
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
13 is unquestionable, the geographical contingency and thus relative rarity of the method means that it
14 has been under limited scrutiny compared to more ubiquitous dating techniques in archaeology. This
15 paper attempts to remedy this by quantifying the spatial relationship between Stone Age sites located
16 beneath the marine limit and the prehistoric shoreline along the Norwegian Skagerrak coast. This is
17 done by means of Monte Carlo simulation, which is employed to combine the uncertainty associated with
18 independent temporal data on the use of the sites in the form of ^{14}C -dates and the reconstruction of local
19 shoreline displacement. The findings largely confirm previous evaluations of this relationship, indicating
20 that sites older than the Late Neolithic tend to have been located on or close to the shoreline when they
21 were occupied. Drawing on the quantitative nature of the results, a new and formalised method for the
22 shoreline dating of sites in the region is proposed and compared to previous 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
31 its archaeology. This follows not only from the dramatic changes to the landscape that this process has
32 represented throughout prehistory, but also from the fact that if archaeological phenomena were situated
33 close to the contemporary shoreline when they were in use, a reconstruction of the trajectory of shoreline
34 displacement can be used to date these phenomena based on their altitude relative to the present day sea-level.
35 This method, also called shoreline dating, has long history of use in the region and is frequently applied
36 to assign an approximate date to diverse archaeological phenomena such as rock art, grave cairns, various
37 harbour and sea-side constructions and, as is the focus of this study, Stone Age sites (e.g. Åkerlund 1996;

- ³⁸ Bjerck 2005; Gjerde 2021; Løken 1977; Nordqvist 1995; Schmitt et al. 2009; Sognnes 2003; Tallavaara and Pesonen 2020; Wikell et al. 2009).
- ⁴⁰ The close association between Stone Age settlements in the northern parts of Scandinavia and shifting prehistoric shorelines was established by the end of the 19th century (De Geer 1896), and was first applied as a dating method at the turn of the century (Brøgger 1905; Hollender 1901). Shoreline dating has been fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen 2009; Bjerck 1990, 2008a; Breivik 2014; Johansen 1963; Mikkelsen 1975; Mjærum 2022; Nummedal 1923; Shetelig 1922; Solheim and Persson 2018). The method is used both independently, and to compliment other sources of temporal data such as typological indicators or radiometric dates. However, given the coarse and fuzzy resolution of established typological frameworks, the vast amount of surveyed sites that only contain generic lithic debitage that could hail from any part of the period, and as the conditions for the preservation of organic material is typically poor in Norway, dating with reference to shoreline displacement is often the only and most precise method by which one can hope to date the sites. Shoreline dating is consequently fundamental to our understanding of the Norwegian Stone Age. This is both because it is central to the temporal framework on which our understanding of the period is based, but also because the method is only applicable so long as the societies in question have continuously settled on or close to the contemporary shoreline. Consequently, adherence or deviation from this pattern also has major implications for the socio-economic foundations of the societies in question.
- ⁵⁶ Despite its important role for Norwegian Stone Age archaeology, the applicability of dating by reference to shoreline displacement has only been evaluated using relatively coarse methods. The aim of this paper is to provide a systematic and comprehensive review of the degree to which radiocarbon dates correspond with the dates informed by our current knowledge of shoreline displacement in a larger area of south-eastern Norway, using a more refined methodological approach. The goal is to quantify the degree to which the assumption of shore-bound settlement holds through the Stone Age, and in turn have this inform an improved method for shoreline dating. As presented in more detail below, this problem involves the combined evaluation of three major analytical dimensions. One is the questions of when the sites were in use, the second pertains to the reconstruction of the contemporaneous sea-level, and the third follows from the fact that the relation between site and shoreline is inherently spatial. Taking inspiration from studies that have integrated various sources of spatio-temporal uncertainty through Monte Carlo simulation (e.g. Bevan et al. 2013; Crema et al. 2010; Crema 2012, 2015; Yubero-Gómez et al. 2016), a similar approach is adopted here.

⁶⁸ 2 Background

- ⁶⁹ Relative sea-level (RSL) can be defined as the mean elevation of the surface of the sea relative to land, or, more formally, the difference in elevation between the geoid and the surface of the Earth as measured from the Earth's centre (Shennan 2015). Variation in this relative distance follow from a range of effects (e.g. Milne et al. 2009). Of central importance here is eustasy and istostasy. The eustatic sea-level is understood as the sea-level if the water has been evenly distributed across the Earth's surface without adjusting for variation in the rigidity of the Earth, its rotation, or the self-gravitation inherent to the water body itself (Shennan 2015). The eustatic sea-level is mainly impacted by glaciation and de-glaciation, which can bind or release large amounts of water into the oceans (Mörner 1976). Istostasy, on the other hand, pertains to adjustments in the crust to regain gravitational equilibrium relative to the underlying viscous mantle. This can be the result of glacial istostasy, which follows from glaciation and de-glaciation and corresponding loading and unloading of weight, as well as from erosion of the crust, which causes its weight to be redistributed. These effects thus causes the lithosphere to either 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 al. 2016; Stroeven et al. 2016, see Figure 1), the isostatic rebound has been so severe that most areas of Norway have been subject to a continuous relative sea-level regression, despite corresponding eustatic sea-level rise (e.g. Mörner 1979; Svendsen and Mangerud 1987). In other words, the RSL has been dropping throughout prehistory. As this process is the result of glacial loading, the rate of uplift is more severe towards the centre

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

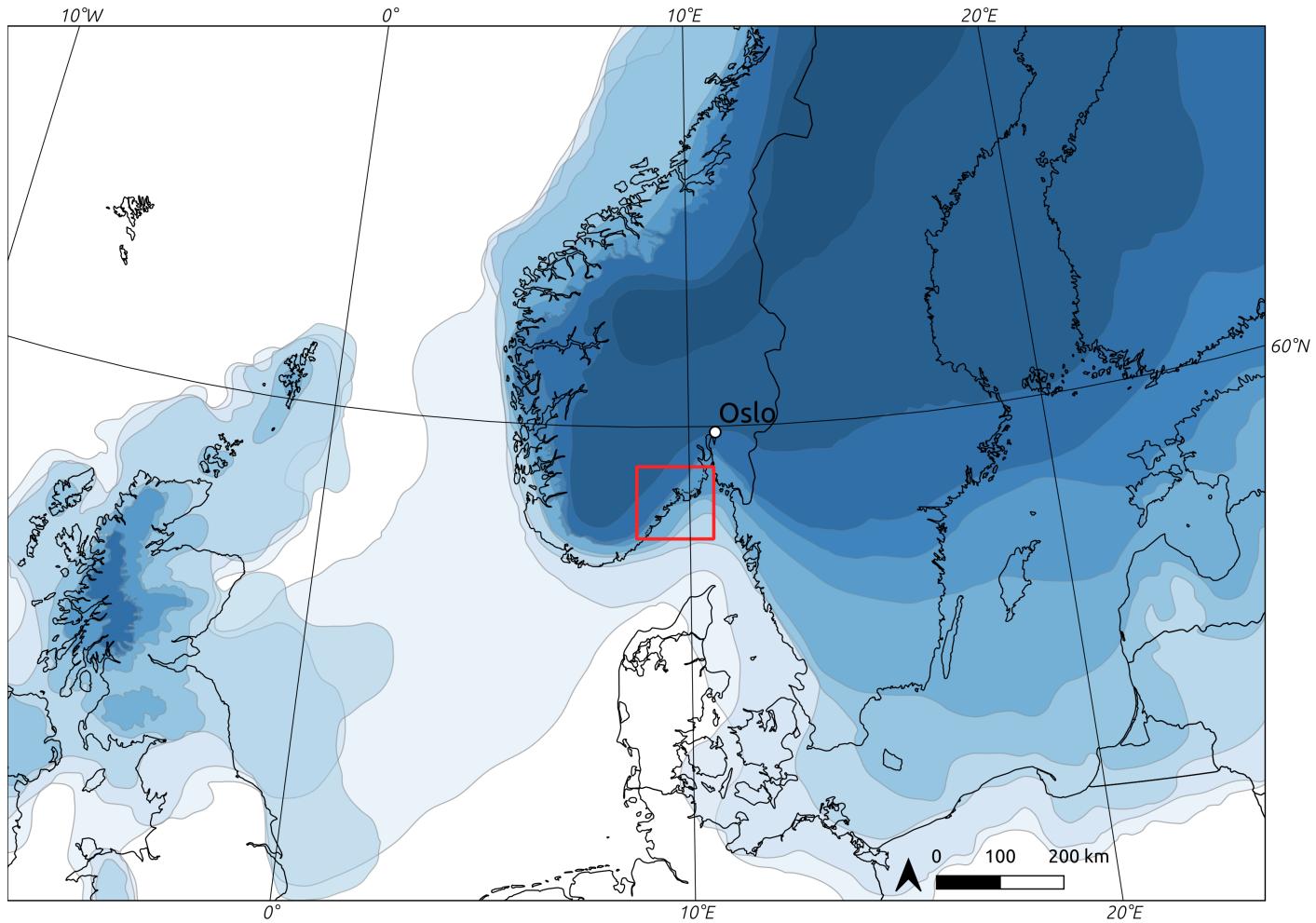


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 kyr BCE. The study area defined later in the text
 is marked with a red outline (deglaciation data from Hughes et al. 2016, but see also Romundset et al. 2019
 in relation to the study area).

100 The method of shoreline dating has been met with scepticism as related to the fundamental premise that
 101 most sites would have been consistently shore-bound, been characterised as a relative dating method for sites
 102 located at different elevations within a constrained geographical area, or been argued to offer no more than
 103 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).

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 hinter- and inland regions, where sites are 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 introduction of the farm 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 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). 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 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 survey projects, which are often guided by both a digital and mental reconstruction of past sea-levels (e.g. Berg-Hansen 2009; Eskeland 2017). 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 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 are sensible and can for the most part be assumed to hold, comprehensive evaluations and attempts at quantification of this tendency are relatively few (see also Ilves and Darmark 2011).

One of the more extensive evaluations of the relationship between archaeological radiocarbon dates and RSL-change was done by Solheim and colleagues (Breivik et al. 2018; Solheim 2020), who compared 102 radiocarbon dates from 33 Mesolithic sites on the western side of the Oslo fjord to the displacement curve for

156 the Larvik area. They found an overlap between the probability distribution of the radiocarbon dates with
157 the shoreline displacement curve for 86.5% of the sites. However, where there was a discrepancy, the main
158 occupation of the sites are still believed to have been shore-bound rather than associated with the deviating
159 ^{14}C -dates. This is based on typological and technological characteristics of the assemblages. Whether these
160 mismatches represent later shorter visits that are responsible for the younger radiocarbon dates, or whether
161 these dates are entirely erroneous can be difficult to evaluate (e.g. Persson 2008; Schülke 2020). However,
162 this distinction is not deemed critical here, as what is of interest is settlements and tool-production areas as
163 evidenced by artefact inventories or multiple site features. Not remnants of stays as ephemeral to only be
164 discernible by isolated features or dubious ^{14}C -dates. The evaluation of the relevance of radiocarbon dates
165 to settlement activity will here therefore be entirely dependent on, and follow the discretion of the original
166 excavation reports.

167 Other previous evaluations of the correspondence between radiocarbon- and RSL-informed dates have typically
168 followed the same structure as that of Breivik et al. (2018), involving a visual inspection of radiocarbon
169 probability density functions plotted against local shoreline displacement curves based on the elevation of the
170 site (e.g. Åkerlund et al. 1995; Åstveit 2018; Solheim 2020; see also Bjerck 2008b; Kleppe 1985; Ramstad
171 2009). This approach has a couple of limitations. First of all, the displacement curves are sometimes applied
172 directly to larger study areas, analogous to what Borreggine et al. (2022) term a bathtub model, with only
173 some studies having taken the variable uplift-rates into account when performing this comparison (e.g. Åstveit
174 2018; Fossum 2020; Møller 1987; Persson 2008). Secondly, with this method, the wider the uncertainty range
175 associated with either radiocarbon date or displacement curve, the higher the probability that the confidence
176 intervals overlap, and the higher the probability that we conclude in favour of our hypothesis. This thus
177 leads to an inferential framework that favours uncertainty, which is hardly desirable. In statistical terms this
178 follows from the fact that while one cannot conclude that two dates are different if their confidence intervals
179 overlap, this does not necessarily mean that they are the same. The question thus necessitates a flip from a
180 null-hypothesis of no significant difference, to one of equivalence (e.g. Lakens et al. 2018), as the question
181 of interest is effectively one of synchronicity between events (cf. Parnell et al. 2008). Another limitation of
182 this often-employed method is that it only takes into account the vertical distance between the sites and the
183 sea-level. While this is the main parameter of interest for shoreline dating, the practical implications of a
184 vertical difference in RSL will be highly dependent on local topography and bathymetry. RSL-change can
185 have more dramatic consequences in a landscape characterised by a low relief, as the horizontal displacement
186 of the shoreline will be greater. Taking the spatial nature of the relationship between site and shoreline into
187 account will consequently help get more directly at the behavioural dimension of this relation, and help move
188 the analysis beyond a purely instrumental consideration of the applicability of shoreline dating.

189 3 Data

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

198 The employed shoreline displacement data is based on the so-called isolation basin method (e.g. Kjemperud
199 1986; Romundset et al. 2011), which involves extracting cores from a series of basins situated on bedrock at
200 different elevations beneath the marine limit, and dating the transition from marine to lacustrine sediments.
201 Each basin thus represent a high precision sea-level index point (SLIP) which are combined using what has
202 been termed the isobase method to devise a continuous time series for RSL-change adjusted to a common
203 isobase. To minimise the impact of variable uplift rates, the cored basins are therefore located in a as
204 constrained area of the landscape as possible. Following from the morphology of the retreating ice sheet, the

uplift is more severe towards the north-east, meaning that this needs to be adjusted for in the case that any basins are located any significant distance from the common isobase perpendicular to this gradient (Figure 2). The SLIPs indicate 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. This 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 (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 alternative approaches see e.g. Barnett et al. 2020; Cahill et al. 2016; 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 157 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 acitivities. 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).

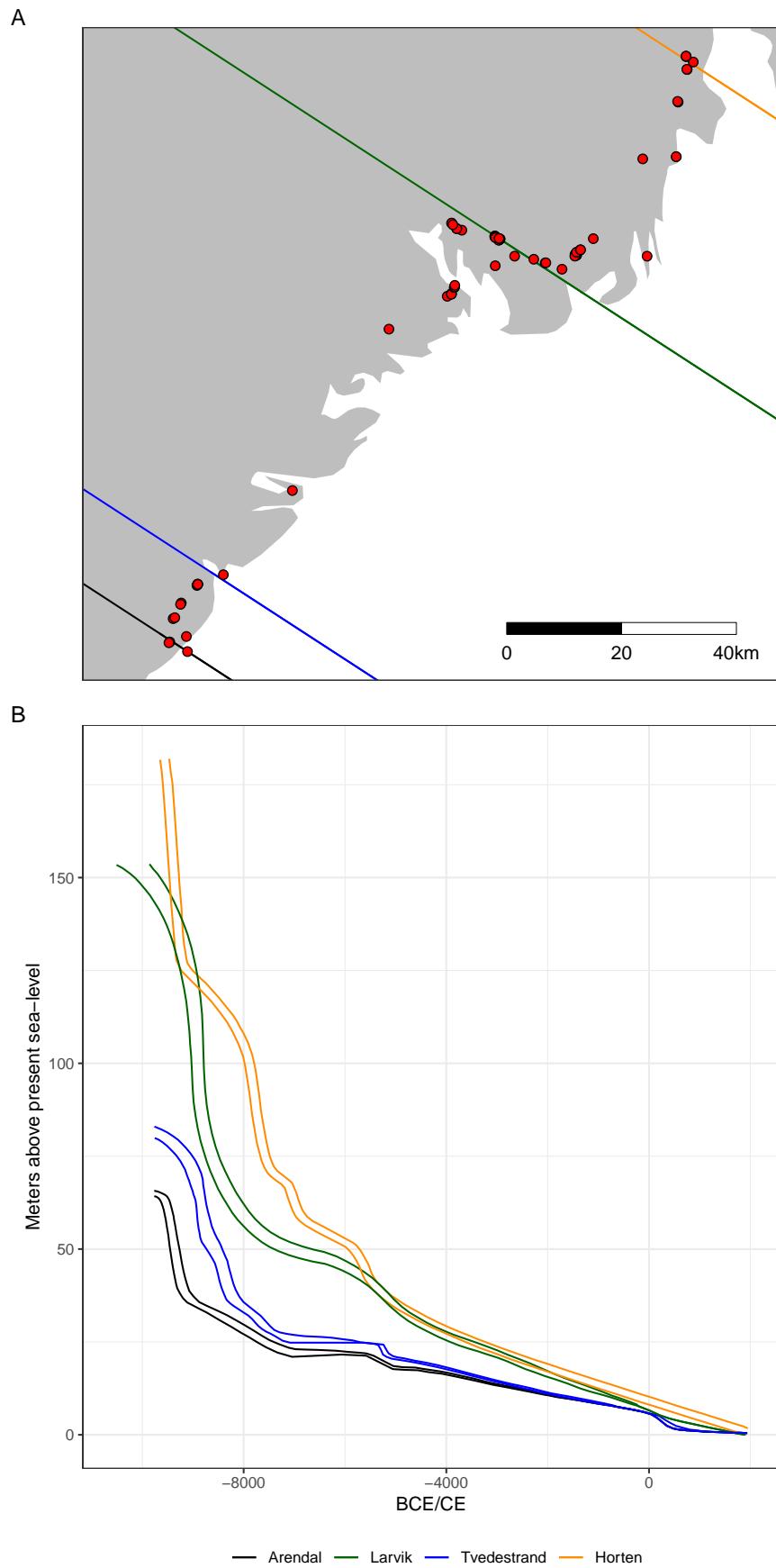


Figure 2: A) Distribution of the 67 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al. 2018, but see Sørensen et al. 2014), B) Displacement⁷ curves. Note the increasing steepness of the curves towards the north-east.

252 4 Methods

253 Shoreline dating is based on the spatial relationship between two phenomena, occupation of sites and shoreline
254 displacement, each associated with their own range of temporal uncertainty. The first task was therefore to
255 ascribe likely date ranges and associated uncertainty to these dimensions. To take account of the gradient in
256 the isostatic rebound, the trajectory of shoreline displacement was first interpolated to each site location based
257 on the distance to the isobases of the displacement curves, using inverse distance weighting (e.g. Conolly
258 2020; Conolly and Lake 2006:94–97). This was done for each year along the entirety of the curves, weighting
259 the interpolation by the squared inverse of the distances. The result of this process is shown for an example
260 site in Figure 3. For the date ranges associated with the sites, all radiocarbon dates were first individually
261 calibrated using the IntCal20 calibration curve (Reimer et al. 2020) using OxCal v4.4.4 (Bronk Ramsey 2009)
262 through the oxcAAR package for R (Hinz et al. 2021). Radiocarbon dates associated with each site were
263 then grouped if they overlapped with 99.7% probability, meaning these were effectively taken to represent
264 the same event, here termed settlement or site phase. In the case where there are multiple dates believed to
265 belong to a single settlement phase, these were modelled using the Boundary function in OxCal and then
266 summed. Multiple phases at a single site were treated as independent of each other.

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

279 Armed with a likely date range for the occupation(s) of each site, an estimated trajectory of relative sea-level
280 change at that location, and a DTM edited to remove substantial modern disturbances, the simulations were
281 performed. A single simulation run involved first drawing a single year from the posterior density estimate of
282 a given occupation phase of a site (Figure 4). This year then has a corresponding likely elevation range for
283 the contemporaneous shoreline from which an elevation value was drawn uniformly, using intervals of 5cm.
284 The sea-level was then raised to this elevation on the DTM by defining all elevation values at or below this
285 altitude as missing. Polygons were then created from the resulting areas with missing values. The horizontal
286 distance was then found by measuring the shortest distance between site and sea polygons, and the vertical
287 distance by subtracting the elevation of the sea-level from the lowest elevation of the site polygon. The topographic
288 distance between site and sea was also found by measuring the distance while taking into account
289 the slope of the terrain on the DTM. This was done using the topoDistance package for R (Wang 2019).
290 The topographic distance was measured between the site polygon and the horizontally closest point on the
291 shoreline. This means that the distance is not necessarily measured as the closest topographic distance to the
292 shoreline, but rather as the shortest topographic path to the horizontally closest point on the shoreline. Not
293 finding the topographically closest point significantly reduced the computational cost of the analysis, and is
294 deemed unlikely to have a considerable impact on the results given the distances considered. The shortest
295 topographic path was found using the Moore neighbourhood of eight cells (e.g. Conolly and Lake 2006:253;
296 Herzog 2013). In the case where the sea polygons intersects the site polygon, all distance measures were
297 set to zero. In the case that the sea polygons completely contain the site, the horizontal and topographic
298 distance measures were made negative, and the vertical distance was instead measured to the highest point
299 on the site polygon. While it is safe to assume that an archaeological site was not occupied when it was
300 located beneath sea-level, a negative result can reflect the inherent uncertainty in this procedure, and might
301 also help identify discrepancies in displacement data or radiocarbon dates. Negative values were therefore
302 retained with the exception of for the sites Gunnarsrød 5 and Pjonkerød R1, where the negative values are
303 believed to result from modern disturbances in the DTM rather than the ^{14}C -dates or displacement curves

304 (see supplementary material for more details).

305 This process was repeated 1000 times for each phase for each site. The choice of 1000 simulation runs follows
306 from an evaluation of when the mean distances between site and shoreline converged when running 5000
307 iterations of the simulation on the site Hovland 5, available in the supplementary material (cf. Crema et al.
308 2010:1125). Hovland 5 was chosen for this evaluation as it has a fairly imprecise date and is located in area
309 of quite complex topography.

310 5 Simulation results

311 Overall, as is indicated by the measures for central tendency and the almost solid line along the 0m mark on
312 the y-axes, the simulations show that the sites tend to have been situated close to the shoreline when they
313 were in use (Figure 6). Some of the sites are situated considerable distances from the shoreline when the dates
314 believed to be erroneous in the original reports are included (Figure 6A), but if one accepts the interpretation
315 that these do not date the main occupation of the sites, as is indicated by the artefact inventories, Figure
316 6B gives considerable support to the notion that the sites were in use when they were situated on or close
317 to the contemporaneous shoreline. The distances for some of the earliest sites appears somewhat high, but
318 this can likely be explained as the result of the steepness of the displacement curves for the earliest part of
319 the Holocene (Figure 2B), which leads the uncertainty of the ^{14}C -dates to give a wider possible elevation
320 range for the simulated sea-level. Another immediately striking result is the apparent deviation from the
321 shoreline towards the end of the Stone Age. From around 2500 BCE several sites are situated a considerable
322 distance from the shoreline, and while a couple remain horizontally and topographically close, most appear
323 to be elevated a considerable distance from the sea-level, as indicated on the plot for vertical distance. While
324 the sample size is limited, there are also a couple of sites located some distance from the shoreline just after
325 4000 BCE. That the findings appear to be off from the chronological framework by around a century must be
326 seen in relation to chronological smearing from the uncertainty in the ^{14}C -dates, and the findings are thus in
327 clear agreement with the literature.

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

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

347 An exponential function has been fit to the distributions for vertical distance using maximum likelihood
348 estimation (Figure 7). While it makes theoretical sense that a process of exponential decay explains this
349 relationship, it is also clear that this does not perfectly match the data. However, this can at least in part be
350 related to methodological factors, where the accumulation of distance-values on the 0m mark likely follow
351 from forcing negative values to zero, from the resolution of the spatial data, and from defining intersecting

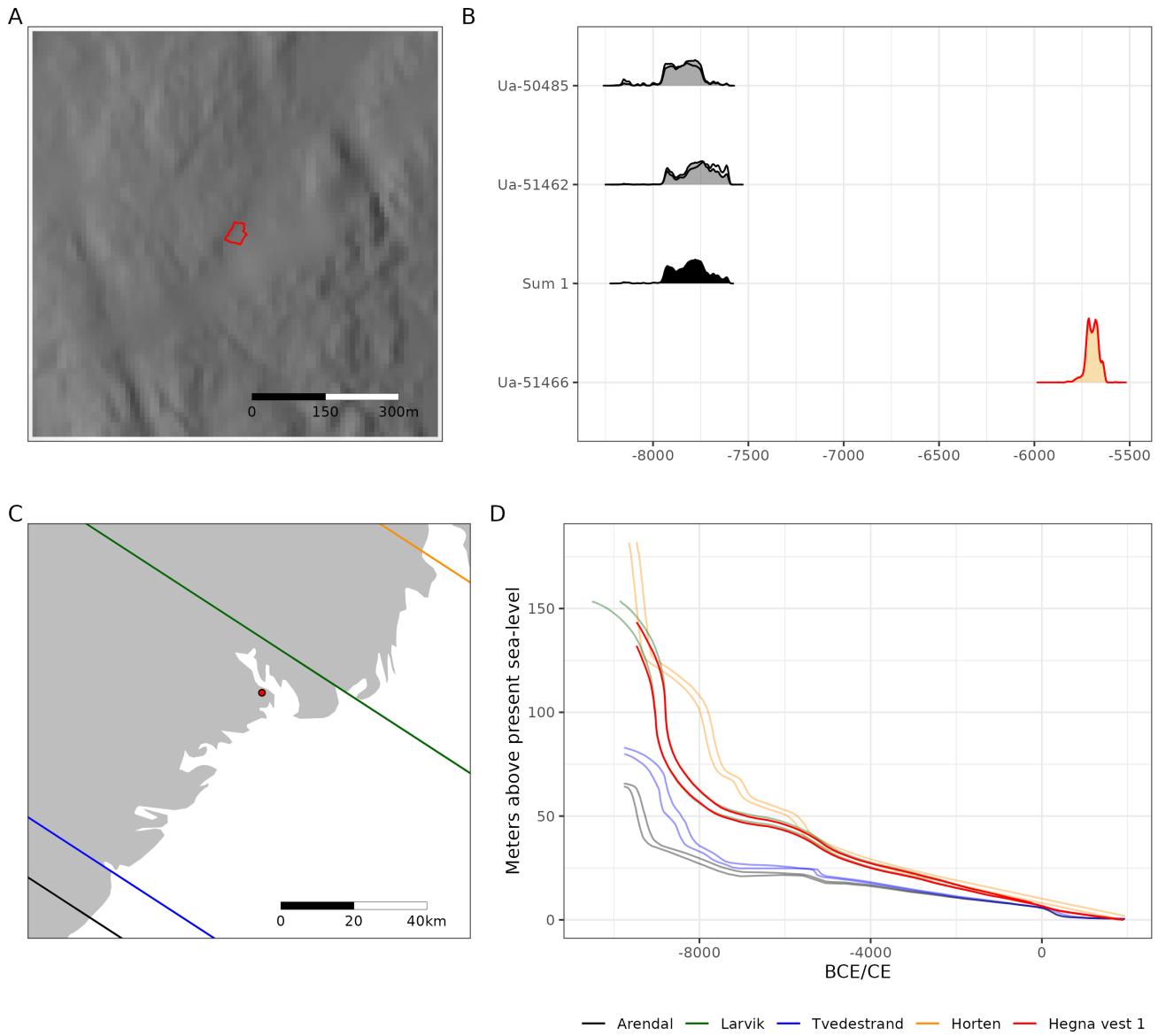


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site on the edited 10m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled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

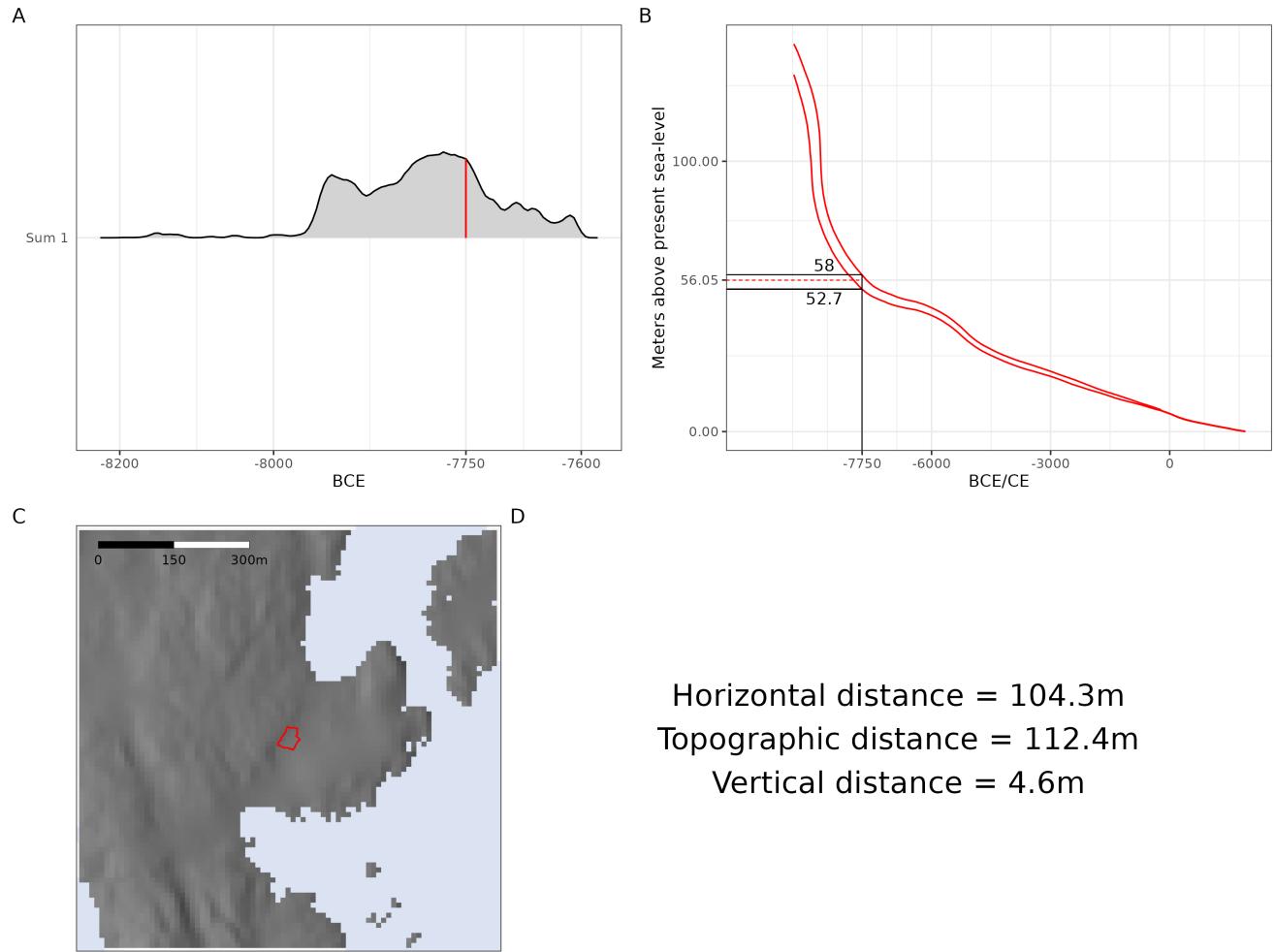


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year from the posterior density estimate. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using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

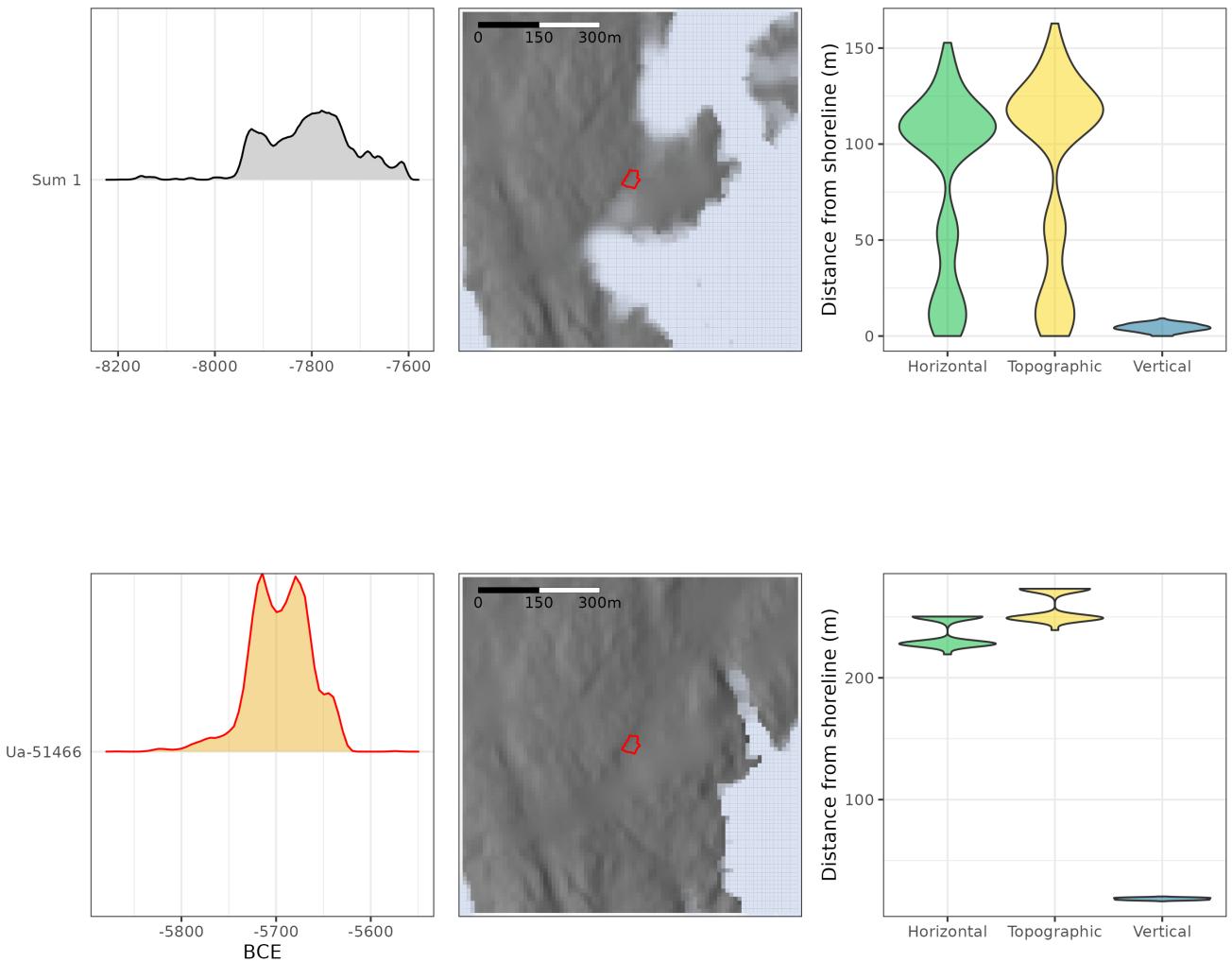
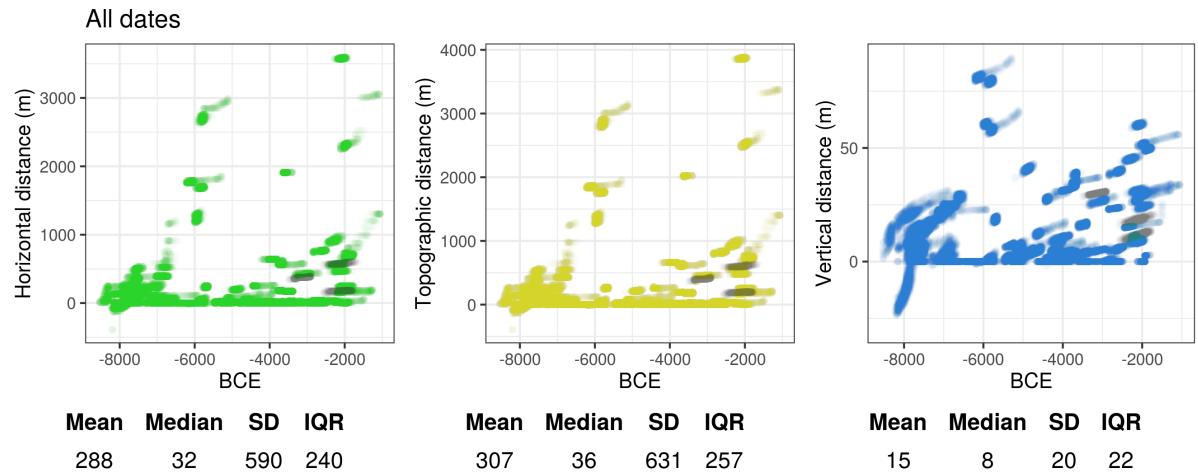


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The first column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The second column displays the result of simulating the raised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

A



B

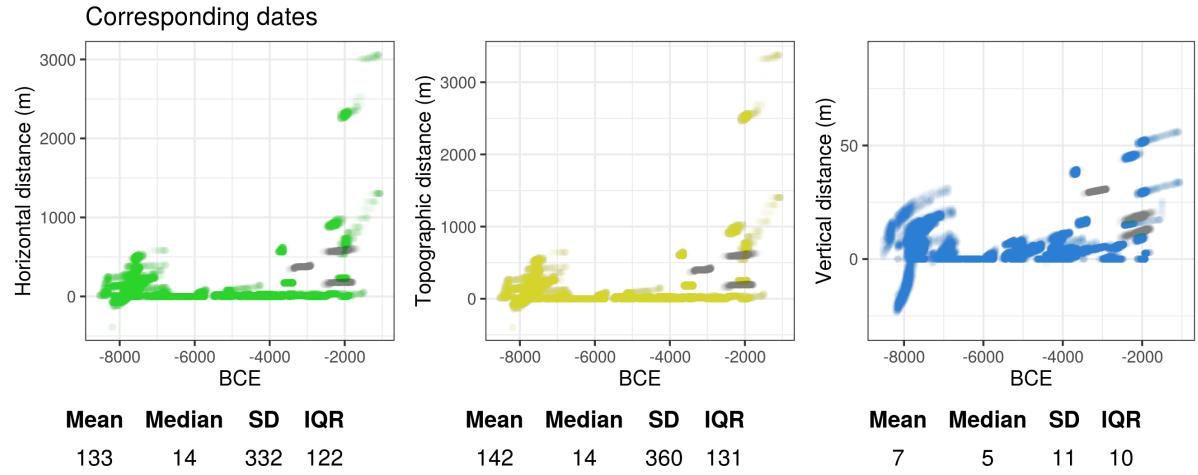


Figure 6: The result of running the analysis across all sites. Each data point is plotted with some transparency, meaning that the more intense the colour, the more often those values occurred. Results associated with agricultural activities are plotted in grey. The first row A) shows the result of including 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.

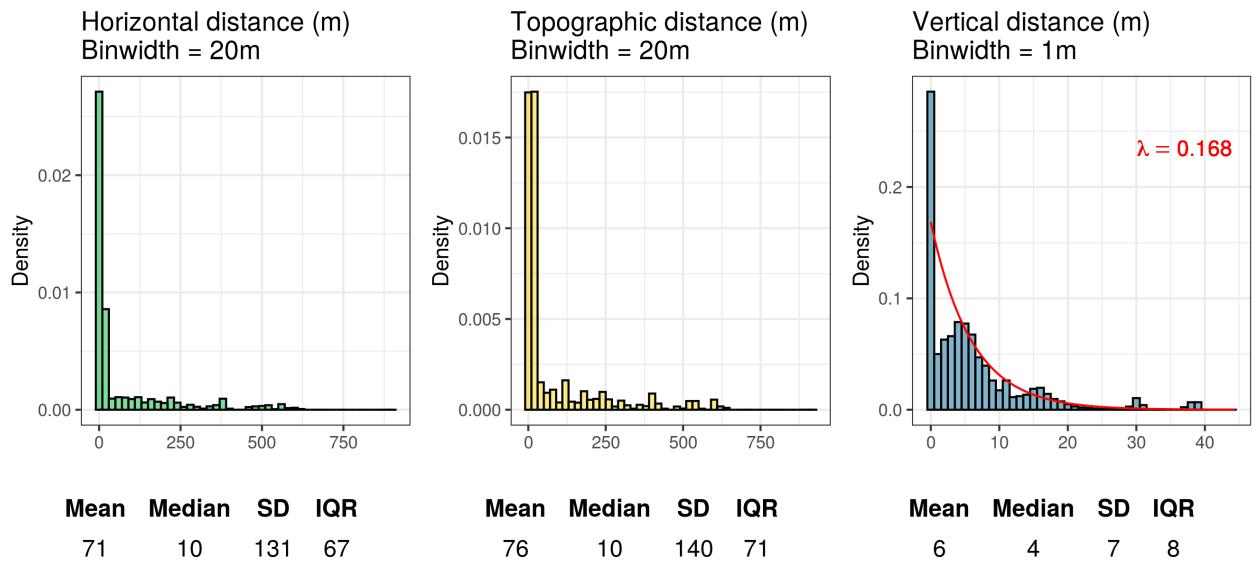
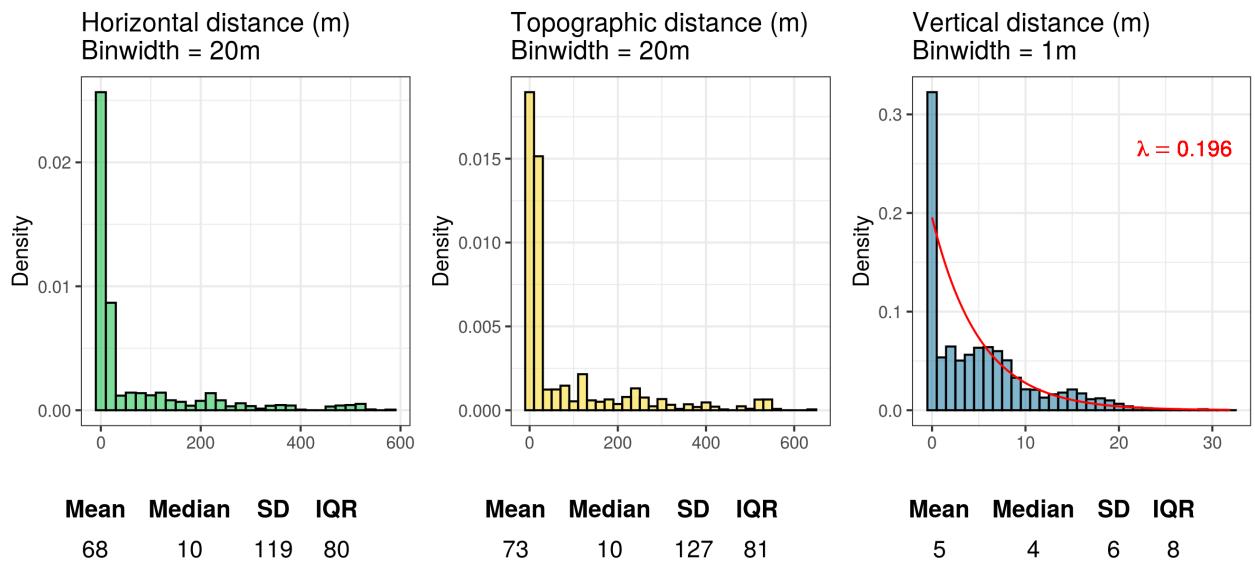
A**B**

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.

352 sea- and site polygon as having a distance of zero. If one accepts this, the probability density function for
353 exponential decay can be used to characterise the vertical distance between sites and the shoreline, and be
354 used to inform a method for shoreline dating that takes this into account.

355 6 Shoreline dating

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

$$p(\alpha - D) = \lambda e^{-\lambda(\alpha - D)} \quad (1)$$

365 where λ is the decay ratio. This can then be coupled with the trajectory of relative sea-level change to find
366 the corresponding calendar date T for the occupation of the site. This is defined by a uniform probability
367 density function over the range between the lower T_l and upper T_u bounds of the displacement curve that
368 has been interpolated to the site location:

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

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

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

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

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

373 An example of an implementation of the outlined approach is given in Figure 8, where $\lambda = 0.168$. This is the
374 decay ratio identified when considering all of the pre-Late Neolithic simulation results (Figure 7A). For the
375 numerical implementation, D is here stepped through as a sequence of increments of 0.001m, starting from the
376 site elevation α . The exponential function is stepped through in its cumulative form, where the probability
377 from the previous 0.001m step is subtracted from the probability at the current step. This probability is then
378 divided equally across the individual calendar years in the range between the lower and the upper limit of
379 the displacement curve at the current 0.001m step. The histogram that is the resulting shoreline date is the
380 sum of performing this procedure on all possible 0.001m values of D , which in practice is until $\alpha - D = 0$ or
381 when 99.999% of the exponential function has been covered.

382 In Figure 9 the outlined procedure is used to shoreline date all of the sites from where this relationship
383 was derived, with the Late Neolithic sites also included for illustrative purposes. Following from having
384 defined the distance between intersecting sea- and site polygons as zero during simulations, the sites were
385 all dated using the mean elevation of the site polygons to allow for some variation in elevation over the site
386 limits. The synchronicity between radiocarbon and shoreline dates was then evaluated using the method

387 presented by Parnell et al. (2008). Here, 100,000 age samples drawn from the probability distribution of each
 388 shoreline date were subtracted from 100,000 age samples drawn from the corresponding modelled ^{14}C -dates.
 389 The resulting range of the 95% highest density region (HDR, Hyndman 1996) was then checked to see if
 390 it crosses zero, in which case the dates are considered to be in agreement (Figure 10). When excluding
 391 the earliest occupation phase at Gunnarsrød 5, the deviation of which is to be expected based on issues
 392 with the DTM (see above), the shoreline date correspond to the radiocarbon dates in 58 out of 68 cases
 393 (84%). Only including dates modelled to be older than 2500 BCE with 95% probability, i.e. older than the
 394 Late Neolithic, improves this to 56 out of 62 cases (90%). When only including dates older than 4000 BCE
 395 with 95% probability, i.e. only Mesolithic site phases, the success rate is further increased to 46/49 (94%).
 396 The three failed Mesolithic shoreline dates are from the early sites Langemyr and Kvastad A2, with the
 397 likely implication that a lower decay ratio than what is used for characterising the distance between site
 398 and shoreline for all sites in aggregate should be used for sites known to be from the earliest part of the
 399 Mesolithic (see also Figure 6).

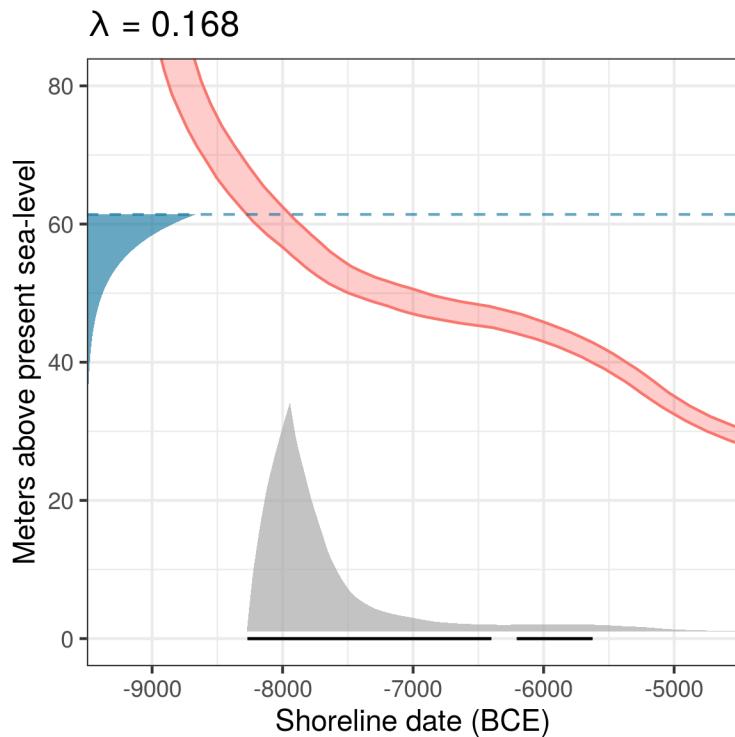


Figure 8: Shoreline dating of Hegna vest 1. The dashed line marks the mean elevation of the site polygon which is used to inform α in the dating of the site. The exponential function decays with ratio λ from Figure 7A. The resulting shoreline date in grey is underlined with the 95% HDR in black.

400 7 Re-dating previously shoreline dated sites

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

407 The comparison with previously reported dates is an illustrative, but unfair exercise for a few reasons. First

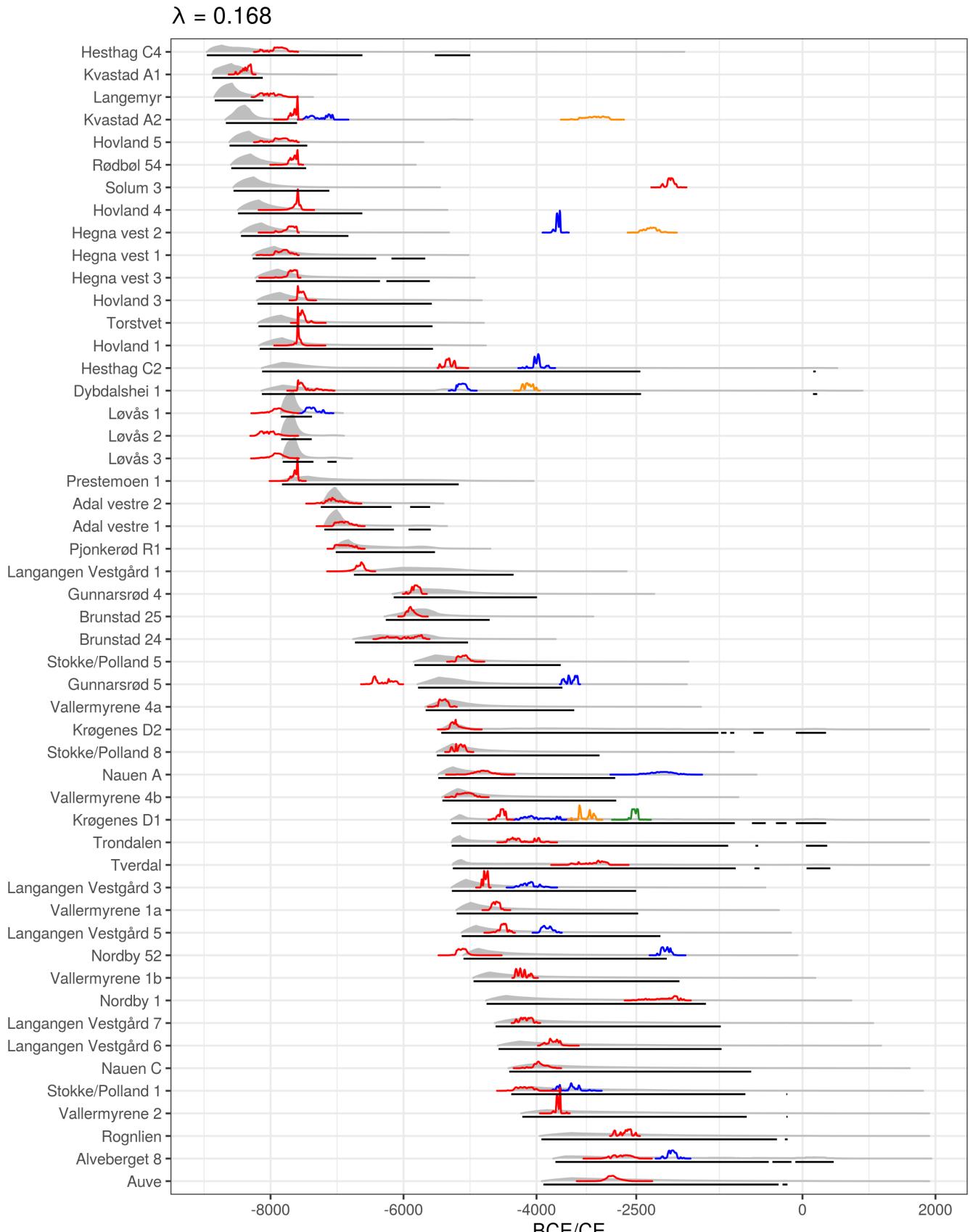


Figure 9: The result of backwards shoreline dating the sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined¹⁷ with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which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

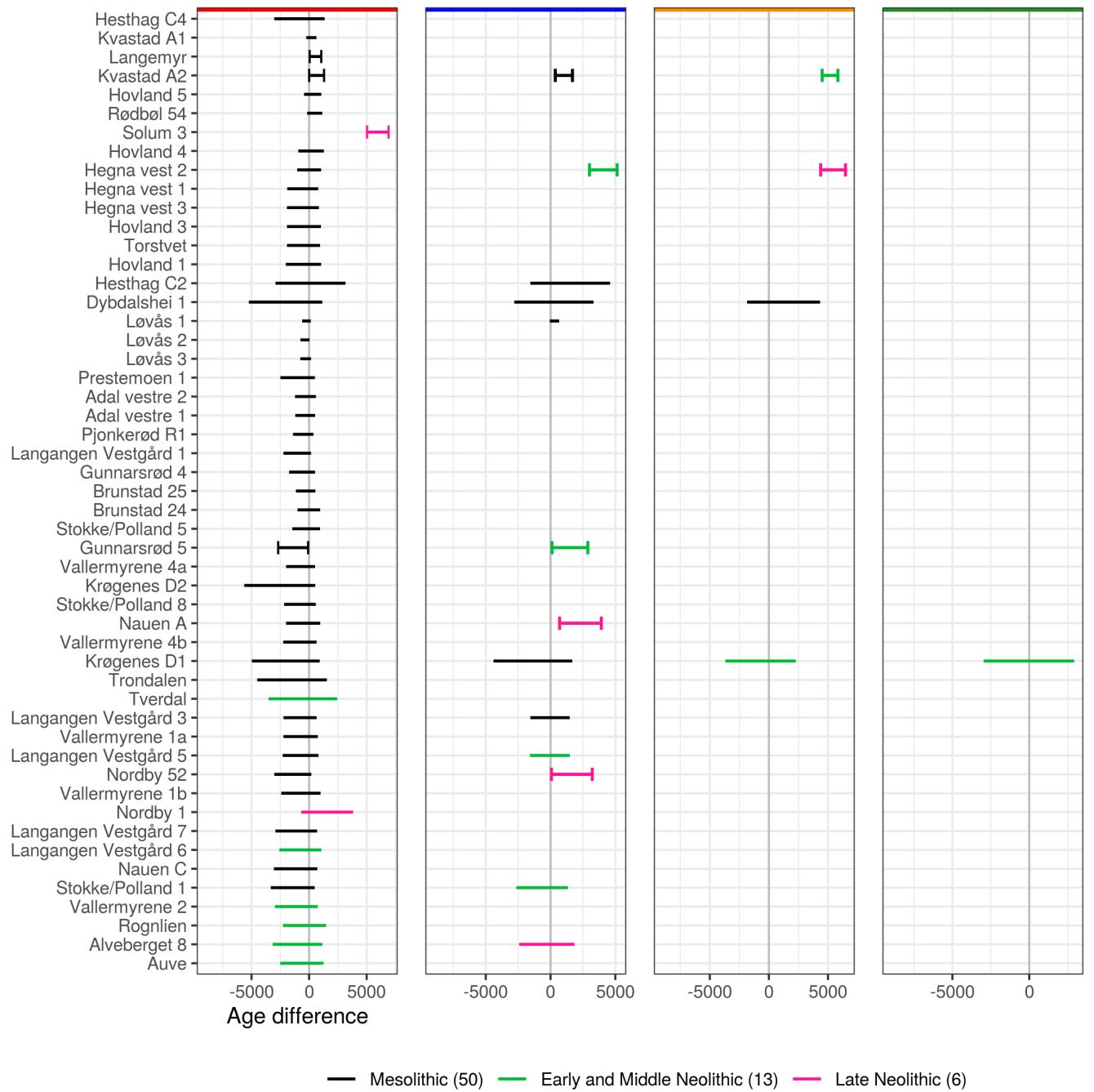


Figure 10: Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Figure 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does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

408 of all the dates provided in the reports are typically stated to be a very rough estimate, and are sometimes
409 given as a point estimate with an undefined, but implied or explicit uncertainty range. Secondly, seeing as
410 these reports are from various dates in time, many are based on now outdated data on RSL-change. Finally,
411 they are sometimes only meant to indicate a lower bound for when the sites could have been in use. Overall,
412 the results could, with some danger of circularity, suggest that shoreline dating has generally been applied
413 with a fairly reasonable degree of success, seeing as these dates have typically been interpreted and informed
414 research in an approximate manner (although see e.g. Roalkvam 2022). That being said, the results do also
415 indicate that shoreline dating has at times been applied with an exaggerated degree of precision. While
416 the implications of a more stable RSL-change for shoreline dating are well known, this also appears to be
417 somewhat under-appreciated in the practical implementation of the method. The results also highlight the
418 spatial and temporal contingency of the method, illustrated by the variation in the range of the 95% HDRs
419 for the dates. In some cases the method provides a very precise date range and in others it offers little more
420 than a *terminus post quem*. This is dependent on the steepness of the displacement curves, leading to the
421 general pattern of older sites situated towards the north-east getting more precise dates (cf. Figure 2B).
422 Furthermore, as some of the date ranges extend well beyond major chronological divisions, even into the
423 Iron Age, they could be severely and securely constrained with only cursory reference to typology. While
424 this would be trivial in some cases, the nature and uncertainty inherent to the method still means that this
425 is arguably a required exercise that should be explicitly performed. This also points to the possibility of
426 drawing on other temporal data, for example within a Bayesian framework, to further improve the precision
427 of the dates that can be achieved with shoreline dating.

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

442 The small discrepancies between the achieved results mainly follow from the fact that a slightly updated
443 version of the local displacement curve is applied here (cf. Sørensen et al. in prep). Jaksland's dates are
444 given a flat 200 and 50 year uncertainty range starting from what he gives as the earliest possible date. The
445 200 year uncertainty range is given if the sites were to be considered in isolation, while his argument for the
446 uncertainty range of only 50 years is based on the location of the sites relative to each other. Since they
447 are located in such a constrained and steep area of the landscape, the difference in elevation between the
448 sites is argued to establish their relative date and thus constrain the uncertainty ranges so that they don't
449 overlap. This information is not integrated in the approach outlined here, but could justify further reducing
450 the uncertainty ranges.

451 Although their accuracy is of course ultimately dependent on the veracity of the geological reconstruction,
452 the high rate of RSL-change in this period does result in very precise dates. Above it was suggested that
453 additional temporal data could be combined with the method to improve its accuracy and precision. Drawing
454 on Jaksland (2014), this example instead highlights the fact that the spatial nature of the method means
455 that a consideration of the surrounding terrain and other sites can also help in increasing the precision of
456 the method if this can be used to exclude certain sea-levels as unlikely for when a site was in use. One
457 approach could also be to assess the spatial implication of a proposed shoreline date by simulating the
458 adjusted sea-levels, as is done for Pauker 1 in Figure 12B, followed for example by a visual evaluation of the
459 topography or by evaluating the distance and steepness of the slope to the shoreline. If this is developed

$$\lambda = 0.168$$

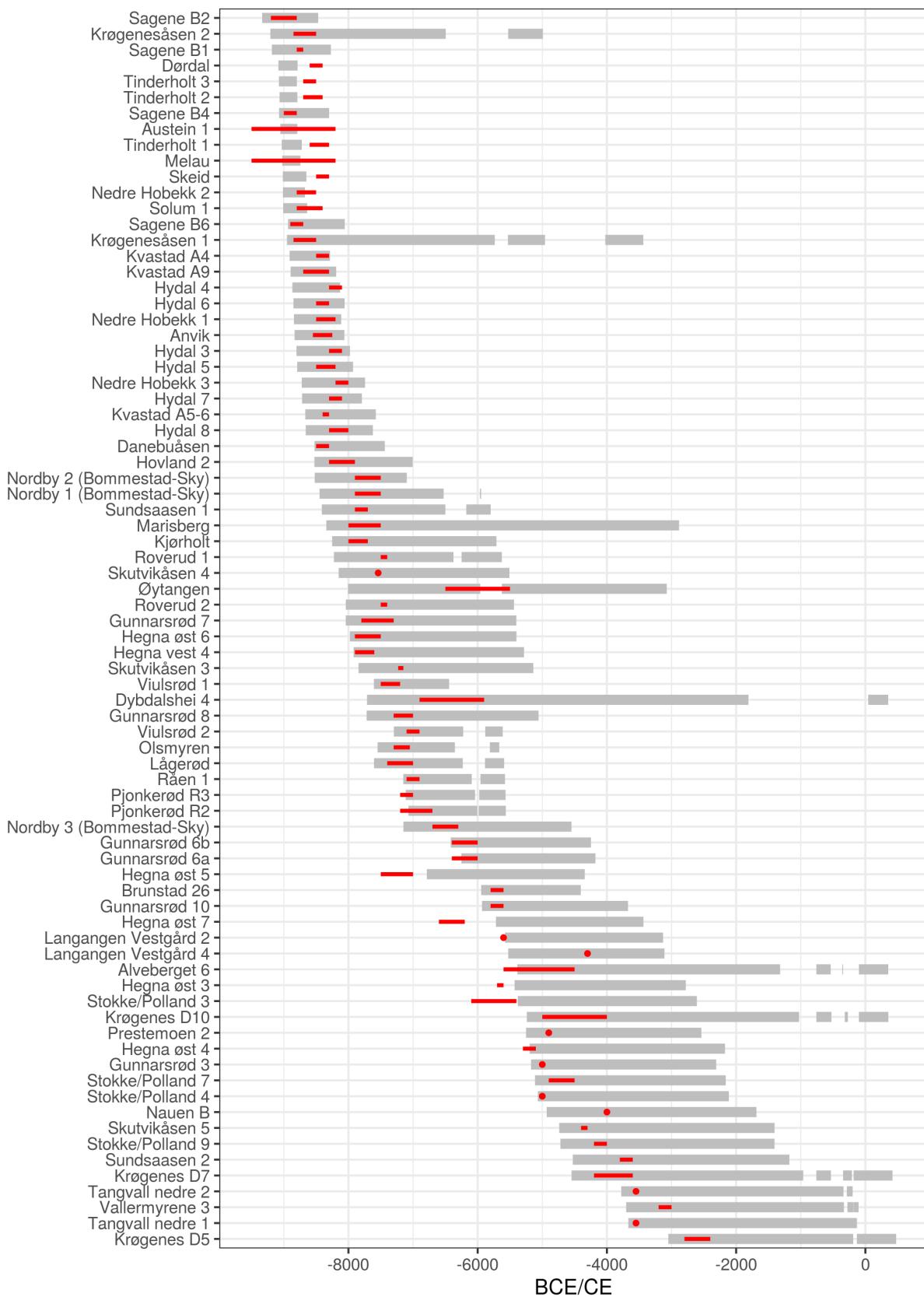


Figure 11: Re-dating excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey²⁰ are compared to the dates originally proposed by the excavation reports in red.

460 further, it could conceivably be possible to exclude certain elevations as unlikely for the position of the
 461 shoreline when the site was in use. Such approaches would make less of an impact in this setting, where the
 462 95% HDR is already quite constrained, but could considerably improve the precision of the method in cases
 463 where RSL-change has been less severe (cf. Figure 11).

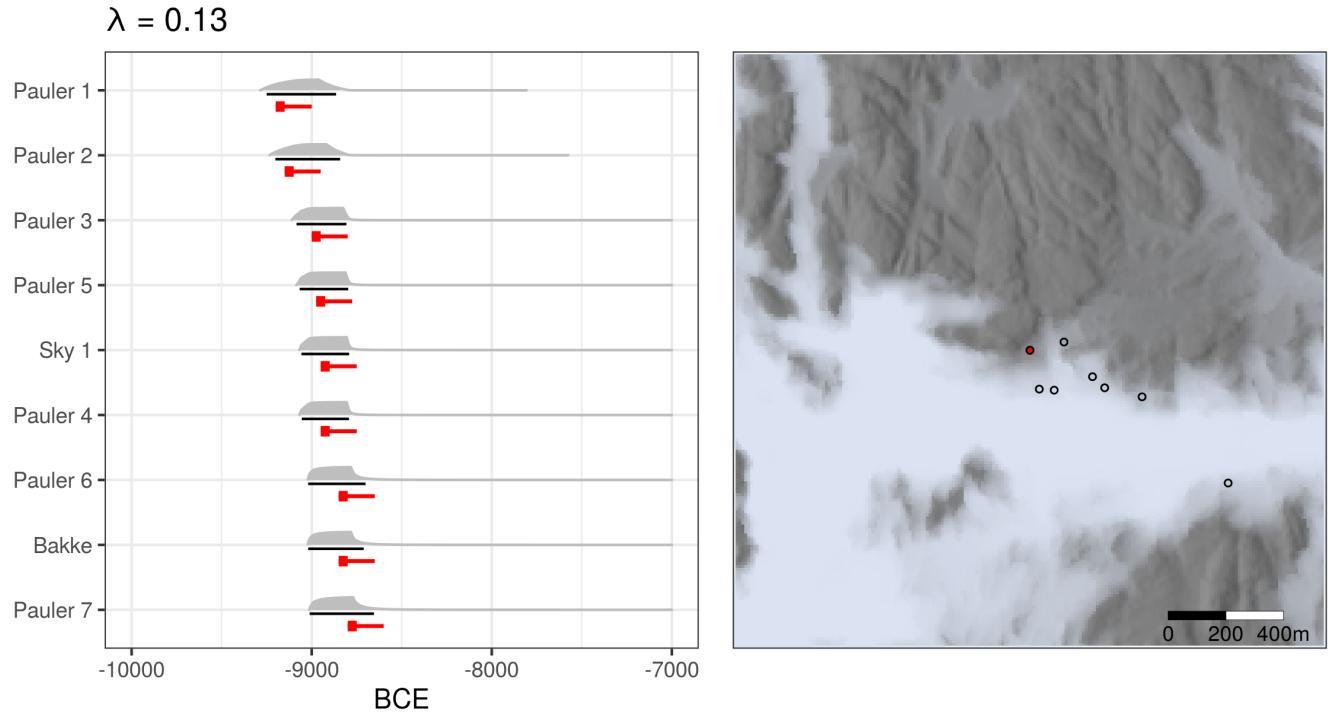


Figure 12: Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red.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

464 8 Concluding remarks

465 The most immediate contribution of this paper is what must be considered a confirmation of previous research
 466 into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated
 467 by the close relationship between sites and the shoreline up until the transition to the Neolithic at c. 4000

468 BCE, after which a couple of sites become situated some distance from the sea, followed by a more decisive
469 break at the transition to the Late Neolithic at c. 2500 BCE. This development is in clear agreement with
470 the literature. Furthermore, based on the quantitative nature of these findings, an initial formulation of
471 a refined method for the shoreline dating of pre-Late Neolithic Stone Age sites has been proposed. Apart
472 from taking the distance between sites and the isobases of the displacement curves into consideration when
473 dating the sites, this involves accounting for the distance between the sites and the shoreline. When no other
474 information is available, it can at present be recommended to use the empirically derived exponential decay
475 ratio of 0.168 (Figure 11A) to characterise this relationship. Furthermore, while this remains to be formalised
476 and explored further, it was also showed how the method can be improved by including more information,
477 both with reference to the topographic location of the sites and other temporal data. As the precision of
478 the method is both geographically and temporally contingent due to the trajectory of RSL-change, where
479 older sites situated towards the north-east in the study area will get a more precise date, the impact of such
480 additional information will also vary.

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

496 Some limitations and sources of likely variation and uncertainty that have not been considered should also
497 be mentioned. First of all the sample size is strained and the future addition of more sites might alter the
498 picture considerably. Secondly, the validity of the outlined method was evaluated by applying it to the data
499 from where the input parameters were derived. Fitting and evaluating a model using the exact same data will
500 likely exaggerate its performance. Thirdly, the DTM has only been corrected for major modern disturbances.
501 This means that other forms of erosion, although likely not that prevalent, has not been taken into account.
502 Fourthly, the DTM has a vertical error which could also benefit from being integrated in the analysis (cf.
503 Lewis 2021). Fifthly, the displacement curves were here interpolated to all site locations without accounting
504 for increased uncertainty as one moves further away from the isobases of the displacement curves. This is
505 also related to the fact that the RSL data can be handled in different ways than with the isobase method
506 that has been used for the compilation of the employed displacement curves. Sixthly, neither the question of
507 how site limits are defined nor the elevation range over which these extend was given much consideration (cf.
508 Mjærum 2022). Finally, the radiocarbon dates and division of settlement phases at each site was here simply
509 done by treating radiocarbon dates not overlapping at 99.7% as representing unrelated occupation events.
510 This could also be handled differently (e.g. Bronk Ramsey 2009, 2015). While each of these factors will have
511 variable impact on the final results, they clearly represent dimensions which would all benefit from further
512 consideration and which means that some of the precision following from the outlined approach is likely to be
513 spurious.

514 Given that shoreline dating is contingent on regularities in human behaviour it should naturally be applied
515 with care. Furthermore, formulating and visualising the method along the lines of how radiocarbon dates
516 are treated, as was done here, does stand the chance of giving a veneer of radiometric accuracy that is
517 not warranted. That being said, the best chance we have of not throwing away precious temporal data, or
518 exaggerating our handle on it, is arguably to rigorously evaluate the method using independent data such as
519 radiocarbon dates, by offering a precise formulation of how it could be applied, by specifying what sources of

520 uncertainty are accounted for and by making this process transparent through the open dissemination of
521 underlying data and programming code.

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

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