
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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8 **1 Introduction**

9 The post-glacial relative sea-level fall that characterises large areas of Fennoscandia is fundamental to
10 its archaeology. This follows not only from the dramatic changes to the landscape that this process has
11 represented throughout prehistory, but also from the fact that if archaeological phenomena were situated
12 close to the contemporary shoreline when they were in use, a reconstruction of the trajectory of shoreline
13 displacement can be used to date these phenomena based on their altitude relative to the present day sea-level.
14 This method, also called shoreline dating, has long history of use in the region and is frequently applied
15 to assign an approximate date to diverse archaeological phenomena such as rock art, grave cairns, various
16 harbour and sea-side constructions and, as is the focus of this study, Stone Age sites (e.g. Åkerlund 1996;
17 Bjerck 2005; Nordqvist 1995; Schmitt et al. 2009; Sognnes 2003; Tallavaara and Pesonen 2020; Wikell et al.
18 2009).

19 The close association between Stone Age settlements in the northern parts of Scandinavia and shifting
20 prehistoric shorelines was established by the end of the 19th century (De Geer 1896), and was first applied
21 as a dating method at the turn of the century (Brøgger 1905; Hollender 1901). Shoreline dating has been
22 fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen 2009; Bjerck 1990, 2008a;
23 Breivik 2014; Johansen 1963; Mikkelsen 1975; Mjærum 2022; Nummedal 1923; Shetelig 1922; Solheim and
24 Persson 2018). The method is used both independently, and to compliment other sources of temporal
25 data such as typological indicators or radiometric dates. However, given the coarse and fuzzy resolution
26 of established typological frameworks, the vast amount of surveyed sites that only contain generic lithic
27debitage that could hail from any part of the period, and as the conditions for the preservation of organic
28 material is typically poor in Norway, dating with reference to shoreline displacement is often the only and
29 most precise method by which one can hope to date the sites. Shoreline dating is consequently fundamental to
30 our understanding of the Norwegian Stone Age. This is both because it is central to the temporal framework
31 on which our understanding of the period is based, but also because the method is only applicable so long as
32 the societies in question have continuously settled on or close to the contemporary shoreline. Consequently,
33 adherence or deviation from this pattern also has major implications for the socio-economic foundations of
34 the societies in question.

35 Despite its important role for Norwegian Stone Age archaeology, the applicability of dating by reference to
36 shoreline displacement has only been evaluated using relatively coarse methods. The aim of this paper is to
37 provide a systematic and comprehensive review of the degree to which radiocarbon dates correspond with the
38 dates informed by our current knowledge of shoreline displacement in a larger area of south-eastern Norway,
39 using a more refined methodological approach. The goal is to quantify the degree to which the assumption

40 of shore-bound settlement holds through the Stone Age, and in turn have this inform an improved method
41 for shoreline dating. As presented in more detail below, this problem involves the combined evaluation of
42 three major analytical dimensions. One is the questions of when the sites were in use, the second pertains to
43 the reconstruction of the contemporaneous sea-level, and the third follows from the fact that the relation
44 between site and shoreline is inherently spatial. Taking inspiration from studies that have integrated various
45 sources of spatio-temporal uncertainty through Monte Carlo simulation (e.g. Bevan et al. 2013; Crema et al.
46 2010; Crema 2012, 2015; Yubero-Gómez et al. 2016), a similar approach is adopted here.

47 2 Background

48 Relative sea-level (RSL) can be defined as the mean elevation of the surface of the sea relative to land, or,
49 more formally, the difference in elevation between the geoid and the surface of the Earth as measured from the
50 Earth's centre (Shennan 2015). Variation in this relative distance follow from a range of effects (e.g. Milne et
51 al. 2009). Of central importance here is eustasy and istostasy. The eustatic sea-level is understood as the
52 sea-level if the water has been evenly distributed across the Earth's surface without adjusting for variation in
53 the rigidity of the Earth, its rotation, or the self-gravitation inherent to the water body itself (Shennan 2015).
54 The eustatic sea-level is mainly impacted by glaciation and de-glaciation, which can bind or release large
55 amounts of water into the oceans (Mörner 1976). Istostasy, on the other hand, pertains to adjustments in the
56 crust to regain gravitational equilibrium relative to the underlying viscous mantle. This can be the result of
57 glacial istostasy, which follows from glaciation and de-glaciation and corresponding loading and unloading of
58 weight, as well as from erosion of the crust, which causes its weight to be redistributed. These effects thus
59 causes the lithosphere to either subside due to increased weight, or to rebound and lift upwards due to lower
60 weight (Milne 2015).

61 Following the end of the Weichselian and the final retreat of the Fennoscandian Ice Sheet (e.g. Hughes et al.
62 2016; Stroeven et al. 2016, see Figure 1), the isostatic rebound has been so severe that most areas of Norway
63 have been subject to a continuous relative sea-level regression, despite corresponding eustatic sea-level rise
64 (e.g. Mörner 1979; Svendsen and Mangerud 1987). In other words, the RSL has been dropping throughout
65 prehistory. As this process is the result of glacial loading, the rate of uplift is more severe towards the centre
66 of the ice sheet. Thus, some areas on the outer coast have had a more stable RSL or been subject to marine
67 transgression (e.g. Romundset et al. 2015; Svendsen and Mangerud 1987). These conditions are directly
68 reflected in the archaeological record. In areas where the sea-level has been stable over longer periods of
69 time, people have often reused coastal site locations multiple times and over long time-spans, creating a
70 mix of settlement phases that are difficult to disentangle (e.g. Hagen 1963; Reitan and Berg-Hansen 2009).
71 Transgression phases, on the other hand, can lead to complete destruction of the sites, bury them in marine
72 sediments, or in the outermost periphery, leave them still submerged today (Bjerck 2008a; Glørstad et al.
73 2020). This can lead to a hiatus in the archaeological record for certain sub-phases in the impacted areas.
74 Comparatively, given a continuous and still ongoing shoreline regression from as high as c. 220 m above
75 present sea-level in the inner Oslo fjord, any one location in south-eastern Norway has only been shore-bound
76 within a relatively limited time-span, and the sites have not been impacted by any transgressions (Hafsten
77 1957, 1983; Romundset et al. 2018; Sørensen 1979). This makes the region especially useful for evaluating
78 the assumption of a shore-bound settlement pattern over a long and continuous time-span.

79 The method of shoreline dating has been met with scepticism as related to the fundamental premise that
80 most sites would have been consistently shore-bound, been characterised as a relative dating method for sites
81 located at different elevations within a constrained geographical area, or been argued to offer no more than
82 an earliest possible date for when a site could have been in use (see review by Nordqvist 1999). The most
83 common application in Norway has arguably been to use shoreline dating to provide an approximate date for
84 the occupation of the sites, often in combination with other dating methods (see for example chapters in
85 Glørstad 2002, 2003, 2004; Jakslund 2001, 2012a, 2012b; Jakslund and Persson 2014; Melvold and Persson
86 2014; Reitan and Persson 2014; Reitan and Sundström 2018; Solheim 2017 and below). Recently the method
87 has also been used independently to date a larger number sites to get a general impression of site frequency
88 over time. This is done by aggregating point estimates of shoreline dates in 100, 200 or 500 year bins (Breivik

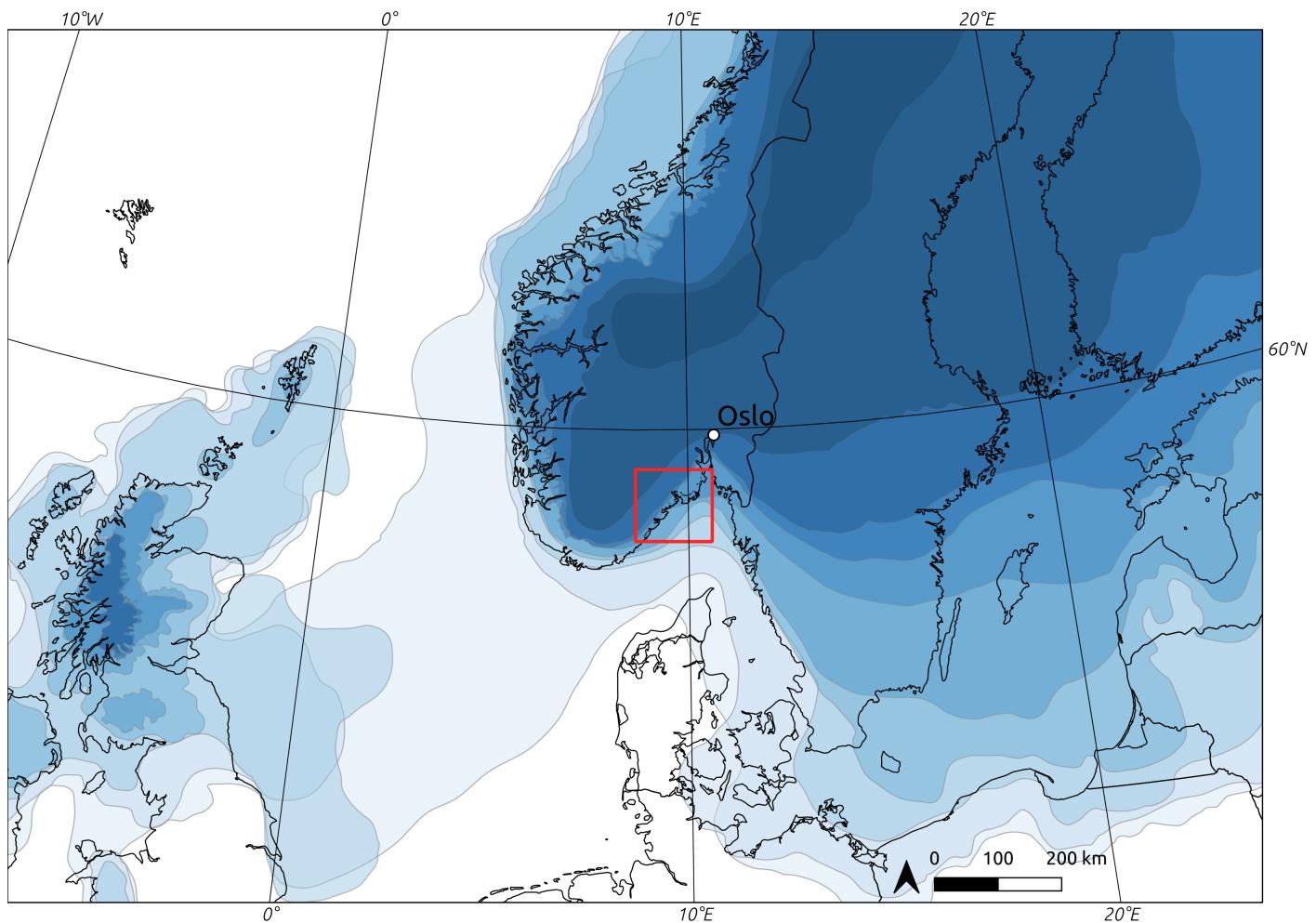


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 kyr BCE. The study area defined later in the text is marked with a red outline (deglaciation data from Hughes et al. 2016, but see also Romundset et al. 2019 in relation to the study area).

⁸⁹ 2014; Breivik and Bjerck 2018; Fossum 2020; Mjærum 2022; Nielsen 2021; Solheim and Persson 2018; see also
⁹⁰ Jørgensen et al. 2020; Tallavaara and Pesonen 2020). In his review, Nordqvist (1999) argues that there can
⁹¹ be little doubt concerning the general applicability of the method – what is less clear is the level of reliability
⁹² and chronological resolution that it can offer (see also Johansen 1963).

⁹³ The shore-bound settlement location of prehistoric hunter-fisher-gatherers in Norway is generally believed
⁹⁴ to follow both from the exploitation of aquatic resources and from movement and communication, which
⁹⁵ would have been efficient on waterways (Bjerck 1990; Brøgger 1905:166; **bjerck2017?**; also discussed by
⁹⁶ Berg-Hansen 2009; Bergsvik 2009). The same logic has also been extended to the hinter- and inland regions,
⁹⁷ where sites are to be predominantly located along rivers and lakes (Brøgger 1905:166; Glørstad 2010:57–87;
⁹⁸ but see also Gundersen 2013; Mjærum 2018; Schülke 2020). This is to take a dramatic turn at the transition
⁹⁹ to the Late Neolithic, around 2400 BCE, with the introduction of the Neolithic proper (Prescott 2020;
¹⁰⁰ cf. Solheim 2021). The introduction of a comprehensive Neolithic cultural package, including a shift to
¹⁰¹ agro-pastoralism and the introduction of the farm is to have led site locations to be more withdrawn from the
¹⁰² shoreline (e.g. Bakka and Kaland 1971; Østmo 2008:223; Prescott 2020). That is not to say that waterways
¹⁰³ and aquatic resources were no longer exploited, but rather that these activities would not have been as
¹⁰⁴ tightly integrated with settlement and tool-production areas as in preceding periods (Glørstad 2012). At
¹⁰⁵ an earlier stage, at the transition to the Early Neolithic (c. 3900 BCE), pottery is introduced to the sites,
¹⁰⁶ and there are some indications of an initial uptake of agriculture at some sites in the Oslo fjord region.
¹⁰⁷ However, this appears to be small in scale and is believed to be combined with a continued and predominantly
¹⁰⁸ hunter-gatherer life-way, possibly followed by a complete de-Neolithisation in the Middle Neolithic (Hinsch
¹⁰⁹ 1955; Nielsen et al. 2019; Østmo 1988:225–227). Nielsen (2021) has recently argued that the initial uptake of
¹¹⁰ agriculture in Early Neolithic south-eastern Norway is combined with a more complex settlement pattern,
¹¹¹ and that a simple foraging/agricultural dichotomy would underplay the variation present in the Early and
¹¹² Middle Neolithic settlement data (see also e.g. Amundsen et al. 2006; Østmo 1988; Solheim 2012:74). Seen
¹¹³ in relation to the question of interest here, the empirical expectation for the above outlined development
¹¹⁴ would thus be a predominantly shore-bound settlement in the Mesolithic, possibly followed by a more varied
¹¹⁵ association between sites and the shore-line with the transition to the Early Neolithic around 3900 BCE, and
¹¹⁶ finally a decisive shift with the Late Neolithic c. 2400 BCE.

¹¹⁷ Based on the generally accepted premise that most pre-Late Neolithic sites in south-eastern Norway located
¹¹⁸ lower than the marine limit were situated on or close to the contemporaneous shoreline, it is common to err
¹¹⁹ on the side of a shore-bound site location unless there is strong evidence to suggest otherwise. This is for
¹²⁰ example reflected in survey projects, which are often guided by both a digital and mental reconstruction
¹²¹ of past sea-levels (e.g. Berg-Hansen 2009; Eskeland 2017). Similarly, following an excavation, if typological
¹²² indicators in the assemblages correspond with available shoreline displacement curves, a shore-bound site
¹²³ location is often assumed, even if the typologically informed date-span is too wide to decisively verify this.
¹²⁴ It is also common to combine this with a qualitative consideration of the landscape surrounding the sites,
¹²⁵ and an evaluation of the degree to which the site location would have been sensible if the site was not shore
¹²⁶ bound (e.g. Jakslund 2014; Johansen 1963; Nummedal 1923). This can for example pertain to accessibility. If
¹²⁷ the site is situated on a ledge in a steep and jagged area of the present day landscape it would make intuitive
¹²⁸ sense that the site was in use when the ocean reached closer to its elevation, as the site would have been
¹²⁹ accessible by means of watercraft. Although it appears that the arguments for such site locations are sensible
¹³⁰ and can for the most part be assumed to hold, comprehensive evaluations and attempts at quantification of
¹³¹ this tendency are relatively few (see also Ilves and Darmark 2011).

¹³² One of the more extensive evaluations of the relationship between archaeological radiocarbon dates and
¹³³ RSL-change was done by Solheim and colleagues (Breivik et al. 2018; Solheim 2020), who compared 102
¹³⁴ radiocarbon dates from 33 Mesolithic sites on the western side of the Oslo fjord to the displacement curve
¹³⁵ for the Larvik area. They found an overlap between the probability density of the radiocarbon dates with
¹³⁶ the shoreline displacement curve for 86.5% of the sites. However, where there was a discrepancy, the main
¹³⁷ occupation of the sites are still believed to have been shore-bound rather than associated with the deviating
¹³⁸ ¹⁴C-dates. This is based on typological and technological characteristics of the assemblages. Whether these
¹³⁹ mismatches represent later shorter visits that are responsible for the younger radiocarbon dates, or whether
¹⁴⁰ these dates are entirely erroneous can be difficult to evaluate (e.g. Persson 2008; Schülke 2020). However,

141 this distinction is not deemed critical here, as what is of interest is settlements and tool-production areas as
142 evidenced by artefact inventories or multiple site features. Not remnants of stays as ephemeral to only be
143 discernible by isolated features or dubious ^{14}C -dates. The evaluation of the relevance of radiocarbon dates
144 to settlement activity will here therefore be entirely dependent on, and follow the discretion of the original
145 excavation reports.

146 Other previous evaluations of the correspondence between radiocarbon- and RSL-informed dates have typically
147 followed the same structure as that of Breivik et al. (2018), involving a visual inspection of radiocarbon
148 probability density functions plotted against local shoreline displacement curves based on the elevation of the
149 site (e.g. Åkerlund et al. 1995; Åstveit 2018; Solheim 2020; see also Bjerck 2008b; Kleppe 1985; Ramstad
150 2009). This approach has a couple of limitations. First of all, the displacement curves are sometimes applied
151 directly to larger study areas, with only some studies having taken the variable uplift-rates into account when
152 performing this comparison (e.g. Åstveit 2018; Fossum 2020; Møller 1987; Persson 2008). Secondly, with this
153 method, the wider the uncertainty range associated with either radiocarbon date or displacement curve, the
154 higher the probability that the confidence intervals overlap, and the higher the probability that we conclude
155 in favour of our hypothesis. This thus leads to an inferential framework that favours uncertainty, which is
156 hardly desirable. In statistical terms this follows from the fact that while one cannot conclude that two dates
157 are different if their confidence intervals overlap, this does not necessarily mean that they are the same. The
158 question thus necessitates a flip from a null-hypothesis of no significant difference, to one of equivalence (e.g.
159 Lakens et al. 2018), as the question of interest is effectively one of synchronicity between events (cf. Parnell
160 et al. 2008). Another limitation of this often-employed method is that it only takes into account the vertical
161 distance between the sites and the sea-level. While this is the main parameter of interest for shoreline dating,
162 the practical implications of a vertical difference in RSL will be highly dependent on local topography and
163 bathymetry. RSL-change can have more dramatic consequences in a landscape characterised by a low relief,
164 as the horizontal displacement of the shoreline will be greater. Taking the spatial nature of the relationship
165 between site and shoreline into account will consequently help get more directly at the behavioural dimension
166 of this relation, and help move the analysis beyond a purely instrumental consideration of the applicability of
167 shoreline dating.

168 3 Data

169 To get at the relationship between sites and the contemporaneous shoreline, this analysis was dependent
170 on a study area with good control of the trajectory of prehistoric shoreline displacement. While there is
171 displacement data available for other areas of south-eastern Norway (e.g. Hafsten 1957; Sørensen 1979, 1999;
172 and recent compilation by Creel et al. 2022), considerable methodological developments in recent years means
173 that the most well-established displacement curves are from the region stretching from Horten county in
174 the north-east, to Arendal in the south-west. This area has newly compiled displacement curves for Horten
175 (**romundset2021?**), Larvik (Sørensen et al. in prep; Sørensen, Henningsmoen, et al. 2014; Sørensen, Høeg,
176 et al. 2014), Tvedstrand (Romundset 2018; Romundset et al. 2018), and Arendal (Romundset 2018).

177 The employed shoreline displacement data is based on the so-called isolation basin method (e.g. Kjemperud
178 1986; Romundset et al. 2011), which involves extracting cores from a series of basins situated on bedrock at
179 different elevations beneath the marine limit, and dating the transition from marine to lacustrine sediments.
180 Each basin thus represent a high precision sea-level index point (SLIP) which are combined using what has
181 been termed the isobase method to devise a continuous time series for RSL-change, projected to a common
182 isobase (see Creel et al. 2022:5). Furthermore, to minimise the impact of variable uplift rates, the basins
183 are located in a as constrained area of the landscape as possible. Following from the morphology of the
184 retreating ice sheet, the uplift is more severe towards the north-east, meaning that this needs to be adjusted
185 for in the case that any basins are located any significant distance from the common isobase perpendicular to
186 this gradient (Figure 2). The SLIPs indicate the isolation of the basins from the highest astronomical tide,
187 which is adjusted to mean sea-level in the compilation of the displacement curves, based on the present day
188 tidal range. This is assumed to have been the same throughout the Holocene (Sørensen, Henningsmoen, et
189 al. 2014:44). The highest astronomical tide in the study area reaches around 30cm above mean sea-level

[Norwegian Mapping Authority (2021); 30cm at the standard port Helgeroa in Larvik]. Furthermore, the confidence bands of the displacement curves and their trajectory are quite complex constructs, and are the integrated result of both expert knowledge and more objectively quantifiable parameters. The reason for this is in part that the curves do not only contain uncertainty as related to radiometric dates, which are well defined, but also hold potential error as related to the interpretation and analysis of sediment cores, the nature and condition of the basin outlets and the adjustment to a common isobase, to name but a few (e.g. Romundset et al. 2011, 2019; 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 155 sites. Of these, 91 sites are associated with a total of 547 radiocarbon dates. Of these, in turn, 67 sites are related to the 259 radiocarbon dates that fall within 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—the institution responsible for archaeological excavations 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>). It was here opted for the 10m resolution DTM rather than the higher-resolution 1m version. In addition to resulting in considerably less processing time, the higher resolution elevation model is more vulnerable to smaller-scale modern disturbances that the 10m version is not impacted by. 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 digital research compendium following Marwick et al. (2018).

4 Methods

The method of shoreline dating is based on the spatial relationship between two phenomena, occupation of sites and shoreline displacement, each associated with their own range of temporal uncertainty. The first task was therefore to ascribe likely date ranges and associated 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 standard squared inverse of the distances. The result of this process

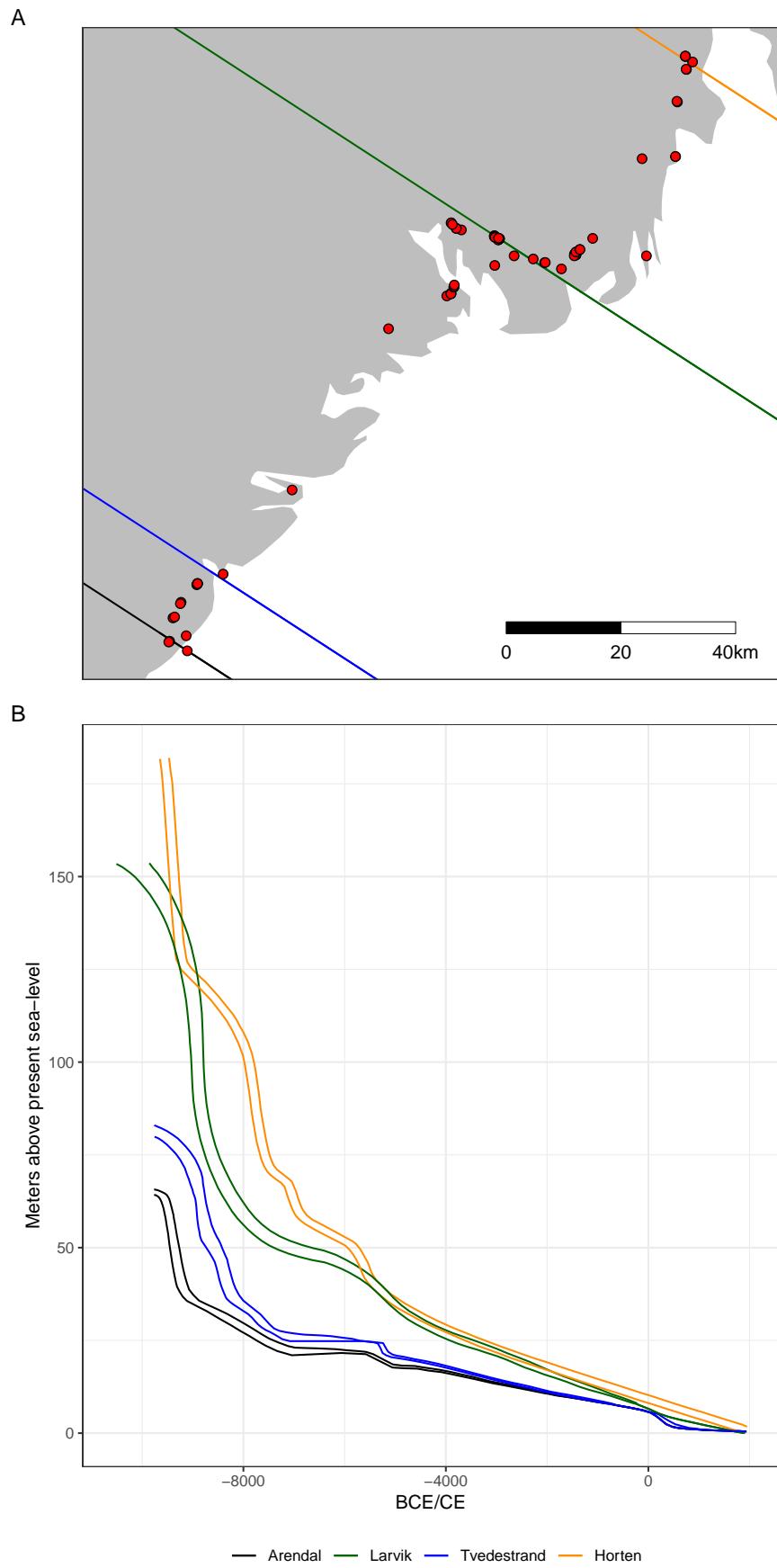


Figure 2: A) Distribution of the 67 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al. 2018), B) Displacement curves. Note the increasing⁷ steepness of the curves towards the north-east.

is shown for an example site in Figure 3. For the date ranges associated with 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 they overlapped with 99.7% probability, meaning these were effectively taken to represent the same event, here termed settlement or site phases. 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. Multiple phases at a single site were treated as independent of each other.

The excavation of archaeological sites typically follow from residential and commercial development, as well as the expansion of infrastructure. As the data collection for the employed 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 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 digital research compendium for this paper, the 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 relative sea-level 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; Herzog 2013). In the case where the sea-polygons intersects 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 beneath 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 with the exception 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. 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, available in the supplementary material (cf. Crema et al. 2010:1125). Hovland 5 was chosen for this evaluation as it has a fairly imprecise date and is located in area of quite complex topography.

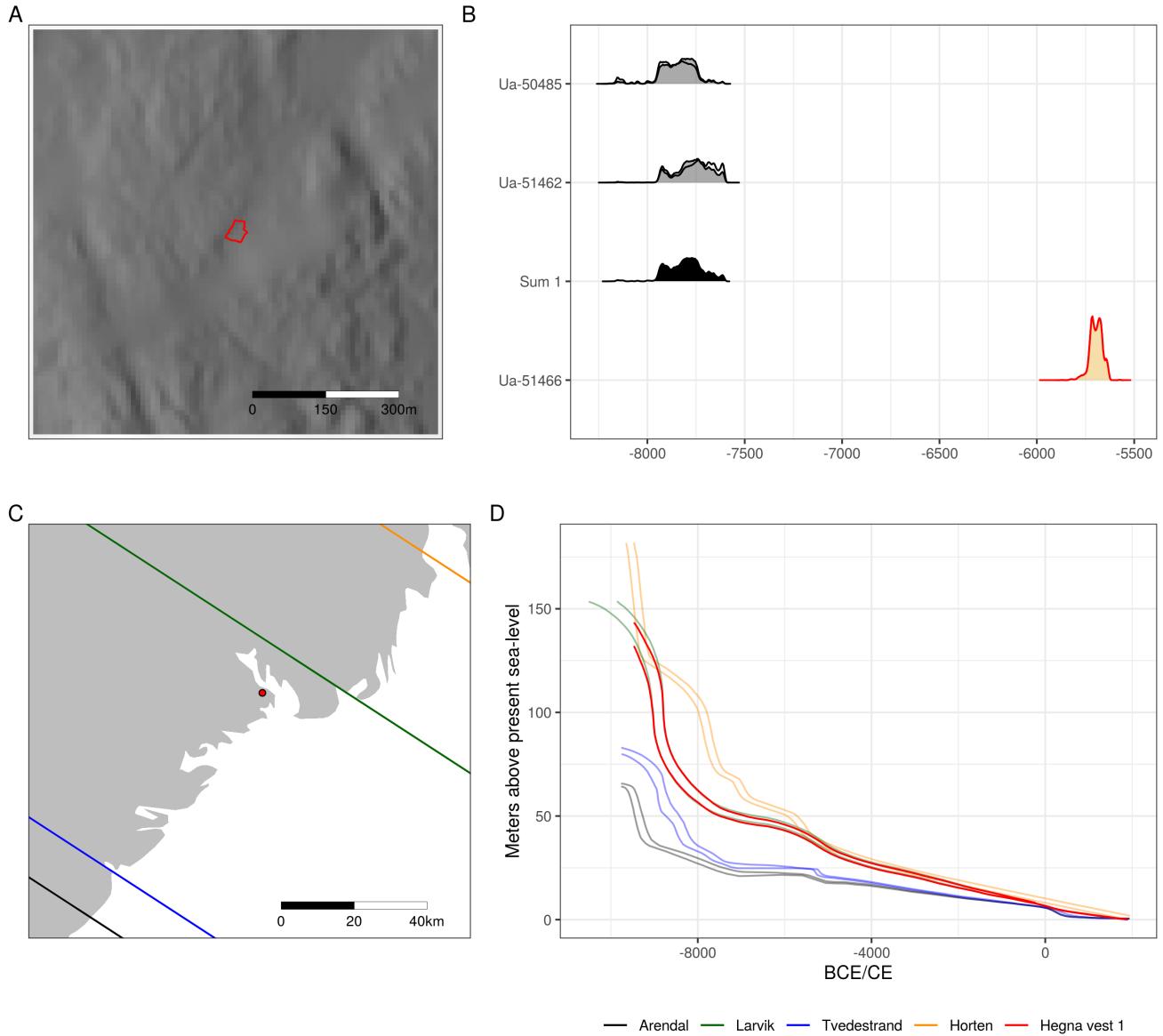


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site on the edited 10m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled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

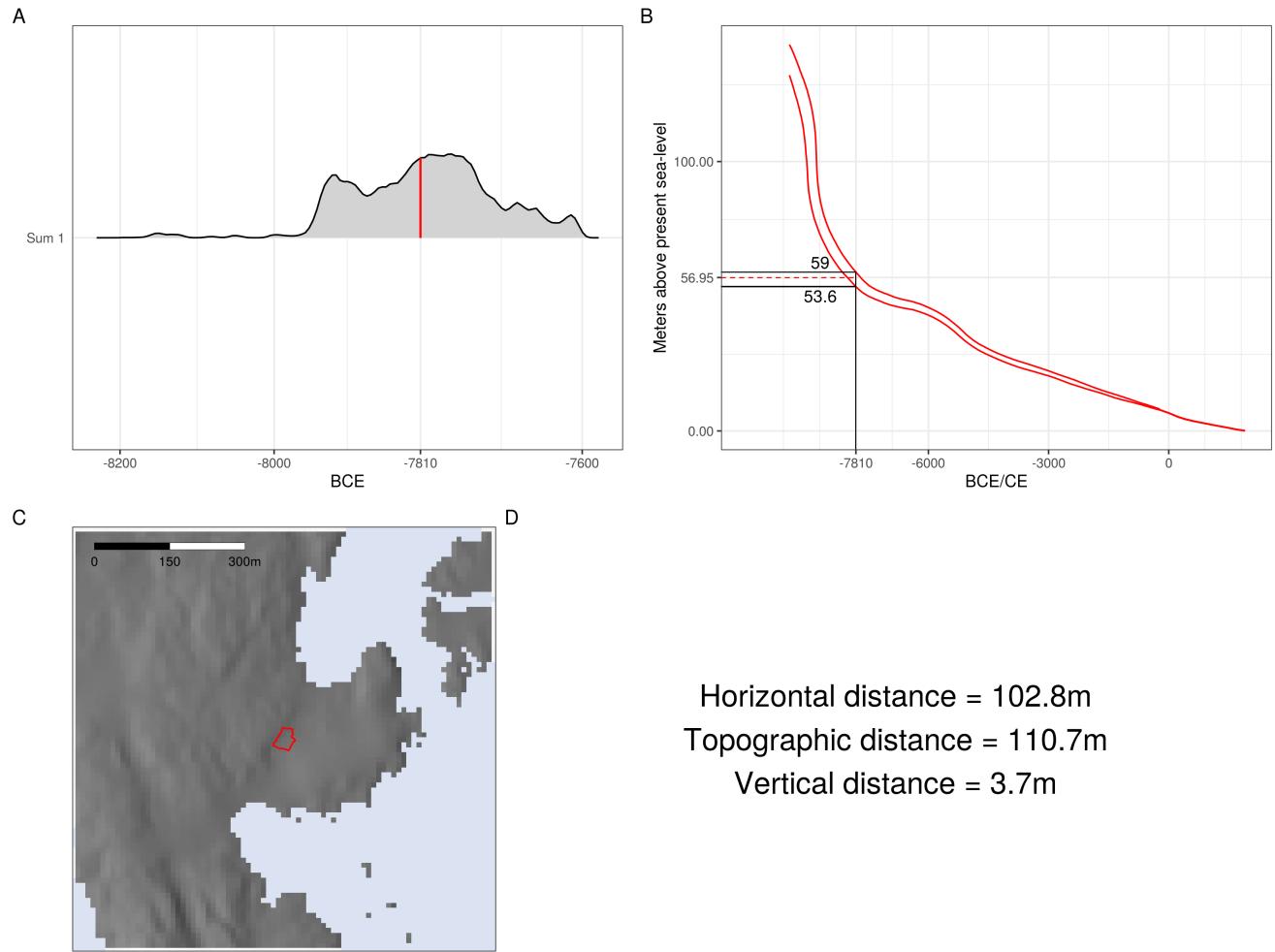


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year from the posterior density estimate. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using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

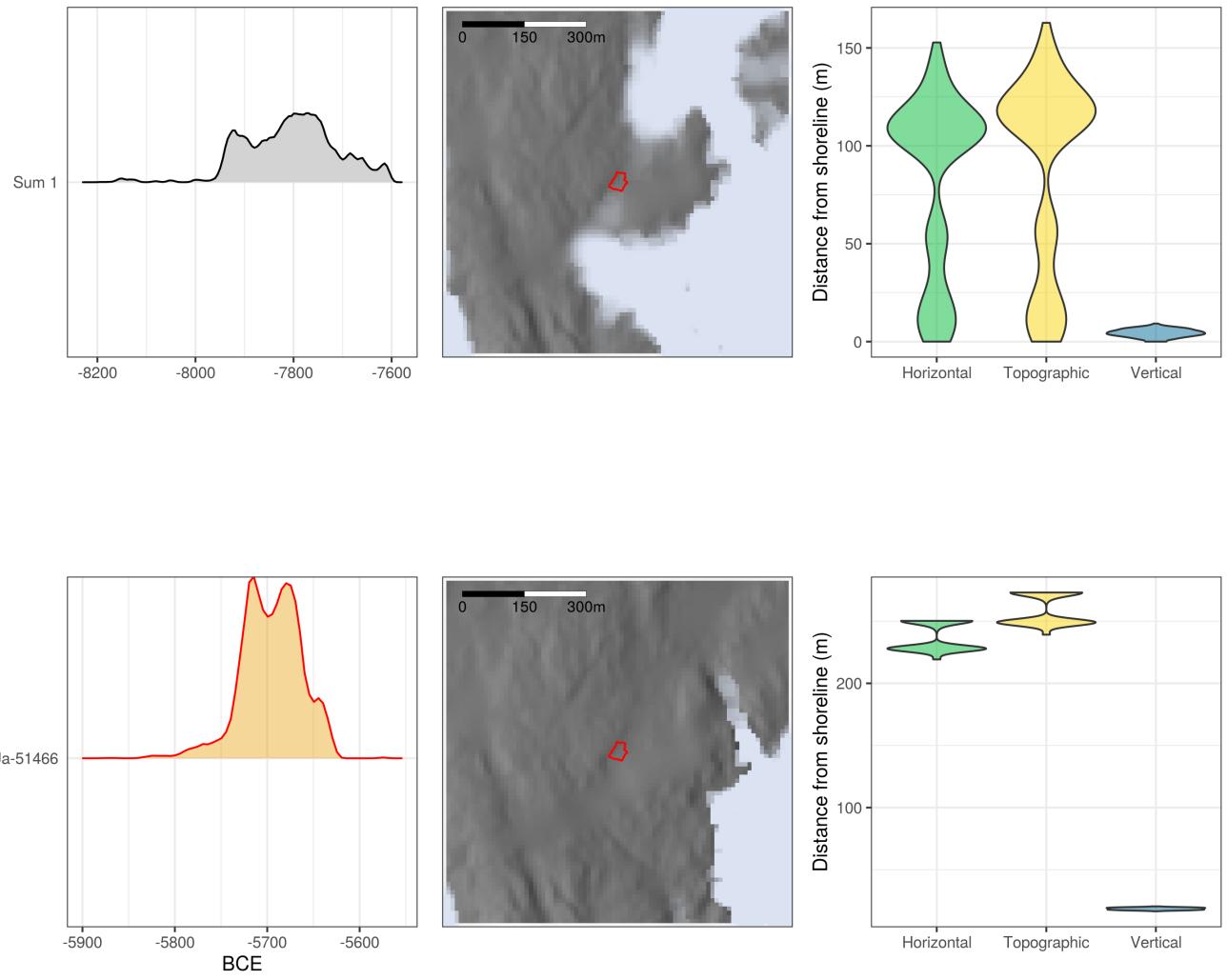


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The first column of plots shows the radiocarbon probability density function from where dates were drawn during simulation. The second column displays the result of simulating the raised sea-level 1000 times. The more opaque the colour, the more times the sea-level was simulated to that location. The third column shows violin plots of the different distance measures across all simulations.

289 5 Simulation results

290 Overall, as is indicated by the measures for central tendency and the almost solid line along the 0m mark on
291 the y-axes, the simulations show that the sites tend to have been situated close to the shoreline when they
292 were in use (Figure 6). Some of the sites are situated considerable distances from the shoreline when the dates
293 believed to be erroneous in the original reports are included (Figure 6A), but if one accepts the interpretation
294 that these do not date the main occupation of the sites, as is indicated by the artefact inventories, Figure
295 6B gives considerable support to the notion that the sites were in use when they were situated on or close
296 to the contemporaneous shoreline. The distances for some of the earliest sites appears somewhat high, but
297 this can likely be explained as the result of the steepness of the displacement curves for the earliest part of
298 the Holocene (Figure 2B), which leads the uncertainty of the ^{14}C -dates to give a wider possible elevation
299 range for the simulated sea-level. Another immediately striking result is the apparent deviation from the
300 shoreline towards the end of the Stone Age. From around 2500 BCE several sites are situated a considerable
301 distance from the shoreline, and while a couple remain horizontally and topographically close, most appear
302 to be elevated a considerable distance from the sea-level, as indicated on the plot for vertical distance. There
303 are also a couple of sites located some distance from the shoreline just after 4000 BCE. While the sample size
304 is limited, this would thus be in line with a development that sees an increase in settlements located in the
305 immediate inland around this time.

306 The negative values around 8000 BCE originate from the sites Løvås 1, 2 and 3. These are recently excavated,
307 well-dated sites situated in a relatively undisturbed area of the landscape. While there would be a danger of
308 circularity of having archaeological sites inform a reconstruction RSL-change, and in turn use these to evaluate
309 the degree of shore-bound settlement, the sites do clearly represent a upper limit for the sea-level, as they
310 would not have been in use when located under water. It could therefore seem that the Løvås sites represent
311 a case where the archaeological material indicates a slight discrepancy in the geological reconstruction of
312 shoreline displacement in the area.

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

325 An exponential function has been fit to the distributions for vertical distance using maximum likelihood
326 estimation (Figure 7). While it makes theoretical sense that a process of exponential decay explains this
327 relationship, it is also clear that this does not perfectly match the data. However, this can at least in part be
328 related to methodological factors, where the accumulation of distance-values on the 0m mark likely follow
329 from forcing negative values to zero, from the resolution of the spatial data, and from defining intersecting
330 sea- and site polygon as having a distance of zero. If one accepts this, the probability density function for
331 exponential decay can be used to characterise the vertical distance between sites and the shoreline, and be
332 used to inform a method for shoreline dating that takes this into account.

333 6 Shoreline dating

334 The procedure for shoreline dating to be outlined is thus aimed at determining the likely age of the occupation
335 of a site based on its altitude above present day sea-level, with reference to shoreline displacement and the
336 likely elevation of the site above the sea-level when it was in use. For simplicity, this is conceptually treated a

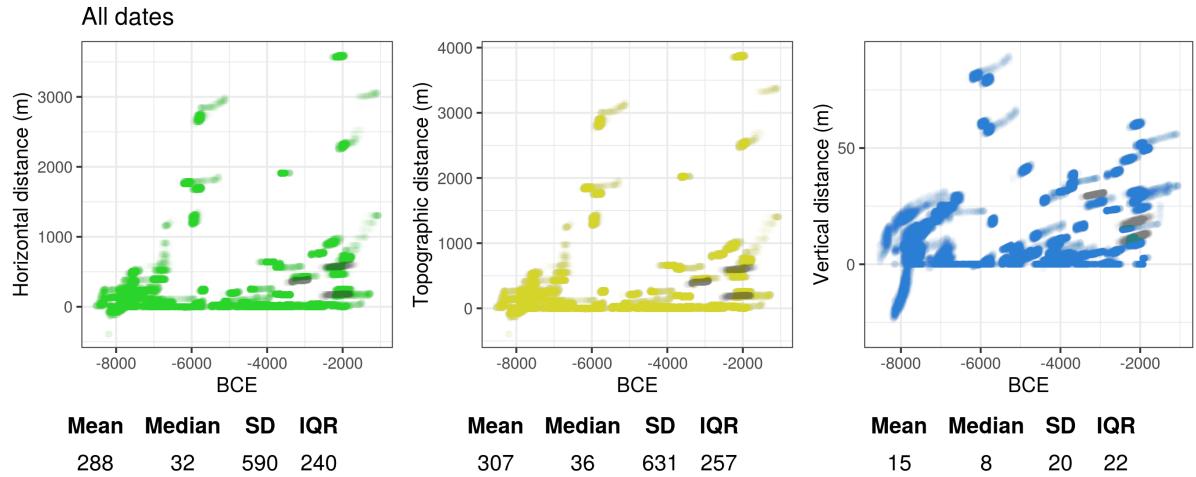
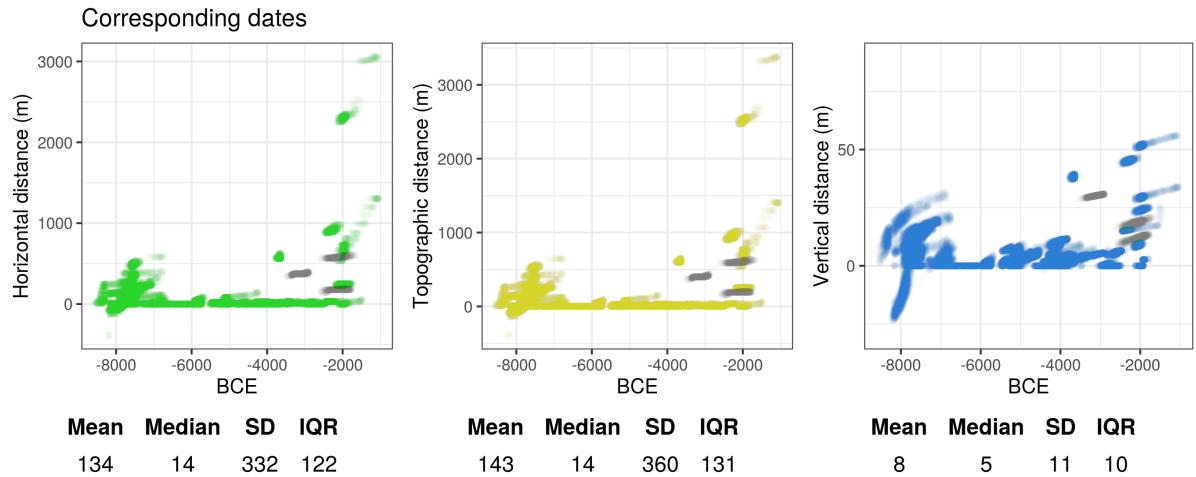
A**B**

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.

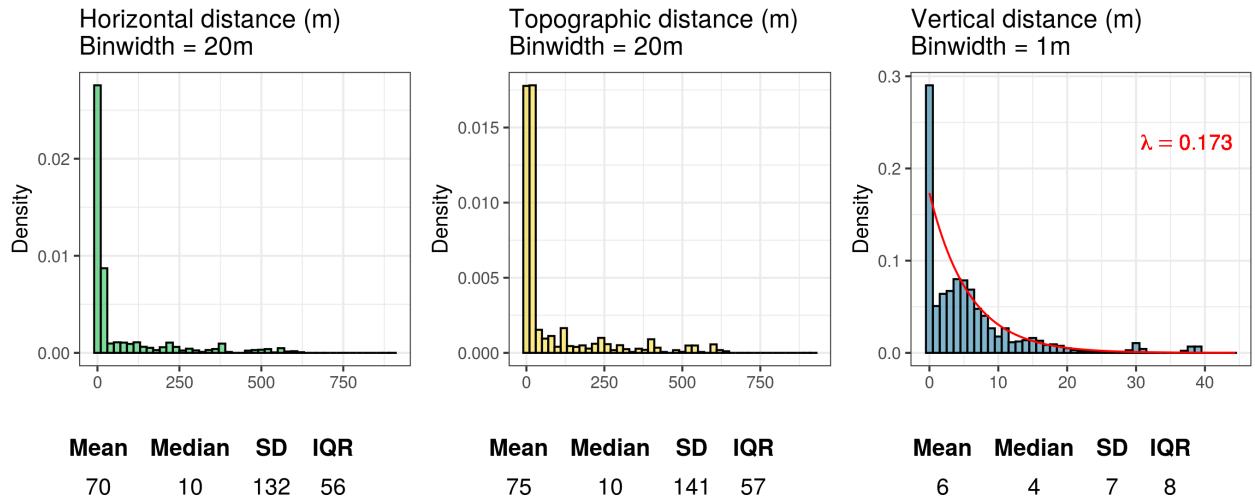
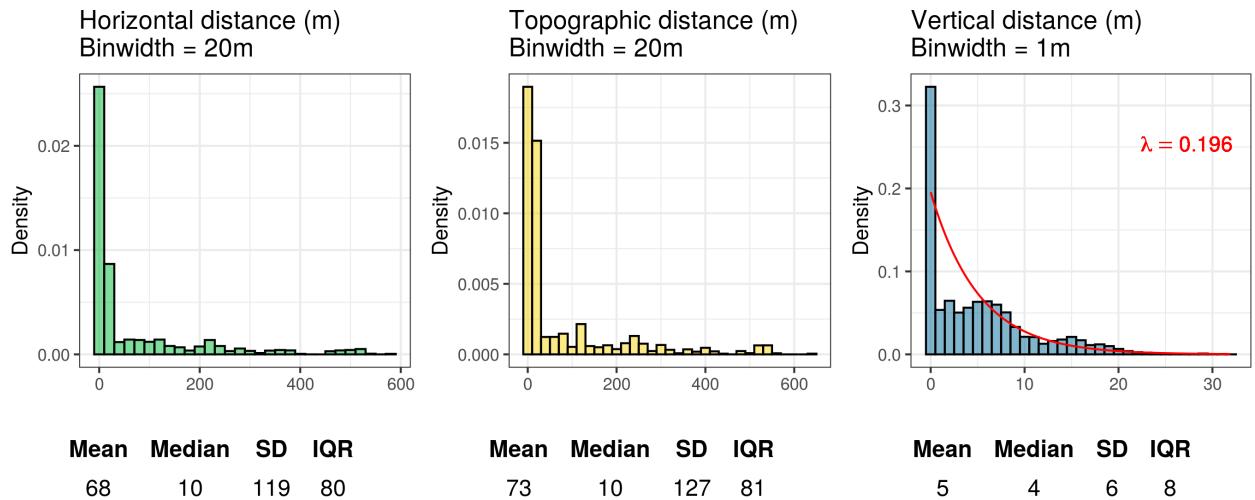
A**B**

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.

single event and thus the possibility of multiple or continuous phases of occupation is not treated explicitly. This leads the problem to become analogous to that of the calibration of a radiocarbon date (see also Figure 8). Drawing on the standard Bayesian formulation for the calibration procedure of individual ^{14}C -dates (e.g. Bronk Ramsey 2009), the probability density associated with the calendar age can then be given as

$$p(x_i | \theta_i) = p(\theta_i | x_i)p(x_i) \quad (1)$$

where for any site i the unknown calendar date is denoted θ and x denotes the elevation of the contemporaneous sea-level, relative to its present level. First, finding the elevation of the sea-level is dependent on the present day elevation of the site α 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 exponential decay

$$p(\alpha - d) = \lambda e^{-\lambda d} \quad (2)$$

where λ is the decay ratio. This can then be coupled with the trajectory of relative sea-level change, denoted RSL , to find the likely elevation of the sea-level. Here the relative sea-level change is defined by a uniform probability density function over the range between the lower and upper bounds of the displacement curve, interpolated to the site location

$$p(RSL) = U[RSL_{lower}, RSL_{upper}] \quad (3)$$

Finding the probability density for the calendar date then becomes a matter of coupling the probability of the distance between site and shoreline to the probability of the altitude of the shoreline, and transferring this probability to each calendar year.

$$placeholder \quad (4)$$

An example of the implementation of Eq. (4) is given in Figure 9, where $\lambda = 0.173$. This is the decay ratio identified when considering all of the pre-Late Neolithic simulation results (Figure 7A). In Figure 9 the outlined procedure is used to shoreline date all of the sites from where this relationship was derived, with the Late Neolithic sites also included for illustrative purposes. Following from having defined the distance between intersecting sea- and site polygons as zero during simulations, the sites were all dated using the mean elevation of the site polygons to allow for some variation in elevation over the site limits. The synchronicity 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 density function of each shoreline date were subtracted from 100,000 age samples drawn from the corresponding 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 (Figure 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 correspond to the radiocarbon dates in 58 out of 68 cases (84%). Only including dates modelled to be older than 2500 BCE with 95% probability, i.e. older than the Late Neolithic, improves this to 56 out of 61 cases (92%). When only including dates older than 4000 BCE with 95% probability, i.e. only Mesolithic site phases, the success rate is further increased to 46/49 (94%). The three failed Mesolithic shoreline dates are from the early sites Langemyr and Kvastad A2, with the likely implication that a lower decay ratio than what is used for characterising the distance between site and shoreline for all sites in aggregate should be used for sites known to be from the earliest part of the Mesolithic (see also Figure 6).

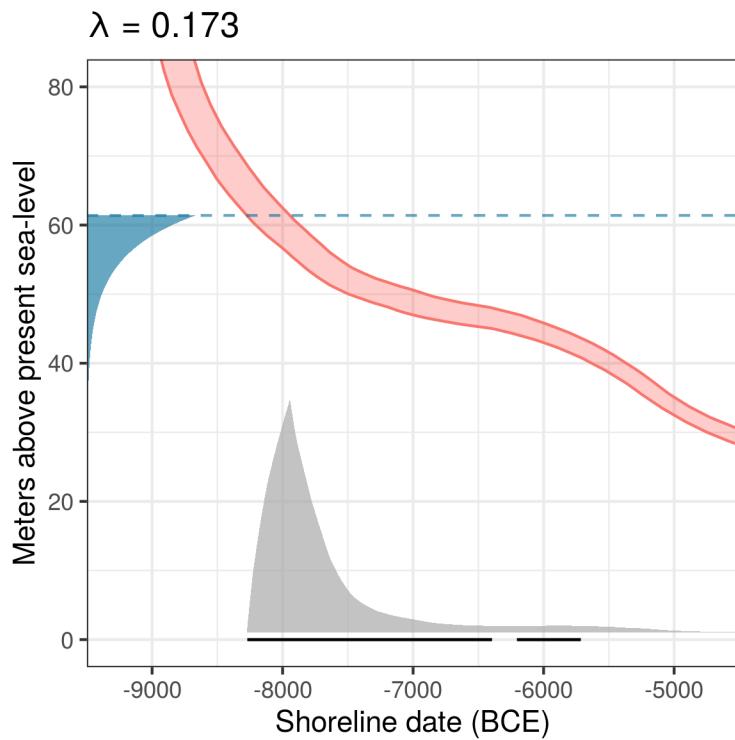


Figure 8: Shoreline dating of Hegna vest 1. The dashed line marks the mean elevation of the site polygon. The exponential function decays with ratio λ from Figure 7A. The resulting shoreline date in grey is underlined with the 95% HDR in black.

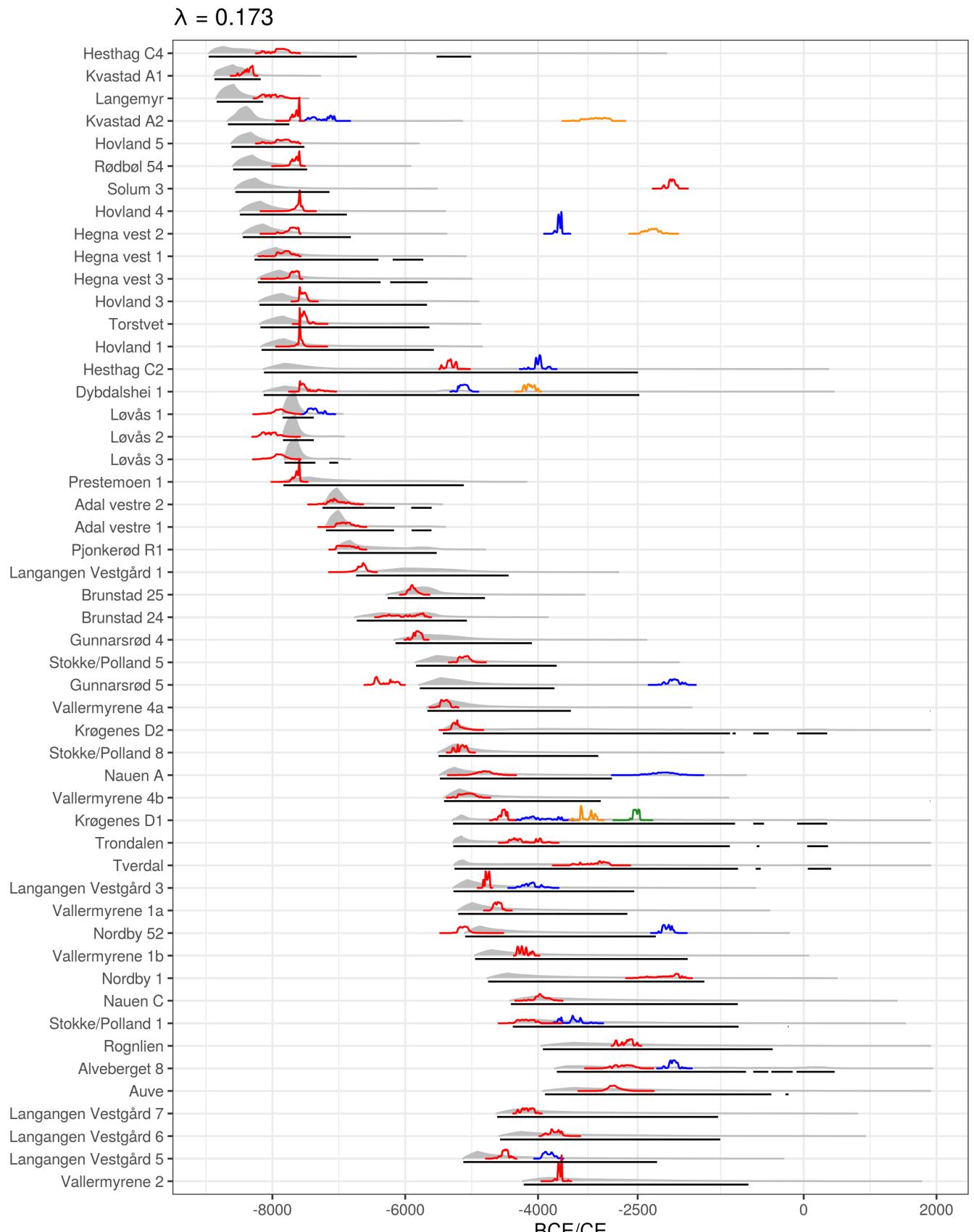


Figure 9: The result of backwards shoreline dating the sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined¹⁷ with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-overlapping dates at 99.7% probability.

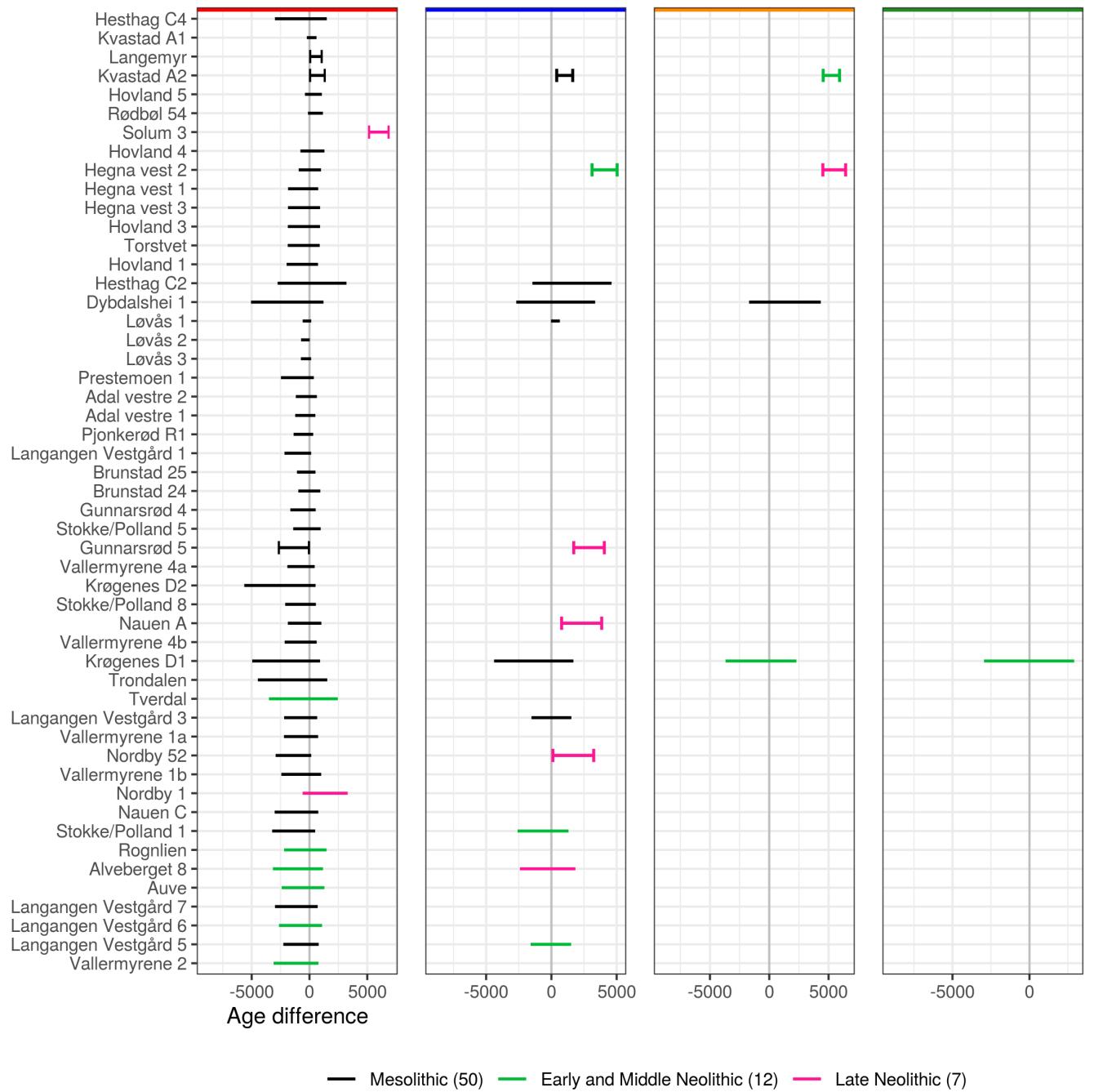


Figure 10: Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Figure 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate the HDR does not 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.

372 7 Re-dating previously shoreline dated sites

373 To further explore the implementation for shoreline dating presented above, excavated and shoreline dated
374 Stone Age sites within the study area where ^{14}C -dates are not available or these are not believed to date the
375 main occupation of the sites have been subjected to the outlined approach (Figure 11). The resulting dates
376 are compared to those originally proposed in the excavation reports for the sites (the numerical results are
377 available in the supplementary material). To avoid issues with recent disturbances on the DTM, the sites
378 have been dated based on the mean of the altitudes provided in the report for each site.

379 The comparison with previously reported dates is an illustrative, but unfair exercise for a few reasons. First
380 of all the dates provided in the reports are typically stated to be a very rough estimate, and are sometimes
381 given as a point estimate with an undefined, but implied or explicit uncertainty range. Secondly, seeing as
382 these reports are from various dates in time, many are based on now outdated data on RSL-change. Finally,
383 they are sometimes only meant to indicate a lower bound for when the sites could have been in use. Overall,
384 the results could, with some danger of circularity, suggest that shoreline dating has generally been applied
385 with a fairly reasonable degree of success, seeing as these dates have typically been interpreted and informed
386 research in an approximate manner (although see e.g. Roalkvam 2022). That being said, the results do also
387 indicate that shoreline dating has at times been applied with an exaggerated degree of precision. While the
388 implications of a more stable RSL-change for the duration of use and re-use of site locations are well known,
389 this also appears to be somewhat under-appreciated for the purposes of shoreline dating. The results also
390 highlight the spatial and temporal contingency of the method, illustrated by the variation in the range of the
391 95% HDRs for the dates. In some cases the method provides a very precise date range and in others it offers
392 little more than a *terminus post quem*. This is dependent on the steepness of the displacement curves, leading
393 to the general pattern of older sites situated towards the north-east getting more precise dates (cf. Figure
394 2B). Furthermore, as some of the date ranges extend well beyond major chronological divisions, even into the
395 Iron Age, they could be severely and securely constrained with only cursory reference to typology. While
396 this would be trivial in some cases, the nature and uncertainty inherent to the method still means that this
397 is arguably a required exercise that should be explicitly performed. This also points to the possibility of
398 drawing on other temporal data, for example within a Bayesian framework, to further improve the precision
399 of the dates that can be achieved with shoreline dating.

400 Not least following from the fact that relatively few Preboreal ^{14}C -dates associated with anthropogenic
401 activity have been achieved in Norway (Åstveit 2018; Damlien and Solheim 2018; Kleppe 2018), the shoreline
402 dating of the earliest sites is essential for understanding the pioneer settlement and the initial colonisation of
403 the Scandinavian peninsula (e.g. Bang-Andersen 2012; Berg-Hansen 2018; Breivik 2014; Fuglestvedt 2012;
404 Glørstad 2016). The shoreline dated Preboreal sites from the Brunlanes-project are among the earliest known
405 sites in Norway (Jaksland 2012a, 2012b; Jaksland and Persson 2014). These have a distinct Early Mesolithic
406 artefact inventory and are situated in a steep area of the landscape where it would be difficult to envision use
407 of the sites after the sea retreated any significant distance from their location. In the original publication
408 of the sites, Jaksland (2014) provides a thorough discussion of shoreline dating in general, and as used for
409 the dating of the Brunlanes sites specifically. A comparison of his results and the ones achieved using the
410 above-outlined approach are given in Figure 12A. The sites have been dated using what Jaksland (2014) gives
411 as the lowest elevation of finds at each site, and by employing a exponential decay ratio of 0.13, to allow for
412 more deviance in the distance between site and shoreline. This corresponds to the decay ratio for sites older
413 than 7000 BCE in Figure 7.

414 The small discrepancies between the achieved results mainly follow from the fact that a slightly updated
415 version of the local displacement curve is applied here (cf. Sørensen et al. in prep). Jaksland's dates are
416 given a flat 200 and 50 year uncertainty range starting from what he gives as the earliest possible date. The
417 200 year uncertainty range is given if the sites were to be considered in isolation, while the argument for
418 the uncertainty range of only 50 years is based on the location of the sites relative to each other. Since
419 they are located in such a constrained and steep area of the landscape, the difference in elevation between
420 the sites is argued to establish their relative date and thus constrain the uncertainty ranges so that they
421 don't overlap. This information is not integrated in the approach outlined here, but could justify further
422 reducing the uncertainty ranges. Although their accuracy is of course ultimately dependent on the veracity of

$$\lambda = 0.173$$

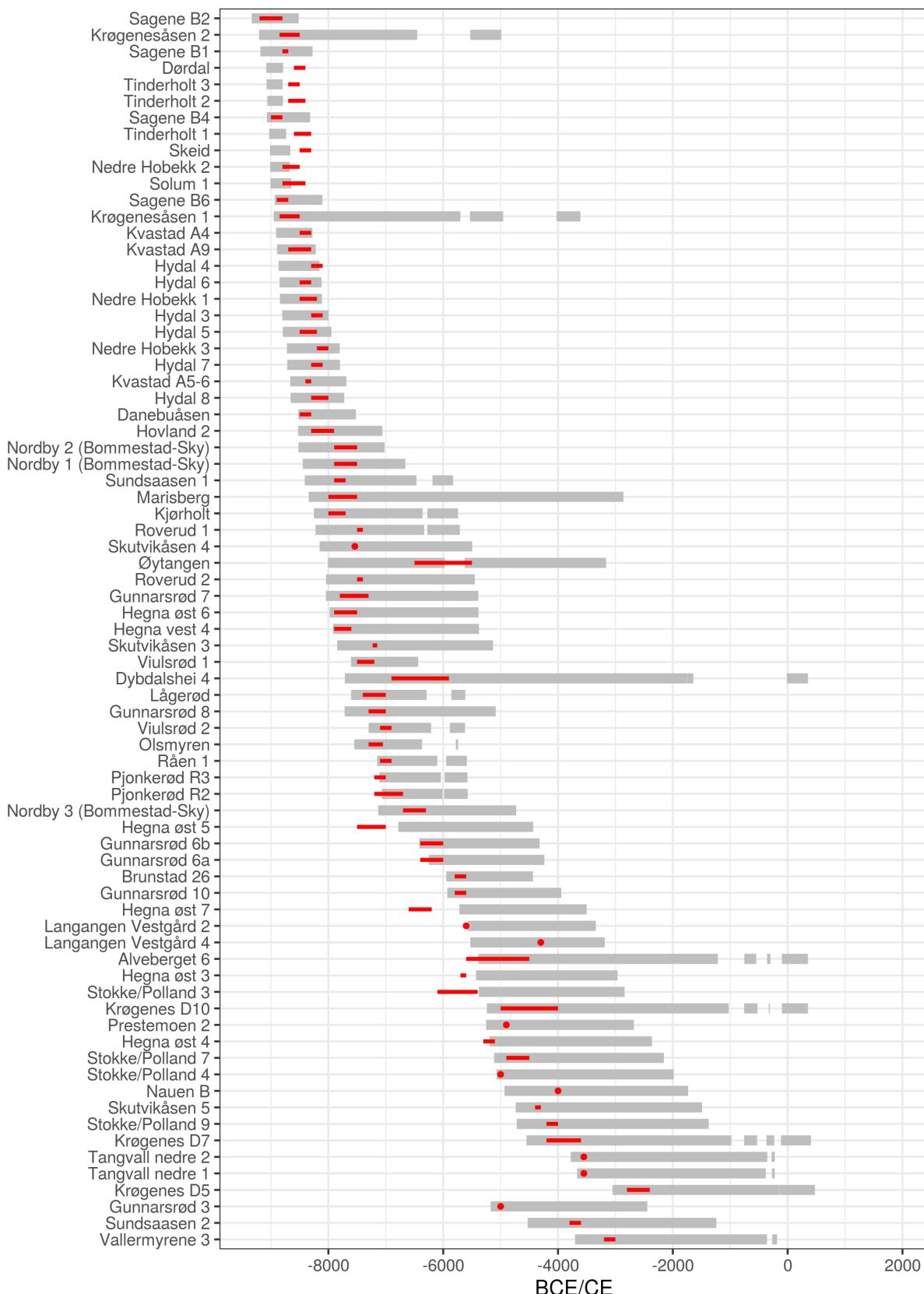


Figure 11: Re-dating excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey²⁰ are compared to the dates originally proposed by the excavation reports in red.

423 the geological reconstruction, the high rate of RSL-change in this period does result in very precise dates.
 424 Above it was suggested that additional temporal data could be combined with the method to improve its
 425 accuracy and precision. This example, on the other hand, highlights the fact that the spatial nature of the
 426 method means that a consideration of the surrounding terrain and other sites can also help in increasing the
 427 precision of the method if this can be used to exclude certain sea-levels as unlikely for when a site was in use.
 428 One approach could also be to assess the spatial implication of a proposed shoreline date by simulating the
 429 adjusted sea-levels, as is done for Paurer 1 in Figure 12B, followed for example by a visual evaluation of the
 430 topography or by evaluating the distance and steepness of the slope to the shoreline. If this is developed
 431 further, it could conceivably be possible to exclude certain elevations as unlikely for the position of the
 432 shoreline when the site was in use. Such approaches would make less of an impact in this setting, where the
 433 95% HDR is already quite constrained, but could considerably improve the precision of the method in cases
 434 where RSL-change has been less severe (cf. Figure 11).

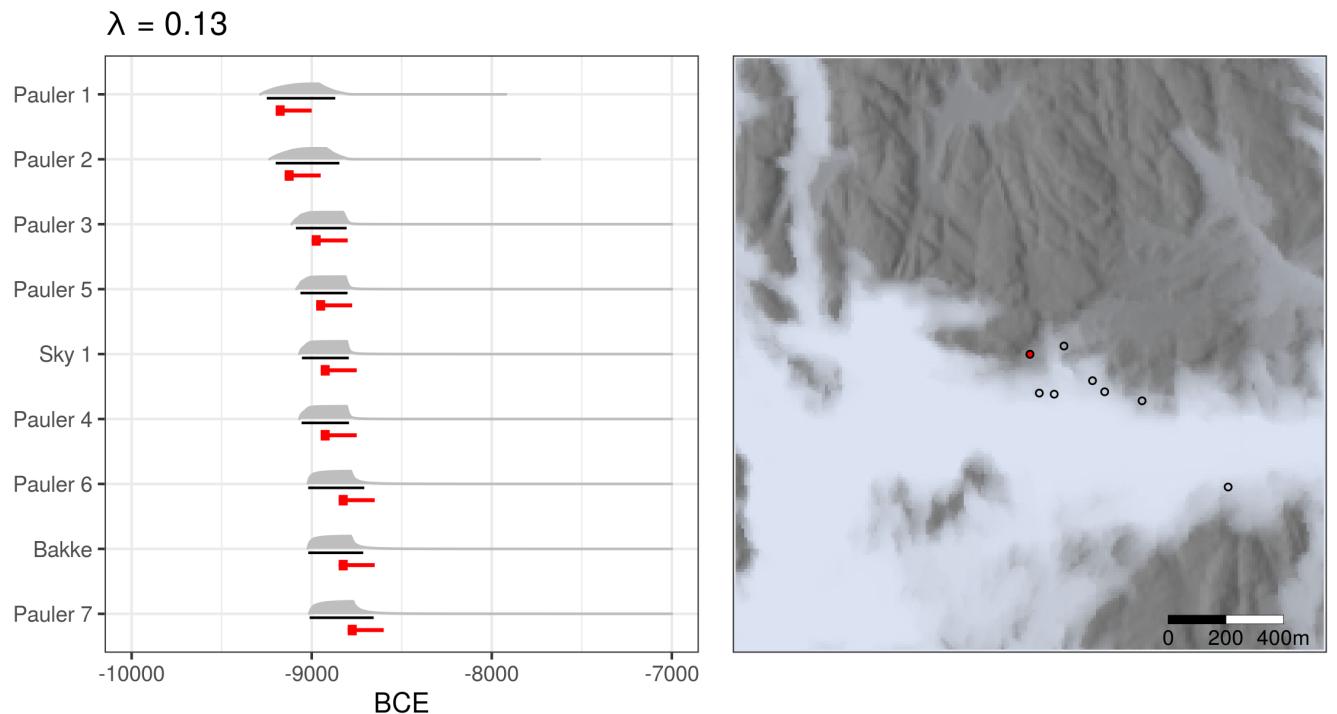


Figure 12: Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red.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

435 8 Concluding remarks

436 The most immediate contribution of this paper is what must be considered a confirmation of previous research
437 into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated
438 by the close relationship between sites and the shoreline up until the transition to the Neolithic at c. 4000
439 BCE, after which a couple of sites become situated some distance from the sea, followed by a more decisive
440 break at the transition to the Late Neolithic at c. 2500 BCE. This development is in clear agreement with
441 the literature. Furthermore, based on the quantitative nature of these findings, an initial formulation of
442 a refined method for the shoreline dating of pre-Late Neolithic Stone Age sites has been proposed. Apart
443 from taking the distance between sites and the isobases of the displacement curves into consideration when
444 dating the sites, this involves implementing Eq. (4) to account for the distance between the sites and the
445 shoreline. When no other information is available, it can at present be recommended to use the empirically
446 derived exponential decay ratio of 0.173 (Figure 11A) to characterise this relationship. Furthermore, while
447 this remains to be formalised and explored further, it was also showed how the accuracy of the method can
448 be improved by including more information, both with reference to the topographic location of the sites and
449 other temporal data. As the precision of the method is both geographically and temporally contingent due to
450 the trajectory of RSL-change, where older sites situated towards the north-east in the study area will get a
451 more precise date, the impact of such additional information will also vary.

452 Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to
453 further evaluate and adjust the findings reported here, but a larger sample size could also lay the foundations
454 for refining the method by identifying subsets of sites for which the application of the method could be
455 adjusted. Given it's behavioural nature, it would for example seem likely that dimensions such as the
456 nature and purpose of visits to the sites will have implications for how close to the shoreline they were
457 located. Furthermore, other dimensions related to the topographic location of the sites could be similarly
458 explored. This for example pertains to the exposure of sites to wave action, which is likely to have been
459 of concern (Roalkvam 2020), and which presumably has implications for how close to the shoreline people
460 settled (Blankholm 2020; Helskog 1978). This is also related to the fact that while the mean sea-level is
461 used for dating the sites, a consideration of the tidal range could possibly also have implications for the site
462 location relative to the shoreline, depending on the topography (Helskog 1978). The potential of exploring
463 dimensions such as these was also hinted at here with the estimation and cursory treatment of the horizontal
464 and topographic distance to the shoreline. If patterns related to such locational patterns can be discerned
465 and unpicked, this will not least be useful for improving the shoreline dating of sites which have only been
466 surveyed and where little information beyond their location is available.

467 Some limitations and sources of likely variation and uncertainty that have not been considered should also be
468 mentioned. First of all the sample size is quite strained and the future addition of more sites might alter the
469 picture considerably. Secondly, the DTM has only been corrected for major modern disturbances. This means
470 that other forms of erosion, although likely not that prevalent, has not been taken into account. Thirdly, the
471 DTM has a vertical error which could also benefit from being integrated in the analysis (cf. Lewis 2021).
472 Fourthly, the displacement curves were here interpolated to all site locations without accounting for increased
473 uncertainty as one moves further away from the isobases of the displacement curves. This is also related to
474 the fact that the RSL data can be handled in different ways than with the isobase method that has been used
475 for the compilation of the employed displacement curves (cf. Creel et al. 2022). Fifthly, neither the question
476 of how site limits are defined nor the elevation range over which these extend was given much consideration
477 (cf. Mjærum 2022). Finally, the radiocarbon dates and division of settlement phases at each site was here
478 simply done by treating radiocarbon dates not overlapping at 99.7% as representing unrelated occupation
479 events. This could also be handled differently (e.g. Bronk Ramsey 2009, 2015). While each of these factors
480 will have variable impact on the final results, they clearly represent dimensions which would all benefit from
481 further consideration and which means that some of the precision following from the outlined approach is
482 likely to be spurious.

483 Finally, this analysis employed a simulation approach to integrate multiple sources of spatio-temporal
484 uncertainty. Here this was simply used to inform the question of the distance between sites and the shoreline.
485 However, this method and general framework can be extended to a wide range of use-cases where one needs

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- ⁴⁸⁶ to visualise, and quantitatively or qualitatively evaluate the relationship between archaeological phenomena,
⁴⁸⁷ the prehistoric shoreline, and the uncertainty inherent in this reconstruction.

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