sup>Rb voltages for samples were typically <0.001 V due to the low Rb/Sr initial ratios of the samples and effective chemical purification, but all data was interference-corrected using a <sup>85</sup>Rb/<sup>87</sup>Rb ratio of 2.588960, normalized to <sup>88</sup>Sr/<sup>86</sup>Sr as above. Ratio outliers two standard deviations outside the mean were removed using a Matlab 2D-mathematical correction routine written by Dr. Stephen Romaniello, at the University of Tennessee. Typical internal <sup>87</sup>Sr/<sup>86</sup>Sr two standard error (SE) precision was <1e-5.

Sequences included bracketing concentration matched SRM 987 standards. SRM 987 was run as a bracketing standard with a measured value of <sup>87</sup>Sr/<sup>86</sup>Sr = 0.710126 ± 0.000096 (2σ, n = 258), which is similar to reported values of <sup>87</sup>Sr/<sup>86</sup>Sr of 0.710251 ± 0.000013 (2σ, n = 5; Balcaen et al. 2005). Each analytical session included a sequence incorporating SRM 987 standard in a range of variable concentrations to verify the accuracy of <sup>87</sup>Sr/<sup>86</sup>Sr values for samples; reported values are all above the threshold for accurate <sup>87</sup>Sr/<sup>86</sup>Sr values within the range of error of the bracketing standards. In addition, SRM 987 doped with calcium up to a ratio of Ca/Sr of 500 was run to simulate the accuracy and precision of isotope ratios in poorly purified samples with low yields. SRM 987 run at 50% concentration doped to a Ca/Sr of 500 was run as a check standard with a measured value of <sup>87</sup>Sr/<sup>86</sup>Sr = 0.710137 ± 0.000131 (2σ, n = 42). IAPSO seawater (Ocean Scientific International Ltd., Havant, UK) run as a secondary check standard had a measured value of 0.709181 ± 0.000009 (2σ, n = 8), in agreement with the published value of 0.709182 ± 0.000004 (Ma et al. 2013). NIST 1400 purified in parallel with samples had a measured value of 0.71305 ± 0.000147 (2σ, n = 9), within error of the published value of 0.713150 ± 0.000016 (Galler et al. 2007). Approximately 5% of samples (n = 6) were run in triplicate, with an average precision on individual measurements of ±0.00005 (2σ).

## 8. Results and discussion

Observed δ<sup>2</sup>H, δ<sup>18</sup>O, and <sup>87</sup>Sr/<sup>86</sup>Sr values for all analyzed water, soil, and plant baseline samples are reported in Appendix 1. Mean and range baseline values for analyzed isotopic systems across each region are reported in Table 4.

| Region       | $\delta^2\text{H}$                  |         |        |    | $\delta^{18}\text{O}$              |        |        |    | $^{87}\text{Sr}/^{86}\text{Sr}$        |         |         |    |
|--------------|-------------------------------------|---------|--------|----|------------------------------------|--------|--------|----|--|---------|---------|----|
|              | Mean                                | Min     | Max    | n  | Mean                               | Min    | Max    | n  | Mean                                   | Min     | Max     | n  |
| Greenland    | -94.04<br>$\pm 15.39$ ( $2\sigma$ ) | -107.93 | -86.42 | 12 | -12.22<br>$\pm 2.39$ ( $2\sigma$ ) | -14.47 | -11.11 | 12 | 0.71374<br>$\pm 0.00888$ ( $2\sigma$ ) | 0.70817 | 0.72511 | 43 |
| Newfoundland | -60.64<br>$\pm 2.98$ ( $2\sigma$ )  | -62.08  | -58.32 | 9  | -8.31<br>$\pm 0.66$ ( $2\sigma$ )  | -8.88  | -7.75  | 9  | 0.71287<br>$\pm 0.00386$ ( $2\sigma$ ) | 0.70934 | 0.71729 | 33 |
| Labrador     | -75.89<br>$\pm 19.36$ ( $2\sigma$ ) | -85.27  | -66.55 | 6  | -10.59<br>$\pm 2.22$ ( $2\sigma$ ) | -11.67 | -9.43  | 6  | 0.71221<br>$\pm 0.00474$ ( $2\sigma$ ) | 0.70934 | 0.71732 | 22 |

Table 4. Table displaying the regional mean and range isotopic baseline values. ‘Mean’, ‘Min’ and ‘Max’  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values are expressed in ‰.

Observed  $^{87}\text{Sr}/^{86}\text{Sr}$  values from archaeological wood artifact samples are reported in Table 5. Values range from 0.71156-0.71264, with a mean of  $^{87}\text{Sr}/^{86}\text{Sr}=0.71241 \pm 0.00066$  ( $2\sigma$ ,  $n=20$ ).

| ACL Number | Specimen Number    | Wood Identification                | $^{87}\text{Sr}/^{86}\text{Sr}$ |
|------------|--------------------|------------------------------------|---------------------------------|
| ACL-9974   | GRE-E171-A#354-S01 | <i>Larix</i> sp.                   | 0.71156                         |
| ACL-9975   | GRE-E171-A#354-S02 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71193                         |
| ACL-9976   | GRE-E171-A#354-S03 | <i>Salix</i> sp.                   | 0.71257                         |
| ACL-9977   | GRE-E171-A#354-S04 | <i>Alnus</i> sp.                   | 0.71257                         |
| ACL-9978   | GRE-E171-A#354-S05 | <i>Salix</i> sp.                   | 0.71249                         |
| ACL-9979   | GRE-E171-A#354-S06 | <i>Larix</i> sp.                   | 0.71260                         |
| ACL-9980   | GRE-E171-A#354-S07 | <i>Betula</i> sp.                  | 0.71264                         |
| ACL-9981   | GRE-E171-A#354-S08 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71247                         |
| ACL-9982   | GRE-E171-A#354-S09 | <i>Picea</i> sp.                   | 0.71256                         |
| ACL-9983   | GRE-E171-A#354-S10 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71261                         |
| ACL-9984   | GRE-E171-A#344-S11 | <i>Larix</i> sp.                   | 0.71242                         |
| ACL-9985   | GRE-E171-A#344-S12 | <i>Alnus</i> sp.                   | 0.71257                         |
| ACL-9986   | GRE-E171-A#344-S13 | <i>Picea</i> sp.                   | 0.71256                         |
| ACL-9987   | GRE-E171-A#344-S14 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71262                         |
| ACL-9988   | GRE-E171-A#344-S15 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71244                         |
| ACL-9989   | GRE-E171-A#344-S16 | <i>Picea</i> sp.                   | 0.71253                         |
| ACL-9990   | GRE-E171-A#344-S17 | <i>Picea</i> sp.                   | 0.71253                         |
| ACL-9991   | GRE-E171-A#344-S18 | <i>Picea</i> sp./ <i>Larix</i> sp. | 0.71160                         |
| ACL-9992   | GRE-E171-A#344-S19 | <i>Pinus</i> sp.                   | 0.71246                         |
| ACL-9993   | GRE-E171-A#344-S20 | Unknown deciduous                  | 0.71264                         |

Table 5. Table displaying the observed  $^{87}\text{Sr}/^{86}\text{Sr}$  values for analyzed archaeological wood samples from Ø171-Tasilikuloq, Greenland. Wood identification by Élie Pinta following standardized procedures by Schweingruber 1990, 2007; Hather 2000; Schoch et al. 2004.

### 8.1.Baseline

Site-specific expected local ranges for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopic systems from study sites across Greenland, Newfoundland, and Labrador are reported in Table 6. Expected local baseline ranges are calculated as two standard deviations from the mean of observed values at each site. Stable hydrogen and oxygen isotope values in analyzed water samples demonstrate a clear discrimination between regions as well as between specific sites considered in this study (Figure 4). Although there is some overlap in  $\delta^2\text{H}$  values (e.g. L'Anse aux Meadows and Pistolet Bay in Newfoundland), as well as in  $\delta^{18}\text{O}$  values (e.g. Igaliku, Greenland and Mary's Harbour, Labrador), the combined use of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  systems allows for biogeochemical differentiation of these sites. This indicates that  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  provide promising means of distinguishing between local and imported wood sources at Greenland Norse settlements.

| Site                    | Location     | $\delta^2\text{H}$ | $\delta^{18}\text{O}$ | n |
|-------------------------|--------------|--------------------|-----------------------|---|
| Narsarsuaq              | Greenland    | -109.77 – -101.333 | -14.87 – -13.313      | 3 |
| NKAH 5500               | Greenland    | -95.59 – -94.243   | -12.44 – -11.663      | 3 |
| Tasilikuloq             | Greenland    | -86.61 – -86.333   | -11.29 – -11.023      | 3 |
| Igaliku                 | Greenland    | -89.75 – -88.653   | -11.87 – -11.283      | 3 |
| L'Anse aux Meadows      | Newfoundland | -62.08 – -60.823   | -8.55 – -8.073        | 3 |
| Pistolet Bay            | Newfoundland | -62.37 – -61.163   | -9.09 – -8.203        | 3 |
| St. Anthony-Island Pond | Newfoundland | -59.35 – -58.033   | -8.36 – -7.593        | 3 |
| L'Anse au Clair         | Labrador     | -68.00 – -66.133   | -9.84 – -9.323        | 3 |
| Mary's Harbour          | Labrador     | -85.70 – -83.743   | -11.81 – -11.383      | 3 |

Table 6. Table displaying the expected local  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  baseline ranges for all analyzed sites expressed in ‰.



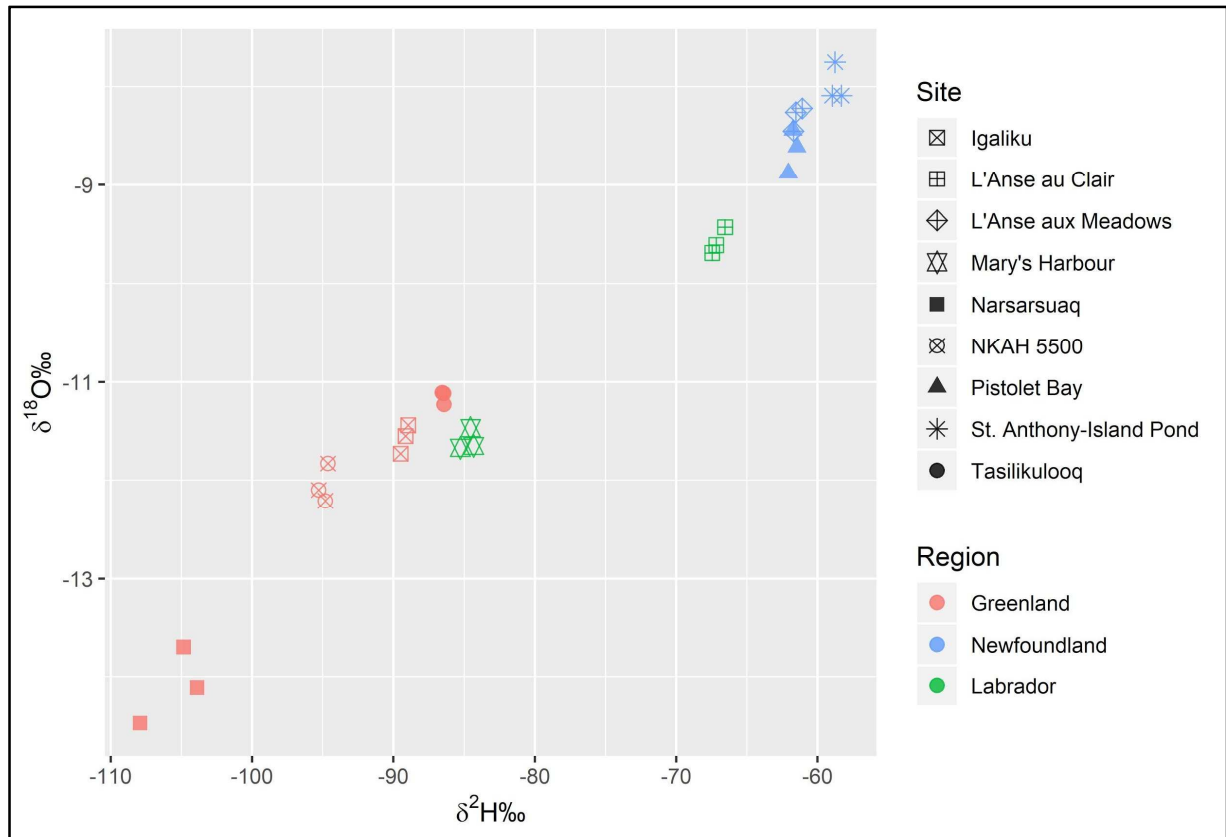


Figure 4. Scatterplot showing analyzed  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values in water samples from the study sites.

In contrast, radiogenic strontium values in water, soil, and modern plants from the study sites provide few clear distinctions between regions of interest and individual sites (Figure 5). Most Greenlandic sites (with the exception of Igaliku), demonstrate a great deal of variability in  $^{87}\text{Sr}/^{86}\text{Sr}$  values. These large local ranges from Greenlandic sampled sites coincide with observed  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges from sites in both Newfoundland and Labrador. Narsarsuaq exhibits the greatest range in observed  $^{87}\text{Sr}/^{86}\text{Sr}$  values. This is likely due to the presence of moraine deposits in the valley connecting the town with the Kiattut and Qooroq glacier, which represent a mixture of eroded rocks and sediments carried from up to several hundred kilometers away (e.g. Kirkbride 2002). Site-specific expected local baseline ranges are reported in Table 7. However, because observed  $^{87}\text{Sr}/^{86}\text{Sr}$  values at many sites are bimodally distributed rather than normally distributed, site baselines are characterized using medians and interquartile ranges, following Price et al. (2008).

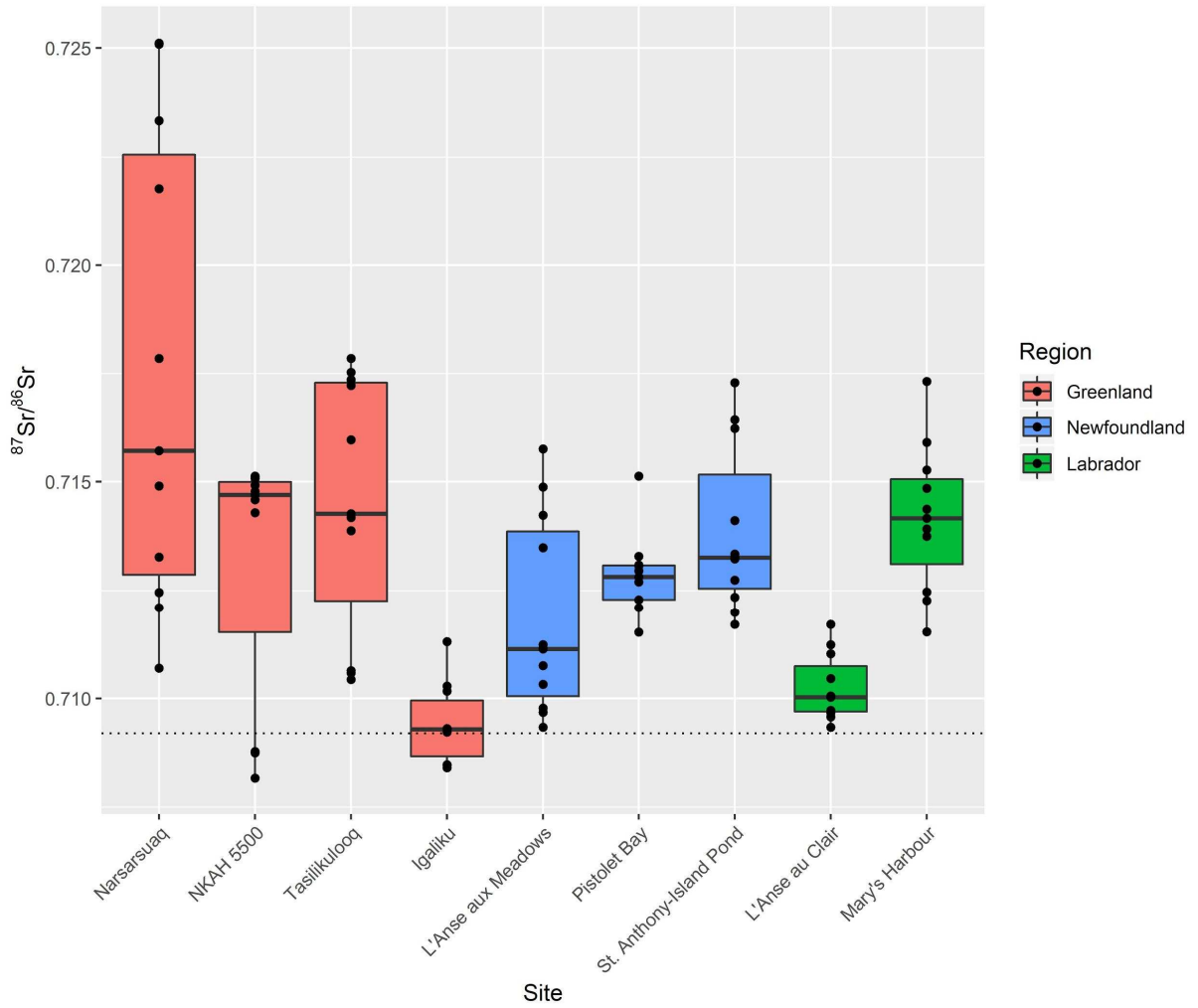


Figure 5. Scatterplot showing analyzed  $^{87}\text{Sr}/^{86}\text{Sr}$  values in water, soil, and modern plant samples from the study sites. The dotted line indicates the seawater average of  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$  (Veizer 1989).

| Site               | Location     | $^{87}\text{Sr}/^{86}\text{Sr}$ | n |
|--------------------|--------------|---------------------------------|---|
| Narsarsuaq         | Greenland    | 0.71287 – 0.7225611             | 8 |
| NKAH 5500          | Greenland    | 0.71154 – 0.7150011             | 8 |
| Tasilikuloq        | Greenland    | 0.71226 – 0.7173011             | 8 |
| Igaliku            | Greenland    | 0.70867 – 0.7099610             | 8 |
| L'Anse aux Meadows | Newfoundland | 0.71006 – 0.7138611             | 8 |
| Pistolet Bay       | Newfoundland | 0.71229 – 0.7130811             | 8 |

|                         |              |                     |   |
|-------------------------|--------------|---------------------|---|
| St. Anthony-Island Pond | Newfoundland | 0.71255 – 0.7151711 | 8 |
| L'Anse au Clair         | Labrador     | 0.70970 – 0.7107511 | 8 |
| Mary's Harbour          | Labrador     | 0.71311 – 0.7150611 | 8 |

Table 7. Table displaying expected local  $^{87}\text{Sr}/^{86}\text{Sr}$  baseline ranges for all analyzed sites.

Lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values are observed the closest to the coast, in particular in Igaliku, Greenland, L'Anse au Clair, Labrador, and L'Anse aux Meadows, Newfoundland. In these areas, lower ratios nearer to the seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  average of 0.7092 are likely the result of the sea spray effect which seems to have particularly impacted the water samples, especially in Greenland where they are consistently lower than  $^{87}\text{Sr}/^{86}\text{Sr}$  values from soil and plants, and the driving factor of observed bimodal distributions at these sites. The impact of sea spray can also be seen at more inland locations, such as NKAH 5500 (~2 km inland), and not only at sites located directly on the seashore. This is consistent with characterizations of bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  in other maritime climates like the British Isles, where sea spray and rainfall derived from seawater make up large contributions to the  $^{87}\text{Sr}/^{86}\text{Sr}$  biosphere of much of western Britain, significantly affecting geologically derived  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Evans et al. 2010).

## 8.2. Archaeological Study

Applying the site-specific expected local  $^{87}\text{Sr}/^{86}\text{Sr}$  baseline to wooden artifacts from Ø171 illustrates both the strengths and challenges associated with using radiogenic strontium isotopes to examine their provenance. A majority of analyzed wood has  $^{87}\text{Sr}/^{86}\text{Sr}$  values falling within Ø171's expected local range ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.71226 - 0.71730$ ). However, of the artifacts with  $^{87}\text{Sr}/^{86}\text{Sr}$  values that appear to be 'local' to Ø171, 11 were identified as being of exogenous origin based on wood taxa identification (Table 5). Only three samples identified as non-Greenlandic native timber (*Picea* sp./*Larix* sp.) fall outside the expected local  $^{87}\text{Sr}/^{86}\text{Sr}$  values for Ø171 (Figure 6). Values non-local to the Ø171 baseline fall within expected local  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges of two of the sites included in this study: NKAH 5500 in Greenland, and L'Anse aux Meadows in Newfoundland. Because of this overlap in  $^{87}\text{Sr}/^{86}\text{Sr}$  values, we cannot draw conclusions about the origins of the wood from these three samples.

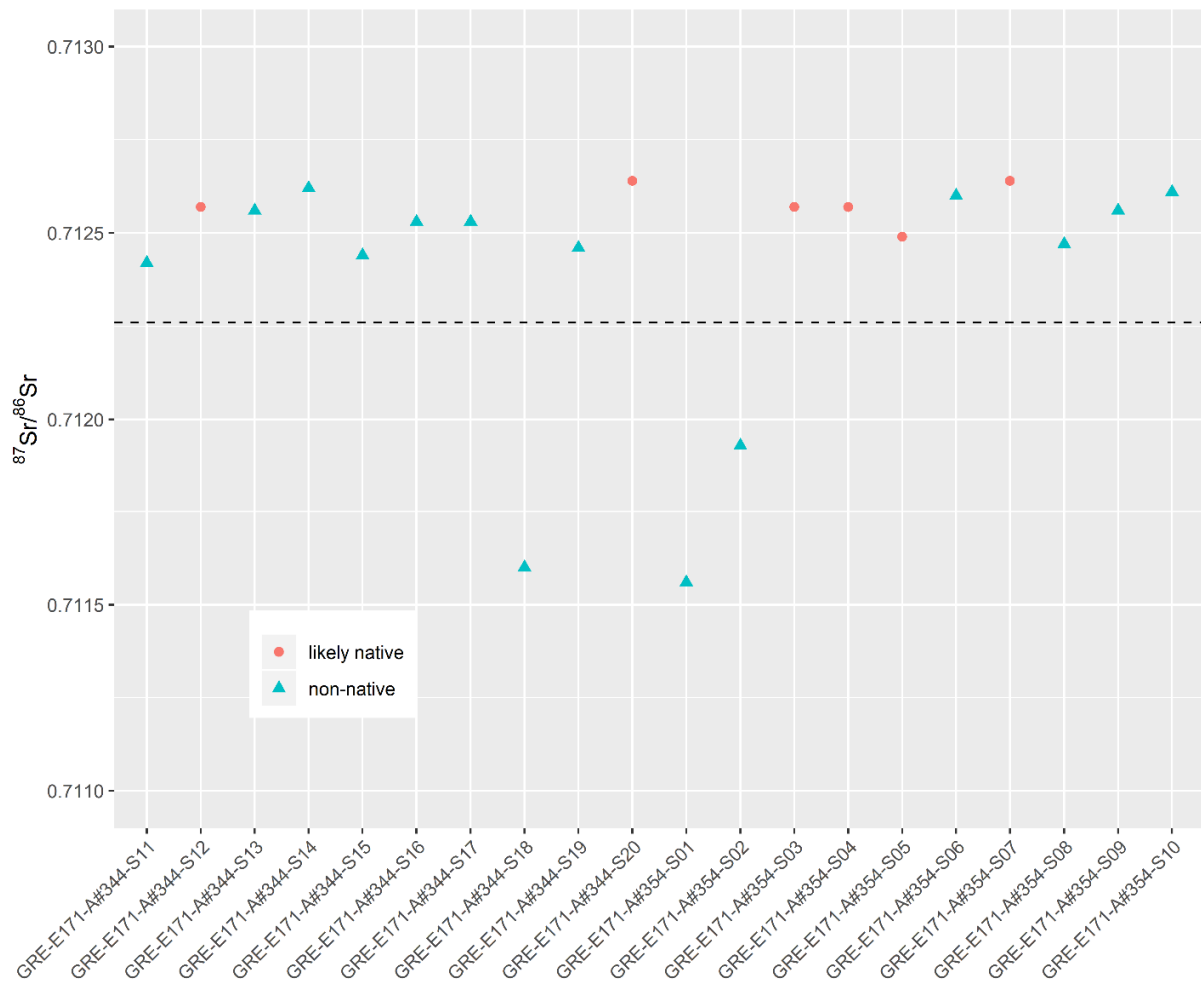


Figure 6. Scatterplot showing  $^{87}\text{Sr}/^{86}\text{Sr}$  values of archaeological wood artifacts from the site Ø171, Greenland. The dashed line indicates the lower boundary of the expected local  $^{87}\text{Sr}/^{86}\text{Sr}$  range for the site. Note: all observed values are significantly higher than the seawater average of  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$  (Veizer 1989).

However, combining biogeochemical results with those of the wood identification, as well as the archaeological context of the Norse Greenlandic settlements, helps better geolocate the provenance of the three isotopically non-local samples. All three are either larch (*Larix* sp.) or undetermined spruce/larch (*Picea* sp./*Larix* sp.), which are not native to Greenland. They therefore cannot have originated from NKAH 5500 and had to be collected as driftwood or imported. Note that larch is not native to northern Europe (Caudullo et al. 2020) and that spruce would not have been a preferred imported taxon (Mooney et al. 2021). It is also worth noting that spruce is very rarely used in Scandinavian boatbuilding (see Mooney 2016b), and thus would not easily be found in Greenland in the form of a reused or salvaged vessel part (see also Andersen and Malmros 1993). The presence of larch (*Larix* sp.) in combination with spruce (*Picea* sp.) is

more likely to reflect an assemblage of either driftwood or imported timber from the North American forests, rather than Scandinavia. Furthermore, all three artefacts are flat wood shavings resulting from woodworking activities which most probably took place at the site, pointing towards the use of raw materials, or partially processed wood. Even if a few examples in the historical literature suggest ships from Norway were transporting timber to Greenland (Larson 1917; ÍF IV 1985), this cargo may not have been distributed evenly across settlements. Although we do not know much about the status of site Ø171 at the moment, it possibly played a subsidiary farmstead role – i.e. where a tenant or cottager lived – to an independent free-holder, perhaps even a magnate (Madsen 2014, 206). If so, its inhabitants may not have owned the land and were probably limited in their actions, although benefiting from a network of kinship and allegiance (e.g. Vésteinsson et al. 2002; Vésteinsson 2007). As mentioned previously, the presence of imported ceramic sherds suggests a connection with mainland Europe (e.g. Høegsberg 2017). If Ø171's inhabitants could afford to trade in pottery, their social status may have also allowed them access to timber, mostly primarily as driftwood (e.g. Andersen and Malmros 1993; Pinta 2018), but perhaps also as an imported/traded commodity. While some suggest only a limited group of Greenland's elite was in charge of the exploitation of resources from the *óbyggðir* (Ljungqvist 2005; Wallace 2009), others note that smallholders were also part of these expeditions (McGovern 1985). Considering the presence of ceramic sherds at Ø171 is a sign of relative wealth, the involvement of its inhabitant in the westward voyages is a conceivable scenario.

The incongruity between the biogeochemical and wood identification results indicates that diagenetic processes have likely skewed the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of all recovered artifacts, making non-native wood species appear isotopically 'local'. These same processes, however, also masked any potential marine  $^{87}\text{Sr}/^{86}\text{Sr}$  signature similar to the seawater average, making it impossible to identify or rule out driftwood as a possible source of the non-native wood artifacts. Thus, while we cannot assume that any of the reported values reflect the original biogenic or seawater (via immersion)  $^{87}\text{Sr}/^{86}\text{Sr}$ , the persistence of three non-local  $^{87}\text{Sr}/^{86}\text{Sr}$  values indicates that diagenetic processes, at least in some cases, were not sufficient to mask a non-local or possibly marine  $^{87}\text{Sr}/^{86}\text{Sr}$  signature.

In conclusion, combining biogeochemical methods with taxonomic provenancing and anthropological data provided 1) the ability to confirm that at least three samples are non-Greenlandic native, and 2) it supported the role played by L'Anse aux Meadows as part of a remote resource acquisition system for the Norse settlements. However, it is still inconclusive how to differentiate between the importation of raw or rough-hewn timber, possibly from Northeastern America, or the exploitation of driftwood. Moving forward, a multi-isotope approach incorporating  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope systems alongside  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopes has the potential to yield more conclusive data, as the former isotope systems demonstrated greater discrimination between regions of interest to Norse Greenlandic wood acquisition patterns.

## 9. Conclusions and future work

This study uses biogeochemical analyses of stable hydrogen ( $\delta^2\text{H}$ ), stable oxygen ( $\delta^{18}\text{O}$ ), and radiogenic strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotopes in modern plant, soil and water samples collected in Greenland, Newfoundland, and Labrador to better understand the use of local, drifted, and imported wood resources in Norse Greenland. These data show that observed local ranges among strontium isotope ratios are highly variable and tend to overlap considerably, thus providing only limited distinctions between regions of interest. A pilot study of  $^{87}\text{Sr}/^{86}\text{Sr}$  values in archaeological wood samples from Greenland helped reaffirming patterns observed in previous studies, suggesting timber importation, possibly from the Northeastern American coast, may have supplemented the exploitation of local driftwood (e.g. Andersen and Malmros 1993; Pinta 2018). On the other hand, generated local baselines for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope ratios clearly discriminate between regions as well as between specific sites. While inclusion of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  in our pilot study was not possible at the time of analysis, this is a promising avenue of future research. Finally, the study notes the need to develop a more comprehensive strontium isoscape for the regions in question. Special attention must also be given to modern contaminants of  $^{87}\text{Sr}/^{86}\text{Sr}$  values in Greenland, which may likely have been affected by climate change related glacial melt. Recent research (Wallace 2020) used a mechanistic lithological predictive model (see Bataille and Bowen 2012) to map the spatial distribution of bioavailable strontium throughout Newfoundland, Labrador, and Greenland. This work is ongoing and will be further refined by the large-scale acquisition of soil, water, and vegetation samples, whose  $^{87}\text{Sr}/^{86}\text{Sr}$  values would then be compared against the mechanistic predicted isotopic ratios using a machine learning approach (see Bataille et al. 2018) to create a more accurate isoscape. Analyzing hydrogen, oxygen, and strontium isotope systems in concert will provide further insights into questions related to Norse mobility, craftsmanship and resource acquisition strategies in the Norse Greenlandic settlements and the wider North Atlantic.

## 10. Appendix

| Lab Number | Specimen Number | Site       | Location | Coordinates                 | Altitude (masl) | Material | $\delta^2\text{H}$ | $\delta^{18}\text{O}$ | $^{87}\text{Sr}/^{86}\text{Sr}$ |
|------------|-----------------|------------|----------|-----------------------------|-----------------|----------|--------------------|-----------------------|---------------------------------|
| ACL-9839   | GRE-01-P01      | Narsarsuaq | GL       | N61°09.897'<br>W045°24.154' | -               | Plant    |                    |                       | 0.72334                         |
| ACL-9840   | GRE-01-P02      | Narsarsuaq | GL       | N61°11.892'<br>W045°19.740' | 10              | Plant    |                    |                       | 0.71785                         |
| ACL-9841   | GRE-01-P03      | Narsarsuaq | GL       | N61°11.873'<br>W045°19.842' | 2               | Plant    |                    |                       | 0.72509                         |
| ACL-9842   | GRE-01-P04      | Narsarsuaq | GL       | N61°11.101'<br>W045°19.905' | 41              | Plant    |                    |                       | 0.71327                         |
| ACL-9843   | GRE-01-P05      | Narsarsuaq | GL       | N61°11.101'<br>W045°19.905' | 41              | Plant    |                    |                       | 0.71490                         |
| ACL-9844   | GRE-01-S01      | Narsarsuaq | GL       | N61°11.873'                 | 2               | Soil     |                    |                       | 0.72178                         |

|          |              |             |    |                             |    |       |         |        |         |
|----------|--------------|-------------|----|-----------------------------|----|-------|---------|--------|---------|
|          |              |             |    | W045°19.842'                |    |       |         |        |         |
| ACL-9845 | GRE-01-S02   | Narsarsuaq  | GL | N61°11.101'<br>W045°19.905' | 41 | Soil  |         |        | 0.71571 |
| ACL-9846 | GRE-01-S03   | Narsarsuaq  | GL | N61°12.203'<br>W045°19.578' | 26 | Soil  |         |        | 0.72511 |
| ACL-9847 | GRE-01-W01-1 | Narsarsuaq  | GL | N61°11.892'<br>W045°19.740' | 10 | Water | -107.93 | -14.47 | 0.71070 |
| ACL-9848 | GRE-01-W02-1 | Narsarsuaq  | GL | N61°11.800'<br>W045°20.312' | 21 | Water | -104.84 | -13.69 | 0.71210 |
| ACL-9849 | GRE-01-W03-1 | Narsarsuaq  | GL | N61°11.101'<br>W045°19.905' | 41 | Water | -103.89 | -14.11 | 0.71246 |
| ACL-9853 | GRE-02-P01   | NKAH 5500   | GL | N60°52.400'<br>W045°14.529' | 88 | Plant |         |        | 0.71459 |
| ACL-9854 | GRE-02-P02   | NKAH 5500   | GL | N60°52.400'<br>W045°14.529' | 88 | Plant |         |        | 0.71492 |
| ACL-9855 | GRE-02-P03   | NKAH 5500   | GL | N60°52.420'<br>W045°14.399' | 81 | Plant |         |        | 0.71510 |
| ACL-9856 | GRE-02-P04   | NKAH 5500   | GL | N60°52.420'<br>W045°14.399' | 81 | Plant |         |        | 0.71470 |
| ACL-9857 | GRE-02-P05   | NKAH 5500   | GL | N60°52.351'<br>W045°14.129' | 85 | Plant |         |        | 0.71513 |
| ACL-9858 | GRE-02-S01   | NKAH 5500   | GL | N60°52.400'<br>W045°14.529' | 88 | Soil  |         |        | 0.71429 |
| ACL-9859 | GRE-02-S02   | NKAH 5500   | GL | N60°52.420'<br>W045°14.399' | 81 | Soil  |         |        | 0.71478 |
| ACL-9860 | GRE-02-S03   | NKAH 5500   | GL | N60°52.351'<br>W045°14.129' | 85 | Soil  |         |        | 0.71507 |
| ACL-9861 | GRE-02-W01-1 | NKAH 5500   | GL | N60°52.217'<br>W045°14.567' | 83 | Water | -94.82  | -12.21 | 0.70875 |
| ACL-9862 | GRE-02-W02-1 | NKAH 5500   | GL | N60°52.217'<br>W045°14.567' | 83 | Water | -95.29  | -12.10 | 0.70878 |
| ACL-9863 | GRE-02-W03-1 | NKAH 5500   | GL | N60°52.351'<br>W045°14.129' | 85 | Water | -94.64  | -11.83 | 0.70817 |
| ACL-9867 | GRE-03-P01   | Tasilikuloq | GL | N60°50.004'<br>W045°24.247' | 28 | Plant |         |        | 0.71785 |
| ACL-9868 | GRE-03-P02   | Tasilikuloq | GL | N60°50.004'<br>W045°24.247' | 28 | Plant |         |        | 0.71596 |
| ACL-9869 | GRE-03-P03   | Tasilikuloq | GL | N60°50.058'<br>W045°24.244' | 19 | Plant |         |        | 0.71427 |
| ACL-9870 | GRE-03-P04   | Tasilikuloq | GL | N60°50.012'<br>W045°24.217' | 32 | Plant |         |        | 0.71388 |
| ACL-9871 | GRE-03-P05   | Tasilikuloq | GL | N60°50.012'<br>W045°24.217' | 32 | Plant |         |        | 0.71753 |

|          |              |                       |    |                              |    |       |        |        |         |
|----------|--------------|-----------------------|----|------------------------------|----|-------|--------|--------|---------|
| ACL-9872 | GRE-03-S01   | Tasilikuloq           | GL | N60°50.012'<br>W045°24.217'  | 32 | Soil  |        |        | 0.71418 |
| ACL-9873 | GRE-03-S02   | Tasilikuloq           | GL | N60°50.004'<br>W045°24.247'  | 28 | Soil  |        |        | 0.71723 |
| ACL-9874 | GRE-03-S03   | Tasilikuloq           | GL | N60°50.058'<br>W045°24.244'  | 19 | Soil  |        |        | 0.71736 |
| ACL-9875 | GRE-03-W01-1 | Tasilikuloq           | GL | N60°49.963'<br>W045°24.512'  | 14 | Water | -86.55 | -11.11 | 0.71044 |
| ACL-9876 | GRE-03-W02-1 | Tasilikuloq           | GL | N60°49.963'<br>W045°24.512'  | 14 | Water | -86.42 | -11.23 | 0.71064 |
| ACL-9877 | GRE-03-W03-1 | Tasilikuloq           | GL | N60°49.963'<br>W045°24.512'  | 14 | Water | -86.45 | -11.12 | 0.71059 |
| ACL-9881 | GRE-04-P01   | Igaliku               | GL | N60°59.755'<br>W045°25.424'  | 14 | Plant |        |        | 0.70923 |
| ACL-9882 | GRE-04-P02   | Igaliku               | GL | N60°59.755'<br>W045°25.424'  | 14 | Plant |        |        | 0.70931 |
| ACL-9883 | GRE-04-P03   | Igaliku               | GL | N60°59.944'<br>W045°24.933'  | 33 | Plant |        |        | 0.71131 |
| ACL-9884 | GRE-04-P04   | Igaliku               | GL | N60°59.080'<br>W045°25.589'  | 17 | Plant |        |        | -       |
| ACL-9885 | GRE-04-P05   | Igaliku               | GL | N60°59.014'<br>W045°25.577'  | 53 | Plant |        |        | 0.70930 |
| ACL-9886 | GRE-04-S01   | Igaliku               | GL | N60°59.755'<br>045°25.424'   | 14 | Soil  |        |        | 0.71029 |
| ACL-9887 | GRE-04-S02   | Igaliku               | GL | N60°59.944'<br>W045°24.933'  | 33 | Soil  |        |        | 0.71017 |
| ACL-9888 | GRE-04-S03   | Igaliku               | GL | N60°59.080'<br>W045°25.589'  | 17 | Soil  |        |        | 0.70929 |
| ACL-9889 | GRE-04-W01-1 | Igaliku               | GL | N60°59.755'<br>W045°25.424'  | 14 | Water | -88.96 | -11.44 | 0.70848 |
| ACL-9890 | GRE-04-W02-1 | Igaliku               | GL | N60°59.755'<br>W045°25.424'  | 14 | Water | -89.15 | -11.55 | 0.70846 |
| ACL-9891 | GRE-04-W03-1 | Igaliku               | GL | N60°59.755'<br>W045°25.424'  | 14 | Water | -89.50 | -11.73 | 0.70841 |
| ACL-9895 | NFL-05-P01   | L'Anse aux<br>Meadows | NL | N51°35.549'<br>W055°31.852   | 7  | Plant |        |        | 0.71033 |
| ACL-9896 | NFL-05-P02   | L'Anse aux<br>Meadows | NL | N51°35.549'<br>W055°31.852   | 7  | Plant |        |        | 0.71124 |
| ACL-9897 | NFL-05-P03   | L'Anse aux<br>Meadows | NL | N 51°35.654'<br>W055°31.905' | 7  | Plant |        |        | 0.71114 |
| ACL-9898 | NFL-05-P04   | L'Anse aux<br>Meadows | NL | N 51°35.654'<br>W055°31.905' | 7  | Plant |        |        | 0.71076 |
| ACL-9899 | NFL-05-P05   | L'Anse aux            | NL | N51°35.768'                  | 5  | Plant |        |        | 0.70968 |



|          |              |                        |    |                             |    |       |        |       |         |
|----------|--------------|------------------------|----|-----------------------------|----|-------|--------|-------|---------|
|          |              | Meadows                |    | W055°32.027'                |    |       |        |       |         |
| ACL-9900 | NFL-05-S01   | L'Anse aux Meadows     | NL | N51°35.542'<br>W055°31.877' | 8  | Soil  |        |       | 0.71575 |
| ACL-9901 | NFL-05-S02   | L'Anse aux Meadows     | NL | N51°35.768'<br>W055°32.027' | 5  | Soil  |        |       | 0.70978 |
| ACL-9902 | NFL-05-S03   | L'Anse aux Meadows     | NL | N51°35.768'<br>W055°32.027' | 5  | Soil  |        |       | 0.70934 |
| ACL-9903 | NFL-05-W01-1 | L'Anse aux Meadows     | NL | N51°35.542'<br>W055°31.877' | 8  | Water | -61.71 | -8.45 | 0.71349 |
| ACL-9904 | NFL-05-W02-1 | L'Anse aux Meadows     | NL | N51°35.542'<br>W055°31.877' | 8  | Water | -61.10 | -8.22 | 0.71423 |
| ACL-9905 | NFL-05-W03-1 | L'Anse aux Meadows     | NL | N51°35.542'<br>W055°31.877' | 8  | Water | -61.55 | -8.26 | 0.71488 |
| ACL-9909 | NFL-08-P01   | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Plant |        |       | 0.71229 |
| ACL-9910 | NFL-08-P02   | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Plant |        |       | 0.71296 |
| ACL-9911 | NFL-08-P03   | Pistolet Bay           | NL | N51°29.540'<br>W055°52.366' | 1  | Plant |        |       | 0.71513 |
| ACL-9912 | NFL-08-P04   | Pistolet Bay           | NL | N51°29.540'<br>W055°52.366' | 1  | Plant |        |       | 0.71329 |
| ACL-9913 | NFL-08-P05   | Pistolet Bay           | NL | N51°29.542'<br>W055°52.400' | 2  | Plant |        |       | 0.71309 |
| ACL-9914 | NFL-08-S01   | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Soil  |        |       | 0.71307 |
| ACL-9915 | NFL-08-S02   | Pistolet Bay           | NL | N51°29.540'<br>W055°52.366' | 1  | Soil  |        |       | 0.71229 |
| ACL-9916 | NFL-08-S03   | Pistolet Bay           | NL | N51°29.542'<br>W055°52.400' | 2  | Soil  |        |       | 0.71210 |
| ACL-9917 | NFL-08-W01-1 | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Water | -62.08 | -8.88 | 0.71270 |
| ACL-9918 | NFL-08-W02-1 | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Water | -61.47 | -8.61 | 0.71282 |
| ACL-9919 | NFL-08-W03-1 | Pistolet Bay           | NL | N51°29.487'<br>W055°52.378' | 1  | Water | -61.75 | -8.44 | 0.71153 |
| ACL-9923 | NFL-09-P01   | St Anthony-Island Pond | NL | N51°20.988'<br>W055°34.702' | 51 | Plant |        |       | 0.71171 |
| ACL-9924 | NFL-09-P02   | St Anthony-Island Pond | NL | N51°20.988'<br>W055°34.702' | 51 | Plant |        |       | 0.71334 |
| ACL-9925 | NFL-09-P03   | St Anthony-Island Pond | NL | N51°20.999'<br>W055°34.739' | 51 | Plant |        |       | 0.71729 |
| ACL-9926 | NFL-09-P04   | St Anthony-Island Pond | NL | N51°21.007'<br>W055°34.739' | 54 | Plant |        |       | 0.71235 |

|          |              |                            |     |                             |    |       |        |       |         |
|----------|--------------|----------------------------|-----|-----------------------------|----|-------|--------|-------|---------|
| ACL-9927 | NFL-09-P05   | St Anthony-<br>Island Pond | NL  | N51°21.002'<br>W055°34.400' | 50 | Plant |        |       | 0.71274 |
| ACL-9928 | NFL-09-S01   | St Anthony-<br>Island Pond | NL  | N51°20.988'<br>W055°34.702' | 51 | Soil  |        |       | 0.71326 |
| ACL-9929 | NFL-09-S02   | St Anthony-<br>Island Pond | NL  | N51°21.007'<br>W055°34.739' | 54 | Soil  |        |       | 0.71642 |
| ACL-9930 | NFL-09-S03   | St Anthony-<br>Island Pond | NL  | N51°21.002'<br>W055°34.400' | 50 | Soil  |        |       | 0.71622 |
| ACL-9931 | NFL-09-W01-1 | St Anthony-<br>Island Pond | NL  | N51°20.988'<br>W055°34.702' | 51 | Water | -58.77 | -7.75 | 0.71199 |
| ACL-9932 | NFL-09-W02-1 | St Anthony-<br>Island Pond | NL  | N51°20.988'<br>W055°34.702' | 51 | Water | -58.97 | -8.09 | 0.71323 |
| ACL-9933 | NFL-09-W03-1 | St Anthony-<br>Island Pond | NL  | N51°20.988'<br>W055°34.702' | 51 | Water | -58.32 | -8.09 | 0.71411 |
| ACL-9937 | LAB-06-P01   | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Plant |        |       | 0.71003 |
| ACL-9938 | LAB-06-P02   | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Plant |        |       | 0.71006 |
| ACL-9939 | LAB-06-P03   | L'Anse au<br>Clair         | LAB | N51°26.466'<br>W057°02.241' | 95 | Plant |        |       | 0.71171 |
| ACL-9940 | LAB-06-P04   | L'Anse au<br>Clair         | LAB | N51°26.466'<br>W057°02.241' | 95 | Plant |        |       | 0.71003 |
| ACL-9941 | LAB-06-P05   | L'Anse au<br>Clair         | LAB | N51°26.468'<br>W057°02.171' | 90 | Plant |        |       | 0.70967 |
| ACL-9942 | LAB-06-S01   | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Soil  |        |       | 0.71046 |
| ACL-9943 | LAB-06-S02   | L'Anse au<br>Clair         | LAB | N51°26.466'<br>W057°02.241' | 95 | Soil  |        |       | 0.71124 |
| ACL-9944 | LAB-06-S03   | L'Anse au<br>Clair         | LAB | N51°26.468'<br>W057°02.171' | 90 | Soil  |        |       | 0.71103 |
| ACL-9945 | LAB-06-W01-1 | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Water | -67.18 | -9.61 | 0.70973 |
| ACL-9946 | LAB-06-W02-1 | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Water | -67.46 | -9.69 | 0.70934 |
| ACL-9947 | LAB-06-W03-1 | L'Anse au<br>Clair         | LAB | N51°26.448'<br>W057°02.243' | 76 | Water | -66.55 | -9.43 | 0.70958 |
| ACL-9951 | LAB-07-P01   | Mary's<br>Harbour          | LAB | N52°18.056'<br>W055°51.512' | 3  | Plant |        |       | 0.71437 |
| ACL-9952 | LAB-07-P02   | Mary's<br>Harbour          | LAB | N52°18.056'<br>W055°51.512' | 3  | Plant |        |       | 0.71485 |
| ACL-9953 | LAB-07-P03   | Mary's<br>Harbour          | LAB | N52°18.054'<br>W055°51.527' | 11 | Plant |        |       | 0.71375 |
| ACL-9954 | LAB-07-P04   | Mary's                     | LAB | N52°18.054'                 | 11 | Plant |        |       | 0.71590 |

|          |              |                |     |                             |    |       |        |        |         |
|----------|--------------|----------------|-----|-----------------------------|----|-------|--------|--------|---------|
|          |              | Harbour        |     | W055°51.527'                |    |       |        |        |         |
| ACL-9955 | LAB-07-P05   | Mary's Harbour | LAB | N52°18.045'<br>W055°51.560' | 17 | Plant |        |        | 0.71527 |
| ACL-9956 | LAB-07-S01   | Mary's Harbour | LAB | N52°18.056'<br>W055°51.512' | 3  | Soil  |        |        | 0.71732 |
| ACL-9957 | LAB-07-S02   | Mary's Harbour | LAB | N52°18.054'<br>W055°51.527' | 11 | Soil  |        |        | 0.71416 |
| ACL-9958 | LAB-07-S03   | Mary's Harbour | LAB | N52°18.045'<br>W055°51.560' | 17 | Soil  |        |        | 0.71392 |
| ACL-9959 | LAB-07-W01-1 | Mary's Harbour | LAB | N52°18.056'<br>W055°51.512' | 3  | Water | -85.27 | -11.67 | 0.71247 |
| ACL-9960 | LAB-07-W02-1 | Mary's Harbour | LAB | N52°18.056'<br>W055°51.512' | 3  | Water | -84.34 | -11.65 | 0.71227 |
| ACL-9961 | LAB-07-W03-1 | Mary's Harbour | LAB | N52°18.056'<br>W055°51.512' | 3  | Water | -84.55 | -11.47 | 0.71154 |

Table A. Table displaying observed  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , and  $^{87}\text{Sr}/^{86}\text{Sr}$  values obtained from modern plant, soil and water samples for establishing a biogeochemical baseline. Notes: GL: Greenland, NL: Newfoundland, LAB: Labrador, masl: meter above sea level.

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