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

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7 **Abstract**

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

23 **Highlights**

- 24 • Simulates the spatial relation between sites and the prehistoric shoreline
25 • Quantification of horizontal, topographic and vertical distance
26 • Confirms close association between sites and the contemporaneous shoreline
27 • Proposes a formalised method for the shoreline dating of pre-Late Neolithic sites

28 Keywords: Shoreline dating; Stone Age; Settlement patterns; Scandinavia; Relative sea-level change

29 **1 Introduction**

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

- ³⁸ Gjerde 2021; Løken 1977; Nordqvist 1995; Schmitt et al. 2009; Sognnes 2003; Tallavaara and Pesonen 2020;
³⁹ Wikell et al. 2009).
- ⁴⁰ The close association between Stone Age settlements in the northern parts of Scandinavia and shifting
⁴¹ prehistoric shorelines was proposed at the end of the 19th century (De Geer 1896), and was first applied
⁴² as a dating method at the turn of the century (Brøgger 1905; Hollender 1901). Shoreline dating has been
⁴³ fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen 2009; Bjerck 1990, 2008a;
⁴⁴ Breivik 2014; Johansen 1963; Mikkelsen 1975a; Mjærum 2022; Nummedal 1923; Olsen and Alsaker 1984;
⁴⁵ Shetelig 1922; Solheim et al. 2020; Solheim and Persson 2018). The method is used both independently, and
⁴⁶ to compliment other sources of temporal data such as typological indicators or radiometric dates. However,
⁴⁷ given the coarse and fuzzy resolution of established typological frameworks, the vast number of surveyed sites
⁴⁸ that only contain generic lithic debitage that could hail from any part of the period, and as the conditions
⁴⁹ for the preservation of organic material is typically poor in Norway, dating with reference to shoreline
⁵⁰ displacement is often the only and most precise method by which one can hope to date the sites. Shoreline
⁵¹ dating is consequently fundamental to our understanding of the Norwegian Stone Age. This is both because
⁵² it is central to the temporal framework on which our understanding of the period is based, but also because
⁵³ the method is only applicable so long as the societies in question have continuously settled on or close to the
⁵⁴ contemporary shoreline. Consequently, adherence or deviation from this pattern also has major implications
⁵⁵ for the socio-economic foundations of the societies in question.
- ⁵⁶ Despite its important role for Fennoscandian archaeology, the applicability of dating by reference to shoreline
⁵⁷ displacement has only been evaluated using relatively coarse methods. The aim of this paper is to provide a
⁵⁸ systematic and comprehensive review of the degree to which radiocarbon dates correspond with the dates
⁵⁹ informed by our current knowledge of shoreline displacement in a larger area of south-eastern Norway, using
⁶⁰ a more refined methodological approach. The goal here is to quantify the degree to which the assumption of
⁶¹ shore-bound settlement holds through the Stone Age in a relatively well sampled portion of Scandinavia,
⁶² and in turn have this quantification inform the development of a formalised method for shoreline dating.
⁶³ As presented in more detail below, this problem involves the combined evaluation of three major analytical
⁶⁴ dimensions. One is the questions of when the sites were in use, the second pertains to the reconstruction of
⁶⁵ the contemporaneous sea-level, and the third follows from the fact that the relation between site and shoreline
⁶⁶ is inherently spatial. Taking inspiration from studies that have integrated various sources of spatio-temporal
⁶⁷ uncertainty through Monte Carlo simulation (e.g. Bevan et al. 2013; Crema et al. 2010; Crema 2012, 2015;
⁶⁸ Yubero-Gómez et al. 2016), a similar approach is adopted here and adapted to post-glacial sea-level change
⁶⁹ and the Stone Age settlement of southern Norway.

⁷⁰ 2 Background

- ⁷¹ Relative sea-level (RSL) can be defined as the mean elevation of the surface of the sea relative to land, or,
⁷² more formally, the difference in elevation between the geoid and the surface of the Earth as measured from the
⁷³ Earth's centre (Shennan 2015). Variation in this relative distance follow from a range of effects (e.g. Milne
⁷⁴ et al. 2009). Of central importance here is eustasy and isostasy. Eustatic sea-level is understood to be the
⁷⁵ sea-level if the water has been evenly distributed across the Earth's surface without adjusting for variation in
⁷⁶ the rigidity of the Earth, its rotation, or the self-gravitation inherent to the water body itself (Shennan 2015).
⁷⁷ The eustatic sea-level is mainly impacted by glaciation and de-glaciation, which can bind or release large
⁷⁸ amounts of water into the oceans (Mörner 1976). Isostasy, on the other hand, pertains to adjustments in the
⁷⁹ crust to regain gravitational equilibrium relative to the underlying viscous mantle caused by mass loading
⁸⁰ and unloading, which occurs with glaciation and deglaciation. These effects causes the lithosphere to either
⁸¹ subside due to increased weight, or to rebound and lift upwards due to lower weight (Milne 2015).
- ⁸² Following the end of the Weichselian and the final retreat of the Fennoscandian Ice Sheet (e.g. Hughes et
⁸³ al. 2016; Stroeven et al. 2016, see Figure 1), the isostatic rebound has caused most areas of Norway to
⁸⁴ have been subjected to a continuous relative sea-level regression, despite corresponding eustatic sea-level rise
⁸⁵ (e.g. Mörner 1979; Svendsen and Mangerud 1987). In other words, the RSL has been dropping throughout
⁸⁶ prehistory. As this process is the result of glacial loading, the rate of uplift is faster towards the centre of the

87 ice sheet relative to the distal aspects. Thus, there is differential glacio-isostatic impact to a site's location
 88 depending on it's relation to the ice sheet's centre of mass, leading some areas on the outer coast to have
 89 had a more stable RSL or been subject to marine transgression (e.g. Romundset et al. 2015; Svendsen and
 90 Mangerud 1987). These conditions are directly reflected in the archaeological record. In areas where the
 91 sea-level has been stable over longer periods of time, people have often reused coastal site locations multiple
 92 times and over long time spans, creating a mix of settlement phases that are difficult to disentangle (e.g.
 93 Hagen 1963; Reitan and Berg-Hansen 2009). Transgression phases, on the other hand, can lead to complete
 94 destruction of the sites, bury them in marine sediments, or in the outermost periphery, submerge them
 95 (Bjerck 2008a; Glørstad et al. 2020). Transgression can therefore lead to a hiatus in the archaeological record
 96 for certain sub-phases in the impacted areas despite the fact that there were likely coastal settlements during
 97 the inferred hiatuses. Comparatively, given a continuous and still ongoing shoreline regression from as high
 98 as c. 220m above present sea-level in the inner Oslo fjord, any one location in south-eastern Norway has
 99 only been shore-bound within a relatively limited time span, and the sites have not been impacted by any
 100 transgressions (Hafsten 1957, 1983; Romundset et al. 2018; Sørensen 1979). This makes the region especially
 101 useful for evaluating the assumption of a shore-bound settlement pattern over a long and continuous time
 102 span.

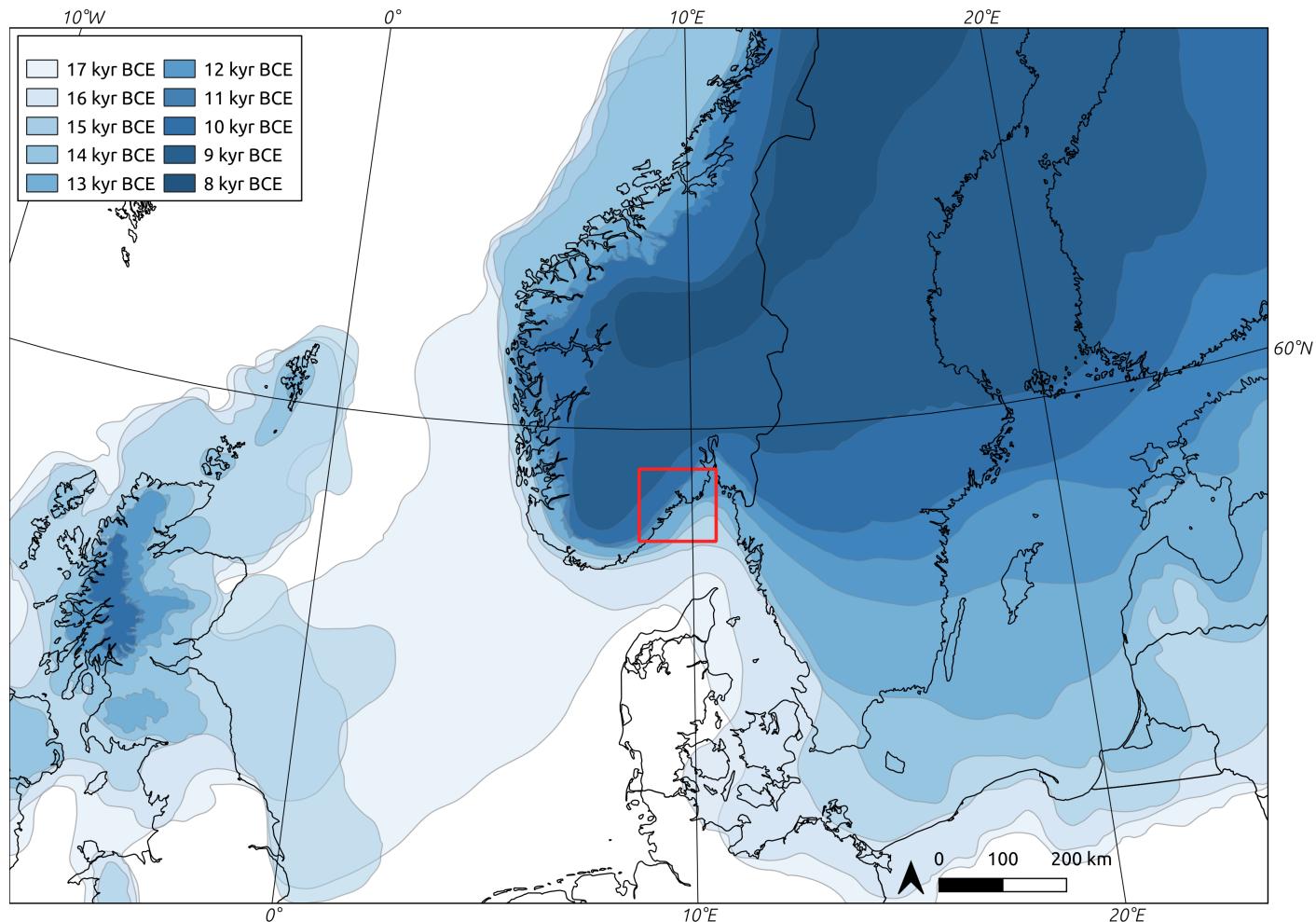


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 thousand years (kyr) BCE. The study area defined later in the text is marked with a red outline (deglaciation data from Hughes et al. 2016, but see also Romundset et al. 2019 in relation to the study area).

103 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; Jakslund 2001, 2012a, 2012b; Jakslund and Persson 2014; Melvold and Persson 2014; Reitan and Persson 2014; Reitan and Sundström 2018; Solheim 2017 and below). Recently the method has also been used independently to date a larger number 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; Bergsvik 2012 for similarly nuanced considerations of the coastal settlement of Neolithic western Norway; see e.g. **bergsvik2002?**). 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 shore-line 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. Jakslund 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

157 tendency are relatively few (see also Ilves and Darmark 2011).

158 One of the more extensive evaluations of the relationship between archaeological radiocarbon dates and
159 RSL-change was done by Solheim and colleagues (Breivik et al. 2018; Solheim 2020), who compared 102
160 radiocarbon dates from 29 Mesolithic sites on the western side of the Oslo fjord to the displacement curve
161 for the Larvik area. They found an overlap between the probability distribution of the radiocarbon dates
162 with the shoreline displacement curve for 86.3% of the dates (Solheim 2020:48). However, where there was
163 a discrepancy, the main occupation of the sites are still believed to have been shore-bound rather than
164 associated with the deviating ^{14}C -dates. This is based on typological and technological characteristics of the
165 assemblages. Whether these mismatches represent later shorter visits that are responsible for the younger
166 radiocarbon dates, or whether these dates are entirely erroneous can be difficult to evaluate (e.g. Persson
167 2008; Schülke 2020). However, this distinction is not deemed critical here, as what is of interest is settlements
168 and tool-production areas as evidenced by artefact inventories or multiple site features. Not remnants of
169 stays as ephemeral to only be discernible by isolated features or dubious ^{14}C -dates. The evaluation of the
170 relevance of radiocarbon dates to settlement activity will here therefore be entirely dependent upon, and
171 follow the discretion of the original excavation reports.

172 Other previous evaluations of the correspondence between radiocarbon- and RSL-informed dates have typically
173 followed the same structure as that of Breivik et al. (2018), involving a visual inspection of radiocarbon
174 probability density functions plotted against local shoreline displacement curves based on the elevation of the
175 site (e.g. Åkerlund et al. 1995; Åstveit 2018; Solheim 2020; see also Bjerck 2008b; Kleppe 1985; Ramstad
176 2009). This approach has a couple of limitations. First, the displacement curves are sometimes applied
177 directly to larger study areas, analogous to what Borreggine et al. (2022) term a bathtub model, with only
178 some studies having taken the variable uplift-rates into account when performing this comparison (e.g. Åstveit
179 2018; Fossum 2020; Møller 1987; Persson 2008). Secondly, with this method, the wider the uncertainty range
180 associated with either radiocarbon date or displacement curve, the higher the probability that the confidence
181 intervals overlap, and the higher the probability that the conclusion supports the hypothesis. This thus
182 leads to an inferential framework that favours uncertainty, which is hardly desirable. In statistical terms this
183 follows from the fact that while one cannot conclude that two dates are different if their confidence intervals
184 overlap, this does not necessarily mean that they are the same. The question thus necessitates a flip from a
185 null-hypothesis of no significant difference, to one of equivalence (e.g. Lakens et al. 2018), as the question
186 of interest is effectively one of synchronicity between events (cf. Parnell et al. 2008). Another limitation of
187 this often-employed method is that it only takes into account the vertical distance between the sites and the
188 sea-level. While this is the main parameter of interest for shoreline dating, the practical implications of a
189 vertical difference in RSL will be highly dependent on local topography and bathymetry. RSL-change can
190 have more dramatic consequences in a landscape characterised by a low relief, as the horizontal displacement
191 of the shoreline will be greater. Taking the spatial nature of the relationship between site and shoreline into
192 account will consequently help get more directly at the behavioural dimension of this relation and help move
193 the analysis beyond a purely instrumental consideration of the applicability of shoreline dating.

194 3 Data

195 To get at the relationship between sites and the contemporaneous shoreline, this analysis was dependent on
196 identifying a study area with good control of the trajectory of prehistoric shoreline displacement. While
197 there is displacement data available for other areas of south-eastern Norway (e.g. Hafsten 1957; Sørensen
198 1979, 1999), considerable methodological developments in recent years means that the most well-established
199 displacement curves are from the region stretching from Horten county in the north-east, to Arendal in the
200 south-west (Figure 2). This area has newly compiled displacement curves for Skoppum in Horten (Romundset
201 2021), Gunnarsrød in Porsgrunn (Sørensen et al. in press; Sørensen, Henningsmoen, et al. 2014; Sørensen,
202 Høeg, et al. 2014), Hanto in Tvedstrand (Romundset 2018; Romundset et al. 2018), and Bjørnebu in
203 Arendal (Romundset 2018).

204 The shoreline displacement data used in this study are based on the so-called isolation basin method (e.g.
205 Kjemerud 1986; Romundset et al. 2011), which involves extracting cores from a series of basins situated on

bedrock at different elevations beneath 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 (Figure 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, Henningsmoen, et al. 2014:44). The highest astronomical tide in the study area reaches around 30cm above mean sea-level (30cm at the standard port Helgeroa in Larvik, Norwegian Mapping Authority 2021). Furthermore, the confidence bands of the displacement curves and their trajectory are quite complex constructs as they are the integrated result of both expert knowledge and more objectively quantifiable parameters. The reason for this is that the curves do not only contain uncertainty as related to radiometric dates, which are well defined, but they 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 (Figure 2). These number 167 sites of which 91 sites are associated with a total of 547 radiocarbon dates. Of these, in turn, 67 sites are related to the 259 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 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 10m resolution DTM was used rather than the higher-resolution 1m 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 10m resolution DTM of the study area is a down-sampled version of the 1m version and has a height accuracy with a systematic error of 0.1m (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 an online repository at <https://osf.io/7f9su/>, organised as a research compendium following 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 Figure 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 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 10m 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 from the posterior density estimate of a given occupation phase of a site (Figure 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 5cm. 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 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 site polygon and the horizontally closest point on the shoreline. This means that the distance is not necessarily measured as the closest topographic distance to the shoreline, but rather as the shortest topographic path to the horizontally closest point on the shoreline. Not finding the topographically closest point 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;

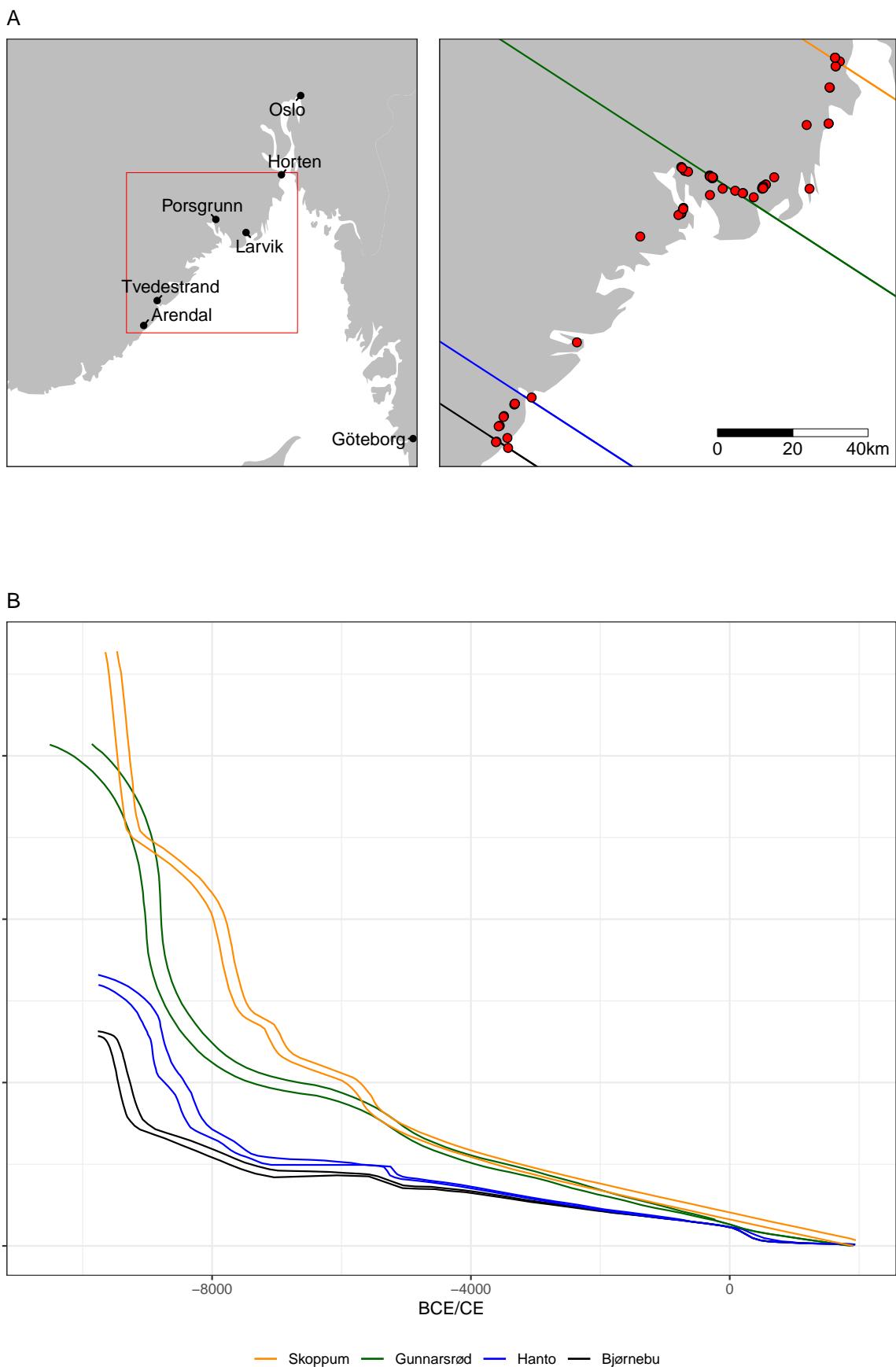


Figure 2: A) Location of the study area and the distribution of the 67 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al. 2018, although see Sørensen et al. 2014), B) Displacement curves. Note the increasing steepness of the curves towards the north-east.

307 Herzog 2013). In the case where the sea polygons intersect the site polygon, all distance measures were set to
308 zero. In the case that the sea polygons completely contain the site, the horizontal and topographic distance
309 measures were made negative, and the vertical distance was instead measured to the highest point on the site
310 polygon. While it is safe to assume that an archaeological site was not occupied when it was located beneath
311 sea-level, a negative result can reflect the inherent uncertainty in this procedure, and might also help identify
312 discrepancies in displacement data or radiocarbon dates. Negative values were therefore retained with the
313 exception of the sites of Gunnarsrød 5 and Pjonkerød R1, where the negative values are believed to result
314 from modern disturbances in the DTM rather than the ^{14}C -dates or displacement curves (see supplementary
315 material for more details).

316 This process was repeated 1000 times for each phase for each site. The choice of 1000 simulation runs follows
317 from an evaluation of when the mean distances between site and shoreline converged when running 5000
318 iterations of the simulation on the site Hovland 5, available in the supplementary material (cf. Crema et al.
319 2010:1125). Hovland 5 was chosen for this evaluation as it has an imprecise age and is located in area of
320 quite complex topography.

321 5 Simulation results

322 Overall, as is indicated by the measures for central tendency and the almost solid line along the 0m mark on
323 the y-axes, the simulations show that the sites tend to have been situated close to the shoreline when they
324 were in use (Figure 6). Some of the sites are situated considerable distances from the shoreline when the dates
325 believed to be erroneous in the original reports are included (Figure 6A), but if one accepts the interpretation
326 that these do not date the main occupation of the sites, as is indicated by the artefact inventories, Figure
327 6B gives considerable support to the notion that the sites were in use when they were situated on or close
328 to the contemporaneous shoreline. The distances for some of the earliest sites appears somewhat high, but
329 this can likely be explained as the result of the rapid RSL fall in the earliest part of the Holocene (Figure
330 2B), which leads the uncertainty of the ^{14}C -dates to give a wider possible elevation range for the simulated
331 sea-level. Another immediately striking result is the apparent deviation from the shoreline towards the
332 end of the Stone Age. After around 2500 BCE several sites are situated a considerable distance from the
333 reconstructed shoreline, and while a couple remain horizontally and topographically close, most appear to be
334 considerably elevated above the sea-level, as indicated on the plot for vertical distance. While the sample size
335 is limited, there are also a couple of sites located some distance from the shoreline just after 4000 BCE. The
336 chronological smearing following from the uncertainty in the ^{14}C -dates means that while the results cannot be
337 used to directly inform discussions that deal with the century scale around these chronological transitions (e.g.
338 Prescott 2020; Solheim 2021), the findings are nonetheless in clear agreement with the general chronological
339 framework in the literature.

340 The negative values around 8000 BCE originate from the sites Løvås 1, 2 and 3. These are recently excavated,
341 well-dated sites situated in a relatively undisturbed area of the landscape (Reitan and Hårstad 2022). While
342 there could be a danger of circularity of having archaeological sites inform a reconstruction RSL-change, and,
343 in turn, use these to evaluate the degree of shore-bound settlement, the sites do clearly represent an upper
344 constraining limit for the sea-level, as they would not have been in use when located under water. It therefore
345 seems that the Løvås sites represent a case where the archaeological material indicates a slight discrepancy in
346 the geologic reconstruction of shoreline displacement in the area.

347 Accepting that shoreline dating appears to lose utility around the transition to the Late Neolithic, as indicated
348 by the clear deviation in site location from the shoreline after this, the results from Figure 6B are presented
349 again in Figure 7A, excluding all simulation results younger than 2500 BCE. Furthermore, all negative values
350 have here been set to zero, under the assumption that these result from uncertainty or errors in the data,
351 and not actual site locations. The resulting best point estimate for the vertical distance between sites and
352 shoreline for the pre-Late Neolithic is given by the median distance of 4m, while 95% of the values fall within
353 the range 0–18m. That is, for 95% of the cases, the shoreline was simulated to be situated on or lower than
354 18m below the site location. While these values remain the same when only the Mesolithic dates are included
355 (Figure 7B), the mean and standard deviation are slightly constrained. Furthermore, while the median for

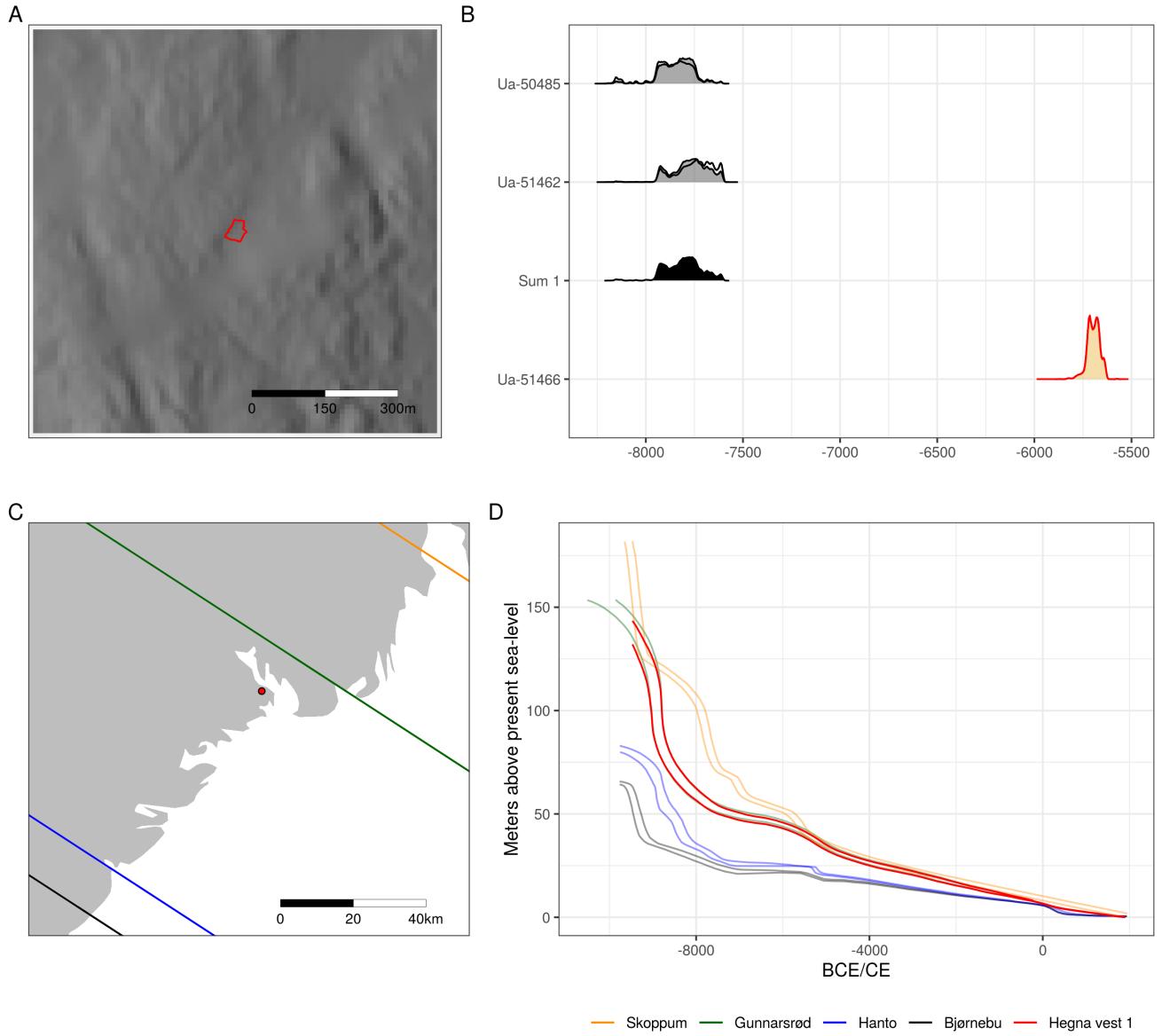


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site on the edited 10m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled 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.

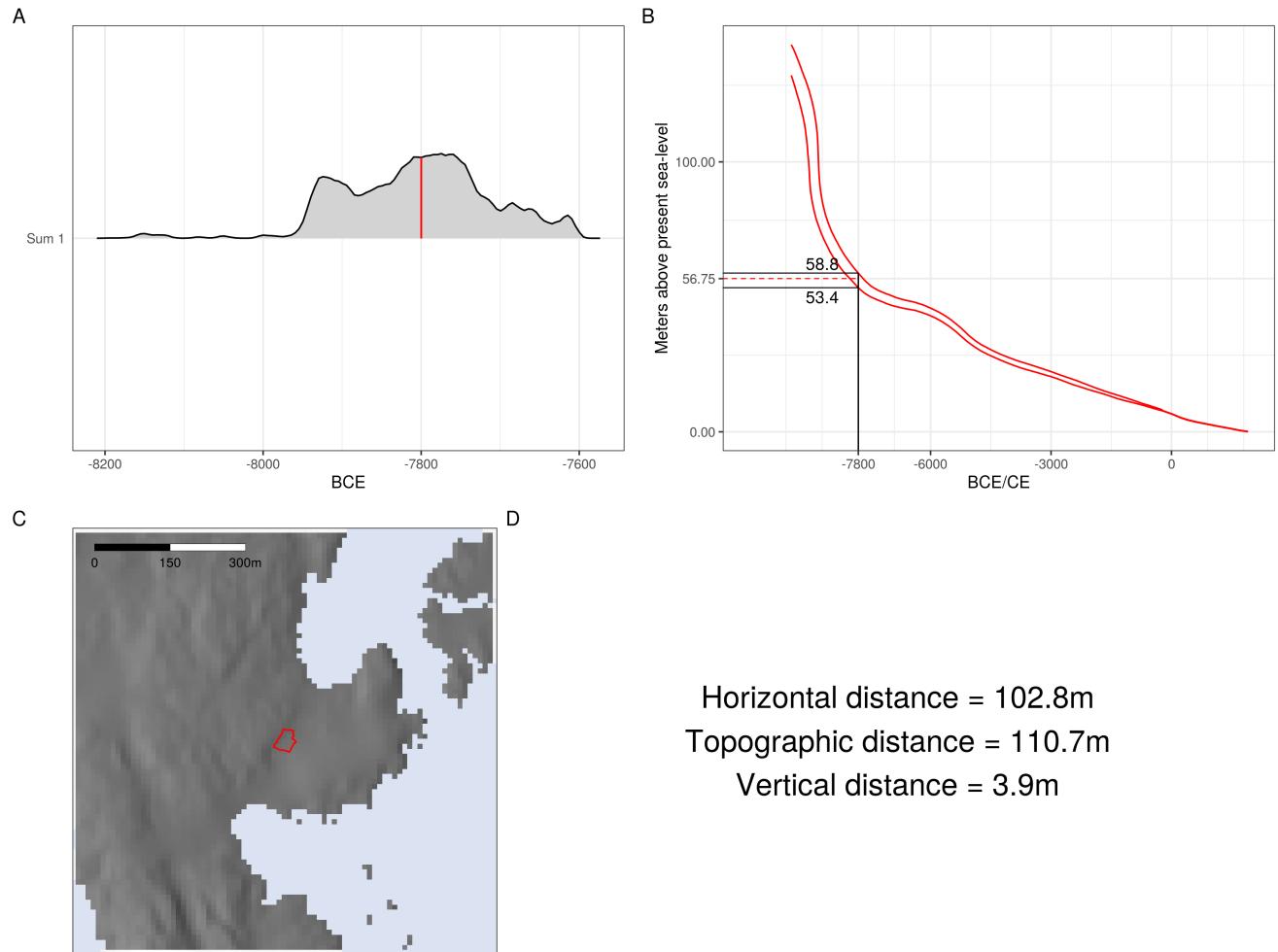


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year from the posterior density estimate. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using 5cm 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.

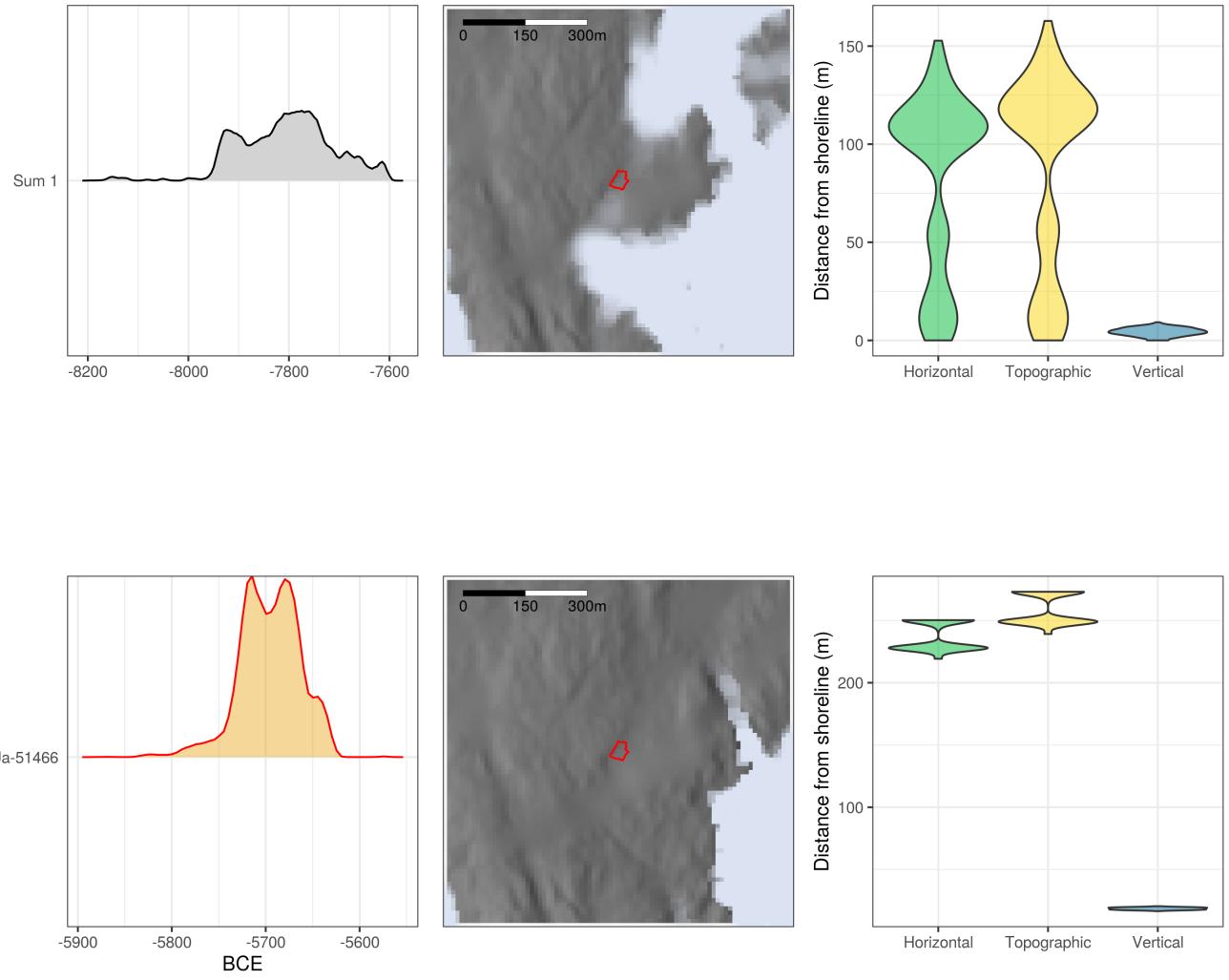
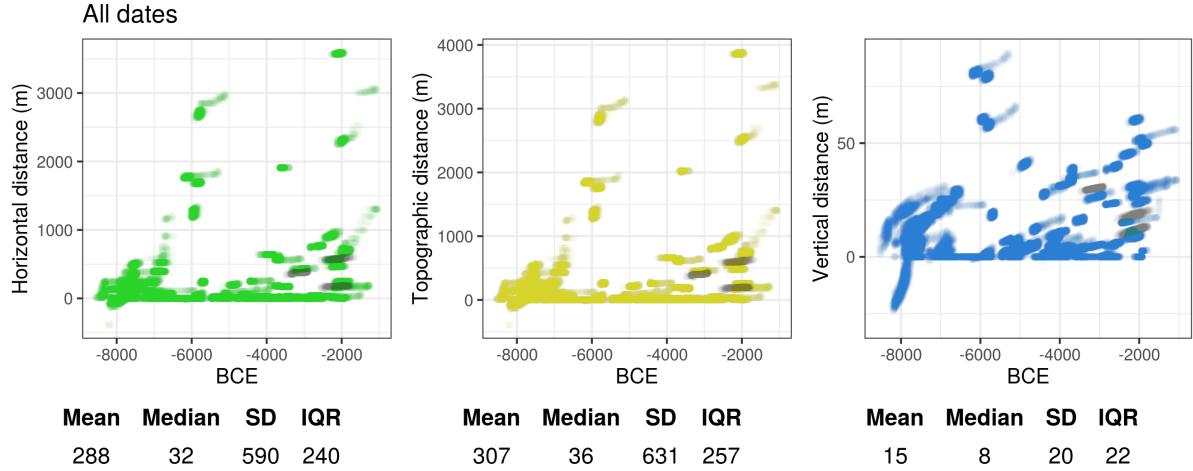


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The leftmost column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The centre column displays the result of simulating the raised 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.

356 horizontal and topographic distance is only 10m across all plots in Figure 7, the magnitude of the statistics
 357 for dispersion is greater than what it is for vertical distance, illustrating the point that minor variations in
 358 vertical distance can have substantial consequences for these distance measures, depending on the surrounding
 359 topography.

A



B

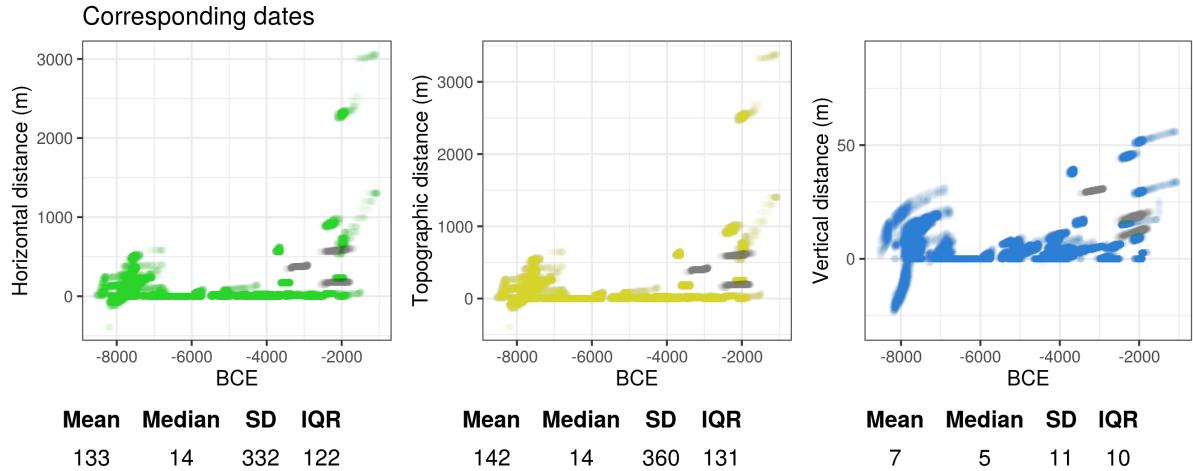


Figure 6: The result of running the analysis across all sites. Each data point is plotted with some transparency, meaning that the more intense the colour, the more often those values occurred. Results associated with agricultural activities are plotted in grey. The first row A) shows the result of including all dates to the Stone Age, including those seen as otherwise unrelated to the main occupation of the sites. The second row B) shows the result of excluding these. The table under each plot lists some corresponding statistics for central tendency and dispersion.

360 It is clear from the distributions that the simulation results have a severe right skew. Most sites were likely
 361 situated less than a meter from the shoreline, and from this there is a sharp decline in density as one moves
 362 further along the x-axis. To characterise this relationship, a series of standard models have been fit to the
 363 simulation results older than 2500 BCE by means of maximum likelihood estimation (Table 1, these are
 364 visualised in the supplementary material). The models have only been fit to positive values, with negative
 365 values first forced to zero before adding a constant of 0.001. The performances of the models were then
 366 compared by means of the Akaike information criterion (AIC) and the Bayesian (or Schwarz) information
 367 criterion (BIC). The AIC and BIC evaluate the degree to which the models fit to the data, while penalising

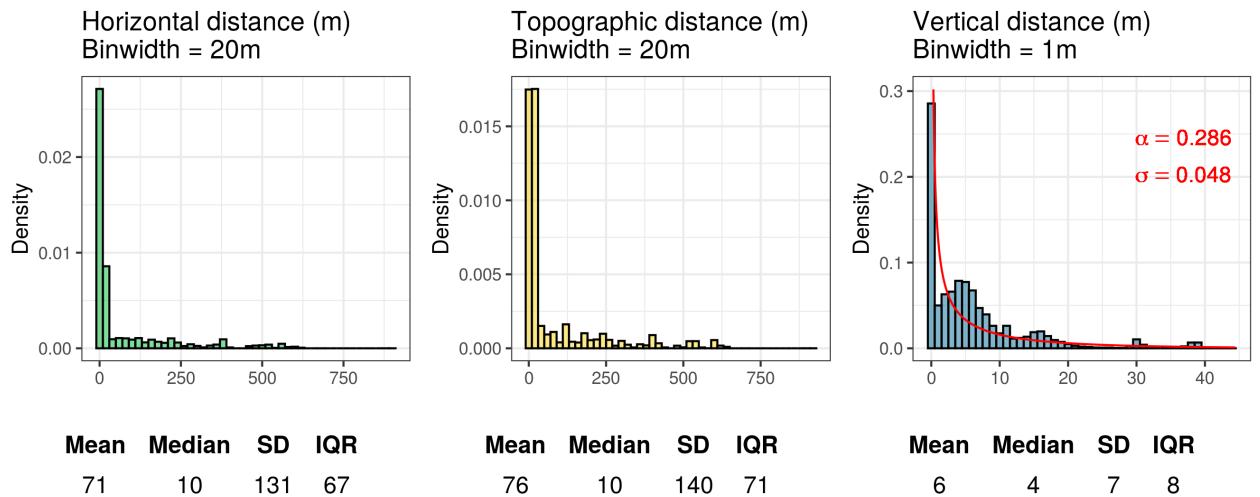
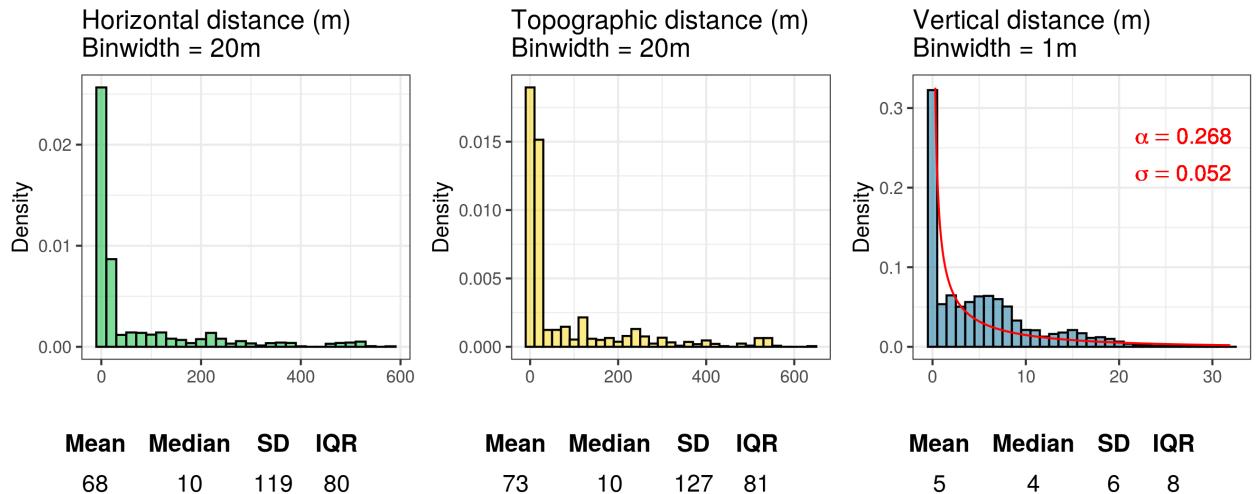
A**B**

Figure 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, and B) simulated results older than 4000 BCE. Note that the superimposed gamma distributions have been fit when adding a constant of 0.001 to the distance values (see supplementary material), and have been cut off on the y-axis for visualisation.

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; **timpson2021?**). As lower values point to a better model, it is evident from both the AIC and BIC results that the gamma is the best model among the candidates. This could also have benefited from a more sophisticated treatment of the zero-values, which is related to the fact that 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 (see 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.

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.

| Model | Parameters | AIC | BIC |
|-------------|--|--------|--------|
| Gamma | Shape (α) = 0.286 Scale (σ) = 0.048 | 230247 | 230229 |
| Log-normal | Mean of the logarithm (μ) = -0.647 SD of the logarithm (σ) = 3.926 | 268082 | 268064 |
| Power law | Exponent (k) = 1.16 | 274052 | 274043 |
| Exponential | Rate (λ) = 0.168 | 348484 | 348475 |
| Logistic | Location (μ) = 4.698 Scale (σ) = 3.558 | 415322 | 415304 |

This trend is reasonably approximated by a exponential function that has been fit to the distributions for vertical distance using maximum likelihood estimation (Figure 7).
this can at least in part be related to methodological factors, where the accumulation of distance-values on the 0m mark likely follow from the resolution of the spatial data, from defining intersecting sea- and site polygon as having a zero distance, from sampling error and, although they are relatively few, from forcing negative values to zero.

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 Figure 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:

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

where the parameters α is the shape and σ the rate for 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

397 calendar date T for the occupation of the site. This is defined by a discrete uniform probability mass function
398 (Ud) over the range between the lower T_l and upper T_u bounds of the displacement curve that has been
399 interpolated to the site location:

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

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

$$p(T|E - D) = p(T|E - D)p(E - D) \quad (3)$$

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

$$p(T|E) = \sum_D p(T|E - D)p(E - D) \quad (4)$$

404 An example of an implementation of the outlined approach is given in Figure 8, where $\alpha = 0.286$ and $\sigma =$
405 0.048. These are the parameters for the gamma distribution identified when considering all pre-Late Neolithic
406 simulation results (Figure 7A). For the numerical implementation, D is here stepped through as a sequence of
407 increments of 0.001m, which, following from the adjustment of the values for fitting the gamma distribution,
408 starts from 0.001m. The gamma distribution is stepped through in its cumulative form, where the probability
409 from the previous 0.001m step is subtracted from the probability at the current step. This probability is then
410 divided equally across the individual calendar years in the range between the lower and the upper limit of the
411 displacement curve at the current 0.001m step. The probability mass function that is the resulting shoreline
412 date is the sum of performing this procedure on all possible 0.001m values of D , which, in practice, is down
413 to and including $E - D = 0.001$ or when 99.999% of the gamma distribution has been stepped through.

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

430 7 Re-dating previously shoreline dated sites

431 To further explore the implementation for shoreline dating presented above, excavated and shoreline dated
432 Stone Age sites within the study area where ^{14}C -dates are not available or these are not believed to date the
433 main occupation of the sites have been subjected to the outlined approach (Figure 11). The resulting dates
434 are compared to those originally proposed in the excavation reports for the sites (the numerical results are
435 available in the supplementary material). To avoid issues with recent disturbances on the DTM, the sites

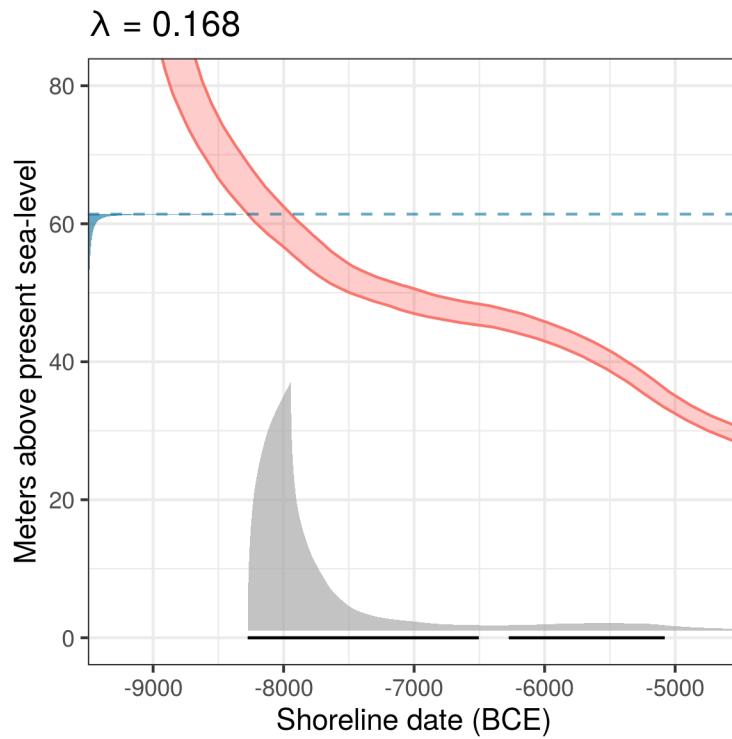


Figure 8: Shoreline dating of Hegna vest 1. The dashed line marks the mean elevation of the site polygon which is used to inform E in the dating of the site. The gamma function on the y-axis have the parameters $\alpha = 0.286$ and $\sigma = 0.286$ (see Figure 7A). The resulting shoreline date in grey is underlined with the 95% HDR in black.

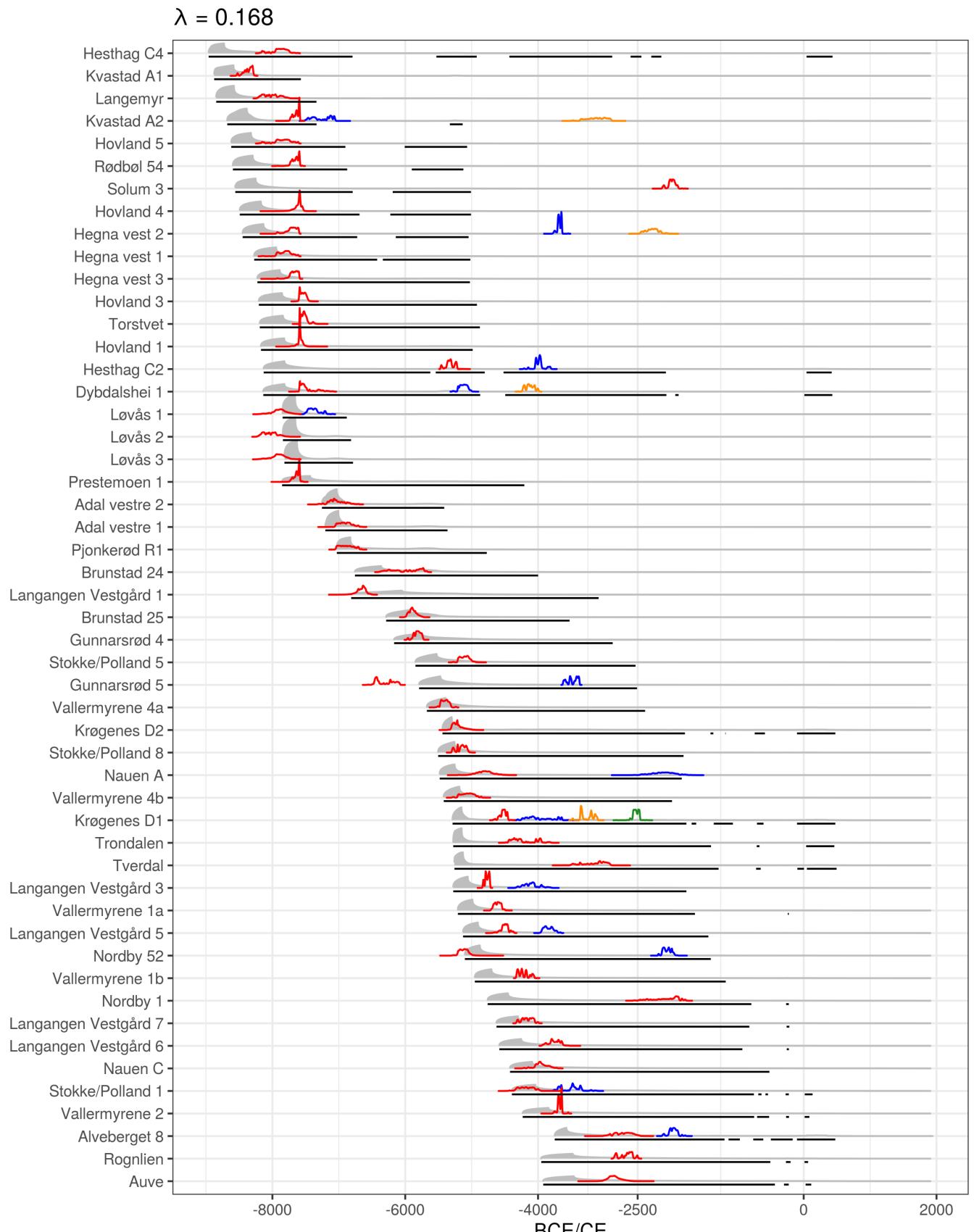


Figure 9: The result of backwards shoreline dating the sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined¹⁸ with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-intersecting dates at 99.7% probability.

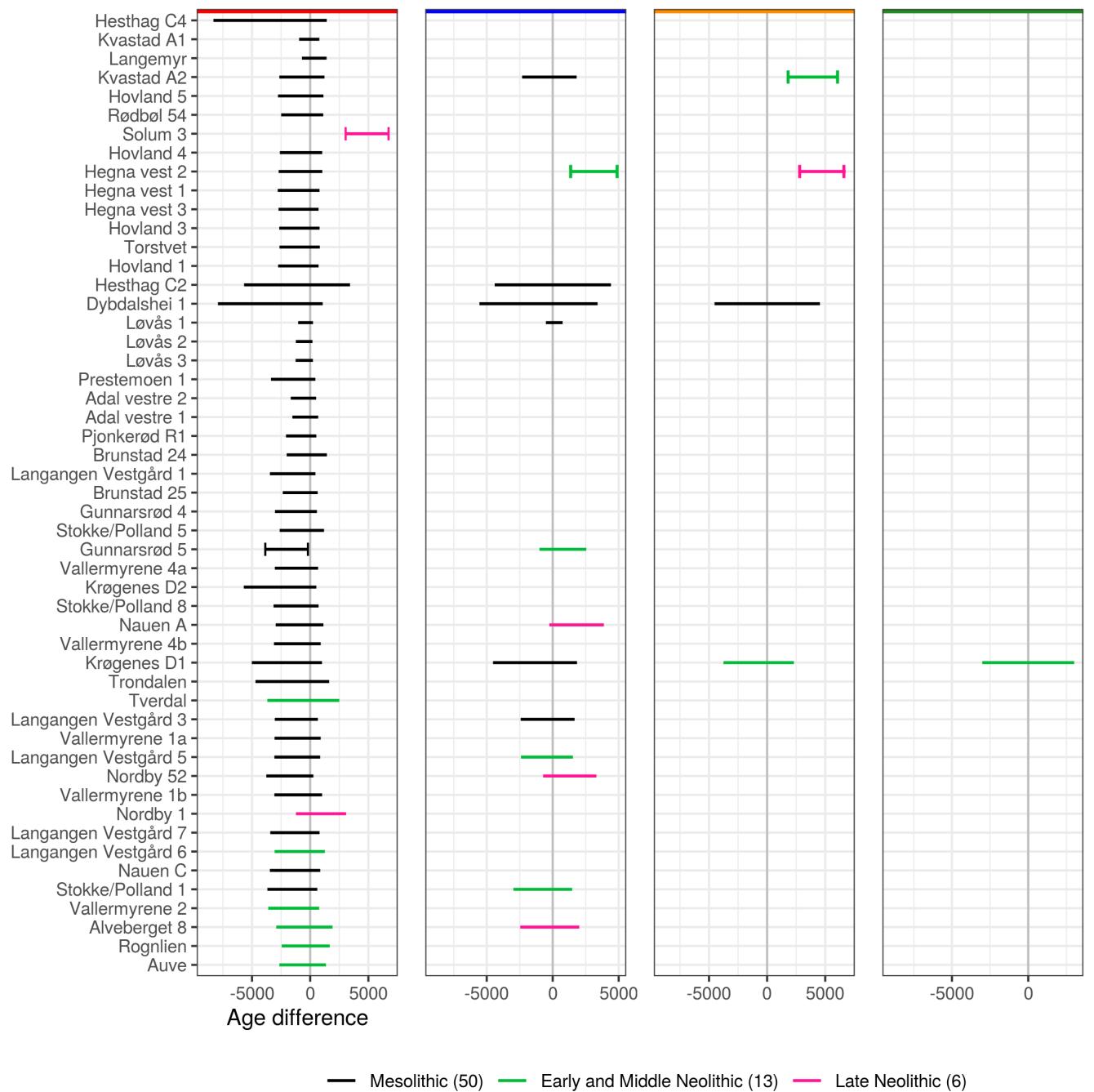


Figure 10: Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Figure 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does 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 Figure 9.

436 have been dated based on the mean of the altitudes provided in the report for each site. As all of the included
437 sites have been excavated after the turn of the millennium, and the wide adoption of GNSS technology, the
438 reported elevations should be trustworthy.

439 The comparison with previously reported dates is an illustrative, but unfair exercise for a few reasons. First,
440 the dates provided in the reports are typically stated to be a very rough estimate, and are sometimes given
441 as a point estimate with an undefined, but implied or explicit uncertainty range. Secondly, seeing as these
442 reports are from various dates in time, many are based on now outdated data on RSL-change. Thirdly,
443 they are sometimes only meant to indicate a lower bound for when the sites could have been in use. And
444 finally, they are often stated to be the combined result of considering shoreline displacement along with
445 characteristics of local topography, as well as artefact typology—although precisely how these are weighted
446 and used to inform the suggested date is not always clear. Overall, the results could, with some danger of
447 circularity, suggest that shoreline dating has generally been applied with a reasonable degree of success, seeing
448 as these dates have typically been interpreted and informed research in an approximate manner (although
449 see e.g. Roalkvam 2022). With these considerations in mind, the results also indicate that shoreline dating
450 has at times been applied with an exaggerated degree of precision. While the implications of a more stable
451 RSL-change for shoreline dating are well known, this also appears to be somewhat under-appreciated in
452 the practical implementation of the method. However, the results also highlight the spatial and temporal
453 contingency of the method, illustrated by the variation in the range of the 95% HDRs for the dates. In
454 some cases the implementation suggested here provides a very precise date range and in others it offers little
455 more than a *terminus post quem*. This is dependent on the steepness of the displacement curves, leading to
456 the general pattern of older sites situated towards the north-east getting more precise dates (cf. Figure 2B).
457 Furthermore, as some of the date ranges extend well beyond major chronological divisions, even into the
458 Iron Age, they could be severely and securely constrained with only cursory reference to typology. While
459 this would be trivial in some cases, the nature and uncertainty inherent to the method still means that this
460 is arguably a required exercise that should be explicitly performed. This also points to the possibility of
461 drawing on other temporal data, for example within a Bayesian framework (e.g. buck1996?), to further
462 improve the precision of the dates that can be achieved with shoreline dating.

463 Not least following from the fact that relatively few ^{14}C -dates older than c. 8000 BCE associated with
464 anthropogenic activity have been achieved in Norway (Åstveit 2018; Damlien and Solheim 2018; Kleppe
465 2018), the shoreline dating of the earliest sites is essential for understanding the pioneer settlement and the
466 initial colonisation of the Scandinavian peninsula (e.g. Bang-Andersen 2012; Berg-Hansen 2018; Breivik
467 2014; Fuglestvedt 2012; Glørstad 2016). The shoreline dated Preboreal sites from the Brunlanes-project are
468 among the earliest known sites in Norway (Jaksland 2012a, 2012b; Jaksland and Persson 2014). These have a
469 distinct Early Mesolithic artefact inventory and are situated in a steep area of the landscape where use of
470 the sites would have been difficult after the sea retreated any significant distance from their location due
471 to accessibility. In the original publication of the sites, Jaksland (2014) provides a thorough discussion of
472 shoreline dating in general, and as used for the dating of the Brunlanes sites specifically. A comparison of his
473 results and the ones achieved using the above-outlined approach are given in Figure 12A. The sites have been
474 dated using what Jaksland (2014) gives as the lowest elevation of finds at each site.

475 The small discrepancies between the achieved results mainly follow from the fact that a slightly updated
476 version of the local displacement curve is applied here (Sørensen et al. in press; cf. Sørensen, Henningsmoen,
477 et al. 2014). Jaksland's dates are given a flat 200- and 50-year uncertainty range starting from what he
478 gives as the earliest possible date. The 200 year uncertainty range is given if the sites were to be considered
479 in isolation, while his argument for the uncertainty range of only 50 years is based on the location of the
480 sites relative to each other. Since they are located in such a constrained and steep area of the landscape,
481 the difference in elevation between the sites is argued to establish their relative date and thus constrain the
482 uncertainty ranges so that they do not overlap. This information is not integrated in the approach outlined
483 here, but it could justify further reducing the uncertainty ranges.

484 Although their accuracy is of course ultimately dependent on the veracity of the geological reconstruction, the
485 high rate of RSL-change in this period does result in very precise dates. Above it was suggested that additional
486 temporal data could be combined with the method to improve its precision. Drawing on Jaksland (2014),
487 this example instead highlights the fact that the spatial nature of the method means that a consideration of

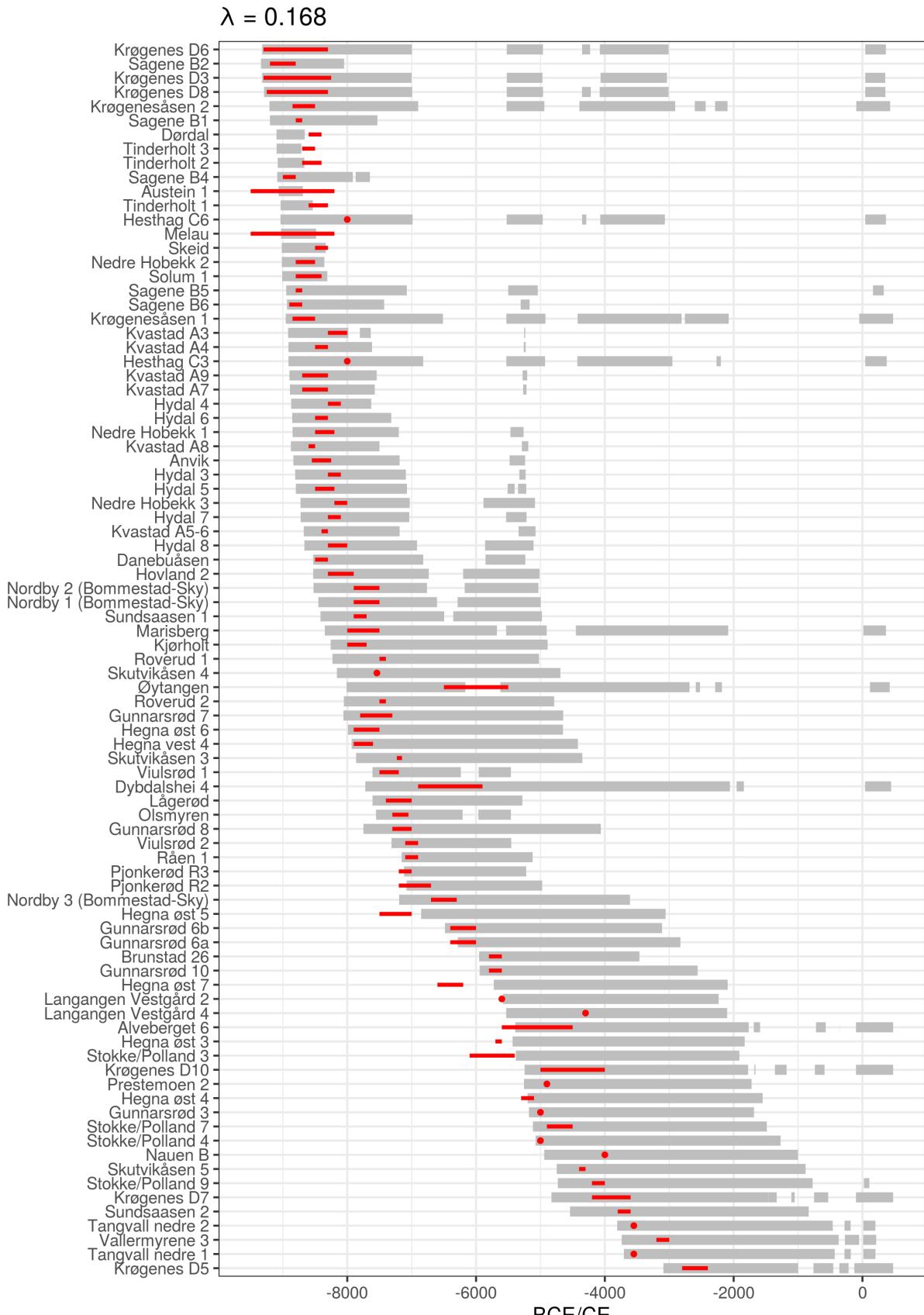


Figure 11: Re-dating excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey²¹ are compared to the dates originally proposed by the excavation reports in red. For clarity 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 that form a better foundation for any further analysis (see

488 the surrounding terrain and other sites can also help to increase the precision of the method if this can be
 489 used to exclude certain RSLs as unlikely for when a site was in use. One approach could also be to assess the
 490 spatial implication of a proposed shoreline date by simulating the adjusted sea-levels, as is done for Paurer 1
 491 in Figure 12B, followed for example by a visual evaluation of the topography or by evaluating the distance
 492 and steepness of the slope to the shoreline. If this method is developed further, it could conceivably be
 493 possible to exclude certain elevations as unlikely for the position of the shoreline when the site was in use.
 494 Such approaches would make less of an impact for the Brunlanes sites, where the 95% HDR is already quite
 495 constrained, but could considerably improve the precision of the method in cases where RSL-change has been
 496 less severe (cf. Figure 11).

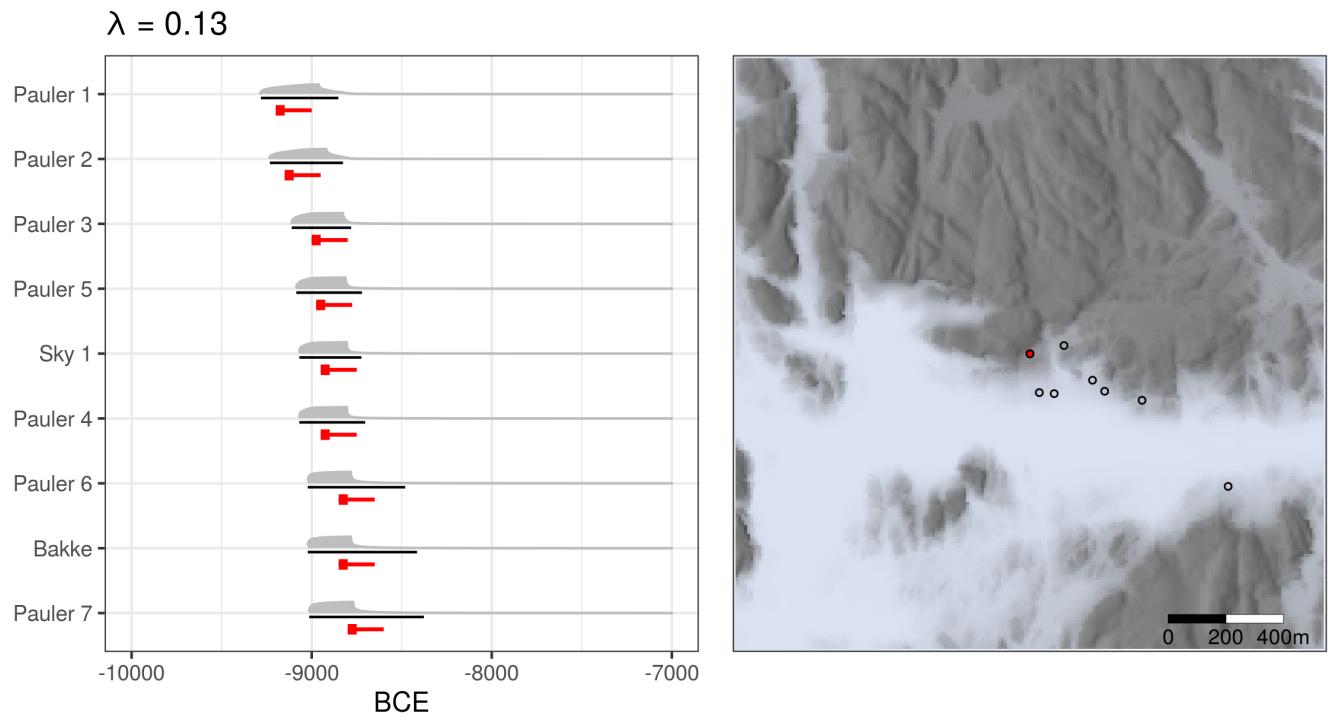


Figure 12: Shoreline dating of the Brunlanes sites using site altitudes provided by Jakobsson (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jakobsson (2014) are plotted in 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 Paurer sites and Sky 1. The sea-level has been simulated using the probability distribution associated with the shoreline date for Paurer 1 (see also map in Jakobsson 2014:fig.12a). Paurer 1 is the red point.

497 8 Concluding remarks

498 The most significant finding of this paper is a confirmation of previous research into the relation between
499 coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated by the close proximity
500 of sites and the shoreline until the transition to the Neolithic at c. 4000 BCE, after which a few sites are
501 situated some distance from the sea, followed by a more decisive break at the transition to the Late Neolithic
502 at c. 2500 BCE. This development is in clear agreement with the literature. Furthermore, based on the
503 quantitative nature of these findings, an initial formulation of a refined method for the shoreline dating of
504 pre-Late Neolithic Stone Age sites has been proposed. Apart from taking the distance between sites and the
505 isobases of the displacement curves into consideration when dating the sites, this involves accounting for the
506 distance between the sites and the shoreline. When no other information is available, it can at present be
507 recommended to use the empirically derived gamma distribution with a shape of 0.286 and scale of 0.048
508 (Figure 7A) to characterise this relationship. Furthermore, while this remains to be formalised and explored
509 further, it was also showed how the method can be improved by including more information, both with
510 reference to the topographic location of the sites and other temporal data. As the precision of the method
511 is both geographically and temporally contingent due to the trajectory of RSL-change, where older sites
512 situated towards the north-east in the study area will get a more precise date, the impact of such additional
513 information will also vary.

514 Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to further
515 evaluate and adjust the findings reported here, but a larger sample size could also lay the foundations for
516 refining the method by identifying subsets of sites for which the application of the method could be adjusted.
517 Given its behavioural nature, it would for example seem likely that dimensions such as the nature and purpose
518 of visits to the sites will have implications for how close to the shoreline they were located. Furthermore,
519 other dimensions related to the topographic location of the sites could be similarly explored. This for example
520 pertains to the exposure of sites to wave action, which is likely to have been of concern (Roalkvam 2020), and
521 which presumably has implications for how close to the shoreline people settled (Blankholm 2020; Helskog
522 1978). This is also related to the fact that while the mean sea-level is used for dating the sites, a consideration
523 of the tidal range could possibly also have implications for the site location relative to the shoreline, depending
524 on the topography (Helskog 1978). The potential of exploring dimensions such as these was also hinted at
525 here with the estimation and cursory treatment of the horizontal and topographic distance to the shoreline.
526 If patterns related to such locational patterns can be discerned and unpacked, this will not least be useful for
527 improving the shoreline dating of sites which have only been surveyed and where little information beyond
528 their location is available.

529 Some limitations and sources of likely variation and uncertainty that have not been considered should also be
530 mentioned. First, the sample size is limited and the future addition of more sites might alter the picture
531 considerably. Secondly, the validity of the outlined method was evaluated by applying it to the data from
532 where the input parameters were derived. Fitting and evaluating a model using the exact same data will likely
533 exaggerate its performance. Thirdly, the DTM has only been corrected for major modern disturbances. This
534 means that other forms of erosion, although likely not that prevalent, have not been considered. Fourthly, the
535 DTM has a vertical error which could also benefit from being integrated in the analysis (Fisher 1993; Lewis
536 2021). Fifthly, the displacement curves were here interpolated to all site locations without accounting for
537 increased uncertainty as one moves further away from the isobases of the displacement curves—an uncertainty
538 that is likely higher for RSL-change further back in time due to the shoreline gradient. This is also related
539 to the fact that the geologic reconstructions hold uncertainty that is not represented in the displacement
540 curves, relating for example to variation in the methods and quality of the data used for the compilation of
541 the curves, as well as the expert interpretations underlying these. Sixthly, neither the question of how site
542 limits are defined nor the elevation range over which these extend was given much consideration (Mjærum
543 2022). Finally, the aggregation and division of settlement phases at each site was here simply done by treating
544 radiocarbon dates not overlapping at 99.7% as representing unrelated occupation events. This could also be
545 handled differently (e.g. Bronk Ramsey 2009, 2015). While each of these factors will have variable impact on
546 the final results, they clearly represent dimensions which would all benefit from further consideration and
547 which means that some of the precision following from the outlined approach is likely to be spurious.

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

556 Finally, this analysis employed a simulation approach to integrate multiple sources of spatio-temporal
557 uncertainty. Here this was simply used to inform the question of the distance between sites and the shoreline.
558 However, this method and general framework can be extended to a wide range of use-cases where one needs
559 to visualise, and quantitatively or qualitatively evaluate the relationship between archaeological phenomena,
560 the prehistoric shoreline, and the uncertainty inherent to this reconstruction.

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