

---

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

4 Isak Roalkvam<sup>1,\*</sup>

5 09 June, 2022

6 **Abstract**

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

22 <sup>1</sup> University of Oslo, Institute of Archaeology, Conservation and History

23 \* Correspondence: Isak Roalkvam <isak.roalkvam@iakh.uio.no>

24 **Highlights**

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

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

30 **1 Introduction**

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

38 harbour and sea-side constructions and, as is the focus of this study, Stone Age sites (e.g. Åkerlund 1996;  
39 Bjerck 2005; Løken 1977; Nordqvist 1995; Schmitt et al. 2009; Sognnes 2003; Tallavaara and Pesonen 2020;  
40 Wikell et al. 2009).

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

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

## 69 2 Background

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

83 Following the end of the Weichselian and the final retreat of the Fennoscandian Ice Sheet (e.g. Hughes et al.  
84 2016; Stroeven et al. 2016, see Figure 1), the isostatic rebound has been so severe that most areas of Norway  
85 have been subject to a continuous relative sea-level regression, despite corresponding eustatic sea-level rise  
86 (e.g. Mörner 1979; Svendsen and Mangerud 1987). In other words, the RSL has been dropping throughout

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

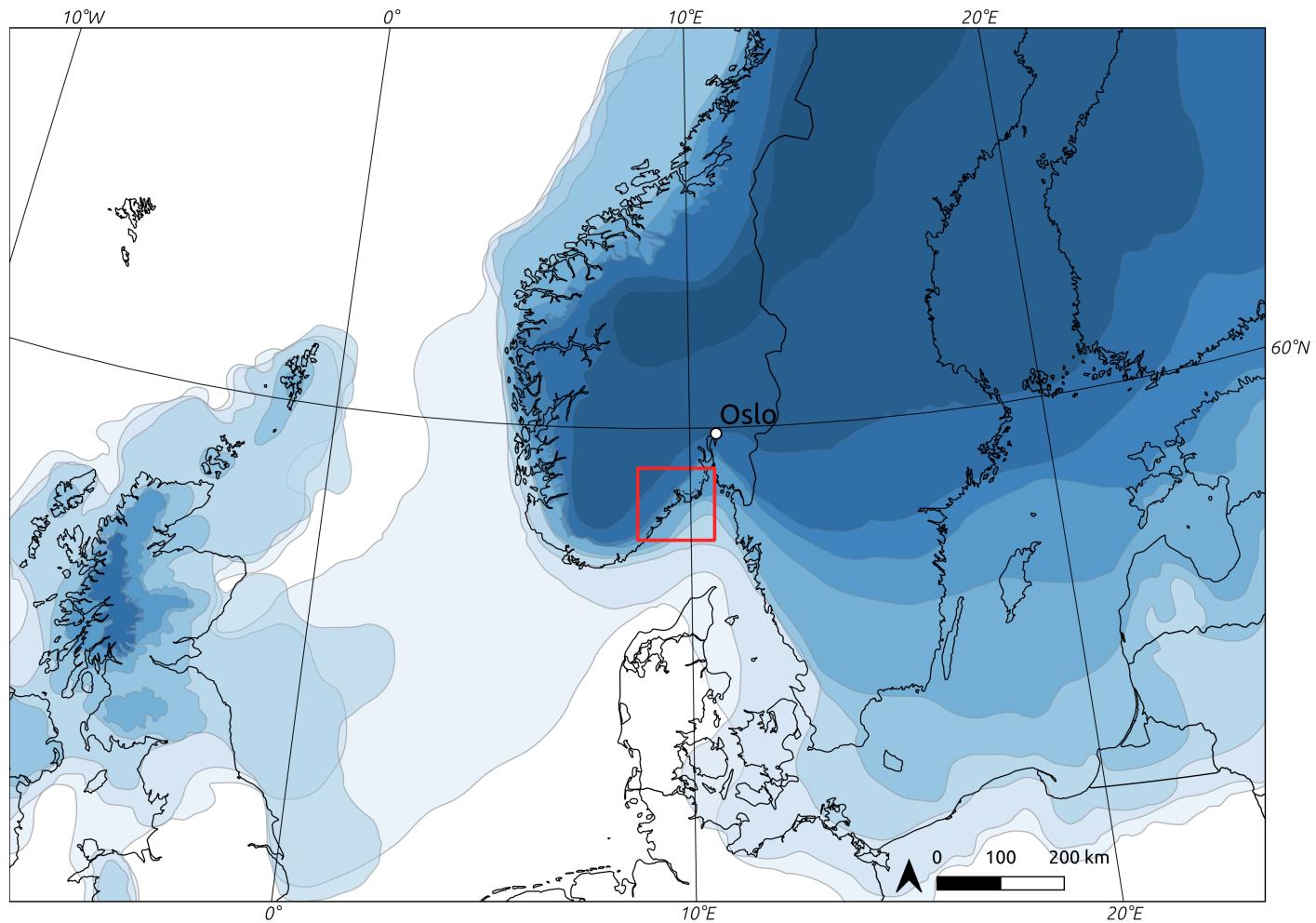


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 kyr BCE. The study area defined later in the text  
 is marked with a red outline (deglaciation data from Hughes et al. 2016, but see also Romundset et al. 2019  
 in relation to the study area).

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

104 an earliest possible date for when a site could have been in use (see review by Nordqvist 1999). The most  
105 common application in Norway has arguably been to use shoreline dating to provide an approximate date for  
106 the occupation of the sites, often in combination with other dating methods (see for example chapters in  
107 Glørstad 2002, 2003, 2004; Jakslund 2001, 2012a, 2012b; Jakslund and Persson 2014; Melvold and Persson  
108 2014; Reitan and Persson 2014; Reitan and Sundström 2018; Solheim 2017 and below). Recently the method  
109 has also been used independently to date a larger number sites to get a general impression of site frequency  
110 over time. This is done by aggregating point estimates of shoreline dates in 100, 200 or 500 year bins (Breivik  
111 2014; Breivik and Bjerck 2018; Fossum 2020; Mjærum 2022; Nielsen 2021; Solheim and Persson 2018; see also  
112 Jørgensen et al. 2020; Tallavaara and Pesonen 2020). In his review, Nordqvist (1999) argues that there can  
113 be little doubt concerning the general applicability of the method – what is less clear is the level of reliability  
114 and chronological resolution that it can offer (see also Johansen 1963, 1997).

115 The shore-bound settlement location of prehistoric hunter-fisher-gatherers in Norway is generally believed  
116 to follow both from the exploitation of aquatic resources and from movement and communication, which  
117 would have been efficient on waterways (Bjerck 1990, 2017; Brøgger 1905:166; also discussed by Berg-Hansen  
118 2009; Bergsvik 2009). The same logic has also been extended to the hinter- and inland regions, where sites  
119 are to be predominantly located along rivers and lakes (Brøgger 1905:166; Glørstad 2010:57–87; but see also  
120 Gundersen 2013; Mjærum 2018; Schülke 2020). This is to take a dramatic turn at the transition to the  
121 Late Neolithic, around 2400 BCE, with the introduction of the Neolithic proper (Prescott 2020; cf. Solheim  
122 2021). The introduction of a comprehensive Neolithic cultural package, including a shift to agro-pastoralism  
123 and the introduction of the farm is to have led site locations to be more withdrawn from the shoreline (e.g.  
124 Bakka and Kaland 1971; Østmo 2008:223; Prescott 2020). That is not to say that waterways and aquatic  
125 resources were no longer exploited, but rather that these activities would not have been as tightly integrated  
126 with settlement and tool-production areas as in preceding periods (Glørstad 2012). At an earlier stage, at  
127 the transition to the Early Neolithic (c. 3900 BCE), pottery is introduced to the sites, and there are some  
128 indications of an initial uptake of agriculture at some sites in the Oslo fjord region. However, this appears  
129 to be small in scale and is believed to be combined with a continued and predominantly hunter-gatherer  
130 life-way, possibly followed by a complete de-Neolithisation in the Middle Neolithic (Hinsch 1955; Nielsen et  
131 al. 2019; Østmo 1988:225–227). Nielsen (2021) has recently argued that the initial uptake of agriculture in  
132 Early Neolithic south-eastern Norway is combined with a more complex settlement pattern, and that a simple  
133 foraging/agricultural dichotomy would underplay the variation present in the Early and Middle Neolithic  
134 settlement data (see also e.g. Amundsen et al. 2006; Østmo 1988; Solheim 2012:74). Seen in relation to  
135 the question of interest here, the empirical expectation for the above outlined development would thus be  
136 a predominantly shore-bound settlement in the Mesolithic, possibly followed by a more varied association  
137 between sites and the shore-line with the transition to the Early Neolithic around 3900 BCE, and finally a  
138 decisive shift with the Late Neolithic c. 2400 BCE.

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

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

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

### 3 Data

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

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

205 constrained area of the landscape as possible. Following from the morphology of the retreating ice sheet, the  
206 uplift is more severe towards the north-east, meaning that this needs to be adjusted for in the case that any  
207 basins are located any significant distance from the common isobase perpendicular to this gradient (Figure  
208 2). The SLIPs indicate the isolation of the basins from the highest astronomical tide, which is adjusted to  
209 mean sea-level in the compilation of the displacement curves, based on the present day tidal range. This is  
210 assumed to have been the same throughout the Holocene (Sørensen, Henningsmoen, et al. 2014:44). The  
211 highest astronomical tide in the study area reaches around 30cm above mean sea-level (Norwegian Mapping  
212 Authority 2021:30cm at the standard port Helgeroa in Larvik). Furthermore, the confidence bands of the  
213 displacement curves and their trajectory are quite complex constructs, and are the integrated result of both  
214 expert knowledge and more objectively quantifiable parameters. The reason for this is in part that the curves  
215 do not only contain uncertainty as related to radiometric dates, which are well defined, but also hold potential  
216 error as related to the interpretation and analysis of sediment cores, the nature and condition of the basin  
217 outlets and the adjustment to a common isobase, to name but a few (e.g. Romundset et al. 2011, 2019; for  
218 alternative approaches see e.g. Barnett et al. 2020; Cahill et al. 2016; Creel et al. 2022). For more details  
219 and evaluations done for the compilation of each curve, the reader is therefore referred to the individual  
220 publications.

221 The archaeological data compiled for the analysis consists of excavated Stone Age sites with available spatial  
222 data from the coastal region between Horten county in the north-east, to Arendal in the south-west (Figure  
223 2). These number 155 sites. Of these, 91 sites are associated with a total of 547 radiocarbon dates. Of these,  
224 in turn, 67 sites are related to the 259 radiocarbon dates that fall within the Stone Age (9500–1700 BCE),  
225 with 95% probability. These sites and  $^{14}\text{C}$ -dates form the basis for the analysis. Spatial data in the form of  
226 site limits and features, as defined by the excavating archaeologists, were retrieved from local databases at the  
227 Museum of Cultural History—the institution responsible for archaeological excavations in the region. In the  
228 compiled dataset, each radiocarbon date has been associated with the site features or excavation unit from  
229 where they originate, or, where these weren't available, the spatial limit of the entire site. Due to somewhat  
230 variable practices between excavations, what available spatial geometry best represents the site limit was  
231 decided based on an evaluation of the excavation reports. This means that the limits are variably given as  
232 that defined during initial survey, area de-turfed before excavation, area stripped with excavator following  
233 the excavation, manually excavated area, or convex hull polygons generated around the site features.

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

244 The elevation data used for the analysis is a digital terrain model (DTM) freely available from the Norwegian  
245 Mapping Authority (Norwegian Mapping Authority 2018, <https://hoydedata.no>). It was here opted for the  
246 10m resolution DTM rather than the higher-resolution 1m version. In addition to resulting in considerably less  
247 processing time, the higher resolution elevation model is more vulnerable to smaller-scale modern disturbances  
248 that the 10m version is not impacted by. The 10m resolution DTM of the study area is a down-sampled  
249 version of the 1m version and has a height accuracy with a systematic error of 0.1m (Norwegian Mapping  
250 Authority 2018). All data and R programming code (R Core Team 2021) required to run the analyses, as  
251 well as the derived data are freely available in an online repository at <https://osf.io/7f9su/>, organised as a  
252 digital research compendium following Marwick et al. (2018).

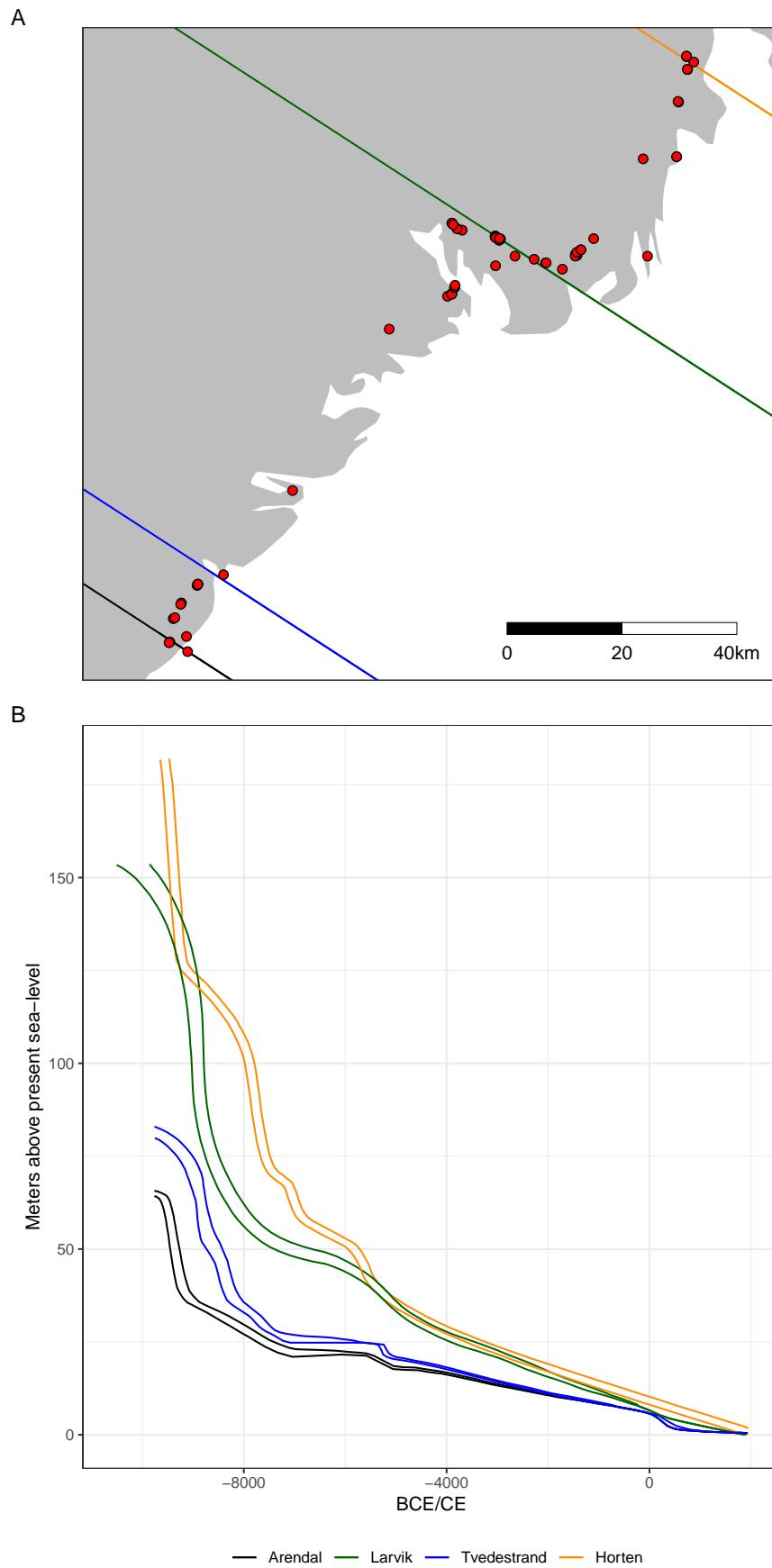


Figure 2: A) Distribution of the 67 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of  $327^\circ$  (Romundset et al. 2018, but see Sørensen et al. 2014), B) Displacement<sup>7</sup> curves. Note the increasing steepness of the curves towards the north-east.

---

## 253 4 Methods

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

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

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

305 (see supplementary material for more details).

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

## 311 5 Simulation results

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

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

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

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

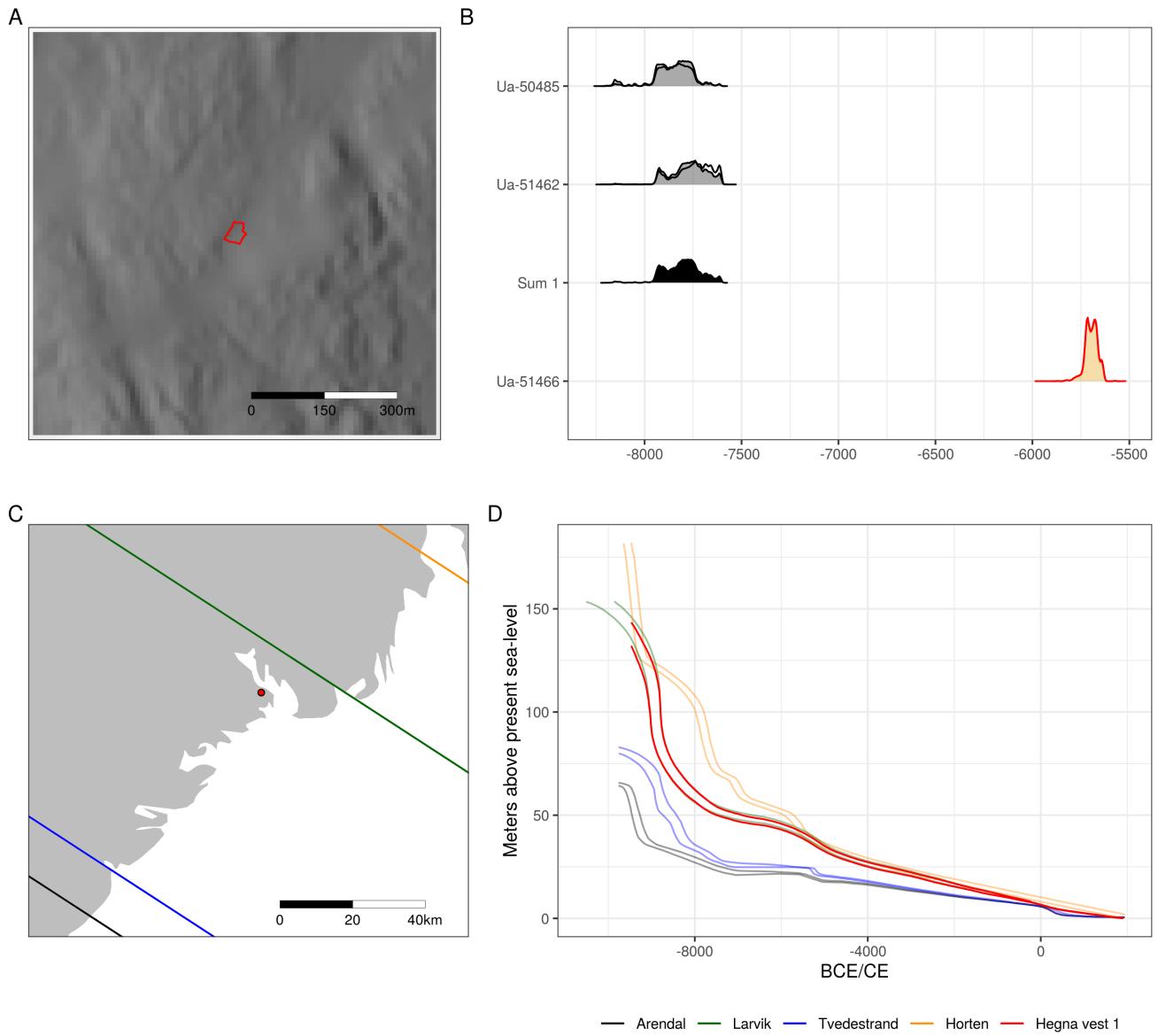


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site on the edited 10m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled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

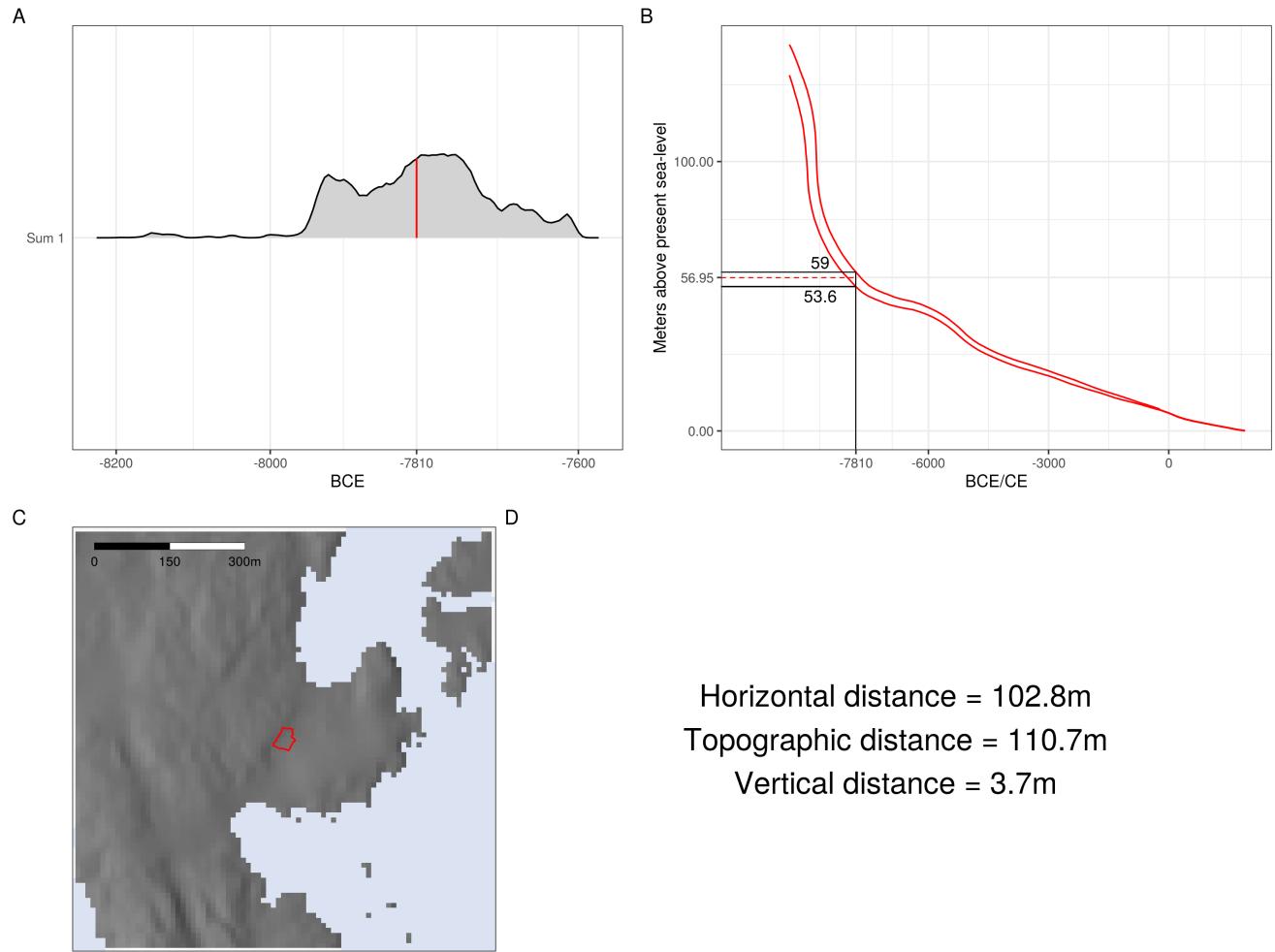


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year from the posterior density estimate. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using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

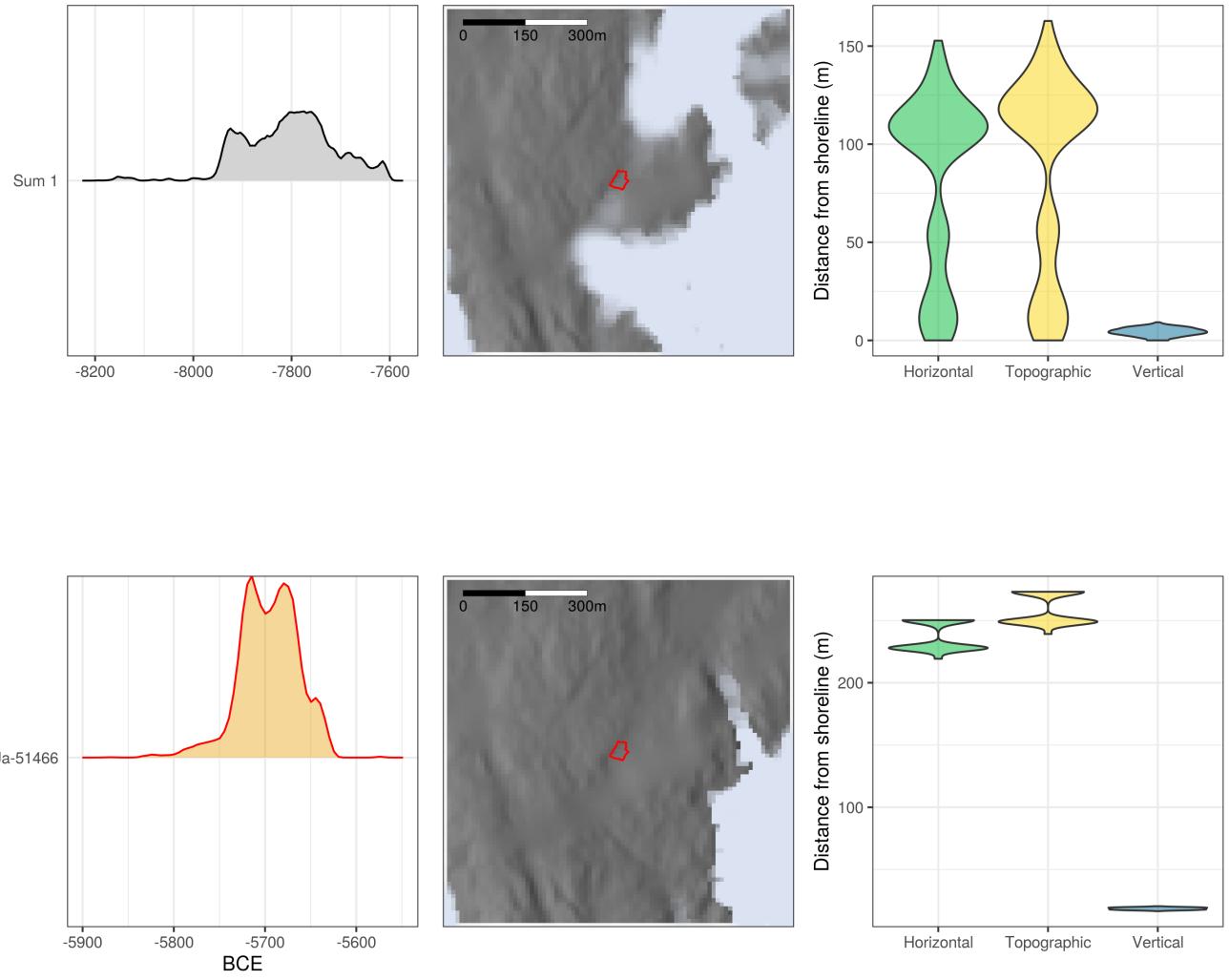


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The first column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The second column displays the result of simulating the raised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

---

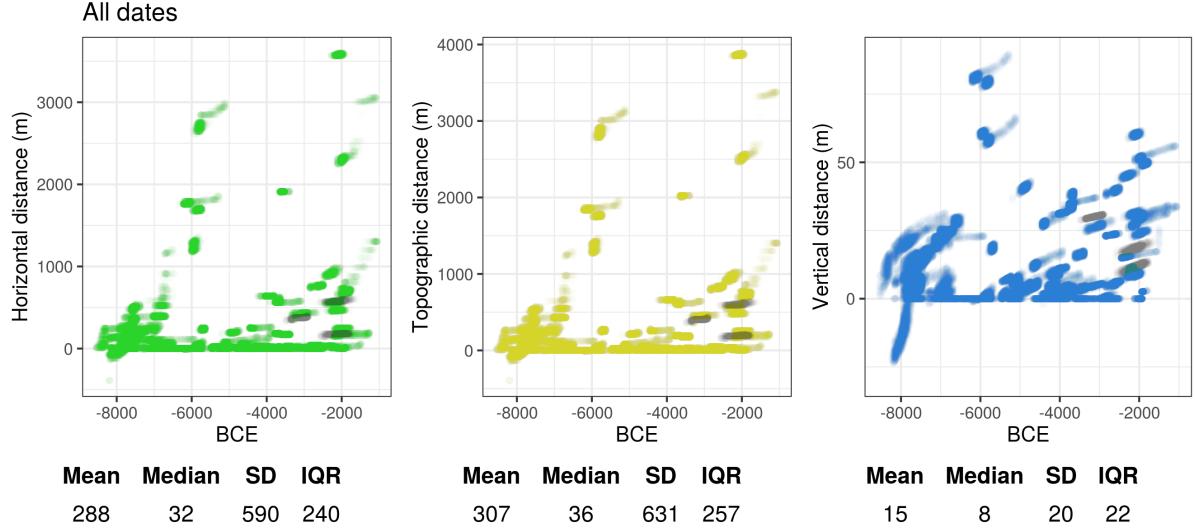
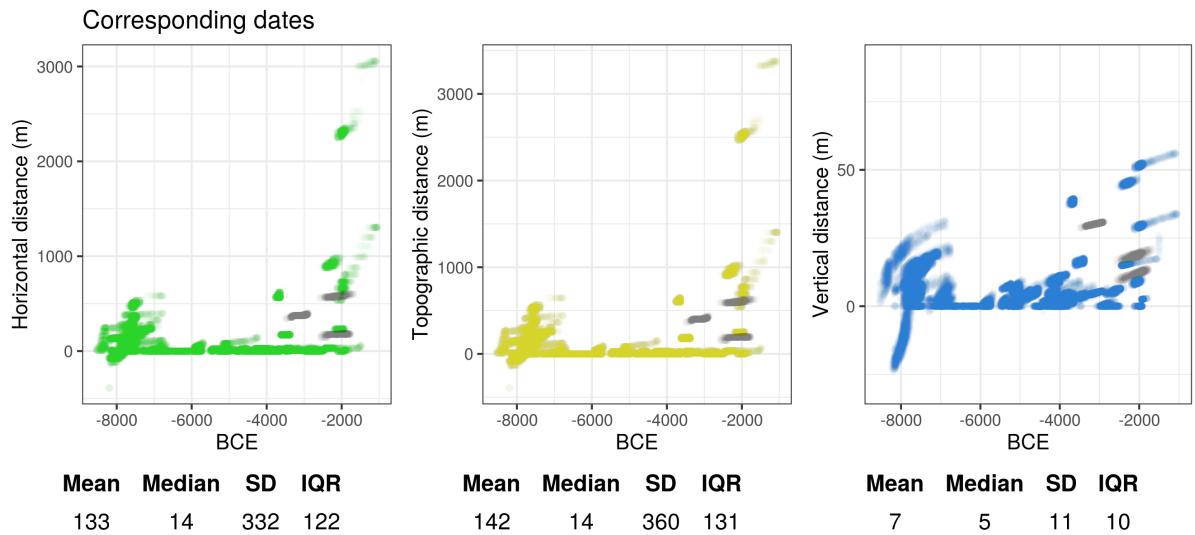
**A****B**

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.

---

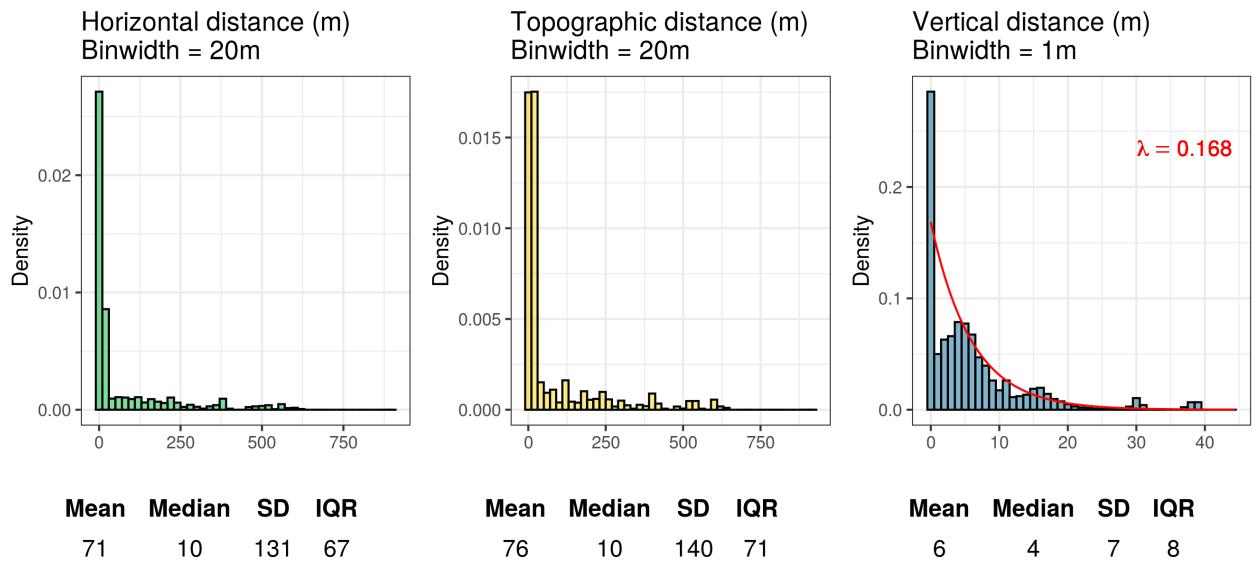
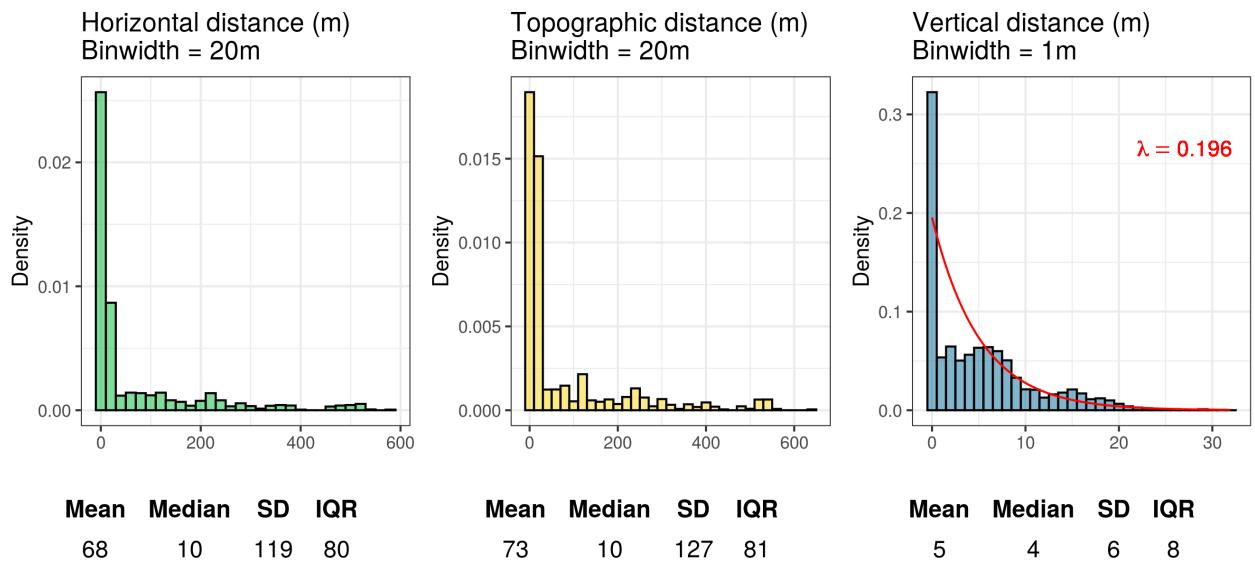
**A****B**

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.

---

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

## 356 6 Shoreline dating

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

$$366 p(\alpha - D) = \lambda e^{-\lambda(\alpha - D)} \quad (1)$$

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

$$370 p(T|\alpha - D) = U[T_{l|\alpha-D}, T_{u|\alpha-D}] \quad (2)$$

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

$$372 p(T|\alpha - D) = p(T|\alpha - D)p(\alpha - D) \text{ [This notation is somewhat questionable]} \quad (3)$$

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

$$374 p(T|\alpha) = \sum_D p(T|\alpha - D)p(\alpha - D) \quad (4)$$

375 An example of an implementation of the outlined approach is given in Figure 8, where  $\lambda = 0.168$ . This is  
the decay ratio identified when considering all of the pre-Late Neolithic simulation results (Figure 7A). For  
376 the numerical implementation,  $D$  is here stepped through as a sequence of increments of 0.001m, starting  
377 from the site elevation  $\alpha$  and extending down to the present sea-level, that is until  $\alpha - D = 0$ . As a note,  
378 this approach is analogous to Procedure 1 as described by Stuvier and Reimer (1989) for the calibration of  
379  $^{14}\text{C}$ -dates. Given the monotonic nature of the displacement curves there is no issue with multiple intercepts  
380 here, which usually comes up in the calibration of a  $^{14}\text{C}$ -date due to the wiggly character of the calibration  
381 curve. In Figure 9 the outlined procedure is used to shoreline date all of the sites from where this relationship  
382 was derived, with the Late Neolithic sites also included for illustrative purposes. Following from having  
383 defined the distance between intersecting sea- and site polygons as zero during simulations, the sites were  
384 all dated using the mean elevation of the site polygons to allow for some variation in elevation over the site  
385 limits. The synchronicity between radiocarbon and shoreline dates was then evaluated using the method  
386 presented by Parnell et al. (2008). Here, 100,000 age samples drawn from the probability distribution of each  
387 shoreline date were subtracted from 100,000 age samples drawn from the corresponding modelled  $^{14}\text{C}$ -dates.  
388 The resulting range of the 95% highest density region (HDR, Hyndman 1996) was then checked to see if

389 it crosses zero, in which case the dates are considered to be in agreement (Figure 10). When excluding  
 390 the earliest occupation phase at Gunnarsrød 5, the deviation of which is to be expected based on issues  
 391 with the DTM (see above), the shoreline date correspond to the radiocarbon dates in 58 out of 68 cases  
 392 (84%). Only including dates modelled to be older than 2500 BCE with 95% probability, i.e. older than the  
 393 Late Neolithic, improves this to 56 out of 61 cases (92%). When only including dates older than 4000 BCE  
 394 with 95% probability, i.e. only Mesolithic site phases, the success rate is further increased to 46/49 (94%).  
 395 The three failed Mesolithic shoreline dates are from the early sites Langemyr and Kvastad A2, with the  
 396 likely implication that a lower decay ratio than what is used for characterising the distance between site  
 397 and shoreline for all sites in aggregate should be used for sites known to be from the earliest part of the  
 398 Mesolithic (see also Figure 6).

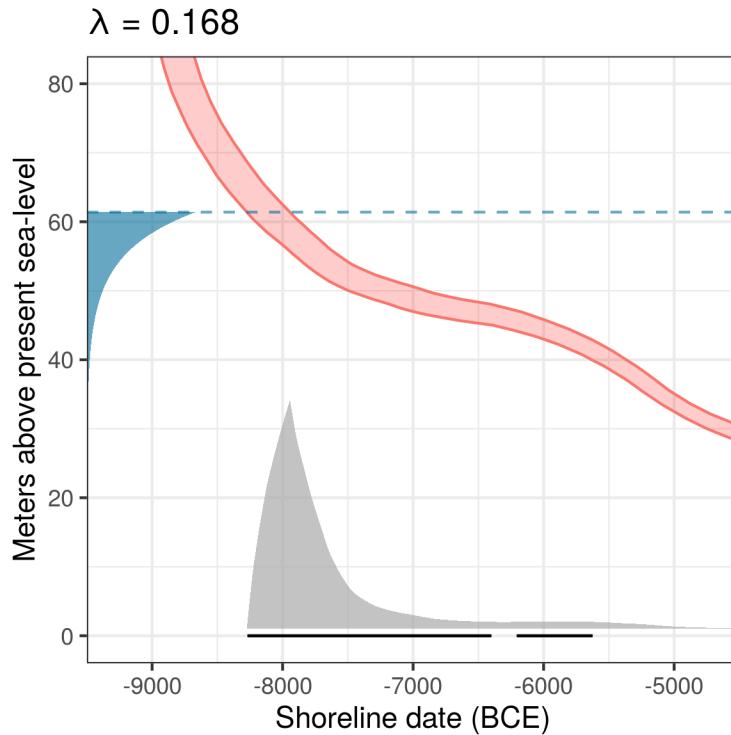


Figure 8: Shoreline dating of Hegna vest 1. The dashed line marks the mean elevation of the site polygon which is used to inform  $\alpha$  in the dating of the site. The exponential function decays with ratio  $\lambda$  from Figure 7A. The resulting shoreline date in grey is underlined with the 95%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

## 399 7 Re-dating previously shoreline dated sites

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

406 The comparison with previously reported dates is an illustrative, but unfair exercise for a few reasons. First  
 407 of all the dates provided in the reports are typically stated to be a very rough estimate, and are sometimes  
 408 given as a point estimate with an undefined, but implied or explicit uncertainty range. Secondly, seeing as  
 409 these reports are from various dates in time, many are based on now outdated data on RSL-change. Finally,

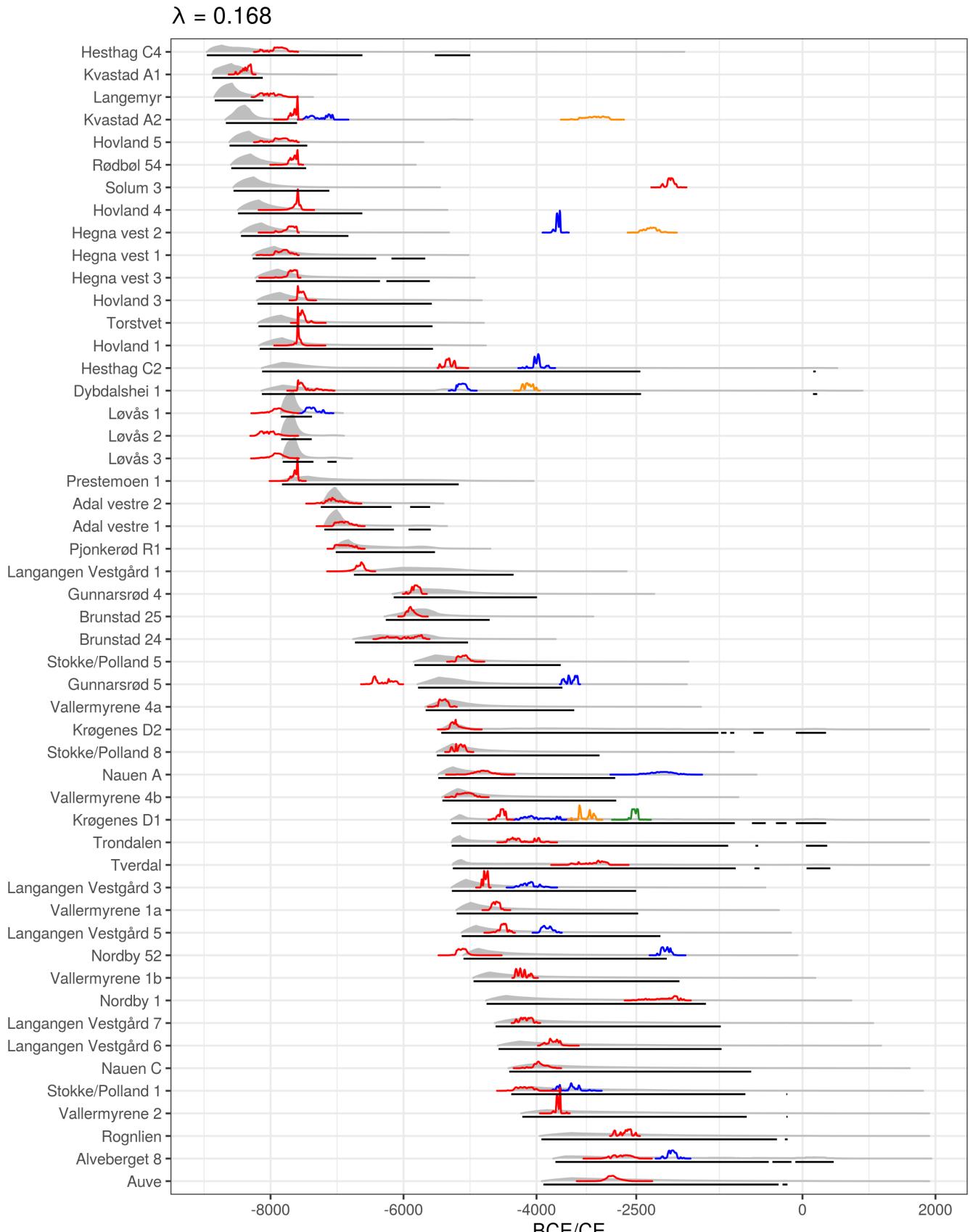


Figure 9: The result of backwards shoreline dating the sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined<sup>17</sup> with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-overlapping dates at 99.7% probability.

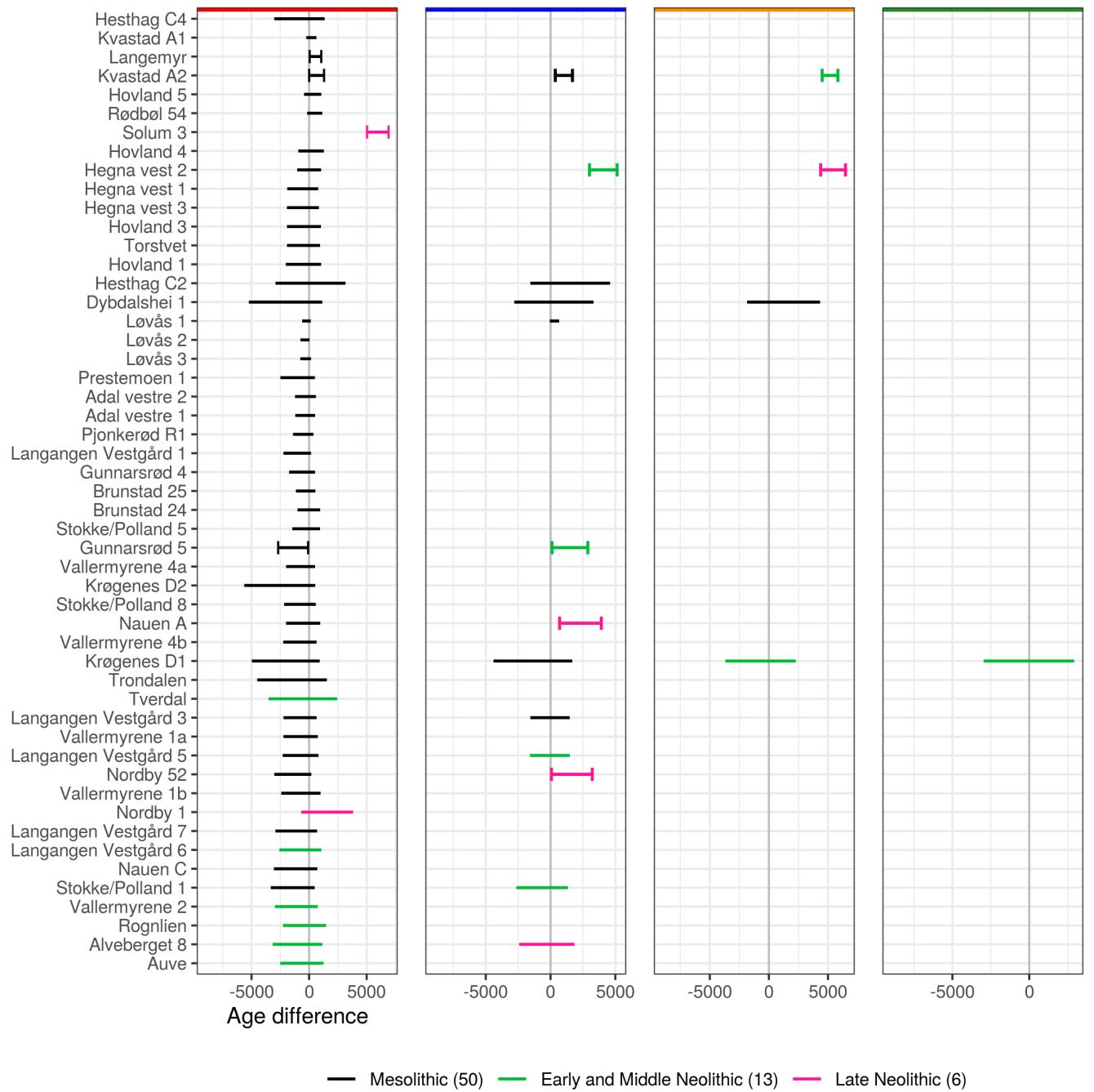


Figure 10: Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Figure 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does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

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

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

441 The small discrepancies between the achieved results mainly follow from the fact that a slightly updated  
442 version of the local displacement curve is applied here (cf. Sørensen et al. in prep). Jaksland's dates are  
443 given a flat 200 and 50 year uncertainty range starting from what he gives as the earliest possible date. The  
444 200 year uncertainty range is given if the sites were to be considered in isolation, while the argument for  
445 the uncertainty range of only 50 years is based on the location of the sites relative to each other. Since  
446 they are located in such a constrained and steep area of the landscape, the difference in elevation between  
447 the sites is argued to establish their relative date and thus constrain the uncertainty ranges so that they  
448 don't overlap. This information is not integrated in the approach outlined here, but could justify further  
449 reducing the uncertainty ranges. Although their accuracy is of course ultimately dependent on the veracity of  
450 the geological reconstruction, the high rate of RSL-change in this period does result in very precise dates.  
451 Above it was suggested that additional temporal data could be combined with the method to improve its  
452 accuracy and precision. Drawing on Jaksland (2014), this example instead highlights the fact that the spatial  
453 nature of the method means that a consideration of the surrounding terrain and other sites can also help in  
454 increasing the precision of the method if this can be used to exclude certain sea-levels as unlikely for when a  
455 site was in use. One approach could also be to assess the spatial implication of a proposed shoreline date by  
456 simulating the adjusted sea-levels, as is done for Paurer 1 in Figure 12B, followed for example by a visual  
457 evaluation of the topography or by evaluating the distance and steepness of the slope to the shoreline. If  
458 this is developed further, it could conceivably be possible to exclude certain elevations as unlikely for the  
459 position of the shoreline when the site was in use. Such approaches would make less of an impact in this  
460 setting, where the 95% HDR is already quite constrained, but could considerably improve the precision of the  
461 method in cases where RSL-change has been less severe (cf. Figure 11).

$$\lambda = 0.168$$

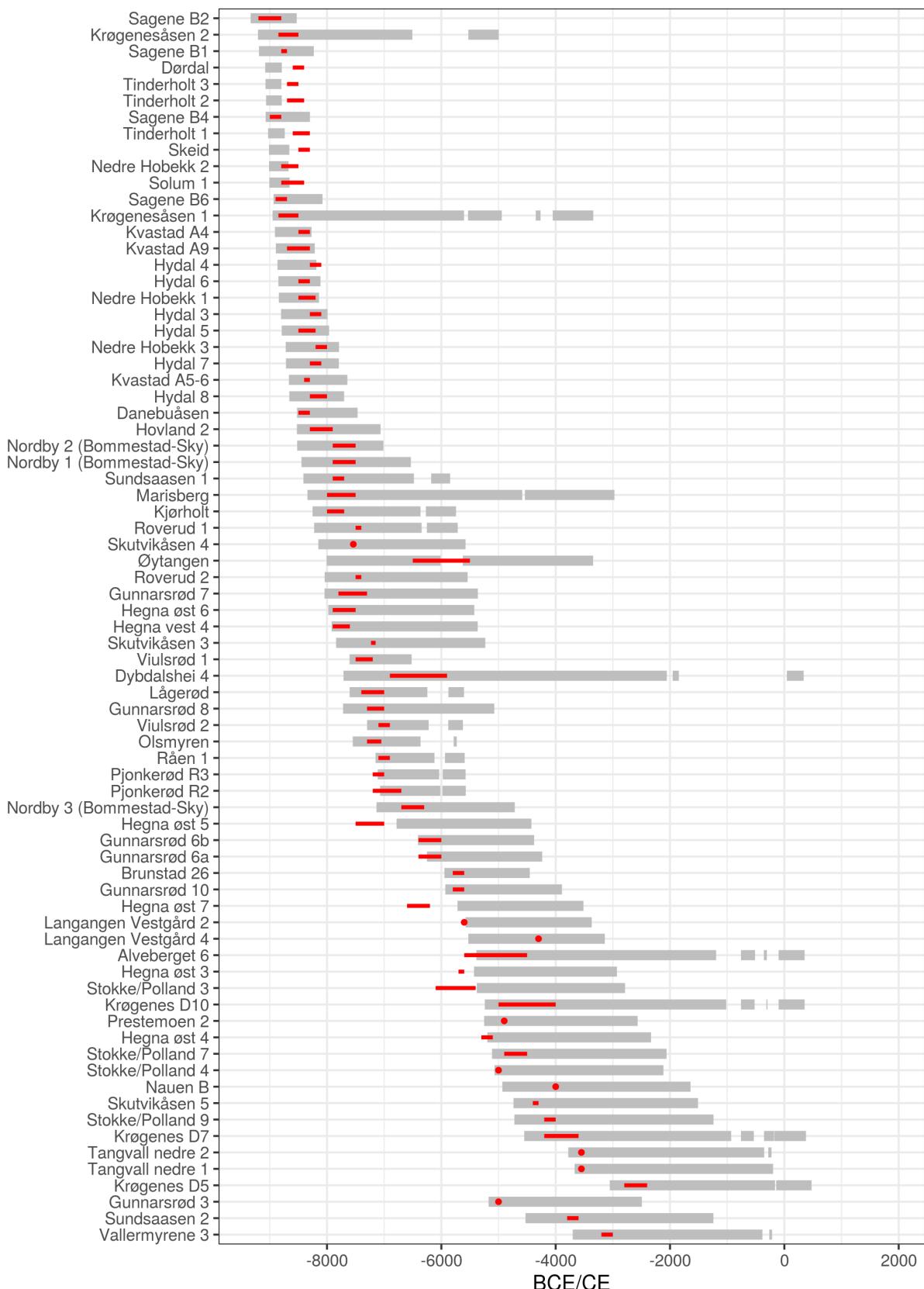


Figure 11: Re-dating excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey<sup>20</sup> are compared to the dates originally proposed by the excavation reports in red.

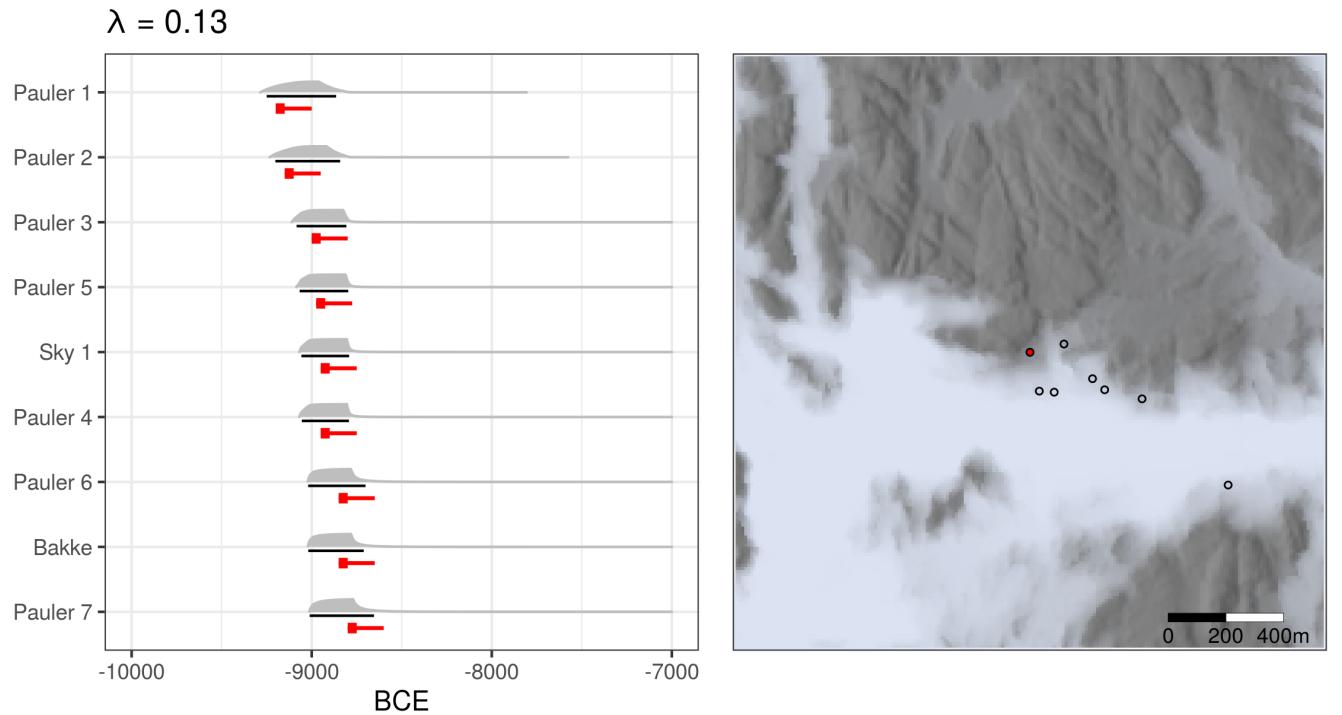


Figure 12: Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red.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

---

## 462 8 Concluding remarks

463 The most immediate contribution of this paper is what must be considered a confirmation of previous research  
464 into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated  
465 by the close relationship between sites and the shoreline up until the transition to the Neolithic at c. 4000  
466 BCE, after which a couple of sites become situated some distance from the sea, followed by a more decisive  
467 break at the transition to the Late Neolithic at c. 2500 BCE. This development is in clear agreement with  
468 the literature. Furthermore, based on the quantitative nature of these findings, an initial formulation of  
469 a refined method for the shoreline dating of pre-Late Neolithic Stone Age sites has been proposed. Apart  
470 from taking the distance between sites and the isobases of the displacement curves into consideration when  
471 dating the sites, this involves accounting for the distance between the sites and the shoreline. When no  
472 other information is available, it can at present be recommended to use the empirically derived exponential  
473 decay ratio of 0.168 (Figure 11A) to characterise this relationship. Furthermore, while this remains to be  
474 formalised and explored further, it was also showed how the accuracy of the method can be improved by  
475 including more information, both with reference to the topographic location of the sites and other temporal  
476 data. As the precision of the method is both geographically and temporally contingent due to the trajectory  
477 of RSL-change, where older sites situated towards the north-east in the study area will get a more precise  
478 date, the impact of such additional information will also vary.

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

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

512 Given that shoreline dating is contingent on regularities in human behaviour it should naturally be applied

---

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

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

---

## 525 9 References

- 526 Åkerlund, Agneta  
527 1996 *Human responses to shore displacement: Living by the sea in Eastern Middle Sweden during the Stone*  
528 *Age*. Riksantikvarieämbetet, Stockholm.
- 529 Åkerlund, Agneta, Jan Risberg, Urve Miller, and Per Gustafsson  
530 1995 On the applicability of the  $^{14}\text{C}$  method to interdisciplinary studies on shore displacement and settlement  
531 location. *PACT* 49:53–84.
- 532 Amundsen, Øystein, Stig Knutsen, Axel Mjærum, and Gaute Reitan  
533 2006 Nøkleby i Ski – en tidligeolittisk jordbruksboplass? *Primitive tider* 9:85–96.
- 534
- 535 Åstveit, Leif Inge  
536 2018 The Early Mesolithic of Western Norway. In *Early Economy and Settlement in Northern Europe. Pioneering, Resource Use, Coping with Change*, edited by Hans Peter Blankholm, pp. 231–274. Equinox, Sheffield.
- 537
- 538 Bakka, Egil, and Peter Emil Kaland  
539 1971 Early farming in Hordaland, western Norway. Problems and approaches in archaeology and pollen  
540 analysis. *Norwegian Archaeological Review* 4:1–17. DOI:10.1080/00293652.1971.9965136.
- 541 Bang-Andersen, Sveinung  
542 2012 Colonizing Contrasting Landscapes. The Pioneer Coast Settlement and Inland Utilization in  
543 Southern Norway 10,000–9500 Years Before Present. *Oxford Journal of Archaeology* 31:103–120.  
DOI:10.1111/j.1468-0092.2012.00381.x.
- 544 Barnett, Robert L., Dan J. Charman, Charles Johns, Sophie L. Ward, Andrew Bevan, Sarah L. Bradley,  
545 Kevin Camidge, Ralph M. Fyfe, W. Roland Gehrels, Maria J. Gehrels, Jackie Hatton, Nicole S. Khan, Peter  
546 Marshall, S. Yoshi Maezumi, Steve Mills, Jacqui Mulville, Marta Perez, Helen M. Roberts, James D. Scourse,  
547 Francis Shepherd, and Todd Stevens  
548 2020 Nonlinear landscape and cultural response to sea-level rise. *Science Advances* 6:107422.  
DOI:10.1126/sciadv.abb6376.
- 549
- 550 Berg-Hansen, Inger Marie  
551 2009 *Steinalderregistrering. Metodologi og forskningshistorie i Norge 1900–2000 med en feltstudie fra Lista i*  
552 *Vest-Agder*. Museum of Cultural History, University of Oslo, Oslo.
- 553 2018 Continuity and Change in Late- and Post-glacial Social Networks: Knowledge Transmission and  
554 Blade Production Methods in Ahrensburgian and Early Mesolithic North West Europe. In *The Early*  
*Settlement of Northern Europe. Transmission of Knowledge and Culture*, edited by Kjel Knutsson,  
Helena Knutsson, Jan Apel, and Håkon Glørstad, pp. 63–98. Equinox, Sheffield.
- 555
- 556 Bergsvik, Knut Andreas  
2009 Caught in the middle: functional and ideological aspects of Mesolithic shores in Norway. In *Mesolithic*  
*Horizons: Papers presented at the Seventh International Conference on the Mesolithic in Europe, Belfast 2005*, edited by Sinéad B. McCartan, Rick Schulting, Graeme Warren, and Peter Woodman,  
pp. 602–609. Oxbow Books, Oxford.
- 557
- 558 Bevan, Andrew, Enrico R. Crema, Xiuzhen Li, and Alessio Palmisano  
559 2013 Intensities, Interactions, and Uncertainties: Some New Approaches to Archaeological Distributions.  
In *Computational Approaches to Archaeological Spaces*, edited by Andrew Bevan and Mark Lake, pp.  
27–52. Left Coast Press, Walnut Creek.
- 560
- 561 Bivand, Roger  
2021 *rgrass7: Interface Between GRASS 7 Geographical Information System and R*. R package version  
0.2-6.
- 562
- 563 Bjerck, Hein Bjartmann  
1990 Mesolithic site types and settlement patterns at Vega, Northern Norway. *Acta Archaeologica* 60:1–32.
- 564
- 565 2005 Strandlinjedatering. In *Norsk arkeologisk leksikon*, edited by Einar Østmo and Lotte Hedeager, pp.  
363–364. Pax, Oslo.

- 568
- 569 2008a Norwegian Mesolithic Trends: A Review. In *Mesolithic Europe*, edited by Geoff Bailey and Penny  
570 Spikins, pp. 60–106. Cambridge University Press, Cambridge.
- 571 2008b Innledende betraktninger. In *NTNU Vitenskapsmuseets arkeologiske undersøkelser Ormen Lange  
Nyhamna*, edited by Hein Bjartmann Bjerck, Leif Inge Åstveit, Trond Meling, Jostein Gundersen,  
572 Guro Jørgensen, and Staale Normann, pp. 548–551. Tapir Akademisk Forlag, Trondheim.
- 573 2017 Settlements and Seafaring: Reflections on the Integration of Boats and Settlements Among Marine  
Foragers in Early Mesolithic Norway and the Yámana of Tierra del Fuego. *The Journal of Island and  
Coastal Archaeology* 12(2):276–299. DOI:10.1080/15564894.2016.1190425.
- 574
- 575 Blankholm, Hans Peter
- 576 2020 In the wake of the wake. An investigation of the impact of the Storegga tsunami on the human  
settlement of inner Varangerfjord, northern Norway. *Quaternary International* 549:65–73. DOI:<https://doi.org/10.1016/j.quaint.2018.05.050>.
- 577
- 578 Borreggine, Marisa, Evelyn Powell, Tamara Pico, Jerry X. Mitrovica, Richard Meadow, and Christian Tryon
- 579 2022 Not a bathtub: A consideration of sea-level physics for archaeological models of human migration.  
*Journal of Archaeological Science* 137:105507. DOI:10.1016/j.jas.2021.105507.
- 580
- 581 Breivik, Heidi Mjelva
- 582 2014 Palaeo-oceanographic development and human adaptive strategies in the Pleistocene–Holocene transition:  
583 A study from the Norwegian coast. *The Holocene* 24:1478–1490. DOI:10.1177/0959683614544061.
- 584 Breivik, Heidi Mjelva, Guro Fossum, and Steinar Solheim
- 585 2018 Exploring human responses to climatic fluctuations and environmental diversity: Two stories  
from Mesolithic Norway. *Quaternary International* 465. Impacts of gradual and abrupt environmental  
586 changes on Late glacial to Middle Holocene cultural changes in Europe:258–275.  
DOI:10.1016/j.quaint.2016.12.019.
- 587
- 588 Breivik, Heidi, and Hein Bjartmann Bjerck
- 2018 Early Mesolithic Central Norway: A Review of Research History, Settlements, and Tool Tradition. In  
*Early Economy and Settlement in Northern Europe. Pioneering, Resource Use, Coping with Change*,  
589 edited by Hans Peter Blankholm, pp. 169–206. Equinox, Sheffield.
- 590 Brøgger, Waldemar Christofer
- 1905 *Strandliniens Beliggenhed under Stenalderen i Det Sydøstlige Norge*. Norges geologiske undersøkelse,  
591 Kristiania.
- 592
- 593 Bronk Ramsey, Christopher
- 2009 Bayesian Analysis of Radiocarbon Dates. *Radiocarbon* 51(1):337–360.  
DOI:10.1017/S0033822200033865.
- 594
- 595 2015 Bayesian Approaches to the Building of Archaeological Chronologies. In *Mathematics and Archaeology*,  
596 edited by Juan A. Barcelo and Igor Bogdanovic, pp. 272–292. CRC Press, Boca Raton.
- 597
- 598 Cahill, Niamh, Andrew C. Kemp, Benjamin P. Horton, and Andrew C. Parnell
- 599 2016 A Bayesian hierarchical model for reconstructing relative sea level: from raw data to rates of change.  
*Climate of the Past* 12(2):525–542. DOI:10.5194/cp-12-525-2016.
- 600
- 601 Conolly, James
- 2020 Spatial interpolation. In *Archaeological Spatial Analysis: A Methodological Guide*, edited by Mark  
602 Gillings, Piraye Hacıgüzeller, and Gary Lock, pp. 118–134. Routledge, London & New York.
- 603
- 604 Conolly, James, and Mark Lake
- 2006 *Geographical Information Systems in Archaeology*. Cambridge University Press, Cambridge.
- 605
- 606
- 607 Creel, Roger C., Jacqueline Austermann, Nicole S. Khan, William J. D’Andrea, Nicholas Balascio, Blake  
608 Dyer, Erica Ashe, and William Menke
- 609 2022 Postglacial relative sea level change in Norway. *Quaternary Science Reviews* 282:107422.  
610 DOI:10.1016/j.quascirev.2022.107422.
- 611 Crema, Enrico R.

- 612 2012 Modelling Temporal Uncertainty in Archaeological Analysis. *Journal of Archaeological Method and*  
613 *Theory* 19(3):440–461. DOI:10.1007/s10816-011-9122-3.
- 614 2015 Time and Probabilistic Reasoning in Settlement Analysis. In *Mathematics and Archaeology*, edited by  
615 Juan A. Barcelo and Igor Bogdanovic, pp. 314–334. CRC Press, Boca Raton.
- 616 Crema, Enrico R., Andrew Bevan, and Mark W. Lake
- 617 2010 A probabilistic framework for assessing spatio-temporal point patterns in the archaeological record.  
618 *Journal of Archaeological Science* 37(5):1118–1130. DOI:10.1016/j.jas.2009.12.012.
- 619 Damlien, Hege, and Steinar Solheim
- 620 2018 The Pioneer Settlement of Eastern Norway. In *Early Economy and Settlement in Northern Europe.*  
621 *Pioneering, Resource Use, Coping with Change*, edited by Hans Peter Blankholm, pp. 335–367.  
Equinox, Sheffield.
- 622 De Geer, Gerard
- 623 1896 *Om Skandinaviens geografiska utveckling efter Istiden*. P. A. Norstedt & Söner, Stockholm.
- 624
- 625 Eskeland, Knut Fossdal
- 626 2017 *Rapport, arkeologisk registrering. E18 Langangen Rugtvedt, 16/06999, Porsgrunn og Bamble kommune.*  
627 Skien.
- 628 Fossum, Guro
- 629 2020 Specialists facing climate change. The 8200 cal BP event and its impact on the coastal settlement in  
the inner Oslo fjord, southeast Norway. In *Coastal Landscapes of the Mesolithic: Human Engagement*  
with the Coast from the Atlantic to the Baltic Sea, edited by Almut Schülke, pp. 179–201. Routledge,  
London & New York.
- 630 Fuglestvedt, Ingrid
- 631 2012 The Pioneer Condition on the Scandinavian Peninsula: the Last Frontier of a ‘Palaeolithic Way’ in  
Europe. *Norwegian Archaeological Review* 45(1):1–29. DOI:10.1080/00293652.2012.669998.
- 632 Gjerpe, Lars Erik, and Grethe Bjørkan Bukkemoen
- 633 2008 Nordby 1 – Toskipede hus fra neolitikum-bronsealder og boplasspor fra jernalder. In *E18-prosjektet*  
*Vestfold. Bind 3. Hus, boplass- og dyrkningspor*, edited by Lars Erik Gjerpe, pp. 7–38. University of  
Oslo, Museum of Cultural History, Oslo.
- 634 Glørstad, Håkon (editor)
- 635 2002 *Svinesundprosjektet. Bind 1. Utgravninger avsluttet i 2001*. University of Oslo, Museum of Cultural  
History, Oslo.
- 636 (editor)
- 637 2003 *Svinesundprosjektet . Bind 2. Utgravninger avsluttet i 2002*. University of Oslo, Museum of Cultural  
History, Oslo.
- 638 (editor)
- 639 2004 *Svinesundprosjektet. Bind 3. Utgravninger avsluttet i 2003*. University of Oslo, Museum of Cultural  
History, Oslo.
- 640 2010 *The Structure and History of the Late Mesolithic Societies in the Oslo Fjord Area 6300–3800 BC*.  
Bricoleur Press, Lindome.
- 641 2012 Historical ideal types and the transition to the Late Neolithic in South Norway. In *Becoming European.*  
*The transformation of third millennium Northern and Western Europe*, edited by Christopher Prescott  
and Håkon Glørstad, pp. 82–99. Oxbow Books, Oxford & Oakville.
- 642 2016 Deglaciation, sea-level change and the Holocene colonization of Norway. *Geological Society, London,*  
*Special Publications* 411:9–25. DOI:10.1144/SP411.7.
- 643 Glørstad, Håkon, Jostein Gundersen, Frode Kvalø, Pål Nymoen, David Simpson, and Birgitte Skar
- 644 2020 Submerged Stone Age from a Norwegian Perspective. In *The Archaeology of Europe’s Drowned*  
*Landscapes*, edited by Geoff Bailey, Nena Galanidou, Hans Peeters, Hauke Jöns, and Moritz Mennenga,  
pp. 125–140. Springer, Cham.
- 645 GRASS Development Team

- 656 2017 *Geographic Resources Analysis Support System (GRASS) Software, Version 7.2*. Open Source Geospa-  
657 tial Foundation.
- 658 Gundersen, Jostein  
659 2013 Verken fjord eller fjell – steinalderen i det kystnære innlandet. Gamle og nye funn fra Notodden i  
660 Telemark. *Viking* 76:35–62.
- 661 Hafsten, Ulf  
662 1957 De senkvarterestrandslinje-forskyvningene i Oslofjorden belyst ved pollenanalytiske undersøkelser.  
663 *Norwegian Journal of Geography* 16(1-8):74–99. DOI:10.1080/00291955708622137.
- 664 1983 Shore-level changes in South Norway during the last 13,000 years, traced by biostrati-  
665 graphical methods and radiometric datings. *Norwegian Journal of Geography* 37(2):63–79.  
DOI:10.1080/00291958308552089.
- 666 Hagen, Anders  
667 1963 Problemkompleks Fosna. Opphav – kontakt med kontinentale grupper – forholdet til Komsa. In  
668 *Boplatsproblem vid Kattegat och Skagerack*, pp. 53–59. Göteborg och Bohusläns forminnesförening &  
Institutionen för nordisk fornkonst, Gothenburg University, Gothenburg.
- 669 Helskog, Knut  
670 1978 Late Holocene sea-level changes seen from prehistoric settlements. *Norwegian Journal of Geography*  
671 32:111–119. DOI:10.1080/00291957808552032.
- 672 Herzog, Irmela  
673 2013 The Potential and Limits of Optimal Path Analysis. In *Computational Approaches to Archaeological  
674 Spaces*, edited by Andrew Bevan and Mark Lake, pp. 179–211. Left Coast Press, Walnut Creek.
- 675 Hinsch, Erik  
676 1955 Traktbegerkultur – Megalitkultur. En studie av Øst-Norges eldste neolitiske gruppe. *Universitetets  
677 Oldsaksamling Årbok* 1951/1953:10–177.
- 678 Hinz, Martin, Clemens Schmid, Daniel Knitter, and Carolin Tietze  
679 2021 *oxcAAR: Interface to 'OxCal' radiocarbon calibration. R package version 1.1.0*.
- 680 Hollender, Artur  
681 1901 Om sveriges nivåförändringar efter människans invandring. *Geologiska Föreningen i Stockholm Förhan-  
682 dlingar* 23(4):1118–1130. DOI:10.1080/00293652.1975.9965220.
- 683 Hughes, Anna L. C., Richard Gyllencreutz, Øystein S. Lohne, Jan Mangerud, and John Inge Svendsen  
684 2016 The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1.  
685 *Boreas* 45(1):1–45. DOI:<https://doi.org/10.1111/bor.12142>.
- 686 Hyndman, Rob J  
687 1996 Computing and Graphing Highest Density Regions. *The American Statistician* 50(2):120–126.
- 688 Ilves, Kristin, and Kim Darmark  
689 2011 Some Critical and Methodological Aspects of Shoreline Determination: Examples from the Baltic Sea  
690 Region. *Journal of Archaeological Method and Theory* 18:147–165. DOI:10.1007/s10816-010-9084-x.
- 691 Jakslund, Lasse (editor)  
692 2001 *Vinterbrolokaliteten – En kronologisk sekvens fra mellom- og senmesolitikum i Ås, Akershus*. University  
693 of Oslo, Museum of Cultural History, Oslo.
- 694 (editor)  
695 2012a *E18 Brunlanesprosjektet. Bind II. Undersøkte lokaliteter fra tidligmesolitikum*. University of Oslo,  
696 Museum of Cultural History, Oslo.
- 697 (editor)  
698 2012b *E18 Brunlanesprosjektet. Bind III. Undersøkte lokaliteter fra tidligmesolitikum og senere*. University  
699 of Oslo, Museum of Cultural History, Oslo.
- 700 2014 Kulturhistorisk sammenstilling. In *E18 brunlanesprosjektet. Bind i. Forutsetninger og kulturhistorisk  
701 sammenstilling*, edited by Lasse Jakslund and Per Persson, pp. 11–46. University of Oslo, Museum of  
Cultural History, Oslo.

- 703
- 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748
- Jaksland, Lasse, and Per Persson (editors)
- 2014 *E18 Brunlanesprosjektet. Bind I. Forutsetninger og kulturhistorisk sammenstilling.* University of Oslo, Museum of Cultural History, Oslo.
- Johansen, Erling
- 1963 Kyst(fangst)boplassenes strandbundenhet og strandlinjekronologien. In *Boplatsproblem vid Kattegat och Skagerack*, pp. 90–92. Göteborg och Bohusläns fornminnesförening & Institutionen för nordisk fornkunskap, Gothenburg University, Gothenburg.
- 1997 Eksperimentelle studier av flint og flint-vandringer i strandsonen. Et forsøk på å vinne ny kunnskap om våre boplasser i steinalderen. *Universitetets Oldsaksamling Årbok* 1995/1996:31–39.
- Jørgensen, Erlend Kirkeng, Petro Pesonen, and Miikka Tallavaara
- 2020 Climatic changes cause synchronous population dynamics and adaptive strategies among coastal hunter-gatherers in Holocene northern Europe. *Quaternary Research*:1–16. DOI:10.1017/qua.2019.86.
- Kjemperud, Alfred
- 1986 Late Weichselian and Holocene shoreline displacement in the Trondheimsfjord area, central Norway. *Boreas* 15(1):61–82. DOI:10.1111/j.1502-3885.1986.tb00744.x.
- Kleppe, Else Johansen
- 1985 *Archaeological Data on Shore Displacements in Norway.* Norges geografiske oppmåling, Hønefoss.
- Kleppe, Jan Ingolf
- 2018 The Pioneer Colonization of Northern Norway. In *Early Economy and Settlement in Northern Europe. Pioneering, Resource Use, Coping with Change*, edited by Hans Peter Blankholm, pp. 13–57. Equinox, Sheffield.
- Lakens, Daniël, Anne M. Scheel, and Peder M. Isager
- 2018 Equivalence Testing for Psychological Research: A Tutorial. *Advances in Methods and Practices in Psychological Science* 1(2):259–269. DOI:10.1177/2515245918770963.
- Lewis, Joseph
- 2021 Probabilistic Modelling for Incorporating Uncertainty in Least Cost Path Results: a Postdictive Roman Road Case Study. *Journal of Archaeological Method and Theory* 28(3):911–924. DOI:10.1007/s10816-021-09522-w.
- Løken, Trond
- 1977 Mølen – et arkeologisk dateringsproblem og en historisk identifikasjonsmulighet. *Universitetets Oldsaksamling Årbok* 1975/1976:67–85.
- Marwick, Ben, Carl Boettiger, and Lincoln Mullen
- 2018 Packaging Data Analytical Work Reproducibly Using R (and Friends). *The American Statistician* 72(1):80–88. DOI:10.1080/00031305.2017.1375986.
- Melvold, Stine, and Per Persson (editors)
- 2014 *Vestfoldbaneprosjektet. Arkeologiske undersøkelser i forbindelse med ny jernbane mellom Larvik og Porsgrunn. Bind 1. Tidlig- Og mellommesolittiske lokaliteter i Vestfold og Telemark.* Portal forlag, Kristiansand.
- Mikkelsen, Egil
- 1975 Mesolithic in South-Eastern Norway. *Norwegian Archaeological Review* 8(1):1118–1130. DOI:10.1080/11035890109445866.
- Milne, Glenn A
- 2015 Glacial isostatic adjustment. In *Handbook of sea-level research*, edited by Ian Shennan, Antony J Long, and Benjamin P Horton, pp. 421–437. Wiley, Chichester.
- Milne, Glenn A., W. Roland Gehrels, Chris W. Hughes, and Mark E. Tamisiea
- 2009 Identifying the causes of sea-level change. *Nature Geoscience* 2(7):471–478. DOI:10.1038/ngeo544.
- Mjærum, Axel

- 749 2018 Hinterland discoveries: Middle Mesolithic woodland utilization and the case of the site Eidsberg,  
750 eastern Norway. *Current Swedish Archaeology* 26(1):159–188. DOI:10.37718/CSA.2018.11.
- 751 2022 A Matter of Scale: Responses to Landscape Changes in the Oslo Fjord, Norway, in the Mesolithic.  
752 *Open Archaeology* 8(1):62–84. DOI:10.1515/opar-2022-0225.
- 753 Møller, Jakob J  
754 1987 Shoreline relation and prehistoric settlement in northern norway. *Norwegian Journal of Geography*  
755 41:45–60. DOI:<http://dx.doi.org/10.1080/00291958708552171>.
- 756 Mörner, Nils-Axel  
757 1976 Eustasy and Geoid Changes. *The Journal of Geology* 84(2):123–151. DOI:10.1086/628184.
- 758  
759 1979 The Fennoscandian Uplift and Late Cenozoic Geodynamics: Geological Evidence. *GeoJournal* 3(3):287–  
760 318. DOI:10.1007/BF00177634.
- 761 Nielsen, Svein Vatsvåg  
762 2021 Early farming in Southeastern Norway: New evidence and interpretations. *Journal of Neolithic  
763 Archaeology* 23:83–113. DOI:10.12766/jna.2021.4.
- 764 Nielsen, Svein Vatsvåg, Per Persson, and Steinar Solheim  
765 2019 De-Neolithisation in southern Norway inferred from statistical modelling of radiocarbon dates. *Journal  
766 of Anthropological Archaeology* 53:82–91. DOI:10.1016/j.jaa.2018.11.004.
- 767 Nordqvist, Bengt  
768 1995 The Mesolithic settlement of the west coast of Sweden - with special emphasis on chronology and  
769 topography of coastal settlements. In *Man and Sea in the Mesolithic. Coastal settlement above and  
below present sea level*, edited by Anders Fischer, pp. 185–196. Oxbow Books, Oxford.
- 770 1999 The Chronology of the Western Swedish Mesolithic and Late Paleolithic: Old Answers in Spite of New  
771 Methods. In *The Mesolithic of Central Scandinavia*, edited by Joel Boaz, pp. 235–253. University of  
Oslo, Oslo.
- 772 Norwegian Mapping Authority  
773 2018 *Produktspesifikasjon. Nasjonal modell for høydedata fra laserskanning (FKB-laser)*. FKB-laser\_v30.
- 774  
775 2021 *Tidevannstabeller for den norske kyst med Svalbard samt Dover, England*.
- 776  
777 Nummedal, Anders  
778 1923 Om flintpladsene. *Norwegian Journal of Geography* 7(2):89–141.
- 779  
780 Østmo, Einar  
781 1988 *Etableringen av jordbrukskultur i Østfold i steinalderen*. The University Collection of National  
782 Antiquities, University of Oslo, Oslo.
- 783 2008 *Auve. En fangstboplass fra yngre steinalder på Vesterøya i Sandefjord. I. Den arkeologiske del*. Museum  
784 of Cultural History, University of Oslo, Oslo.
- 785 Parnell, A. C., J. Haslett, J. R. M. Allen, C. E. Buck, and B. Huntley  
786 2008 A flexible approach to assessing synchronicity of past events using Bayesian reconstructions of sedimenta-  
787 tion history. *Quaternary Science Reviews* 27(19–20):1872–1885. DOI:10.1016/j.quascirev.2008.07.009.
- 788 Persson, Per  
789 2008 Nauen 5.2 – Stenåldersboplater och fossil åkermark. In *E18-prosjektet Vestfold. Bind 2. Steinalderbo-  
790 plasser, boplasspor, graver og dyrkningsspor*, edited by Lars Erik Gjerpe, pp. 163–198. University of  
Oslo, Museum of Cultural History, Oslo.
- 791 Prescott, Christopher  
792 2020 Interpreting Complex Diachronic "Neolithic"-Period Data in Norway. In *Farmers at the Frontier –  
793 A Pan European Perspective on Neolithisation*, edited by Kurt J. Gron, Lasse Sørensen, and Peter  
Rowley-Conwy, pp. 381–400. Oxbow Books, Oxford.
- 794 R Core Team

- 795 2021 *R: A language and environment for statistical computing*. R Foundation for Statistical Computing,  
796 Vienna, Austria.
- 797 Ramstad, Morten
- 798 2009 Eldre steinalder på Melkøya, representativitet, strandlinjer og transgresjon. In *Undersøkelsene på  
Melkøya. Melkøyaprosjektet – Kulturhistoriske registreringer og utgravninger 2001 og 2002*, edited by  
Anders Hesjedal, Morten Ramstad, and Anja R. Niemi, pp. 491–495. Tromsø museum, Universitets-  
799 museet, Tromsø.
- 800 Reimer, Paula J., William E. N. Austin, Edouard Bard, Alex Bayliss, Paul G. Blackwell, Christopher Bronk  
801 Ramsey, Martin Butzin, Hai Cheng, R. Lawrence Edwards, Michael Friedrich, Pieter M. Grootes, Thomas  
802 P. Guilderson, Irka Hajdas, Timothy J. Heaton, Alan G. Hogg, Konrad A. Hughen, Bernd Kromer, Sturt  
803 W. Manning, Raimund Muscheler, Jonathan G. Palmer, Charlotte Pearson, Johannes van der Plicht, Ron  
804 W. Reimer, David A. Richards, E. Marian Scott, John R. Southon, Christian S. M. Turney, Lukas Wacker,  
805 Florian Adolphi, Ulf Büntgen, Manuela Capano, Simon M. Fahrni, Alexandra Fogtmann-Schulz, Ronny  
806 Friedrich, Peter Köhler, Sabrina Kudsk, Fusa Miyake, Jesper Olsen, Frederick Reinig, Minoru Sakamoto,  
807 Adam Sookdeo, and Sahra Talamo
- 808 2020 The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radiocarbon*  
809 62(4):725–757. DOI:10.1017/RDC.2020.41.
- 810 Reitan, Gaute, and Inger Marie Berg-Hansen
- 811 2009 *Lundevågenprosjektet, delrapport 1. Sammenfattende rapport. Lunde, 6/1, 6/35 og Skjolnes 7/23,  
7/27, Farsund kommune, Vest-Agder*. Oslo.
- 812
- 813 Reitan, Gaute, and Per Persson (editors)
- 814 2014 *Vestfoldbaneprosjektet. Arkeologiske undersøkelser i forbindelse med ny jernbane mellom Larvik og  
Porsgrunn. Bind 2. Seinmesolittiske, neolittiske og yngre lokaliteter i Vestfold og Telemark*. Portal  
815 forlag, Kristiansand.
- 816 Reitan, Gaute, and Lars Sundström (editors)
- 817 2018 *The Stone Age Coastal Settlement in Aust-Agder, Southeast Norway*. Cappelen Damm Akademisk,  
818 Oslo.
- 819 Roalkvam, Isak
- 820 2020 Algorithmic classification and statistical modelling of coastal settlement patterns in Mesolithic south-  
821 eastern Norway. *Journal of Computer Applications in Archaeology* 3(1):288–307. DOI:<https://doi.org/10.5334/jcaa.60>.
- 822 2022 Exploring the composition of lithic assemblages in Mesolithic south-eastern Norway. *Journal of  
823 Archaeological Science: Reports* 42:103371. DOI:10.1016/j.jasrep.2022.103371.
- 824 Rønberg, Frank Halvar N.
- 825 2012 *Bosettings- og aktivitetsspor. Larønningen, 221/2138. Skien, Telemark*. University of Oslo, Museum  
826 of Cultural History, Oslo.
- 827 Romundset, Anders
- 828 2018 Postglacial shoreline displacement in the Tvedstrand-Arendal area. In *The Stone Age Coastal  
Settlement in Aust-Agder, Southeast Norway*, edited by Gaute Reitan and Lars Sundström, pp.  
829 463–478. Cappelen Damm Akademisk, Oslo.
- 830 Romundset, Anders, Stein Bondevik, and Ole Bennike
- 831 2011 Postglacial uplift and relative sea level changes in Finnmark, northern Norway. *Quaternary Science  
Reviews* 30(19-20):2398–2421. DOI:10.1016/j.quascirev.2011.06.007.
- 832
- 833 Romundset, Anders, Ola Fredin, and Fredrik Høgaas
- 834 2015 A Holocene sea-level curve and revised isobase map based on isolation basins from near the southern  
835 tip of Norway. *Boreas* 44:383–400. DOI:10.1111/bor.12105.
- 836 Romundset, Anders, Thomas R. Lakeman, and Fredrik Høgaas
- 837 2018 Quantifying variable rates of postglacial relative sea level fall from a cluster of 24 isolation basins in  
838 southern Norway. *Quaternary Science Reviews* 197:175–192. DOI:10.1016/j.quascirev.2018.07.041.

- 839 2019 Coastal lake records add constraints to the age and magnitude of the Younger Dryas ice-front oscillation  
840 along the Skagerrak coastline in southern Norway. *Journal of Quaternary Science* 34(2):112–124.  
DOI:<https://doi.org/10.1002/jqs.3085>.
- 841 Schmitt, Lou, Stephan Larsson, Jan Burdukiewicz, John Ziker, Krister Svedhage, Jeanette Zamon, and  
842 Steffen Holger
- 843 2009 Chronological Insights, Cultural Change, and Resource Exploitation on the West Coast of Sweden  
844 During the Late Palaeolithic/Early Mesolithic Transition. *Oxford Journal of Archaeology* 28:1–27.  
DOI:[10.1111/j.1468-0092.2008.00317.x](https://doi.org/10.1111/j.1468-0092.2008.00317.x).
- 845 Schülke, Almut
- 846 2020 First visit or revisit? Motivations of mobility and the use and reuse of sites in the changing coastal  
areas of Mesolithic southeastern Norway. In *Coastal Landscapes of the Mesolithic: Human Engagement  
with the Coast from the Atlantic to the Baltic Sea*, edited by Almut Schülke, pp. 359–393. Routledge,  
London & New York.
- 847 Shennan, Ian
- 848 2015 Handbook of sea-level research: Framing research questions. In *Handbook of Sea-Level Research*, edited  
849 by Ian Shennan, Antony J Long, and Benjamin P Horton, pp. 3–25. Wiley, Chichester.
- 850 Shetelig, Haakon
- 851 1922 *Primitive Tider i Norge – En oversikt over stenalderen*. John Griegs Forlag, Bergen.
- 852 Sognnes, Kalle
- 853 2003 On shoreline dating of rock art. *Acta Archaeologica* 74:189–209.
- 854 Solheim, Steinar
- 855 2012 Lokal praksis og fremmed opphav. Arbeidsdeling, sosiale relasjoner og differensiering i østnorsk  
856 tidlige neolitikum. Unpublished PhD thesis, Oslo.
- 857 (editor)
- 858 2017 *E18 Rugtvedt-Dørdal. Arkeologiske undersøkelser av lokaliteter fra steinalder og jernalder i Bamble  
859 kommune, Telemark fylke*. Portal forlag, Kristiansand.
- 860 2020 Mesolithic coastal landscapes. Demography, settlement patterns and subsistence economy in south-  
861 eastern Norway. In *Coastal Landscapes of the Mesolithic: Human Engagement with the Coast from the  
862 Atlantic to the Baltic Sea*, edited by Almut Schülke. Routledge, London & New York.
- 863 2021 Timing the Emergence and Development of Arable Farming in Southeastern Norway by Using Summed  
864 Probability Distribution of Radiocarbon Dates and a Bayesian Age Model. *Radiocarbon* 63(5):1–22.  
DOI:[10.1017/RDC.2021.80](https://doi.org/10.1017/RDC.2021.80).
- 865 Solheim, Steinar, and Per Persson
- 866 2018 Early and mid-Holocene coastal settlement and demography in southeastern Norway: Comparing dis-  
867 tribution of radiocarbon dates and shoreline-dated sites, 8500–2000 cal. BCE. *Journal of Archaeological  
868 Science: Reports* 19:334–343. DOI:[10.1016/j.jasrep.2018.03.007](https://doi.org/10.1016/j.jasrep.2018.03.007).
- 869 Sørensen, Rolf
- 870 1979 Late Weichselian deglaciation in the Oslofjord area, south Norway. *Boreas* 8(2):241–246. DOI:<https://doi.org/10.1111/j.1502-3885.1979.tb00806.x>.
- 871 1999 En <sup>14</sup>C datert og dendrokronologisk kalibrert strandforksyvningskurve for sørøst-Norge. Sørøst-Norge.  
872 In *Museumslandskap. Artikkelsamling til Kerstin Griffin på 60-årsdagen. Bind A*, edited by Lotte  
873 Selsing and Grete Lillehammer, pp. 227–242. AmS-rapport 12A. Museum of Archaeology, Stavanger.
- 874 Sørensen, Rolf, Kari E. Henningsmoen, Helge I. Høeg, and Veronika Gälman
- 875 2014 Holocene landhevningsstudier i søndre Vestfold og sørøstre Telemark – Revidert kurve. In *Vestfold-  
876 baneprosjektet. Arkeologiske undersøkelser i forbindelse med ny jernbane mellom Larvik og Porsgrunn.  
Bind 1*, edited by Stine Melvold and Per Persson, pp. 36–47. Portal, Kristiansand.
- 877 Sørensen, Rolf, Kari E Henningsmoen, Helge I Høeg, and Veronika Gälman

- 879 in prep Holocen vegetasjonshistorie og landhevning i søndre Vestfold og sørøstre Telemark. In *The Stone*  
880 *Age in Telemark. Archaeological results and scientific analysis from Vestfoldbaneprosjektet and E18*  
881 *Rugtvedt-Dørdal*, edited by Per Persson and Steinar Solheim.
- 882 Sørensen, Rolf, Helge I. Høeg, Kari E. Henningsmoen, Göran Skog, Solveig F. Labowsky, and Bjørg Stabell  
883 2014 Utviklingen av det senglasiale og tidlig preboreale landskapet og vegetasjonen omkring steinalder-  
884 boplassene ved Pauler. In *E18 Brunlanesprosjektet. Bind I. Forutsetninger og kulturhistorisk sam-*  
885 *menstilling*, edited by Lasse Jakland and Per Persson, pp. 171–213. University of Oslo, Museum of  
886 Cultural History, Oslo.
- 887 Stokke, Jo-Simon Frøshaug, and Gaute Reitan  
888 2018 Kvastad A2. Lokalitet med funn fra tidlig- og mellommesolitikum og dyrkningsspor fra mellom- og  
889 senneolitikum. In *The Stone Age Coastal Settlement in Aust-Agder, Southeast Norway*, edited by  
890 Gaute Reitan and Lars Sundström, pp. 375–407. Cappelen Damm Akademisk, Oslo.
- 891 Stroeven, Arjen P., Clas Hättestrand, Johan Kleman, Jakob Heyman, Derek Fabel, Ola Fredin, Bradley W.  
892 Goodfellow, Jonathan M. Harbor, John D. Jansen, Lars Olsen, Marc W. Caffee, David Fink, Jan Lundqvist,  
893 Gunhild C. Rosqvist, Bo Strömborg, and Krister N. Jansson  
894 2016 Deglaciation of Fennoscandia. *Quaternary Science Reviews* 147:91–121.  
DOI:10.1016/j.quascirev.2015.09.016.
- 895 Stuvier, Minze, and Paula Reimer  
896 1989 Histograms obtained from computerized radiocarbon age calibration. *Radiocarbon* 31(3):817–823.  
DOI:10.1017/S0033822200012431.
- 897 Svendsen, John Inge, and Jan Mangerud  
898 1987 Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of*  
899 *Quaternary Science* 2(2):113–132. DOI:10.1002/jqs.3390020205.
- 900 Tallavaara, Miikka, and Petro Pesonen  
901 2020 Human ecodynamics in the north-west coast of Finland 10,000–2000 years ago. *Quaternary Interna-*  
902 *tional* 549:26–35. DOI:10.1016/j.quaint.2018.06.032.
- 903 van der Plicht, Johannes  
904 1993 The Groningen Radiocarbon Calibration Program. *Radiocarbon* 35(1):231–237.  
DOI:10.1017/S0033822200013916.
- 905 Wang, Ian  
906 2019 *topoDistance: Calculating topographic paths and distances. R package version 1.0.1. Https://CRAN.r-*  
*project.org/package=topoDistance.*
- 907 Wenn, Camilla Cecilie  
908 2012 *Bosettingsspor, produksjonsområde og dyrkningsspor fra Neolitikum til Folkevandringstid. Bratsberg,*  
909 *63/69, 244. Skien kommune, Telemark*. University of Oslo, Museum of Cultural History, Oslo.
- 910 Wikell, Roger, Fredrik Molin, and Mattias Pettersson  
911 2009 The Archipelago of Eastern Middle Sweden - Mesolithic Settlement in Comparison with  $^{14}\text{C}$  and  
Shoreline Dating. In *Chronology and Evolution within the Mesolithic of North-West Europe*, edited  
by Philippe Crombé, Mark van Strydonck, Joris Sergant, Mathieu Boudin, and Machteld Bats, pp.  
417–434. Cambridge Scholar Publishing, Brussels.
- 912 Yubero-Gómez, María, Xavier Rubio-Campillo, and Javier López-Cachero  
913 2016 The study of spatiotemporal patterns integrating temporal uncertainty in late prehistoric settlements  
914 in northeastern Spain. *Archaeological and Anthropological Sciences* 8(3):477–490. DOI:10.1007/s12520-  
015-0231-x.