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A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast

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ABSTRACT

A central premise for the Stone Age archaeology of northern Scandinavia is that most coastal sites were located on or close to the contemporary shoreline when they were in use. By reconstructing the trajectory of rapid and continuous relative sea-level fall that characterises large regions of Fennoscandia, this offers a dating method termed 'shoreline dating' which is widely applied. However, while the potentially immense benefits of an additional source of temporal data separate from radiometric and typological methods is unquestionable, the geographical contingency and thus relative rarity of the method means that it has been under limited scrutiny compared to more established dating techniques in archaeology. This paper attempts to remedy this by quantifying the spatial relationship between Stone Age sites located below the marine limit and the prehistoric shoreline along the Norwegian Skagerrak coast. Monte Carlo simulation is employed to combine the uncertainty associated with independent temporal data on the use of the sites in the form of ^{14}C-dates and the reconstruction of local shoreline displacement. The findings largely confirm previous hypotheses that sites older than the Late Neolithic tend to have been located on or close to the shoreline when they were occupied. Drawing on the quantitative nature of the results, a new and formalised method for the shoreline dating of sites in the region is proposed and compared to previous applications of the technique.

1. Introduction

The post-glacial relative sea-level fall that characterises large areas of Fennoscandia is fundamental to its archaeology. This follows not only from the dramatic changes to the landscape that this process created throughout prehistory, but also from the fact that if archaeological phenomena were situated close to the contemporary shoreline when they were in use, a reconstruction of the trajectory of shoreline displacement can be used to date these phenomena based on their altitude relative to the present day sea-level. This method, also called shoreline dating, has long history of use in the region and is frequently applied to assign an approximate date to diverse archaeological phenomena such as rock art, grave cairns, various harbour and sea-side constructions and, as is the focus of this study, Stone Age sites (e.g. Åkerlund, 1996; Bjerck, 2005; Gjerde, 2021; Løken, 1977; Nordqvist, 1995; Schmitt et al., 2009; Sognnes, 2003; Tallavaara and Pesonen, 2020; Wikell et al., 2009).

The close association between Stone Age settlements in the northern parts of Scandinavia and shifting prehistoric shorelines was proposed at the end of the 19th century (De Geer, 1896), and was first applied as a dating method at the turn of the century (Brøgger, 1905; Hollender, 1901). Shoreline dating has been fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen, 2009; Bjerck, 1990, 2008a; Breivik, 2014; Johansen, 1963; Mansrud and Persson, 2018; Mikkelsen, 1975a; Mjærum, 2022; Nummedal, 1923; Olsen and Alsaker, 1984; Shetelig, 1922; Solheim et al., 2020; Solheim and Persson, 2018). The method is used both independently, and to compliment other sources of temporal data such as typological indicators or radiometric dates. However, given the coarse and fuzzy resolution of established typological frameworks, the vast number of surveyed sites that only contain generic lithic debitage that could hail from any part of the period, and as the conditions for the preservation of organic material is typically poor in Norway, dating with reference to shoreline displacement is often the only and most precise method by which one can hope to date the sites. Shoreline dating is consequently

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fundamental to our understanding of the Norwegian Stone Age. This is both because it is central to the temporal framework on which our understanding of the period is based, but also because the method is only applicable so long as the societies in question have continuously settled on or close to the contemporary shoreline. Consequently, adherence or deviation from this pattern also has major implications for the socio-economic foundations of the societies in question.

Despite its important role for Fennoscandian archaeology, the applicability of dating by reference to shoreline displacement has only been evaluated using relatively coarse methods. The aim of this paper is to provide a systematic and comprehensive review of the degree to which radiocarbon dates correspond with the dates informed by our current knowledge of shoreline displacement in a larger area of south-eastern Norway, using a more refined methodological approach. The goal here is to quantify the degree to which the assumption of shore-bound settlement holds through the Stone Age in a relatively well sampled portion of Scandinavia, and in turn have this quantification inform the development of a formalised method for shoreline dating. As presented in more detail below, this problem involves the combined evaluation of three major analytical dimensions. One is the questions of when the sites were in use, the second pertains to the reconstruction of the contemporaneous sea-level, and the third follows from the fact that the relation between site and shoreline is inherently spatial. Taking inspiration from studies that have integrated various sources of spatio-temporal uncertainty through Monte Carlo simulation (e.g. Bevan et al., 2013; Crema et al., 2010; Crema, 2012, 2015; Yubero-Gómez et al., 2016), a similar approach is adopted here and adapted to post-glacial sea-level change and the Stone Age settlement of southern Norway.

2. Background

Relative sea-level (RSL) can be defined as the mean elevation of the surface of the sea relative to land, or, more formally, the difference in elevation between the geoid and the surface of the Earth as measured from the Earth's centre (Shennan, 2015). Variation in this relative distance follow from a range of effects (e.g. Milne et al., 2009). Of central importance here is eustasy and isostasy. Eustatic sea-level is understood to be the sea-level if the water has been evenly distributed across the Earth's surface without adjusting for variation in the rigidity of the Earth, its rotation, or the self-gravitation inherent to the water body itself (Shennan, 2015). The eustatic sea-level is mainly impacted by glaciation and de-glaciation, which can bind or release large amounts of water into the oceans (Mörner, 1976). Isostasy, on the other hand, pertains to adjustments in the crust to regain gravitational equilibrium relative to the underlying viscous mantle caused by mass loading and unloading, which occurs with glaciation and deglaciation. These effects causes the lithosphere to either subside due to increased weight, or to rebound and lift upwards due to lower weight (Milne, 2015).

Following the end of the Weichselian and the final retreat of the Fennoscandian Ice Sheet (e.g. Hughes et al., 2016; Stroeven et al., 2016, see Fig. 1), the isostatic rebound has caused most areas of Norway to have been subjected to a continuous relative sea-level regression, despite corresponding eustatic sea-level rise (e.g. Mörner, 1979; Svendsen and Mangerud, 1987). In other words, the RSL has been dropping throughout prehistory. As this process is the result of glacial loading, the rate of uplift is faster towards the centre of the ice sheet relative to the distal aspects. Thus, there is differential glacio-isostatic impact to a site's location depending on its relation to the ice sheet's centre of mass, leading some areas on the outer coast to have had a more stable RSL or been subject to marine transgression (e.g. Romundset et al., 2015; Svendsen and Mangerud, 1987). These conditions are directly reflected in the archaeological record. In areas where the sea-level has been stable over longer periods of time, people have often reused coastal site locations multiple times and over long time spans, creating a mix of settlement phases that are difficult to disentangle (e.g. Hagen, 1963; Reitan and Berg-Hansen, 2009). Transgression phases, on

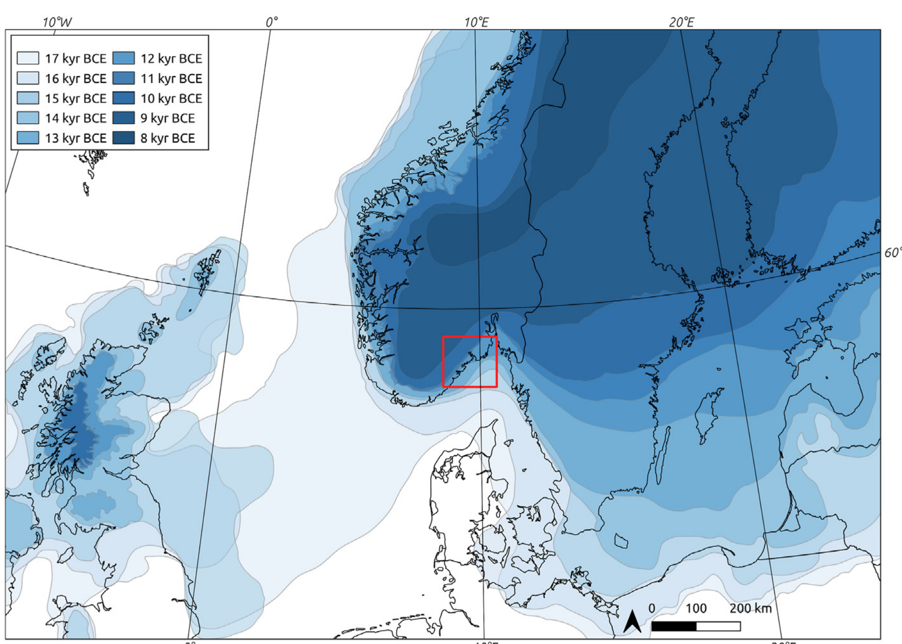

Fig. 1. Deglaciation at 1000-year intervals from c. 17–8 thousand years (kyr) BCE. The study area defined later in the text is marked with a red outline (deglaciation data from Hughes et al., 2016, but see also Romundset et al., 2019 in relation to the study area). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the other hand, can lead to complete destruction of the sites, bury them in marine sediments, or in the outermost periphery, submerge them (Bjerck, 2008a; Glørstad et al., 2020). Transgression can therefore lead to a hiatus in the archaeological record for certain sub-phases in the impacted areas despite the fact that there were likely coastal settlements during the inferred hiatuses. Comparatively, given a continuous and still ongoing shoreline regression from as high as c. 220 m above present sea-level in the inner Oslo fjord, any one location in south-eastern Norway has only been shore-bound within a relatively limited time span, and the sites have not been impacted by any transgressions (Hafsten, 1957, 1983; Romundset et al., 2018; Sørensen, 1979). This makes the region especially useful for evaluating the assumption of a shore-bound settlement pattern over a long and continuous time span.

The method of shoreline dating has been met with scepticism as related to the fundamental premise that most sites would have been consistently shore-bound, it has been characterised as a relative dating method for sites located within a constrained geographical area, or it has been argued to offer no more than an earliest possible date for when a site could have been in use (see review by Nordqvist, 1999). The most common application in Norway has arguably been to use shoreline dating to provide an approximate date for the occupation of the sites, often in combination with other dating methods (see for example chapters in Glørstad, 2002, 2003, 2004; Jaksland, 2001; Jaksland, 2012a, 2012b; Jaksland and Persson, 2014; Melvold and Persson, 2014a; Reitan and Persson, 2014; Reitan and Sundström, 2018; Solheim, 2017; Solheim and Damlien, 2013 and below). Recently the method has also been used independently to date a larger number of sites to get a general impression of site frequency over time. This is done by aggregating point estimates of shoreline dates in 100-, 200- or 500-year bins (Breivik, 2014; Breivik and Bjerck, 2018; Fossum, 2020; Mjærum, 2022; Nielsen, 2021; Solheim and Persson, 2018; see also Jørgensen et al., 2020; Tallavaara and Pesonen, 2020). In his review, Nordqvist (1999) argues that there can be little doubt concerning the general applicability of the method—what is less clear is the level of reliability and chronological resolution that it can offer (see also Johansen, 1963, 1997; Mikkelsen, 1975b:100).

The shore-bound settlement location of prehistoric hunter-fisher-gatherers in Norway is generally believed to follow both from the exploitation of aquatic resources and from movement and communication, which would have been efficient on waterways (Bjerck, 1990, 2017; Brøgger, 1905:166; also discussed by Berg-Hansen, 2009; Bergsvik, 2009). The same logic has also been extended to the hinterland and inland regions, where sites are believed to be predominantly located along rivers and lakes (Brøgger, 1905:166; Glørstad, 2010:57–87; but see also Gundersen, 2013; Mjærum, 2018; Schülke, 2020). This is to take a dramatic turn at the transition to the Late Neolithic, around 2400 BCE, with the introduction of the Neolithic proper (Prescott, 2020; cf. Solheim, 2021). The introduction of a comprehensive Neolithic cultural package, including a shift to agro-pastoralism and the development of settled farmsteads is to have led site locations to be more withdrawn from the shoreline (e.g. Bakka and Kaland, 1971; Østmo, 2008:223; Prescott, 2020). That is not to say that waterways and aquatic resources were no longer exploited, but rather that these activities would not have been as tightly integrated with settlement and tool-production areas as in preceding periods (Glørstad, 2012). At an earlier stage, at the transition to the Early Neolithic (c. 3900 BCE), pottery is introduced to the sites, and there are some indications of an initial uptake of agriculture at some sites in the Oslo fjord region. However, this appears to be small in scale and is believed to be combined with a continued and predominantly hunter-gatherer life-way, possibly followed by a return to foraging and complete de-Neolithisation in the Middle Neolithic (Hinsch, 1955; Nielsen et al., 2019; Østmo, 1988:225–227). Nielsen (2021) has recently argued that the initial uptake of agriculture in Early Neolithic south-eastern Norway is combined with a more complex settlement pattern, and that a simple foraging/agricultural dichotomy would underplay the variation present in the Early and Middle Neolithic settlement data (see also e.g. Amundsen et al., 2006; Østmo, 1988; Solheim, 2012:74; see e.g. Bergsvik, 2002; Bergsvik, 2012 for similarly nuanced considerations of the coastal settlement of Neolithic western Norway). Seen in relation to the question of interest here, the empirical expectation for the above outlined development would thus be a predominantly shore-bound settlement in the Mesolithic, possibly followed by a more varied association between sites and the shoreline with the transition to the Early Neolithic around 3900 BCE, and finally a decisive shift with the Late Neolithic c. 2400 BCE.

Based on the generally accepted premise that most pre-Late Neolithic sites in south-eastern Norway located lower than the marine limit (the highest elevation of the sea after the retreat of the ice) were situated on or close to the contemporaneous shoreline, it is common to err on the side of a shore-bound site location unless there is strong evidence to suggest otherwise. This is for example reflected in archaeological survey practices, which are often guided by both a digital and mental reconstruction of past sea-levels (see e.g. Berg-Hansen, 2009; Eskeland, 2017; Nummedal, 1923; Simpson, 2009). Similarly, following an excavation, if typological indicators in the assemblages correspond with available shoreline displacement curves, a shore-bound site location is often assumed, even if the typologically informed date span is too wide to decisively verify this. It is also common to combine this with a qualitative consideration of the landscape surrounding the sites, and an evaluation of the degree to which the site location would appear to have been sensible if the site was not shore-bound (e.g. Jaksland, 2014; Johansen, 1963; Nummedal, 1923). This can for example pertain to accessibility. If the site is situated on a ledge in a steep and jagged area of the present-day landscape it would make intuitive sense that the site was in use when the ocean reached closer to its elevation, as the site would have been accessible by means of watercraft. Although it appears that the arguments for such site locations can for the most part be assumed to hold, comprehensive evaluations and attempts at quantification of this tendency are relatively few (see also Berg-Hansen et al., 2022:644; Ilves and Darmark, 2011).

One of the more extensive evaluations of the relationship between archaeological radiocarbon dates and RSL-change was done by Solheim and colleagues (Breivik et al., 2018; Solheim, 2020), who compared 102 radiocarbon dates from 29 Mesolithic sites on the western side of the Oslo fjord to the displacement curve for the Larvik area. They found an overlap between the probability distribution of the radiocarbon dates with the shoreline displacement curve for 86.3% of the dates (Solheim, 2020:48). However, where there was a discrepancy, the main occupation of the sites is still believed to have been shore-bound rather than associated with the deviating ^{14}C-dates. This is based on typological and technological characteristics of the assemblages. Whether these mismatches represent later shorter visits that are responsible for the younger radiocarbon dates, or whether these dates are entirely erroneous can be difficult to evaluate (e.g. Persson, 2008; Schülke, 2020). However, this distinction is not deemed critical here, as what is of interest is settlements and tool-production areas as evidenced by artefact inventories or multiple site features. Not remnants of stays as ephemeral to only be discernible by isolated features or dubious ^{14}C-dates. The evaluation of the relevance of radiocarbon dates to settlement activity will here therefore be entirely dependent upon and follow the discretion of the original excavation reports.

Other previous evaluations of the correspondence between radiocarbon- and RSL-informed dates have typically followed the same structure as that of Breivik et al. (2018), involving a visual inspection of radiocarbon probability mass functions plotted against local shoreline displacement curves based on the elevation of the site (e.g. Åkerlund et al., 1995; Åstveit, 2018; Berg-Hansen et al., 2022; Solheim, 2020; see also Bjerck, 2008b; Kleppe, 1985; Ramstad, 2009). This approach has a couple of limitations. First, the displacement curves are sometimes applied directly to larger study areas, analogous to what Borreggine et al. (2022) term a bathtub model, with only some studies having taken the variable uplift-rates into account when performing this comparison (e.g. Åstveit, 2018; Fossum, 2020; Møller, 1987; Persson, 2008; Rosenvinge et al., 2022). Secondly, with this method, the wider the uncertainty range associated with either radiocarbon date or displacement curve, the higher the probability that the confidence intervals overlap, and the higher the probability that the conclusion supports the hypothesis. This thus leads to an inferential framework that favours uncertainty, which is hardly desirable. In statistical terms this follows from the fact that while one cannot conclude that two dates are different if their confidence intervals overlap, this does not necessarily mean that they are the same. The question thus necessitates a flip from a null-hypothesis of no significant difference, to one of equivalence (e.g. Lakens et al., 2018), as the question of interest is effectively one of synchroneity between events (cf. Parnell et al., 2008). Another limitation of this often-employed method is that it only takes into account the vertical distance between the sites and the sea-level. While this is the main parameter of interest for shoreline dating, the practical implications of a vertical difference in RSL will be highly dependent on local topography and bathymetry. RSL-change can have more dramatic consequences in a landscape characterised by a low relief, as the horizontal displacement of the shoreline will be greater. Taking the spatial nature of the relationship between site and shoreline into account will consequently help get more directly at the behavioural dimension of this relation and help move the analysis beyond a purely instrumental consideration of the applicability of shoreline dating.

3. Data

To get at the relationship between sites and the contemporaneous shoreline, this analysis was dependent on identifying a study area with good control of the trajectory of prehistoric shoreline displacement. While there is displacement data available for other areas of south-eastern Norway (e.g. Hafsten, 1957; Sørensen, 1979, 1999), considerable methodological developments in recent years means that the most well-established displacement curves are from the region stretching from Horten county in the north-east, to Arendal in the south-west (Fig. 2). This area has newly compiled displacement curves for Skoppum in Horten (Romundset, 2021), Gunnarsrød in Porsgrunn (Sørensen et al. in press; Sørensen et al., 2014a,b), Hanto in Tvedestrand (Romundset, 2018; Romundset et al., 2018), and Bjørnebu in Arendal (Romundset, 2018).

The shoreline displacement data used in this study are based on the so-called isolation basin method (e.g. Kjemperud, 1986; Romundset et al., 2011), which involves extracting cores from a series of basins situated on bedrock at different elevations below the marine limit, and dating the transition from marine to lacustrine sediments. Each basin thus represents a high precision sea-level index point (SLIP) which are combined in a continuous time series for RSL-change adjusted to a common shoreline isobase. The isobases are here contours indicating equal shoreline displacement over the same time span (Svendsen and Mangerud, 1987:116). To minimise the impact of variable uplift rates, the cored basins are located in as constrained of an area of the landscape as possible. Following from the morphology of the retreating ice sheet, the uplift is more stark towards the north-east, which needs to be adjusted for in the case that any basins are located any significant distance from the common isobase that runs perpendicular to this uplift gradient (Fig. 2). Furthermore, as the uplift has been greater immediately following the retreat of the ice, such adjustments, and thus potential uncertainty, will be more critical further back in time. The resulting SLIPs are most commonly interpreted as representing the isolation of the basins from the highest astronomical tide, which is adjusted to mean sea-level in the compilation of the displacement curves, based on the present-day tidal range. For simplicity, the tidal range is assumed to have been the same throughout the Holocene (Sørensen et al., 2014a:44). The highest astronomical tide in the study area reaches around 30 cm above mean sea-level (30 cm at the standard port Helgeroa in Larvik, Norwegian Mapping Authority, 2021).

As the displacement curves and their trajectory are quite complex constructs and the integrated result of both expert knowledge and more objectively quantifiable parameters, the geologists that have undertaken the studies have not found reason to assign variable uncertainty within the confidence envelopes of the displacement curves (Romundset et al., 2018:187; Sørensen et al., 2014a:44). The reason for this is that the trajectory of the curves is not only based on radiometric dates, the uncertainty of which are well-defined, but are for example also dependent on the interpretation and analysis of sediment cores, the nature and condition of the basin outlets and the adjustment to a common isobase, as well as being based on expert knowledge of regional post-glacial geologic developments and local geomorphology, to name but a few factors (e.g. Romundset et al., 2011, 2018; Svendsen and Mangerud, 1987; for an alternative approach see Creel et al., 2022). For more details and evaluations done for the compilation of each curve, the reader is therefore referred to the individual publications.

The archaeological data compiled for the analysis consists of excavated Stone Age sites with available spatial data from the coastal region between Horten county in the north-east, to Arendal in the south-west (Fig. 2). These number 167 sites, of which 91 are associated with the total of 547 radiocarbon dates. Of these, in turn, 66 sites are related to the 255 radiocarbon date ranges that intersect the Stone Age (9500–1700 BCE), with 95% probability. These sites and ^{14}C-dates form the basis for the analysis. Spatial data in the form of site limits and features, as defined by the excavating archaeologists, were retrieved from local databases at the Museum of Cultural History of the University of Oslo—the institution responsible for archaeological excavations and data curation in the region. In the compiled dataset, each radiocarbon date has been associated with the site features or excavation unit from where they originate, or, where these weren't available, the spatial limit of the entire site. Due to somewhat variable practices between excavations, what available spatial geometry best represents the site limit was decided based on an evaluation of the excavation reports. This means that the limits are variably given as that defined during initial survey, area de-turfed before excavation, area stripped with excavator following the excavation, manually excavated area, or convex hull polygons generated around the site features.

Three of the sites have been associated with agriculture, either directly or in the form building structures. The first is Nordby 1 at which the ^{14}C-dates are associated with a Late Neolithic long-house (Gjerpe and Bukkemoen, 2008). The Middle Neolithic phase at Kvastad A2 (Stokke and Reitan, 2018) and Late Neolithic phase at Nauen A (Persson, 2008) are both directly related to farming activities. Both of these sites also have radiocarbon dates and lithic inventory associated with Mesolithic forager activities. Following from the expected deviance from the settlement patterns that are

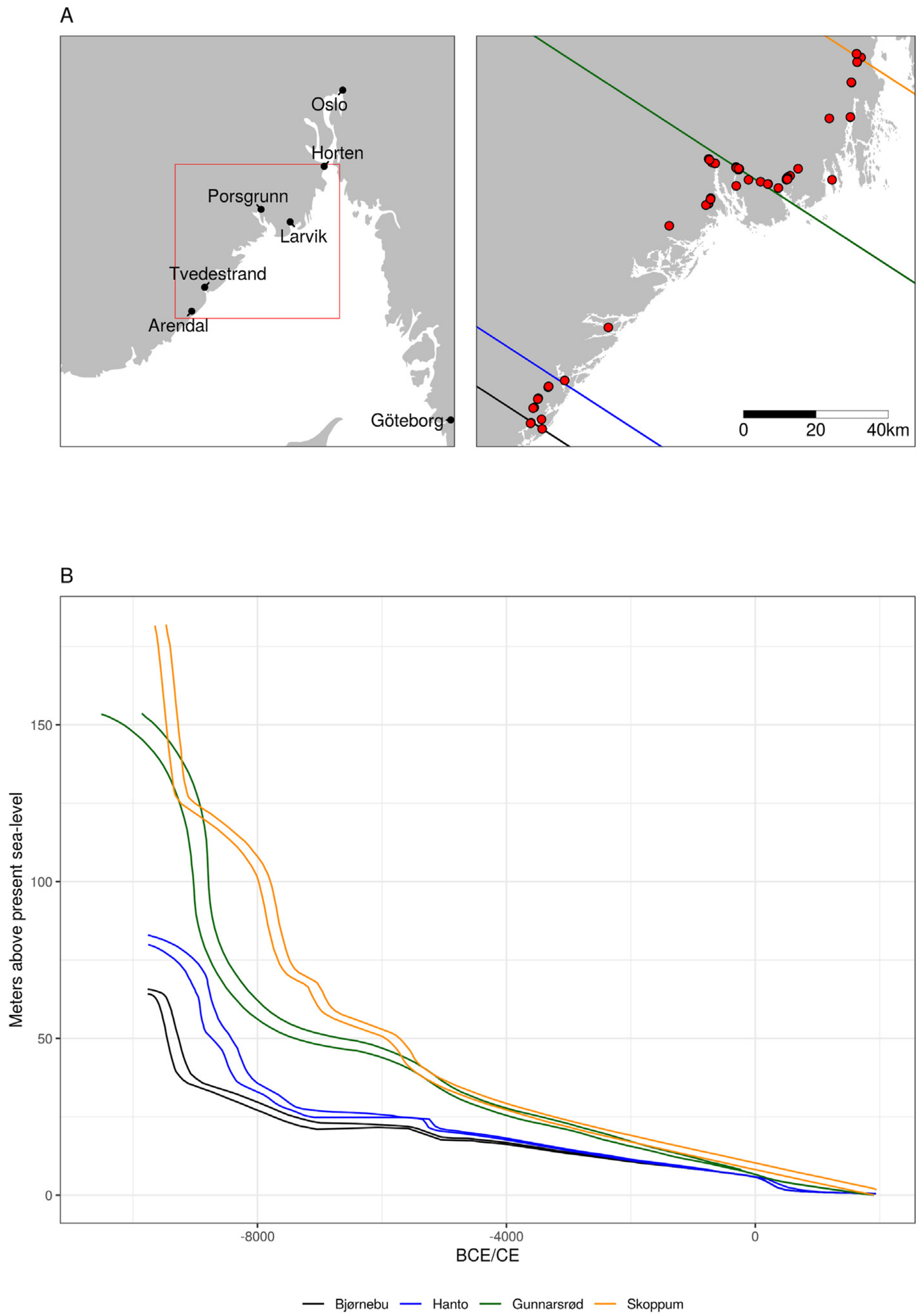

Fig. 2. A) Location of the study area and the distribution of the 66 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al., 2018, although see Sørensen et al., 2014a). B) Displacement curves. Note the increasing steepness of the curves towards the north-east.

to characterise forager sites, these agricultural phases are highlighted in the analysis below. Finally, Nielsen (2021) has recently suggested that Early and Middle Neolithic features from the otherwise younger sites Bratsberg (Wenn, 2012) and Larønningen (Røberg, 2012) could be related to early agricultural activity in the Oslo fjord region. Due to the uncertain and somewhat speculative nature of this suggestion, these are omitted here.

The elevation data used for the analysis is a digital terrain model (DTM) freely available from the Norwegian Mapping Authority (Norwegian Mapping Authority, 2018; https://hoydedata.no). The 10 m resolution DTM was used rather than the higher-resolution 1 m version, both because this resulted in considerably less processing time and because the higher resolution elevation model is more vulnerable to smaller-scale modern disturbances. The 10 m resolution DTM of the study area is a down-sampled version of the 1 m version and has a height accuracy with a systematic error of 0.1 m (Norwegian Mapping Authority, 2018). All data and R programming code (R Core Team, 2021) required to run the analyses, as well as the derived data are freely available in a version-controlled repository at https://doi.org/10.17605/osf.io/7f9su, organised as a research compendium following Marwick (2017; Marwick et al., 2018).

4. Methods

Shoreline dating is based on the spatial relationship between two phenomena, occupation of sites and shoreline displacement, each associated with temporal uncertainty. The first task was therefore to ascribe a likely date and associated degree of uncertainty to these dimensions. To take account of the gradient in the isostatic rebound, the trajectory of shoreline displacement was first interpolated to each site location based on the distance to the isobases of the displacement curves, using inverse distance weighting (e.g. Conolly, 2020; Conolly and Lake, 2006:94–97). This was done for each year along the entirety of the curves, weighting the interpolation by the squared inverse of the distances. The result of this process is shown for an example site in Fig. 3. For the sites all radiocarbon dates were first individually calibrated using the IntCal20 calibration curve (Reimer et al., 2020) using OxCal v4.4.4 (Bronk Ramsey, 2009) through the oxcAAR package for R (Hinz et al., 2021). Radiocarbon dates associated with each site were then grouped if their date ranges intersected at 99.7% probability, meaning these were effectively taken to be associated with the same occupation event, here termed settlement or site phase. In the case where there are multiple dates believed to belong to a single settlement phase, these were modelled using the Boundary function in OxCal and then summed using the Sum function. Multiple phases at a single site were treated as independent of each other.

The excavation of archaeological sites in Norway typically occur in advance of residential and commercial infrastructure development. As the data collection for the utilised DTM was begun by the Norwegian Mapping Authority in 2016, the area of the DTM immediately surrounding the sites has sometimes been severely impacted by disturbances after the excavation. In addition to employing the 10 m resolution DTM to alleviate some of these issues, this also necessitated some additional editing of the elevation raster. This involved manually defining the extent of problem areas such as railways, highways, quarries and the like. The DTM values on these were then set to missing, and new elevation values were interpolated from the surrounding terrain. This was done using regularised spline interpolation with tension (e.g. Conolly, 2020), using the default settings of r.fillnulls from GRASS GIS (GRASS Development Team, 2017) in R through the package rgrass7 (Bivand, 2021). In addition to code and original spatial data being available in the online repository for the paper, the location and analysis of each individual site is presented in the supplementary material where it has been noted when the area surrounding a site has been edited in this manner.

Armed with a likely date range for the occupation(s) of each site, an estimated trajectory of RSL change at that location, and a DTM edited to remove substantial modern disturbances, the simulations were performed. A single simulation run involved first drawing a single year weighted by the posterior probability distribution of a given occupation phase of a site (Fig. 4). This year then has a corresponding likely elevation range for the contemporaneous shoreline from which an elevation value was drawn uniformly, using intervals of 5 cm. The sea-level was then raised to this elevation on the DTM by defining all elevation values at or below this altitude as missing. Polygons were then created from the resulting areas with missing values. The horizontal distance was then found by measuring the shortest distance between site and sea polygons, and the vertical distance by subtracting the elevation of the sea-level from the lowest elevation of the site polygon. The topographic distance between site and sea was also found by

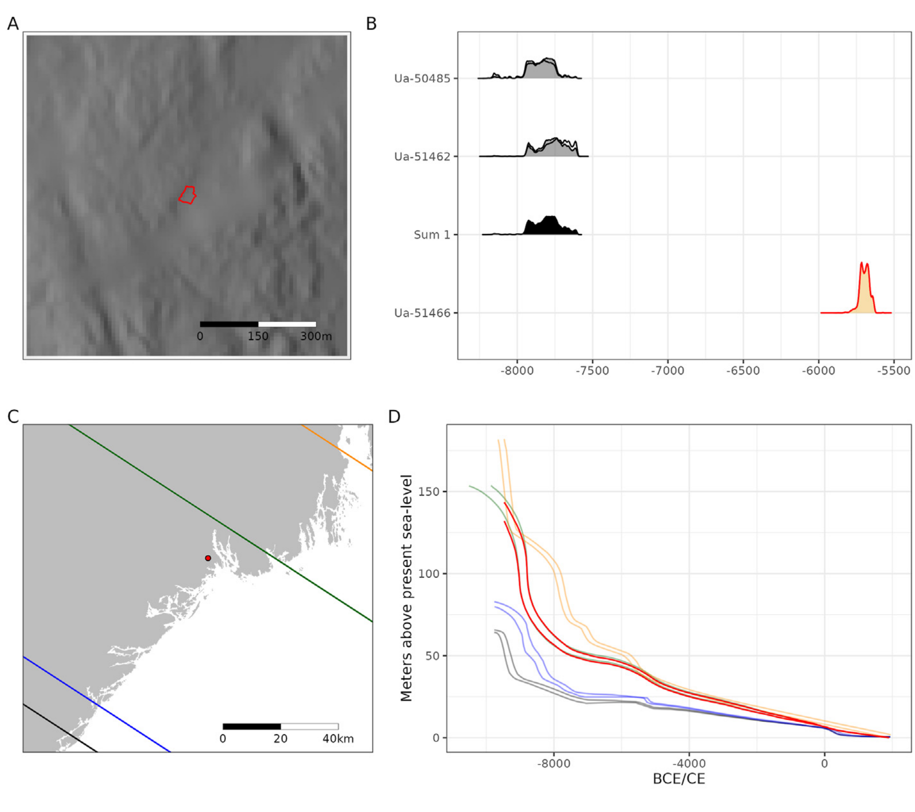

Fig. 3. Example site Hegna vest 1 (Fossum, 2017). A) Location of the site on the edited 10 m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled using the Boundary function in OxCal and then summed. The red outline indicates that the date does not match the typological indicators in the artefact assemblage of the site. C) The location of the site within the study area relative to isobases of the displacement curves. D) Displacement curve interpolated to the site location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

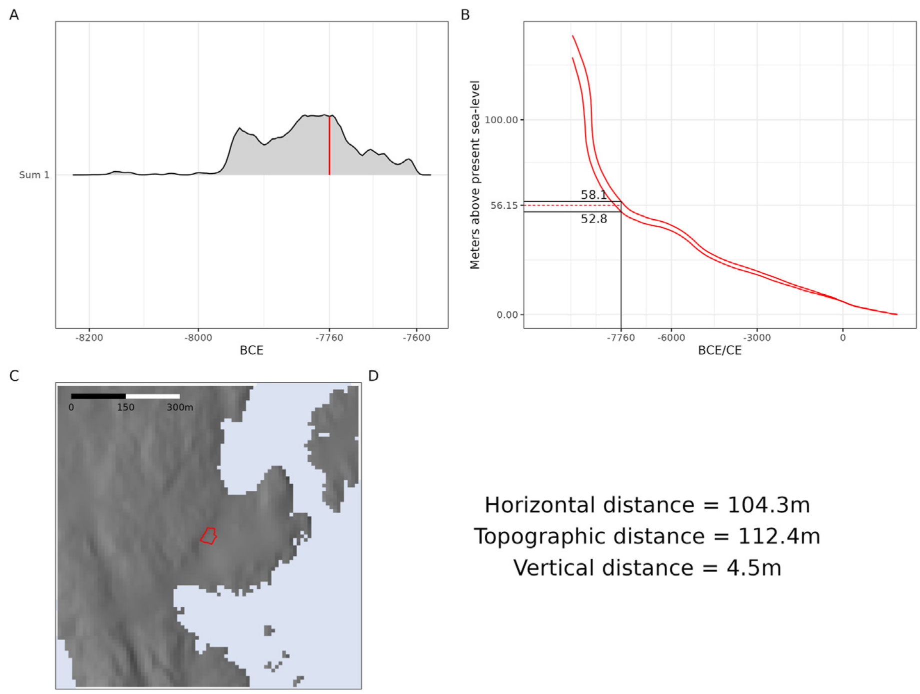

Fig. 4. Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year, weighted by the posterior probability distribution. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using 5 cm intervals. C) The sea-level is then adjusted on the DTM to this elevation and the various distance measures are found. D) The numerical result of the simulation run.

measuring the distance while taking into account the slope of the terrain on the DTM. This was done using the topoDistance package for R (Wang, 2019). The topographic distance was measured between the points on the site and sea polygons that were identified as being the closest when measured horizontally. Because it is measured as the shortest topographic path between the horizontally closest points, this means that the distance does not necessarily match the closest topographic distance if the entirety of the polygons had been considered. Not finding the topographically closest points significantly reduced the computational cost of the analysis, and is deemed unlikely to have a considerable impact on the results, given the distances considered. The shortest topographic path was found using the Moore neighbourhood of eight cells (e.g. Conolly and Lake, 2006:253; Herzog, 2013).

In the case where the sea polygons intersect the site polygon, all distance measures were set to zero. In the case that the sea polygons completely contain the site, the horizontal and topographic distance measures were made negative, and the vertical distance was instead measured to the highest point on the site polygon. While it is safe to assume that an archaeological site was not occupied when it was located below sea-level, a negative result can reflect the inherent uncertainty in this procedure, and might also help identify discrepancies in displacement data or radiocarbon dates. Negative values were therefore retained except of for the sites Gunnarsrød 5 and Pjonkerød R1, where the negative values are believed to result from modern disturbances in the DTM rather than the ^{14}C-dates or displacement curves (see supplementary material for more details).

This process was repeated 1000 times for each phase for each site (Fig. 5). The choice of 1000 simulation runs follows from an evaluation of when the mean distances between site and shoreline converged when running 5000 iterations of the simulation on the site Hovland 5 (cf. Crema et al., 2010:1125). This evaluation is presented in the supplementary material. Hovland 5 was chosen for this assessment as it has an imprecise age and is located in area of quite complex topography (Mansrud and Koxvold, 2013).

5. Simulation results

Overall, as is indicated by the measures for central tendency and the almost solid line along the 0 m mark on the y-axes, the simulations show that the sites tend to have been situated close to the shoreline when they were in use (Fig. 6). As is also illustrated by the measures for dispersion, some of the sites are situated considerable distances from the shoreline when the dates believed to be erroneous in the original reports are included (Fig. 6A). However, if one accepts the interpretation that these do not date the main occupation of the sites, as is indicated by the artefact inventories, Fig. 6B gives considerable support to the notion that the sites were in use when they were situated on or close to the contemporaneous shoreline. The distances for the earliest sites appears somewhat high, with the highest vertical distance of the results older than 7500 BCE being 27.9 m. But this can likely be explained as the result of the rapid RSL fall in the earliest part of the Holocene (Fig. 2B), which leads the uncertainty of the ^{14}C-dates to give a wider possible elevation range for the simulated sea-level. This is also indicated by the fact that the median vertical distance for the same simulation results is 6.1 m, and 15 of the 18 sites associated with these results have simulated vertical distances that extend below 5 m.

Another immediately striking result is the apparent deviation from the shoreline towards the end of the Stone Age. Of the results from after 2500 BCE, which are associated with 8 sites, only one has simulation results for vertical distance that includes zero. The highest simulated vertical distance among these is 56.5 m and the median is 12.9 m. Furthermore, some deviation from the shoreline is evident from just after 4000 BCE as well. Of the 21 sites associated with the period between 4000 and 2500 BCE, two sites have all vertical distance results above 25 m. However, the median vertical distance of the results from this period is only 4.3 m, indicating that

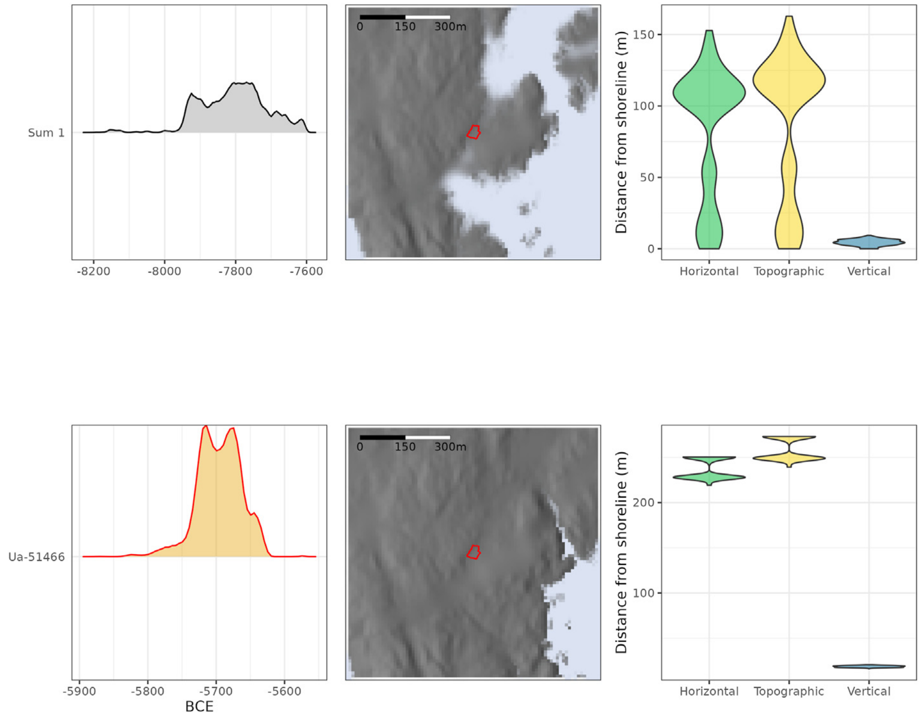

Fig. 5. The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The leftmost column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The centre column displays the result of simulating the raised sea-level 1000 times. The more opaque the colour appears, the more times the sea-level was simulated in that location. The rightmost column shows violin plots of the different distance measures across all simulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

while some sites have a markedly withdrawn location, most are still situated close to the shoreline. The chronological smearing following from the uncertainty in the ^{14}C-dates means that while the results cannot be used to directly inform discussions that deal with the century scale around these chronological transitions (e.g. Prescott, 2020; Solheim, 2021), the findings are nonetheless in clear agreement with the general chronological developments suggested in the literature.

The negative values around 8000 BCE originate from the sites Løvås 1, 2 and 3. Berg-Hansen et al. (2022:644) made a similar observation in their assessment of the correspondence between shoreline displacement and radiocarbon dates from these sites. The sites are recently excavated, well-dated and are situated in a relatively undisturbed area of the landscape (Berg-Hansen et al., 2022; Reitan and Hårstad, 2022). While there could be a danger of circularity of having archaeological sites inform a reconstruction RSL-change, and, in turn, use these to evaluate the degree of shore-bound settlement, the sites do clearly represent an upper constraining limit for the sea-level, as they would not have been in use when located under water. It therefore seems that the Løvås sites represent a case where the archaeological material indicates a slight discrepancy in the geologic reconstruction of shoreline displacement in the area.

Accepting that shoreline dating appears to lose utility around the transition to the Late Neolithic, as indicated by the clear deviation in site location from the shoreline after this, the results from Fig. 6B are presented again in Fig. 7A, excluding all simulation results younger than 2500 BCE. Furthermore, all negative values have here been set to zero, under the assumption that these result from uncertainty or errors in the data, and not actual site locations. The resulting best point estimate for the vertical distance between sites and shoreline for the pre-Late Neolithic is given by the median distance of 4 m, while 95% of the values fall within the range 0–18 m. That is, for 95% of the cases, the shoreline was simulated to be situated on or less than 18 m below the site location. While these values remain the same when only the Mesolithic dates are included (Fig. 7B), the mean and standard deviation are slightly constrained. Furthermore, while the median for horizontal and topographic distance is only 10 m across all plots in Fig. 7, the relative magnitude of the statistics for dispersion is greater than what it is for vertical distance, illustrating the point that minor variations in vertical distance can have substantial consequences for these distance measures, depending on the surrounding topography.

It is clear that the distributions in Fig. 7 have a severe right skew. Most sites were likely situated less than a meter from the shoreline, and from this there is a sharp decline in density as one moves further along the x-axes. To characterise this relationship, a series of standard models for distributions with a right skew have been fit to the simulation results for vertical distance older than 2500 BCE (Fig. 7A) by means of maximum likelihood estimation (Table 1). As most of the models only accept positive values, a constant of 0.001 was added to avoid values of zero. It was attempted to both remove negative values and force these to zero before adding the constant. As the difference between these two solutions was negligible, and as the assumption here is that negative values in actuality reflect a distance of zero, the latter approach was chosen (a plot displaying the negative values and the compared models is available in the supplementary material).

The performance of the models was then compared by means of the Akaike information criterion (AIC) and the Bayesian (or Schwarz) information criterion (BIC). The AIC and BIC evaluate the degree to which the models fit to the data, while penalising for the number of model parameters to avoid over-fitting (e.g. Burnham and Anderson, 2002; for applications in archaeology see e.g. Eve and Crema, 2014; Timpson et al., 2021). As lower values point to

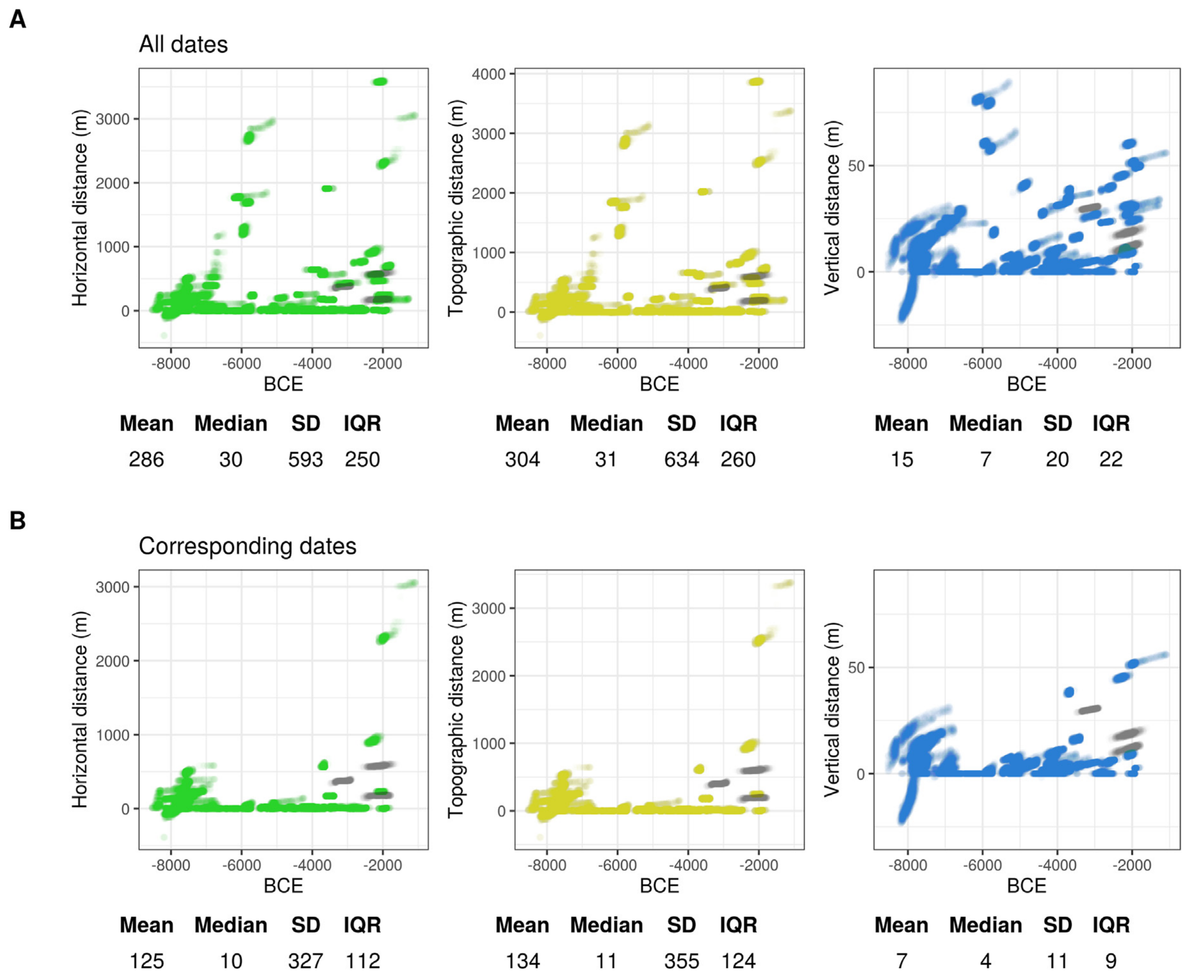

Fig. 6. The result of running the analysis across all sites. Each data point is plotted with some transparency, meaning that the more intense the colour, the more often those values occurred. Results associated with agricultural activities are plotted in grey. The first row A) shows the result of including all dates to the Stone Age, including those seen as otherwise unrelated to the main occupation of the sites (66 sites and 166 site phases). The second row B) shows the result of excluding these (resulting in 51 sites and 69 site phases). The table under each plot lists some corresponding statistics for central tendency and dispersion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a better model, it is evident from both the AIC and BIC that the gamma is the best among the candidate models. It is worth noting that this could have benefited from a more sophisticated treatment of the zero-values. This is because these are likely to be a mix of both exact zeros, the case when there is an actual intersection between site and sea, and, although probably to a far lesser extent, zeroes that result from the case when the distance between site and sea is below the detection limit due to the employed methods and the resolution of the spatial data (e.g. Dunn and Smyth, 2005; Helsel, 2005). In conclusion, however, the gamma appears to represent a reasonable approximation of the data. If one accepts this, the probability density function for the gamma distribution can be used to characterise the vertical distance between sites and the shoreline and be used to inform a method for shoreline dating that takes this into account.

6. Shoreline dating

The procedure for shoreline dating to be outlined is aimed at determining the likely age of the occupation of a site based on its altitude above present day sea-level, with reference to shoreline displacement and the likely elevation of the site above the sea-level when it was in use. For simplicity, this is conceptually treated a single event and thus the possibility of multiple or continuous phases of occupation is not treated explicitly. This leads the problem to become similar to that of the calibration of a radiocarbon date (see Fig. 8, Bronk Ramsey, 2009; Stuvier and Reimer, 1989; van der Plicht, 1993). First, finding the elevation of the sea-level at the time the site was in use is dependent on the present-day elevation of the site E and the distance between site and the shoreline D. Based on the simulation results above, the distance from the elevation of the site to the contemporaneous shoreline is defined by the probability density function for the gamma distribution:

$$p(E-D) = \frac{1}{\sigma^{\alpha}\Gamma(\alpha)}(E-D)^{\alpha-1}e^{-(E-D)/\sigma} \tag{1}$$

where α is the shape and σ the scale of the distribution, and $\Gamma(\alpha)$ denotes the gamma function. This can then be coupled with the trajectory of relative sea-level change to find the corresponding calendar date T for the occupation of the site. This is defined by a discrete uniform probability mass function (Ud) on the calendar scale over the range between the lower T_l and upper T_u bounds of the displacement curve that has been interpolated to the site location:

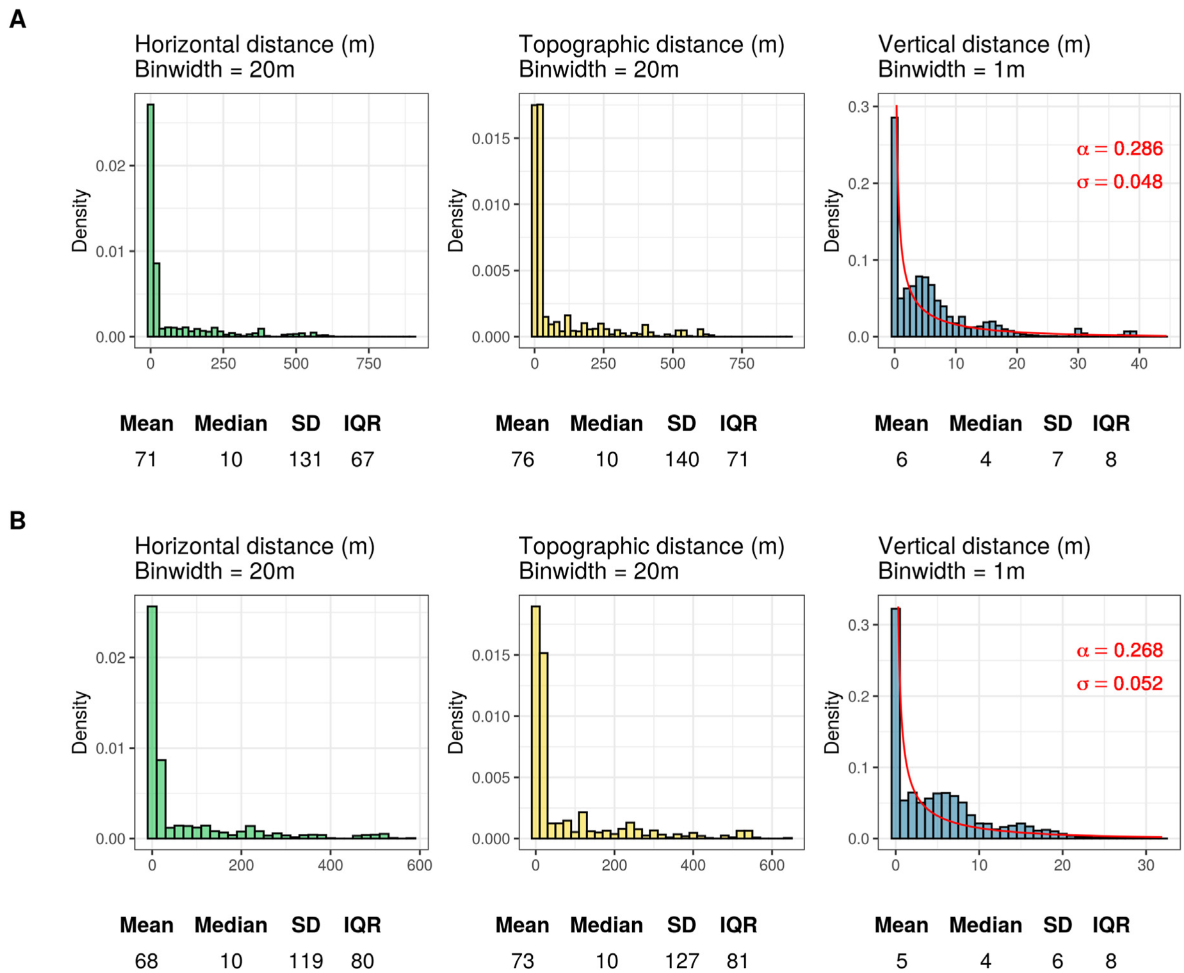

Fig. 7. Histograms showing the simulated distance from the shoreline using radiocarbon dates corresponding to the site inventories. Negative values have been set to zero. A) Simulated results older than 2500 BCE (50 sites and 66 site phases) and B) simulated results older than 4000 BCE (43 sites and 51 site phases). Note that the cut-off is done based on the calendar year associated with each distance value. Consequently, sites and site phases are only completely excluded if the entire posterior probability of the radiocarbon dates falls later than the cut-off. Furthermore, the superimposed gamma distributions have been fit when adding a constant of 0.001 to the distance values and have been cut off on the y-axis for visualisation. The gamma distribution in A forms the basis for the analysis to follow, but a version has also been fit to the vertical distances in B to further illustrate the difference between the distributions.

Table 1
Comparison of models fit to the simulated vertical distances older than 2500 BCE, with negative results set to zero and a constant of 0.001 added to the values. The models are listed in the order of performance. A plot with all of the models is available in the supplementary material.

Model	Parameters	AIC	BIC
Gamma	Shape (α) = 0.286 Scale (σ) = 0.048	230,247	230,229
Log-normal	Mean of the logarithm (μ) = −0.647 SD of the logarithm (σ) = 3.926	268,082	268,064
Power law	Exponent (k) = 1.16	274,052	274,043
Exponential	Rate (λ) = 0.168	348,484	348,475
Logistic	Location (μ) = 4.698 Scale (σ) = 3.558	415,322	415,304

$$p(T|E-D) = Ud\left[T_{l|E-D}, T_{u|E-D}\right] \tag{2}$$

Finding the probability for the date of the site then becomes a matter of transferring the probability of the distance between site and shoreline to calendar dates using the displacement curve:

$$p(T|E-D) = p(T|E-D)p(E-D) \tag{3}$$

We can then get rid of parameter D by summing all possible distances between site and the shoreline. Given its elevation, the probability for the date of the occupation of a site is then:

$$p(T|E) = \sum_{D} p(T|E-D)p(E-D) \tag{4}$$

An example of an implementation of the outlined approach is given in Fig. 8, where $\alpha = 0.286$ and $\sigma = 0.048$. These are the parameters for the gamma distribution identified when considering all pre-Late Neolithic simulation results (Fig. 7A) and are the parameters used in all applications of the proposed method that follow below. For the numerical implementation, D is here stepped through as a sequence of increments of 0.001 m, which, following from the adjustment of the values for fitting the compared models, starts from 0.001 m. The gamma distribution is stepped through in its cumulative form, where the probability from the previous 0.001 m step is subtracted from the probability at the current step. This probability is then divided equally across the individual calendar years in the range between the lower and the upper limit of the displacement curve at the current 0.001 m step. The probability mass function that is the resulting shoreline date is the sum of performing this procedure on all possible 0.001 m values of D,

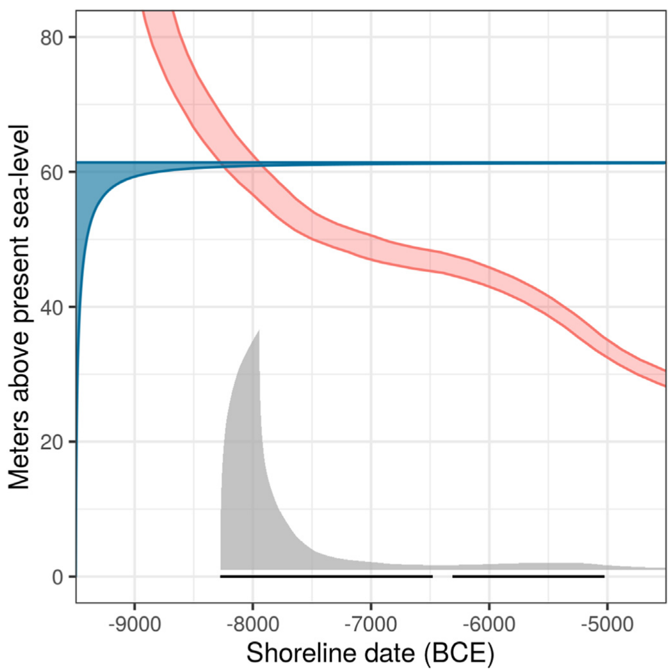

Fig. 8. Shoreline dating of Hegna vest 1. The mean elevation of the site polygon is used to inform E in the dating of the site. The gamma distribution in blue on the y-axis extends the full range of possible values for E − D and has the parameters $\alpha = 0.286$ and $\sigma = 0.048$ (see Fig. 7A). The red envelope marks the shoreline displacement curve interpolated to the site location. The resulting shoreline date in grey is underlined with the 95% HDR in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

which, in practice, is down to and including $E - D = 0.001$ or when 99.999% of the gamma distribution has been stepped through.

To evaluate the outlined procedure, it is used to shoreline date the sites from where the method was derived to check if the resulting shoreline dates correspond to the radiocarbon dates associated with the sites (Fig. 9). The Late Neolithic sites are also included here for illustrative purposes, even though these have not informed the gamma parameters in use. Following from having defined the distance between intersecting sea- and site polygons as zero during simulations, the sites were dated using the mean elevation of the site polygons to allow for some variation in elevation over the site limits. The synchroneity between radiocarbon and shoreline dates was then evaluated using the method presented by Parnell et al. (2008). Here, 100,000 age samples drawn from the probability mass function of each shoreline date were subtracted from 100,000 age samples drawn from the corresponding probability mass function of the modelled ^{14}C-dates. The resulting range of the 95% highest density region (HDR, Hyndman, 1996) was then checked to see if it crosses zero, in which case the dates are considered to be in agreement (Fig. 10). When excluding the earliest occupation phase at Gunnarsrød 5, the deviation of which is to be expected based on issues with the DTM (see above), the shoreline date corresponds to the radiocarbon dates in 64 out of 68 cases (93%). Only including dates modelled to be older than 2500 BCE with 95% probability, i.e. older than the Late Neolithic, improves this to 60 out of 62 cases (97%). When only including dates older than 4000 BCE with 95% probability, i.e. only Mesolithic site phases, the success rate is further increased to 49/49 (100%).

7. Re-dating previously shoreline dated sites

To further explore the implementation for shoreline dating presented above, 87 excavated and shoreline dated Stone Age sites within the study area where ^{14}C-dates are not available or these are not believed to date the main occupation of the sites have been subjected to the outlined approach (Fig. 11). The resulting dates are compared to those originally proposed in the excavation reports for the sites (the numerical results are available in the supplementary material). To avoid issues with recent disturbances in the DTM, the sites have been dated based on the mean of the altitudes provided in the report for each site. As all of the included sites have been excavated after the turn of the millennium, and the wide adoption of GNSS technology, the reported elevations should be trustworthy.

This comparison is useful for illustrating both how the method has previously been employed, and for revealing nuances of the implementation that is proposed here. However, the comparison is also unfair to the previously proposed dates for a few reasons. First, the dates provided in the reports are typically stated to be a very rough estimate and are sometimes given as a point estimate with an undefined, but implied or explicit uncertainty range. Secondly, seeing as these reports are from various dates in time, many are based on now outdated data on RSL-change. Thirdly, they are sometimes only meant to indicate a lower bound for when the sites could have been in use. Additionally, the dates are often stated to be the result of also considering artefact typology and characteristics of local topography to inform the likely elevation of the sea when the site was in use—although precisely how these are weighted and used to inform the suggested date is often not as clear.

With a few exceptions, the previously hypothesised dates and the ones achieved here appear to roughly correspond when it comes to the start date for the occupation of the sites. The clearest difference mainly pertains to the fact that the previously proposed date ranges are, almost without exception, more constrained than the 95% HDRs resulting from the proposed method. Considering the right skew of the probability mass functions underlying the 95% HDRs and the general overlap for the start dates, these results could, with some danger of circularity, suggest that shoreline dating has generally been applied with a reasonable degree of success. This also follows from the fact that these dates have typically informed research in an approximate manner (although see e.g. Roalkvam, 2022).

With these considerations in mind, the results also indicate that shoreline dating has at times been applied with an exaggerated degree of precision. While the implications of a more stable RSL-change for shoreline dating are well known, this also appears to be somewhat under-appreciated in the practical implementation of the method. The results indicate that the spatial and temporal contingency of the method is better captured by the implementation suggested here, as is illustrated by the variation in the range of the 95% HDRs for the dates. In some cases the proposed method provides a relatively precise date and in others the HDR offers little more than a *terminus post quem*. This is dependent on the steepness of the displacement curves, leading to the general pattern of older sites situated towards the north-east getting more precise dates (cf. Fig. 2B). However, as some of the 95% HDRs extend well beyond major chronological divisions, even into the Iron Age, it is also clear that some of these could be severely and securely constrained with only cursory reference to typology. While this would be trivial in some cases, the nature and uncertainty inherent to the method still means that this is arguably an exercise that should be explicitly performed. This also points to the possibility of drawing on other temporal data to further improve the precision of the dates that can be achieved with shoreline dating.

Not least following from the fact that relatively few ^{14}C-dates older than c. 8000 BCE associated with anthropogenic activity have been achieved in Norway (Åstveit, 2018; Damlien and Solheim, 2018; Kleppe, 2018), the shoreline dating of the earliest sites is

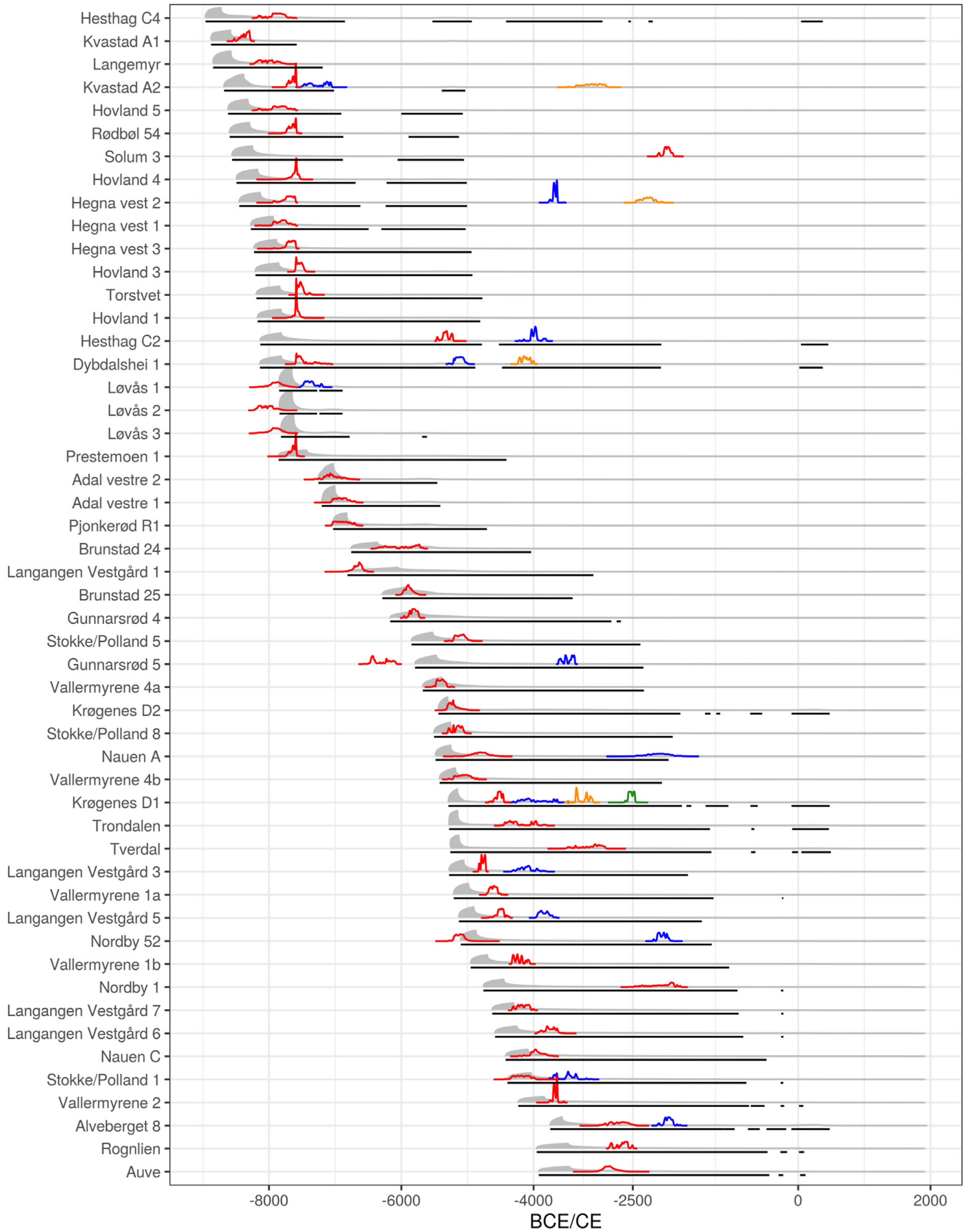

Fig. 9. The result of backwards shoreline dating the 51 sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-intersecting dates at 99.7% probability. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

essential for understanding the pioneer settlement and the initial colonisation of the Scandinavian peninsula (e.g. Bang-Andersen, 2012; Berg-Hansen, 2018; Breivik, 2014; Fuglestvedt, 2012; Glørstad, 2016). The shoreline dated Preboreal sites from the Brunlanes-project are among the earliest known sites in Norway (Jaksland, 2012a, 2012b; Jaksland and Persson, 2014). These have a distinct Early Mesolithic artefact inventory and are situated in a steep area of the landscape where use of the sites would have been

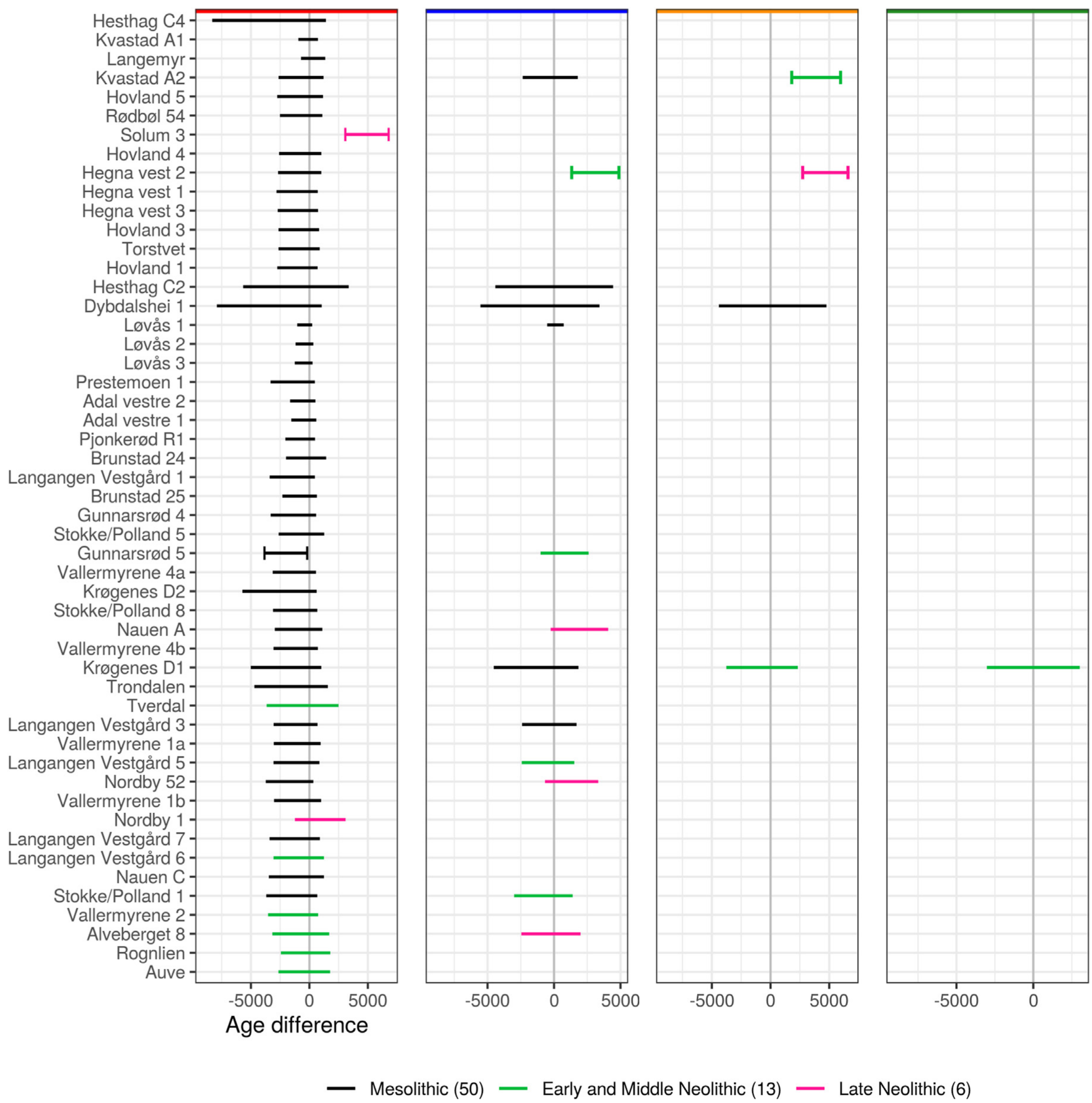

Fig. 10. Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Fig. 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does not cross zero and that the dates do not correspond. The division and colour coding at the top of the plots reflect the division of site phases given in Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

difficult after the sea retreated any significant distance from their location due to accessibility. In the original publication of the sites, Jaksland (2014) provides a thorough discussion of shoreline dating in general, and as used for the dating of the Brunlanes sites specifically. A comparison of his results and the ones achieved using the above-outlined approach are given in Fig. 12A. The sites have been dated using what Jaksland (2014) gives as the lowest elevation of finds at each site.

The small discrepancies between the achieved results mainly follow from the fact that a slightly updated version of the local displacement curve is applied here (Sørensen et al. in press; cf. Sørensen et al., 2014a). Jaksland's dates are given a flat 200- and 50-year uncertainty range starting from what he gives as the earliest possible date. The 200-year uncertainty range is given if the sites were to be considered in isolation, while his argument for the uncertainty range of only 50 years is based on the location of the sites relative to each other. Since they are located in such a constrained and steep area of the landscape, the difference in elevation between the sites is argued to establish their relative date and thus constrain the uncertainty ranges so that they do not overlap. This information is not integrated in the approach outlined here, but it could justify further reducing the uncertainty ranges. Although their accuracy is of course ultimately dependent on the veracity of the geological reconstruction, the high rate of RSL change in this period does nonetheless result in very precise dates.

Above it was suggested that additional temporal data could be combined with the method to improve its precision. Drawing on Jaksland (2014), this example instead highlights the fact that the spatial nature of the method means that a consideration of the surrounding terrain and other sites can also help to increase the precision of the method if this can be used to exclude certain RSLs as unlikely for when a site was in use. One potential way to do this

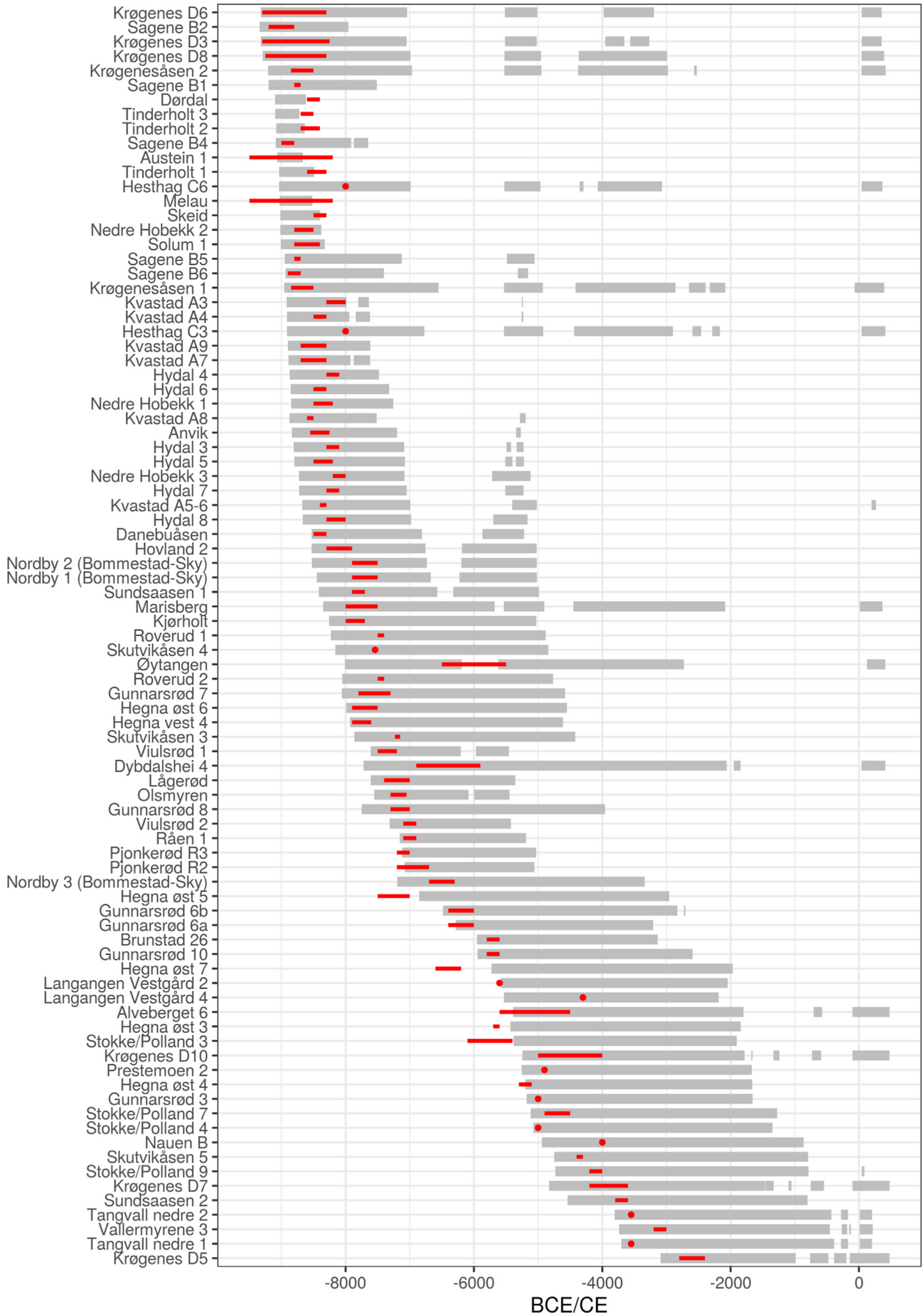

Fig. 11. Re-dating 87 excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey are compared to the dates originally proposed by the excavation reports in red. For clarity in the figure, only the 95% HDRs of the shoreline dates are displayed. However, the reader is asked to keep in mind that these are associated with a probability mass function with a right skew that form a better foundation for any further analysis (see e.g. Telford et al., 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

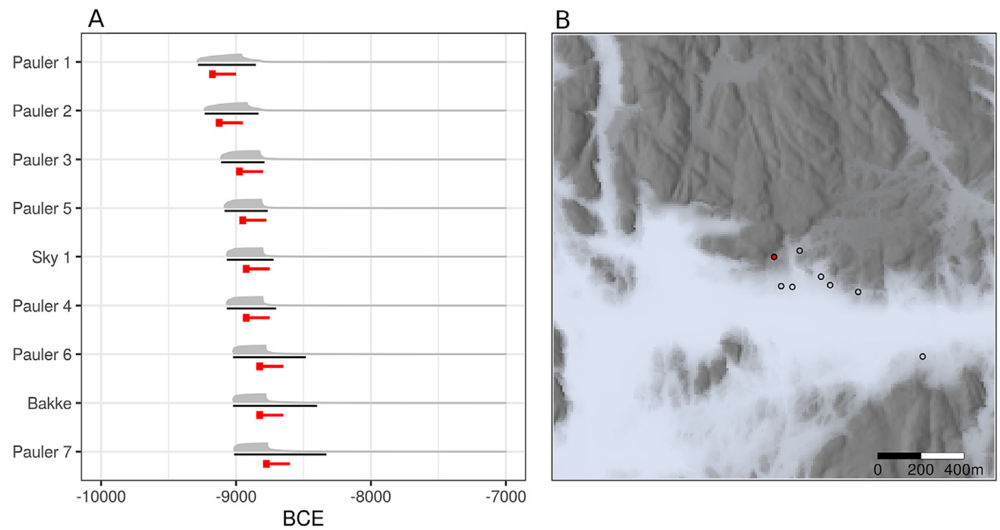

Fig. 12. Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red. The box indicates a 50-year uncertainty range which in combination with the red line extends 200 years. B) Map showing the centroids of the Pauler sites and Sky 1. The sea-level has been simulated using the probability distribution associated with the shoreline date for Pauler 1 (see also map in Jaksland, 2014:Fig. 12a). Pauler 1 is the red point. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be through the analysis of phosphate concentrations in soils, which has the potential to offer insights on the likely position of the shoreline when a site was in use (Ilves and Darmark, 2011). This has been done in the Baltic Sea region (e.g. Broadbent, 1979; Ilves and Darmark, 2011; Sundström et al., 2006), but has yet to provide reliable results in Norway (e.g. Melvold and Persson, 2014b; Viken, 2018). The identification of other physical traces of shore formation processes and the deposition of beach sediments in relation to archaeological material also holds similar potential (e.g. Bondevik et al., 2019). Finally, another approach could also be to assess the spatial implication of a proposed shoreline date by simulating the adjusted sea-levels, as is done for Pauler 1 in Fig. 12B, followed for example by a visual evaluation of the topography or by evaluating the distance and steepness of the slope to the shoreline. If such methods are developed further, it could conceivably be possible to exclude certain elevations as unlikely for the position of the shoreline when the site was in use. Such approaches would make less of an impact for the Brunlanes sites, where the 95% HDRs are already quite constrained, but could considerably improve the precision of the method in cases where RSL-change has been less severe (cf. Fig. 11).

8. Concluding remarks

The most significant finding of this paper is a confirmation of previous research into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated by the close proximity of sites and the shoreline until the transition to the Neolithic at c. 4000 BCE, after which a few sites are situated some distance from the sea, followed by a more decisive break at the transition to the Late Neolithic at c. 2500 BCE. This development is in clear agreement with the literature. Furthermore, based on the quantitative nature of these findings, an initial formulation of a refined method for the shoreline dating of pre-Late Neolithic Stone Age sites has been proposed. Apart from taking the distance between sites and the isobases of the displacement curves into consideration when dating the sites, this involves accounting for the distance between the sites and the shoreline. When no other information is available, it can at present be recommended to use the empirically derived gamma distribution with a shape of 0.286 and scale of 0.048 (Fig. 7A) to characterise this relationship. Furthermore, while this remains to be formalised and explored further, it was also demonstrated how the method could potentially be improved by including more information on both the topographic location of the sites and other temporal data. To the degree that making such a distinction is useful, this could be derived from assessments of both a qualitative and quantitative nature, with Bayesian inference forming a natural framework for integrating such considerations (e.g. Buck et al., 1996; Otarola-Castillo et al., 2023). As the precision of the method is both geographically and temporally contingent due to the trajectory of RSL-change, where older sites situated towards the north-east in the study area will get a more precise date, the impact of such additional information will also vary.

Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to further evaluate and adjust the findings reported here, but a larger sample size could also lay the foundations for refining the method by identifying subsets of sites for which the application of the method could be adjusted. For example, from Fig. 7 it is clear that the Mesolithic sites have generally been located closer to the shoreline than the later sites. It was not attempted to explore this further here, given the constrained sample size and the accuracy that was achieved with the parameters in use. However, the future addition of more data might give justification for using different models or parameter settings when dating sites from certain time intervals. Furthermore, following from its behavioural nature, it is also likely that dimensions such as the nature and purpose of visits to the sites will have implications for how close to the shoreline the sites were located. This is illustrated here by the site phases associated with agricultural activity, marked in Fig. 6, which were all found to be located some distance from the sea. A wide range of different behavioural dimensions could potentially provide nuance to how the method should be applied.

Other factors related to the topographic location of the sites could also be similarly explored. This for example pertains to the exposure of sites to wave action, which is likely to have been of concern (Roalkvam, 2020), and which presumably has implications for how close to the shoreline people settled. This is also related to the fact that while the mean sea-level is used for dating the sites, a consideration of the tidal range and potential impact of storm surges could also have implications for the location of a site relative to the shoreline, depending on the topography (Bondevik et al., 2019; Helskog, 1978). The potential of exploring such dimensions was also hinted at here with the estimation and cursory treatment of the horizontal and topographic distance to the shoreline. If patterns related to such locational patterns can be discerned and unpacked, this will not least be useful for improving the shoreline dating of sites which have only been surveyed and where little information beyond their location is available. A mention should also be made here of the fact that catastrophic events such as tsunamis might also be of relevance (e.g. Blankholm, 2020; Nielsen, 2020; Nyland et al., 2021). Evidence for the impact of tsunamis in the Stone Age has not been identified in south-eastern Norway as of yet (see Romundset et al., 2015:398; cf. Romundset et al., 2018; Sørensen et al., 2014a), and might therefore not be of direct relevance to the coastal settlement in the region. However, the outburst flood resulting from the catastrophic drainage of the glacial lake Nedre Glomsjø around 8500–8000 BCE (Høgaas and Longva, 2019), located in Mid-Norway some 230 km north of present-day Oslo, could have had consequences for how the coast was utilised (Solheim et al., 2020:9).

Some limitations and sources of likely variation and uncertainty that have not been considered should also be mentioned. First, the sample size is limited and the future addition of more sites might alter the picture considerably. Secondly, the validity of the outlined method was evaluated by applying it to the data from where the input parameters were derived. Fitting and evaluating a model using the exact same data will likely exaggerate its performance. Thirdly, the DTM has only been corrected for major modern disturbances. This means that other forms of erosion, although likely not that prevalent, have not been considered. Fourthly, the DTM has a vertical error which could also benefit from being integrated in the analysis (Fisher, 1993; Lewis, 2021). Fifthly, the displacement curves were here interpolated to all site locations without accounting for increased uncertainty as one moves further away from the isobases of the displacement curves—an uncertainty that is likely higher for RSL-change further back in time due to the shoreline gradient. This is also related to the fact that the geologic reconstructions hold uncertainty that is not represented in the displacement curves, relating for example to variation in the methods and quality of the data used for the compilation of the curves, as well as the expert interpretations underlying these. Sixthly, neither the question of how site limits are defined nor the elevation range over which these extend was given much consideration (Mjærum, 2022). Finally, the aggregation and division of settlement phases at each site was here simply done by treating radiocarbon dates not overlapping at 99.7% as representing unrelated occupation events, which were then modelled by use of the Boundary and Sum functions in OxCal. This could also be handled differently (e.g. Bronk Ramsey, 2009, 2015). While each of these factors will have variable impact on the final results, they clearly represent dimensions which would all benefit from further consideration and which means that some of the precision following from the outlined approach is likely to be spurious.

Given that shoreline dating is contingent on regular patterns of human behaviour it should naturally be applied with care. Furthermore, formulating and visualising the method along the lines of how radiocarbon dates are treated, as was done here, does stand the chance of giving a veneer of radiometric accuracy to shoreline dating that is not warranted. That being said, the best chance we have of not throwing away precious temporal data, or exaggerate our handle on it, is arguably to rigorously evaluate the method using independent data such as radiocarbon dates, by offering a precise formulation of how it could be applied, by specifying what sources of uncertainty are accounted for and by making this process transparent through the open dissemination of underlying data and programming code.

As the nature of the relationship between sites and sea is likely to vary temporally and geographically (e.g. Nyland, 2020), the proposed implementation and parametrisation of shoreline dating cannot be expected to be directly applicable elsewhere. When this is combined with the fact that the rate of RSL-change also varies geographically and temporally (e.g. Svendsen and Mangerud, 1987), this means that the accuracy and precision of the method will also vary. However, the methodological framework used to evaluate the relationship between sites and sea is readily extendible to other regions of northern Scandinavia where reliable data on shoreline displacement is available, thus making such extensions feasible. Furthermore, the simulation approach used to integrate multiple sources of spatio-temporal uncertainty was used here to inform the question of the distance between sites and the shoreline. However, this method and general framework can be extended to a wide range of use-cases where one needs to visualise, and quantitatively or qualitatively evaluate the relationship between archaeological phenomena, the prehistoric shoreline, and the uncertainty inherent to this reconstruction.

Contributions

Isak Roalkvam: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and programming scripts used for the analysis is openly available in a online repository at https://doi.org/10.17605/osf.io/7f9su

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2022.107880.

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