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OF OSLO

Master's Thesis

Progression of Pre-Viking Age and Viking Age Maritime Technology

The Geographic Progression of Scandinavian Sail Technology from the Baltic to the North Atlantic

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Foreword

This Master's Thesis was researched and written to fulfill the graduation requirement of the University of Oslo and University of Iceland for Viking and Medieval Norse Studies. I researched and wrote this Thesis from January to May 2023.

I decided to research this topic due to a new found interest in sailing resulting from a purchase and restoration of a sailboat. The difficulties of perfecting the skill of sailing gave me a keen appreciation for the Vikings who sailed in open hulled primitive ships.

I would like to thank my Mentor, Anders Winroth, whose book, *The Age of the Vikings*, inspired my interest in Viking history. I would like to thank Alessandro Palumbo for his clear and helpful advice during the review process of this thesis. I would also like to thank my parents for supporting my desire to study in Iceland and Norway.

Finally, I would like to thank my friends. The people who I have met in both Iceland and Norway, as well as my closest and very dear friends who I was not able to be with for the last two years. Thank you for your company, friendship and support in times of need.

To all who read this Thesis, I hope you enjoy the subject, and the way I have presented it.

Noah Meseck

Oslo, Norway May 31, 2023

Summary

This paper examines the introduction of sail power to the ships of Scandinavia during an approximate 350 year period from just before the beginning of, and to the end of, the Viking Era. The Viking Era being bookmarked between the Raid on Lindisfarne in 793 AD, to the Battle of Stamford Bridge in 1066 AD. This thesis reviews the advancements in sailing that developed prior to and during the Viking Era. I examined sailing technology improvements, and evidence of sailing was examined along a geographic line flowing from the archipelago of islands in the Ålands Sea south past Gotland, and through the Baltic before heading out to the North Sea, beyond to the Norwegian Sea, and across the North Atlantic to North America. I believe that sail technology developed along this path for a number of reasons. The navigational challenges along this geographic path increased incrementally. When I examined the economic challenges of adding sails, it was clear that the Ålands Sea provided the best risk reward ratio for the introduction of sail power. Once sailing made sense from a risk and economic standpoint, sail power was adopted over a period of perhaps ten decades. I examined a timeline of archeological ship finds in this paper, with the technological advancements of each ship noted along with the historical context for each vessel. I also researched the reconstructions of each ship (if any), along with knowledge gained through this experimental archaeology. Next, I examined general sailing conditions along the same geographical path from the Ålands Sea to the North Atlantic. I also researched the iconographic evidence along the same path. Unfortunately, there is a lack of archeological ship evidence during the period of the most transformative development. This time period is bookended by the Oseberg ship built in 820 AD, and the much more advanced Gokstad ship of 890 AD. By the end of the ninth century, the design of the Gokstad ship demonstrates that Viking sailing had taken great leaps forward, and ship building technology was sufficiently developed to provide reliable maritime transport throughout the North Sea and the Atlantic. The evidence I found in ship design after the Gokstad ship showed that improvements continued throughout the age which specialized sail power for specific tasks, including troop transport, economic cargo transport, and regional trade and defense. These ship building advancements were not necessary for the Vikings to journey west across the Atlantic. I believe the next technology required to make this possible was navigational skills. I examined the types of skills and tools that would have been developed. I also used an example from the written sources to

prove the skill sets that were developed by the time of the discovery of North America by Bjarni Herjólfsson. The sailing conditions, archaeological evidence, and navigational skills required in each region, as well as iconographic evidence, all support the development of sailing along the path from the Ålands Sea, south past Gotland through the Baltic Sea, out into the North Sea by way of the Danish Straits, and onward across the Norwegian Sea to Greenland and North America.
Keywords: Viking Sailing Ships, Scandinavian Sail Technology, Viking Adoption of Sail Timeline

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Appendix

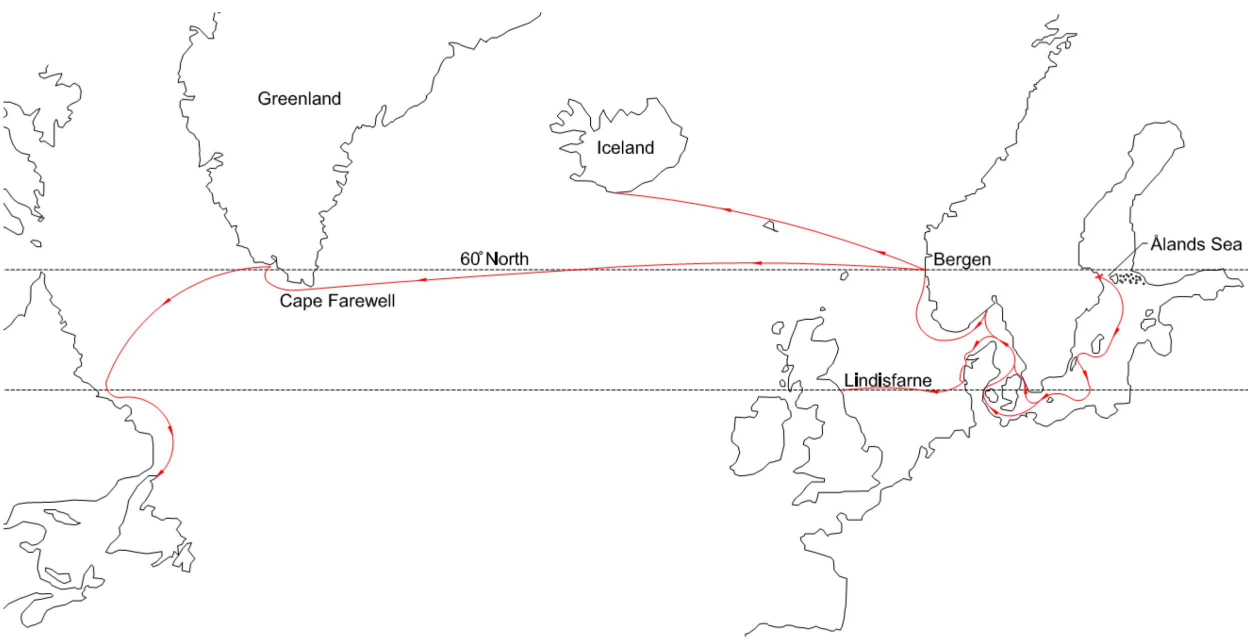
Introduction

The people of Scandinavia were a seafaring people. The geography in which they lived made this a necessity. The world's oldest depiction of a boat was discovered in a rock carving at Valle by the Efjord in Fordland County in Northern Norway. The carving is estimated to be between 10,000 and 11,000 years old and depicts a skin boat.[1] Only a small percentage of the population of Scandinavia were sailors. Regardless of this fact, Scandinavians of the Viking Era are identified with their long, narrow clinker-built ships which are credited with their ability to carry out raids, project power abroad, and settle new lands. These ships are usually depicted with one square rigged sail on a center mast. It is not uncommon for those researching Viking ships to speculate that sail propulsion was used earlier than the archaeological record seems to suggest. In early research into the adoption of sail power in Scandinavia, I did not find work that covered a possible starting point for the use of sail power or progression of the technology from one place to another. The recent discovery of a Scandinavian sailing ship in Salme Estonia, near some of what is purported to be some of the best sailing waters in Scandinavia, made me wonder if the Scandinavians may have started adopting sails in this area. Some quick research into Baltic sailing led me to believe that this was very probable. In researching the introduction of sail propulsion to Viking ships, I found archeological evidence to suggest that the Scandinavians began using sail propulsion regularly only when it made economic sense to do so, and developed new technology along a logical geographic path of ever more complicated sailing conditions. My sailing experience, and the experience of those who sailed the replica constructions, present a picture of ships that were certainly very swift, but had sufficient issues from a sailing and safety standpoint that would have made one hesitate to put to sea. This is particularly true in the early ships like the Oseberg ship. As a result, when sailing was introduced, evidence and good sailing practice suggest that it developed first where favorable wind power and geography made its use the most practicable. I believe that evidence suggests that the development and use of sailing ships developed from the regions where sailing provided the least risk to areas where increasing skill and technology were required. I believe progression occurred in a geographic line, beginning in the Ålands Sea south to Gotland, through Denmark into the North Sea, and finally

[1] Gotland Museum and respective authors, "GOTLAND'S PICTURE STONES Bearers of an Enigmatic Legacy," PDF gotländskt arkiv 2012 Reports from the Friends of the Historical Museum Association Volume 84, 2012, https://uni.hi.is/adalh/files/2013/02/Hildr-Eng.pdf.

across the Norwegian Sea to Iceland, then across the North Atlantic to Greenland and North America (reference map below). I believe this progression is supported by archeological evidence. I have reviewed the archaeological ship finds, and have listed them in chronological order to show how technology progressed. I also believe this path to the open sea is supported by the geography and sailing conditions which become increasingly challenging following a path from the Ålands Sea to the Denmark Strait on the east coast of Greenland. I feel that to make ever longer crossings, the Vikings would have had to develop navigational tools and skills which I researched, and which also supports the same geographic line of sailing progression. A review of iconographic evidence follows chronologically along this same path. As the Vikings improved sailing technology and navigational skill, they were able to sail farther afield eventually navigating around Cape Farewell on the southern tip of Greenland and on to North America.

Map of the Path of Sailing Development



Map Drawn By: Noah Meseck

Previous Research

For Ships

The book series *Ships and Boats of the North, Volumes 1,2,3,4.1 and 5* from the Viking Ship Museum in Roskilde, with contributions from other organizations and museums, is the most comprehensive source of information on the archaeological record of Norse ships. The information in these books is a must have for anyone interested in this subject. In general, the work of the Viking Ship Museum in Roskilde Demark is second to none in working knowledge of Viking era ships.

For Sails

The Introduction of Sails to Scandinavia: Raw Materials, Labor, and Land by: Lise Bender Jørgensen, Norwegian University of Science and Technology provided critical information about the resources required to manufacture sails and rigging. This paper is a valuable resource for understanding of the skills and resources needed for sail power of Viking Era ships.

Viking-Age Sails: Form and Proportion by Vibeke Bischoff, published online 6 January 2017 by Springer Science+Business Media New York provided a good introduction to both sails and rigging.

For Navigation and All Around Viking Ship Knowledge

The Oseberg ship: Reflections on the choice of methodology when testing experimental archaeological reconstructions by Vibeke Bischoff, provided great insight into the performance of the Saga Oseberg reconstruction. This account of sailing performance was very helpful in understanding the level of sailing ability that may have existed at the beginning of the Viking era.

The interviews with the captains of all of the Viking reconstructions were very insightful. Both my interview with Jan Knutsen (see Appendix) and the online interviews with the Captains of the Ottar and the Draken Harald Hårfagre.

Method

I organized this thesis in a way that would hopefully give the reader an understanding of the process of adopting sail power. Sailing can be frustrating at times, changing quickly to terrifying. This is why I suggest that the use of sail power would have developed first in an area where sailing would have been easy to learn and develop. Once the decision is made to start sailing, the next hurdle to overcome would have been the cost of adding all of the accoutrements to the ship that would have allowed for the safe efficient use of sail power. After the first two hurdles were overcome, the next steps would have been the gradual development of sailing technology, which is evidenced in the chronological list of archaeological ship finds. To fully understand the advancements of each ship, I also reviewed the reconstructions and their sailing characteristics. To support my theory of the path of development from the Ålands Sea out of the Baltic, I reviewed the sailing conditions along this path demonstrating the ever-increasing level of sailing skills needed for each geographic step. As further support, I followed the timeline of iconographic evidence along the same path.

The topics are presented in the following order:

Dangers of Sailing: Sailing is unpredictable and introduces dangerous, often disastrous risks of sailing that rowing does not. I have recently purchased a sailboat which has given me a new perspective on this method of propulsion. I can now understand many reasons that sailing would have been avoided. I started this paper by describing the pitfalls of sail power.

Agriculture and the Cost of Adding Sails: Evidence shows that adding sail power to a ship was very expensive. As a result, the return on investment had to make sense. I reviewed the extensive process of harvesting and weaving materials for sails and rigging which demonstrate these expenses.

Hull and Rigging Design: The long narrow clinker-built ships favored by the Scandinavians were fast with a shallow draft, but not designed for safe sailing at first. As time went on, design changes made the ships more seaworthy. As this happened, the Vikings were able to travel to previously unreachable destinations with regularity and relative safety. Along with improved hull design, sail and rigging technology had to be developed by trial and error through years of sailing since few had taken to the open oceans prior to this time. Unfortunately, a seaworthy ship equal to the task of the Raid at Lindisfarne has not yet been discovered, which leaves the conclusion to be either there were ships closer to the technology found in the 890 AD Gokstad ship, or the raid was conducted using the technology found in the Oseberg ship.

Availability of useful wind: With the risk and expense of sail power considered, it would not make sense to add a sail to a ship if there wasn't adequate useable wind power in the right direction to propel the ship more efficiently than oar power. The difficulty in this section was finding useable data on winds in the open ocean. In the end, I had to be content with general data for each region which is perhaps all the Viking would have had at the time.

Learning Navigation: Sailing beyond sight of land for any length of time requires a sailor to develop methods of navigation. To be successful, the Vikings needed to find ways to set a course, determine latitude, and determine distance sailed east and west (longitude).

Iconographic Evidence of Sailing: In addition to the logical progression of technology related to geography and sailing conditions, sailing can be traced by iconographic evidence. Picture stones, coins, and other artwork with depictions of sails can help tell the story of sail adoption and its migration. The timeline of the iconographic evidence followed the same path from the Baltic as my theoretical pathway of sail technology.

Evaluation

The Dangers of Sailing

I recently purchased and restored an old sailboat and started to sail. While there was a lot of good information on sailing available, nothing you read could communicate what the experience of being on a boat powered by something as dynamic as the wind can give you. Watching a boat under sail from the shore, you may think it is one of the most relaxing methods of transportation you could experience. This is far from the truth. Sailing particularly if is a new experience, is difficult. For this reason, sailing is considered a sport. It can also be unpredictable and terrifying at times. Those who have sailed even for a short time, have stories of frightening or even dangerous experiences. Most of these are due to the sometimes sudden and dramatic changes in the wind. The other experience that is common among those who have been on a sailboat is the boredom and frustration of having little or no wind. The design of a Viking long ship is in general long, narrow in beam, and shallow in draft. The length and shallow draft of these ships would have given the craft the advantage of speed. Speed is advantageous, but it isn't everything. The narrow beam and shallow draft would have given the ships a tendency to heel over in high winds. This could be counteracted when under steady wind by moving the crew to windward to level the ship. Often winds can change quickly and with little warning. When this happens, the condition of the ship and sea state can change rapidly resulting in a sudden heeling of the ship to leeward. The heeling of the boat allows waves to come over the sides of the ship more easily. If the ship heeled over enough, sea water would sweep into the ship resulting in the catastrophic and sudden sinking of the vessel. The ships of the Viking era did not have watertight decks that could shed sea and rainwater out of the ship through scuppers. Without a watertight deck and scupper system, these vessels would be vulnerable to sinking in high seas or high wind and sea conditions. Once the ship took on significant water, the decking would need to be removed and the water bailed out quickly. Failing to do so would cause the ship to list or trim. If listing happened while heeling under sail, catastrophe would have come quickly.

In 2007, a reconstruction of the Skuldelev 2 ship was sailed from Roskilde to Dublin. In video documentation of this journey, the constant bailing of water was an ongoing chore. The reconstruction was equipped with a modern manual pump for this task, but the Vikings would have needed to use buckets or other containers to perform this work. The sailors on this voyage had several modern advantages, including weather forecasts which resulted in the ship being towed part of the way across the North Sea to avoid a forecasted storm. The Vikings did not have weather radar or forecasts, and had to take their chances risking everything for glory and riches on their raiding journeys. They did develop ways of reducing that risk as they improved their ships and rigging over time.[2] Rowing a long boat kept these ships under predicable speed and heading. This would have been much safer even if it required more work. With a ship full of strong men, it would not be surprising that rowing would be preferred in many cases. Even in a ship equipped with sails, rowing would have been preferred to sailing in many cases, not the least of which being an approaching storm or when the rigging was damaged. The crew of the Sea Stallion found that when sailing into the wind to the highest degree, that the ship could sail in that direction, rowing was faster than sailing. When tacking, the ship achieved 1 knot speed. At oar in the same conditions, the ship did 1.8 to 2 knots.[3] Oar power would have been a good way to make progress in the absence of wind, or when shoving off from shore and steering the ship into position prior to hoisting the large sail to keep it out of the wind until the yard and rigging were secured. When considering the vulnerabilities of the Scandinavian long ships under sail, it is not surprising that sails would need to provide a practical advantage to be worth the risks that came as part of adding them to your ship. That said, sail power was an increasing necessity as the distances of ocean crossings increased. In favorable conditions, sail power would have been much preferred both in effort, speed, and manpower costs over oar power despite the risks. Later in this paper I examine each sailing region based on the risks of sailing. (see Availability of Wind below)

Agriculture and Cost of Adding Sails

Sails and rigging required significant resources to produce. These resources would have included tremendous labor, sheep, wool, and textile production. I believe this cost not only delayed the adoption of sail adoption, but influenced where sails were first used due to the cost and availability of agricultural resources, primarily wool.

[2] "Viking Voyage - BBC Timewatch," 2007 Documentary on the sailing of "Havhingsten fra Glendalough" ("Sea Stallion from Glendalough"), a Danish reconstruction of the Skuldelev 2 ship, September 3, 2014, https://youtu.be/Q8jhnrNHk3g.

[3] IBID

Wool and Sheep

Wool is assumed due to its use as sail cloth into the modern era. The construction of the Sea Stallion, a replica of the Skuldelev 2 ship, provided knowledge of what resources were required to add sails to a longship. Just for one longship, more than two kilometers of ropes and 120 meters of sailcloth would have been required. The hours required almost necessarily would have required forced labor which the Vikings had the means of providing. To produce one woolen sail would have required a significant number of sheep. Three woolen sails were produced at the Tømmervik Textile Trust, situated on the island of Hitra. Traditional methods were used to make the wool and the sails. The wool was harvested from Old Norse sheep breeds that would have been raised in the Viking and pre-Viking era. Wool from these sheep has a high lanolin content that would have improved the water repellence of the sail cloth. These sheep have a long course and strong outer coat with long hairs that would have provided good strength for the sail material.[4] Each of these sheep can provide about 2 kg of fleece, some of which would have been lost during processing as waste.[5] Also, not all of the fleece would have been suitable for sail cloth. Estimates from this experiment came up with a figure of about 500g/sheep of fleece for sail cloth.[6] Sail cloth used about 1000g/square meter for large sails.[7] The Sea Stallion used 112 square meters of sail for a total of 112kg grams of wool. This would require the usable sail fleece of 224 Old Norse sheep. Since these sheep were generally raised in small numbers on family farms, the wool for one sail would have required the contribution of wool from about 18 or more farms to produce.[8] Norway alone had an estimated 27,000 to 30,000 thousand farms during the Viking age, each with about three dozen sheep.[9] Sweden has more land suitable to raising sheep as in 2023, the population of sheep in Sweden was 10.6 million. The population of sheep in Denmark was 5.9 million and Norway has 5.5 million sheep.[10] Assuming the ratio was similar during the Viking Era, Sweden would have been able to afford to transfer wool to sail

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[4] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land.
[5] IBID
[6] IBID
[7] IBID
[8] IBID
[9] IBID
[10] "Sheep Population by Country," Sheep population by country 2023, accessed May 14, 2023, https://worldpopulationreview.com/country-rankings/sheep-population-by-country.

production more readily than their neighbors. I believe this fact would have made Sweden a prime candidate for the early sail production due to the availability of wool in the region. Once the Vikings began settling in and raiding the British Isles and Ireland, they would have had access to considerable wool production. The 2023 the numbers of sheep in the UK and Ireland were 72.7 million.[11] That is more than three times the 2023 sheep population of Sweden, Denmark and Norway combined. Wool could have been imported from neighboring Poland and Germany as well. These countries combined had a sheep population of 124 million in 2023 which is 5.6 times the potential wool production of all three Scandinavian countries combined.[12]

Once the raw material of wool is produced on farms it needs to be harvested and processed. This is a multi-step procedure with each step requiring a great deal of manual labor to accomplish. The best wool would have been plucked from the sheep during molting their winter coat in early June. Wool harvested in this manner tends to absorb less water than wool harvested by shearing.[13] The wool then needs to be sorted. The best sail cloth would have been made from the long hairs from the outer coat. The selected wool would have been combed and made into roving which was wound tightly, wetted and dried to take some of the elasticity out of the fibers. This would produce stiffer cloth that would not stretch as much in its final sail form.[14] The stiffer the sail cloth, the better the performance would have been. A sail maker that could provide a better product would have been sought after by ship owners. The next steps included warping, weaving, wetting, fulling, and brushing. The example of the 112-meter sail of the Sea Stallion above would have required 5,700 hours spinning and weaving.[15] According to the Viking Ship Museum, the Sea Stallion took a total of 40,000 hours to build with 67 percent of that time spent on the hull. The rest of the hours were spent on the making of the other components including sails and rigging. The Sea Stallion used cotton sailcloth. Had they used wool, the number of

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[11] "Sheep Population by Country."
[12] IBID
[13] Carol A. Christiansen, "A Reanalysis of Fleece Evolution Studies," PDF from Acta Archaeologica Lodziensia nr 50/1, 11-17, 2004, https://bazhum.muzhp.pl/media//files/Acta_Archaeologica_Lodziensia/Acta_Archaeologica_Lodziensia-r2004-t-n50_1/Acta_Archaeologica_Lodziensia-r2004-t-n50_1-s45-54/Acta_Archaeologica_Lodziensia-r2004-t-n50_1-s45-54.pdf.
[14] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land
[15] IBID

hours would have increased, as well as the percentage of hours spent on the sail.[16] The success of these ships would have had a transformative effect on the regional economy due to the consumption of wool, not only for sails, but for other items required to outfit a ship for a voyage.

Wool was also needed for other purposes on board ships. As sail power increased the profitability of operating ships, more ships were built. The sailors on these ships needed special clothing and blankets to keep them warm and somewhat dry while at sea. Wool provides insulation against cold and is able to handle the wet conditions on board ships with little or no protection from the elements. Evidence from modern times from fishermen in Lofoten shows that each man brought a full complement of woolen clothing for a three-month outing fishing on the Norwegian Sea, undergarments, five pairs of sea mittens, as well as a couple of pairs of normal mittens, plus several pairs of leggings, stockings, sweaters, and shirts. All of this gear totaled 6.6 kg of wool requiring three sheep to provide raw materials for. In addition to clothing, sailors would require a heavy wool rug of 15 kg adding 7 to 15 to the number of sheep needed to keep each sailor supplied.[17] Much of the clothing may have been made by a sailor's family or farm workers which may have included forced labor.[18]

Not all wool production could have been done on farms by family members and servants once the Viking Era reached its peak. Wool production would have needed a large labor force once the number of ships increased during the Viking Era. During the time of King Canute, the number of woolen sails carried by the full fleet of the Vikings including boats and ships of all types, totaled 1 million square meters of sail cloth. Wool production was traditionally performed by women. If this is true, then one would expect graves of weaving centers to have high numbers of female graves. There is archaeological evidence of urban centers for commerce in such industries. In typical Norwegian rural burials of the Viking Era, women's graves make up for about 20 percent of the graves. In Birka Sweden, the percentage of women graves from the era is 60 percent.[19] It has been suggested that this is due to a high concentration of textile production.

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[16] "Skuldelev 2 The Sea Stallion from Glendaloug," The Sea Stallion from Glendaloug (Skuldelev 2), accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/experimental-archaeological-research/ship-reconstruction/skuldelev-2.
[17] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land.
[18] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land.
[19] Neil S. Price, *The Children of Ash and Elm: A History of the Vikings* (London: Penguin Books, 2022).

If this part of Sweden is the birthplace of Viking sail power, it stands to reason that it would have the highest concentration of textile workers. Another center of ship building during the Viking era was Hedeby. That city also has a higher concentration of female graves at 38 percent.[20] Many of these workers would have been part of a forced labor population. Finds of shackles and chains in the harbor at Hedeby suggest that human cargo was sold at point of entry and put to work.[21] The first Christians in Sweden were predominantly slaves. The Christian missionary, Ansgar, came in contact with these Christian slaves when he went to Birka in 829.[22]

Plant Fibers

In addition to the wool products for sails, clothing, and bedding, rigging in the form of ropes, blocks, pins, iron rings, and leather straps would have been required. Hemp and flax would have been required for much of the rope making, as well as possible fibers for sail cloth. The two kilometers of rope required to rig the Skuldelev 2 would have needed to be grown, harvested, and processed into ropes.[23] Once that was done, special weaves and braids would have been added to produced lines and sheets that were designed for each purpose on the ship including, shrouds, stays, sheets, reefing lines, dock lines, anchor lines, and others. Prior to the ship building boom that followed, the success of the sailing ships much less of these products would have been in demand. Evidence supports the transformative effects that the success of sail power had on Scandinavian agriculture. Pollen diagrams show that grazing increased in Western Norway during the 7th and 8th centuries. While this may have been dairy, as well as wool production, other evidence indicates a more direct connection to agriculture and support to supply ropes, sails, and rigging made of hemp and flax.[24] In 1940, price lists from Emmenthal in Switzerland show that 15 square meters of land can yield enough flax stems to produce one linen

[20] IBID
[21] IBID
[22] Bishop Rimbert, "Life of Anskar, the Apostle of the North, 801-865," trans. Charles H Robinson, Medieval sourcebooks, accessed May 14, 2023, https://sourcebooks.fordham.edu/basis/anskar.asp.
[23] 1. "Skuldelev 2, Further Research from the Museum" The Sea Stallion from Glendalough, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-reconstructions/the-sea-stallion-from-glendalough-skuldelev-2.
[24] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land.

tablecloth.[25] When multiplied for the size of a sail it can be calculated that about 12,500 square meters of flax could produce enough fiber for one sail. Hemp produces 50-100 percent more usable fibers than flax and would have been easier to cultivate. Cultivation of hemp appears to have increased after 600 AD in Sweden, as well as Norway.[26] This increase in fiber production coincides with the introduction of sail power to Scandinavian ships and their increased demand for ropes and sails during the same time frame.[27]

Hull and Rigging Design

Viking ship overview

Before reviewing each of the ships in the Architectural record, a quick overview will provide a good basic understanding of the importance of the improvements found in each ship. The hull of the Viking long ship most resembles a modern canoe as its basic design, but with a more pronounced keel. I reviewed each ship from the archaeological record in chronological order below. This review illustrated that this shape was modified as the ships were required to perform new tasks. I knew from my experience, that as sails were added to Scandinavian ships, additional planks would have been desired to increase the freeboard dimension or distance from the waterline to the gunnel. Adding these additional planks would make it harder to row the ship. The length of the oars would have to increase if the oars were to rest above the gunnel. If the oars are not increased, the angle of the oars to the surface of the water will increase making rowing more difficult. I noticed that to solve this problem, the ships had holes cut in the side of the hull above the waterline. These holes could be opened to pass the oars through. When oars were not in use these holes could be closed off to prevent water from entering through them. These hole covers would have been reasonably waterproof against waves. If the ship heeled over under sail placing the holes below the waterline, they would have potentially let in water in large amounts. As a result, in my opinion, the ships could not have been kept heeled to a state that kept these holes below the waterline. The modern sailing ship relies on a deep and heavy keel below the waterline to counteract the force of the wind on the ship above the waterline. As I reviewed

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[25] Lise Bender Jørgensen, "The Introduction of Sails to Scandinavia: Raw Materials, Labour and Land," Academia.edu, June 7, 2014, https://www.academia.edu/1972259/The_Introducion_of_Sails_to_Scandinavia_Raw_materials_Labour_and_Land.
[26] IBID
[27] IBID

the later ships on which the use of sails increased, I noticed that the number of oar holes were reduced on certain ships. With the shallow draft of the early Viking ships, they were not ideal for safe ocean sailing by today's standards, but for their time they represented leading edge in sailing technology by the 9th century. Even with their advancements, the open hull design must have resulted in many losses of ships and men over the years. The Anglo-Saxon Chronicle records one particularly calamitous voyage in 877 when a hundred and twenty ships perished as sea near Sanwich.[28] The story of Eric the Red's expedition to settle Greenland attests to this. In the story, only 14 of the 25 ships that left Iceland made it to their destination.[29] Even if the numbers aren't completely accurate, these stories show that the loss of ships was not uncommon even if these results were exceptionally poor. In the ship chronology later in this paper, the improvements in hull design are detailed in historical order. This list of ships, along with the date they were built, provides a clear picture of the type of ships that were used at different points in the Viking narrative.

A review of the ships below demonstrate that the ships of Viking Age were purpose built. For the purpose of this paper, I will be examining only ships that could have benefitted from advantages of sail power. Most ships, starting with the Gokstad ship (890 AD), were capable of traveling on open seas. The exception to this may be the Tune Ship (910 AD). These were generally larger craft capable of sailing across the Baltic, North Sea, the Norwegian Sea, and beyond. Ships of a substantial size were needed for this purpose to keep from overturning in storm conditions. The freeboard dimension would have had to be large enough to keep the ships from taking on water over the sides too easily. Even though many of these ships do not follow my geographical path from the Ålands Sea to the North Atlantic, I have included them to show the specialization of sailing vessels developed during the Viking Era. There were trading ships designed to carry trade goods, long ships for carrying large numbers of men and materials quickly for conducting raids, and small light ships with very shallow draft designed to sail far inland up rivers. Each of these types of ships would have had a use for sail power for different reasons.

[28]. James Ingram, *The Anglo-Saxon Chronicle* (London: Translation by Rev. James Ingram, 1823). (67)
[29] Magnús Magnússon and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America: Grænlendinga Saga and Eirik's Saga* (London: Penguin Books, 1987).

The ships often associated with the Vikings are the longships. These ships were long with a narrow beam and shallow draft. The ships could be run up on a beach, or other favorable shoreline, where the raiders could disembark, strike their target, and set back for home quickly and easily. These ships would have been filled with strong able-bodied men capable of manning the oars. When traveling in areas with no wind or unfavorable wind, propulsion by oar would have often been preferred. Experimental archaeology has demonstrated that even on longships filled with oarsmen, sail propulsion had advantages when conditions were right. Experimental archaeology on reconstructed longships has shown that while a large ship may do 3 knots under oar, speeds in excess of 11 knots or more were achievable under sail.[30] The longships under sail have some surprising behaviors. In a modern sloop or cutter, tacking is a very smooth operation while sailing upwind, while jibing can be a violent transition. In square rigged longships, the opposite is true, particularly in a heavy wind. When tacking upwind, the wind switches from the rear of the sail to the front of the sail pushing it up against the mast. At this point, the long ship will lose all forward momentum or even reverse. The sailor manning the tiller needs to be aware of this, and reverse the steer board to maintain the tack. This can also be a dangerous maneuver. If the sail isn't moved from one side of the ship to the other quickly, the sail can fill with air across the beam making the sail unmanageable, or even forcing the ship to heel over if there is not enough speed to steer the ship. Once the sail is resecured to the beater pole, the tack can be completed and the ship will make way again.[31] When jibing a longship, the square sail only requires a small adjustment and a new course is set. The reconstructed longships have proven that when conditions were good, these ships were very capable of sailing close hauled, achieving as much as 50 degrees off the wind in upwind sailing. The Viking sailors had figured out that, with a couple of lines tied to the luff of the sail, they could then hold the leading edge of the sail tight and straight allowing the ship to sail farther upwind. They also developed a beitass. This is sometimes referred to a spar or beater pole. The term beating to windward, refers to the use of this device that could force the lower leading edge of the sail forward and to windward. This beater would also help pull the luff out of the sail making a nice straight edge in the front of the sail creating an effective foil. All of these tight, secure lines would also make the ship susceptible

[30] Björn Ahlander, "Viking Longship Captain Ahlander Discusses USA Visit," Interview with Björn Ahlander, October 26, 2018, https://youtu.be/-OkFdckkfIA

[31] 160219 tacking with Draken Harald Hårfagre, February 24, 2016, https://www.youtube.com/watch?v=J1XYTZkXA-c.

to disaster if the wind switched to the beam unpredictably. So many lines holding the sail tight would be difficult to adjust quickly. This could result in the ship capsizing.[32] As a result, when conditions were not good, the narrow beam and low freeboard meant that longships were not ideal upwind sailers from a safety perspective.

Sailing may not have been ideal in high seas, with unpredictable strong winds that could switch to across the beam quickly filling the sail and capsizing the ship. The reconstruction of the longship at the Viking Museum at Ladby Denmark has evidence that the Vikings had experience with this deadly problem. The rigging on the model of the longship excavated there, shows a clever set of sheets tied to the center of the sail that could quickly pull the center of the leeward side of the sail up against the mast. At the same time, the tack line and the clue line could be released, or even cut loose. This would quickly dump wind from the sail while keeping it under control.[33] This innovation would have been a lifesaver for the Vikings. Another innovation found in Viking ships is the unique steer board design. With the steer board mounted to the right or starboard side of the ship, steering to port should have been impaired. The steer board on Viking ships were designed with a foil shape like a modern airplane wing. This provided lift when steering to port to compensate for this problem.[34] These innovations would have been implemented over time through experimentation and innovation in a review of archaeological finds and their re-constructions in chronological order. This demonstrates the steady process of innovation throughout the Viking age.

Hull and Rigging Improvements Over Time

In this section, I examined the ships of the archaeological record. I have listed them in chronological order to demonstrate clearly how the ships advanced through the years. This thesis focuses on the advancements in sailing technology. The first ship from the record that would have been able to sail the open oceans occurs early in the list. I reviewed the other ships to show their specialized advancements which confirmed that the Viking's understanding of sailing and ship building advanced along many lines. Archaeological finds of sail powered Scandinavian

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[32] Tom Cunliffe, "Port, Starboard and a Viking Burial Ship with Tom Cunliffe," Tom Cunliffe Professor, National Sailing School., August 22, 2020, https://youtu.be/dSwsmV6pxqw.
[33] IBID
[34] Björn Ahlander, "Viking Longship Captain Ahlander Discusses USA Visit," Interview with Björn Ahlander, October 26, 2018, https://youtu.be/-OkFdckkfIA

ships have their earliest date to 650-750 AD.[35] The technology found in Viking ships display improvements throughout the Viking Age. A chronological review of these ships provides a clearer picture of the design of ships during the Viking era. The transition from human to sail power is demonstrated with incremental advancements over time which occurred in this general order:

Additional strakes and modified hull profile to increase freeboard.

Improved mast step technology.

Improved rigging for better upwind sailing performance.

Increased cargo capacity and better seaworthiness for trading vessels with reduced crew size.

Longer faster hull designs for swifter warships with increased troop capacity on war ships.

Many of the ships from the Archaeological record have been reconstructed. I have detailed these ships with descriptions of the knowledge gained by this experimental archaeology.

The Sutton Hoo (610-635 AD)

The Sutton Hoo was a very early Anglo-Saxon ship which dates to between 610-635 AD. This was not technically a Viking ship, but is a good example of the ships of the region during the transition to sail power. For this reason, I have included it in this chronology of ships. Before the Viking Age, the Saxons were invading the French coast with clinker-built ships.[36] The clinker built lapstrake ship had a length of 26.1 meters and a beam of 4.4 meters wide which gave it a length to beam ratio of about 6:1.[37] The ship only had 9 strakes that did not turn vertically which did not provide the freeboard dimension desired for sailing.[38] The ship was stripped of all internal bracing, steering oar, and everything other than the hull prior to burial. The ship is believed to have been able to accommodate 28 oarsmen.[39] The ship had only 14 pairs of holes for oars, with no accommodations for oars amidships where they should have been most useful. There is speculation that the Sutton Hoo ship may have been propelled by sail power,

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[35] Ragnar Saage, “Research Results of the Salme Ship Burials in 2011–2012,” Academia.edu, November 16, 2015, https://www.academia.edu/5841620/Research_results_of_the_Salme_ship_burials_in_2011_2012.

[36] Charles D. Stanton, *Medieval Maritime Warfare* (Pen & Sword Military, 2015).

[37] Tegan Foley, “Building a Replica of the Sutton Hoo ‘Ghost Ship,’” The Woodworker, July 28, 2022, https://www.thewoodworkermag.com/building-replica-sutton-hoo-%E2%80%98ghost-ship%E2%80%99.

[38] IBID

[39] IBID

though no evidence of a mast or stepping were found on the ship. The shape of the hull was not ideal for sailing. The current in the River Deben, near where the ship was discovered, can reach 5 knots which would have exceeded the ship's speed under oar power forcing the ship to tie off and wait for favorable tide to reduce the current to make progress up stream. In this case, a sail would have allowed progress against the current in good conditions which supports the possibility of sail power.[40] A half scale replica was constructed. This reconstruction was fitted with a mast and sailed on calm waters successfully. With the wind, the ship sailed well, but performed poorly upwind.[41] A full-scale replica is currently under construction and will be completed soon. This ship is a very early example of a clinker-built Anglo-Saxon ship believed to be tied to the Gulfing clan of Sweden, giving the ship a Scandinavian connection. While the Sutton Hoo is better known for the rich treasure trove of grave goods than for the ship, the reconstruction of the Sutton Hoo will provide a wealth of knowledge about the performance of early clinker-built ships under sail power.[42]

The Salme Ships (650-750 AD)

Two ships were recently discovered in Salme, Estonia. These ships date from the end of the pre-Viking age, around 650-750 AD.[43] The construction of these ships predate the raid on Lindesfarne in 793 AD.[44] It also predates the first mention of three ships of "Danish men" in England in 787 AD.[45] The men buried aboard these ships were from Sweden.[46] Evidence indicates that the men met with a violent end.[47] These early ships are the first examples of what remains of what was presumably a Norse amphibious assault and raiding party. The ships were small and primitive compared to the ships built centuries later, but were a precursor of things to come for the neighbors of the Norsemen. The two Salme ships differed in construction. Salme I

[40] Tegan Foley, "Building a Replica of the Sutton Hoo 'Ghost Ship,'" The Woodworker, July 28, 2022, https://www.thewoodworkermag.com/building-replica-sutton-hoo-%E2%80%98ghost-ship%E2%80%99.
[41] Katy Stickland, "Sutton Hoo Ship: To Sail or Not to Sail," Yachting Monthly, October 13, 2021, https://www.yachtingmonthly.com/cruising-life/sutton-hoo-ship-to-sail-or-not-to-sail-81731.
[42] "The Sutton Hoo Ship's Company: Reconstructing the Sutton Hoo Ship," The Sutton Hoo Ship's Company, March 1, 2020, https://saxonship.org/the-project/.
[43] Ragnar Saage, "Research Results of the Salme Ship Burials in 2011–2012," Academia.edu, November 16, 2015, https://www.academia.edu/5841620/Research_results_of_the_Salme_ship_burials_in_2011_2012.
[44] James Ingram, *The Anglo-Saxon Chronicle* (London: Translation by Rev. James Ingram, 1823). (55)
[45] James Ingram, *The Anglo-Saxon Chronicle* (London: Translation by Rev. James Ingram, 1823). (53)
[46] "Salme Ship Burials," Osiliana, May 9, 2023, https://osiliana.eu/en/salme-ship-burials/.
[47] IBID

measured 11.5 meters, did not have a vertical keel, and would have likely been powered by twelve oarsmen and no sail.[48] The trip from Sweden to Salme Estonia would have been a long one in a rowboat. The route with the shortest ocean crossings would have been from Sweden across the Åland Sea. From there the men could have proceeded through the Åland islands without ever being in site of land. A second crossing heading south from modern day Helsinki, across the Gulf of Finland, 46 nautical miles to Tallin Estonia would have also been possible with 15 to 20 hours of rowing in favorable conditions with a speed of 2-3 knots. It is impossible to say with certainty what route was taken, but the voyage above could have been done without overnight rowing, and would have allowed for frequent stops for overnight camping on shore. Frequent stops for water and food were a necessity during early maritime travel. The fact that a journey of this length was taken in an oar powered boat may indicate that sails were not in common use at this time. The second ship found in the same area, Salme II, had a vertical keel and other evidence of sail propulsion.[49] While both Salme I and II were oak, clinker-built lap strake ships, the Salme II was larger and of more robust construction. The size and quality of the clinker nails were larger and more uniform which suggests the ship may have been built by a more skilled and established boat builder. Salme II was larger at approximately 17.5 meters long with a 3-meter beam giving the ship a length beam ratio of about 6:1. Height of the hull is estimated to be 1.55 meters with a draught of 0.4-0.9 meters.[50] This shows the freeboard of the ship was dangerously small. The ship would have been sailed mostly downwind in good conditions. Improvements in hull design in future ships reduced the risk of swamping the ships, and improved the sailing capabilities. The remains of a linen sail were draped over the bodies providing additional evidence of the use of sail propulsion.[51] The lack of evidence of the typical large keelson may suggest that the sail was not substantial. It is not possible to tell how well the ship sailed to the wind or what other capabilities it was equipped for.

[48] Ragnar Saage, "Research Results of the Salme Ship Burials in 2011–2012," Academia.edu, November 16, 2015, https://www.academia.edu/5841620/Research_results_of_the_Salme_ship_burials_in_2011_2012.
[49] IBID
[50] "Salme Ship Burials," Osiliana, May 9, 2023, https://osiliana.eu/en/salme-ship-burials/.
[51] Ragnar Saage, "Research Results of the Salme Ship Burials in 2011–2012," Academia.edu, November 16, 2015, https://www.academia.edu/5841620/Research_results_of_the_Salme_ship_burials_in_2011_2012.

The Storhaug Mound Ship on Karmøy (770 AD)

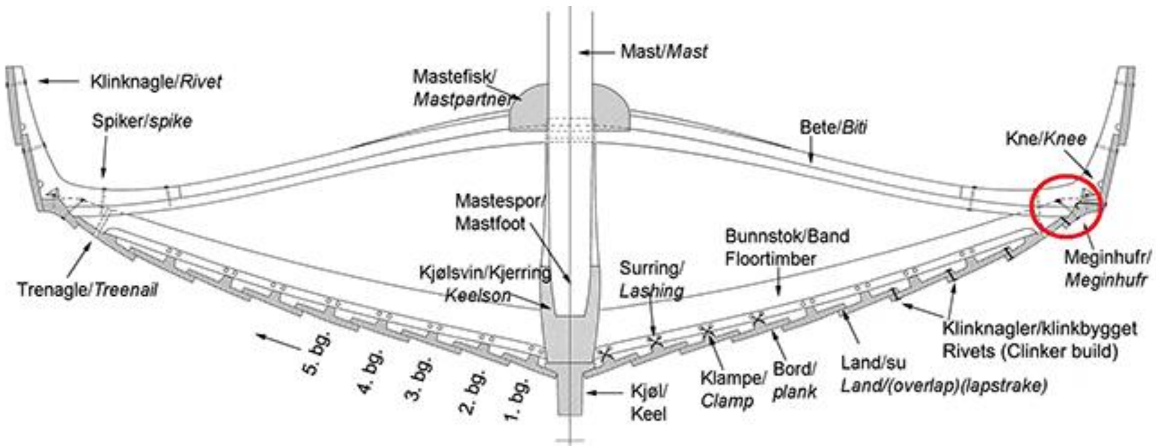
A current excavation on Karmøy in Torvastad dates from 770 AD. Ground penetrating radar showed a keel and possible remnants of the yard of the ship. This region controlled traffic through the Karmsundet, and was a critical region during the Viking age. The ship has been determined to be a sailing ship over 20 meters in length.[52] This may be the first evidence of a ship with sail power in Norway. Although another ship under analysis, the Gjellestad ship, may predate it. A doctoral student at the Archaeological Museum, Massimilano Ditta, has not released final information on the ship's construction. As I result, I was not able to determine if the ship would have been expected to sail the open waters of the North Atlantic.[53]

The Oseberg Ship (820 AD)

The Oseberg ship dates from 820 AD which was about 27 years after the raid at Lindisfarne.[54] It was a clinker built, lapstrake ship made from oak. The Oseberg ship is an early example of a Viking combination sailing and rowing vessel. The ship was discovered very well preserved. The ship's length was 21.5 meters with a 5-meter beam, giving the ship a length to beam ratio of about 4:1.[55] The reconstruction of this ship in 1987 proved nuances of hull design. The ship was reconstructed as displayed, but sank on its maiden voyage. Analysis of the reconstruction showed that the front of the ship dipped too low into the waves while under sail, swamping the ship and sinking her.[56] Her low length to beam ratio could have contributed to this as well. A larger ratio helps a ship lift the front of the ship when moving forward.[57] For a time, some speculated that the ship was purpose built as a burial ship and was never intended to sail. Further study found that the original Oseberg vessel had a flatter bottom in the forward section which would have provided lift to the stem of the ship. A new reconstruction was built. The new hull shape provided lift to the bow of the ship and it sailed successfully.[58] The ship's freeboard

[52] Ida Irene Bergstrøm, "New Discovery of a Viking Ship in Norway," Sciencenorway, April 24, 2023, https://sciencenorway.no/archaeology-viking-age-vikings/new-discovery-of-a-viking-ship-in-norway/2187930.
[53] IBID
[54] "New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[55] IBID
[56] IBID
[57] IBID
[58] Vibeke Bischoff, "The Oseberg Ship: Reflections on the Choice of Methodology When TES...," Archaeonautica. L'archéologie maritime et navale de la préhistoire à l'époque contemporaine, July 1, 2022, https://journals.openedition.org/archaeonautica/2505?lang=en.

dimension is small which also made sailing risky compared to ships built later in the Viking era. The Meginfufr strake in the hull construction shows that effort was being made to increase freeboard at this time. (see diagram below) It should be noted that the raid at Lindisfarne predates this ship by 27 years, putting it in possible use during that time. This suggests that a ship of similar technology may have been used during that raid. The timeline between the Oseberg ship and the next ship, the Gokstad ship, contains a great deal of activity, including the establishment of the Great Viking Army, the Danelaw, and the raid on Paris.[59] It is clear from the improvements of the Gokstad ship, that a great deal of activity had also occurred in the shipyards of the Vikings. There have been reconstructions of the Oseberg ship (see below).



Cross section of the Oseberg ship with explanations, Vibeke Bischoff [60]

The Gokstad Ship (890 AD)

The Gokstad Ship dates from 890 AD.[61] It was a clinker-built, oak ship, and a classic Knarr of the modern definition.[62] The ship is 23.22 meters long with a 5.18 meter beam giving the ship a length to beam ratio of about 4:1.[63] This gave the ship a similar length to beam ratio to the Oseberg ship, but the ships were very different in many other respects. The ship displayed

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59 Josh Butler, "The Great Heathen Army," Historic UK, accessed May 30, 2023, https://www.historic-uk.com/HistoryUK/HistoryofEngland/Great-Heathen-Army/.

60 Vibeke Bischoff, "Bischoff, v. 2010. Hull Form of the Oseberg Ship.," Maritime Archaeology Newsletter from Denmark, No. 25, January 1, 2010, https://www.academia.edu/37850973/Bischoff_V_2010_Hull_form_of_the_Oseberg_ship.

61 "Gokstad," Museum of Cultural History University of Oslo, accessed May 30, 2023, https://www.khm.uio.no/english/visit-us/viking-ship-museum/exhibitions/gokstad/.

62 Eldar Heide, "The Early Viking Ship Types," Sjøfartshistorisk Årbok 2012 PDF, May 24, 2014, https://www.academia.edu/6944485/The_early_Viking_ship_types. (101)

63 "The Gokstad Ship," Museum of Cultural History, accessed May 14, 2023, https://www.khm.uio.no/english/visit-us/viking-ship-museum/exhibitions/gokstad/the-gokstad-ship/index.html

several advancements in sailing technology, and would have been a great leap forward in ship building.[64] The freeboard was significantly increased, and the mast step was much stronger (see diagram below). With the development of ships like the Gokstad ship, the Vikings had ships with seaworthiness to sail the Atlantic. This has been proven through experimental archaeology (see The Reconstructions below). The ship's strakes are cut thinner, providing less weight and greater hull flexibility. A total of 16 rows of oak strakes provided a meter of freeboard. The ship had 32 oars (16 each side) with oar ports which could be closed and sealed when under sail.[65] The ship had removable pine deck planks which provided easy access for bailing.[66] The ship had a large sail support, and the keelson spans four ribs.[67] Above the keelson, the large mastfish and upright complete the mast assembly. The Gokstad boat also has clear evidence of support slots for a beitass or spar pole.[68] This device was used to hold the forward edge of the sail tight and straight. The introduction of beitass, in conjunction with lines on the leading edge of the sail, would have improved upwind sailing performance. The addition of this pole gave the sailors of the Gokstad the ability to tighten the luff of the sail, and push it to windward. Viking style reconstructions using this apparatus have been able to sail to as much as 50 degrees off of the wind. This is remarkable and surprised many when proven in sailings of reproduction of Viking ships.[69] Rigging and sail technology seem to remain static from the late 9th century onward. Any subtle changes that may have occurred in rigging have not been preserved in the archaeological record. Carpentry improvements, allowing for longer narrower ships, have been found in the sailing ships after this time period. This ship comes from the time of the settlement of Iceland (875 AD).[70] The Gokstad ship was not only a fast ship, but had a respectable cargo capacity. Built just 15 years after Ingolf and Hjorleif first settled Iceland, it is believed to represent the type of ships they could have sailed to their new home. Examination of the texts of Landnámabók, possible contents put aboard the ship would have included water in limited

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64 IBID
65 IBID
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67 Kunt Paasche, "The Tune Viking Ship Reconsidered," International Journal of Nautical Archeology Vol 49 Issue 1, accessed May 14, 2023, https://onlinelibrary.wiley.com/doi/full/10.1111/1095-9270.12391
68 "Features of a Viking Ship, accessed May 14, 2023, University of Cork. http://www.worldtreeproject.org/exhibits/show/ships/shipfeatures.
69 Björn Ahlander, "Viking Longship Captain Ahlander Discusses USA Visit," Interview with Björn Ahlander, October 26, 2018, https://youtu.be/-OkFdckkfIA.
70 Ari Þorgilsson and T. Ellwood, *Landnámabók: Viking Settlers & Their Customs in Iceland* (Port Townsend, WA: Huginn and Muninn Publishing, 2016). (23)

quantities, grain, butter, animals, at least one ox, woodworking tools, possibly weapons, some construction materials, slaves and women, and a set of High Seat pillars.[71] A letter from Alcuin of York to King Ethelred suggests that a raid on Lindisfarne by sea was not considered possible with the known technology at the time.[72] The ship(s) used in early raids including Lindisfarne (793 AD) and the ships of the great Viking army (865-880 AD) probably contained at least some of the sailing and hull design advancements found in the Gokstad ship. To date, no archaeological evidence exists to support this. The design, age, and seaworthiness of this ship have made it a favorite for reconstruction projects designed to recreate the Viking voyages to North America. Several reconstructions have been made of this ship (see The Reconstructions below).

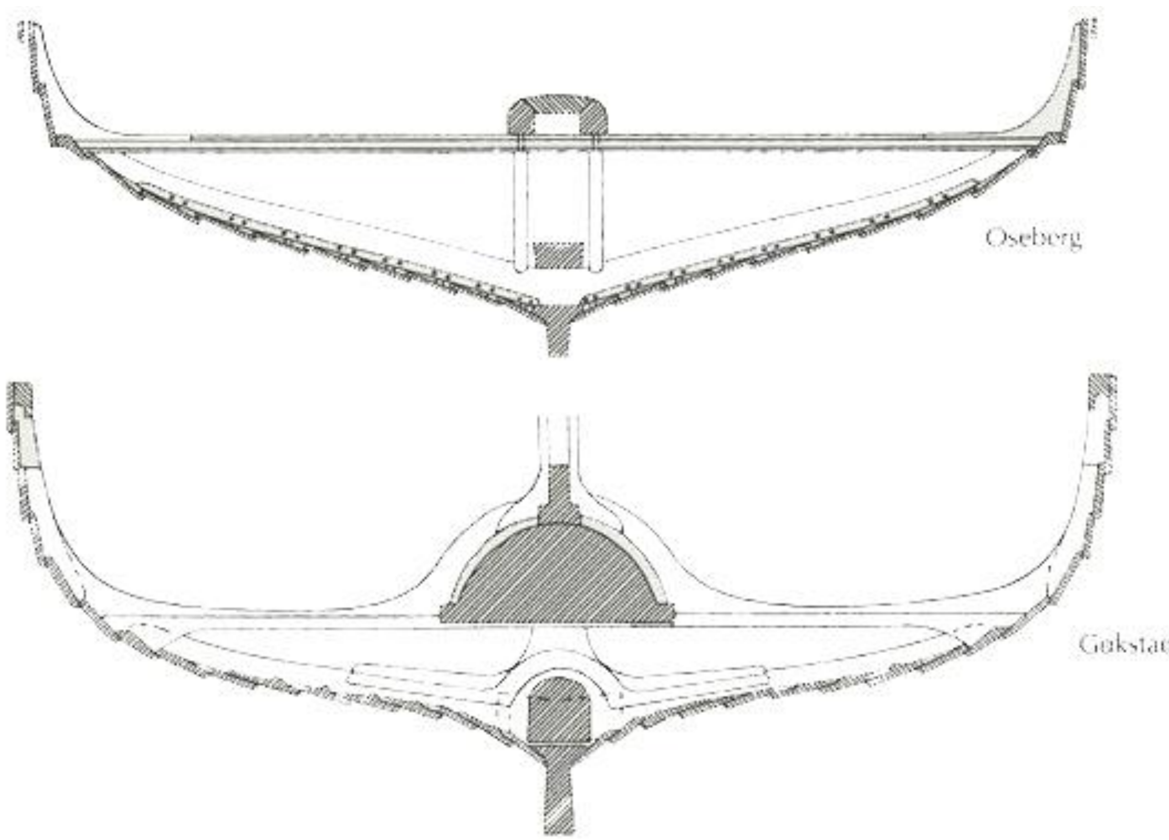

Diagram of freeboard and mast support improvements from the Oseberg to the Gokstad ships[73]

[71] IBID
[72] University of Chicago, "Lindisfarne," Database on Anglo-Saxon England, accessed May 14, 2023, https://penelope.uchicago.edu/~grout/encyclopaedia_romana/britannia/anglo-saxon/lindisfarne/lindisfarne.html.
[73] Keith Ross, "The Development of Maritime Technical Capability," Maritime Archaeology Graduate Symposium 2020, accessed May 14, 2023, https://honorfrostfoundation.org/wp-content/uploads/2020/08/MAGS2020_RossKeith-.pdf.

The Tune Ship (910 AD)

The Tune ship dates from 910 AD. It is a clinker built, lapstrake ship made from oak. This ship was larger than the Salme II, but shorter than the Oseberg ship. The length of the Tune ship was 18.7 meters with a 4.2 meter beam giving the ship a length to beam ratio of about 4.5:1.[74] The size of the keelson indicates support for a large square sail, but the low freeboard would make sailing in a strong cross wind dangerous. It is difficult to tell how many strakes were originally on this ship since the top portion of the Tune ship does not exist.[75] The ship was excavated in 1867 using poor methods by today's standards. The work was started by the curious landowner who uncovered the top of the ship himself before seeking professional help. As a result, the top strakes may have rotted away.[76] Originally the Tune ship was believed to have 10 strakes. This number would have given the ship a very low freeboard. It has been speculated that the ship had 12 strakes due to evidence of surviving knees to support this number.[77] Even with this number of strakes, the flat bottom of the Tune ship would have kept the freeboard dimension very small and dangerous in high winds or seas. This same flat shape in the foreword part of the ship would have helped lift the ship over the waves.[78] There isn't sufficient evidence to determine whether the Tune ship had beitass poles, or lines on the front edge of the square sail for upwind sailing. Though it is reasonable to expect that any ship witnessing this simple and inexpensive modification would have taken advantage of the technology. The Gokstad ship provides evidence that Viking ships had been using this upwind sailing improvement for at least 20 years before the Tune ship was in use.[79] The Tune ship was built for speed and was light weight. With no cargo capacity, it was probably used for carrying armed men on short trips for defense or quick attacks. The ship was also equipped with oar holes for 24 oarsmen.[80] The low

[74] Kunt Paasche, "The Tune Viking Ship Reconsidered," International Journal of Nautical Archeology Vol 49 Issue 1, accessed May 14, 2023, https://onlinelibrary.wiley.com/doi/full/10.1111/1095-9270.12391.
[75] IBID
[76] Kunt Paasche, "The Tune Viking Ship Reconsidered," International Journal of Nautical Archeology Vol 49 Issue 1, accessed May 14, 2023, https://onlinelibrary.wiley.com/doi/full/10.1111/1095-9270.12391.
[77] IBID
[78] IBID
[79] "Features of a Viking Ship, accessed May 14, 2023, University of Cork. http://www.worldtreeproject.org/exhibits/show/ships/shipfeatures.
[80] Kunt Paasche, "The Tune Viking Ship Reconsidered," International Journal of Nautical Archeology Vol 49 Issue 1, accessed May 14, 2023, https://onlinelibrary.wiley.com/doi/full/10.1111/1095-9270.12391.

freeboard of this ship is similar to that of the Oseberg.[81] This may suggest that more seaworthy ships, like the Gokstad ship, was used during the same time period as the Oseberg and Tune ships for different purposes.

The Ladby Ship (925-950 AD)

The Ladby ship dates from around 925-950 AD, though accurate dating has not been possible since the wood of the ship has rotted away preventing accurate dating by dendrochronology. Dating of the ship was done through analysis of the grave objects and ornamentation.[82] The ship was a clinker built, lapstrake ship and the placement of the iron clinker nails, along with the remains of some rotten wood, provided the information needed to reconstruct the ship.[83] Iron rings found at midship also provided evidence of sail propulsion on the Ladby ship.[84] The ship was 21.5 meters long and 3 meters wide, giving this ship an impressive length to beam ratio of about 7:1. This ship would have been a swift sailer, and an early example of a skeið or longship. Its length would have given it great lateral resistance when sailing at speed.[85] It had a dimension of 1 meter from the keel to the gunwale. This was half the dimension of the Gokstad ship making it more like the Tune ship in design and usage, though with her extra length and narrow beam, she was probably swifter under sail. The unique find on the Ladby ship is its anchor and anchor chain. The iron anchor was not a new development. There is an iron anchor found in Bulbury of Dorset, England dating from the first century, but the swivels in the anchor chain to prevent it from binding were unique.[86] The chain also contained hooks for adjusting the length of the chain. The main advantage of this chain was its weight, and the way that oriented the anchor on the sea floor. This was particularly useful in a deep anchorage. The ropes used by the Vikings were buoyant. With more rope below, the surface the buoyancy of the rope would hole the anchor vertically, preventing it from digging into the sea floor which was essential for the anchor to do its job. The weight of this chain pulled the top

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[81] IBID
[82] Anne C Sørensen, *Ships and Boats of the North*, vol. 3 (Roskilde: The National Museum of Denmark, 2001).
[83] "Ladby," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/ladby.
[84] IBID
[85] Anne C Sørensen, *Ships and Boats of the North*, vol. 3 (Roskilde: The National Museum of Denmark, 2001).
[86] IBID

of the anchor down and helped to keep it set.[87] When a ship is at anchor it is not uncommon for the line near the anchor to become damaged by the anchor or by other debris or rocks near the anchor. For these reasons, it is common today to use a couple of meters of chain near the anchor before switching to other easier to manage rope. The Ladby ship is the first example of the use of chain on a Viking ship's anchor.[88] This would not have been an inexpensive item on the ship. So far, no other Viking ship has been found with this type of anchor chain.[89] It can be speculated that this was a unique requirement requested by the owner of this ship. Vikings were known to anchor offshore, waiting for the opportune moment to attack to take advantage of the utmost element of surprise. One written source states, "We shall let the anchor hold us in Randersfjord, while the linen-oak the Gerðr of incantation lulls her husband to sleep," King Harald Hardruler. While King Harald lived many years after the construction of the Ladby ship, this line from Lausavísur shows how useful a well-designed anchor would have been to the Vikings for success in the life and death struggle that was to come.[90] In the scenario just mentioned, the ship would have been far enough away from shore to prevent detection. This would often result in a deep anchorage. A replica of the Ladby ship was constructed (see The Reconstructions below).

The Puck 2 Ship (900-950 AD)

The Puck 2 ship was built in the first half of the 10th century, placing it in use just after or at the same time the Ladby, Tune, and Gokstad ships. The ship was 21 meters long and had a 2.16-meter beam giving this ship a slender length to beam ratio of nearly 10:1.[91] The ship was discovered in the medieval harbor of Puck in present day Poland. The ship was a lapstrake, oak ship with some alder and birch floor timbers. The ship would have been considered skeið or longship.[92] Unlike most ships of Scandinavia, the Puck 2 was assembled with 1.5 cm wooden pegs or "tree nails." This seeming reversal of technology is a result of regional construction

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[87] IBID
[88] IBID
[89] IBID
[90] "Saga-Book XXI," Viking Society For Northern Research University College London, 1982, https://vsnr.org/wp-content/uploads/2021/11/Saga-Book-XXXIV.pdf.
[91] Paweł Litwinienko and Janusz Różycki, "An Attempt to Create a Digital Reconstruction of the Puck 2 Wreck Hull," Archaeonautica. L'archéologie maritime et navale de la préhistoire à l'époque contemporaine, July 1, 2022, https://journals.openedition.org/archaeonautica/2644?lang=en.
[92] Eldar Heide, "The Early Viking Ship Types," Sjøfartshistorisk Årbok 2012 PDF, May 24, 2014, https://www.academia.edu/6944485/The_early_Viking_ship_types.

practices. The Puck 2 was a Slavic built ship with hybrid Slavic and Scandinavian features.[93] The ship was discovered with a keelson and mast step indicating it was a sailing vessel. The keelson and mast step were of a Scandinavian design. The overall construction of the ship has both Slavic and Scandinavian elements. This is not surprising when considering the close contacts that the Vikings had with Poland during the time of this ship's construction.[94] Just a few decades after the Puck 2 was built, we have proof that Sweyn Forkbeard (960-1014 AD) was frequenting the region. During the time this ship may have been in use, Sweyn married the daughter of the Duke of Poland.[95] With these close ties, it is not surprising that ship building and sailing technology would find its way from Scandinavia to Poland. The slender length to beam ratio should have resulted in a swift sailing ship, but its tree nailed construction may have presented maintenance issues due to the flexing of the hull in high seas.[96] Reconstruction of ships with this fastening technology, or reconstruction of this ship specifically, could provide knowledge of the performance, maintenance, and longevity of ships of this type.

Haithabu Harbor or Hedeby Ship (985 AD)

The Haithabu Harbor, or Hedeby Ship, was located in Hedeby, which had become the center of Scandinavian shipping during the Viking age. The ship was a clinker built, lapstrake ship of oak with construction designed to reduce weight when compared to previous ships. The ship was built in 985 AD. This ship was a skeið or longship.[97] Dimensions are 30.9 meters long with a 2.7 meter beam, giving it a length to beam ratio of 11.4:1. The ship could accommodate about 60 oars.[98] The technological advancement seen in this ship was in its length and weight.

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[93] Paweł Litwinienko and Janusz Różycki, "An Attempt to Create a Digital Reconstruction of the Puck 2 Wreck Hull," Archaeonautica. L'archéologie maritime et navale de la préhistoire à l'époque contemporaine, July 1, 2022, https://journals.openedition.org/archaeonautica/2644?lang=en

[94] Jan Bill, "Puck 2 - a Slavic Longship," trans. Gillian Fellows-Jensen, Museum for vikingernes skibe og søfart, accessed May 14, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/puck-2-a-slavic-longship.

[95] "Sweyn Forkbeard Facts & Biography," English History, March 10, 2022, https://englishhistory.net/vikings/sweyn-forkbeard/.

[96] Paweł Litwinienko and Janusz Różycki, "An Attempt to Create a Digital Reconstruction of the Puck 2 Wreck Hull," Archaeonautica. L'archéologie maritime et navale de la préhistoire à l'époque contemporaine, July 1, 2022, https://journals.openedition.org/archaeonautica/2644?lang=en

[97] Eldar Heide, "The Early Viking Ship Types," Sjøfartshistorisk Årbok 2012 PDF, May 24, 2014, https://www.academia.edu/6944485/The_early_Viking_ship_types.

[98] Red: Marianne Juelsgård Horte Jan Bill, "The Longship from Haithabu Harbour," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/the-longship-from-haithabu-harbour.

Making ships longer increased the troop-carrying capacity, as well as the speed. The longer the ship, the faster its potential speed through the water. This is particularly true if the length of the ship is achieved without increasing weight or draft. The designers and builders of the Haithabu ship took advantage of this technological advancement. This long narrow ship was equipped with a square sail, and was undoubtedly fast.[99] While we do not have evidence of the sail size of the ship, we can assume the sail was increased in size to match her increased length since to achieve her potential as a fast-moving long ship, the propulsion would need to be increased with larger sails. The attention to weight reduction was apparent in several aspects of construction. While the ship was constructed with clinker nails as was typical, the clinkers on this ship were changed to smaller clinkers spaced close together. This new technology allowed for thinner, lighter planks to be used since the bending strength between the increased rivets could be reduced. The planks were very long and knot free.[100] To reduce the number of strakes required, the planks used were 25-37 cm wide. These long, wide planks would have required the harvesting of very tall straight oak trees up to 1 m in diameter.[101] The splices between planks were made with tongue scarfs. This lighter, thinner hull also required additional bracing to withstand the typical forces on the hull while sailing. The braces going across the ship are 85 cm apart, with additional half ribs on the back of the planks between the braces. The resulting hull was lighter than previous long ships, but did not sacrifice strength.[102] This ship's construction was done in Hedeby.[103] This would have been an expensive ship, and would have been cutting edge construction. It is not surprising that its construction would have taken place where one could assume the greatest knowledge of ships would have been concentrated at the time. The ship was destroyed by fire near the end of its useful service.[104] This was possibly in a military action in which the ship could have been set ablaze, and sent into an enemy fleet. If dating of the ship is correct, the ship would have been constructed during the last years of Harald Bluetooth (ruled 958-986 AD), or the first years of Sweyn Forkbeard (ruled 986-1014 AD), for either the

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[100] 1. Red: Marianne Juelsgård Horte Jan Bill, "The Longship from Haithabu Harbour," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/the-longship-from-haithabu-harbour.

[101] IBID

[102] Ole Crumlin-Pedersen, *Ships and Boats of the North: Viking Age Ships and Ship Building in Hedeby/ Haithabu and Schleswig*, vol. 2 (Roskilde: The National Museum of Denmark, 1997).

[103] IBID

[104] IBID

kings themselves, or for someone under their rule with the financial means to afford this expensive vessel.[105] This ship was also built the same year that Bjarni Herjolsson sighted North America, but was not the type of ship he sailed.[106]

The Klåstad ship (995 AD)

The Klåstad ship was built in 995 AD. It is an oak lapstrake, clinker-built cargo ship. The ship is 20.5 meters long with a beam of 5.5 meters.[107] This gave the ship a length to beam ratio of 3.7:1. The ship is equipped with only 8 oars, and would be considered a knarr.[108] This ship was not set up for a combination of sailing and rowing, but rather relied on sail propulsion with oars being used for short-term maneuvering.[109] For instance, the oars could have been used to bring the ship up to the dock since doing so under sail is difficult and dangerous. Dockside oars would need to be stowed prior to docking for obvious reasons. Oars could have also been used to turn the ship to the desired course when raising or lowering the sail, and as emergency propulsion when the rigging was damaged or in unfavorable conditions. The ship was designed for a limited crew of less than ten men. The ship had a large cargo capacity.[110] As a cargo ship, the life or death need for propulsion in any conditions didn't exist. Rather the ship could wait for favorable conditions to continue on course. Though making progress with the cargo was desirable, it would not have been essential. The smaller crew would have resulted in less wages and greater profit. Considering the amount of piracy on the seaways, it would not be unreasonable to speculate that these ships would have traveled in groups with an armed escort, particularly when loaded with cargo. In 2018 a re-construction of the Klåstad ship was built (see The Reconstructions below).

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[105] "Sweyn Forkbeard Facts & Biography," English History, March 10, 2022, https://englishhistory.net/vikings/sweyn-forkbeard/.
[106] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).
[107] "The Klastad Ship," Oseberg Viking Heritage, December 7, 2021, https://osebergvikingarv.no/eng/the-klastad-ship/.
[108] IBID
[109] IBID
[110] IBID

Roskilde 6 (1025 AD)

The Roskilde 6 ship dates to after 1025 AD.[111] It is a clinker built, lapstrake ship of oak. The ship measures 36 meters long, and had a beam of 3.7 meters, giving it a length to beam ratio of 9.7:1. This ship was a longship, and could accommodate 78 oars.[112] Both the Roskilde 6, and the Haithabu ship, were longships with advanced construction methods designed to increase speed and capacity through increased length with minimal weight. This ship was not as narrow as the Haithabu Harbor ship, but was longer. To date, the Roskilde 6 is the longest ship that has been discovered.[113] As with many ships, the upper strakes, and other elements of the ship where clues to the rigging of the ship, have not been preserved. Fortunately, the lower preserved parts of Roskilde 6 do provide evidence of advancements in carpentry developed as a result of longer hull designs.[114] These advancements reflected an apparent desire for more reliability and strength in the longship's construction. The Roskilde 6 has even tighter rib spacing than the Haithabu Harbor ship. The Roskilde 6 had a spacing of just 80 cm between ribs.[115] The keel assembly and construction were modified and improved to provide greater structural integrity. When a ship of this length travels through the water, it is subjected to bending and torsional stresses due to the inherent unevenness of the surface of the water. While these ships were designed to accept some of these stresses with flexibility designed into their construction, some of the construction improvements to this keel show that the Vikings were having problems with their longships in high seas. The keel of the Roskilde 6 is constructed from three sections of oak. In past examples, these sections of keel were spaced with hooked scarf joints with a length about three times the width of the keel. The scarf joints on the Roskilde 2 were 2 meters long, with horizontal stability designed into the joint to keep the ship's keel from bending across the beam of the ship.[116] This improvement would have added horizontal load resistance to the keel that did

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[111] "Viking Archaeology," Viking Archaeology - The Viking Ship Roskilde 6, accessed May 30, 2023, http://www.viking.archeurope.info/index.php?page=the-viking-ship-roskilde-6.

[112] Jan Bill, "Roskilde 6," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/roskilde-6.

[113] "Viking Archaeology," Viking Archaeology - The Viking Ship Roskilde 6, accessed May 30, 2023, http://www.viking.archeurope.info/index.php?page=the-viking-ship-roskilde-6.

[114] Jan Bill, "Roskilde 6," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/the-longships/findings-of-longships-from-the-viking-age/roskilde-6.

[115] IBID

[116] IBID

not exist in previous ships, including the Haithabu Harbor longship of four decades earlier. The ship would have been very costly to build and crew. The timing of its construction place it at the height of the Viking Age in the fleet of Cnut the Great (ruled 1016-1035).[117]

Skuldelev 5 (1030 AD)

The Skuldelev 5 is dated from the same period as the Roskilde 6 at 1030 AD. The ship is 17.3 meters long and 2.47 meters wide giving her a length to beam ratio of 7:1. The ship could accommodate 26 oarsmen.[118] As we can see by this example, not all Viking ships were built to break new ground. The Skuldelev 5 was a low prestige Danish war ship. This example demonstrates that, by this time, sailing had become reliable enough that constant advancement was not considered necessary. Some ships were built using proven designs with proven technology. This was the case with the Skuldelev 5. Unlike the expensive construction and advanced sailing technology of the Roskilde 6, or the Haithabu Harbor ship before her, the Skuldelev 5 is a relatively inexpensive ship built with the budget in mind. The ship was constructed from oak, pine, alder, and ash. Many of her planks were used lumber salvaged from previous constructions.[119] She was fitted with both sails and oars. The ship was not large by 1025 AD standards, and didn't have a high freeboard for making way under sail in adverse conditions.[120] The Skuldelev 5 would not have been a ship to take on a Viking expedition. This would have been a more practical ship for short-haul, defensive capabilities to protect its home port.[121] A re-construction of this ship has been built (see The Reconstructions below).

Skuldelev 1 (1030 AD)

The Skuldelev 1 was a ship designed for general seaworthiness, particularly under sail power with increased cargo carrying capacity. The ship was most like a knarr, and was built in

[117] "Canute 'the Great' (r. 1016-1035)," The Royal Family, accessed May 30, 2023, https://www.royal.uk/canute-great-r-1016-1035.
[118] 1. "Skuldelev 5," The small longship, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-viking-ships/skuldelev-5.
[119] IBID
[120] Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002)
[121] Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002).

about 1030 AD.[122] She was a clinker built, lapstrake ship, 15.8 meters long with a 4.8 meter beam giving it a length to beam ratio of about 3:1.[123] Unlike previously mentioned ships, this vessel was constructed of strong planks of pine. This shows the practical economics of this ship since more abundant pine would have been more cost effective.[124] This would not have been as fast as other ships during this time, but with a total displacement of 26 tons, the ship would have been useful for carrying cargo of 20 tons.[125] It would have done this reliably and at low cost. The ship had only four oars and could have been sailed with a crew of 6-15 men.[126] The timing was right for this type of cargo ship. Though piracy was presumably a risk during the entire Viking age, the fact that England, Denmark, and Norway were ruled by one king at the time of this ship's construction, would have reduced this risk.[127] Reconstructions have been made of the Skuldelev 1 (see below).

Skuldelev 3 (1040 AD)

The Skuldelev 3 was built in about 1040 AD. The ship is a clinker built, lapstrake oak cargo ship, but not a knarr.[128] It was designed for more coastal sailing and hauling of cargo from Denmark through the Baltic Sea. It is 14 meters long with a 3.3 meter beam giving her a length to beam ratio of 4.24:1.[129] The ship was propelled by sail, and would have been crewed by 5-8 sailors. It would have traveled at an average speed of 4-5 knots, with a top speed of 8-10 knots.[130] A reconstruction of the Skuldelev 3 was completed in 1984.

[122] "Skuldelev 1," The ocean-going trader, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-viking-ships/skuldelev-1.
[123] IBID
[124] IBID
[125] Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002)
[126] "Skuldelev 1," The ocean-going trader, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-viking-ships/skuldelev-1.
[127] Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002)
[128] "Skuldelev 3," Research on Skuldelev 3, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-viking-ships/skuldelev-3.
[129] IBID
[130] Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002)

Skuldelev 2 (1042 AD)

The Skuldelev 2 was a Viking longship dating from 1042 AD.[131] The ship was an oak, clinker built lapstrake ship. The ship had a length of 20.28 meters, and a beam of 3.76 meters, giving it a length to beam ratio of 7.78:1.[132] The ship had capacity for 60 oars.[133] The ship's ratio is lower than the Haithabu Harbor and Roskilde 6 ships, but may have been a more sturdy ship to sail in adverse conditions. The ship was sailed in heavy seas around and in currents of the Irish Sea, through the North Minch channel between the Outer Hebrides and Scotland, and through the North Sea. The ship was constructed in Dublin and excavated in Roskilde, so we know the ship sailed in these waters.[134] The hull was braced with a rib spacing of 70 cm.[135] The ship may have been built with a wider beam to improve seaworthiness for the waters in which she sailed. The ship had an unusually long keelson, which spanned 14.1 meters down the length of the bottom of the hull.[136] The keelson was braced and spliced with a hooked scarf to provide support to the hull to help it withstand the bending forces imposed when the center of the ship was suspended in the trough of the waves.[137] This construction suggests the Irish shipbuilders were familiar with the stresses that could damage or destroy ships where the Skuldelev 2 sailed, and sought to develop ships that could sail through these conditions.[138] This ship, and the Skuldelev 3 above, were constructed after the death of Cnut the Great (1016-1035), just 24 years before the end of the Viking Age in 1066 AD.[139] The Skuldelev 2 has been reconstructed and sailed in her home waters. (see The Reconstructions below).

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131 "Skuldelev 2," The great longship Skuldelev 2 Museum Exhibits, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-viking-ships/skuldelev-2.
132 IBID
133 IBID
134 Ole Crumlin-Pedersen, *Ships and Boats of the North: The Skuldelev Ships I*, vol. 4.1 (Roskilde: The National Museum of Denmark, 2002)
135 IBID
136 IBID
137 IBID
138 IBID
139 "The Battle of Stamford Bridge, 1066," Historic UK, accessed May 30, 2023, https://www.historic-uk.com/HistoryMagazine/DestinationsUK/The-Battle-of-Stamford-Bridge/.

The Reconstructions

Many of the ships from the archeological record have been reconstructed and sailed. This experimental archaeology has added knowledge of how each ship sailed, providing some often-surprising results. I have included details of these ships, and their sailing characteristics found through test sailings as an example of the progress achieved in sailing during the Viking Age. Building and sailing these reconstructions is the only way to really know what the capabilities of each ship are. What I found was that with the developments discovered in the Gokstad ship, the Vikings achieved a design that was seaworthy enough to sail the open oceans by no later than 890 AD.

The Oseberg Ship Reconstructions

I took particular interest in the Oseberg reconstructions. The raid on Lindisfarne took place in 793 AD, and the first mention of the Danish men in the Anglo-Saxon Chronicle is in 787 AD. With that in mind, it is reasonable to expect that the ship(s) used in these raids would have been similar or inferior to the Oseberg ship built 27 years later. A reconstruction of the Oseberg ship could provide knowledge of how difficult the journey to Lindisfarne may have been in a ship like the Oseberg.

The Dronnigen 1987

The first reconstruction of the Oseberg ship (820 AD) was constructed in 1987.[140] The reconstruction was based on the ship as it was displayed in the museum. The ship was powered by sail at the time of its maiden voyage, and reached a speed of 8-10 knots.[141] A few minutes into this maiden voyage, after reaching a speed of 9 knots and heeling at a modest 10 degrees, the Dronnigen took on water over her sheer strake and quickly sank.[142] To determine what went wrong, a thorough study the hull form to see if the shape of the hull of the Dronnigen was

[140] New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[141] IBID
[142] IBID

different from the original Oseberg ship. Careful examination suggested the hull shape of the Dronnigen was not correct to the original ship.[143]

The Saga Oseberg 2006

In 2006, the original Oseberg ship was reexamined with a critical eye. It was photographed inside and out, and scanned inside and out as well. During this process, cracks and deformations of several boards were carefully examined to help produce a new hull form true to the original.[144] Original drawings and photographs of the original excavation were also used to this purpose. The evidence showed that the ship as displayed in the museum did not have the same shape hull as the original Oseberg ship. A 1:10 scale model was then built out of cardboard.[145] Each part was produced separately and the model was assembled. Once this model was constructed, it was reproduced in a waterproof material along with a model of the Dronnigen. The two models were tested at the Norwegian Marine Technology Research Institute.[146] The sailing performance of the two models were simulated under multiple conditions, speeds, and heel angles. It was discovered that water flow around the two models was very different, with the new model performing much better.[147] The new hull shape provided greater lift to the front of the ship. The new hull was built with a curved or rockered keel in lieu of a flatter straight keel.[148] A new reconstruction the Saga Oseberg was built. In July of 2013, the ship was test sailed with a full crew, all were experienced sailors. Slightly more ballast was placed aft, based on the experience with similar boats. When the sail was set, an attempt was made to sail upwind. The ship was unable to tack and drifted sideways.[149] In an effort to improve the ship's performance, a longer steering oar was installed. The original Oseberg ship was found with its steering oar, so this change now altered the Saga Oseberg from the original ship. This

[143] Vibeke Bischoff, "The Oseberg Ship: New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[144] New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[145] New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[146] IBID
[147] IBID
[148] Vibeke Bischoff, "The Oseberg Ship: New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[149] IBID

change was not sufficient to steer the ship. The ship had substantial lee helm, and was unable to sail windward.[150] The rockered keel took away control, and it was suggested that false keel extensions be added to reduce this curve. Other suggestions for improving performance were to increase the length of the steering oar, install a trapezoidal sail in lieu of a rectangular one, and to move the mast aft to counteract the lee helm by directing more sail force to the rear of the ship. The mast could not be moved without changing the original design of the ship, negating the experimental archaeology of the reproduction and was, therefore, ruled out. It was also decided that the evidence of sail shape in iconography suggested only rectangular sails, so this change was also ruled out. The steering oar could also not be changed for the same reasons.[151] Further test sailings were performed, changing only variables that did not alter the original ship's design. The replica steering oar was reinstalled, and a focus was shifted to altering the location of the ballast by moving a group of people forward and aft. With the weight shifted to a balanced position by placing people forward of the mast, the ship achieved a balanced helm. When the ballast was centered, the ship sailed much differently and was able to beat to windward. The ship also maneuvered more easily, and the tiller was less heavy.[152] The oars of the original ship were of varying length. It was determined that the shorter oars were meant for midship positions. The ship achieved a speed of 5 knots under oar power.[153] Once the ship was sorted out, and the sailors knew how she behaved, it proved a good ship. The lack of freeboard would have made this a dangerous design to sail across the North Sea, but not impossible.[154] This reconstruction is currently (2023) in the harbor in Tønsberg, Norway.

Gokstad Ship Reconstructions

The design improvements and improved seaworthiness of the Gokstad ship (890 AD) have made it a favorite for experimental archaeology. This has been particularly true when recreating North Atlantic crossings from Norway to North America by way of the Faroe Islands, Iceland, and Greenland. The Gokstad reconstructions have proven that by 890 AD, the Vikings

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[151] IBID
[152] Vibeke Bischoff, "The Oseberg Ship: New Oseberg Ship, Reconstruction of the Hull Form," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/building-projects/the-oseberg-ship.
[153] IBID
[154] IBID

had the ship building technology to sail the open oceans. The next development in sailing technology needed to cross the North Atlantic would be navigation (see Learning Navigation below).

The Viking 1893

In 1893, the Gokstad replica of The Viking sailed with twelve men from Bergen to Newfoundland. The ship proved seaworthy and fast, averaging ten knots or more, completing the journey in 28 days. The ship was crewed by only 12 men. The Viking was next sailed through the Great Lakes and on to Chicago. The ship then went down the Mississippi to New Orleans. The ship returned to Chicago one year later. Today, the hull of the ship still exists, but is in need of restoration and preservation.[155]

The Islendingur 1996

Again in 1996, a Gokstad replica of The Islendingur was constructed and sailed to North America, stopping at L'Anse aux Meadows. The ship then continued on to New York City. The ship was built and captained by Gunnar Marel Eggertsson of Iceland. This trip was made with a crew of nine and averaged seven knots. The ship's voyage in the summer of 2000 was undertaken to commemorate the millennial celebration of Leif Eriksson's arrival in North America. This reproduction proved the usefulness and safety of this ship's design a second time. The Islendingur is currently on display in "The Viking World Museum" near the Keflavik Airport in Iceland.[156]

The Oseberg Viking Heritage Reconstruction 2023

Currently (2023), the Oseberg Viking Heritage is building a full-scale replica of the Gokstad Ship in Tønsberg, Norway. The construction will be built of traditional materials using traditional methods. Parts that are being made off-site will be transported to Tønsberg via other reconstructed Viking Era ships operated by the Oseberg Viking Heritage. Construction is taking

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[155] University of Chicago, "Gokstad Ship," Gokstad ship, accessed May 15, 2023, https://penelope.uchicago.edu/~grout/encyclopaedia_romana/britannia/anglo-saxon/maldon/gokstad.html.
[156] "Voyage of the Islendingur," Voyage of the islendingur, accessed May 15, 2023, https://www.releases.gov.nl.ca/releases/2000/tcr/0427bg01.htm.

place outdoors, and can be viewed by the harbor in Tønsberg. When I visited the site in April 2023, the keel was laid and three strakes had been installed.

The Ladby Ship Reconstruction

The Ladby Dragon 2016

A replica of the Ladby Ship (925-950 AD) was completed in May of 2016. The reconstruction of the Ladby ship is on display in the water during summer season at the Viking Museum Ladby. In the winter, it is pulled from the water and on display in a tent nearby.[157]

The Klåstad Ship Reconstruction

The Saga Farmann 2018

In 2018, a reconstruction of the Klåstad Ship (995 AD) was completed. I interviewed Jan Knutsen on April 6, 2023. Jan was in charge of the reconstruction, as well as the test sailing of the ship. He provided me with a great deal of information based on his experience with this reconstructed Viking ship.[158] The oars of the original ship were held in place with keiper on the top of the sheer strake. On the reconstruction, these proved to be too weak to have been used on a regular basis for propulsion. It is more likely the ship was sailed and only propelled under oar when docking or other necessary tasks.[159] The ship was originally fitted with a sail of 110 square meters. This sail proved to be too much for the ship. The mast was shortened, and a smaller sail of about 90 square meters replaced it.[160] The Saga Farmann sits in the harbor in Tønsberg, Norway, next to the Saga Oseberg mentioned above. Sailing the Saga Oseberg, the hands discovered that sail required ten men to hoist the sail. With this in mind, the Saga Farmann was outfitted with a winch type apparatus to hoist the ship, as found on the Kalmar ship in Sweden built in 1160 AD. There was no evidence to suggest that this device existed on the Klåstad Ship, other than the apparent small number of hands used to sail her.[161] The Saga Farman is generally sailed with a compliment of eight, but can be handled by six if they have experience. The ship

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[157] "Viking Museum Ladby - A Brief Overview," OpdagDanmark, accessed May 15, 2023, https://www.opdagdanmark.dk/en/oplevelser/vikingemuseet-ladby/#:~:text=The%20Ladby%20Dragon,the%20country%20in%20the%20920s.

[158] Noah K Meseck and Jan Knutsen, Transcript of Interview with Jan Knutsen, other, April 6, 2023. See Appendix

[159] IBID

[160] IBID

[161] IBID

does not sail upwind very well. In good conditions with an experienced crew, she can go upwind a little. No spar pole or other advantages were employed to help upwind sailing.[162] Jan revealed that for general use, the Saga Oseberg does use a spar pole to help her sail upwind. Under sail, the Saga Farmann did not heel excessively, and did not take on water in normal conditions. The ship was seaworthy and safe to sail.[163] Tacking was difficult, and it sometimes took several attempts to get her through the wind to change tack. With practice, a skilled crew can tack the ship.[164] In April of 2022, Ole Harald at Oseberg Viking Heritage reported that there is an intended expedition planned for the Saga Farmann to go to Istanbul in the summer of 2023.[165] As of the writing of this thesis the Saga Farmann is on its way to Istanbul and is in Mainz, Germany following the Rhine River.[166]

Skuldelev 5 Reconstruction

Helge Ask 1991

In 1991, a reconstruction of the Skuldelev 5 (1030 AD), the Helge Ask was built by the Viking Ship Museum in Roskilde, Denmark. The ship was found to match up with a 46 square meter sail and 26 oars. Crewed by 30 sailors, the ship has an estimated top speed of 15 knots. The reconstruction has a weight of 2.00 tons. This was the first ship the museum reconstructed.[167]

Skuldelev 1 Reconstructions

Saga Siglar 1984

In 1984, another replica of the Skuldelev 1 (1030 AD), the Saga Siglar, was sailed around the world by Captain Ragnar Torseth and a crew of seven. Also along for the ride, was the Captain's 11 year old son. The ship sailed from Norway on June 17th of that year, and reached New York City by way of Iceland and Greenland in September, following the path of Leif Eriksson. From there, the ship continued up the Hudson River through the Great Lakes, down the

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[162] IBID
[163] IBID
[164] IBID
[165] Ole Harald, "Water under the Keel Once More...," Oseberg Viking Heritage, April 8, 2022, https://osebergvikingarv.no/eng/2022/04/08/water-under-the-keel-once-more/.
[166] Saga Farmann , accessed May 30, 2023, https://www.sagafarmann.com/.
[167] "Helge Ask," Reconstruction of Skuldelev 5, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/the-boat-collection/helge-ask.

Mississippi River, and onward to the Pacific through the Panama Canal. In 1985, the ship sailed into Sydney Harbor. The ship then continued on, eventually passing through the Suez Canal to Europe, and back to Norway. This proved to the world the seaworthiness of this open vessel.[168]

Ottar 2000

In 2000, a reconstruction of the Skuldelev 1 (1030 AD), the Ottar, was built by the Viking Ship Museum in Roskilde, Denmark. During construction, the builders learned a lot about woodworking tools and techniques of the period. The ship has two large cargo holds, and large areas with deck planks for the crew to work on. The ship is very seaworthy for a ship of its day. The museum fitted this ship originally with a 90 square meter woolen sail. The wool was spun very tightly to provide a windproof, durable cloth. The ship was treated with horse mane grease and water. Finally, once the sail was broken in, it was rubbed with beef tallow on the front of the sail. The museum has found the ship useful in longer voyages out at sea due to its seaworthiness. As a cargo ship, the vessel only has 4 oars, and can be crewed by as few as 6 sailors. In trials, the measured top speed under sail was 10 knots with an average speed of 5 knots, with speed at oars of 1.5 knots.[169]

Skuldelev 2 Reconstruction

Sea Stallion of Glendalough 2004

A reconstruction of the Skuldelev 2 (1042 AD) was completed in 2004. The Sea Stallion was built by the Viking Ship Museum in Roskilde, Denmark. An inventory of the resources used to make the hull were taken, and included a total of over 20 oak trees, 37 pine trees, 3 ash trees, and 10 willow trees for the ship, plus 10 linden trees for shields.[170] This gave great insight to the lumber resources needed to build and maintain a fleet of these ships. In 2008, the BBC sponsored a voyage of this reconstruction from Roskilde to Dublin. This voyage was designed to learn of the challenges and hardships that the crew of the original Skuldelev 2 would have faced. The

[168] "A Replica Viking Ship, the Saga Siglar, Sailed Into...," UPI, September 26, 1985, https://www.upi.com/Archives/1985/09/26/A-replica-Viking-ship-the-Saga-Siglar-sailed-into/2471496555200/.
[169] "Ottar: Rekonstruktion Af Skuldelev 1, et Havgående Handelsskib Fra Vikingetiden, 1030," vikingeskibsmuseet, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/fagligt/museets-baadsamling/ottar.
[170] "Skuldelev 2," The Sea Stallion from Glendalough, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/visit-the-museum/exhibitions/the-five-reconstructions/the-sea-stallion-from-glendalough-skuldelev-2.

voyage also provided information on the sailing characteristics of the ship. The reconstruction used a 112 square meter sail.[171] The route they chose to take started in Roskilde to southern Norway. From there, across the North Sea to the Orkney Islands, before turning south through the Minch Channel of the Hebrides, and over the Irish Sea to Dublin.[172] At one point on this voyage, the ship's rudder strap broke. During the repair, the yard was brought down to reef the sail. During this time, the ship was without any steering control, and the ship turned sideways to the waves.[173] In this position, if the waves begin to break, even a modern ship can be badly damaged. An open ship, like a Viking ship, can be swamped and sunk very quickly. During the journey, bailing became a constant chore which is not surprising considering the lack of a watertight deck on Viking ships. The Sea Stallion had modern hand pumps to bail out the ship.[174] Presumably, the Vikings would have been using buckets to perform this task. Another repair was required when the lines of the starboard end of the yard became tangled and needed to be cut. The ship also faced strong force 9 winds (40 knots).[175] This long journey communicated the difficulty of sailing these long ships. The sail and yard were very heavy, making reefing difficult since the sail had to be lowered to accomplish this task. Once the sail was fully reefed, the ship moved along swiftly at 9 knots.[176] The ship performed very well. The voyage also went through food provisions of 600 kg of meat, one-half ton of porridge, and about 1 ton of bread. The ship averaged 4.5 knots for the duration of the voyage.[177]

Draken Harald Hårfagre 2012

In 2012, construction was completed on the Draken Harald Hårfagre. The ship is a clinker-built, lap strake oak ship. The ship is 35 meters long and 8 meters wide, giving her a

[171] "Skuldelev 2 The Sea Stallion from Glendaloug," The Sea Stallion from Glendaloug (Skuldelev 2), accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/en/professions/boatyard/experimental-archaeological-research/ship-reconstruction/skuldelev-2.
[172] "Viking Voyage - BBC Timewatch," 2007 Documentary on the sailing of "Havhingsten fra Glendalough" ("Sea Stallion from Glendalough"), a Danish reconstruction of the Skuldelev 2 ship, September 3, 2014, https://youtu.be/Q8jhnrNHk3g
[173] "Viking Voyage - BBC Timewatch," 2007 Documentary on the sailing of "Havhingsten fra Glendalough" ("Sea Stallion from Glendalough"), a Danish reconstruction of the Skuldelev 2 ship, September 3, 2014, https://youtu.be/Q8jhnrNHk3g
[174] IBID
[175] IBID
[176] IBID
[177] IBID

length to beam ratio of 4.4:1.[178] The ship is comparable in design to the Gokstad ship, but 1.5 times larger. The ship is as long as a longship, but wider in the beam. The Draken Harald Hårfagre is not a reconstruction, so building her did not provide a window into the sailing characteristics of a confirmed Viking Era ship known in the architectural record. Nevertheless, the ship is an example of a Viking ship. The ship was built with traditional methods and tools. It was fastened and sealed with traditional materials and techniques, and it was rigged with hemp rope. One exception is that the large 260 square meter sail is made of silk. In 2016, the ship sailed from Norway to America in the path of the Vikings, including most notably Leif Eriksson.[179] In October of 2018, Defense and Aerospace Report editor Vago Muradian interviewed the captain of the Draken Harald Hårfagre, Björn Ahlander. Captain Ahlander has been sailing square rigged ships since 1969, most recently rigging master on the large square-rigged Swedish ship, the Götheborg.[180] The Draken Harald Hårfagre is built for 100 sailors at the oars, but can be sailed with much less than that. The ship is generally sailed with 34 sailors.[181] The ship made speeds of over three knots under oar power for a short period of time. Under sail, the ship made a top speed of 14 knots, and in storms, the ship still made 11 knots.[182] Captain Ahlander pointed out that the ship sails very well into the wind. Sailing to 50 degrees off of the wind when traveling at a good speed. The ship does use a bietass pole to help with this.[183] The ship behaves differently from other ships that Captain Ahlander has sailed. The ship does not heel over that badly in wind gusts, but speeds up well. He attributed this to the wide beam and hull shape of the ship.[184] Captain Ahlander confirmed what Jan Knutsen stated in my interview with him with regard to tacking these square-rigged ships. Tacking the Draken Harald Hårfagre is difficult, when turning into the wind on a tack, the large sail backfills which reverses the direction of the ship. Once the ship has come about sufficiently and the sail has been braced over and sheeted on the other side, the ship resumes forward momentum. This technique took a long time to learn. They also learned it was best to tack the Viking rig by turning with the wind to

[178] "About the Ship: Draken Harald Hårfagre: The World's Largest Viking Ship Sailing in Modern Times," Draken Harald Hårfagre, accessed May 15, 2023, https://www.drakenhh.com/about-the-ship.
[179] "About the Ship: Draken Harald Hårfagre: The World's Largest Viking Ship Sailing in Modern Times," Draken Harald Hårfagre, accessed May 15, 2023, https://www.drakenhh.com/about-the-ship.
[180] Björn Ahlander, "Viking Longship Captain Ahlander Discusses USA Visit," Interview with Björn Ahlander, October 26, 2018, https://youtu.be/-OkFdckkfIA.
[181] IBID
[182] IBID
[183] IBID
[184] IBID

perform a jibe in heavy weather, rather than tacking into the wind.[185] Both Captain Ahlander and the crew of the Sea Stallion stated that the amount of flexibility the ship has in heavy seas can be unnerving to witness. The ship is well balanced and didn't take a lot of strength to steer, unless the weather was bad. The steering oar is designed as some of the Viking ships were with one flat side and one curved side. This design provided lift to compensate for the disadvantage of having the steering oar set to one side and it worked very well.[186] The ship is much less responsive at slow speed. Like the Sea Stallion, the Draken Harald Hårfagre had problems in storms. For the crew of the Draken Harald Hårfagre, the excitement occurred in a storm off of the Orkney Archipelago. In high winds, the mast snapped in two, sending the 1.5 ton yard and sail down onto the deck. Fortunately, no one was injured, and the event gave the crew an opportunity to repair their ship themselves in a way that would have been similar to repairs in the Viking era, not unlike the repairs that Thorvald Eriksson had to perform off the coast of North America.[187] The ship sailed on the east coast of the United States until the Covid shut down in 2020. Since then, the ship has been docked at Mystic Seaport Museum in Connecticut. In 2023, at the time of this paper, the ship was not hiring crew and but was making plans to sail again in the 2024.[188]

Availability of Wind

I examined the winds and general sailing conditions of the seas around Scandinavia to determine which seas had the safest sailing conditions. The logic being that the best risk/reward ratio would result in the adaption of ships to sail power in the safest seas first. I found that the safest areas of sailing with access to foreign trade in Europe existed in the Ålands Sea followed by the Baltic. Difficult conditions increased as you headed into the North Sea. As anyone who has spent a day in a sailboat with little or no wind can tell you, sailing without wind is one of the most frustrating things you can do on the water. In the fjords of Norway, where the Scandinavians would have first started using boats, there is often little or no wind. When there is wind it is often unpredictable. Once you leave the shelter of the fjords, the winds and sea conditions become very challenging. I believe this lack of usable wind power in the fjords,

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[185] IBID
[186] Björn Ahlander, "Viking Longship Captain Ahlander Discusses USA Visit," Interview with Björn Ahlander, October 26, 2018, https://youtu.be/-OkFdckkfIA.
[187] IBID
[188] "Join the Crew: Draken Harald Hårfagre," Draken Harald Hårfagre, accessed May 30, 2023, https://www.drakenhh.com/join-the-crew.

combined with the complicated wind and sea patterns beyond them, provided a very practical reason not to use sails in these areas until the technology advanced sufficiently to support the cost and risk of adding sail power. This technology was developed in the Baltic, and improved on the North Sea. The first regions that evidence of sailing appears also happens to be where there is more reliable wind, as well as wind closer to shore in the form of on and offshore breezes.[189]

Which Regions of Scandinavia Have the Best Sailing Conditions

In the early days of Scandinavian sailing, mariners used coastal sailing which provided a way to get around without using celestial navigation. Another advantage to coastal sailing is the phenomenon of onshore and offshore winds. Along coastlines, particularly in summer months, the sun heats the air above the land more rapidly than it heats the air above the water. The air onshore rises and pulls in air from offshore. When the sun goes down, the wind often switches direction. These onshore breezes would allow ships to sail parallel to any shoreline on a beam reach in both directions easily.[190] Once you venture farther out onto the sea, this effect dissipates and prevailing winds become more important for navigating. To travel across the regional seas and eventually to North America, the Vikings would not only need to implement sailing technology to their ships, they would also need to learn the wind patterns of any ocean they wanted to navigate regularly. Recent historical data of the region shows that the region around Denmark in the southern Baltic had the most consistent summer wind, with the least amount of excessive dangerous wind conditions. This was followed by the rest of the Baltic Sea. The Norwegian Sea proved to be the least desirable place to adopt sail power. The west coast of Norway consists of coastal islands and fjords, devoid of wind for much of the summer. Wind can be found just offshore, but this wind can be very strong and potentially dangerous. This transition seems to occur very quickly. The phenomenon of falling winds also occurs, producing violent dropping winds of the mountains.[191] Eventually sails were used in this region, but I believe this was only after the people of this region became more comfortable with sailing and

[189] Ashajyoti, "The Difference between Land and Sea Breezes," Science Query, February 17, 2022, https://sciencequery.com/the-difference-between-land-and-sea-breezes/.
[190] IBID
[191] Konstantinos Christakos et al., "The Importance of Wind Forcing in Fjord Wave Modelling - Ocean Dynamics," SpringerLink, December 3, 2019, https://link.springer.com/article/10.1007/s10236-019-01323-w.

developed better equipment and experience in the methods of sailing their unique ships. I believe sailing would have been limited to the interisland waterways of the coast in the beginning. In any location, winds do not remain consistent. Storms and complex weather systems create changing wind patterns. The wind direction and strength can cause changes in current. I reviewed only general wind patterns since random storm conditions can occur anywhere. I reviewed the wind patterns for each region to show the locations most likely favorable for early sail adoption from a wind and current standpoint.

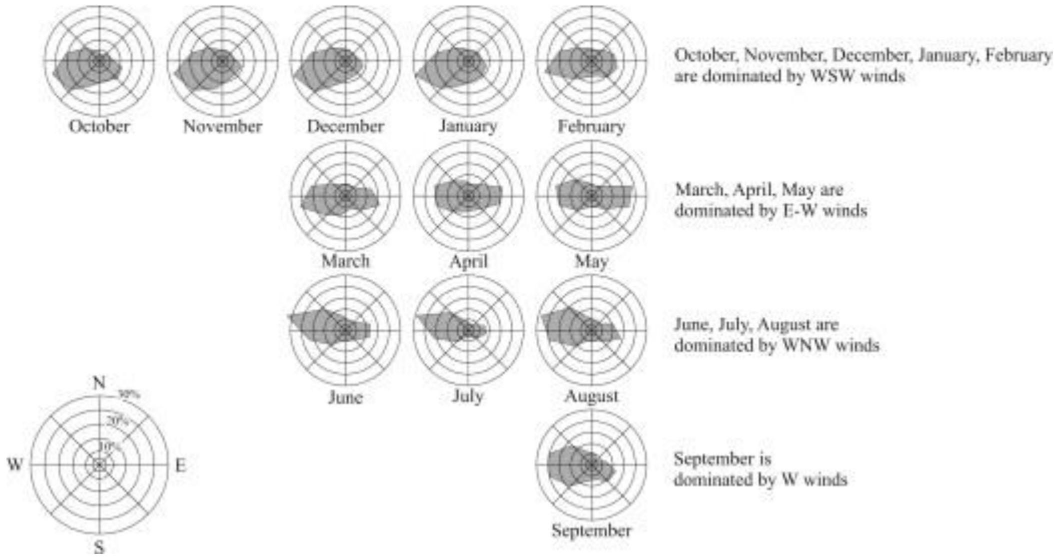
The Baltic Sea

The Baltic Sea wind patterns are almost ideal for much of the summer for sailing between Stockholm and Estonia, precisely where the earliest sailing ship was found in Salme. Winds tend to blow on a heading from west or east and tend to stay at speeds from 3 to 14 knots.[192] These wind speeds provide a safe range for sailing any ship, and particularly a nice range for the earliest example of the sailing ship found in Salme Estonia. A wind from the west would provide excellent wind to power a sailing vessel sailing from Stockholm to anywhere in the eastern Baltic and into the Gulf of Finland. The winds mentioned above would have put eastbound ships at all of the best points of sail for a square-rigged ship, as long as you waited for favorable wind. The many islands of the Ålands Sea would provide many places to tie up and wait. For the return trip, one would not have to wait long for an east wind to take the ship home. Even today, the Ålands Sea archipelago is a favorite destination for sailors. One could also use the currents with a west wind to head home on a beam reach by tacking. The currents in this region are generally northerly, along the eastern edge of the Baltic, and south flowing along the coast of Sweden, and are generally under 3 knots except at pinch points, or during tidal flows around pinch points, for water movement like Ålands Sea.[193] The sea route from Norrtälje or Östhammar, Sweden to Finland through the Ålands Sea, through an island chain to Finland would have been a route available to oar powered vessels years before sailing ships came into use.[194] This area would

[192] Wenyan Zhang, Jan Harff, and Ralf Schneider, "Analysis of 50-Year Wind Data of the Southern Baltic Sea for Modelling Coastal Morphological Evolution – a Case Study from the Darss-Zingst Peninsula," Oceanologia Published by Institute of Physics, Ernst-Moritz-Arndt University of Greifswald, Felix-Hausdorff-Str. 6, Greifswald 17489, Germany;Institute of Marine and Coastal Sciences, Szczecin University, Adama Mickiewicza 18, Szczecin 70–383, Poland , September 17, 2014, https://www.sciencedirect.com/science/article/pii/S0078323411500521.
[193] IBID
[194] IBID

have provided a good testing ground for early sail adoption since one was never far from land should catastrophe hit, as it most certainly did in the early days of sailing. Early sailboats with limited points of sail from running to beam reach could have sailed west to Finland, then returned home using south winds and favorable currents to take them north of the islands. They could then turn southwest to return home, or without favorable winds, they could have returned through the islands under oar power. Few navigation skills would have been needed to make the journey as far as St Petersburg, or up the rivers into Russia and Estonia, since either islands or the shoreline would have always been in site, with the exception of the short jaunt across the Ålands Sea. A guide familiar with the many small rocks barely beneath the surface would have been valuable when navigating through the islands of the Ålands Sea.[195] Once the sailors of the region became more comfortable with sailing, and improved their ship and rigging designs for this purpose, they could have attempted longer stretches at sea between land. Fortunately, the Baltic is laid out like a classroom for just such advancement. Just to the south of the Ålands Sea in the central Baltic, another feature exists in this sailing sweet spot. Gotland Island, lying about one third of the way along the east-west route from Sweden and Latvia and Estonia, would have been a useful waypoint for early sailors. Pictures stones on Gotland dating from the 7th century indicate that this island had a strong sailing tradition during this time period.[196] (See Iconographic Evidence of Sailing below.)

[195] Esben Jessen, "The Secrets of Viking Navigation - an Interview with Captain Esben Jessen," Interview with Esben Jessen, December 1, 2021, https://youtu.be/YzDvSY7xf9I.
[196] aðalheiður guðmundsdóttir, "Gotland's Picture Stones," PDF ISBN 978-91-88036-86-5 - háskóli íslands, accessed May 14, 2023, https://uni.hi.is/adalh/files/2013/02/Hildr-Eng.pdf.



Baltic Sea predominant wind directions based on data from 1958 to 2007.[197]

The Danish Straits

The next lesson for the early Scandinavian sailors would have been sailing the three passages between the Baltic and the Kattegat. In this region, winds and currents must be considered together, as winds in these passages have a great effect on the currents, and cause both to act for the sailor or against him. The eastern most passage is the Øresund. It runs between Sweden and the east coast of Sjaelland in Denmark. The currents here are negligible, with plenty of places for ships to harbor along the coast. Winds vary in the sound, so a sailor could wait at harbor for favorable wind to make the passage through the sound.[198] The center passage, the Great Belt, is a wide, deep passage, but has strong variable currents that are controlled by the wind. As the wind pushes the water about, the currents in this route shift. Winds from the northwest generally cause

[197] Wenyan Zhang, Jan Harff, and Ralf Schneider, "Analysis of 50-Year Wind Data of the Southern Baltic Sea for Modelling Coastal Morphological Evolution – a Case Study from the Darss-Zingst Peninsula," Oceanologia Published by Institute of Physics, Ernst-Moritz-Arndt University of Greifswald, Felix-Hausdorff-Str. 6, Greifswald 17489, Germany;Institute of Marine and Coastal Sciences, Szczecin University, Adama Mickiewicza 18, Szczecin 70–383, Poland , September 17, 2014, https://www.sciencedirect.com/science/article/pii/S0078323411500521.
[198] National Geospatial- Intelligence Agency, "Sailing Directions (Enroute) Baltic Sea (Southern Part)," PDF from National Geospatial- Intelligence Agency, accessed May 14, 2023, https://msi.nga.mil/api/publications/download?key=16694491/SFH00000/Pub194bk.pdf&type=view.

a south current. Most other winds will cause a northbound current, but even then there may be currents flowing one direction on the east side of the channel, and the opposite side on the west side.[199] The currents are also affected by the uneven bottom topography in the channel. The currents are not treacherous, and could have been used to the advantage of a sailor with the ability to read the currents. The ability to ride the currents, and know how they worked would have been a valuable skill once learned when using this passage. The third and western most passage, the little belt is very narrow particularly at its northern most point.[200] As a result of this, the Little Belt is affected by the spring runoff into the Baltic which causes the current in this passage to run north. Other times of the year, the current will run with the wind. Winds from the south and east will push the current northward, and winds from the north and west will cause a southbound current. Due to the narrow nature of this passage, the currents tend to run stronger.[201] All passages tend to run in the general direction of the wind which will result in a calmer sea state. The negative effect of the nature of the wind and currents in these passages meant that favorable winds would have been very important to make the passage between the Baltic and the Kattegat.[202] Each of these passages would have been used to access the thriving port of Hedeby during the height of the Viking age. As a result, controlling traffic through these ports would have been critical for control of the region.

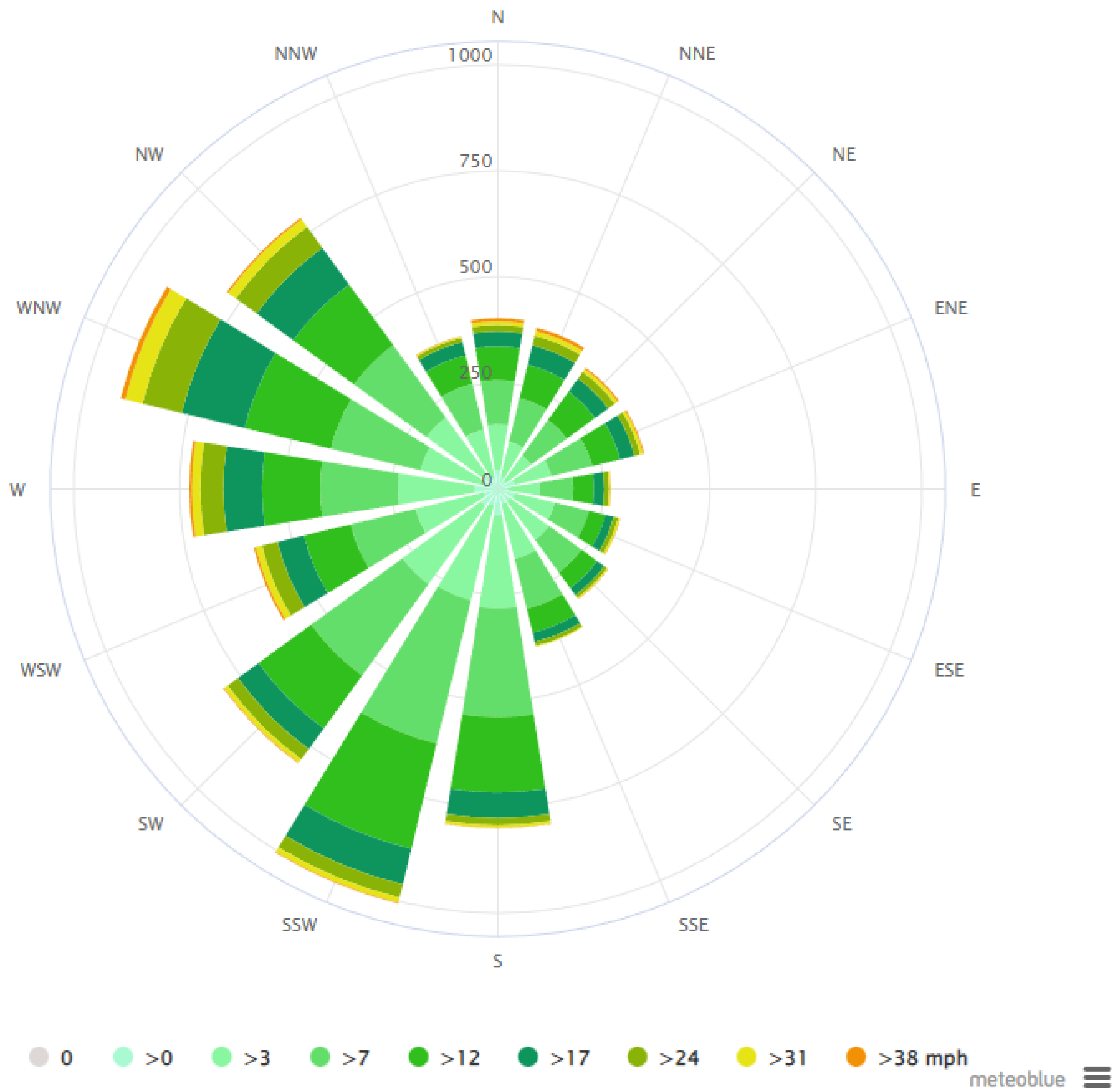
The North Sea

Wind in the North Sea is favorable for sailing from April through October. Although storms are possible all year in any sea, winter months on the North Sea can be particularly dangerous with high winds and large waves. We know from the written sources, that the Norwegians did not typically sail during these months.[203] Prevailing winds in the North Sea range from northwesterly to southerly winds. The winds from the south are generally less powerful, and would have provided effective propulsion for ships traveling to and from England. Southern winds were more common

[199] IBID
[200] IBID
[201] National Geospatial- Intelligence Agency, "Sailing Directions (Enroute) Baltic Sea (Southern Part)," PDF from National Geospatial- Intelligence Agency, accessed May 14, 2023, https://msi.nga.mil/api/publications/download?key=16694491/SFH00000/Pub194bk.pdf&type=view.
[202] IBID
[203] Snorre Sturlason, *Heimskringla, or, the Lives of the Norse Kings*, ed. Erling Monsen, trans. A. H. Smith (New York: Dover Publications, 1990).

in the summer months.[204] A southern wind would not only provide excellent propulsion for ships heading north, but more importantly would have supported east-west travel on beam reach. This provided a good source of propulsion for round trip travel across the bodies of water that the Scandinavians traveled on during the early days of the Viking Era. It is not surprising then that the raid at Lindisfarne occurred at a latitude equal to Denmark. The Viking arrival in Wessex in the south of the island would have been more of a challenge. Using shoreline routes, these raiders could have taken advantage of on and offshore breezes to propel them along on beam reach to a narrow point in the channel to make a crossing using favorable winds. The sandy shoreline along the Netherlands and Belgium would have proved an ideal place to beach their ships while they waited for conditions to improve.[205]

[204] "Simulated Historical Climate & Weather Data for North Sea," meteoblue, May 12, 2023, https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/north-sea_united-states_5129210.
[205] "Simulated Historical Climate & Weather Data for North Sea," meteoblue, May 12, 2023, https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/north-sea_united-states_5129210.



North Sea wind direction in hours per year.[206] (Metoblue)

The Seas of the United Kingdom

The seas around the United Kingdom are where the Vikings would have had to sharpen their sailing skills. The islands disrupt both wind and ocean currents creating challenging sailing conditions and fast currents. Most frequent winds in the Irish Sea are from the west and northwest. Storms of force 6 (22 knots) or stronger can occur all year, but are most common during the winter months between December and March, with the best sailing from April to

206 IBID

August.[207] This pattern supports the summer-only sailing season adopted by the Vikings.[208] Wind patterns in the Hebrides tend to blow from the southwest at average speeds of 14 knots, which support good sailing toward Scandinavia from this location by way of southern Norway using the south winds of the North Sea.[209] The English Channel can have winds from any direction, but prevailing winds tend to blow through the channel providing good sailing for a crossing. To sail in the channel, the Vikings would have had to wait for favorable winds. Next, these winds would have had to correspond with the currents, which can be very strong in the channel.[210] Currents into harbors can be so strong that a ship would have to wait for the tide to change to get into or out of a harbor. The tidal stream in parts of the Thames Estuary can be strong. Similarly, Portsmouth harbors in spring and fall, tidal currents can flow at 3.4 knots upstream and over 4 knots downstream.[211] Currents through the Channel Islands are strong, but can be used to one's advantage. Knowledge of these tidal flows would have been required to navigate the English Channel smoothly and effectively. Elsewhere around the British Isles, the average wind speed increases as you head north, with average wind speeds in the south averaging 10.7 knots around the Isle of Wight, and increasing to over 14 knots around the Orkneys and Shetland in the north.[212] These northern islands were the stepping off points for the Vikings' exploration and settlement of Iceland and Greenland, and the eventual expeditions to North America. By the late 9th century, the Viking ship and rigging had been built with greater freeboard and bietas poles for better seaworthiness and improved upwind sailing capabilities (see the Gokstad Ship above). The Viking mariners would have also learned to effectively know where they were located from a latitude standpoint. With these technological advancements and

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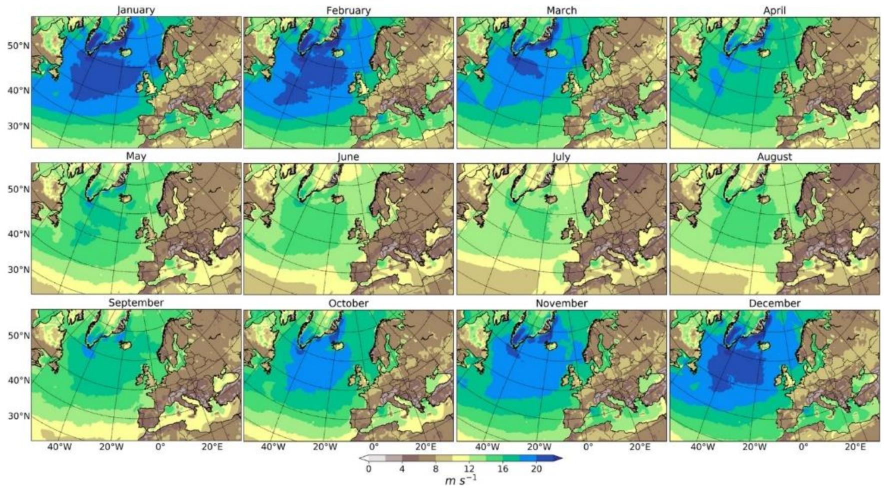
[207] M J Howarth, "Hydrography of the Irish Sea," SEA6 Technical Report POL Internal Document 174, n.d., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/197294/SEA6_Hydrography_POL.pdf.
[208] Snorre Sturlason, *Heimskringla, or, the Lives of the Norse Kings*, ed. Erling Monsen, trans. A. H. Smith (New York: Dover Publications, 1990).
[209] M J Howarth, "Hydrography of the Irish Sea," SEA6 Technical Report POL Internal Document 174, n.d., https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/197294/SEA6_Hydrography_POL.pdf.
[210] IBID
[211] "Tidal Streams Portsmouth Harbour," Hourly tidal streams through Portsmouth Narrows: by VisitMyHarbour [Tidal Streams] - VisitMyHarbour articles, accessed May 15, 2023, https://www.visitmyharbour.com/articles/3167/hourly-tidal-streams-through-portsmouth-narrows.
[212] "Where Are the Windiest Parts of the UK?," Met Office Government Statistics, accessed May 15, 2023, https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/wind/windiest-place-in-uk.

skills, the Scandinavians began sailing west across the Norwegian Sea (see Learning Navigation below).

The Norwegian Sea and the North Atlantic

The wind patterns in the Norwegian Sea were ideal for eastbound spring trips and westbound summer travel. Prevailing winds start in spring from the west and shift to south southeast by August.[213] Without forecasts, these general rules would be most useful to increase the odds of a short passage. Winds during the summer months were generally not as strong, averaging between 12 and 14 knots.[214] In late summer and fall, hurricanes following the North Atlantic current could prove disastrous to any ships that encountered them.[215] Wind around Iceland is very strong. Winds in the Denmark Strait and on the east coast of Greenland are among the most treacherous on the planet.[216] These winds, along with the dangers of icebergs and growlers, kept most Greenland navigation isolated and limited to the west coast of the landmass by way of Cape Farewell. Of the 35 ships in Eric the Red's colonial voyage, only 14 made it to the west cost of Greenland, with the rest either turning around or perishing at sea.[217] This route proved so difficult that it played a large role in the abandonment of the colony years later, but before that the storms at the south end of Greenland led to the discovery of North America (see Learning Navigation below).

[213] "Wind and Weather Statistic Norwegian Sea," Windfinder Wind Statistics, accessed May 15, 2023, https://www.windfinder.com/windstatistics/norwegian_sea.
[214] IBID
[215] IBID
[216] Terhi K Laurila, Victoria A Sinclair, and Hilppa Gregow, "Climatology, Variability, and Trends in near-Surface Wind Speeds over the North Atlantic and Europe during 1979–2018 Based on ERA5," Royal Meteorological society, December 6, 2020, https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.6957.
[217] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).



Monthly mean windspeed data 1979-2018.[218]

Learning Navigation

Navigation During the Viking Era

The next skill I examined to determine the Viking's path to the open ocean was navigation. Navigational skills also support my theory of a geographic progression from the Baltic through the North Sea and on to the west across the Norwegian Sea, into the North Atlantic and beyond to Iceland, Greenland, and North America. Each step along the way contained longer passages of open ocean. In the early years of Scandinavian sailing, navigation would have been done by landmarks. By keeping close to shore, the early mariners would have had several advantages beyond knowing where they were. As noted above, the early sailing vessels were easier to swamp in heavy seas than the ships developed later. They also didn't sail upwind very well. Keeping close to shore allowed the sailors to pull in every night and sail only in the daytime. They could also pull in for several days, and wait for favorable winds. This would have allowed them to replenish supplies, particularly water and food. They were also able to take advantage of on and offshore breezes, allowing them to sail on a beam reach, up and down the coast on many summer days. Once the Viking Era began and they began to sail out of sight of land, the sailors had to learn new techniques for learning how to measure heading, latitude and east/west distance sailed or longitude. I could tell by the regularity, that their ships

[218] Terhi K Laurila, Victoria A Sinclair, and Hilppa Gregow, "Climatology, Variability, and Trends in near-Surface Wind Speeds over the North Atlantic and Europe during 1979–2018 Based on ERA5," Royal Meteorological society, December 6, 2020, https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.6957.

went back and forth from Iceland to Norway that they had mastered these techniques well enough to reasonably expect to arrive safely at their destination on most voyages.[219] I also examined the journey of Bjarni Herjolfsson and discovered that an experienced sailor could reestablish the ship's location by using the tools and knowledge of his disposal.[220] It is probable that each navigator had tools and techniques he liked to use better or trusted more. The Vikings have no record of a sailing academy that would have standardized methods of navigation. As a result, I have assumed that each sailor would have developed his own methods through years of on-the-job training, as well as apprenticeship obtained by sailing with other experienced sailors.

Measuring Heading

Observational Navigation

When sailing only one day out of sight of land, heading could be maintained well enough by simple examination of the sun during daylight hours, and the stars at night in clear weather. The Vikings could have used the sea birds and clouds as well. Once you began to approach land, if you knew which birds to look for, they would lead you to the next landfall. Once you came close enough, you would once again see land.[221] Esben Jessen, the Captain of the Ottar reconstruction mentioned above, recounted that on his approach to Lindisfarne from the open ocean, the very first land they sighted was the hill behind the monastery on Lindisfarne. As a sailor, this suggested to him that it was no surprise that this became a target for this, early Viking raid.[222] Even before you can see landforms, there is another phenomenon that is visible over large landforms. Clouds form over large landforms like mountains. These clouds are called lenticular clouds. When the air is forced over large landforms, these clouds develop, and can be seen much earlier than even the mountains themselves. This only helps if the weather conditions are clear enough. It also only helps if you are approaching large landforms like mountains.[223] Luckily for the Vikings, the Faroe Islands, Iceland, and Greenland all have mountains. Another thing that can be observed are the waves. In some locations, the waves provide an echo off of

[219] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).
[220] IBID
[221] Esben Jessen, "The Secrets of Viking Navigation - an Interview with Captain Esben Jessen," Interview with Esben Jessen, December 1, 2021, https://youtu.be/YzDvSY7xf9I.
[222] IBID
[223] IBID

shallow water or landforms. Like a type of sonar, these refracted waves can also give clues to the location of landforms.[224] Over time, these mariners would have learned the location of whale feeding grounds and other clues to their location. A good navigator would have used everything, along with his experience to determine to the best of his ability which way the ship was going.[225]

Sun Compass

I discovered that instruments were developed to keep a ship on course. Archaeological evidence suggests that the Vikings also had some instruments to help determine their course. One of these instruments is a simple sundial compass called a Uunartoq Disc. An example of this device was found in 1948.[226] Some use the lack of written source material and problems with the artifact to dismiss this device.[227] I believe it is important to remember that the early recorders of the Sagas were not navigators and, therefore, it is very likely that the tools and techniques used in sailing would not have been written down by them. I also believe that the location of this artifact and its usefulness when used on a constant latitude suggest to me that it was used at least on the route on which it was found, and at least by some navigators, if not most. The device is a wooden disc with a peg in the center. The disc can be mounted on a weighted handle to help level it.[228] Before a journey, the disc can be placed in a fixed location. Sunrise and sunset locations of the shadow can be marked, as well as any other useful indications the navigator saw fit. While it is true that the sun's shadow does not remain constant, the marks would be accurate enough until a new landfall could be made, and a new, inexpensive disc could be marked. This device also loses accuracy with changing latitude. This artifact was found in Greenland. Bergen in Norway lies at 60 degrees north latitude.[229] Cape Farewell, at the southern tip of Greenland, is

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224 "The University of Texas at Dallas Ocean Waves," PDF University of Dallas Texas, accessed May 30, 2023, https://personal.utdallas.edu/~mitterer/Oceanography/pdfs/OCEChapt09.pdf.
225 Esben Jessen, "The Secrets of Viking Navigation - an Interview with Captain Esben Jessen," Interview with Esben Jessen, December 1, 2021, https://youtu.be/YzDvSY7xf9I.
226 Mikkel H. Thomsen, "Instrument Navigation in the Viking Age?," Museum for vikingernes skibe og søfart, accessed May 15, 2023, https://www.vikingeskibsmuseet.dk/en/professions/education/knowledge-of-sailing/instrument-navigation-in-the-viking-age.
227 Lisa Zyga, "Errors on Viking Sun Compass Hint at Alternative Purpose," Phys.org, April 30, 2013, https://phys.org/news/2013-04-errors-viking-sun-compass-hint.html#:~:text=One%20of%20the%20most%20prominent,70%20mm%20(2.75%20in.).
228 Esben Jessen, "The Secrets of Viking Navigation - an Interview with Captain Esben Jessen," Interview with Esben Jessen, December 1, 2021, https://youtu.be/YzDvSY7xf9I.
229 Dénes Száz and Gábor Gábor Horváth, "Success of Sky-Polarimetric Viking Navigation: Revealing the Chance ...," Royal Society Open Science, 2018, https://royalsocietypublishing.org/doi/10.1098/rsos.172187.

just below 60 degrees north latitude. If you were sailing west to Greenland and you wanted to make sure you didn't miss Cape Farewell, you would keep your latitude north of Bergen as a result the marks on the disc which would remain useful for much of your voyage.[230] If you sailed to the same places at the same time of the year several times, custom marks could be added making this device very useful.

Sunstone

One navigation instrument that is supported by the written sources is the sunstone. To date, this device does not have evidence in archaeology. As such, the exact type of stone cannot be definitively proven. In November 2011, Guy Ropars of the University of Rennes in Brittany published a report on the subject.[231] He suggests that a material called Iceland Spar, a transparent crystal, could have been used to locate the sun even on a cloudy day, or after sunset in the north during the summer months.[232] When a spot is placed on the top of the crystal, the light of that spot is refracted producing two spots on the bottom of the stone. When the stone is pointed directly at the sun, these two spots will match in color and clarity. A sunstone was recently discovered on a ship dating after the Viking Era.[233] This supports the idea that these crystals were used in navigation. Knowing where the sun is very accurately did not mean the Vikings could set a course that was very accurate in cloudy weather. They did not have a way to keep time. This instrument could have located the sun, but the time of day would have to be approximated in bad weather.[234] Years of sailing would have allowed them to approximate the time of day to an accuracy that would have been acceptable. Even if this device was not entirely reliable, it would have been a welcome aid when no other method of sighting celestial objects was available.

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[230] IBID

[231] Albert Le Floch et al., "The Sixteenth Century Alderney Crystal: A Calcite as an Efficient ...," The Royal Society, 2013, https://royalsocietypublishing.org/doi/10.1098/rspa.2012.0651.

[232] Laurent Banguet, "Viking 'sunstone' More than a Myth," Phys.org, November 2, 2011, https://phys.org/news/2011-11-viking-sunstone-myth.html#:~:text=Here's%20how%20it%20works%3A%20If,%2C%22%20Ropars%20explained%20by%20phone.

[233] Laurent Banguet, "Viking 'sunstone' More than a Myth," Phys.org, November 2, 2011, https://phys.org/news/2011-11-viking-sunstone-myth.html#:~:text=Here's%20how%20it%20works%3A%20If,%2C%22%20Ropars%20explained%20by%20phone.

[234] Dénes Száz and Gábor Gábor Horváth, "Success of Sky-Polarimetric Viking Navigation: Revealing the Chance ...," Royal Society Open Science, 2018, https://royalsocietypublishing.org/doi/10.1098/rsos.172187.

Measuring Latitude

In my research, I found that measuring latitude to a functional accuracy would not have been very difficult for the Viking sailors, as long as the weather was reasonably clear. There would have been many ways to do this depending on the time of day and the time of year. If you were sailing in the spring and fall, the north star could have been used at night to determine both polar north and latitude. There would have been several ways to measure this reasonably accurately. Each navigator could have chosen his own method. The Vikings would have known that Bergen and Cape Farewell and Greenland were in the same position. We call this 60 degrees north today, but the Vikings would have called it something else (Bergen latitude perhaps).[235] They would have also known the latitude of other destinations. A navigator could have used a simple stick to measure latitude, as long as the person used his own stick made for his arm's length. A series of marks could be placed on the stick, which could then be held plumb at arm's length. The top mark would be the north star. All of the other marks would have been compared to the horizon. The marks for Iceland would have been toward the bottom of the stick, and Cape Farewell and Bergen would have shared a mark farther up and so on. This would have been close enough to get a sailor within sight of land. Other variations of this could have been a stick to reach the north star with a string hanging down. Anything would do, as long as the device was made by the user and was held plumb.[236] A similar method could be used to find latitude using the sun at noon, but accommodation would need to be made for seasons. Calibrating your instrument just prior to departure would be one way to do this. Once the Vikings were on their mark, they could then sail in the direction of their destination and expect to hit it.[237] The trick is not to get blown off of your target just as you approach your destination. This sometimes happened if the sun and north star were not visible for several days, or even more likely in the case of a storm. In a storm, survival would have come before navigation. Once you were out of

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[235] Dénes Száz and Gábor Gábor Horváth, "Success of Sky-Polarimetric Viking Navigation: Revealing the Chance ...," Royal Society Open Science, 2018, https://royalsocietypublishing.org/doi/10.1098/rsos.172187.

[236] "Exploring Our Fluid Earth," Traditional Ways of Knowing: Estimating Latitude University of Hawaii, accessed May 15, 2023, https://manoa.hawaii.edu/exploringourfluidearth/physical/navigation-and-transportation/wayfinding-and-navigation/traditional-ways-knowing-estimating-latitude.

[237] Dénes Száz and Gábor Gábor Horváth, "Success of Sky-Polarimetric Viking Navigation: Revealing the Chance ...," Royal Society Open Science, 2018, https://royalsocietypublishing.org/doi/10.1098/rsos.172187.

the storm, latitude could be reestablished. Determining longitude, as we know it today, would have been a challenge.

Measuring Longitude

The Vikings would not have considered longitude as we know it today. It is probable that they didn't see the earth for the sphere that it is. What they did measure was distance traveled. We know from the Vinland Sagas, that the Vikings knew how many days sail lay between ports.[238] Of course, if you have no wind or need to do a lot of tacking, your days could increase, but they would have known this. Most sailors even today that spend a lot of time sailing, know about how fast they are going. The Vikings, with their experience, would have also been able to estimate their progress reasonably enough to know when to expect to spot land.[239] Ebsen Jessen, Captain of the Ottar, a replica of Skuldelev 1, experimented with his crew to see if they could calculate speed without instruments. He discovered that a well-trained crew could calculate speed and, therefore, distance sailed accurately enough to be useful.[240] With this in mind, it is clear that the Viking navigators could have made sure to be at the correct latitude when they were about to approach their destination. The smaller their target, the more critical it would have been to keep on their latitude. If they missed their target and sailed passed, they would need to use other clues and their experience to know when to turn around.

The Voyage of Bjarni Herjolfsson (reference map below)

Since I began sailing, I have been impressed with the voyage of Bjarni Herjolfsson. He had never been farther west than Iceland. Very few people had sailed to Greenland at that time, and many who attempted the journey didn't make it. To meet up with his father, he sailed west and was blown off course into the unknown ocean and yet he survived and discovered North America in the process.[241] Examination of the voyage of Bjarni Herjolfsson, the first European to document the existence of North America, provides excellent insight into the navigational

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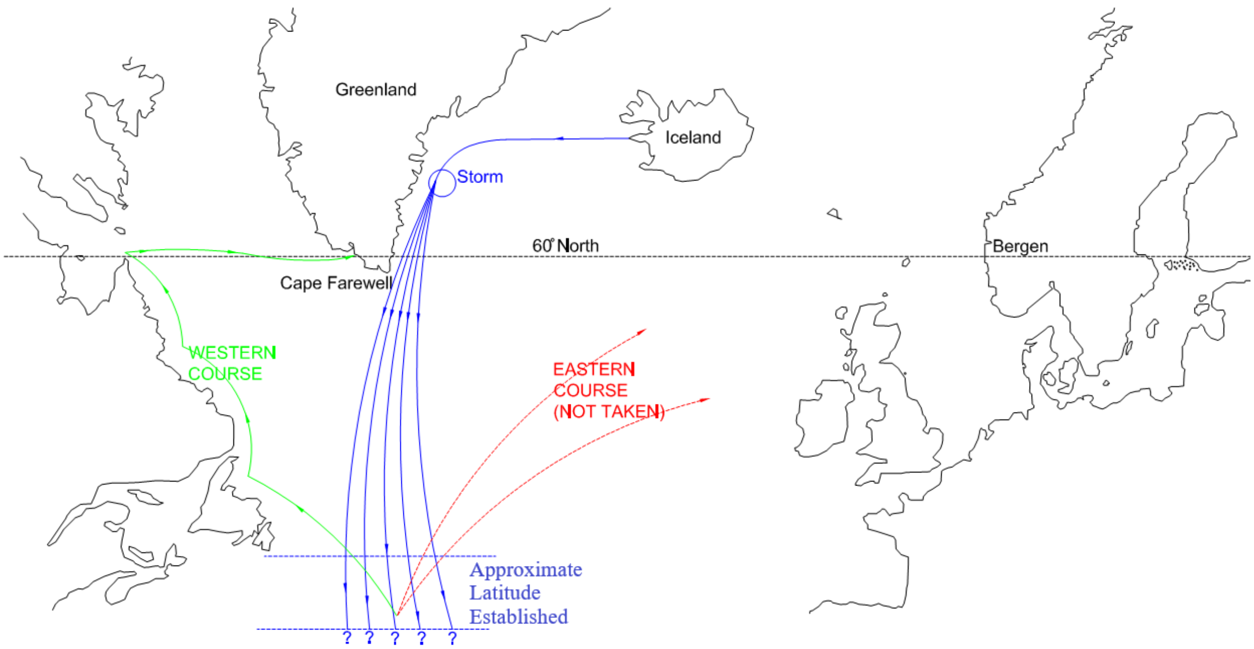
[238] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).
[239] Esben Jessen, "The Secrets of Viking Navigation - an Interview with Captain Esben Jessen," Interview with Esben Jessen, December 1, 2021, https://youtu.be/YzDvSY7xf9I.
[240] IBID
[241] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).

thought processes of the Viking era sailors. While Bjarni was away filling his ship with goods from Norway to sell in Iceland, his father left Iceland and followed Eric the Red to Greenland. Bjarni arrived in Iceland to the news that his father had gone. He decided to continue on with his ship to Greenland. His crew went with him which says something of his leadership. He had never been to Greenland, but enough had to provide Bjarni of the latitude of the cape, and a description of the barren snow-covered mountains that characterized the country. The first clue of the way Bjarni set his course is detailed in the fact that they used the mountains of Snæfellsnes to set their course for the first three days by keeping it in the same position to the stern of their ship.[242] Just after they had sailed out of sight of land they were hit with strong north winds and fog. These conditions persisted for several days. Bjarni sailed with the strong winds too for safety. By the time the sun came out, they had missed the cape, but it is important to consider that Bjarni did not know this. He also didn't know that any land existed past Greenland. When the sun came back out, Bjarni only knew for sure that he was too far south. This detail of knowing he was somewhere south of Cape Farewell, he could sail northeast. Once he reached the latitude of Bergen/Cape Farewell, he could then turn west and hit Greenland. Bjarni understood without a chart that this could have sent him right back to Iceland or England or Europe. His other option was to head northwest. No one knew what was in that direction, but at least he wouldn't end up back in Europe where he would have had to face the anger of his crew, and possibly lose the sailing season and end up wintering away from his father. He chose to head northwest.[243] He knew his father had settled on the west coast of Greenland. Heading west would be most likely to give him the correct approach once he turned to starboard, and would avoid the terrible conditions the crew encountered on Greenland's east coast if they were considered typical. When he hit land, he knew from the descriptions of Greenland that he was not there. Bjarni, with his ship already full and not wanting to go ashore, decided to sail northward toward his desired latitude sighting land along the way.[244] When he passed the Cape Chidley Islands, the land disappeared. This occurred at the same time that he reached the latitude of Bergen/Cape Farewell. Now there could be no doubt at all that they had gone too far west and that the land he

[242] Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).
[243] IBID
[244] IBID

had been sailing along was a new land.[245] Bjarni turned to starboard, and a few days later the mountains of Greenland appeared which matched the descriptions of the land they had been told.[246] This story demonstrates the hardships they faced not knowing longitude. At the same time, this shows that the Vikings of Bjarni's time knew how to navigate in the open ocean, including how to reestablish their longitude by using logic along with the tools they did have. Even if Bjarni had not spotted land, his course would have no-doubt remained much the same, and this story would not have been recorded as many such stories that have been lost to history.

Map of the Probable Path of Bjarni Herjolfsson



Map Drawn By: Noah Meseck

Iconographic Evidence of Sailing

To support my theory of a path to sailing from the Ålands Sea to the North Atlantic I also reviewed the iconographic evidence. This evidence also followed a timeline that led from the Baltic with the Gotland Picture stones starting in the 7th century down to the coins of Denmark in the 9th century. The Bayeux Tapestry at the end of the Viking Era rounds out the story.

245 Magnus Magnusson and Hermann Pálsson, *The Vinland Sagas: The Norse Discovery of America* (London: Penguin Books, 2003).
246 IBID

Gotland Picture Stones

Gotland is the largest of the Baltic islands with an area of approximately 3,000 square kilometers. The picture stone is an artform from this island dating back to the 5th century. Depictions of sailing ships can be found from the 7th century in a series of picture stones from this island off the cost of Sweden in the middle of the Baltic Sea and south of the Ålands Sea. These early illustrations give us not only the earliest evidence of sail power from the region, but also some information on the rigging on the early sailing ships of the region.[247] The Stora Hammars Stones date from the 7th century.[248] The Tjängvide (I) picture stone from Gotland dates from the same era. The depictions of sails on these stones show a diagonal square pattern. This pattern would have produced a stiff, strong sail able to withstand the high stresses placed on the cloth.[249] The picture stone from Hunninge at Klinte dates from about 100 years later and also shows this diagonal pattern in the sail.[250] Some rigging can be seen in these picture stones as well. The Tjängvide (I) picture stone shows some standing rigging in the form of stays, as well as some sheets along the bottom of the sail. The Stankyrka Smiss picture stone dating from the 10th century also depicts a diagonally patterned sail and sheets at the base of the sail. In this depiction, the sheets are woven in a diagonal pattern from the sail down to the lines attached to the hull. A sailor is shown on each sheet which would have been the case when handling these heavy sails.[251] The Hejnum Riddare picture stone shows a similar diagonal pattern on the sail and interwoven sail sheets. This stone also depicts a bowline used to hold the leading edge of the sail forward and tight to assist in upwind sailing. This stone also shows a forestay and a yard brace.[252] Why does the early Iconographic evidence in the picture stones show diagonal patterns on sails? While there is not yet a definitive answer to this question, several theories exist. The first is that these early sails were made of squares of cloth produced by various farmers and other

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[247] aðalheiður guðmundsdóttir, "Gotland's Picture Stones," PDF ISBN 978-91-88036-86-5 - háskóli íslands, accessed May 14, 2023, https://uni.hi.is/adalh/files/2013/02/Hildr-Eng.pdf.
[248] IBID
[249] IBID
[250] "The Picture Stone from Hunninge at Klinte," Viking Age Archaeology - The Picture Stone from Hunninge at Klinte, accessed May 15, 2023, http://viking.archeurope.info/index.php?page=the-picture-stone-from-hunninge-at-klinte.
[251] "The Picture Stone from Smiss in Stenkyrka," Viking Archaeology - The Picture Stone from Smiss in Stenkyrka, accessed May 15, 2023, http://viking.archeurope.info/index.php?page=the-picture-stone-from-smiss-in-stenkyrka.
[252] "Viking Age Stone from Hejnum, Riddare," Images of the Pictures Stones, accessed May 14, 2023, https://www.researchgate.net/figure/Type-C-D-Viking-Age-stone-from-Hejnum-Riddare-The-clearest-example-that-the-dragon_fig5_287096117.

producers of the era.[253] The sections of cloth available at the time may have been produced in lengths, only as tall as the loom it was woven on. The result would have been a sail made of multiple squares of cloth from several sources. Another theory is that the material used in these early sails would have been too elastic. As a result, diagonal reinforcing material of rope or leather strapping may have been desired to improve the sail strength and performance.[254] Later, iconographic evidence from the 11th century in the Bayeux Tapestry, shows vertical sail cloth.[255] Over time cloth was produced in longer lengths. It is possible that as sail cloth technology was also improved, the sail cloth was less elastic. If that occurred, reinforcing was no longer needed. If not needed, the reduced weight by its elimination would have been a welcome improvement.

Coins

Carolingian coins from Dorestad from 814-818 AD show simple Viking ship depictions with a mast and shrouds.[256] In 2018, a cache of 252 coins from between 800-825 AD was discovered in Ribe Denmark.[257] Of all these, three coins depicted a Viking ship with a sail tied to the yard. The ship is equipped with shields, a mast, and sail. Also shown on the coin are a forestay and backstay. The scene is completed with a fish swimming beneath the keel.[258] Other Danish coins from the time period show different depictions of sailing ships, including one with a reefed sail.[259]

The Bayeux Tapestry

The Bayeux Tapestry was commissioned by William the Conqueror's half-brother, Bishop Odo, for the new cathedral in Bayeux France in the 11th century. The tapestry is, in fact,

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253 "Wool Sailcloth," Viking Ship Museum, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/fagligt/baadevaerft/eksperimentalarkaeologi/maritime-haandvaerk/maritim-teknologi/wool-sailcloth.

254 "The Picture Stone from Hunninge at Klinte," Viking Age Archaeology - The Picture Stone from Hunninge at Klinte, accessed May 15, 2023, http://viking.archeurope.info/index.php?page=the-picture-stone-from-hunninge-at-klinte.

255 "The Bayeux Tapestry," Bayeux Museum, April 24, 2023, https://www.bayeuxmuseum.com/en

256 Karen Schousboe, "Amazing Treasure of Viking Coins Discovered at Ribe," Medieval Histories, September 6, 2019, https://www.medieval.eu/amazing-treasure-of-viking-coins-discovered-at-ribe/.

257 Brita Malmer, "Skeppsmyntet Från Okholm: Om Danska 800-Talsmynt Med Fisksymboler," Skeppsmyntet från okholm, accessed May 15, 2023, https://www.danskmoent.dk/artikler/bmskib.htm.

258 Karen Schousboe, "Amazing Treasure of Viking Coins Discovered at Ribe," Medieval Histories, September 6, 2019, https://www.medieval.eu/amazing-treasure-of-viking-coins-discovered-at-ribe/.

259 Brita Malmer, "Skeppsmyntet Från Okholm: Om Danska 800-Talsmynt Med Fisksymboler," Skeppsmyntet från okholm, accessed May 15, 2023, https://www.danskmoent.dk/artikler/bmskib.htm.

an embroidery. It is 68.3 meters long and 70 cm wide. It is made up of 9 linen panels with wool thread embroidery.[260] The piece tells the story of the conquest of England, and is laid out in narrative form to tell that story. There are several Viking Era ships depicted in the piece. By this time, the sails were shown with vertical strips of sail cloth with alternating colors. This is the style of sail cloth that experimental archaeologists at the Viking Museum use today, and is the modern image of the Viking sail most people are familiar with.[261] This depiction is from the end of the Viking Era as such the ships here have all of the advancements of 400 plus years of sailing knowledge and improvements. The ship's rigging is shown, as well as iron anchors, which seem to be the standard by this time. The ships were still using steering oars, and had not converted to center rudders yet.[262] A piece of information regarding the embarking and disembarking of these ships when pulled onto a beach which I found interesting was shown in the Bayeux Tapestry. When coming ashore Vikings took off their shoes and rolled up or removed their trousers when getting in and out of the ships. They also stepped the masts of their ships upon landfall.[263] I assume stepping the masts avoided the risk of damage to the rigging while the ships were stored ashore.

[260] "The Bayeux Tapestry," Bayeux Museum, April 24, 2023, https://www.bayeuxmuseum.com/en
[261] "Wool Sailcloth," Viking Ship Museum, accessed May 30, 2023, https://www.vikingeskibsmuseet.dk/fagligt/baadevaerft/eksperimentalarkaeologi/maritime-haandvaerk/maritim-teknologi/wool-sailcloth.
[262] "The Bayeux Tapestry," Bayeux Museum, April 24, 2023, https://www.bayeuxmuseum.com/en.
[263] IBID

Conclusion

In this thesis, I have reviewed the possibilities for the early adoption of sails on the ships of Scandinavia. Evidence suggests that the earliest development of sailing ships would have begun in the calm and relatively predictable waters of the Ålands Sea. The early sailors would have then progressed into more challenging sailing conditions south to Gotland, through Denmark into the North Sea, and finally across the Norwegian Sea to Iceland, then across the North Atlantic to Greenland and North America. This advancement in technology started just prior to the Viking era. The path started in the Ålands Sea when sails were introduced along a shipping lane that would have been traveled by oar powered boats. The recent Salme ship finds dating from 650-750 AD, including one oar powered ship and one sail powered ship, provide archaeological support to this theory. Development of sail power starting in this region also makes sense from an economic standpoint of risk and reward. In the Ålands Sea sails could be added first in an area with relatively mild sailing conditions, with numerous places to stop and wait for favorable conditions, and to resupply or perform repairs. From there, sailors and ship builders could have improved skills and ship designs allowing them to cover greater distances. The region just south of the Ålands Sea provided the next challenge. This region provided sailors with a passage between Sweden and the rest of the Baltic, passing by and stopping at the island of Gotland as a convenient waypoint along the way. This is supported by early depictions of Viking ships with sails on picture stones in Gotland dating from the 7th century. These picture stones are the earliest iconographic evidence of sailing in Scandinavia. Ships of this era could have also easily navigated around Demark, through the Danish Straits, into the Kattegat, and around the shores of the Skagerrak and the southern North Sea. The next leap forward would have been to shorten the distance by crossing these same bodies of ocean as their ships and skills were improved. The dramatic improvements between the Oseberg ship and the Gokstad ship finds suggest that this is exactly what occurred. Compared to the Oseberg ship (820 AD), the Gokstad ship (890 AD) is designed with superior seaworthiness and advanced sailing technology. This suggests that the need for these improvements existed at this time and location, which correspond with the start of the Viking raids noted in the Anglo-Saxon Chronicles, including the raid on Lindisfarne in 793 AD. Iconographic evidence in the form of coins minted in Denmark from the early 9th century also show that sailing had become an important part of Norse life at this time in that region. As the Vikings continued to raid across the North Sea, they would have developed the navigational skills for their next leap in sailing greater distances of open ocean. The written sources place the crossing of the North Sea during the settlement of Iceland in 875 AD. The three advancements in sailing that the Vikings had developed by this time were improved ship seaworthiness, advanced upwind sailing, both demonstrated first in the Gokstad ship, and navigation techniques for finding their way during multi-day passages. The 1948 find of the Uunartoq Disc in Greenland, and support from the written sources, particularly the voyage of Bjarni Herjolfsson, provide insight into the skills that the Viking navigators had developed during the 10th century. While not entirely conclusive, evidence of a geographical progression presented in this paper provides support for an ever more challenging path that Viking sailing may have developed along.

Further Work

For more insights into early Scandinavian ship building, researching possible archaeological finds of ships in and along the shores of the Gulf of Finland could provide exciting insights into the early years of Norse shipbuilding. Test sailings in the Baltic and Gulf of Finland could be compared to the sailings of ships that have taken place in the North Sea and Norwegian Sea to compare sailing conditions between the two regions which may shed light on the theory presented in this paper. To date, evidence suggests that the Vikings may have carried out their early raids in ships like the Oseberg ship. If this is the case, it would be interesting to conduct a test sailing of this ship from Denmark to Lindisfarne to see how feasible the journey would have been. A possible find of a ship with improvements between the Oseberg ship and Gokstad ship would provide valuable information about the development of truly seaworthy ships during this time period. The Karmøy excavation may provide information during this period. The insights from modern sailors with experience in the regions covered in this paper would also prove useful in supporting or refuting the theory put forth in this paper.

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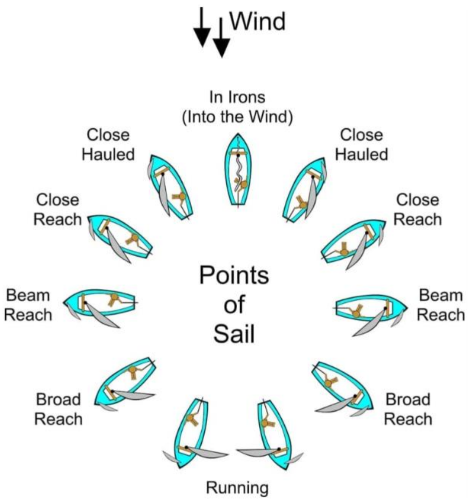
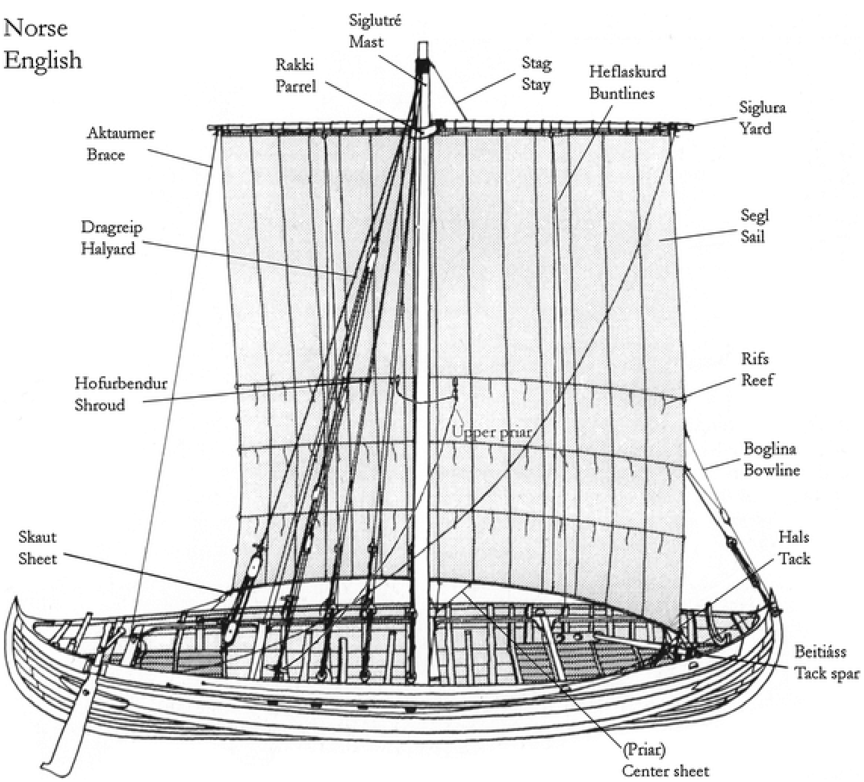
Glossary

POINTS OF SAIL:



American Sailing Association

VIKING ERA SHIP DIAGRAM WITH LABELS:



Viking Ship Museum in Roskilde (Vinner 1995)

Appendix

Transcript of Interview with Jan Knutsen
Captain of the Saga Farmann

April 6, 2023 10:00 a.m.
Questions by: Noah Meseck
Answers by: Jan Knutsen

Q: Is your ship named Saga Farmann?

A: Yes, the ship was named that Saga because they speak a lot about waiting for wind in that story.

Q: Is the ship a full-scale reconstruction of the Klåstad ship?

A: Yes. The original was built in 995. It was the first ship in the world found that was not a burial ship. It was wrecked on shore, the land rose and buried it. A farmer found it in 1893. It was found 13 years after Gokstad, but they did not dig it up. In 1970, they dug it up to save it because of road construction. The person that saved it was J. Kristiansen. The quality of the ship made them decide to save it. The boards, the keel, and the ribs were pretty good on one side. Vestfold is where they found it. The recreation was launched in 2018.

Q: When was your ship completed?

A: The recreation was launched in 2018.

Q: What is the length of the Saga Farmann?

A: 20.7 meters

Q: What is the Beam (width) of the ship?

A: 5.2 meters

Q: How many oars does the ship have?

A: They only found three oarlocks. There may have been more. The design of the oarlocks were weak. When recreated they failed easily. This told me that the oars were not used regularly for propulsion. This suggests that the ship had to sail.

Q: What size sail did you fit her with?

A: The original sail was 110 sq meters. The mast was too high so it was lowered. The sail was reduced to 90 sq meters. This was done to keep the sail from overpowering the construction. They put a winch type apparatus to hoist the sail like the Kalmar ship in Sweden built in 1160. It takes two people to hoist the sail. The Oseberg takes ten people to hoist the sail without that device.

Q: What size crew was required to sail the ship comfortably?

A: The reconstructed ship sails with a complement of 8 people. The ship can be sailed with six people if they have experience.

Q: How well did she sail upwind?

A: The ship cannot sail up wind very well. With a skilled crew, you can sail her a little up wind.

Q: Did she heal over much with the wind on the beam?

A: The ship is safe and rarely took on water.

Q: Did you use a beater pole (spar pole) or other device to sail up wind?

A: They did not use a spar pole, but the Oseberg recreation uses one these days.

Q: How difficult was the ship to handle under tacking and jibing?

A: Tacking is difficult. It sometimes takes several tries. A skilled crew can get it to tack.

Q: What was the top speed of the ship?

A: Top speed was 10 Knots.

Q: What else can you tell me about the Saga Farmann?

A: The ship was long and thin which makes it faster. The cargo of the original ship consisted of some unused wet stones. The great boards are thin and lightweight. The boards are called meginhufr. The delicate nature of the boards didn't make sense for a cargo ship to the builder of the reconstruction. This suggested to him that the original was a war ship. The sagas talked about throwing stones as projectiles which may be why they are there. The battle is from the Battle of Nesjar 1016 year. The ship would have been about 20 years old when it sank.