THE SALME SHIP BURIALS

Two Eighth-Century Mass Graves on Saaremaa Island, Estonia

RECENT RESEARCH

ACTA Universitatis Tallinnensis: Humaniora

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Edited by Lembi Lõugas and Heidi Luik

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The Salme Ship Burials: Two Eighth-Century Mass Graves on Saaremaa Island, Estonia. Recent Research

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THE VIKING
PHENOMENON

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PREFACE

The first (I) ship burial in Salme was discovered in 2008, the second (II) in 2010, although this unique complex of finds still provides research material for both archaeologists and specialists in other related fields. In addition to previously published articles on the Salme I and II ship burials, a major publication on fieldwork and a catalogue of finds titled *The Salme Ship Burials: Two Eighth-Century Mass Graves on Saaremaa Island, Estonia. Fieldwork and Catalogue* was published by the Archaeological Research Collection of Tallinn University at the end of 2023. The production of this publication was mainly supported by Tallinn University and Uppsala University (including projects such as The Salme Event: Two Vendel Period Mass Burials in Ships on Saaremaa, Estonia, and the Viking Phenomenon project), with a large number of other institutions also contributing to the research on these 8th century burials (read more in the preface to *Fieldwork and Catalogue*).

This collection of research articles, subtitled *Recent Research*, reflects only a portion of the topics that the unique Salme ship burial complex offers. Therefore, this publication will not be the last 'Salme book': various scientific approaches to the ships, the fallen and buried warriors and their equipment can be expected in the future. This collection brings together thirteen articles under one cover, including both previous research and writing containing new information and new analysis. The articles are in English with summaries in Estonian and are collected under five thematic headings: Landscape, Weaponry and Design, Personal and Collective, Ships, and Analysis of Bio-remains.

In the first article on the topic of landscape, Alar Rosentau, Triine Nirgi, Marge Konsa, Argo Jõeleht and Tiit Hang write about the formation of the paleolandscape of southwestern Saaremaa in the first millennium AD. The aim of their study was to find out about changes in sea level and the coast and thereby reconstruct the landscape around Salme at the time of the burial. In the second article, Marika Mägi writes about the cultural landscape surrounding the Salme find and about pre-Viking Saaremaa as a whole. Mägi analyses archaeological, geological and historical-cartographic data on the vicinity of Salme, presents an overview of Saaremaa antiquities from the 7th to 9th centuries, and presents new archaeological finds from recent years.

In the second thematic section, which deals with the weaponry and design, Indrek Jets, together with co-author Luciano Pezzoli, who studies Viking Age symbolism and ornaments and conducts reconstructions, writes in the third article about the ornaments present on the swords found in the Salme II ship burial. The text is illustrated with elaborate, high-quality, reconstructions of the sword ornaments. Of particular note is the pommel of sword 419. In the fourth article, top experts in their field Susanne Greiff and Dieter Quast write about analysis of the garnets on the same pommel, providing an idea of the distant origin of these semi-precious stones.

The third part of the collection of articles examines finds that can be associated with a specific person, or were taken to the afterlife together with those buried. The fifth article, written by Heidi Luik, Andreas Hennius and John Ljungkvist, discusses one of the largest categories of find from the Salme ships: hemispherical bone gaming pieces, as well as dice. Such gaming pieces were used to play *hnefatafl*, a widespread game in Scandinavia, and probably other board games as well. In the sixth article, Heidi Luik and John Ljungkvist continue the description and interpretation of artefacts made of organic material, including combs and other objects made of antler and teeth. The seventh article is about the brooches found in the Salme ship burials. Ulla Nordfors focuses on a group of Iron Age brooches, which she calls Salme-type iron bow brooches, paying particular attention to the thirteen brooch finds discovered at Salme.

The fourth part of the collection deals with research and methods related to the ships. In the eighth article, Priit Lätti describes the methodologies, possibilities and shortcomings related to ship modelling, and suggests what the ships might have looked like. In the ninth article, Kaarel Sikk uses retrospective photogrammetry to demonstrate how the post-excavation study of the Salme II ship and its finds will take place. One of the main goals was to investigate how to create spatially reliable three-dimensional models from photographs taken early in the era of 'cheap' digital photography, and what new information they could provide.

The fifth part of the collection includes analysis of bio-remains found at Salme. The tenth and eleventh articles deal with studies of the human skeletons discovered in the Salme I and II ships. In the tenth article, Martin Malve writes about the human burials of the Salme I ship and the pathological signs on the bones and teeth, as well as injuries indicating violent death. His analysis also increased the number of people buried in the Salme I ship by one. In the eleventh article, Raili Allmäe analyses the skeletons of 34 individuals buried in the Salme II ship, providing a comprehensive overview of their physical anthropology and health markers. The second part of this article describes injuries found on skeletons, i.e. cut and puncture wounds caused by sharp instruments on skeletons at the time of death. Next comes the twelfth article, written by Ülle Aguraiuja-Lätti, Lembi Lõugas and Alar Rosentau, which deals with the chronology of the Salme ship burials and analysis of the diet and origins of the buried. The study presents new stable isotope analysis and radiocarbon dating data on both humans and animals buried in the Salme ships to better understand the chronology of the burial complex and the dietary habits of the men. The thirteenth and last article, by Sander Nuut, Lembi Lõugas and Ülle Aguraiuja-Lätti, focuses on analysis of the remains of dogs and birds of prey found in the Salme ships. Dogs and birds of prey appear to have played an important role in (pre-)Viking burial culture, and their status was different from that of domestic animals, whose meat pieces were simply placed with the deceased.

In addition to the gratitude expressed by the authors to the institutions and/or specific person or people who supported their research and the completion of the article, we would like to express our gratitude to Tallinn University (including projects TF3123 and TUF25014) for the completion of this collection of articles as a whole. The previous Tallinn University and Uppsala University projects, The Salme Event: Two Vendel Period Mass Burials in Ships on Saaremaa, Estonia, and the Viking Phenomenon project are also of key importance, as without them the previous basic research could not have been carried out. We thank the reviewers of the book manuscript, Leszek Gardeła (University of Munich) and Søren Michael Sindbæk (Aarhus University).

Lembi Lõugas and Heidi Luik

EESSÕNA

Salme esimene (I) laevmatus avastati 2008. ja teine (II) 2010. aastal, kuid siiani pakub see unikaalne leiukompleks uurimisainest nii arheoloogidele kui ka arheoloogiaga seotud teiste uurimisvaldkondade inimestele. Lisaks varem publitseeritud artiklitele Salme I ja II laevmatuse kohta ilmus Tallinna Ülikooli arheoloogia teaduskogu väljaandena 2023. aasta lõpus mahukas välitöid ja leiukataloogi käsitlev publikatsioon pealkirjaga „The Salme Ship Burials: Two Eight-Century Mass Graves on Saaremaa Island, Estonia. Fieldwork and Catalogue". Selle väljaande valmimist toetasid põhiliselt Tallinna Ülikool ja Uppsala Ülikool (sh projektid „Salme Event: Two Vendel Period Mass Burials in Ships on Saaremaa, Estonia" ja „Viking Phenomenon") ning uurimisele panid õla alla suur hulk teisi institutsioone (loe täpsemalt „Fieldwork and Catalogue" eessõnast).

Käesolev artiklikogumik alapealkirjaga „Recent Studies" (hiljutised uurimused) kajastab tõepoolest vaid osa teemadest, mida Salme laevmatuste unikaalne leiukompleks välja pakub. Seega ei jää siinne publikatsioon viimaseks Salme-raamatuks, vaid edaspidigi on oodata teaduslikke käsitlusi nii laevade kui ka Salmele maetud hukkunud sõdalaste ning nende varustuse kohta.

Kogumik koondab kolmeteist artiklit, mille hulgas on nii varasemaid uurimusi kui ka uut teavet ja uusi analüüse sisaldavaid kirjutisi. Artiklid on inglise keeles, aga neid saadavad eestikeelsed resümeed. Temaatiliselt on artiklid jagatud viide alateemasse: „Landscape" (maastik),

„Weaponry and design" (relvastus ja disain), „Personal and collective" (isiklik ja kollektiivne), „Ships" (laevad) ja „Analyses of bio-remains" (biojäänuste analüüsid).

Maastike teema esimeses artiklis kirjutavad Alar Rosentau, Triine Nirgi, Marge Konsa, Argo Jõeleht ja Tiit Hang Edela-Saaremaa paleomaastiku kujunemisest esimesel aastatuhandel. Uuringu eesmärk oli teada saada merevee taseme ja ranniku muutusi ning seeläbi rekonstrueerida Salme ümbruse maastik matuse toimumise ajal 8. sajandil. Teises artiklis kirjutab Marika Mägi kultuurmaastikust Salme leiu ümber ja eelviikingiaegsest Saaremaast tervikuna. Selles analüüsitakse arheoloogilisi, geoloogilisi ja ajaloolis-kartograafilisi andmeid Salme lähiümbruse kohta, esitatakse ülevaade 7.–9. sajandi Saaremaa muististest ja viimastel aastatel saadud uutest arheoloogilistest leidudest.

Teises temaatilises osas, mis käsitleb relvastust ja disaini, kirjutab kogumiku kolmandas artiklis Indrek Jets koos viikingiaja sümboolikat ja ornamente uuriva ja rekonstruktsioone tegeva kaasautori Luciano Pezzoliga Salme II laevmatusest leitud mõõkadel esinevatest ornamentidest. Kirjutis on illustreeritud mõõkade ornamentide väga keeruliste ja kvaliteetsete rekonstruktsioonidega. Erilist tähelepanu saab mõõga nr 419 käepideme nupp. Neljandas artiklis tutvustavad nupul olevate granaatide analüüsi oma ala tippasjatundjad Susanne Greiff ja Dieter Quast, andes seeläbi aimu nende poolvääriskivide kaugest päritolust.

Artiklikogumiku kolmandas osas tulevad uurimise alla leiud, mida saab seostada konkreetse isikuga või mis on koos maetutega teispoolsusesse kaasa pandud. Kogumiku viies artikkel, mille on kirjutanud Heidi Luik, Andreas Hennius ja John Ljungkvist, käsitleb Salme laevade üht kõige suurematest leiukategooriatest: luust poolkerakujulisi mängunuppe, lisaks ka täringuid. Selliseid mängunuppe kasutati Skandinaavias laialt levinud *hnefatafl*'i ja arvatavasti ka teiste lauamängude mängimiseks. Kuuendas artiklis jätkavad Heidi Luik ja John Ljungkvist luumaterjalidest esemete – kammide ning teiste sarvest ja hammastest esemete kirjeldamist ja tõlgendamist. Seitsmes artikkel on Salme laevmatustest leitud sõlgede päralt. Ulla Nordfors keskendub ühele rauaaegsete sõlgede rühmale, mida ta nimetab Salme tüüpi rauast kaarsõlgedeks, pöörates erilist tähelepanu kolmeteistkümnele Salmelt leitud sõlele.

Neljas osa käsitleb Salme laevadega seotud uuringuid ja meetodeid. Kogumiku kaheksandas artiklis kirjeldab Priit Lätti Salme laevade mudeldamise metoodikaid, võimalusi ja puudusi ning arutleb selle üle, millised võisid laevad välja näha. Üheksandas artiklis näitab Kaarel Sikk retrospektiivse fotogramm-meetria abil, kuidas toimub Salme II laeva ja selle leiuainese kaevamistejärgne uurimine. Üks peamisi eesmärke oli uurida, kuidas varase „odava" digitaalfotograafia ajastul tehtud fotode põhjal luua ruumiliselt usaldusväärseid kolmemõõtmelisi mudeleid ning millist uut teavet need võivad pakkuda.

Viies osa hõlmab erinevaid bio- ehk elujäänuste analüüse. Kogumiku kümnes ja üheteistkümnes artikkel käsitlevad Salme I ja II laeva maetute luustike uuringuid. Kümnendas kirjutab Martin Malve Salme I laeva maetutest ning luudel ja hammastel esinevatest patoloogilistest tunnustest ja vägivaldset surma näitavatest vigastustest. Tema analüüsi järel suurenes esimesse laeva maetute arv ühe võrra. Üheteistkümnendas artiklis analüüsib Raili Allmäe Salme II laeva maetud 34 indiviidi luustikke, andes põhjaliku ülevaate nende füüsilisest antropoloogiast ja tervisemarkeritest. Artikli teises osas kirjeldatakse luustikel esinevaid vigastusi, s.o surmaaegseid terariistadega tekitatud lõike- ja torkehaavu. Kaheteistkümnes artikkel, mille on kirjutatud Ülle Aguraiuja-Lätti, Lembi Lõugas ja Alar Rosentau, käsitleb Salme laevmatuste kronoloogiat ning maetute toitumise ja päritolu analüüse. Uuring esitab uusi stabiilsete isotoopide analüüsi ja radiosüsinikdateeringute andmeid nii Salme laevadesse maetud inimeste kui ka loomade kohta, et paremini mõista matusekompleksi kronoloogiat ja meeste toitumisharjumusi. Viimane ehk kogumiku kolmeteistkümnes artikkel, mille autorid on Sander Nuut, Lembi Lõugas ja Ülle Aguraiuja-Lätti, keskendub Salme laevadest leitud koerte ja röövlindude jäänuste analüüsidele. Koerad ja röövlinnud näivad olevat mänginud olulist rolli (eel-)viikingiaegses matmiskultuuris ning nende staatus oli erinev koduloomadest, kelle lihakeha tükke lihtsalt maetutele kaasa pandi.

Kuigi iga autor on artikli lõpus avaldanud tänu oma uurimuse ja artikli valmimist toetanud institutsioonidele ja/või konkreetse(te)le isiku(te)le, siis kogumiku kui terviku valmimise eest avaldame siinkohal tänu Tallinna Ülikoolile (sh projektid TF3123 ja TUF25014). Võtmetähtsusega on ka varasemad Tallinna Ülikooli ja Uppsala Ülikooli projektid „Salme Event: Two Vendel Period Mass Burials in Ships on Saaremaa, Estonia" ja „Viking Phenomenon", kuna ilma nendeta poleks varasemaid alusuuringuid teostatud. Täname raamatu käsikirja retsensente Leszek Gardełat (Müncheni Ülikool) ja Søren Michael Sindbæki (Aarhusi ülikool).

Lembi Lõugas ja Heidi Luik

I
LANDSCAPE

1. PALAEO-LANDSCAPES AND SHORELINE DISPLACEMENT IN SOUTHWESTERN SAAREMAA AT THE END OF THE 1st MILLENNIUM

Alar Rosentau[1], Triine Nirgi[1], Marge Konsa[2], Argo Jõeleht[1] and Tiit Hang[1]

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ABSTRACT

In this article, we explore Late-Holocene relative sea level (RSL) and coastal changes to provide palaeo-landscape reconstructions for the southwest of Saaremaa Island, including the area of the Salme ship burials. According to the archaeological interpretations, these ships belonged to a Viking crew, possibly from the Mälar region, eastern Sweden. The geoarchaeological fieldwork was carried out in the Salme area between 2015 and 2020, combining geomorphological, lithostratigraphical, and diatom analysis supported by ground-penetrating radar data and GIS-based modelling and AMS radiocarbon and luminescence dating. Field studies provided information about the RSL changes and palaeo-geography of the Vendel Period trading route in SW Saaremaa and possible burial mechanisms of the Salme vessels c. AD 750–775. The reconstructed RSL curve for SW Saaremaa shows that sea level was around 2 m above the present level during the ship burials and that a semi-enclosed strait existed at the Salme area at that time, with wider western and narrower eastern sections. Our study shows that the Salme ships were buried c. AD 750–775 into the sandy-gravelly coastal deposits that had accumulated there at least 450 years earlier. Reconstructions show that the ships were located about 2–2.5 m above coeval sea level and more than 100 m from the northeastern shore of the Salme strait. Thus, both ships were moved from the shore to higher ground for burial. The Salme ship burials are chronologically placed within a period of increased storminess dated between AD 720 and 790, when a maritime climate was transitioning towards a more continental and drier regime. This may have posed significant challenges for undertaking longer sea voyages.

KEYWORDS: *relative sea level changes, landscape reconstruction, Salme Strait, Viking Age, palaeo-climate, geoarchaeology*

INTRODUCTION

The interplay between the Holocene climate change, sea level rise, and post-glacial isostatic land uplift, together with sediment transport has profoundly reshaped the coastlines of Saaremaa Island over the past millennia, resulting in the infilling and drying up of former bays and the closure of straits. The redistribution of coastal sediments has facilitated the development of spit systems, while certain coastal sections have experienced net sediment loss due to wave erosion. Palaeo-waterways have, therefore, undergone transformations and sometimes disappeared, as exemplified by the Viking Age (Vendel Period) maritime route through the Salme Strait between Saaremaa and the Sõrve palaeo-islands, where two ship burials containing rich assemblages of archaeological artefacts have been unearthed. Radiocarbon dating of find material and typochronology of artefacts places these burials within the timeframe of AD 750–775, making them the oldest known burials of Viking Age Scandinavians in the world (Aguraiuja-Lätti *et al.* 2026). According to isotopic analysis, the individuals who were buried with the ships at Salme were of a non-local provenance and probably

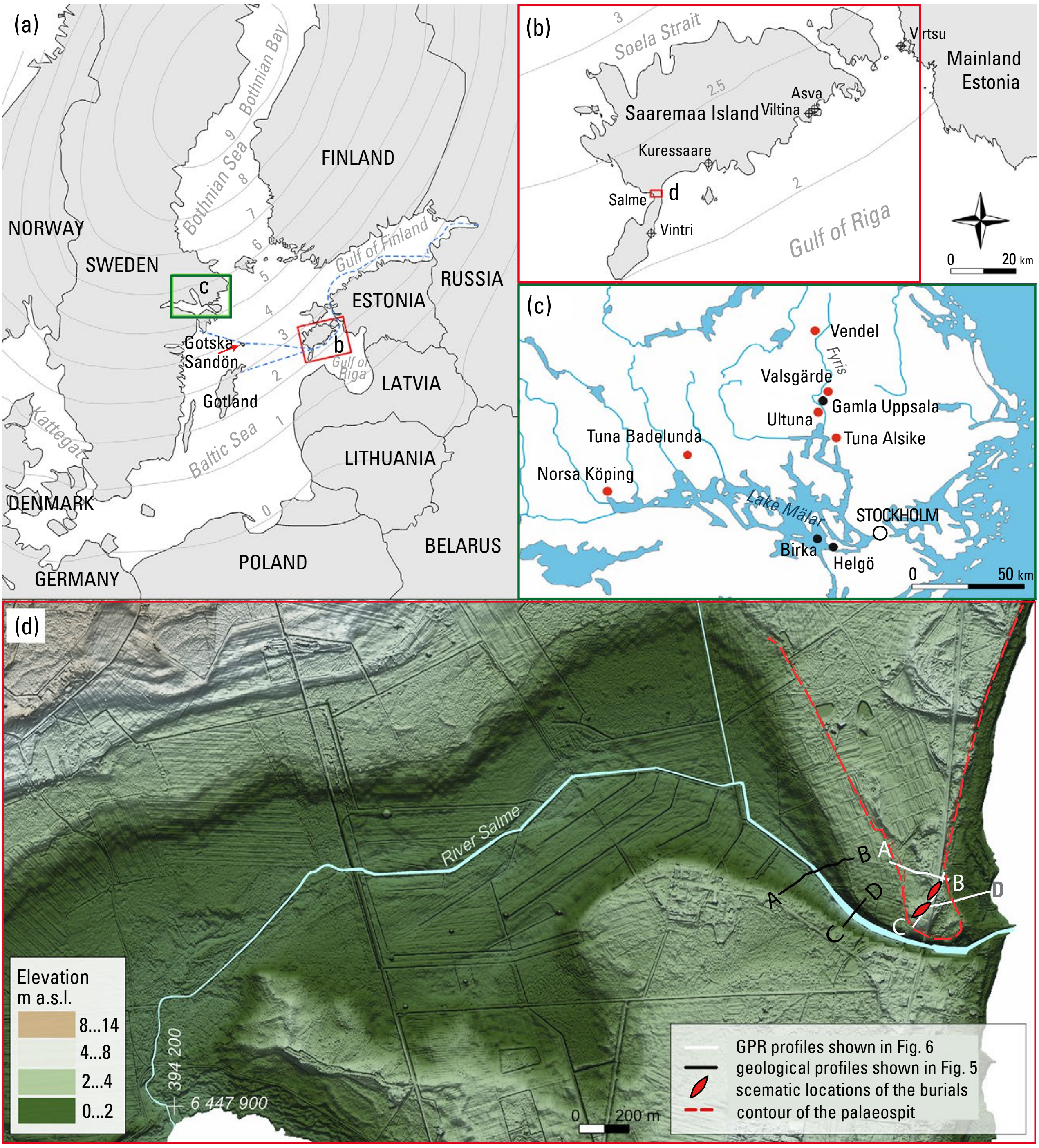

Figure 1. *(a) An overview map of the Baltic Sea area with present-day absolute land uplift isobases (mm/year, after Vestøl* et al. *2019) and possible Viking Age transport networks from Lake Mälar area to Salme (Price* et al. *2016), (b) an overview map of Saaremaa Island with locations of the sites mentioned in the article with land uplift isabases, (c) the map of the Lake Mälar area with Viking Age sites discussed in the text and (d) the LiDAR topography of the Salme area, with locations of geological and GPR profiles and Salme ship burials (ships not to scale).*

originated from the Lake Mälar region in central Sweden (Fig. 1a, c).

The crews were probably attacked while crossing one of the main trade routes across the Baltic Sea that ran across the archipelago of the Åland Islands towards the amber-rich Courland region of Latvia (Price *et al.* 2016). The shortest route from Courland to the Lake Mälar district in Sweden possibly ran through the Salme Strait, which existed in place of today's shallow and narrow Salme River (Fig. 1d). Due to postglacial land uplift, which is in this area about 2.3 mm a^{-1} (Fig. 1b), the strait was later closed and became a river. However, the configuration and depth of the strait, relative sea level (RSL) during the Vendel Period, and the exact location of the ship burials in relation to the coastline at the time are still the subject of exciting discussions.

This study investigates the palaeo-geographic evolution of Saaremaa Island, with a particular emphasis on the Salme ship burial sites. It explores coastline and RSL changes, along with climatic shifts during the first millennium AD. The study is grounded in fieldwork carried out in the Salme area since 2015, the results of which have been largely published by Nirgi *et al.* (2022). This article provides a more detailed analysis of the formation and development of the Viking Age Salme Strait and its possible role as an ancient battlefield. Additionally, the study discusses the selection of the burial sites for the vessels.

GEOLOGICAL BACKGROUND

Saaremaa Island, which forms the main barrier between the Gulf of Riga and the Baltic Sea, is the largest island in Estonia and the fourth largest island in the Baltic Sea (Fig. 1a). The island's main landforms are inherited from the last glaciation and were later reworked by the Baltic Sea, which is almost non-tidal. Saaremaa Island is characterised by a slow post-glacial isostatic rebound with absolute uplift relative to the geoid in between 3 and 2 mm/year (Fig. 1b).

The geoarchaeologically investigated area in Salme is located on Saaremaa Island, on both sides of the River Salme, which separates the Sõrve Peninsula from the Saaremaa mainland (Fig. 1d). The river is a remnant of the former Salme Strait, which itself was part of a trade route and a passage to settlements on both sides of Saaremaa Island. The strait was actively used before and during the Viking Age. Today, only a small river remains in the strait, having been straightened and deepened in most parts.

The easternmost part of the River Salme flows through an old sandy-gravelly coastal spit which stands out in the relief, being higher than the surroundings (Fig. 1d). The sandy-gravelly sediments lie on bluish-grey layered silty clay (varved clay) which in turn lays on glacial till with an upper surface *c.* 13–16 m below the ground surface. On the eastern side, the spit is abruptly bordered by the sea, whilst to the west it slowly slopes towards the River Salme. The river channel has been cut into the clay. Most of the Salme palaeo-strait area can now be described as a coastal plain with altitudes of between 0.5 and 2.0 m a.s.l. (Nirgi *et al.* 2022).

Salme ship burials were located north of the River Salme and 230–270 m west of the present coastline (Fig. 1d). The bottom of Ship I was 4.1 m, and the bottom of Ship II was 3.7 m above present-day sea level. The ships were 40 m apart, and both were similarly oriented in a northeast to southwest direction. The upper areas of the clinker-built ships had not been preserved and grave mounds were absent, which is otherwise rather common with this form of burial.

PALAEO-CLIMATE, STORMINESS, AND VIKING AGE SEA VOYAGES

Climatically, the area between Lake Mälar in central Sweden and Salme on the Island of Saaremaa, in the eastern Baltic Sea, is in the larger westerlies zone of the temperate latitudes, where maritime and continental weather patterns alternate (Kont *et al.* 2007). During the NAO+ phases, mild winters with high precipitation and strong winds prevail, while the NAO− phases bring relatively cold and stable weather (Jaagus *et al.* 2008). Detailed records on coastal paleoclimate and storminess describing the NAO patterns are available from the Undarsmosse coastal peat bog from SW Sweden (De Jong *et al.* 2006, fig. 1). Sedimentary data from the Undarsmosse coastal peat bog suggest that maritime weather patterns dominated in southern Scandinavia and probably also on Saaremaa Island between *c.* AD 450 and 720, and relatively dry (continental) conditions, probably with low annual precipitation and warmer summer conditions between AD 790 and 1120 (De Jong *et al.* 2006).

The transition period (AD 720–790) between these phases is characterised by increased aeolian activity and more frequent storm events (De Jong *et al.* 2006). Aeolian sand influx data from the Järve coastal peat bog NE of the Salme site show increased sand input probably related to increased storminess in the area during the relatively long period between *c.* AD 750–1150 (Vaasma *et al.* 2025). The sedimentary record from the Salme Strait begins in AD 830 and shows two periods of increased storminess, dated around AD 920 and 1150 (Nirgi *et al.* 2022).

The Salme ship burials are chronologically placed within a period of increased storminess at about AD 720–790, when the maritime climate was transitioning towards a more continental and drier regime. This transitional phase probably posed significant challenges for those undertaking longer sea voyages. The exact routes used for crossings from the Mälar region (central Sweden) to Salme remain uncertain. One plausible route would have led from the Swedish coast via the island of Gotska Sandön to the coast of Saaremaa. Gotska Sandön has yielded several archaeological finds associated with Viking activity (Fig. 1a). Due to post-glacial land uplift, sea-levels along the Swedish coast during the Vendel Period were approximately 7 metres higher than today (Karlsson & Risberg 2005), and the coastline would have been located somewhat further inland compared to the present. Reaching Saaremaa Island by sail, while taking advantage of the predominantly westerly and southwesterly winds typical during the summer months (Jaagus *et al.* 2008) would probably have taken one to two days from Mälar to Gotska Sandön given the distance of approximately 60 km. The crossing from Gotska Sandön to Saaremaa would have required even more time, as the distance is nearly 100 km. Navigating in open waters would have necessitated careful consideration of wind shifts and wave conditions, especially given that there is a stretch of about 60 km in which neither landmass would have been visible.

An alternative route might have been via Gotland Island (Fig. 1a), where numerous Viking Age settlements and harbour sites are known (Carlsson 1992). Similar to the previously suggested route, the predominantly westerly and southwesterly summer winds would have been favourable for such voyages.

As the possible marine crossing remains chronologically within the period of increased storminess, it is also possible to speculate that, depending on storm conditions, it is likely that, the Viking crews from the Mälar region were forced to enter the Salme Strait to shelter and were attacked by the locals.

GEOARCHAEOLOGICAL INVESTIGATIONS IN THE SALME AREA

Geoarchaeological fieldwork was carried out in the Salme area between 2015 and 2020, including geomorphological, lithostratigraphical, and diatom analysis supported by ground-penetrating radar survey and GIS-based modelling, as well as AMS radiocarbon and luminescence (OSL) dating.

SEDIMENT SAMPLING AND CHRONOLOGY

Nine trenches were dug on a profile that was perpendicular to the coastline in order to investigate the sedimentary structures of the coastal landform system in the Salme area, and to get samples for luminescence dating. The OSL samples were collected from undisturbed sandy-gravelly sediments using opaque plastic tubes. Three samples from three trial pits were analysed at the Lund Luminescence Laboratory, Sweden.

Sediments of the former Salme palaeo-strait were described in 32 cores along two profiles (Fig. 1d). Coring was carried out using a 1 m long Russian-type peat corer (inner ø 50 mm). Altitudes for the trial pits and coring sites were determined using the LiDAR digital elevation model (Estonian Land Board 2020). All the altitudes are given in the European height system (EVRS, Amsterdam zero). A 2.5 m long master core was obtained from the bank of the River Salme at coring site SV02 from the C–D profile (Fig. 1d) so that samples could be taken for sedimentological and biostratigraphical analysis, and for age determination. Additional data on the spatial distribution of the sediments in the Salme area were incorporated from geotechnical studies by Metsküla *et al.* (1984) and Eller & Sedman (1985). The seeds of terrestrial plants and some pieces of charcoal were collected from the Salme master core for AMS (Accelerator Mass Spectrometry) radiocarbon dating. Eight samples from the master core and one additional sample of a shell fragment from the coastal deposit were analysed at the Tandem Laboratory in Sweden. OxCal v4.2.3 software (Bronk Ramsey 2009) was used to create an age-depth model to assess the sediment accumulation rate for the sediment sequence in the palaeo-strait.

DIATOM ANALYSIS

The diatom samples from the sediments of the former Salme Strait were investigated to study salinity changes in the strait and the isolation history of the strait (Nirgi *et al*. 2022). Altogether 12 diatom samples were analysed from the Salme master core. A total of 132 diatom taxa belonging to 55 genera were identified in the 188 cm long sediment sequence, which covers a time span of about 380 years (AD 920–1300).

GROUND-PENETRATING RADAR ANALYSIS

Ground-penetrating radar (GPR) was used to gain more information about the bedding and distribution of sediments in the Salme study area. A Zond-12e radar device (Radar Systems Inc., Latvia) with a 300 MHz antenna was used. In total, 8 km GPR profiles were derived from the study area (Nirgi *et al*. 2022).

RECONSTRUCTIONS OF RELATIVE SEA LEVEL

The data were divided into three groups according to their indicative meaning: (1) sea level index points; (2) marine limiting data; and (3) terrestrial limiting data. Indicative meaning reflects the position of RSL in relation to the data point at its time of deposition (Hijma *et al*. 2015; Khan *et al*. 2019). Therefore, for example, the dates from archaeological settlements were used as terrestrial limiting data, but data points from marine sediments were used as lower limiters. The curve was roughly drawn according to RSL data, whereas the vertical values were calculated by a formula in the HOLSEA database, which considered the altitudes of the samples together with given errors.

PALAEO-GEOGRAPHIC RECONSTRUCTIONS

The palaeo-geographic reconstructions for Saaremaa and the former Salme Strait are based on the GIS approach (Rosentau *et al*. 2011), whereby palaeo-water level surfaces were subtracted from the 1 × 1 m resolution LiDAR-DTM (Estonian Land Board 2020). In order to create accurate palaeo-reconstructions, the younger sediments (with a max thickness of 2.1 m) in the narrowest part of the Salme Strait area were subtracted from the LiDAR-derived DTM according to data by Eller & Sedman (1985), Metsküla *et al*. (1984) and AMS radiocarbon dating and sediment thickness data from the study by Nirgi *et al*. (2022).

LATE-HOLOCENE RELATIVE SEA LEVEL CHANGES IN SOUTHWEST SAAREMAA

The RSL curve for the Salme area is based on 29 sea-level indicators, including 6 sea-level index points and 23 marine and terrestrial limiting points, and covers the last 3,000 years (Fig. 2). The RSL curve shows nearly linear regression since the Bronze Age, which was mainly affected by glacial isostatic uplift. Two radiocarbon dates from the buried organic bed in coastal deposits from the Vintri site 15 km south of Salme (Nirgi *et al*. 2017) show RSL to be around 5.5 m a.s.l. at about BC 700. Luminescence ages from the upper part of the Salme coastal deposits suggest an RSL fall to an elevation of *c*. 4 m a.s.l. during the following 700 years. Elevations of the Viking Age trading sites at Viltina (AD 1000–1150) and Mullutu (*c*. 70% of finds in Mullutu belong to the 8th–11th century) with remains of jetty constructions (Mägi 2009) suggest a further 2–2.5 m lowering in RSL during the next 900 years (Fig. 2). Sedimentary and diatom data from the bottom of the former Salme Strait indicate the closing of the strait sometime after AD 1270 and suggest that RSL dropped in the area below the elevation at 0.75 m a.s.l. (Fig. 2). This RSL elevation is also supported by the earliest boardwalk constructions in a neighbouring Kuressaare fortified settlement, which are dated back to AD 1320–1350 and which help to suggest that RSL was less than 1 m a.s.l. there at that time. Dated boardwalk constructions were initially established slightly above mean sea level but were then damaged several times, most likely during storms that were accompanied by higher water levels, as evidenced by archaeological excavations (Püüa 2013). Since the beginning of the industrial era around AD 1850, RSL regression has almost stopped in the area due to the accelerated sea level rise related to human impact (Luik *et al*. 2025). This is also consistent with the neighbouring Virtsu tide gauge data from the 20th century which reveals a near-zero RSL trend (Tõnisson *et al*. 2019). RSL reconstruction before the industrial era is in good agreement with present-day uplift rates of around 2.3 mm/year in the Salme area (Vestøl *et al*. 2019), suggesting only minor (80–100 cm) eustatic sea level rise during the last 3,000 years (Fig. 2). The Late-Holocene RSL curve from the Pomeranian non-uplifting coast (Lampe & Janke 2004) suggests that eustatic sea level has risen in the Baltic Sea by about 90 cm since 700 BC, and this is in good agreement with our current RSL and uplift data from the Salme area (Fig. 2).

Elevations derived from the archaeological excavations at the Salme I and Salme II burial sites suggest that

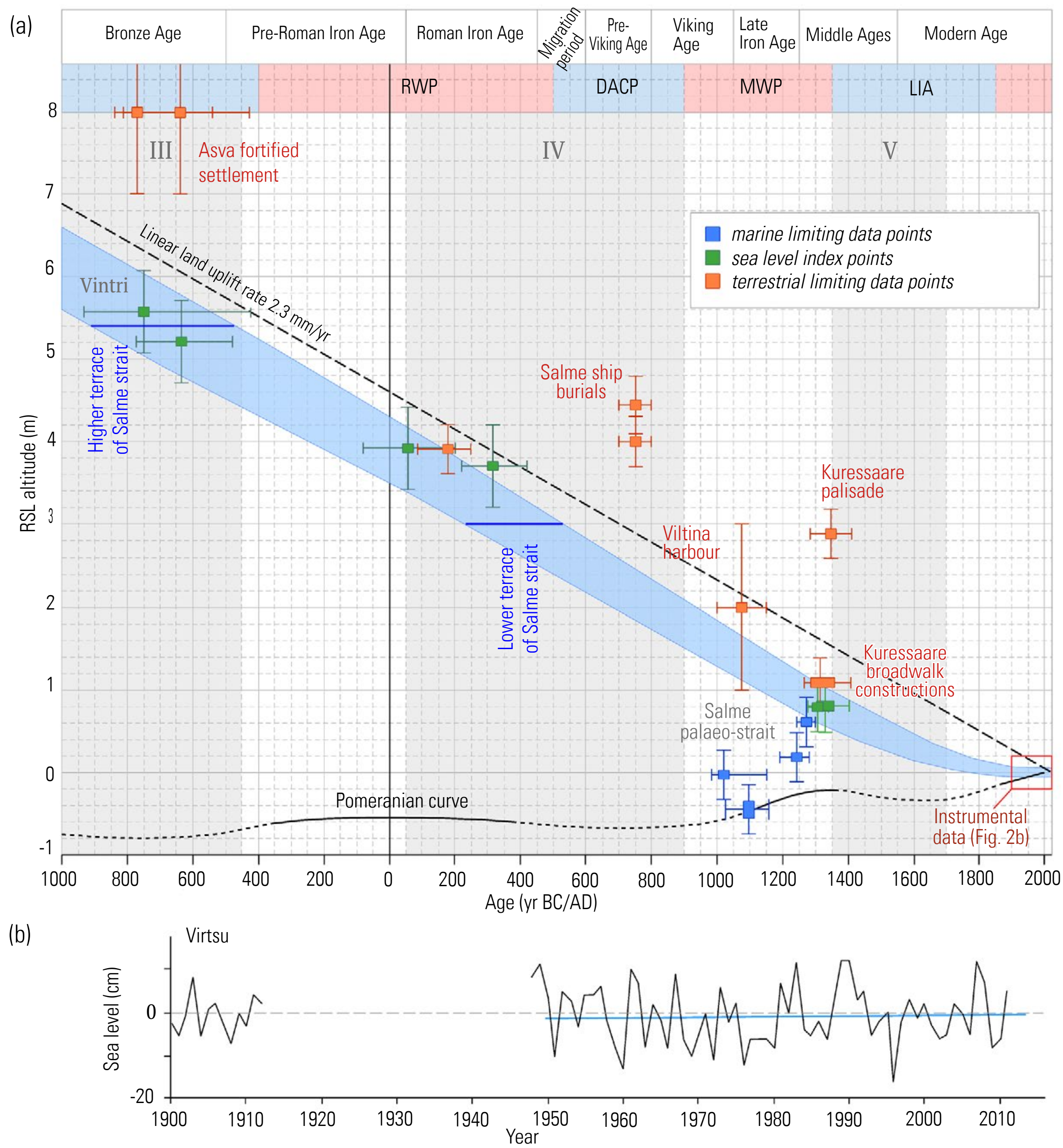

Figure 2. *(a) Late-Holocene RSL curve for Salme (blue line) compared with the RSL curve of the Pomeranian coast (Lampe & Janke 2004) and with the linear land uplift trendline. Late-Holocene storm periods III, IV, and V according to Sorrel* et al. *(2012) are marked as grey zones, and the alternation of warm and cold periods according to Reimann et al. (2011) and Neukom* et al. *(2019) are marked by blue and red zones at the top of the graph (LIA – Little Ice Age, DACP – Dark Age Cold Period, MWP – Mediaeval Warm Period, RWP – Roman Warm Period) and (b) variations in the annual average relative sea levels in Virtsu (western Estonia) (modified from Tõnisson* et al. *2019).*

both vessels remain clearly above the RSL of 2 m, coeval with burial time. The elevations of both vessels can be revealed by found material, especially by the distribution of the rivets in the ships' ports. In the Salme I vessel, the rivets can be found at an elevation between 4.59 and 3.89 m a.s.l. while in Salme II between 4.12 and 3.50 m a.s.l. Our RSL reconstruction suggests that the burials are located at about 2–2.5 m above coeval sea level (2 m) (Fig. 2). This comparison also suggests that these vessels were not sunk at sea and dropped onto the shore by the waves, but were probably moved from the shore to the higher ground for the burial.

PALAEO-LANDSCAPES, THE SEDIMENTARY ENVIRONMENT AND SHORELINE DISPLACEMENT IN SW SAAREMAA AT THE END OF THE 1st MILLENNIUM

Due to the uneven isostatic land uplift since AD 770, the northwestern part of the Saaremaa has been uplifted by about 1 m more compared to the Sõrve Ps and Salme area in the southwest of the island. RSL was *c.* 2.2 m a.s.l. in Salme, being *c.* 3.2 m a.s.l. in the Harilaid area and only 1.9 m a.s.l. at the southern end of the Sõrve peninsula in around AD 770–775 (Fig. 3). On the northwestern coast of Saaremaa, several capes and islets were still submerged. At the same time, several deeply incised bays existed, including Ennu, Sutu, Oessaare, and Kõiguste along the coast of southern Saaremaa during the 1st millennium, while the Sõrve paleo-island in the southwest was separated from the Saaremaa mainland by the Salme palaeo-strait (Fig. 3). To the north of the Salme strait was the Mullutu lagoon at about 20 km long and 10 km wide. At the wind-protected entrance of the lagoon, on the steep sandy-gravelly slope, a Viking Age harbour site has been discovered (Mägi 2009).

Between the Salme Strait and Mullutu lagoon, a coastal spit system developed over several millennia (Fig. 3). According to our OSL and radiocarbon dates, the spit system formation started initially as an underwater bar around BC 3300–3500, corresponding to sediments from the lower unit in Salme GPR sections. The upper unit accumulated on top of this initial landform in the shallower water with the high energy level of wave activity. Such a sedimentary environment favoured the formation of a series of spit ridges, pointing to longshore sediment transportation from the southwest through the Salme Strait (Fig. 3). This development took place between BC 1900 and AD 200 and ceased probably due to the closure of the Salme Strait. After the closure of the strait, the *c.* 7 km long dune belt was formed between the Salme and Mullutu (Fig. 3).

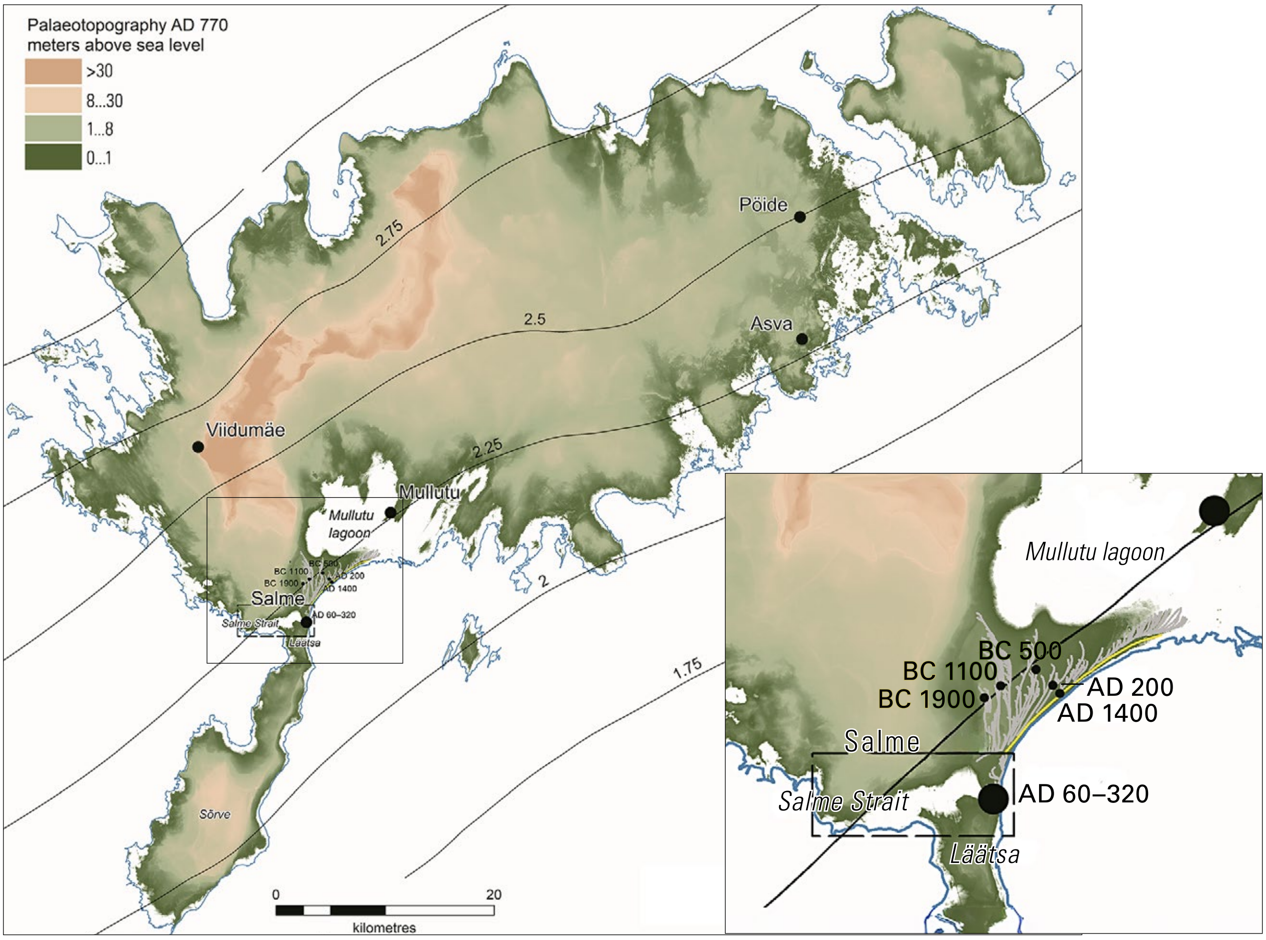

Figure 3. *Palaeo-geographic reconstruction of Saaremaa Island with Viking Age archaeological sites, RSL isobases (m a.s.l.) at around AD 770. Development of the spit system (grey) between BC 1900 and AD 200 and formation of the Little Ice Age dune belt around AD 1400 (yellow) are also shown on the enlarged detail of the map (after Luik* et al. *2025).*

SEDIMENTS IN THE SALME STRAIT AND THEIR AGE

According to the coring data, sandy deposits dominate in the open and wider western part of the Salme palaeo-strait, whereas in the narrow eastern part, fine-grained organic-rich sediments (laminated silty gyttja) also occur in a relatively limited area (Fig. 4a). A 2.5 m long master core (SV02) was taken from the left bank of the Salme River, which comprised four sedimentary units (Fig. 5). Sediments from the lowermost unit consist of a 2 cm thick gravelly sand layer with shell detritus laying on top of glaciolacustrine varved clay. A 150 cm thick layer of laminated silty-sandy gyttja covers this thin sand layer. Organic content in the silty-sandy gyttja typically remains below 10%, and at around 7% on average. The mineral component of the silty-sandy gyttja is very fine (silty), poorly sorted sand in the upper 0.8 m interval, and fine to medium, poorly or moderately sorted sand below this. The two uppermost units are sandy organic-rich floodplain sediment layers, separated according to organic content into lower sandy peat with an organic content of 12–29%, and upper sandy peat with an organic content of 42–67%. The thickness of both units is 15 cm (Fig. 5).

Altogether, eight samples of terrestrial seeds and charcoal were AMS radiocarbon dated (Nirgi *et al.* 2022). Five of these samples were used to construct an age–depth model (Fig. 5b). According to this model, accumulation of organic-rich sediments lasted for about 360 years, between AD 920 and 1280 (Fig. 5b). This means that the accumulation of organic-rich sediments started only after the Salme ship burials and presumable battle in the narrow part of the strait, the bottom of which was sandy-gravelly.

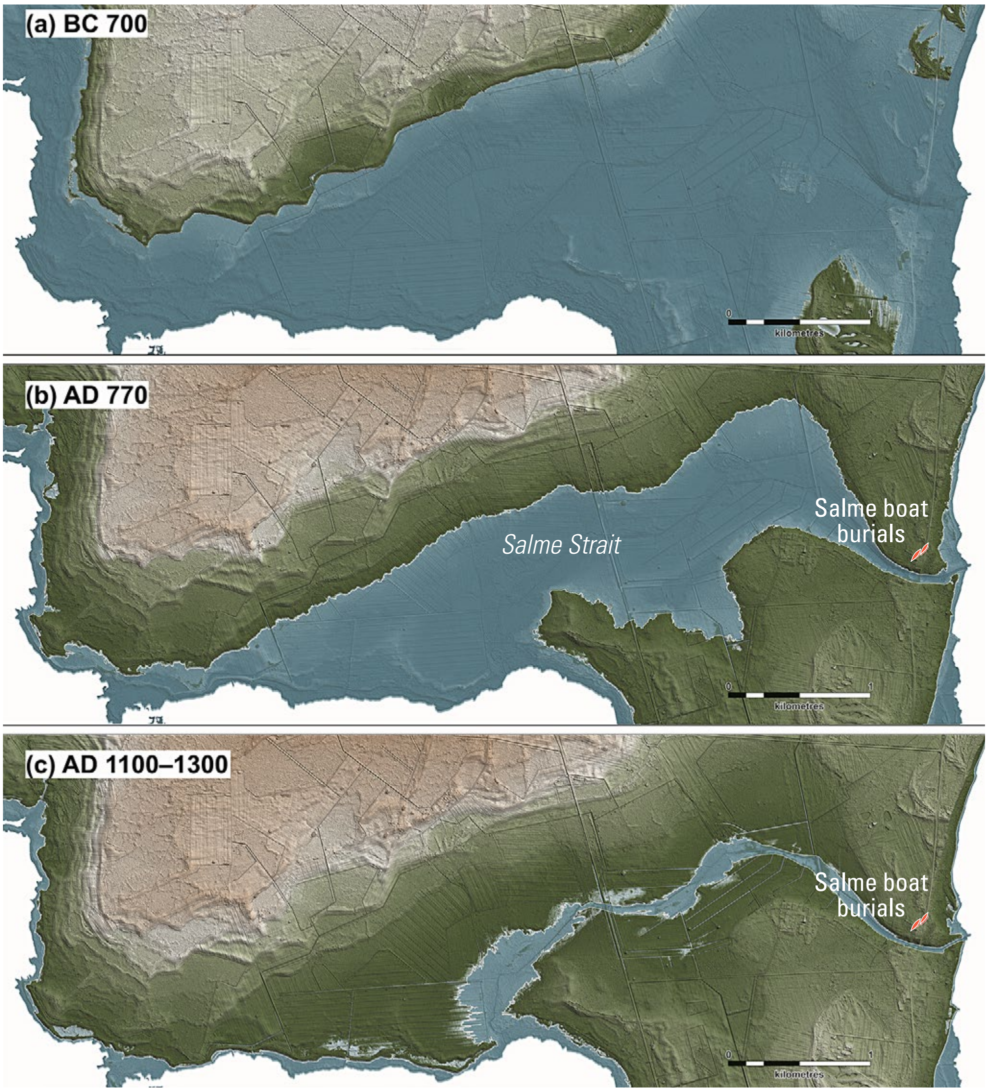

Figure 4. *Palaeo-geographic reconstructions showing the development of the Salme Strait: (a) from the Bronze Age at BC 700, (b) from the Vendel Period at AD 770, when the ships were buried in Salme, (c) to the period between AD 1100 and 1300, just before the isolation of the strait. White is today's sea level.*