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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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6 09 November, 2022

7 **Abstract**

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

23 **Highlights**

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

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

29 **1 Introduction**

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

<sup>38</sup> Gjerde 2021; Løken 1977; Nordqvist 1995; Schmitt et al. 2009; Sognnes 2003; Tallavaara and Pesonen 2020;  
<sup>39</sup> Wikell et al. 2009).

<sup>40</sup> The close association between Stone Age settlements in the northern parts of Scandinavia and shifting  
<sup>41</sup> prehistoric shorelines was proposed at the end of the 19th century (De Geer 1896), and was first applied  
<sup>42</sup> as a dating method at the turn of the century (Brøgger 1905; Hollender 1901). Shoreline dating has been  
<sup>43</sup> fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen 2009; Bjerck 1990, 2008a;  
<sup>44</sup> Breivik 2014; Johansen 1963; Mansrud and Persson 2018; Mikkelsen 1975a; Mjærum 2022; Nummedal 1923;  
<sup>45</sup> Olsen and Alsaker 1984; Shetelig 1922; Solheim et al. 2020; Solheim and Persson 2018). The method is  
<sup>46</sup> used both independently, and to compliment other sources of temporal data such as typological indicators or  
<sup>47</sup> radiometric dates. However, given the coarse and fuzzy resolution of established typological frameworks, the  
<sup>48</sup> vast number of surveyed sites that only contain generic lithicdebitage that could hail from any part of the  
<sup>49</sup> period, and as the conditions for the preservation of organic material is typically poor in Norway, dating with  
<sup>50</sup> reference to shoreline displacement is often the only and most precise method by which one can hope to date  
<sup>51</sup> the sites. Shoreline dating is consequently fundamental to our understanding of the Norwegian Stone Age.  
<sup>52</sup> This is both because it is central to the temporal framework on which our understanding of the period is  
<sup>53</sup> based, but also because the method is only applicable so long as the societies in question have continuously  
<sup>54</sup> settled on or close to the contemporary shoreline. Consequently, adherence or deviation from this pattern  
<sup>55</sup> also has major implications for the socio-economic foundations of the societies in question.

<sup>56</sup> Despite its important role for Fennoscandian archaeology, the applicability of dating by reference to shoreline  
<sup>57</sup> displacement has only been evaluated using relatively coarse methods. The aim of this paper is to provide a  
<sup>58</sup> systematic and comprehensive review of the degree to which radiocarbon dates correspond with the dates  
<sup>59</sup> informed by our current knowledge of shoreline displacement in a larger area of south-eastern Norway, using  
<sup>60</sup> a more refined methodological approach. The goal here is to quantify the degree to which the assumption of  
<sup>61</sup> shore-bound settlement holds through the Stone Age in a relatively well sampled portion of Scandinavia,  
<sup>62</sup> and in turn have this quantification inform the development of a formalised method for shoreline dating.  
<sup>63</sup> As presented in more detail below, this problem involves the combined evaluation of three major analytical  
<sup>64</sup> dimensions. One is the questions of when the sites were in use, the second pertains to the reconstruction of  
<sup>65</sup> the contemporaneous sea-level, and the third follows from the fact that the relation between site and shoreline  
<sup>66</sup> is inherently spatial. Taking inspiration from studies that have integrated various sources of spatio-temporal  
<sup>67</sup> uncertainty through Monte Carlo simulation (e.g. Bevan et al. 2013; Crema et al. 2010; Crema 2012, 2015;  
<sup>68</sup> Yubero-Gómez et al. 2016), a similar approach is adopted here and adapted to post-glacial sea-level change  
<sup>69</sup> and the Stone Age settlement of southern Norway.

## <sup>70</sup> 2 Background

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

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

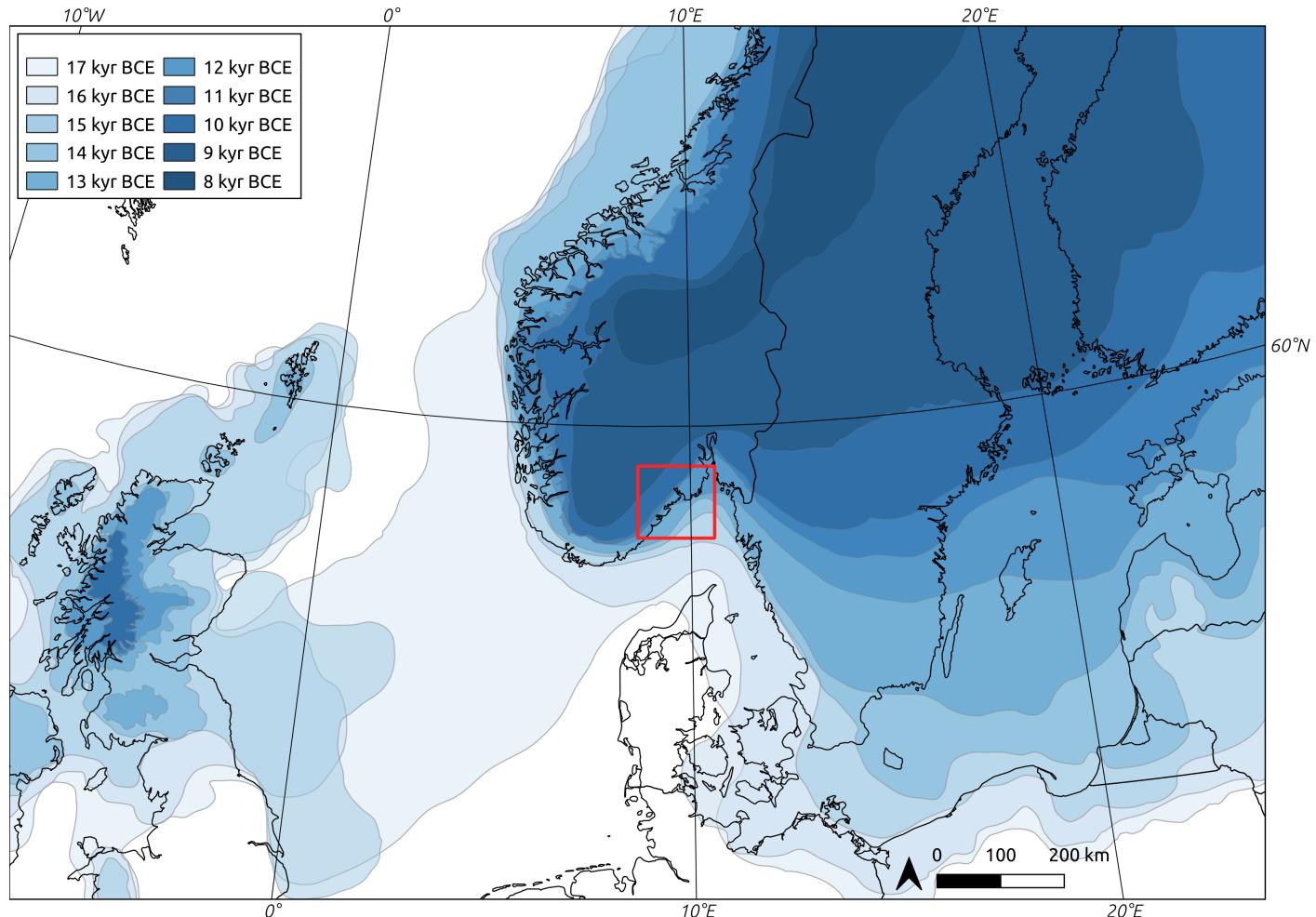


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 thousand years (kyr) BCE. The study area defined later in the text is marked with a red outline (deglaciation data from Hughes et al. 2016, but see also Romundset et al. 2019 in relation to the study area).

103 The method of shoreline dating has been met with scepticism as related to the fundamental premise that most  
 104 sites would have been consistently shore-bound, it has been characterised as a relative dating method for sites

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

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

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

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

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

### 195 3 Data

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

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

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

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

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

Three of the sites have been associated with agriculture, either directly or in the form building structures. The first is Nordby 1 at which the  $^{14}\text{C}$ -dates are associated with a Late Neolithic long-house (Gjerpe and Bukkemoen 2008). The Middle Neolithic phase at Kvastad A2 (Stokke and Reitan 2018) and Late Neolithic phase at Nauen A (Persson 2008) are both directly related to farming activities. Both of these sites also have radiocarbon dates and lithic inventory associated with Mesolithic forager activities. Following from the expected deviance from the settlement patterns that are to characterise forager sites, these agricultural phases are highlighted in the analysis below. Finally, Nielsen (2021) has recently suggested that Early and Middle Neolithic features from the otherwise younger sites Bratsberg (Wenn 2012) and Larønningen (Røberg 2012) could be related to early agricultural activity in the Oslo fjord region. Due to the uncertain and somewhat speculative nature of this suggestion, these are omitted here.

The elevation data used for the analysis is a digital terrain model (DTM) freely available from the Norwegian Mapping Authority (Norwegian Mapping Authority 2018, <https://hoydedata.no>). The 10m resolution DTM

259 was used rather than the higher-resolution 1m version, both because this resulted in considerably less  
260 processing time and because the higher resolution elevation model is more vulnerable to smaller-scale modern  
261 disturbances. The 10m resolution DTM of the study area is a down-sampled version of the 1m version and  
262 has a height accuracy with a systematic error of 0.1m (Norwegian Mapping Authority 2018). All data and R  
263 programming code (R Core Team 2021) required to run the analyses, as well as the derived data are freely  
264 available in an online repository at <https://osf.io/7f9su/>, organised as a research compendium following  
265 Marwick et al. (2018).

## 266 4 Methods

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

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

293 Armed with a likely date range for the occupation(s) of each site, an estimated trajectory of RSL change at  
294 that location, and a DTM edited to remove substantial modern disturbances, the simulations were performed.  
295 A single simulation run involved first drawing a single year weighted by the posterior probability distribution  
296 of a given occupation phase of a site (Figure 4). This year then has a corresponding likely elevation range for  
297 the contemporaneous shoreline from which an elevation value was drawn uniformly, using intervals of 5cm.  
298 The sea-level was then raised to this elevation on the DTM by defining all elevation values at or below this  
299 altitude as missing. Polygons were then created from the resulting areas with missing values. The horizontal  
300 distance was then found by measuring the shortest distance between site and sea polygons, and the vertical  
301 distance by subtracting the elevation of the sea-level from the lowest elevation of the site polygon. The  
302 topographic distance between site and sea was also found by measuring the distance while taking into account  
303 the slope of the terrain on the DTM. This was done using the topoDistance package for R (Wang 2019). The  
304 topographic distance was measured between the points on the site and sea polygons that were identified  
305 as being the closest when measured horizontally. Because it is measured as the shortest topographic path  
306 between the horizontally closest points, this means that the distance does not necessarily match the closest  
307 topographic distance if the entirety of the polygons had been considered. Not finding the topographically

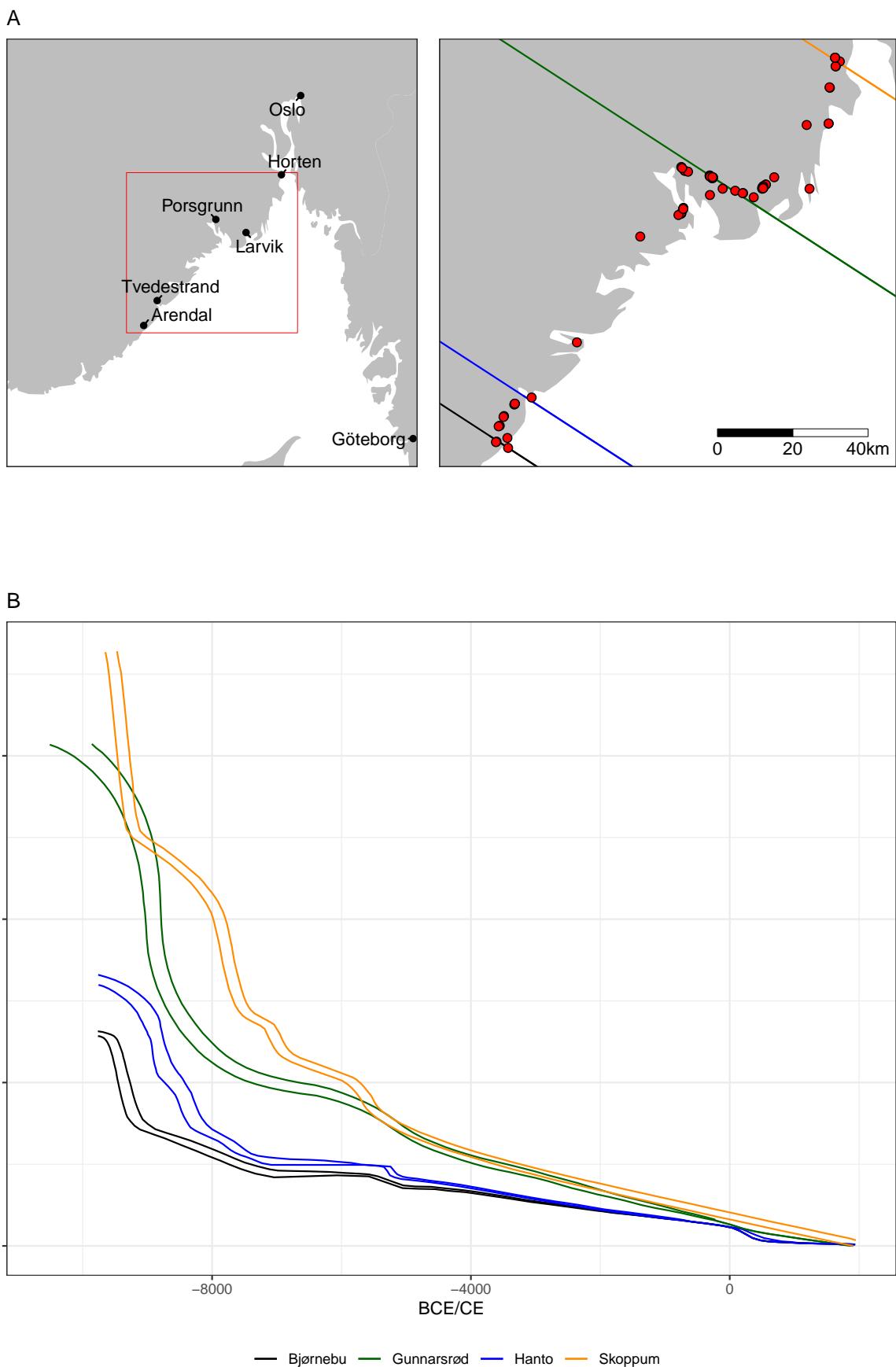


Figure 2: A) Location of the study area and the distribution of the 66 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of  $327^\circ$  (Romundset et al. 2018, although see Sørensen et al. 2014) & B) Displacement curves. Note the increasing steepness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

closest points significantly reduced the computational cost of the analysis, and is deemed unlikely to have a considerable impact on the results, given the distances considered. The shortest topographic path was found using the Moore neighbourhood of eight cells (e.g. Conolly and Lake 2006:253; Herzog 2013).

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

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

## 5 Simulation results

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

Another immediately striking result is the apparent deviation from the shoreline towards the end of the Stone Age. After around 2500 BCE several sites are situated a considerable distance from the reconstructed shoreline, and while a couple remain horizontally and topographically close, most appear to be considerably elevated above the sea-level. Of the results from after 2500 BCE, which are associated with 8 sites, only 1 has simulation results for vertical distance that includes zero. The highest simulated vertical distance among these is 56.5m and the median is 12.9m. Furthermore, some deviation is evident from just after 4000 BCE well. The sample size is limited, but of the 21 sites associated with the period between 4000 and 2500 BCE, 2 sites have all vertical distance results above 25m. However, the median vertical distance of the results from this period is only 4.3m, indicating that while some sites have a markedly withdrawn location, most are still situated close to the shoreline. The chronological smearing following from the uncertainty in the  $^{14}\text{C}$ -dates means that while the results cannot be used to directly inform discussions that deal with the century scale around these chronological transitions (e.g. Prescott 2020; Solheim 2021), the findings are nonetheless in clear agreement with the general chronological developments suggested in the literature.

The negative values around 8000 BCE originate from the sites Løvås 1, 2 and 3. Berg-Hansen et al. (2022:644) made a similar observation in their assessment of the correspondence between shoreline displacement and radiocarbon dates from these sites. These are recently excavated, well-dated sites situated in a relatively undisturbed area of the landscape (Berg-Hansen et al. 2022; Reitan and Hårstad 2022). While there could be

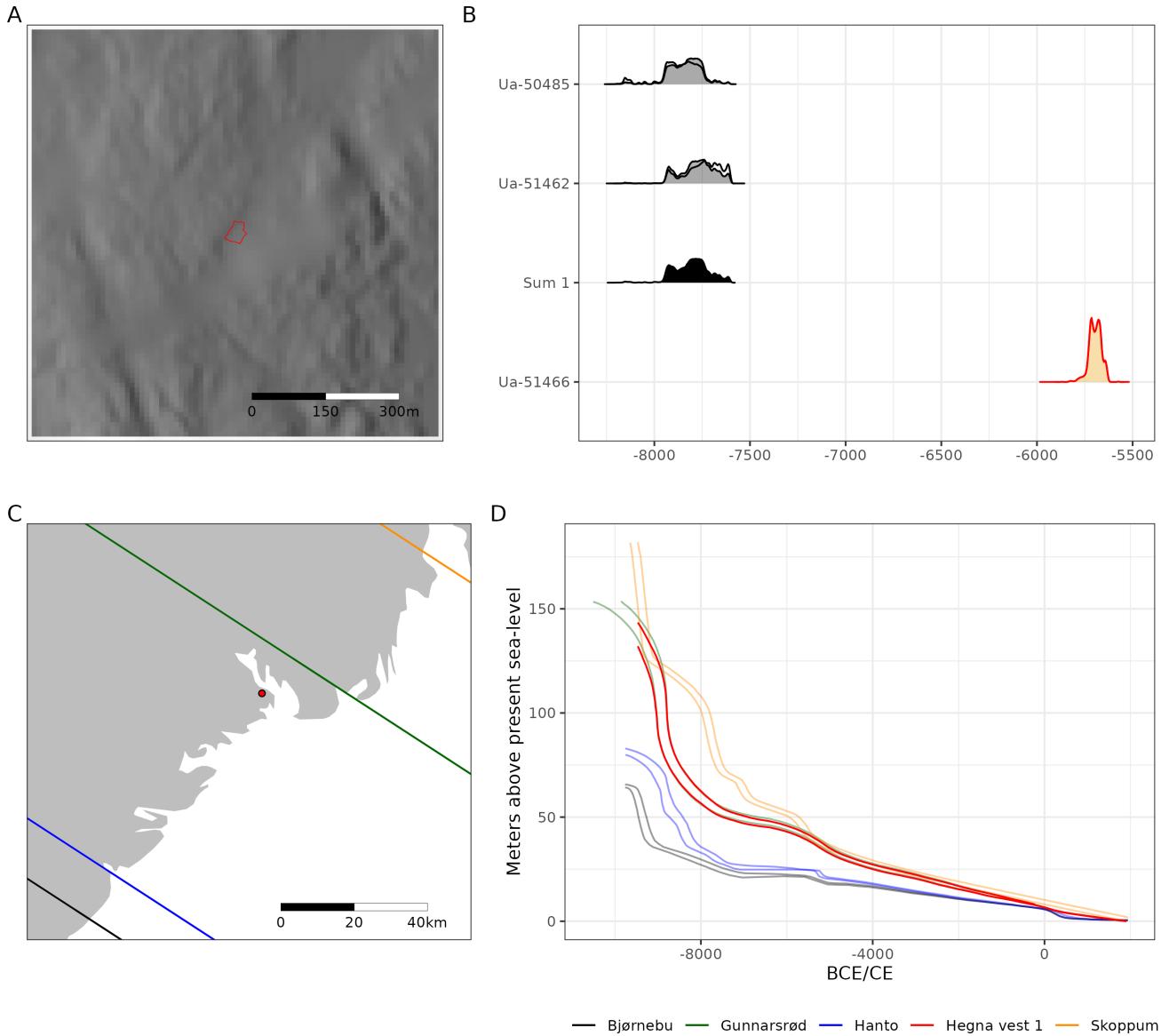


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site on the edited 10m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled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

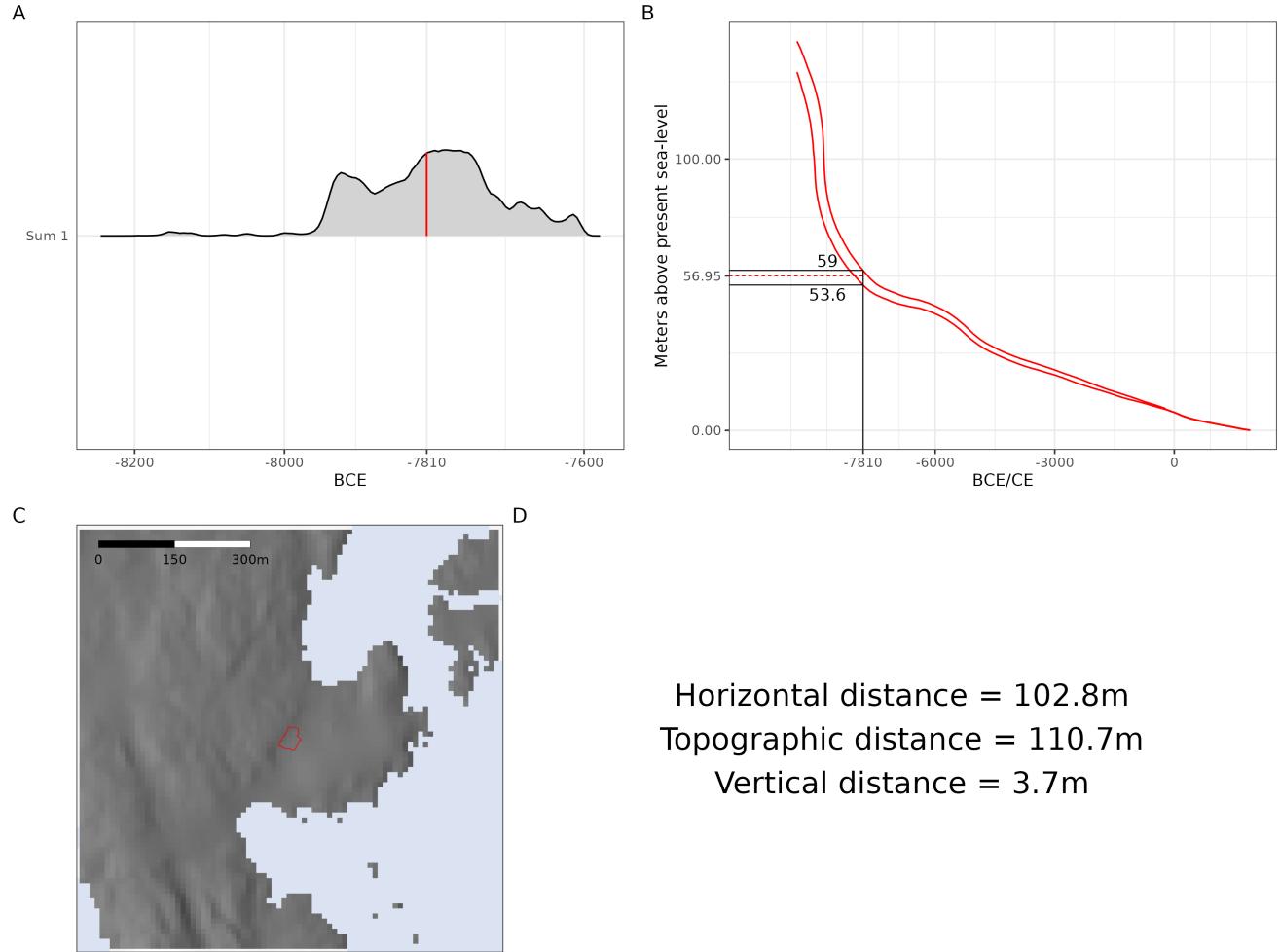


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year, weighted by the the posterior probability distribution. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly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

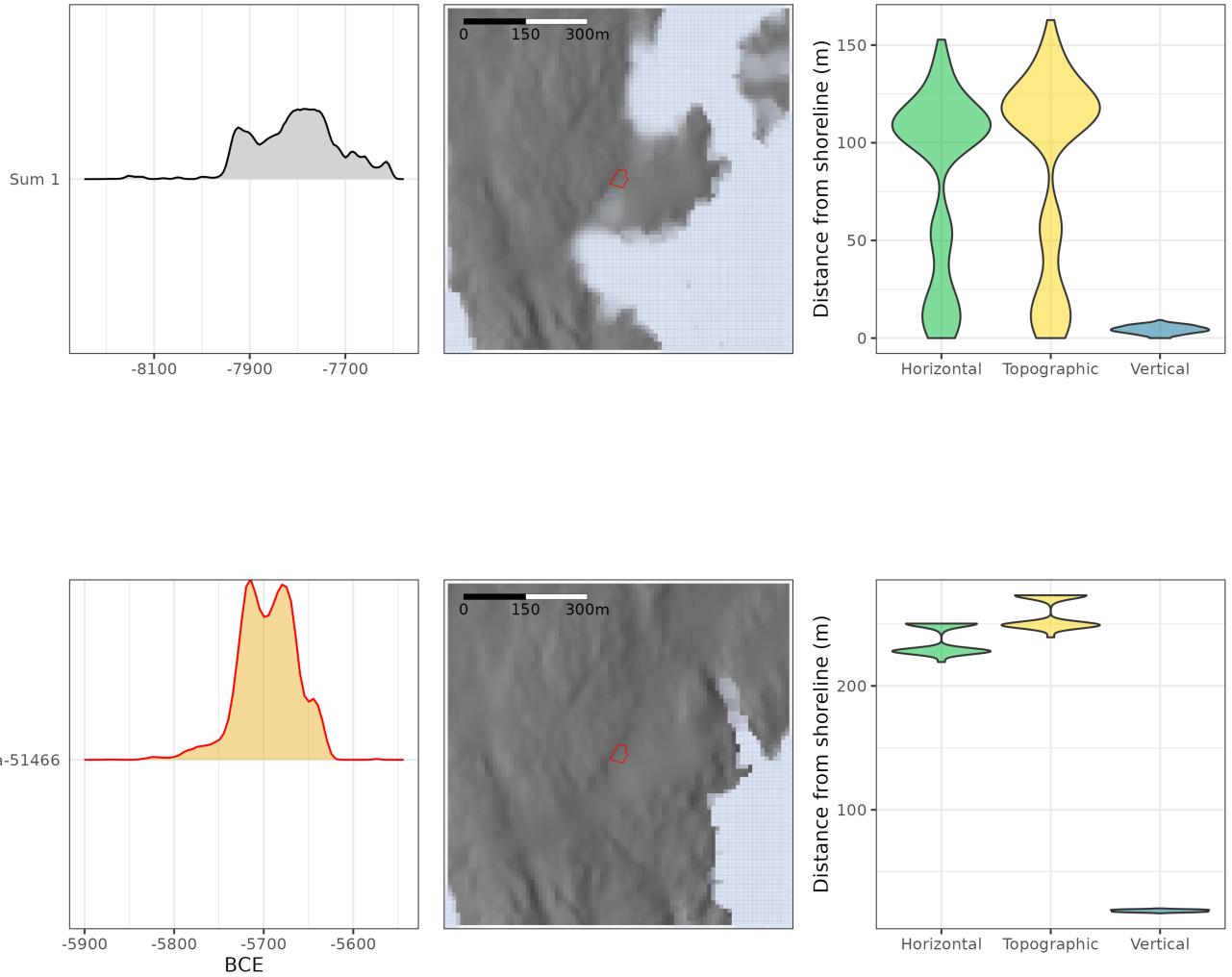


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The leftmost column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The centre column displays the result of simulating the raised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

356 a danger of circularity of having archaeological sites inform a reconstruction RSL-change, and, in turn, use  
357 these to evaluate the degree of shore-bound settlement, the sites do clearly represent an upper constraining  
358 limit for the sea-level, as they would not have been in use when located under water. It therefore seems  
359 that the Løvås sites represent a case where the archaeological material indicates a slight discrepancy in the  
360 geologic reconstruction of shoreline displacement in the area.

361 Accepting that shoreline dating appears to lose utility around the transition to the Late Neolithic, as indicated  
362 by the clear deviation in site location from the shoreline after this, the results from Figure 6B are presented  
363 again in Figure 7A, excluding all simulation results younger than 2500 BCE. Furthermore, all negative values  
364 have here been set to zero, under the assumption that these result from uncertainty or errors in the data,  
365 and not actual site locations. The resulting best point estimate for the vertical distance between sites and  
366 shoreline for the pre-Late Neolithic is given by the median distance of 4m, while 95% of the values fall within  
367 the range 0–18m. That is, for 95% of the cases, the shoreline was simulated to be situated on or lower than  
368 18m below the site location. While these values remain the same when only the Mesolithic dates are included  
369 (Figure 7B), the mean and standard deviation are slightly constrained. Furthermore, while the median for  
370 horizontal and topographic distance is only 10m across all plots in Figure 7, the magnitude of the statistics  
371 for dispersion is greater than what it is for vertical distance, illustrating the point that minor variations in  
372 vertical distance can have substantial consequences for these distance measures, depending on the surrounding  
373 topography.

374 It is clear that the distributions in Figure 7 have a severe right skew. Most sites were likely situated less  
375 than a meter from the shoreline, and from this there is a sharp decline in density as one moves further along  
376 the x-axes. To characterise this relationship, a series of standard models for distributions with a right skew  
377 have been fit to the simulation results for vertical distance older than 2500 BCE (Figure 7A) by means of  
378 maximum likelihood estimation (Table 1). As most of the models only accept positive values a constant of  
379 0.001 was added to avoid values of zero. It was attempted to both remove negative values and force these to  
380 zero before adding the constant. As the difference between these two solutions was negligible, and as the  
381 assumption here is that negative values in actuality reflect a distance of zero, the latter approach was chosen  
382 (a plot displaying the negative values and the compared models is available in the supplementary material).

383 The performance of the models was then compared by means of the Akaike information criterion (AIC)  
384 and the Bayesian (or Schwarz) information criterion (BIC). The AIC and BIC evaluate the degree to which  
385 the models fit to the data, while penalising for the number of model parameters to avoid over-fitting (e.g.  
386 Burnham and Anderson 2002; for applications in archaeology see e.g. Eve and Crema 2014; Timpson et al.  
387 2021). As lower values point to a better model, it is evident from both the AIC and BIC that the gamma  
388 is the best among the candidate models. It is worth noting that this could have benefited from a more  
389 sophisticated treatment of the zero-values. This is because these are likely to be a mix of both exact zeros,  
390 the case when there is an actual intersection between site and sea, and, although probably to a far lesser  
391 extent, zeroes that result from the case when the distance between site and sea is below the detection limit  
392 due to the employed methods and the resolution of the spatial data (e.g. Dunn and Smyth 2005; Helsel  
393 2005). In conclusion, however, the gamma appears to represent a reasonable approximation of the data. If  
394 one accepts this, the probability density function for the gamma distribution can be used to characterise the  
395 vertical distance between sites and the shoreline and be used to inform a method for shoreline dating that  
396 takes this into account.

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

Model	Parameters	AIC	BIC
Gamma	Shape ( $\alpha$ ) = 0.286	230247	230229
	Scale ( $\sigma$ ) = 0.048		
Log-normal	Mean of the logarithm ( $\mu$ ) = -0.647	268082	268064
	SD of the logarithm ( $\sigma$ ) = 3.926		
Power law	Exponent ( $k$ ) = 1.16	274052	274043
Exponential	Rate ( $\lambda$ ) = 0.168	348484	348475

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Logistic	Location ( $\mu$ ) = 4.698	415322	415304
	Scale ( $\sigma$ ) = 3.558		

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## 397 6 Shoreline dating

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

$$407 p(E - D) = \frac{1}{\sigma^\alpha \Gamma(\alpha)} (E - D)^{\alpha-1} e^{-(E-D)/\sigma} \quad (1)$$

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

$$412 p(T|E - D) = Ud[T_l|E-D, T_u|E-D] \quad (2)$$

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

$$414 p(T|E - D) = p(T|E - D)p(E - D) \quad (3)$$

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

$$416 p(T|E) = \sum_D p(T|E - D)p(E - D) \quad (4)$$

416 An example of an implementation of the outlined approach is given in Figure 8, where  $\alpha = 0.286$  and  $\sigma =$   
 417 0.048. These are the parameters for the gamma distribution identified when considering all pre-Late Neolithic  
 418 simulation results (Figure 7A) and are the parameters used in all applications of the proposed method that  
 419 follow below. For the numerical implementation,  $D$  is here stepped through as a sequence of increments of  
 420 0.001m, which, following from the adjustment of the values for fitting the gamma distribution, starts from  
 421 0.001m. The gamma distribution is stepped through in it's cumulative form, where the probability from  
 422 the previous 0.001m step is subtracted from the probability at the current step. This probability is then  
 423 divided equally across the individual calendar years in the range between the lower and the upper limit of the  
 424 displacement curve at the current 0.001m step. The probability mass function that is the resulting shoreline  
 425 date is the sum of performing this procedure on all possible 0.001m values of  $D$ , which, in practice, is down  
 426 to and including  $E - D = 0.001$  or when 99.999% of the gamma distribution has been stepped through.

427 To evaluate the outlined procedure it is used to shoreline date the sites from where the method was derived to  
 428 check if the resulting shoreline dates correspond to the radiocarbon dates associated with the sites (Figure 9).

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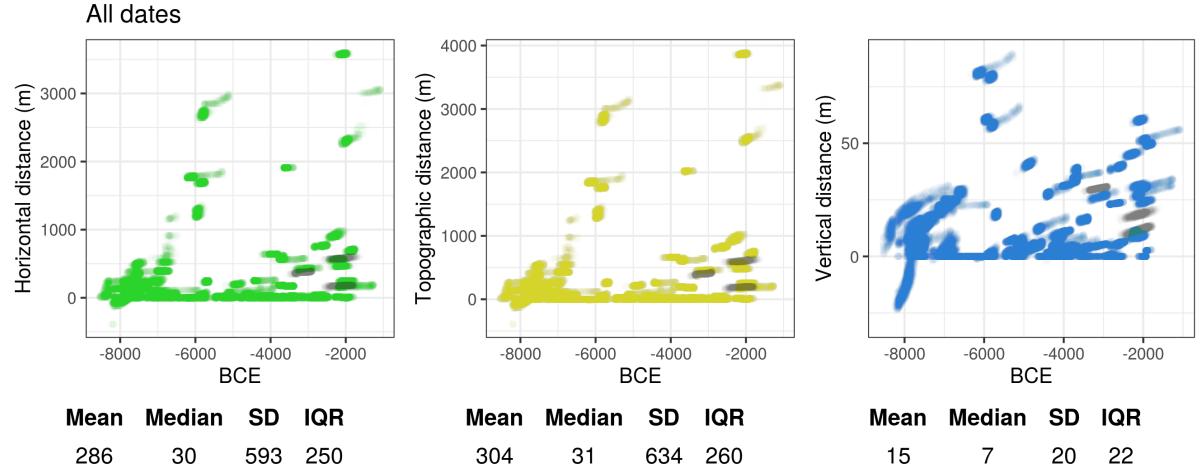
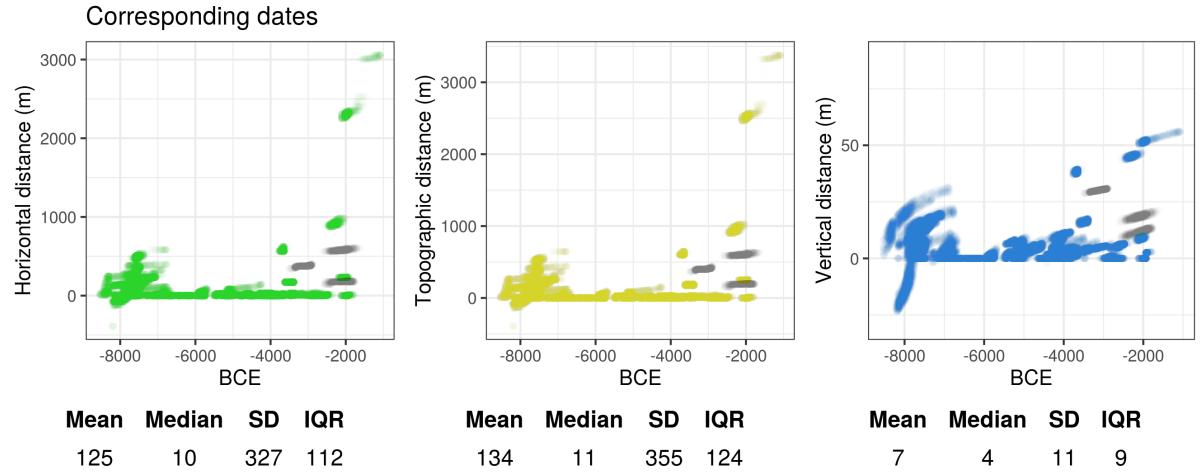
**A****B**

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 (66 sites and 166 site phases). The second row B) shows the result of excluding these (resulting in 51 sites and 69 site phases). The table under each plot lists some corresponding statistics for central tendency and dispersion.

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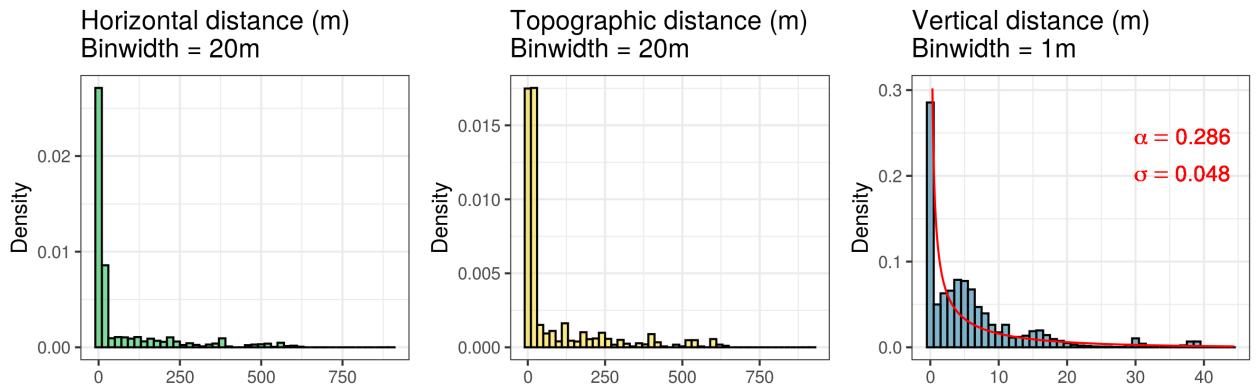
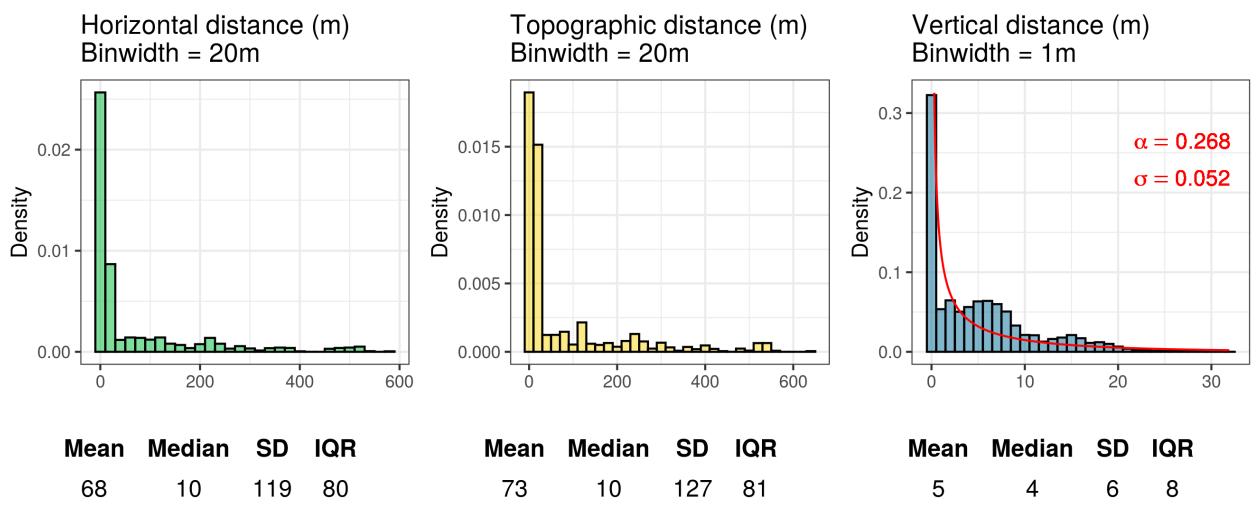
**A****B**

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

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

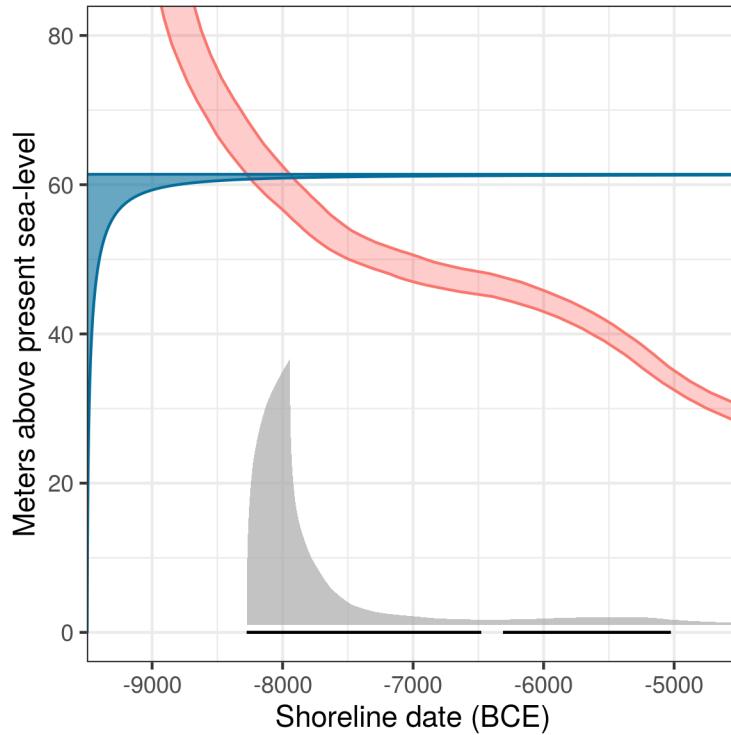


Figure 8: Shoreline dating of Hegna vest 1. The mean elevation of the site polygon is used to inform  $E$  in the dating of the site. The gamma distribution in blue on the y-axis extends the full range of possible values for  $E - D$  and has the parameters  $\alpha = 0.286$  and  $\sigma = 0.286$  (see Figure 7A). The red line marks the shoreline displacement curve interpolated to the site location. The resulting shoreline date in grey is underlined with the 95% HDR in black.

## 443 7 Re-dating previously shoreline dated sites

444 To further explore the implementation for shoreline dating presented above, 87 excavated and shoreline dated  
 445 Stone Age sites within the study area where  $^{14}\text{C}$ -dates are not available or these are not believed to date the  
 446 main occupation of the sites have been subjected to the outlined approach (Figure 11). The resulting dates  
 447 are compared to those originally proposed in the excavation reports for the sites (the numerical results are  
 448 available in the supplementary material). To avoid issues with recent disturbances in the DTM, the sites have  
 449 been dated based on the mean of the altitudes provided in the report for each site. As all of the included

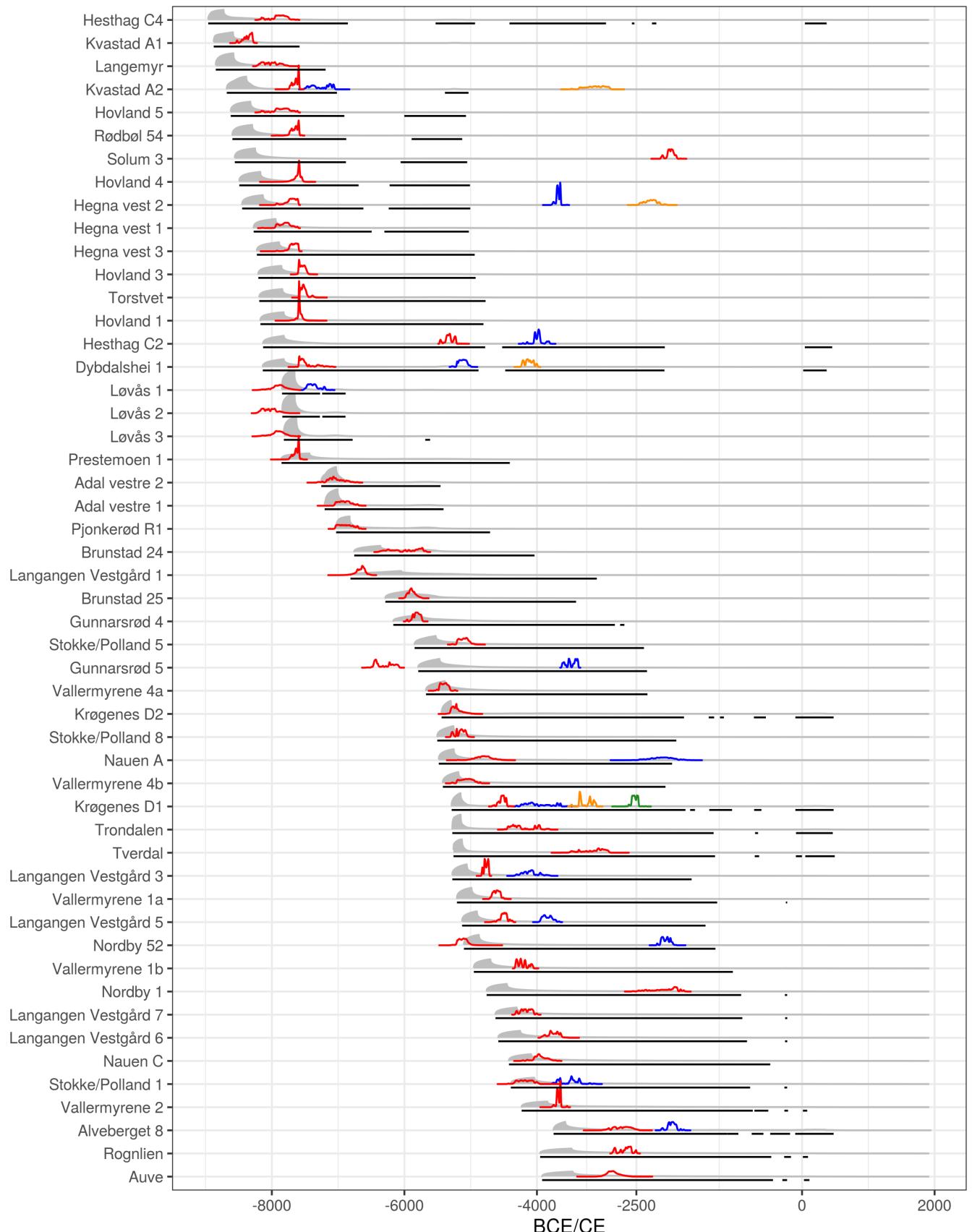


Figure 9: The result of backwards shoreline dating the 51 sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined with the 95% HDR18 in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-intersecting dates at 99.7% probability.

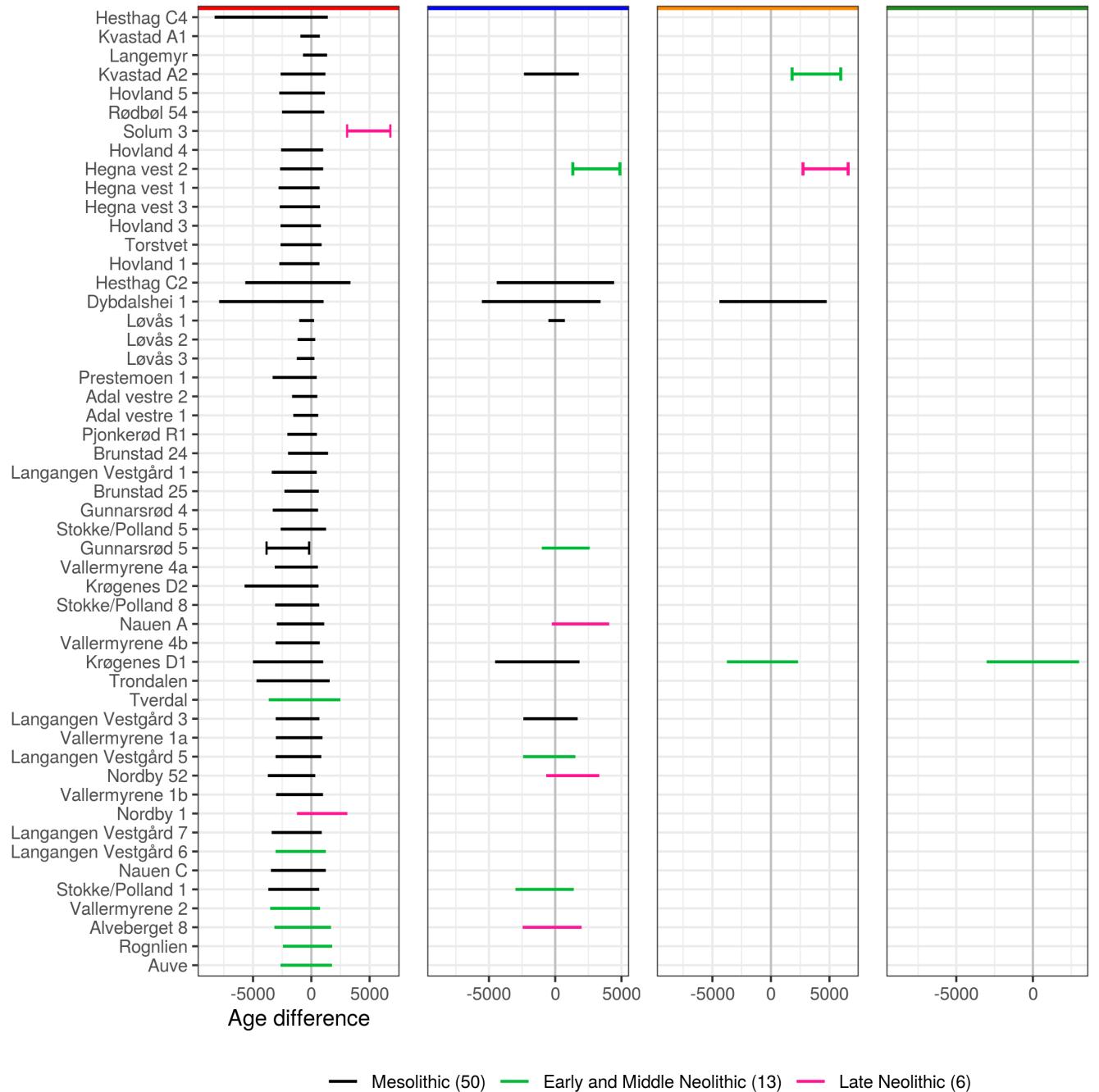


Figure 10: Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Figure 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does not cross zero and that the dates do not correspond. The division and colour coding at the top of the plots reflect the division of site phases given in Figure 9.

450 sites have been excavated after the turn of the millennium, and the wide adoption of GNSS technology, the  
451 reported elevations should be trustworthy.

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

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

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

484 Not least following from the fact that relatively few  $^{14}\text{C}$ -dates older than c. 8000 BCE associated with  
485 anthropogenic activity have been achieved in Norway (Åstveit 2018; Damlien and Solheim 2018; Kleppe  
486 2018), the shoreline dating of the earliest sites is essential for understanding the pioneer settlement and the  
487 initial colonisation of the Scandinavian peninsula (e.g. Bang-Andersen 2012; Berg-Hansen 2018; Breivik  
488 2014; Fuglestvedt 2012; Glørstad 2016). The shoreline dated Preboreal sites from the Brunlanes-project are  
489 among the earliest known sites in Norway (Jaksland 2012a, 2012b; Jaksland and Persson 2014). These have a  
490 distinct Early Mesolithic artefact inventory and are situated in a steep area of the landscape where use of  
491 the sites would have been difficult after the sea retreated any significant distance from their location due  
492 to accessibility. In the original publication of the sites, Jaksland (2014) provides a thorough discussion of  
493 shoreline dating in general, and as used for the dating of the Brunlanes sites specifically. A comparison of his  
494 results and the ones achieved using the above-outlined approach are given in Figure 12A. The sites have been  
495 dated using what Jaksland (2014) gives as the lowest elevation of finds at each site.

496 The small discrepancies between the achieved results mainly follow from the fact that a slightly updated  
497 version of the local displacement curve is applied here (Sørensen et al. in press; cf. Sørensen, Henningsmoen,  
498 et al. 2014). Jaksland's dates are given a flat 200- and 50-year uncertainty range starting from what he  
499 gives as the earliest possible date. The 200 year uncertainty range is given if the sites were to be considered  
500 in isolation, while his argument for the uncertainty range of only 50 years is based on the location of the

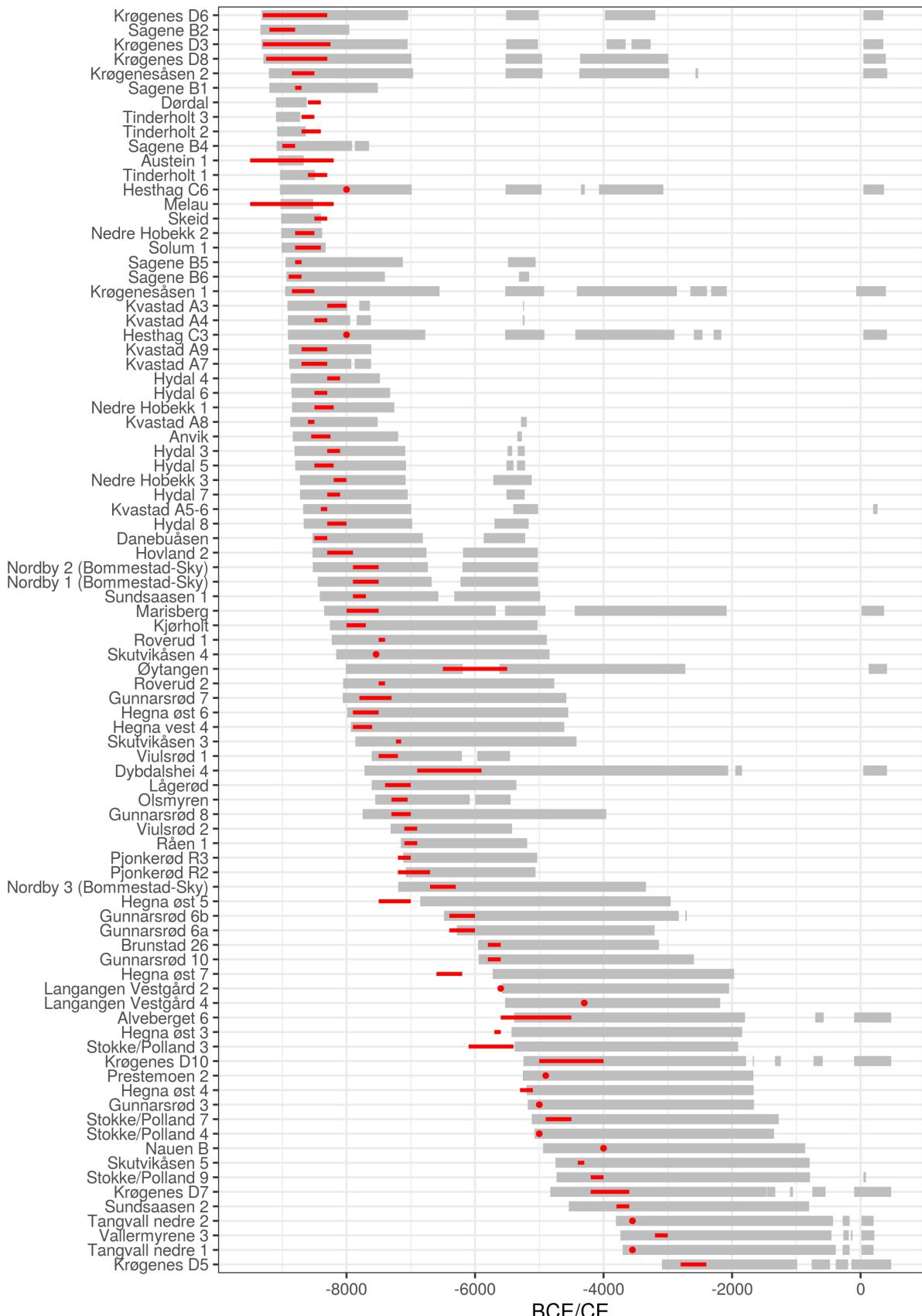


Figure 11: Re-dating 87 excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey are compared to the dates originally proposed by the excavation reports in red. For clarity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

501 sites relative to each other. Since they are located in such a constrained and steep area of the landscape,  
502 the difference in elevation between the sites is argued to establish their relative date and thus constrain  
503 the uncertainty ranges so that they do not overlap. This information is not integrated in the approach  
504 outlined here, but it could justify further reducing the uncertainty ranges. Although their accuracy is of  
505 course ultimately dependent on the veracity of the geological reconstruction, the high rate of RSL-change in  
506 this period does nonetheless result in very precise dates.

507 Above it was suggested that additional temporal data could be combined with the method to improve its  
508 precision. Drawing on Jakobsson (2014), this example instead highlights the fact that the spatial nature of  
509 the method means that a consideration of the surrounding terrain and other sites can also help to increase  
510 the precision of the method if this can be used to exclude certain RSLs as unlikely for when a site was in  
511 use. One potential way to do this could be through the analysis of phosphate concentrations in soils, which  
512 has the potential to offer insights on the likely position of the shoreline when a site was in use (Ilves and  
513 Darmark 2011). This has been done in the Baltic sea region (e.g. Broadbent 1979; Ilves and Darmark 2011;  
514 Sundström et al. 2006), but has yet to provide reliable results in Norway (e.g. Melvold and Persson 2014b;  
515 Viken 2018). The identification of other physical traces of shore formation processes and the deposition of  
516 beach sediments in relation to archaeological material also holds similar potential (e.g. Bondevik et al. 2019).  
517 Finally, another approach could also be to assess the spatial implication of a proposed shoreline date by  
518 simulating the adjusted sea-levels, as is done for Pauder 1 in Figure 12B, followed for example by a visual  
519 evaluation of the topography or by evaluating the distance and steepness of the slope to the shoreline. If such  
520 methods are developed further, it could conceivably be possible to exclude certain elevations as unlikely for  
521 the position of the shoreline when the site was in use. Such approaches would make less of an impact for the  
522 Brønlanes sites, where the 95% HDRs are already quite constrained, but could considerably improve the  
523 precision of the method in cases where RSL-change has been less severe (cf. Figure 11).

## 524 8 Concluding remarks

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

543 Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to further  
544 evaluate and adjust the findings reported here, but a larger sample size could also lay the foundations for  
545 refining the method by identifying subsets of sites for which the application of the method could be adjusted.  
546 For example, from Figure 7 it is clear that the Mesolithic sites have generally been located closer to the  
547 shoreline than the later sites. It was not attempted to explore this further here, given the constrained sample  
548 size and the accuracy that was achieved with the parameters in use. However, the future addition of more  
549 data might give justification for using different models or parameter settings when dating sites from certain

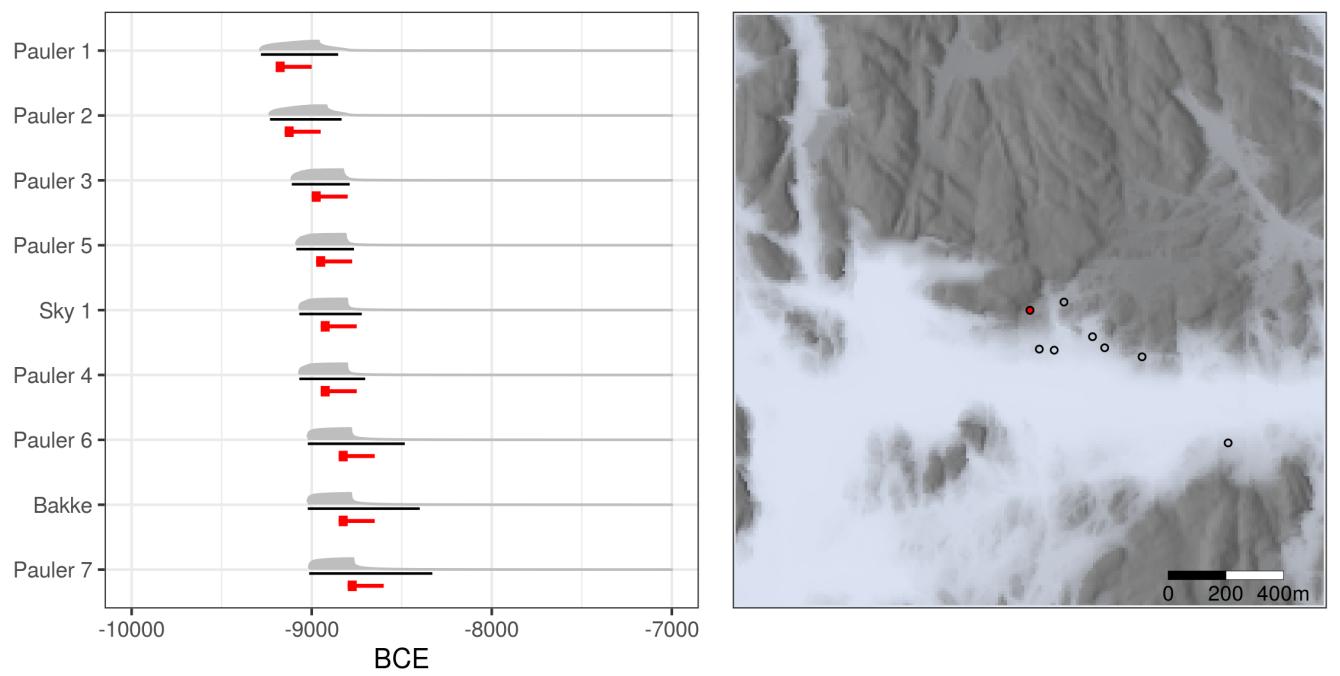


Figure 12: Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red.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

time intervals. Furthermore, following from its behavioural nature, it is also likely that dimensions such as the nature and purpose of visits to the sites will have implications for how close to the shoreline the sites were located. This is illustrated here by the site phases associated with agricultural activity, marked in Figure 6, which were all found to be located some distance from the sea. A wide range of different behavioural dimensions could potentially provide nuance to how the method should be applied.

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

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

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

As the nature of the relationship between sites and sea is likely to vary temporally and geographically (e.g. Nyland 2020), the proposed implementation and parametrisation of shoreline dating can not be expected

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602 to be directly applicable elsewhere. When this is combined with the fact that the rate of RSL-change also  
603 varies geographically and temporally (e.g. Svendsen and Mangerud 1987), this means that the accuracy  
604 and precision of the method will also vary. However, the methodological framework used to evaluate the  
605 relationship between sites and sea is readily extendible to other regions of northern Scandinavia where reliable  
606 data on shoreline displacement is available, thus making such extensions feasible. Furthermore, the simulation  
607 approach used to integrate multiple sources of spatio-temporal uncertainty was used here to inform the  
608 question of the distance between sites and the shoreline. However, this method and general framework can  
609 be extended to a wide range of use-cases where one needs to visualise, and quantitatively or qualitatively  
610 evaluate the relationship between archaeological phenomena, the prehistoric shoreline, and the uncertainty  
611 inherent to this reconstruction.

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