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

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1 Introduction

The post-glacial relative sea-level fall that characterises large areas of Fennoscandia is fundamental to its archaeology. This follows not only from the dramatic changes to the landscape that this process has represented throughout prehistory, but also from the fact that if archaeological phenomena were situated close to the contemporary shoreline when they were in use, a reconstruction of the trajectory of shoreline displacement can be used to date these phenomena based on their altitude relative to the present day sea-level. This method, also called shoreline dating, has long history of use in the region and is frequently applied to assign an approximate date to diverse archaeological phenomena such as rock art, grave cairns, various harbour and sea-side constructions and, as is the focus of this study, Stone Age sites (e.g. Åkerlund, 1996; Bjerck, 2005; Ilves and Darmark, 2011; Nordqvist, 1995; Schmitt et al., 2009; Sognnes, 2003; Tallavaara and Pesonen, 2020).

The close association between Scandinavian Stone Age settlements and shifting prehistoric shorelines was becoming apparent by the end of the 19th century (**degeer1896?**), and was firmly established and first applied as a dating method in Sweden (Hollender, 1901) and Norway (Brøgger, 1905) at the turn of the century. Shoreline dating has been fundamental to Stone Age archaeology in Norway ever since (e.g. Berg-Hansen, 2009; Bjerck, 2008, 1990; Breivik, 2014; Mikkelsen, 1975; Nummedal, 1923; Solheim and Persson, 2018). The method is used both independently, and to compliment other sources of temporal data such as typological indicators or radiometric dates. However, given the coarse and fuzzy resolution of established typological frameworks, the vast amount of surveyed sites that only contain generic lithic debitage that could hail from any part of the period, and as the conditions for the preservation of organic material is typically poor in Norway, dating with reference to shoreline displacement is often the only and most accurate method by which one can hope to date the sites. Shoreline dating is consequently fundamental to our understanding of the Norwegian Stone Age. This is both because it is central to the temporal framework on which our understanding of the period is based, but also because the method is only applicable so long as the societies in question have continuously settled on or close to the contemporary shoreline. Consequently, adherence or deviation from this pattern also has major implications for the socio-economic foundations of the societies in question.

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

2 Background

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

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

The shore-bound settlement location of prehistoric hunter-fisher-gatherers in Norway is generally believed to follow both from the exploitation of aquatic resources and from movement and communication, which would have been efficient on waterways (Berg-Hansen, 2009; Bergsvik, 2009). The same logic has also been extended to the hinter- and inland regions, where sites are to be located along rivers and lakes (Brøgger, 1905; Glørstad, 2010, pp. 57–87; but see Gundersen, 2013; Mjærum, 2018; Schülke, 2020). This is to take a dramatic turn at the transition to the Late Neolithic, around 2400 BCE, with the introduction of the Neolithic proper (Prescott, 2020; Solheim, 2021). The introduction of a comprehensive Neolithic cultural package, including a shift to agro-pastoralism and the introduction of the farm is to have led site locations to be more withdrawn from the shoreline (e.g. Bakka and Kaland, 1971; Østmo, 2008, p. 223; **prescott2012?**). That is not to say that waterways and aquatic resources were no longer exploited, but rather that these activities would not have been as tightly integrated with settlement and tool-production areas as in preceding

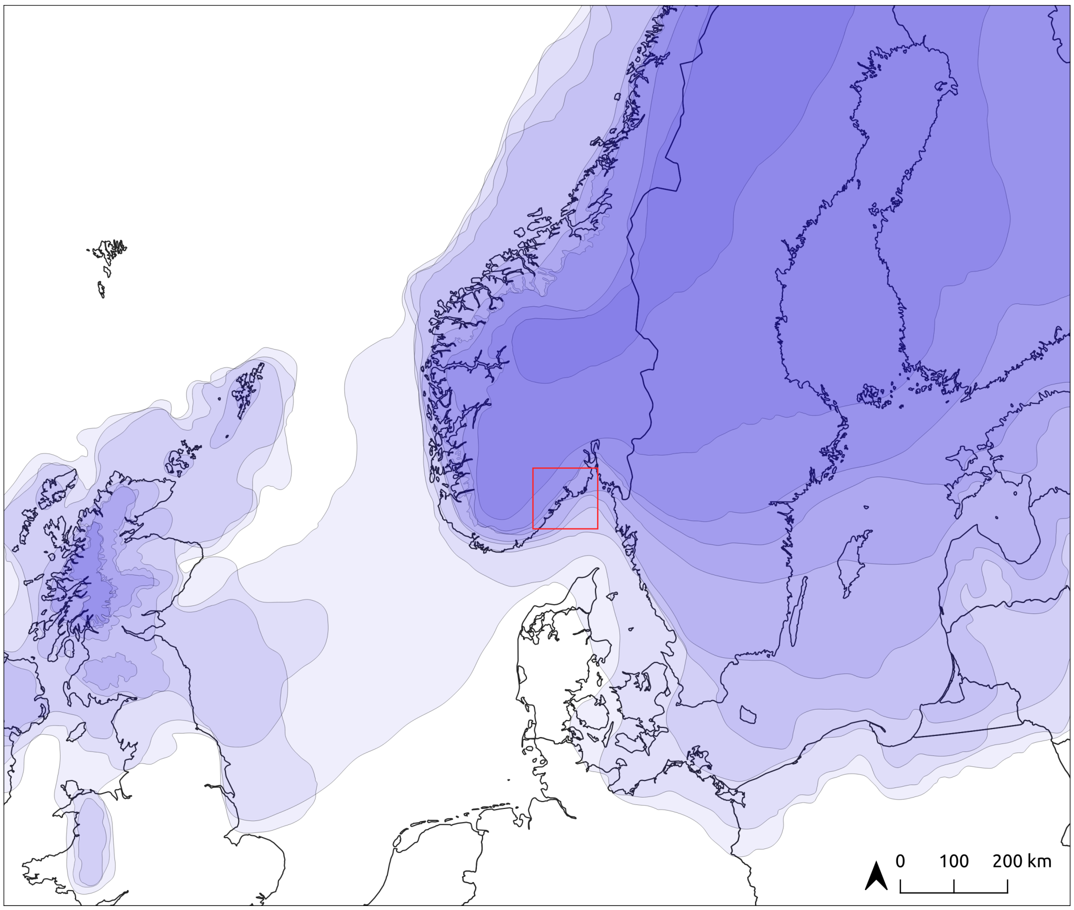


Figure 1: Deglaciation at 1000 year intervals from c. 17–8 kyr BCE (data from Hughes et al. 2016, but see Romundset et al. 2019). The study area defined later in the text is marked with a red outline.

periods (Glørstad, 2011). At an earlier stage, at the transition to the Early Neolithic (c. 3900 BCE), pottery is introduced to the sites, and there are some indications of an initial uptake of agriculture at some sites in the Oslo fjord region. However, this appears to be small in scale and is believed to be combined with a continued and predominantly hunter-gatherer life-way, possibly followed by a complete de-Neolithisation in the Middle Neolithic (Nielsen et al., 2019; Østmo, 1988, pp. 225–227; **hinsch1955?**). Nielsen (2021) has recently argued that the initial uptake of agriculture in the Early Neolithic is combined with a more complex settlement pattern, and that a simple forager/farming dichotomy would underplay the variation present in the Early and Middle Neolithic settlement data (see also e.g. Amundsen et al., 2006; Østmo, 1988; Solheim, 2012, p. 74). Seen in relation to the question of interest here, the empirical expectation for the above outlined development would thus be a predominantly shore-bound settlement in the Mesolithic, possibly followed by a more varied association between sites and the shore-line from around 3900 BCE, and a decisive shift around 2400 BCE.

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

One of the more comprehensive evaluations of this relationship was done by Solheim and colleagues (Breivik et al., 2018; Solheim, 2020), who compared 102 ^{14}C-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 density 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}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 are entirely erroneous results of contamination 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 evidenced by artefact inventories or multiple site features, and not remnants of stays as ephemeral to only be discernible by individual features or dubious ^{14}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. Åstveit, 2018; Solheim, 2020; see also Åkerlund et al., 1995). This approach has a couple of limitations. First of all, the displacement curves are commonly applied directly to larger study areas, with only a few studies having taken the variable uplift-rates into account when performing this comparison (e.g. 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 synchroneity 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 move the analysis beyond a purely instrumental consideration of the applicability of shoreline dating. Suggested ways to help mitigate and integrate the issues presented above into to the analysis are presented in the methods section.

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, 1999, 1979), 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 press, 2014a, 2014b), Tvedestrand (Romundset et al., 2018; Romundset, 2018), and Arendal (Romundset, 2018).

The employed shoreline displacement curves are all based on the so-called isolation basin method (e.g. Kjemperud, 1986; Romundset et al., 2011). This 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 in the cores. Each curve is thus construed from a series of cored basins located at different elevations, each representing a high precision sea-level index point (SLIP). Furthermore, to minimise the impact of variable uplift rates, the basins are located in a as constrained area of the landscape as possible. Following from the morphology of the retreating ice sheet, the uplift is more severe towards the north-east, meaning that this needs to be adjusted for in the case that any basins are located any significant distance from a common isobase perpendicular to this gradient. The SLIPs from the isolaton basin method indicate the isolation from the highest astronomical tide. For the displacement curve, this is then adjusted to mean sea-level based on the present day tidal range, which is assumed to have been the same throughout the Holocene (Sørensen et al., 2014a, p. 44). Furthermore, the confidence bands of the displacement curves and their trajectory are quite complex constructs, and are the integrated result of both expert knowledge and more objectively quantifiable parameters. The reason for this is in part that the curves do not only contain uncertainty as related to radiometric dates, which are well defined, but also hold potential error as related to the interpretation and analysis of sediment cores, the nature and condition of the basin outlets and the adjustment to a common isobase, to name but a few (e.g. Romundset et al., 2019, 2011). For more details and evaluations done for the compilation of each curve, the reader is therefore referred to the individual publications.

The archaeological data compiled for the analysis consists of all excavated Stone Age sites with available spatial data from the coastal region between Horten county in the north-east, to Arendal in the south-west (Figure 2). These number a total 155 sites. Of these, 93 sites are associated with a total of 578 radiocarbon dates. Of these, in turn, 69 sites are related to the 266 radiocarbon dates that fall within the Stone Age (9500–1700 BCE) with 95 % probability. These sites and ^{14}C-dates form the basis for the analysis. Spatial data in the form of site limits and features, as defined by the excavating archaeologists, were retrieved from local databases at the Museum of Cultural History—the institution responsible for archaeological excavations in the region. In the compiled dataset, each radiocarbon date has been associated with the site features or excavation unit from where they originate, or, where these weren't available, the spatial limit of the entire site.

Due to somewhat variable practices between excavations, what available spatial geometry best represents the site limit was decided based on an evaluation of the excavation reports. This means that the limits are variably given as that defined during initial survey, area de-turfed before excavation, area stripped with excavator following the excavation, manually excavated area, or convex hull polygons generated around the site features.

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

[Table with sites]

The elevation data used for the analysis is a digital terrain model (DTM) freely available from the Norwegian Mapping Authority (**mapping2019?**). It was here opted for the 10m resolution DTM rather than the higher-resolution 1m version. In addition to resulting in considerably less processing time, the higher resolution elevation model is more vulnerable to smaller-scale modern disturbances that the 10m version is not impacted by. The 10m DTM is a down-sampled version of the 1m resolution DTM, which is based on aerial laser scanning using a minimum of two and up to five points per m^2 and has a vertical error of (**mapping2019?**). All data and R programming code (R Core Team, 2021) required to run the analyses, as well as the derived data are freely available in an online repository at https://osf.io/7f9su/, organised as a digital research compendium following Marwick et al. (2018).

4 Methods

Shoreline dating could be termed a chorological dating method. That is, it is a method where the target phenomenon is given a likely date of occurence with reference to its geographical location – in this case its altitude relative to the present day sea-level. The method is based on the spatial relationship between two phenomena, occupation of sites and shoreline displacement, each associated with their own range of temporal uncertainty. The first task was therefore to ascribe likely date ranges and associated uncertainty to these dimensions. To take account of the gradient in the isostatic rebound, the trajectory of shoreline displacement was first interpolated to each site location from the displacement curves using inverse distance weighting based on the distance between the site and the isobases of the displacement curves (e.g. Conolly, 2020; Conolly and Lake, 2006, pp. 94–97). This was done for each year along the entirety of the curves, weighting the interpolation by the squared inverse of the distances. The result of this process is shown for an example site in Figure 3. For the date ranges associated with the sites, all radiocarbon dates were first individually calibrated using the IntCal20 calibration curve (Reimer et al., 2020) using OxCal v4.4.4 (Bronk Ramsey, 2009) through the oxcAAR package for R (Hinz et al., 2021). Radiocarbon dates associated with each site were then grouped if they overlapped with 99.7% probability, meaning these were effectively taken to represent the same settlement phase. In the case where there are multiple dates believed to belong to a single phase, these were subjected to Bayesian modelling using the Boundary function in OxCal and then summed. Multiple phases at a single site were treated as independent of each other.

As the excavation of archaeological sites typically follow from residential and commercial development, as well as the expansion of infrastructure, the area immediately surrounding the sites has sometimes been severely impacted by modern disturbances. In addition to employing 10m resolution DTM to alleviate some of these issues, this also necessitated some additional editing of the elevation raster. This involved manually defining the extent of problem areas such as railways, highways, quarries and the like. The DTM values on these

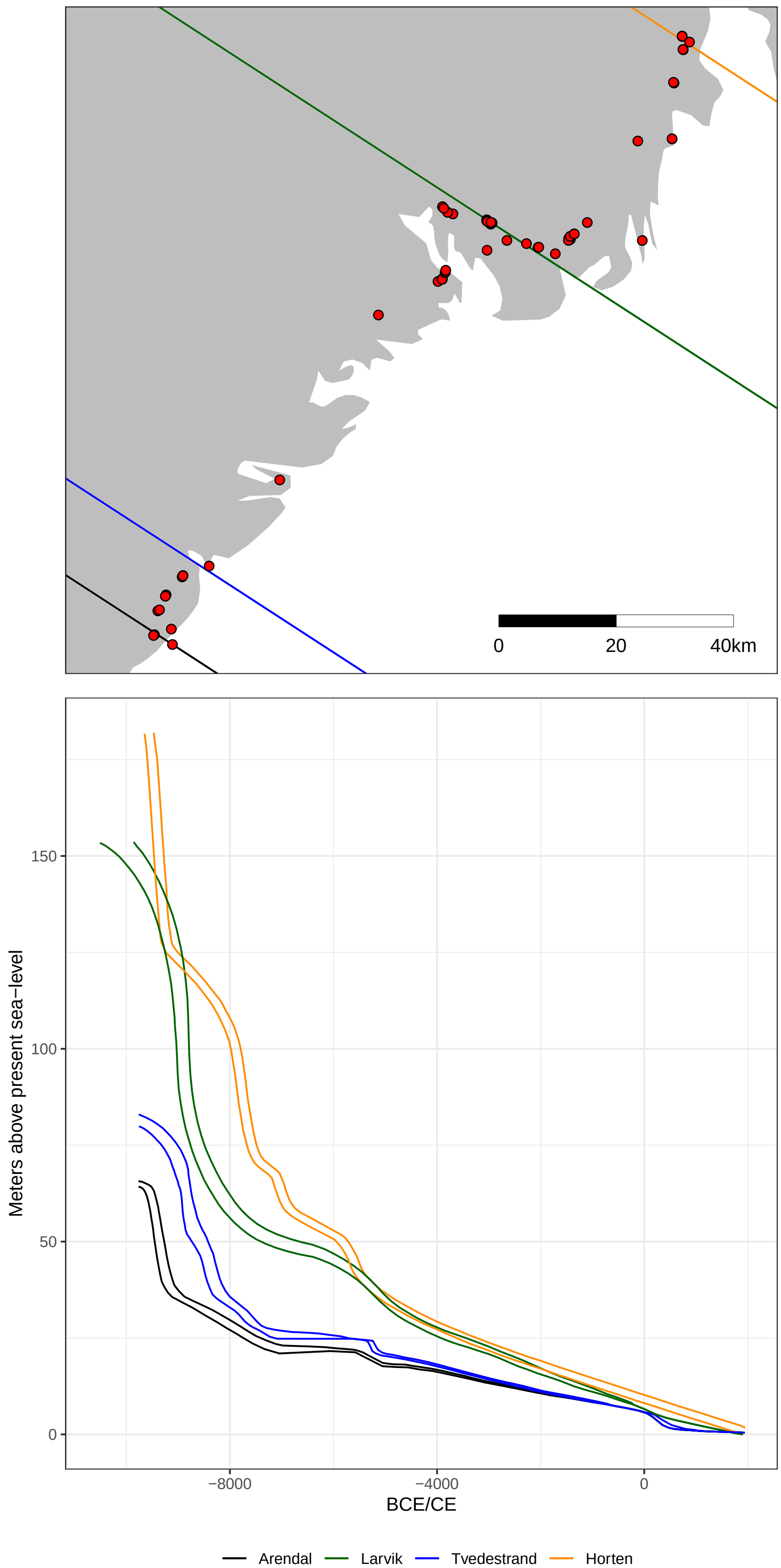


Figure 2: A) Distribution of the 69 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al. 2018), B) Displacement curves. Note the increasing steepness of the curves towards the north-east.

were then set to missing, and new elevation values were interpolated from the surrounding terrain. This was done using regularised spline interpolation with tension (e.g. Conolly, 2020), using the default settings of r.fillnulls from GRASS GIS (GRASS Development Team, 2017) in R through the package rgrass7 (Bivand, 2021). In addition to code and original spatial data being available in the research compendium for this paper, it has also been noted in the supplementary material when the area surrounding a site has been edited in this manner.

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

This process was repeated 1000 times for each phase for each site. The choice of 1000 simulation runs follows from an evaluation of when the mean distances between site and shoreline converged when running 5000 iterations of the simulation on the site Hovland 5, available in the supplementary material (cf. Crema et al., 2010, p. 1125). Hovland 5 was chosen for this evaluation as it has a fairly uncertain date range, and is located in area of quite complex topography. At 1000 simulation runs the analysis of each site took up to a few hours, depending on the distance to the simulated shorelines and the necessary size of the window of analysis.

5 Simulation results

Overall, as is indicated by the measures for central tendency and the almost solid line along the 0 mark on the y-axes, the simulations show that the sites tend to have been situated close to the shoreline when they were in use (Figure 6). Some of the sites are situated considerable distances from the shoreline when the dates believed to be erroneous in the original reports are included, but if one accepts the interpretation that these do not date the main occupation of the sites, as is indicated by the artefact inventories, the second row of Figure 6 gives considerable support to the notion that the sites were in use when they were situated on or close to the contemporaneous shoreline. The distances for some of the earliest sites appears somewhat high, but this can likely be explained as the result of the steepness of the displacement curves for the earliest part of the Holocene (Figure 2B), which leads the uncertainty of the ^{14}C-dates to give a wider possible elevation range for the sea-level. Another immediately striking result is the apparent deviation from

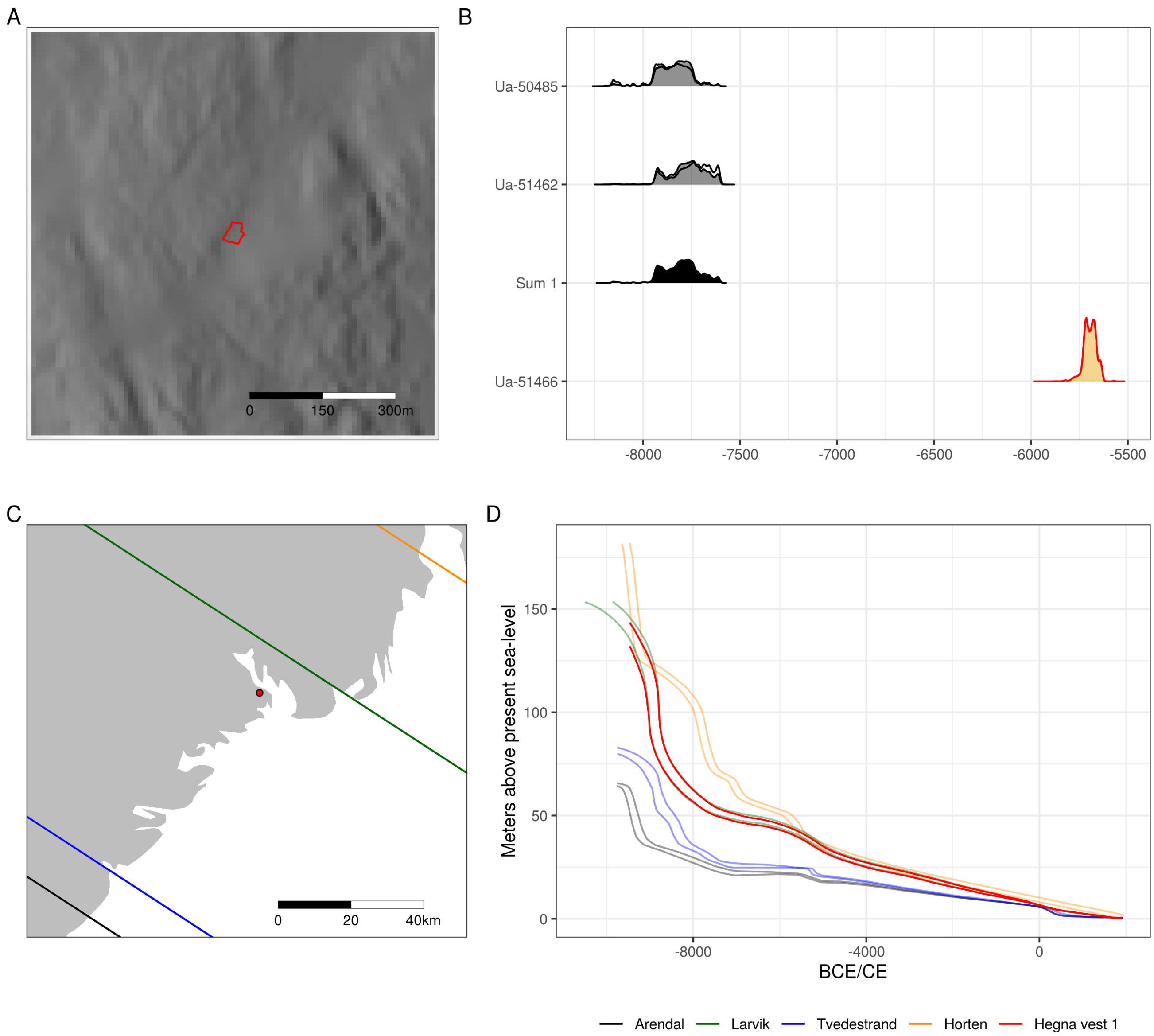


Figure 3: Example site Hegna vest 1 (Fossum 2017). A) Location of the site in the present day landscape. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled using 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.

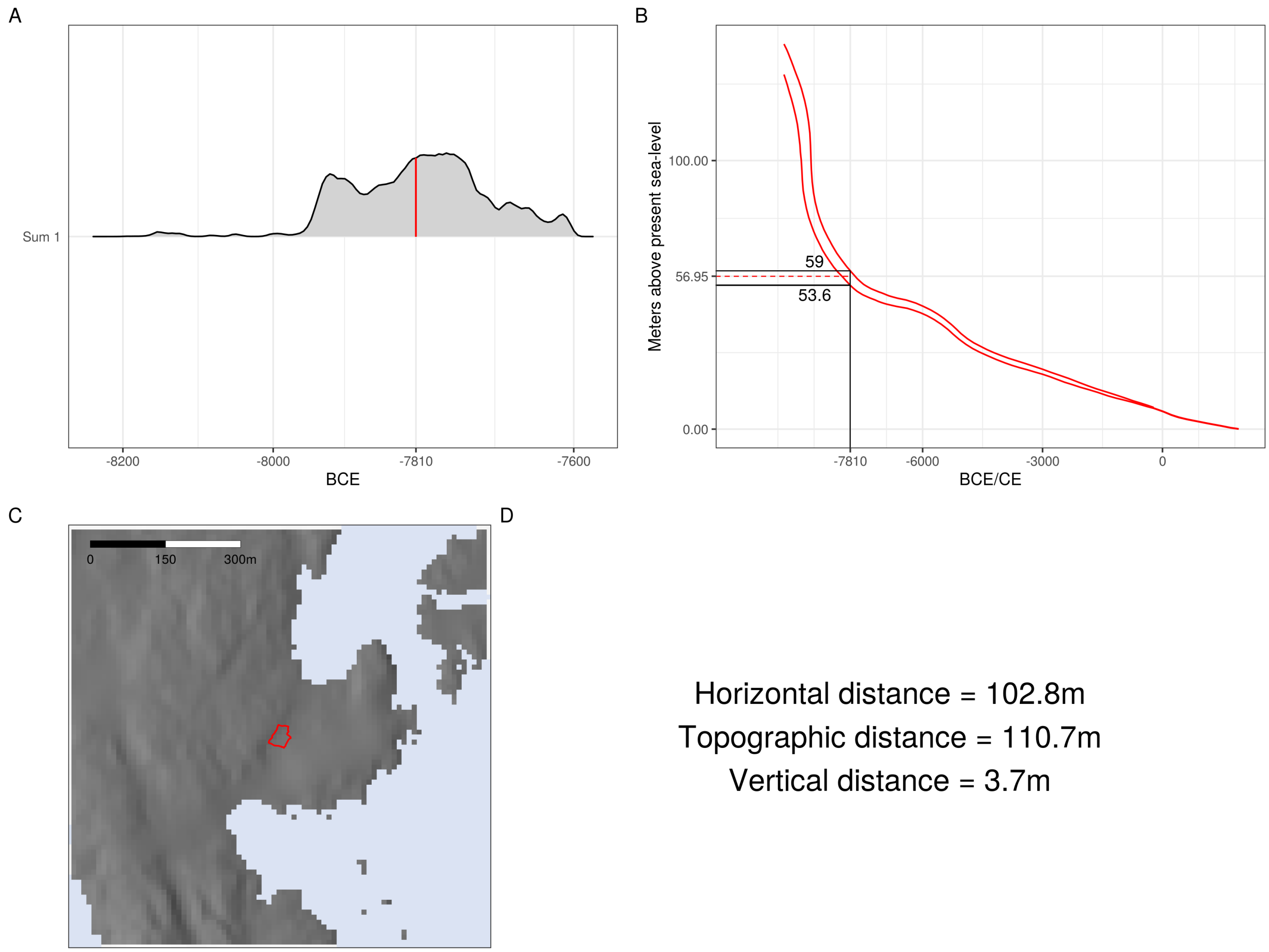


Figure 4: Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year from the posterior density esimate. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using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

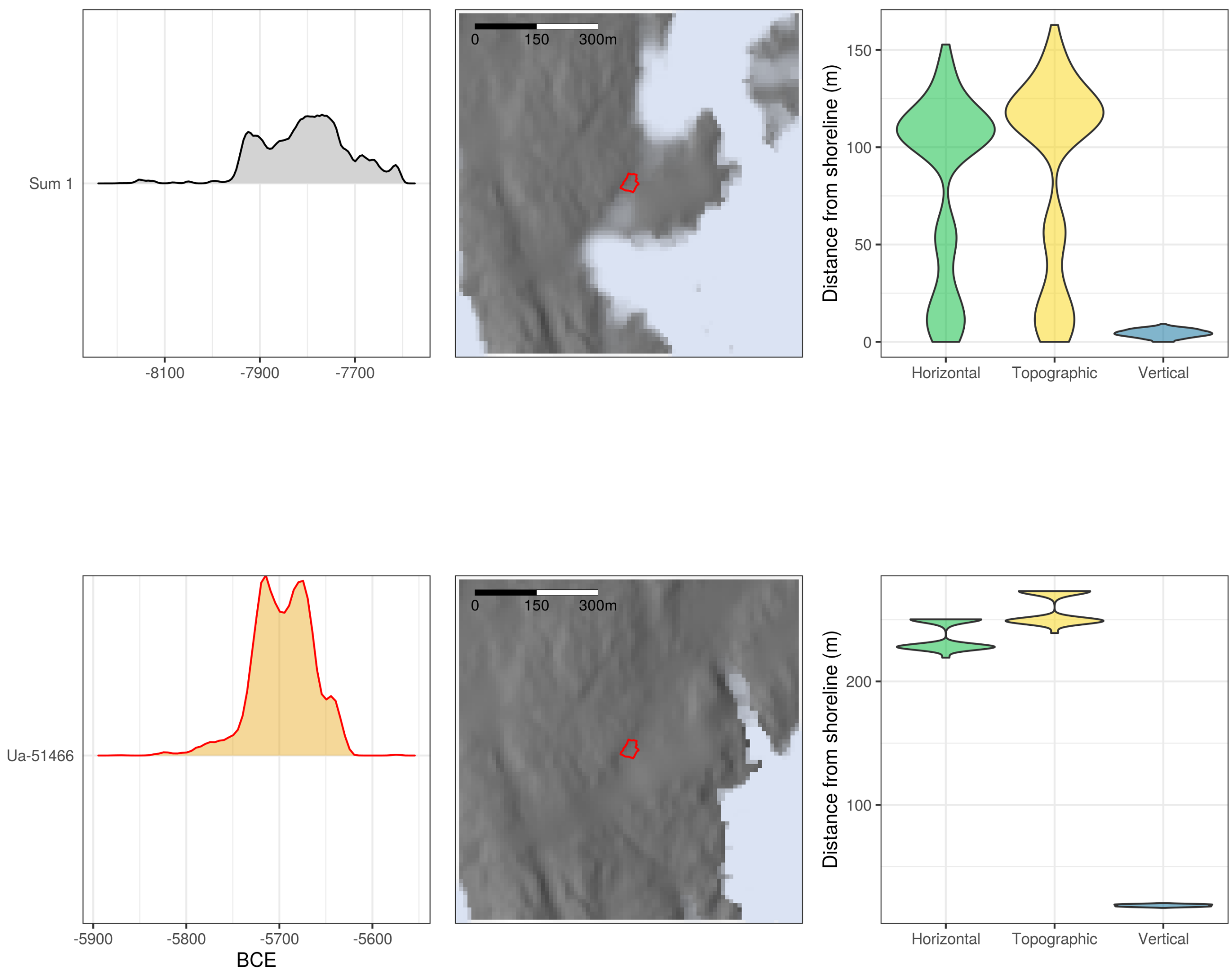


Figure 5: The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The first column of plots shows the radiocarbon probability density function from where dates were drawn during simulation. The second column displays the result of simulating the raised sea-level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

the shoreline towards the end of the Stone Age, corresponding with the literature. From around 2500 BCE several sites are situated a considerable distance from the shoreline, and while a couple remain horizontally and topographically close, most appear to be elevated a considerable distance from the sea-level, as indicated on the plot for vertical distance. There are also a couple of sites located some distance from the shoreline just after 4000 BCE. While the sample size is limited, this would thus be in line with a development that sees an increase in settlements located in the immediate inland around this time.

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

Accepting that shoreline dating appears to loose utility around the transition to the Late Neolithic, as indicated by the clear deviation in site location from the shoreline after this, the results for the second row of Figure 6 is given again in Figure 7, excluding all simulation results younger than 2500 BCE. Furthermore, all negative values have here been set to zero, under the assumption that these result from uncertainty or errors in the data, and not actual site locations. The resulting best point estimate for the vertical distance between site and shoreline for the pre-Late Neolithic is given by the median at 4m, while 95% of the values fall within the range 0–17m. That is, for 95% of the cases, the shoreline was situated on or down to 17m below the site location. While these values remain the same, the mean and standard deviation is constrained slightly when only considering the Mesolithic dates. While the median for horizontal and topographic distances is only 10m and 10m respectively, it is also evident that their range is substantially wider than that for vertical distance, illustrating the point that minor variations in vertical distance can have substantial consequences for these distance measures, depending on the surrounding topography.

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

Where x is [. . .] In Figure 8 this formula is used to shoreline date the same sites from where this relationship was derived. Following from having defined the distance between intersecting sea- and site polygons as zero during simulations, the sites were dated using the mean elevation of the site polygons to allow for some deviance in elevation. The result of comparing the synchroneity of the dates using the method presented by Parnell et al. (2008) is given in Figure 8B. Here, 100,000 age samples drawn from each ^{14}C-date was subtracted from 100,000 age samples drawn from the corresponding shoreline date. The resulting range between the 2.5th and 97.5th percentile were then checked to see if they cross zero, in which case the dates are considered synchronous. The result of this procedure indicates that the shoreline date correspond with the radiocarbon dates for 44 out of 49 sites (90%). The deviation from the shoreline date at the two Løvås sites and Gunnarsrød 5 is to be expected based on the simulation results (see above), but not at Langangen Vestgård 1 and Nordby 52. For these two sites the zero age difference can be seen to fall just outside the 95% interval (Figure 8B), and in the simulation of the distance to the shoreline this was simulated to be 0m across virtually all of the 1000 simulation runs for both sites (see supplementary material). If one accepts that sensitivity in the method leads to the failure to accurately date these two sites, and that the failed dating of the two Løsvås sites and Gunnarsrød 5 are instead due to extraneous factors and not the method itself, one could alternatively see the success rate as defined by 44 out of 46 sites (96%) having been correctly dated.

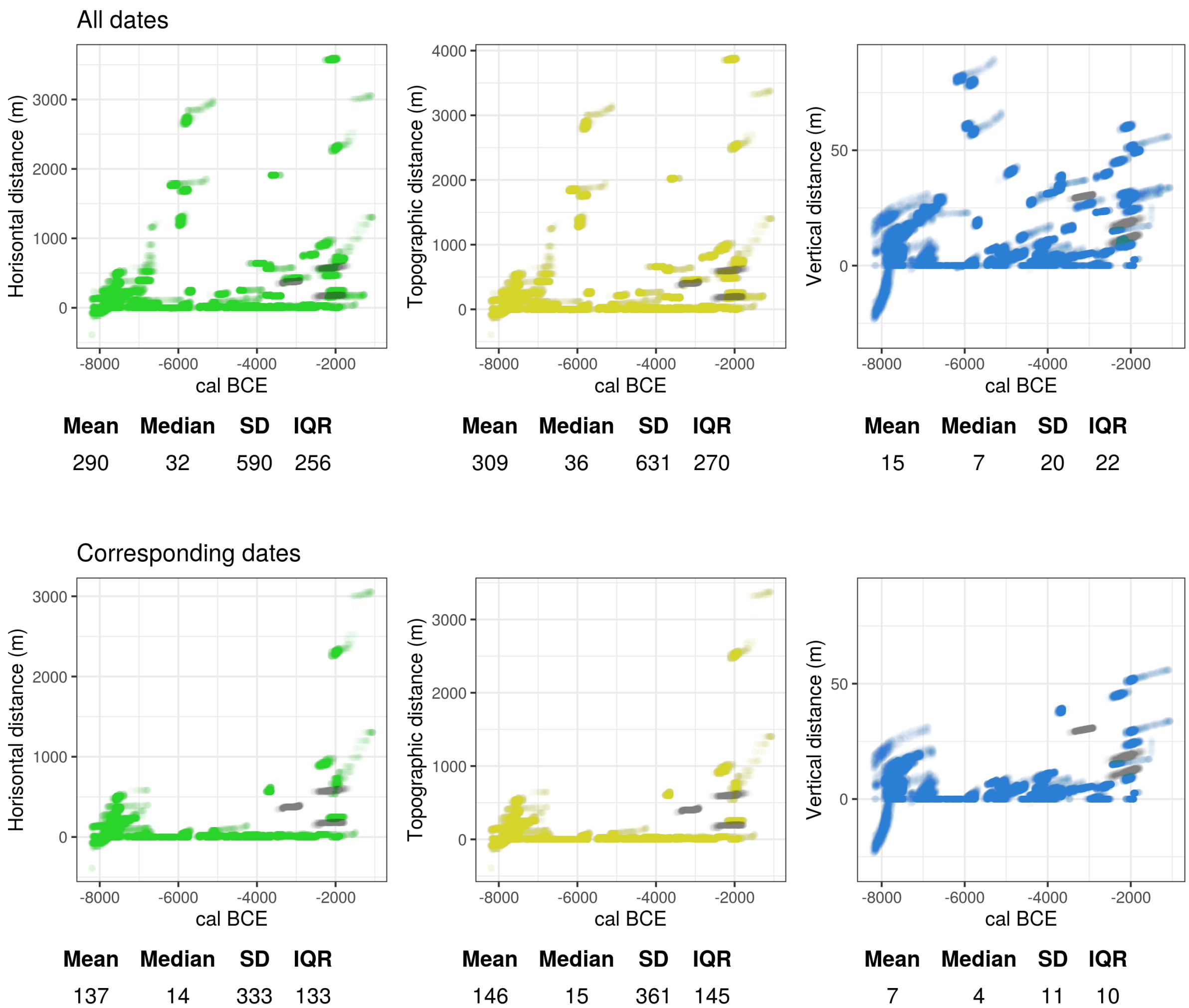


Figure 6: The result of running the analysis across all sites. Each data point is plotted with some transparency, meaning that the more intense the colour, the more often those values occured. Results associated with agricultural acitivites are plotted in grey. The first row shows the result of including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

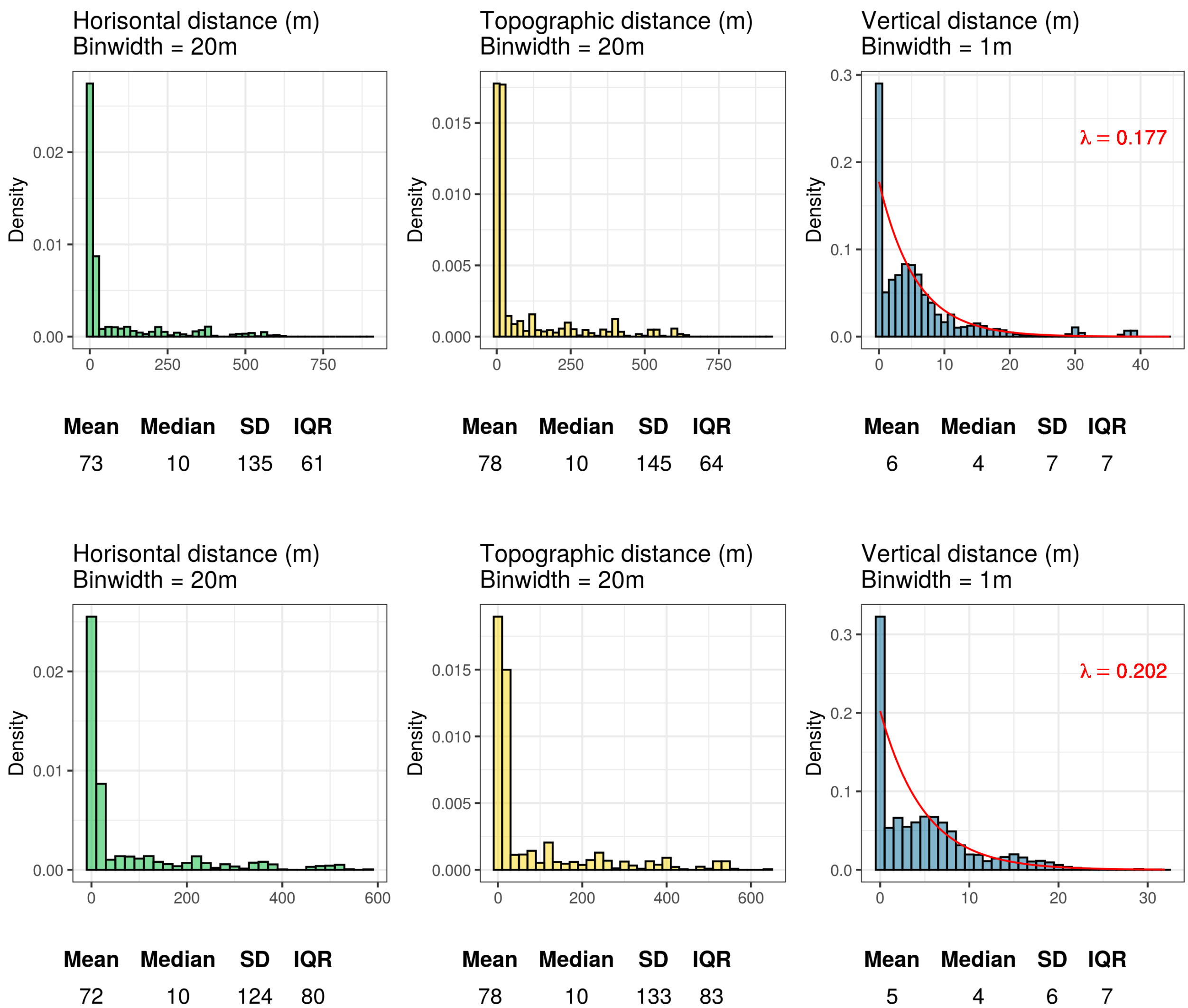


Figure 7: Histograms showing distance from shoreline using dates corresponding to the site inventory. Negative values have been set to zero. The first row only includes dates older than 2500 BCE and the second row only dates older than 4000 BCE.

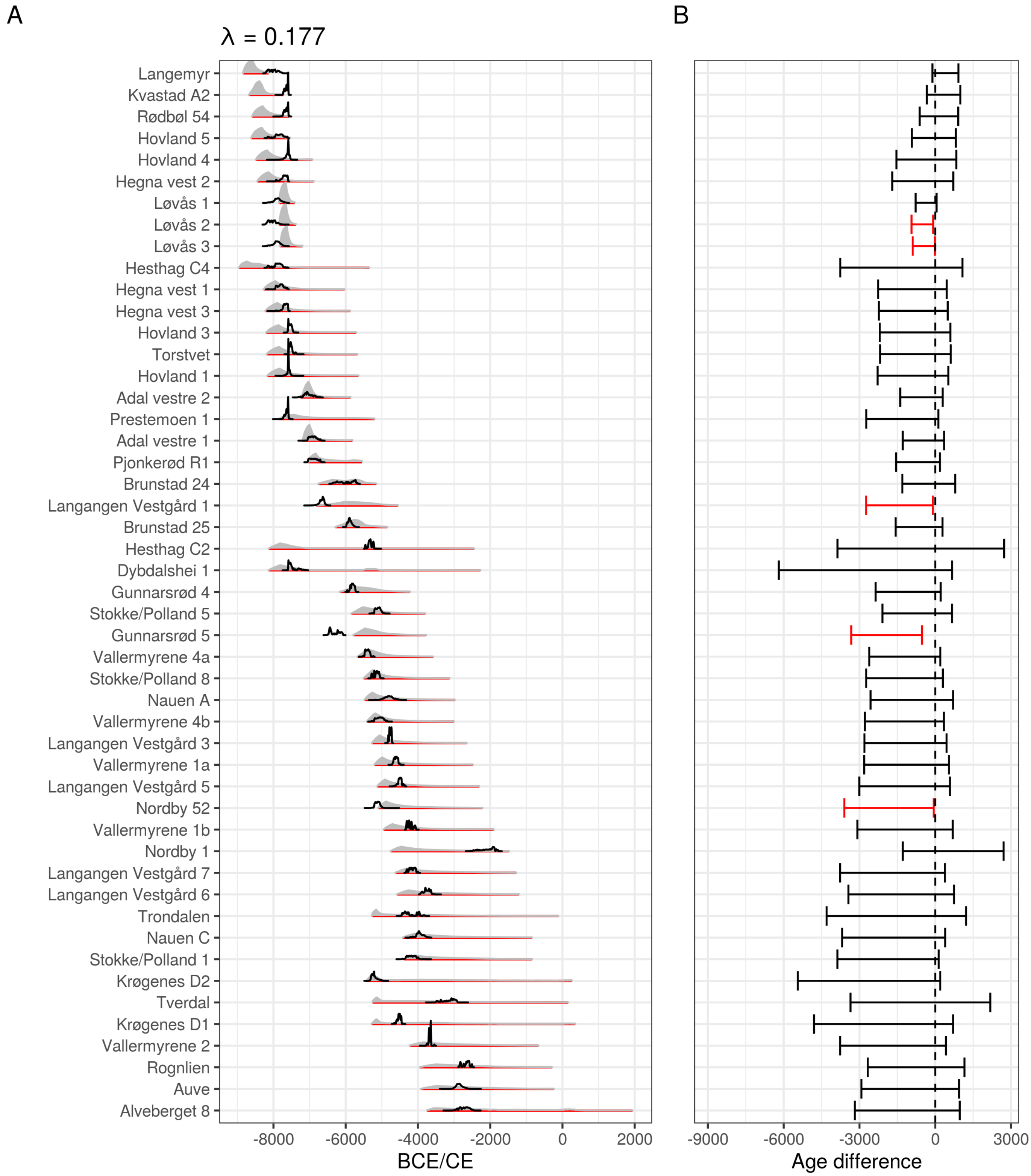


Figure 8: The result of backwards shoreline dating the sites with radiocarbon dates corresponding to the artefact inventory. The sites are dated using the mean elevation of the site polygon and by employing the exponential decay function identified in Figure 7 for characterising the distance between sites and shoreline. A) The 95% probability range for the shoreline dates are plotted in gray and underlined in red. These are plotted against the oldest radiocarbon-informed phase for each site in black. B) Using the method described by Parnell et al. (2008), the synchroneity of the dates is evaluated. When the 95% interval for age difference crosses zero the dates are considered synchronous.

6 Shoreline dating

In Figure 9, excavated Stone Age sites within the study area where ^{14}C-dates are not available or are not believed to date the main occupation of the sites are subjected to the method for shoreline dating outlined above. These are compared to the dates originally proposed in the excavation reports for the sites. To avoid issues with recent disturbances in the DTM, the sites have been dated based on the mean of the altitudes provided in the report for each site. This is an illustrative, but unfair exercise for a few reasons. First of all the dates provided in the reports are typically stated to be a very rough estimate, and are sometimes given as a point estimate with an implied or explicit but undefined uncertainty range. Secondly, seeing as these reports are from various dates in time, many are based on now outdated data on RSL-change. Finally, they are often only meant to indicate a lower bound for when the sites could have been in use. I do, however, think that the results indicate that shoreline dating, in general, has been applied with a fairly reasonable degree of success, seeing as these dates have typically been interpreted and informed research in an approximate manner. The results from applying the method devised here highlights the spatial and temporal contingency of the method, illustrated by the variation in the range of the 95% intervals for the dates. In some cases it provides a very precise date range and in others it offers little more than a *terminus post quem*. This is dependent on the steepness of the displacement curves, leading to the general pattern of older sites situated towards the north-east getting more precise date ranges. However, a few of the date ranges extend well beyond major chronological divisions, even the entire Stone Age, and could be severely and securely constrained with only cursory reference to typology. This thus points to the possibility of drawing on other temporal data such as typological indicators or radiocarbon dates, for example within a Bayesian framework, to improve the precision of the dating of the sites.

Not least following from the fact that very few pre-Boreal ^{14}C-dates associated with anthropogenic activity have been achieved in Norway, the shoreline dating of the earliest sites is essential for understanding the pioneer settlement and the initial colonisation of the Scandinavian peninsula (e.g. Bang-Andersen, 2012; Breivik, 2014; Glørstad, 2016). The shoreline dated pre-Boreal sites from the Brunlanes-project are among the earliest known sites in Norway (Jaksland, 2012a, 2012b; Jaksland and Persson, 2014). These have a distinct Early Mesolithic artefact inventory and are situated in a steep area of the landscape where it would be difficult to envision use of the sites after the sea retreated any significant distance from their location. In the original publication of the sites, Jaksland (2014) provides a thorough discussion of shoreline dating in general, and as used for the dating of the Brunlanes sites specifically. A comparison of his results and the ones achieved using the above-outlined approach are given in Figure 10A. The small discrepancies between the results mainly follow from the fact that a slightly updated version of the displacement curve is applied here (cf. Sørensen et al., in press). Jaksland's dates are given a flat 200 and 50 year uncertainty range starting from what he gives as the earliest possible date. The 200 year uncertainty range is given if the sites were to be considered in isolation, while the argument for the uncertainty range of only 50 years is based on the location of the sites relative to each other. Since they are located in such a constrained and steep area of the landscape, the difference in elevation between the sites is argued to establish their relative date and thus constrain the uncertainty ranges so that they don't overlap. This information is not integrated in the approach outlined here, but could justify reducing the the uncertainty ranges. Although their accuracy is of course ultimately dependent on the veracity of the geological reconstruction, the high rate of RSL-change in this period does nonetheless result in very precise dates. Above it was shown how additional temporal data could be combined with the method to improve its accuracy and precision. This example, on the other hand, highlights the fact that the spatial nature of the method means that a consideration of the surrounding terrain and other sites can also help in increasing the precision of the method if this can be used to exclude certain sea-levels as unlikely for when a site was in use. One approach could also be to assess the spatial implication of a proposed shoreline date by simulating the adjusted sea-levels, as is done for Pauler 1 in Figure 10B, followed for example by a visual evaluation of the topography or by evaluating the steepness of the slope to the shoreline. Based on this, it could be possible to exclude certain elevations as unlikely for the position of the shoreline for when the site was in use. Such approaches would make less of an impact in this setting, where the 95% probability range is already quite constrained, but could considerably improve the precision of the method in cases where RSL-change as been less severe (cf. Figure 9).

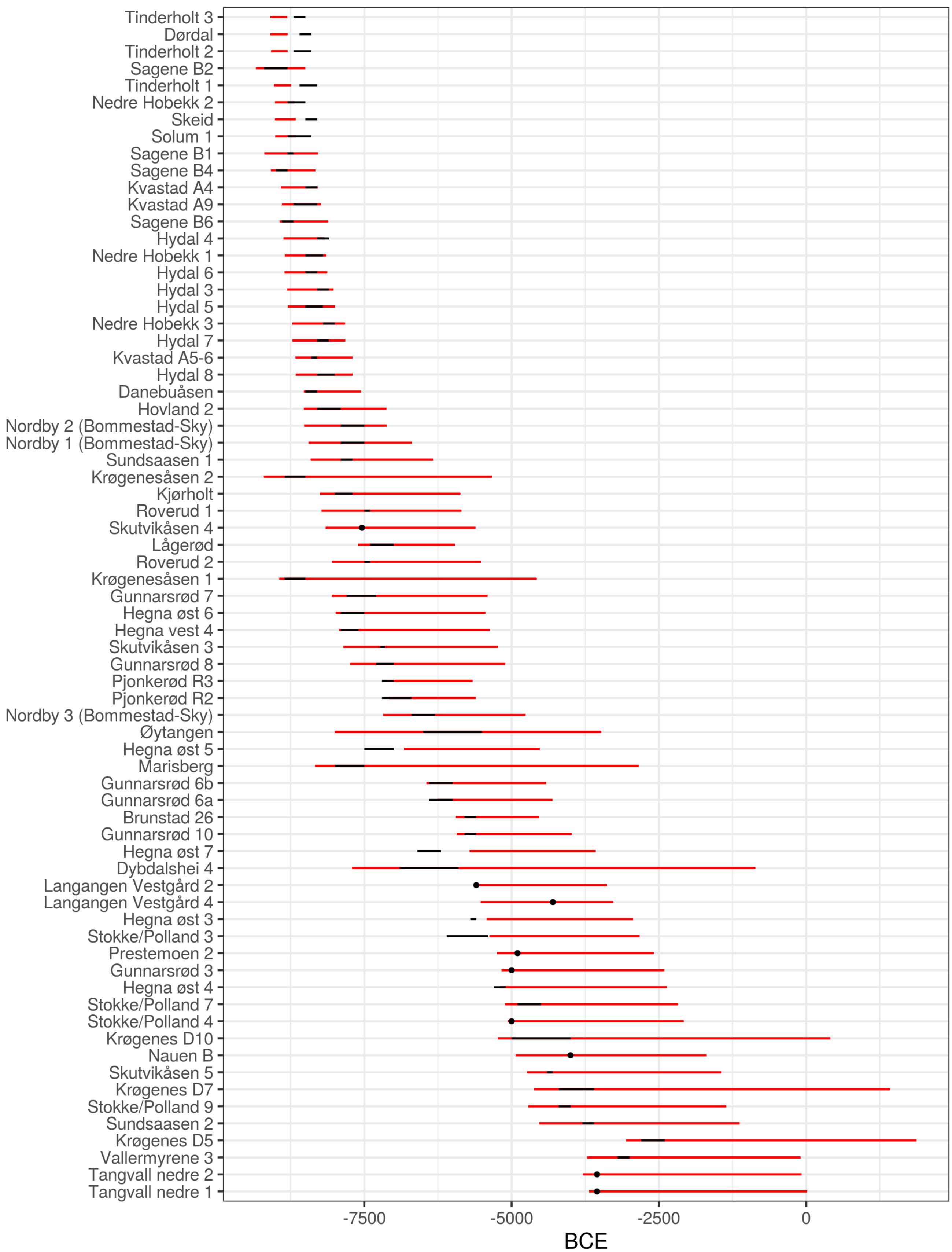
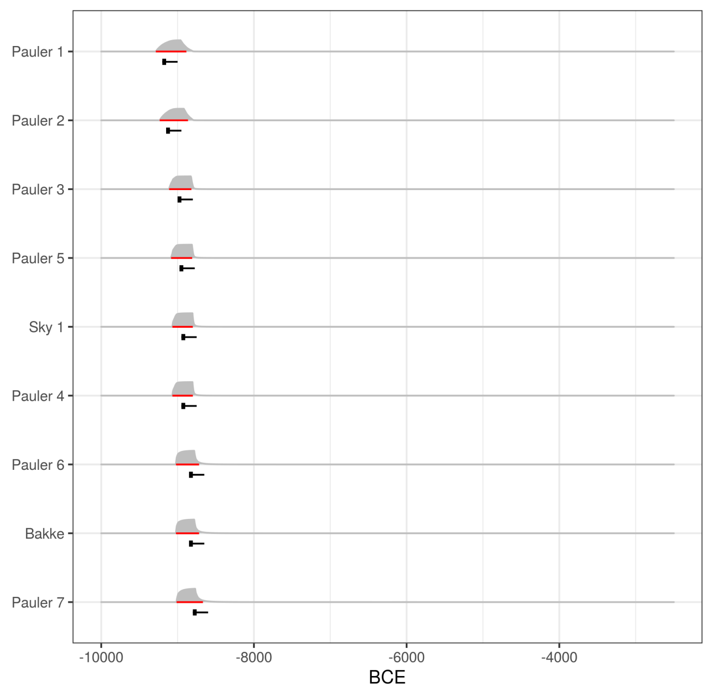


Figure 9: Shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% probability ranges in red are comapred to the dates originally proposed by the excavation reports in black.



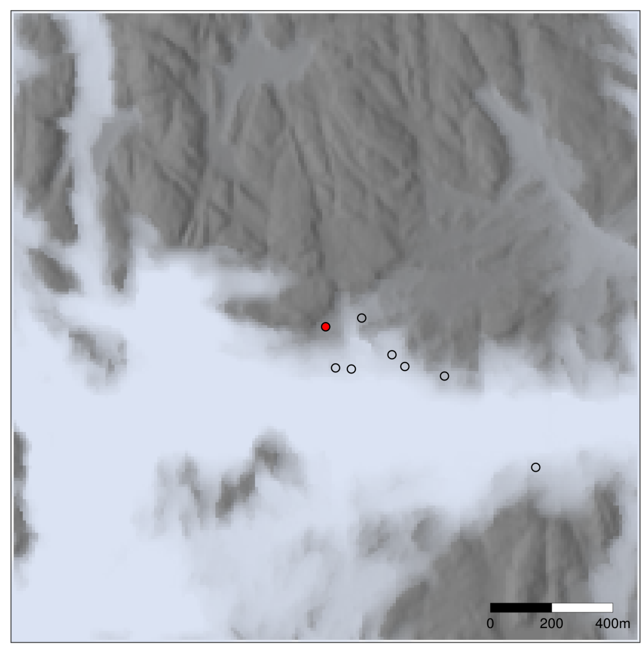


Figure 10: Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. Dates provided by Jaksland (2014) are plotted in black. The box indicates a 50 year uncertainty range which in combination with the black line extends 200 years. Follwing Jaksland's approach these start from the earliest possible date. B) Map showing the centroids of the Pauler sites and Sky 1. The sea-level has been simulated using the probability density associated with the shoreline date for Pauler 1 (see also map in Jaksland 2014:fig.12a). Pauler 1 is the red point.

7 Concluding remarks

It is worth highlighting some sources of likely variation and uncertainty that have not been considered here. First of all the DTM has only been corrected for major modern disturbances. This means that erosion, although likely not that prevalent, has not been taken into account. Secondly, the DTM has a vertical error (cf. Lewis, 2021). Thirdly, the displacement curves were here interpolated to all site locations without accounting for increased uncertainty as one moves away from the isobases of the displacement curves. Finally, the definition of the site limits nor the elevation range over which these extend was not considered.

The most immediate contribution of this paper is what must be considered a confirmation of previous research into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated by the close relationship between sites and the shoreline up until the transition to the Neolithic at c. 3900 BCE, after which a couple of sites become situated some distance from the shoreline. This is followed by a more decisive break at the transition to the Late Neolithic at c. 2400 BCE – in clear agreement with the literature. Furthermore, based on the quantitative nature of these findings, a refined method for the shoreline dating of Stone Age sites has been proposed. This involves both taking the distance between sites and the isobases of the displacement curves into consideration when dating the sites, and implementing formula x to account for the distance between the sites and the shoreline. When no other information is available, it can at present be recommended to use the empirically derived exponential decay ratios identified in Figure 9 to characterise this relationship. However, the accuracy of the method can be improved by including more information, both with reference to the topographic location of the sites and other temporal data such as radiocarbon dates and typological indicators in the artefact inventories. The precision of the method is, as shown above, both geographically and temporally contingent due to the trajectory of RSL-change, where older sites situated towards the north-east in the study area will get a more precise date than younger sites located towards the south-west. The impact of such additional information will therefore also vary.

Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to further test and adjust the findings reported here, but a larger sample size could also lay the foundations for refining the method by identifying subsets of sites for which the application of the method could be adjusted and refined. Given it's behavioural nature, it would for example seem likely that dimensions such as the nature and purpose of visits to the sites will have implications for how close to the shoreline they were located. Furthermore, other dimensions related to the topographic location of the sites could be similarly explored. This for example pertains to the exposure of sites to wave action, which is likely to have been of concern (e.g. Roalkvam, 2020), and which presumably has implications for how close to the shoreline people settled (Blankholm, 2020). This is also related to the fact that while mean sea-level is used for dating the sites, a consideration of the tidal range could possibly have implications for the site location relative to the shoreline, depending on the topography. If such locational patterns can be discerned, this will not least be useful for improving the shoreline dating of sites which have only been surveyed and where little information on the nature of the occupation of the site beyond its location is available.

Finally, this analysis was based on a simulation approach for integrating multiple sources of spatio-temporal uncertainty. Here this was simply used to inform the question of the distance between sites and shorelines. However, this method can be extended to a wide range of use-cases where one needs to visualise and quantitatively or qualitatively evaluate the relationship between archaeological phenomena, the prehistoric shore-line, and the uncertainty inherent in this reconstruction.

This approach will be useful either when shoreline dating a large number of sites where no other information than site elevation is taken into account (e.g. Breivik, 2014; Fossum, 2020; Nielsen, 2021; Solheim and Persson, 2018), which is typically done using a uniform range of uncertainty, likely overestimating the precision of the method in most cases and possibly underestimating it in some.

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