Computational modelling of the coastal Mesolithic in south-eastern Norway

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Summary

Through a series of case-studies that employ Mesolithic data from the Skagerrak coast of south-eastern Norway, this thesis is concerned with contributing to getting a handle on the vast amounts of data that have been and continue to be generated by Mesolithic archaeology in Norway. Fundamental questions concerning the quantity, composition and chronological control we have of the material available to us dictates not only our understanding of the period, but also determines what questions we can hope to answer. This follows from the resolution and quality of the archaeological record, and the varying spatial and temporal scales that different behavioural and societal dynamics operate over. The degree to which the characteristics of our data matches those necessary to illuminate these dynamics thus informs the kind of archaeology we can reliably hope to do.

Given that this data is neither recorded or can be approached without a predefined understanding of what dimensions of it are of interest, the material was explored using a series of heuristic models that are frequently drawn on in the literature to understand prehistoric hunter-gatherer societies and the coastal Mesolithic of Northern Europe. These pertain especially to the dating of the archaeological material, patterns of land-use and mobility, as well as general trends of demographic development.

The thesis consists of four papers and an introductory text. The introductory text establishes the context and motivation for undertaking the studies, relates them to each other, and presents further avenues along which the results can be explored, extended, and potentially be substantiated further. With an aim to make these efforts transparent, reproducible and extendable, the entirety of the project has been undertaken within a framework of open science. This means that all text, figures, data and code is made freely available for anyone to access and scrutinise. Along the same lines, and in part following from the quantitative nature of the derived results, all substantive inferences are instantiated as explicit causal hypotheses in the introductory text. The purpose of this is to promote clear routes for critical engagement and further research efforts.

Some central results from the papers of the thesis follows first from a quantitative assessment of the relationship between Stone Age sites and the contemporaneous shoreline in the region. This largely verified the previously suggested tendency of the sites to have been located close to the shoreline when they were occupied. Following from the quantitative nature of this assessment, this resulted in the development of a new method for shoreline dating Stone Age sites in the region, based on their altitude relative to the present-day sea-level. This method for shoreline dating has been made available as a freely available package for the R programming language through the second paper of the thesis, making the method readily accessible for anyone to apply and assess.

The third paper of the thesis focused on approaches for analysing the composition of a larger number of lithic assemblages by structuring the analysis through the use of multivariate statistics. First, this was done to assess the temporal development in the occurrence of artefact types that are in established use in Norwegian archaeology, with the findings largely verifying the current general understanding of these developments. More novel insights follows from the second line of investigation which explored dimensions of the assemblages that have frequently been drawn on outside the Fennoscandian setting to map variation in land-use and mobility patterns associated with the formation of lithic assemblages. Specifically, the volumetric density of lithics on the sites and the proportion of these that have been subjected to secondary modification were found to be negatively correlated. Furthermore, this was also found to follow a temporal development with an increase in the density of lithics and decrease in secondarily worked lithics over time. Drawing on the substantive implications that this relationship has been ascribed in other context, the findings could indicate a corresponding overall decrease in occupational duration at the sites through the period. While the relevance of this framework for the Fennoscandian Mesolithic is in need of further substantiation and evaluation, these developments match those previously suggested in the literature concerned with the Mesolithic of south-eastern Norway, giving some additional support for its relevance as a quantitative measure for land-use and mobility patterns in the Fennoscandian Mesolithic.

By drawing on approaches that have been used for analogous treatment of radiocarbon dates, the final paper of the thesis develops a method for assessing the summed probability of multiple shoreline dates with the aim of mapping the frequency distribution of shoreline dated sites over time. This was then compared to an analysis of the summed probability of radiocarbon dates from within the same area, as both measures have previously been suggested to be related to demographic dynamics. The development of the two proxies diverged, with the frequency of shoreline dated sites following some process of decline through the period and the frequency of radiocarbon dates commencing later than the shoreline dates, and reaching a stable plateau after an initial period of growth. Consequently, while it seems reasonable that both measures hold some demographic signal, the divergence between them would mean that some effects are confounding this relationship. In the paper it was suggested that mobility patterns is an important determinant for the development in the frequency of shoreline dated sites over time. While mobility patterns were also suggested to impact the frequency of radiocarbon dates, it was proposed that this effect is not as substantial as for the shoreline dated sites. However, properly understanding this relationship will depend on directly assessing the influence of a range of potential confounding effects.

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Chapter 1

Introduction

For most of its existence, human life has been spent in Stone Age hunter-gatherer societies. Whether inadvertently or not, this past is frequently envisioned as constituting the primordial state of humanity, effectively collapsing it into a more or less dimensionless point of origin. However, the societal variation in this period has been immense and remains not only largely uncharted, but has often remained under-appreciated even within disciplines dealing with past human societies (e.g. Kelly 2013:269–275; Singh and Glowacki 2022). Furthermore, one way to view modernity is as technological and organisational complexification and effectivisation that has led to an ever increasing degree of societal and ecological homogenisation, necessary to meet the increasing energy demands of these systems (Kaaronen et al. 2021). The time-depth of the archaeological record thus gives analytical access to a degree of societal variation that is otherwise unprecedented in human existence, and holds lessons for diverse, localised and long-term human adaptation that is not available for study through anthropological or historical sources. As cultural diversity is argued to facilitate societal systems that are better able to withstand perturbations – much in the same way as biodiversity increases the robustness of ecosystems – this knowledge can be important in a future that we know will bring human societies under increasing degrees of external and internal pressure (e.g. Boivin and Crowther 2021; Burke et al. 2021; Kaaronen et al. 2021).

1.1 Archaeological inquiry and the Norwegian Mesolithic

One way to conceive of scientific inquiry is as a strategy by which we try to confront theoretical constructs with empirical observation, aimed at aligning our beliefs as reliably as possible with what is true (Godfrey-Smith 2003:161). A lot remains to be unpacked from this sentence. However, for now it is enough to note that the empirical side of this equation is a critical point for archaeology, as the fragmented and uncertain nature of the archaeological record means that there will always be a multitude of possible explanations that could account for any observed empirical pattern. Reducing this number of candidate explanations is first and foremost dependent on evidence, which in the case of archaeology are scarce.

Furthermore, as establishing true explanations of a past social reality is at best exceedingly difficult, perhaps impossible, it must be the result of cumulative and recursive efforts from entire research communities over time. Accepting this means that one can adopt a strategy to try to make one's research as open and amenable to scrutiny, extension, criticism and alternative approaches as possible. While easier said than done, an attempt at adopting such a strategy is done here.

To accommodate the above points, this thesis aims to stringently explore and contrast empirical trends that have been deemed important to understand past hunter-gatherer societies, drawing on the extensive material from the coastal Mesolithic (c. 9300–3900 BCE) of south-eastern Norway. Based on this, the project aims to culminate with the generation and presentation of some hypotheses concerning possible causal drivers behind the observed patterns. Exploration and stringency are explicitly voiced here for a couple of reasons. Exploration concerns an aspiration to approach the material with a degree of secession from previous hypotheses concerning the societal developments in the period, and to instead have observed empirical trends dictate the hypotheses presented. This can facilitate a freer investigation of empirical patterns, as it reduces the risk of forcing the treatment, consciously or not, towards a single explanation or end-goal. However, a complete break with previous beliefs is clearly neither possible nor desirable. For one these will in part have dictated how the material under study has been retrieved and recorded, how I will approach it, and is necessary for it to be possible to contextualise and make sense of any observed patterns. Stringency, and with it transparency of the analytical choices made, will make it easier for both me and others to follow the logic of the arguments presented, and make it easier to identify when and in what ways prior beliefs might have led an interpretation astray.

The Norwegian Mesolithic is defined as lasting from c. 9300–4000 BCE, a period in which life was led exclusively has hunter-fisher-gatherers. The material thus represents around 5500 years of mid- to high-latitude hunter-fisher-gatherer adaptation. As in many other areas of the world, the last few decades have seen a dramatic increase in the material generated by Norwegian archaeology. In terms of sheer number of sites and associated data, this is most marked for the coastal Stone Age material (e.g. Bergsvik et al. 2020; Damlien et al. 2021). Furthermore, given that this increase in material is achieved on the back of public spending, it is arguably a disciplinary obligation to utilise this data for research purposes.

While there are many possible arguments for why archaeology is worthwhile at all, some more vague than others, the economic burden of archaeological practice is clearly easier to justify if the data we generate also informs the research we do. However, getting even a basic overview of this now vast material necessitates the use of quantitative and computational methods designed to handle, describe, explore, present, summarise and infer from such quantities of data. Following some early optimism in the 60s and 70s, such methods have, until recently, seen sporadic and relatively limited application for research purposes in Norwegian archaeology (e.g. Prescott 2013).

Quantification offers standardisation and simplification, and by extension scalability and comparability. As with all disciplines concerned with the complexity of social life, whether past or present, archaeology also benefits from multiple perspectives that move between the nuance of particularities and the general trends illuminated by aggregated analysis. I would argue that the latter is at present still underdeveloped in Norwegian archaeology. With renewed and ongoing enthusiasm for such approaches, it is important that this is combined with a continually critical view of the answers these approaches can provide, and those which they cannot.

One of the great disciplinary benefits of archaeology, as compared to other disciplines concerned with the study of human societies, is argued by many to follow from the time depth it offers (e.g. Barton et al. 2012; Gamble 2014; Hodder 1987; van der Leeuw and Redman 2002). Furthermore, while there are instances where the archaeological record allows what could be called glimpses into an ethnographic past of individual lives, the vast majority of the material we have access to is hampered by a degree of temporal uncertainty and mixing of events that necessitates a perspective that is developed to meet the nature and quality of the archaeological record on its own terms (Bailey 2007; Perreault 2019). Both fully utilising the archaeological material and playing to the strengths of the discipline is thus dependent on knowledge of the quality of the material available to us, while also being dependent on developing methodologies fit for handling this data.

1.2 Aims and research questions

The overarching goal of this thesis is to contribute to answering the following:

i) What is the extent and quality of the archaeological record from Mesolithic Norway?

ii) What consequences does this have for our disciplinary agenda and for our understanding of the Norwegian Mesolithic?

The answer to these questions is a disciplinary-wide undertaking, and no single thesis can hope to arrive at a final answer. To contribute to their elucidation, the thesis is centred on three more specific research questions. The first of these can be viewed as largely instrumental in that it pertains to the degree and certainty with which we can fix the occurrence of our data on the calendar scale:

1) What chronological control do we have of the occupation of coastal Stone Age sites within the study area?

As Vankilde (2007:22) has put it: 'Chronology is the backbone of social interpretation'. Following from an answer to this first question, the following two questions are explored:

2) What general patterns characterises the lithic inventories of the sites over time?
3) How is the frequency of sites distributed over time?

As will be laid out in more detail in later chapters, all three of these questions have built into them assumptions concerning what questions and dimensions of the available data are of interest for our understanding of the Mesolithic in the region, and their answers hold a wide range of potential implications for how the cultural historical developments through the period should be understood.

1.3 Study area

The study area of this thesis is delineated to coastal south-eastern Norway. No strict cultural-historical demarcation to surrounding regions is assumed, nor does that appear to have been the case throughout the Mesolithic.

Furthermore, what is termed the coastal Mesolithic naturally did not exist in isolation from inland regions. While the Mesolithic sites in Norway are concentrated on the coast (e.g. Bjerck 2008), the reason behind the geographical limiting of the study is mainly analytical. First, while Mesolithic data is available from a wider region of south-eastern Norway, including inland areas, the last few decades have seen an virtual explosion of investigations in the coastal region between Horten municipality in the north east to Arendal in the south west (e.g. Damlien et al. (2021), indicated in Figure 1.1). This has also been accompanied by geological studies to map the dramatic sea-level change that has impacted the Norwegian coast through the Holocene (e.g. Romundset 2018; Sørensen, Henningsmoen, et al. 2014). The region thus represents an archaeologically well-sampled area where we also have good control of the trajectory of shoreline displacement. While the findings in the study can be assumed to have relevance for surrounding areas, this subsection of south-eastern Norway therefore limits the spatial extent of the considered data. Furthermore, while this region holds high-quality archaeological material, investigated and recorded using modern methods, there is also an abundance of legacy data from the region, especially in the form of comparatively low-resolution and low-quality survey data. This constrained region thus also offers an excellent case-study for exploring the implications of dealing with data of wildly varying quality.

1.4 Open research and reproducibility

In making the case for open sharing practices in archaeological research, Ben Marwick (2017:426) compares the principle of artefact provenancing with dissemination of raw data and methods that underlie a study. Without any information on the origin or find-context of an artefact, its archaeological value is practically none. Comparatively, by openly sharing data and programming code that underlies a study, other researchers can assess the procedures that have led to the results. Apart from facilitating an evaluation of its reliability, this allows others to extend on the analysis and the employed data, to learn and reconstruct how methods are implemented, and to attempt to repeat all or parts of the analysis themselves. Open research is thus beneficial to archaeology as a cumulative research endeavour as it will both increase the frequency of rejection and adjustment of proposed explanations, allow others to explore the foundations and inner workings of these explanations, and because it will increase the pace of method sharing, evaluation and adjustment. While the benefits are clear, Ince et al. (2012:485) have even gone as far as stating that 'anything less than release of actual source code is an indefensible approach for any scientific results that depend on computation'.

Furthermore, making scholarly publications free for anyone to read has been argued by many to lead to a democratisation of the discipline. This will allow non-professionals, prospective students, non-academic collaborators and others without institutional access or the means to pay for access to read the publications (e.g. Lake 2012; Marwick et al. 2017; Marwick 2020). All text, programming code, figures and underlying data associated with this thesis is therefore made freely accessible for anyone.

To this end, this thesis has been written in its entirety using the R programming language (R Core Team 2021). Unlike for example mouse-driven computational analyses, this means that an unambiguous record of the entire analytical pipeline is recorded in the form of programming scripts, moving from the initial loading and cleaning of raw data, through to analysis, visualisation and final reporting of results. Given the large amount of analytical choices that have to made in the course of any analysis, this can never be adequately presented in prose. Furthermore, what a researcher believes they have done need not correspond with what they have actually done. The high-resolution analytical record that is the programming script makes this entirely transparent. All data, programming code, figures and text used in this thesis is freely available in version-controlled online repositories on GitHub (https://github.com/isakro) and on persistent archiving

Figure 1.1: The location of the study area in south-eastern Norway is indicated by the black frame. See the next chapter for a more detailed map and presentation of the study area. The coordinate reference system used throughout this thesis and in the accompanying papers is WGS84 / UTM zone 32N (EPSG: 32632).

Table 1.1: Overview of repositories and pre-prints. GitHub repositories can be accessed by adding the name of the repository after https://github.com/isakro/, and the archived repositories by adding the DOI after https://doi.org/ in a web browser.

Text	Pre/post-print	GitHub repository	Repository DOI
Introductory text	NA	thesis	10.17605/osf.io/h3jdf
Paper 1	osf.io/3x7ju	assessing.sealevel.dating	10.17605/osf.io/7f9su
Paper 2	NA	shoredate	10.5281/zenodo.7971859
Paper 3	osf.io/cqaps	exploring-assemblages-se-norway	10.17605/osf.io/ehjfc
Paper 4		se.norway.shoredate.14c	10.17605/osf.io/fqwt5

services where the repositories are provided a digital object identifier (DOI). The repositories for the papers have been organised following the framework of Marwick (2017; Marwick et al. 2018) by use of the related R package *rrtools* (Marwick 2019), while this introductory text has been written and organised using the R package *bookdown* (Xie 2016). Furthermore, Paper 3, which unlike the other published papers is not open access with the publisher, has been uploaded as a post-print to allow for free access. A complete overview with links to the various online archives associated with the individual papers and this introductory text is provided in Table 1.1.

1.5 Overview of papers

1.5.1 Paper 1: *A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast*

The first paper of the thesis offers an approach for integrating the various sources of uncertainty associated with reconstructing the relationship between ^{14}C-dated archaeological phenomena and past sea-level change. This is used to quantify the distance between Stone Age sites and the prehistoric shoreline within the study area. That coastal sites would have been located on or close to the prehistoric shoreline is a fundamental premise in Norwegian Stone Age archaeology. In combination with reconstructions of past shoreline displacement, this is frequently used to date the sites based on their altitude relative to the present day sea-level – a method known as shoreline dating. The findings of the paper largely reflect the development proposed in the literature, with a predominantly shore-bound coastal settlement in the Mesolithic, followed by a few sites being located some distance from the shoreline at the transition to the Early Neolithic (c. 3900 BCE) and a more decisive shift with the Late Neolithic (c. 2400 BCE). The result of this analysis is used to propose a formalised method for shoreline dating sites older than the Late Neolithic. This takes into account uncertainty as related to the displacement of the shoreline and the likely distance between sites and the shoreline when they were occupied.

1.5.2 Paper 2: *shoredate: An R package for shoreline dating coastal Stone Age sites*

Based on the findings from the first paper, the second paper of the thesis is a presentation of the R package *shoredate*, which provides tools for performing and handling shoreline dates. The focal point and main functionality of the package is developed for the Norwegian Skagerrak coast, but functionality and guides for extending the package for application in other regions is also provided. The package has been written in compliance with the developmental framework presented by Wickham and Bryan (n.d.), and is made freely available for anyone to install to R from the Comprehensive R Archive Network (CRAN): https://cran.r-project.org/package=shoredate. The paper itself gives a brief presentation of the package, but the publication of software with the *Journal of Open Source Software* also involves a useful and open review process of the source code and associated documentation and user-guides. Having published the package and released it as open source software on CRAN means that the method for shoreline dating is now available for researchers and student to employ, and that underlying code is available for anyone to explore, evaluate, criticise or extend upon. The full details of *shoredate* can be found through the website for the package: https://isakro.github.io/shoredate/.

1.5.3 Paper 3: *Exploring the composition of lithic assemblages in Mesolithic south-eastern Norway*

The second part of the thesis is aimed more squarely on elucidating past cultural history, as opposed to the more instrumental focus of the first two papers, which established tools for improving our chronological understanding of the period. The third paper of the thesis is an exploratory study aimed at identifying variability in the contents of a set of lithic assemblages. The main goals of the paper are to evaluate the typo-technological framework currently in use in Norwegian Mesolithic research, and to assess the temporal development for variables that have been linked to variation in land-use and mobility patterns. It is demonstrated that elements of the so-called Whole Assemblage Behavioural Indicators (WABI, e.g. Clark and Barton 2017) align with previous research into developments of mobility patterns in Mesolithic Norway, suggesting that the WABI could be a relevant framework also in this context. This is specifically reflected in a negative relationship between density of lithics, and the proportion of secondarily worked lithics in the assemblages over time, which is taken to reflect a transition from a more curated towards a expedient technological organisation with the transition from the Early to Middle Mesolithic (c. 8200 BCE). This is in turn argued to follow from a shift in land-use patterns and a overall reduction in mobility.

1.5.4 Paper 4: *Comparing summed probability distributions of shoreline and radiocarbon dates from the Mesolithic Skagerrak coast of Norway*

Unpacking the complex interplay between environmental conditions, settlement patterns and population density has been deemed of fundamental importance to archaeological inquiry (e.g. French 2016; Shennan 2000). The fourth and final paper of the thesis, written in collaboration with Steinar Solheim, is aimed at combining findings from the previous papers to evaluate the interplay between some empirical indicators suggested in the literature to be related to these dimensions. Concretely, the paper begins the task of elucidating the complex relationship between variation in relative population size as potentially reflected in the frequency of shoreline dated sites and the intensity of radiocarbon dates over time.

The main substantive findings of the paper were that the frequency of shoreline dated sites is relatively high from the start of the Mesolithic, from around c. 9500 BCE, and then undergoes some process of decline. The frequency of radiocarbon dates, on the other hand, only starts from around 8500 BCE and quickly increases along the trajectory of a model of logistic growth. This increase has plateaued by the first centuries after 8000 BCE, and then remains stable for the duration of the Mesolithic. In the paper, we suggest that the different behaviour of the proxies reflect that the frequency of shoreline dated sites is more heavily influenced by variation in mobility patterns, compared to that of radiocarbon dates, which we suggest is more heavily determined by population density. Clarifying this relationship will, however, depend on drawing on other measures that track the developments of factors such as mobility patterns that we suggests cause the discrepancy between the proxies.

1.6 Structure of the thesis

This introductory text is divided into six chapters, which contextualises the individual papers and point towards some future avenues along which these can be extended upon. The introductory text is followed by the four papers and the appendices associated with these.

Following this introduction, the next chapter lays out the environmental and archaeological background for the Mesolithic in the study region. Chapter 3 presents the major analytical perspectives that underlie the undertaken studies and the research questions that are posed. Chapter 4 lays out a more foundational strategy for archaeological inquiry in the form of model-based archaeology, which I believe offers a valuable framework for both understanding the contribution of the individual papers and how these can be developed further. In chapter 5 the papers are then cast within this model-based framework, both to clarify the arguments that underlie them, and to point out some future directions for how these can be fruitfully extended upon. The final chapter concludes by summarising the overarching contributions of the thesis.

Chapter 2

The Mesolithic in south-eastern Norway

This chapter presents the context of the study, beginning with the overarching environmental developments relevant to the Mesolithic of south-eastern Norway, before general archaeological understandings and discussions of the period is presented. Focus is on the developments in the coastal areas of south-eastern Norway, but insights from studies undertaken in Norway and Fennoscandia more widely will be drawn on at times. The location of the study area is given in Figure 2.1 (see Figure 1.1 for a map displaying the location of the study region within Northern Europe).

2.1 Environmental setting

The environmental setting for the Mesolithic in Scandinavia is first and foremost defined by the end of the last glacial period with the transition to the Holocene around 9700 BCE, following the end of the Younger Dryas cold period (Mangerud and Svendsen 2022; Skar and Breivik 2018). This was caused by changes to the Earth's orbital parameters that led to an increase in solar irradiance (e.g. Berger and Loutre 1991). Most pronounced of the resulting interrelated environmental developments is the melting of the Fennoscandian Ice Sheet, corresponding relative sea-level change, changes in atmospheric and oceanic circulation impacting temperature and precipitation, as well as the developments of the Baltic Sea, which has transitioned between being open and closed off from the ocean (see Figure 2.2).

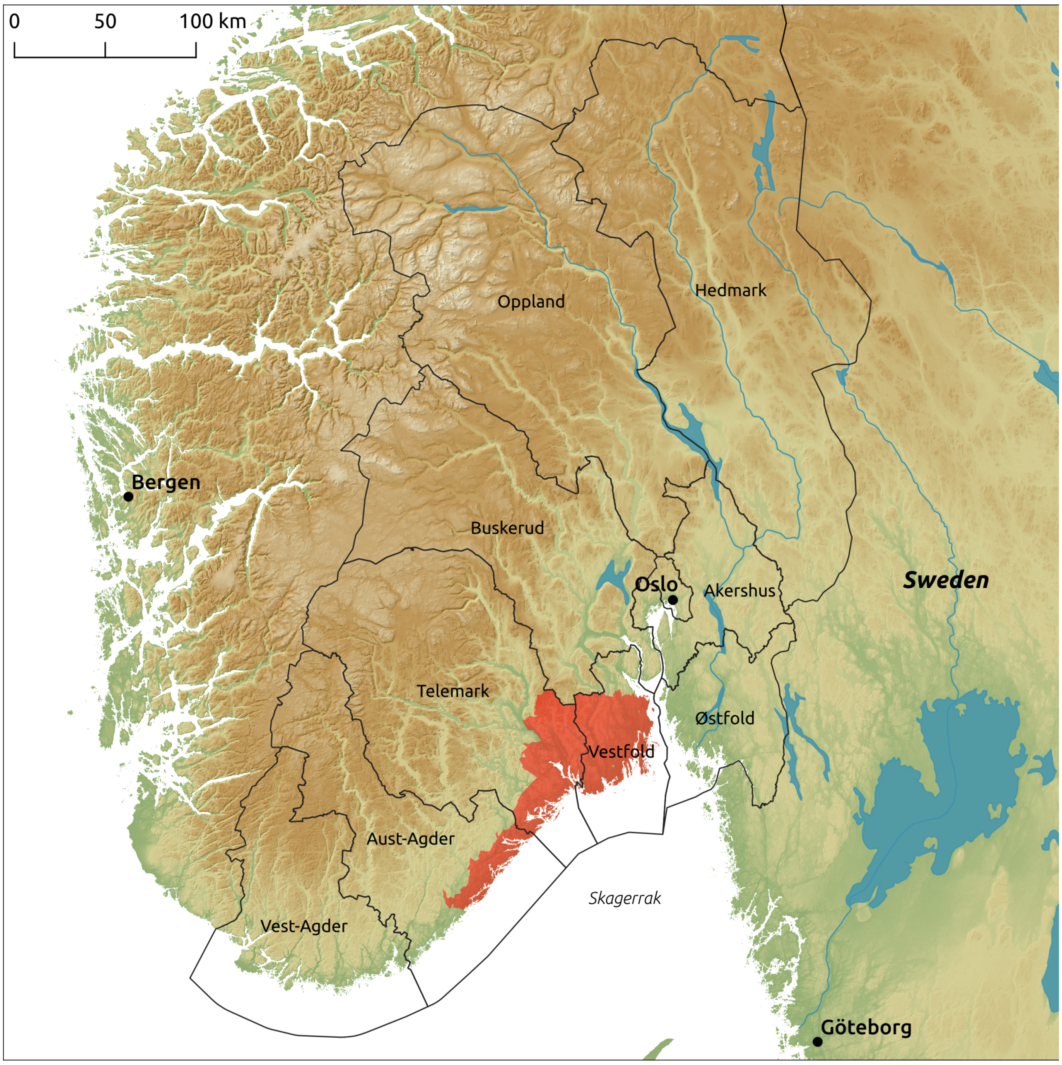

Figure 2.1: Overview of study area. The red area marks where the material directly studied in this thesis stems from (see individual papers for details), defined here by the borders of the municipalities from where the material originates. The counties outlined in black make up the administrative region of the University of Oslo, the Museum of Cultural History. The counties are given as they were defined before 2020, when several of these were combined due to administrative changes. The coastal region from around Göteborg to Vest-Agder is usually considered relatively uniform in terms of material culture throughout the Mesolithic.

2.1.1 Climate

Climate reconstructions for the northern hemisphere based on oxygen isotopes from the Greenland ice cores indicate gradually increasing temperatures from the end of the Younger Dryas c. 9700 BCE (S. O. Rasmussen et al. 2014), the onset of which generally corresponds, possibly with a slight time-lag, with developments in Fennoscandia and Norway (Lohne et al. 2013, 2014; Manninen et al. 2018; Säppa et al. 2009). This warming trend is interspersed by a few abrupt climate reversals, mainly caused by freshwater-forced weakening of thermohaline oceanic circulation. The first of these is the Preboreal oscillation (PBO) around 9400 BCE (Björck et al. 1997), followed by the Erdalen event indicated by glacial re-advances c. 8400 BCE and 7700 BCE (Nesje 2009). The most pronounced of the cooling events occurs c. 6200 BCE (the 8.2ka event Säppa et al. 2009; Wiersma and Renssen 2006; correlating with the Finse event identified in glacial records, e.g. Nesje et al. 2005). Although these are the most marked events, sediment cores from the North Atlantic also indicate more environmental fluctuations through the rest of the Holocene than what is indicated in the Greenland ice cores (Nesje et al. 2014:244).

Pollen-based reconstructions from Northern Europe indicate that the trend of increasing temperatures reached the local Holocene thermal maximum c. 6000–2800 BCE, which is around 2000 years later than what is indicated in the Greenland ice cores (Säppa et al. 2009; see Sørensen, Høeg, et al. 2014; Wieckowska-Lüth et al. 2017 for south-eastern Norway), likely reflecting a difference between regions primarily influenced by orbital forcing and those affected by the presence of melting ice sheets (Renssen et al. 2009). This warming trend is evident from a range of records, including glacial fluctuations, where Scandinavian glaciers reached their most contracted state around 4600–4000 BCE (Nesje 2009). Furthermore, as the altitudinal tree limit is reflective of thermal conditions, the dating of subfossil pine stems can provide a minimum indicator for this climate proxy. The altitudinal limit of pine (*Pinus sylvestris*) in the area of the Hardangervidda mountain plateau in central southern Norway was significantly higher than at present from the Late Boreal and through most of the Atlantic period. When adjusted for isostatic uplift, the limit reached its highest point at upwards of 240 m above the present limit in the period c. 5200–4200 BCE (Dahl and Nesje 1996). From around this point on the temperatures decline, with some fluctuations, towards the present, and the climate was increasingly characterised by being colder, wetter and more unstable (Säppa et al. 2009), also indicated by decline in pine-tree limits and the reforming and re-advance of glaciers from c. 4000 BCE (Bjune et al. 2006; Dahl and Nesje 1996; Nesje 2009).

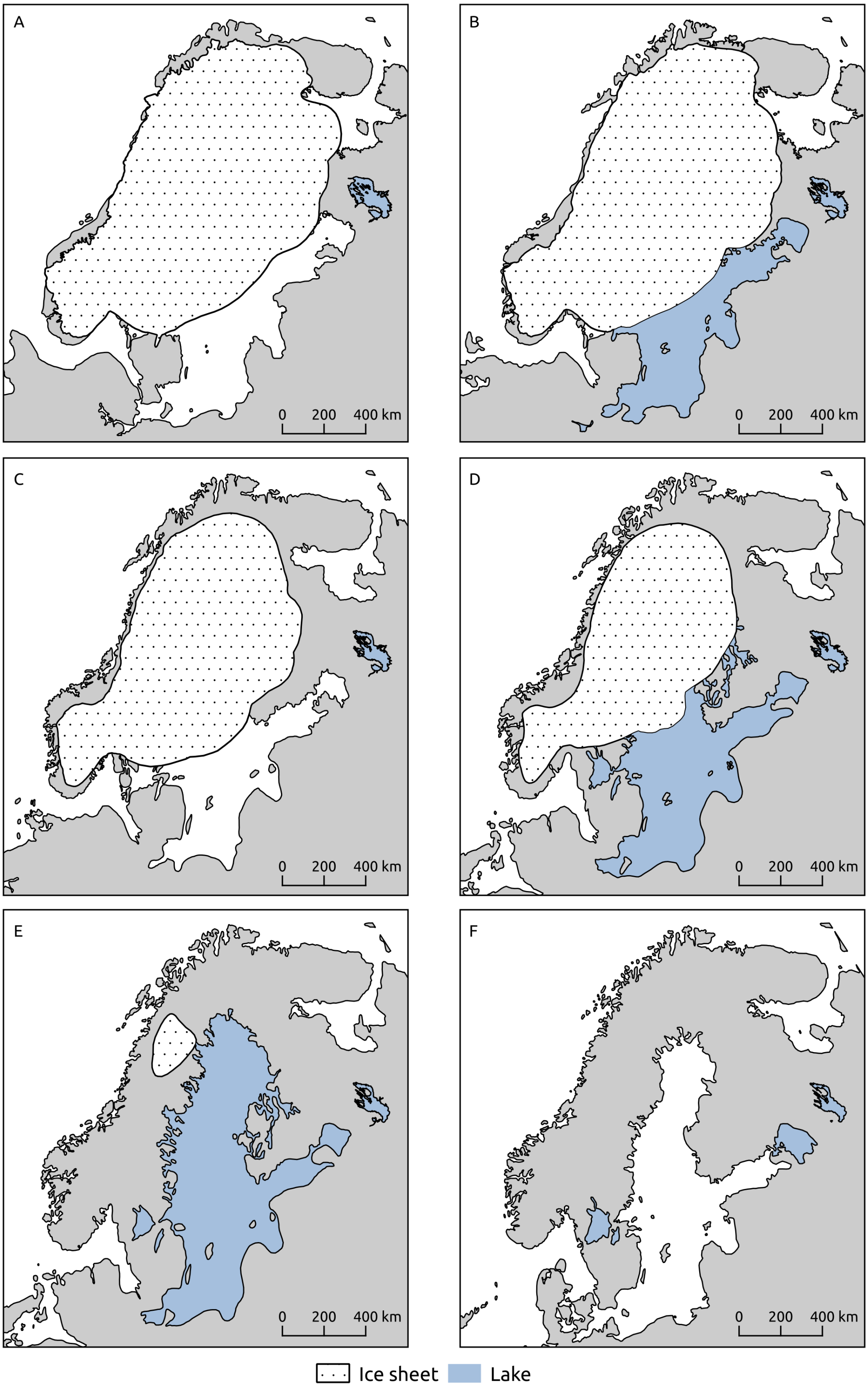

Figure 2.2: Overall trends of deglaciation, relative sea-level change and the Baltic Sea stages. A) Younger Dryas, c. 10,700–9700 BCE; B) Early Preboreal, c. 9700–9200 BCE; C) Late Preboreal, c. 9200–8700 BCE; D) Early Boreal, c. 8700–8000; E) Late Boreal, c. 8000–7200 BCE; F) Late Atlantic, c. 6500–4500 BCE. Data from the European Prehistoric and Historic Atlas, Centre for Baltic and Scandinavian Archaeology (https://zbsa.eu/), with further references therein.

2.1.2 Sea-level change and deglaciation

The colloquial understanding of the term sea-level generally equates to what is typically termed relative sea-level in geology, denoting the elevation of the sea relative to land, or, more formally, the difference in elevation between the sediment surface of the Earth and the mean sea-level (otherwise known as the geoid) when measured with reference to the Earth's centre (Mitrovica and Milne 2003; Shennan 2015:7). Continental ice sheets have been the primary determinant for relative sea-level variation through the Quaternary (Milne 2015; Milne and Shennan 2013). First, these effects follow from mass that is gained and lost from ice sheets with accumulation and ablation. The exchange of mass between the ocean and ice sheet impacts the the eustatic or ice-equivalent sea-level. The eustatic sea-level is defined as the sea-level if the ocean water had been evenly distributed across a non-rotating rigid earth, without accounting for gravitational effects (Shennan 2015:6). At the end of last glacial period, especially the melting of ice sheets in North America, Northern Eurasia and of the enlarged ice sheets in Greenland and Antarctica caused a rapid increase in the eustatic sea-level (e.g. Steffen and Wu 2011). However, non-eustatic effects impacts the relative sea-level at all locations on Earth, and no location is therefore likely to directly reflect the eustatic sea-level (Shennan 2015). Put differently, the eustatic sea-level is not directly measurable, as the impact of ice sheets, as well as tectonic crustal movement and water salinity and temperature will variably impact the relative sea-level at any given location (Milne and Mitrovica 2008).

The varying weight of ice sheets leads to adjustments in the lithosphere, called glacial isostatic adjustment (GIA), following from mass loading and unloading that causes the viscous mantle and elastic crust of the Earth to subside with increased weight and lift upwards with reduced weight. The mass of the ice sheet also impacts the gravity field, and the mass of the ice sheet determines its gravitational pull on surrounding seawater. These effects have thus been most marked in so-called near-field areas, that is, areas that have been covered by the ice. In their categorisation of the ocean into zones based on major characteristics of post-glacial relative sea-level change, Clark et al. (1978) classify zone I as areas that have been subject to a monotonic relative sea-level fall, as they have been dominated by these effects after the retreat of the ice.

In areas peripheral to near-field regions of class I, the collapse of an ice sheet and rebound of near-field areas will cause depression of the so-called forebulge. The forebulge is a result of visco-elastic uplift of the lithosphere peripheral to the depressed regions (e.g. Mitrovica and Milne 2002; Steffen and Wu 2011:191–194). With the collapsing forebulge, regions of class II have experienced continuous submergence. As the effects that distinguish zone I and II are dependent on the distance to the ice sheet, there is a transitional zone between the two that has been impacted by an initial emergence of land, followed by submergence, where the degree of emergence contra submergence is higher closer to the ice margin (Clark et al. 1978). The Fennoscandian forebulge has been found to have had a maximum magnitude of c. 60 m, and to have been located around 100 km from the maximum extent of the ice sheet (Fjeldskaar 1994), possibly with some migration, placing it offshore from Norway and well into the European mainland (Steffen and Wu 2011:191–194). The Fennoscandian forebulge is thus of limited relevance to the areas dealt with in this thesis.

In contrast to near-field areas, relative sea-level change in far-field regions is more heavily determined by eustatic sea-level change, which has thus generally led to inundation of these areas with the melting of continental ice sheets. However, the relative sea-level in far-field areas do also show deviation from the eustatic sea-level (Milne and Mitrovica 2008). Some of these effects are more subtle, such as so-called ocean siphoning where the collapse of forebulges and hydro-isostatic depression of ocean floors causes water to migrate to fill the vacated spaces, and continental levering where an increased water load cause oceanic regions to subside while continental shelves flex upwards (Mitrovica and Milne 2002). Finally, GIA induced variation in Earth's rotation and gravitational attraction can also substantially impact the relative sea-level by impacting the configuration of the geoid. The geoid, or geodetic sea-level, is the equipotential surface of the Earth's gravity field, which is affected by differences in the density, flow patterns and structure of the Earth which impacts its rotational vector (Milne and Mitrovica 1998; Mörner 1976). While these effects can influence all areas on Earth, they are especially defining of the non-eustatic signals in far-field regions.

The relative sea-level is thus mainly the result of eustatic, isostatic and geoidal effects, in addition to thermosteric effects on the salinity, temperature and thereby the density of the ocean water, where different locations and points in time have been differentially impacted by these effects. At the Last Glacial Maximum, c. 20,000 BCE, around 5.5% of the world's water was bound in ice, compared to 1.1% today. Around one seventh of this was in turn bound in the Fennoscandian Ice Sheet (Steffen and Wu 2011). As a result, relative sea-level change in Fennoscandia has been dominated by GIA effects (see Figures 2.2 and 2.3). Mörner (1979) described the Fennoscandian uplift in terms of a cone that roughly corresponds with the extent and variable weight of the ice sheet, where the intensity of uplift has intensified along a gradient towards the centre of the cone. This is centred on the coast of the Bothnian Bay around the city of Umeå in Northern Sweden, where the uplift has had the highest magnitude, with dissipating uplift moving out from this centre. Although the intensity of uplift has varied substantially throughout prehistory, with the influence of GIA gradually dissipating, the relative intensity of uplift has roughly, although with some variation (see e.g. Sørensen et al. 1987), corresponded with the present-day direction of the uplift gradient given in Figure 2.3 (see Steffen and Wu 2011; Vestøl et al. 2019; cf. Mörner 1979:Figure 26).

As a result of the GIA, the study area for this thesis falls within the class I zone of Clark et al. (1978), characterised by a continuous and still on-going sea-level regression. In areas of Fennoscandia more peripheral to the centre of uplift in the Bothnian Bay, the sea-level fall has been comparatively less stark, been subject to periods of sea-level transgression, and in the outer-most periphery, inundation (e.g. Lohne et al. 2007; Romundset et al. 2011, 2015; Svendsen and Mangerud 1987, cf. Figure 2.2).

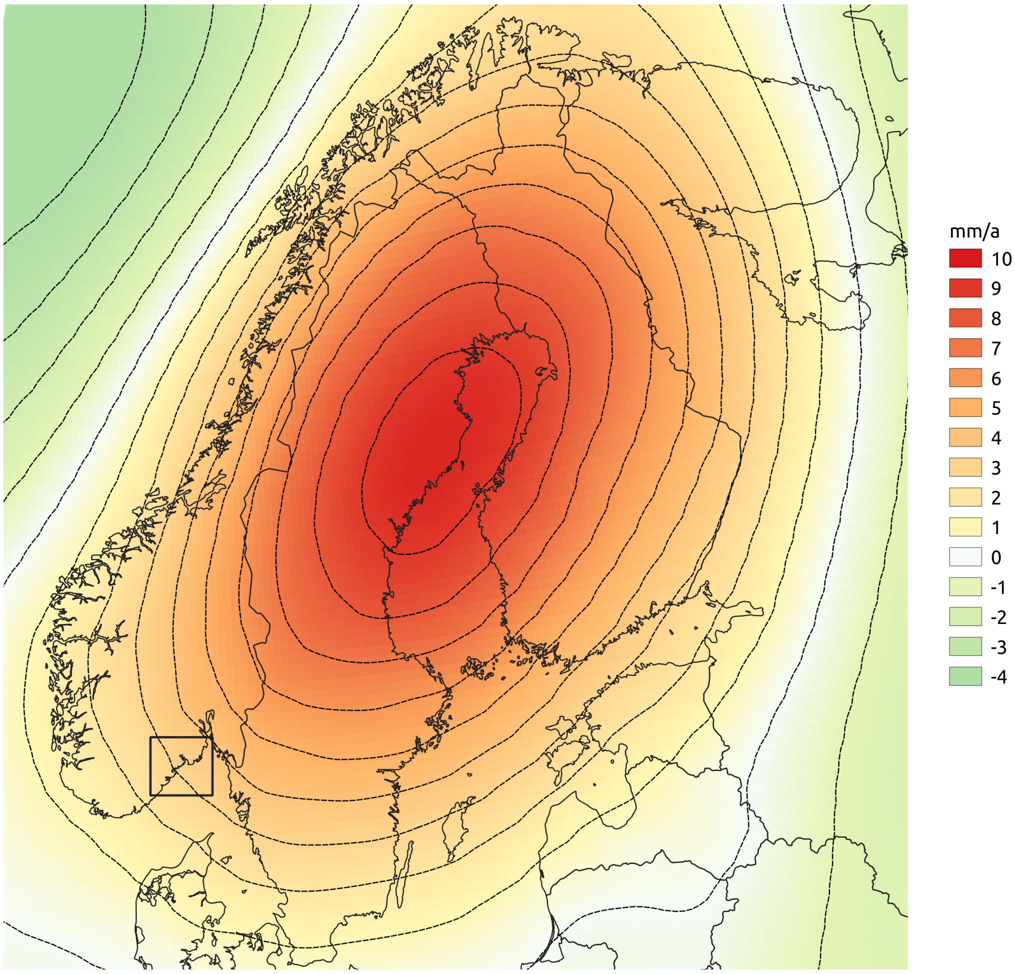

Figure 2.3: Present annual absolute uplift in Fennoscandia relative to the Earth's centre of mass. Note that the absolute uplift is independent of the relative sea-level, which is also determined by other effects. The location of the study area of this thesis is outlined with a black frame. Data from the official land uplift model NKG2016LU of the Nordic Commission of Geodesy (Vestøl et al. 2019).

The development of relative sea-level change within the study area is given by shoreline displacement curves in Figure 2.4. This development has been quite dramatic, which can be illustrated by reference to the marine limit in the region. The marine limit is the highest post-glacial elevation of the shoreline. The highest known marine limit in Fennoscandia is around 286 meters above present sea-level (masl) at Skuleberget in Ångermanland in east-central Sweden (Berglund 2012). Comparatively, the marine limit is around 220 masl in the innermost part of the Oslo fjord. In Horten, at the northern limit of the study area for this thesis, the marine limit is c. 182 masl (Berg-Hansen et al. 2022; Romundset 2021, Figure 2.4). In the centre of the study area, in Porsgrunn, the marine limit is around 155 masl (Sørensen, Henningsmoen, et al. 2014), and furthest to the south, in Arendal, around 70 masl (Romundset et al. 2018). These differences show the gradient in the earliest post-glacial shoreline, resulting from differential loading of the ice sheet.

2.1.3 Flora

The increases in temperatures led to a transition from Arctic to Boreal vegetation in the early Holocene of south-eastern Norway, with a succession from pioneer species of bushes and grasses, to the establishment of open birch forest towards the end of the 10th millennium BCE (Birks 2015; Høeg et al. 2018:194). This was followed by the marked spread of hazel (*Corylus avellana*) and pine c. 8500–8000 BCE, with elm (*Ulmus glabra*) and oak (*Quercus robur*) following a few hundred years later (Høeg et al. 2018; Sørensen, Høeg, et al. 2014:202). The spread of various deciduous trees increased in the Atlantic period, and from around 5500 BCE there was a marked increase in oak as well as the introduction of linden (*Tilia cordata*), the most heat-demanding of these tree-species (Høeg et al. 2018:199).

There is also some regional climatic variation in the present-day coastal areas of south-eastern Norway. The inner, more sheltered parts of the Oslo fjord has a more continental climate, characterised by cold winters and warm summers in which most of the precipitation falls. Towards the distal coastal areas the climate is more oceanic in character, with comparatively warmer winters with more precipitation and somewhat colder summers than in the inner coastal areas – differences that also impact vegetation (Hafsten 1956:16–29).

A note should also be made here that anthropogenic influence on vegetation cover in the Mesolithic is evident from palynological indicators of fire management at some sites (e.g. Selsing 2016; Wieckowska-Lüth et al. 2018), and is possibly also related to the spread of hazel through foraging of hazel nuts (Høeg et al. 2019:105–109). However, human-induced changes to vegetation is most pronounced towards the end of the Neolithic with the wide adoption of agriculture (e.g. Hjelle et al. 2018; Høeg et al. 2018:199; Wieckowska-Lüth et al. 2018).

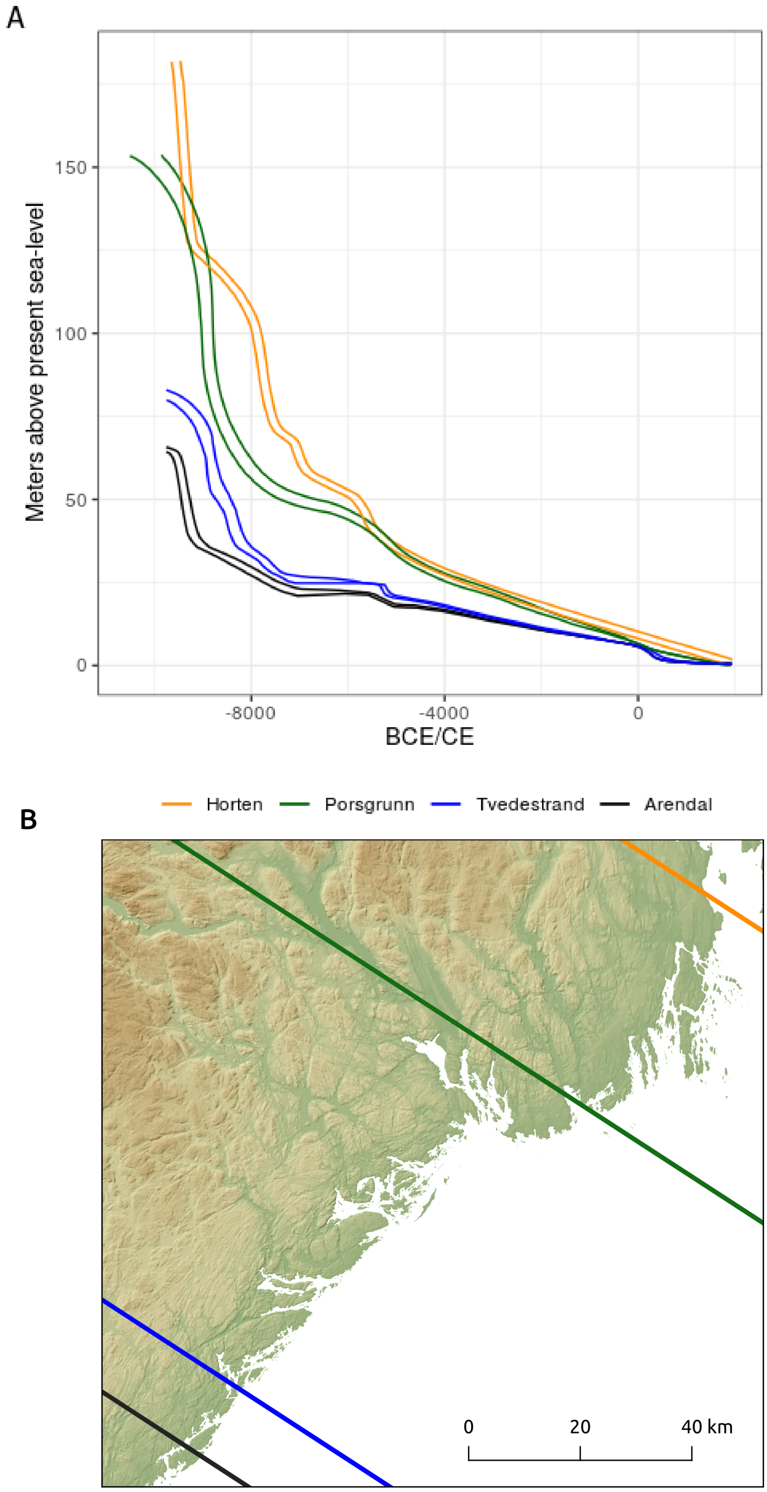

Figure 2.4: Relative sea-level change in the study area in south-eastern Norway (see Figures 1.1 and 2.3 for an overview of its location). A) Shoreline displacement curves for Horten, Porsgrunn, Tvedestrand and Arendal. B) Location of the isobases corresponding to the displacement curves. The isobases represent contours along which the relative sea-level change has followed the same trajectory.

2.1.4 Palaeoceonography

An important driver for oceanic and climatic conditions in Norway is the Norwegian Atlantic Current (NwAC), a surface current which carries warm saline waters along the outer Norwegian coast as an extension of the North Atlantic Current. As there is a close connection between atmospheric conditions and upper ocean systems, developments in sea surface temperatures (SST) in the Norwegian Sea correspond with general climatic shifts (Berner et al. 2010). At the transition from the Younger Dryas to the Preboreal there is a rapid increase in SST with increased inflow of Atlantic water, which is characteristic of the conditions through the HTM (Andersen et al. 2004). This trend is also impacted by the cooling PBO, and the Erdalen and Finse events (Berner et al. 2010; T. L. Rasmussen et al. 2014). From around 2500 BCE there is a general transition towards lower SST, which is characteristic for the Norwegian Sea for the remainder of the Holocene (Andersen et al. 2004).

Zooming in to the palaeoceonographic developments in Skaggerrak, Gyllencreutz et al. (2006) identify four major developmental stages. From the period 13,000–11,000 BCE, Skagerrak is a large fjord, open to the west and enclosed by land to the south and the ice-front to the north. Warmer Atlantic water impacts Skagerrak already from the start of this period, but the circulation in Skagerrak is likely to have been weak. At around 11,000 BCE, drainage started from the Baltic Sea, at this stage the Baltic Ice Lake, through the Öresund strait to the south (Andrén et al. 2011, see Figure 2.2A). Due to the difference in elevation, this involved a unidirectional outflow of glacial melt-water from the Baltic Ice Lake through the Öresund strait, until the final drainage of the ice lake around 9700 BCE. The resulting Baltic Sea stage, which thus corresponds with the onset of the Holocene epoch, is termed the Yoldia Sea. While the Yoldia Sea had open contact with Skagerrak through straits in south-central Sweden through Lake Vänern and the area around and north of Göteborg, it would take c. 300 years before saline water could enter through the narrow straits (Andrén et al. 2011, indicated in Figure 2.2B and 2.2C). Due to isostatic uplift, the Baltic Sea was again closed off from the ocean around 8700 BCE, marking the onset of the Ancylus Lake stage, in which the Baltic sea was a large freshwater lake until c. 6900 BCE (Figure 2.2D and 2.2E).

In the period from 7500–6000 BCE, the present-day circulation patterns are established in Skagerrak. The opening of the English Channel and the isolation of Doggerbank in the North Sea, starting from around 8000 BCE–7000 BCE, resulted in an increased Atlantic inflow to Skagerrak, and in the period from around 8100–6900 BCE the gradual eustatic opening of the Öresund and Danish Straits established an opening to the Baltic Sea in the south, marking the onset of the Littorina Sea stage (Figure 2.2F). In combination, these developments lead Gyllencreutz et al. (2006) to consider most major features of the current circulation system in Skagerrak to have been established by c. 6500 BCE (see Figure 2.5, and Christensen et al. 2018).

While the inner parts of the Oslo fjord are sheltered from Skagerrak today, this has followed from relative sea-level change. In addition to a different configuration of the secondary fjord system and different positions for river run-offs, the fjord itself would have been a larger bay in the earliest part of the Holocene. This has implications for the circulation and salinity of the inner-most parts of the fjord, which would have been more exposed to Skagerrak (Staalstrøm et al. 2021) and which would also have had implications for the climatic conditions that today differentiate the inner and outer parts of the fjord (cf. Hafsten 1956).

2.1.5 Fauna

The above developments have framed the population dynamics of terrestrial and marine fauna in south-eastern Norway through the Mesolithic, where the transition from Arctic to more temperate conditions led to the displacement of cold-tolerant terrestrial species, and the salinity and temperature of Skagerrak similarly impacted marine species (e.g. Boethius 2018a; Breivik 2014; Damlien et al. 2021:24; Jonsson 2014; Mansrud and Persson 2018; Sørensen, Høeg, et al. 2014).

In the transition towards a Boreal climate, terrestrial Arctic species such as reindeer (*Rangifer tarandus*) and polar fox (*Alopex lagopus*) moved to the mountainous regions, while species such red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), elk (*Alces alces*), beaver (*Castor fiber*) and wild boar (*Sus scrofa*) increasingly populated the forest-covered landscape in the lower lying areas (Hufthammer 2006; Jonsson 1995). Aurochs (*Bos primigenius*) and European bison (*Bison bonasus*) reached at least as far north as central southern Sweden, but likely disappeared with the opening of the Öresund and Danish Straits (Hallgren 2018).

Following the retreat of the ice, the spread of cold-resistant marine fauna compatible with low ocean salinity would have been more rapid than that of terrestrial species (Jonsson 2014). Important drivers of Late Holocene bio-productivity in Skagerrak has been nutrient-rich terrestrial inflow from flooding and river run-offs, internal release of nutrients through upwelling, and external influx of nutrients from Baltic and Atlantic waters (Fonselius 1996; Polovodova Asteman et al. 2018), which is related to the strength and salinity of inflow from the Atlantic Ocean and outflow of brackish water from the Baltic Sea. Comparatively, the influence of the melting ice sheet in the Preboreal, and the constrained outflow and strong tidal current from the Baltic Ice Lake through Lake Vänern, has been argued to have given rise to large amounts of primary phytoplankton in Skagerrak in this period.

This would in turn have attracted fish, where the early presence of capelin

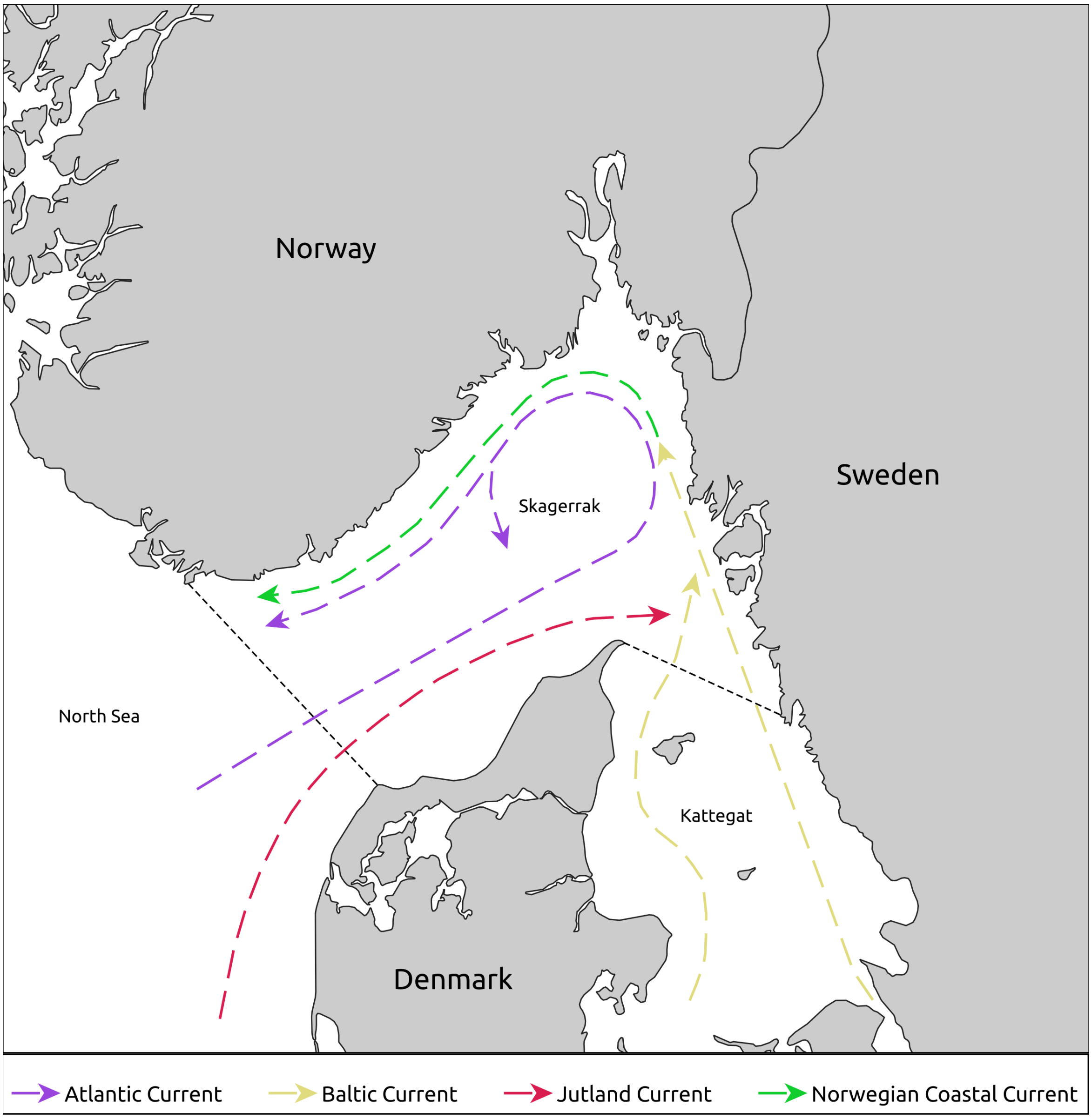

Figure 2.5: Main currents in present-day Skagerrak (redrawn after Staalstrøm et al. 2021:fig.5, see also Christensen et al. 2018).

(*Mallotus villosus*) has been highlighted (e.g. Jonsson 2014; Sørensen, Henningsmoen, et al. 2014), which would have quickly populated these areas and could form the dietary basis for whales such as the fin whale (*Balaenoptera physalus*) and humpback whale (*Megaptera novaeangliae*), seals such as ringed seal (*Phoca hispida*) and harp seal (*Phoca groenlandica*), and predatory fish such as polar cod (*Boreogadus saida*), cod (*Gadidae*), and cusk (*Brosme brosme*). With the reduced inflow of glacial melt-water and the closing off of the Ancylus Lake in the Boreal, this could have led to a reduction in primary biomass, in turn impacting the abundance and composition of marine fauna (Jonsson 1995, 2014; Sørensen, Henningsmoen, et al. 2014; see also Boethius 2018a; Breivik 2014; Mansrud and Persson 2018), with e.g. herring (*Clupea harengus*) preferring warmer waters than the capelin. Furthermore, freshwater fish such as pike (*Esox lucius*) and perch (*Perca fluviatilis*) eventually reached Eastern Norway through river systems from the Ancylus Lake, and anadromous species such as trout (*Salmo trutta*), salmon (*Salmo salar*) and Arctic char (*Salvelinus alpinus*) also migrated along the coast (Jonsson 1995; Refseth et al. 1998). Furthermore, it has also been suggested that humans transported trout to establish these populations in rivers and lakes in the mountainous regions already in the Mesolithic – with the species being present from at least the 5th millennium BCE (Mjærum 2016; Mjærum and Mansrud 2020).

2.2 Archaeological background

Having presented the general environmental developments of the period, the following section gives an outline of how chronological and societal developments in the Mesolithic of south-eastern Norway have been characterised and understood archaeologically. As outlined by Bjerck (2008:61), the first focused research on the Norwegian Mesolithic is ascribed to Hansen (1904), who studied the material that A. W. Brøgger (1905) later saw as a defining element of the Nøstvet culture. In 1909, Nummedal made discoveries of flint artefacts in western Norway that were deemed likely to have an earlier date than the Nøstvet material, and which led to the definition of another cultural unit termed Fosna (Nummedal 1923). Nummedal later also discovered material in northern Norway that had parallels with, but was considered distinct from Fosna and was given the label Komsa (Nummedal 1926). While the geographical and temporal relationship between these cultural units were recognised as unresolved and was subject to much debate, the common understanding was for many decades that southern Norway was defined by the chronologically sequential phases Fosna and Nøstvet, while Komsa was seen as defining of the entire Mesolithic period in northern Norway (see e.g. Indrelid 1978:147).

Table 2.1: Chronological framework. Glørstad's (2010) divison of phases reflects the more traditional framework, to which Reitan (2016, 2022) has recently suggested considerable adjustments.

Glørstad (2010)	
Early Mesolithic, Fosna phase	9300–8200 BCE
Middle Mesolithic, Tørkop phase	8200–6300 BCE
Late Mesolithic, Nøstvet phase	6300–4600 BCE
Late Mesolithic, Kjeøy phase	4600–3800 BCE
Reitan (2022)	
Single-Edged point phase	9300–8600 BCE
Høgnipen point phase	8600–8300 BCE
Microlith phase	8300–7000 BCE
Pecked adze phase	7000–5600 BCE
Nøstvet adze phase	5600–4500 BCE
Transverse arrowhead phase	4500–3900 BCE

With renewed debates in the 1970s, that were arguably founded on a better understanding of lithic technology (Bjerck 1994), significant alterations to the chronological framework was proposed. Mikkelsen (1975a) suggested a quadripartite division of the Mesolithic in south-eastern Norway by dividing the period into the Early Mesolithic Fosna phase, the Middle Mesolithic Tørkop phase, and the Late Mesolithic phases Nøstvet and Kjeøy. While there have been subsequent discussions and adjustments (e.g. Glørstad 2004; Jaksland 2001), the chronology used to characterise the Mesolithic of south-eastern Norway has generally followed along the lines of the framework used by Glørstad (2010:23, see Table 2.1).

In a comprehensive reassessment that draws on results from the last decades of excavations, Reitan (2022) has recently suggested a new chronological framework for the Mesolithic period in south-eastern Norway (also Reitan 2016). As his focus has mainly been on technological and typo-chronological developments, and given their recent date of publication, this framework has yet to be comprehensively evaluated in terms of correspondence with other societal developments. The presentation of major chronological trends in the sections below thus follows the traditional periodisation, as this underlies most of the cited studies. As the papers for this thesis largely operate independently of this periodisation, as will be presented in more detail in later chapters, the chronological framework used here is mainly meant to set a heuristic and general frame of reference for the developments that are believed to have characterised the Mesolithic in the region.

Before the 1990s, the Mesolithic material from south-eastern Norway was mainly derived from stray finds (see e.g. Bjørn 1934a, 1934b; Hagen 1946), some early surveys and investigations in the mountain regions (Indrelid 1977; e.g. Odner 1965), and investigations of a handful of sites in the coastal areas (e.g. Johansen 1964; Mikkelsen 1975b, 1989; Mikkelsen et al. 1999; Østmo 1976; cf. Glørstad 2006:11–70). From around the 1990s and onwards, there has been a dramatic increase in excavations of Mesolithic sites in south-eastern Norway. This extends from smaller scale investigations of individual sites (see Damlien et al. 2021 for a recent overview), to larger multi-year projects in the counties of Østfold (Glørstad 2004), Hedmark (Boaz 1997; Stene 2010), Vestfold and Telemark (Berg-Hansen et al. 2022; Jaksland 2014; Melvold and Persson 2014; Reitan and Persson 2014; Solheim 2017a), Vest-Agder (Ballin and Jensen 1995; Reitan and Berg-Hansen 2009), Aust-Agder (Reitan and Sundström 2018), and Akershus (Ballin 1998; Jaksland 2001; Rosenvinge et al. 2022). The material directly studied for this thesis stems from Vestfold, Telemark and Aust-Agder (Figure 2.1). This study area is located firmly within what has been considered an area of comparable material culture throughout the Mesolithic in the northern Skagerrak area, and the region falls within the administrative region of the Museum of Cultural History under the University of Oslo, which is responsible for all excavations of Stone Age sites in the region.

2.2.1 The Early Mesolithic (9300–8300 BCE)

The first human presence in Norway is recorded from around 9500–9300 BCE, which marks the start of the EM. A central discussion has concerned whether people first migrated into the area of present-day Norway from a route along the coast of western Sweden, from the north-east along the North-Norwegian coast (Bjørn 1929), or across the Norwegian trench to south-western Norway from Doggerbank (Odner 1966:135–136). The most recent evidence suggest that a crossing from Doggerbank would not have been feasible due to the distances involved at the time (Glørstad 2016; Glørstad et al. 2017). The present consensus is therefore that the earliest human dispersal into present-day Norway is likely to have originated on the coast of what is today western Sweden around 9500–9300 BCE (e.g. Bang-Andersen 2012; Bjerck 2008, 2021; Fuglestvedt 2012; Glørstad, Gundersen, et al. 2020). From here, human occupation is believed to have rapidly extended along most of the Norwegian coastline, while a north-eastern migration reached Kola and northern Norway some time before 9000 BCE (Manninen, Damlien, et al. 2021), possibly even before 9500 BCE (Kleppe 2018). These two routes are associated with the genetically defined 'western' hunter-gatherers that migrated from the south, and 'eastern' hunter-gatherers migrating from the north (Günther et al. 2018), each identifiable also in terms of distinct material culture and associated technological traits (Manninen, Damlien, et al. 2021).

Pioneer sites in Norway and Western Sweden have traditionally been ascribed the archaeological cultures or techno-complexes Fosna and Hensbacka, respectively. Today these are seen as representing the same phenomena (e.g. Bjerck 2008:75). Fosna/Hensbacka sites are to have fairly homogeneous lithic inventories, and are held by many as having a common origin tracing back to South-Scandinavian and North-European Palaeolithic Ahrensburg groups (e.g. Bang-Andersen 2012; Bjerck 2008; Fuglestvedt 2012; Schmitt et al. 2009). The analyses of artefact inventories, the presence of high-quality South-Scandinavian flint, and the chronological support of radiocarbon dates have in sum led to the consensus on this continental connection (e.g. Bang-Andersen 2012; Fischer 1996; Fuglestvedt 2007, 2009; Glørstad 2016; Schmitt et al. 2006).

Based particularly on analyses of lithic technology (Fuglestvedt 2007, 2009, 2010), Fuglestvedt (2012:8) has even proposed that the terms Fosna/Hensbacka be abandoned altogether, in favour of Ahrensburg, as this would accentuate the continental elements that appear so defining for these pioneer sites. Although this has been met with varying degrees of enthusiasm (e.g. Åstveit 2014, with comments; Bjerck 2008:73), particularly by those emphasising the strong marine orientation of the Fosna/Hensbacka, there has also been the occasional use of variations such as 'coastal Ahrensburg' to denote the Fosna/Hensbacka (Prøsch-Danielsen and Høgestøl 1995). Following a recent analysis of lithic inventories from the transition from the Palaeolithic to the Mesolithic in Northern Europe, and comparison with Fosna/Hensbacka sites in Norway and Sweden, Berg-Hansen (2017, 2018) has emphasised nuances in the Fonsa/Hensbacka assemblages that she argues have a clearer similarity with EM Maglemose sites in Denmark. While there are elements of this technology that point back to the Ahrensburg, she argues that these societies should therefore, as with the Maglemose, be considered explicitly Mesolithic and not a northern continuation of Palaeolithic life-ways. At any rate, these discussions do go to show that there is a clear affinity between the first human population on the Scandinavian Peninsula and continental hunter-gatherer groups.

To account for the apparent pan-regional homogeneity that is to characterise the archaeological material in the earliest part of the Mesolithic, a central question is by what process Norway and western Sweden were initially colonised (e.g. Bang-Andersen 2012; Berg-Hansen 2017; Bjerck 2009; Blankholm 2008; Fuglestvedt 2012; Glørstad 2016; Schmitt et al. 2009). An important aspect in this regard is the fact that the coastal areas in western Norway were largely ice-free around 3000 years before the first recorded human presence in Norway (Mangerud and Svendsen 2022), and must have been rich and desirable areas in terms of resources early on (Bang-Andersen 2012; Bjerck 1994, 2009; Glørstad 2016).

Bjerck (1994; 2008:85; 2009; 2017) has explained the fact that people did not start exploiting these regions until around 9300 BC with reference to less developed marine subsistence strategies among North-European hunter-gatherer groups. The coastal location of the majority of Fosna/Hensbacka sites will undoubtedly have necessitated extensive adjustment to marine environments, including by the use of boats. Following the delay induced by this, the hunting of seal, conceptually not that different from the hunting of large terrestrial mammals, might have spurred an increased development of boating technology, while at the same time lending itself to the continued use of a continental artefact inventory (Bjerck et al. 2016; Bjerck 2009). Proficient and effective use of boats might in turn have resulted in a relatively rapid colonisation of Fosna/Hensbacka areas, possibly as fast as over a period of only 200–300 years (Bang-Andersen 2012; Bjerck 1994), providing a possible explanation for the homogeneous assemblages. These could reflect mobility of a kind not allowing for familiarisation with local resources for tool production, nor the development of distinct inventories adjusted to various geographical settings. The assemblages might therefore represent a sort of catch-all tool-kit, suitable to meet the variable demands of a 'pioneer condition' (Bjerck 2017; see also Breivik and Callanan 2016). Furthermore, both Fuglestvedt (e.g. 2009:371–372) and Berg-Hansen (e.g. 2017:232) have argued that the homogeneity in the lithic inventories could be related to closely knit social ties, which has enabled this technological conservatism. Homogeneity and continuity in lithic technology over vast expanses of Scandinavia would, in this view, be difficult to envision with a thinly spread population consisting of more isolated groups (see also Rowley-Conwy and Piper 2017).

Glørstad (2016) places more emphasis on how the process of deglaciation might have delayed human migration to present-day Norway, as opposed to the logistic challenges these areas might have represented for North-European hunter-gatherer groups. The morphology of the Oslo fjord means that although large coastal areas in Norway were ice-free in the first centuries of the Holocene, the inner most parts of the fjord would have been covered by ice further up in time. Although the timing for deglaciation of the inner parts of the fjord is not precisely dated (Mangerud and Svendsen 2022:64), this would have partly obstructed the further spread of environmental elements from the continent. The fjord itself would also have been a broader bay, making any crossing by boat a formidable, if not impossible task before the protective archipelago could be followed along at least most of the coastline. Parallel to this, isostatic uplift eventually resulted in the decline of the central coast of Western Sweden as a prime location in terms of marine resources (Schmitt et al. 2009). This was due to the closing off of straits connecting the North Sea and present-day Baltic Sea – a process that concluded around the later parts of the Preboreal (see Figure 2.2). As a result, southern foraging groups might have found it increasingly necessary and convenient to extend northwards along the coast (Glørstad 2016). Previous explanations such as that of Bjerck might therefore have overemphasised the unique challenges posed by the geographical setting of Norwegian coastal landscapes. This debate is by no means concluded, however, and authors such as Bjerck (2013, 2017) and Bang-Andersen (2013) have met many of Glørstad's suggestions with reluctance, including what they consider a downplay of the logistical demands that these coastal areas must have presented, also following the retreat of the ice.

In general, the Early Mesolithic in Norway is understood as characterised by highly mobile groups, reflected by what is typically interpreted as small, homogeneous sites located at exposed locations in the landscape (e.g. Bjerck 1994, 2008; Fuglestvedt 2012; Nærøy 2000), as well as lighter, more expedient dwelling structures in the form of tent-like structures (e.g. Åstveit 2009; Fretheim 2017:219). As there is little organic material on which to base inferences on subsistence from this period, there is little direct evidence to go on when attempting to determine what available resources made up the diet of people in Norway in the first centuries of human occupation. Given the North-European origin of the first humans in Norway, the hunting of reindeer has been suggested to be a possible driver behind the initial colonisation. However, the EM sites are predominantly found along the coast, and so there is little doubt that aquatic resources have played a central role (Bang-Andersen 2012; Bjerck 2008; Fuglestvedt 2014; Indrelid 1978; Svendsen 2018).

However, it cannot be excluded that a variety of species of terrestrial mammals, fish, fowl and flora have also been important constituents of the diet (Åstveit 2014; Fuglestvedt 2014; Mansrud and Persson 2018). While the settlement is focused on the coast, there is also a presence in the inland and mountain regions of south- and north-western Norway from a very early stage, which is believed to have been related to the hunting of reindeer (Bang-Andersen 2012; Breivik and Callanan 2016; Hagen 1963; Svendsen 2018). Persson (2018:207) argues that the contemporaneous establishment of coastal and inland sites is an indication that pioneer populations were neither specialised inland reindeer hunters nor specialised marine foragers who then later expanded their resource base (see also Åstveit 2018). Furthermore, Mansrud and Persson (2018) argue that the presence of microliths, which is to be indicative of bow-and-arrow technology, combined with the environmental backdrop of increasing temperatures, the reduced oceanic influence from the melting ice sheet, and the strengthening of the NwAC, in sum points towards a wider spectrum of resource exploitation. This as opposed to what has in the literature sometimes been cast in a dichotomous and one-sided focus on either seal or reindeer (see e.g. discussion by Åstveit 2014 with comments).

Given the lack of direct evidence for subsistence strategies, the analysis of settlement patterns and overall palaeoecological developments is typically drawn on to make general inferences regarding the question of resource exploitation. The coastal EM sites have been characterised as having a tendency to be situated on small islands (Breivik 2014; Nyland 2012), and been exposed to the sea (Bang-Andersen 2003; Breivik 2014). This is argued to reflect the importance of marine mammals, especially seal, in the EM.

As a counterpoint, there have been several exceptions demonstrated against the tendency of EM sites to be situated at exposed locations and on islands (Darmark et al. 2018), and some authors have argued that the degree of site homogeneity and differences in settlement patterns compared to later periods has been exaggerated or is not properly understood (Åstveit 2014; Glørstad 2013; Viken 2018; see also Damlien et al. 2021:79–81). Furthermore, in a recent study I found that the settlement patterns in a subregion of south-eastern Norway was fairly similar across the EM, MM and LM (Roalkvam 2020). Of the considered variables, the most important driver of settlement patterns was found to be degree of exposure, where the sites were found to be located with relatively open immediate surroundings, while at the same time being sheltered from larger stretches of open sea. However, one of the locational patterns that was not considered was the location of the sites within the wider landscape. The term exposure has been used to denote both how commanding the view would have been from the sites and how exposed the sites would have been to wind and wave-action (Svendsen 2014), but has also pertained to their location relative to deeper fjords and outermost coast (e.g. Bergsvik 2001; Bjerck 2008; Jaksland 2001; Lindblom 1984; Nyland 2012; Svendsen 2018). It has been argued that EM sites would have mainly been located on the outer coast, and that the fjords were not utilised until a later stage, which could reflect the distinction between resource bases mainly focused on marine mammals contra fish.

In recent work, Breivik (2014, 2020) has focused on diachronic variation through the EM in Norway. She argues that while the PBO was defining for the conditions for earliest human colonisation of Norway, with favourable conditions for Arctic marine mammals such as seal, the strengthening of the NwAC led to a more stable marine environment towards 8800 BCE. This change in environmental conditions could be related to what she identifies as a shift in settlement patterns and site types around the middle of the EM. While the developments in Skagerrak has seen a varied impact from Atlantic waters, and is heavily influenced by developments of the Baltic Sea, this diachronic distinction nonetheless underscores the point that treating the EM as a unified aggregative temporal unit could suppress important temporal variation within the phase – variation that is potentially better accommodated by the separation that Reitan (2022) makes between the Single-Edged point phase and the Høgnipen point phase (Table 2.1, see also Chapter 3).

2.2.2 The Middle Mesolithic (8300–6300 BCE)

While the Middle Mesolithic (MM) was defined as a separate typo-chronological phase in the 1970s, Bjerck (2008:92–98) stated as late as 2008 that the period was associated with a limited archaeological material, thus posing an analytical challenge. This is in part related to sea-level transgressions in this period along the coast of southern and western Norway. In south-eastern Norway, which has not been subject to sea-level transgression, the lack of MM material could in part be related to the fact that MM sites are located at elevations that have historically not been impacted by the expansion of infrastructure, and thus not targeted by archaeological investigations (Jaksland 2001:27). This picture has changed dramatically over the last couple of decades, and in addition to the excavation of individual sites, an expansive MM material has been investigated within the study area of this thesis in larger projects such as E18 Bommestad–Sky (Solheim and Damlien 2013), Vestfoldbaneprosjektet (Melvold and Persson 2014), E18 Tvedestrand–Arendal (Reitan and Sundström 2018), and Intercity Vestfold (Berg-Hansen et al. 2022).

Discussion pertaining to the MM have in part been concerned with whether the period has more in common with the highly mobile societies of the EM or with what was is typically seen as more sedentary or semi-sedentary LM societies (e.g. Bang-Andersen and Bjerck 2005; Berg-Hansen et al. 2022; Glørstad 2010; Mansrud 2014; Solheim and Persson 2016; see also the third paper of this thesis, Roalkvam 2022). There is a clear shift in material technology around the end of the 9th century BCE (Bergsvik and David 2015; Damlien 2016; Eymundsson et al. 2018; Mansrud and Persson 2018; Reitan 2022; Solheim et al. 2020; Sørensen et al. 2013), which coincides with a genetic mix between the populations originally migrating to the Scandinavian Peninsula from the south and those extending southwards from the north-east (Günther et al. 2018; Manninen, Damlien, et al. 2021; Skar 2022). However, several aspects of these societies are still believed to show similarities with the EM. For one, MM sites have, as with the EM sites, traditionally been seen as remnants of shorter stays (Jaksland 2001; Mansrud 2014:87). Furthermore, based on sites from northern Vestfold, Berg-Hansen et al. (2022:662) have argued that coastal settlement patterns in the start of the MM appear to be a continuation of those from the EM, characterised by a site location concentrated to the outer coast.

However, other aspects of the MM show a clearer break with the preceding EM. Bjerck (2008) notes that the MM is characterised by a degree of regionalisation in the lithic material that is not evident in the EM material. One feature of the lithic inventories is an increased use of locally occurring non-flint material, which is often held to indicate an increased familiarity and attachment to local areas (Berg 1997:109; Jaksland 2001:110). This is most clearly represented by the introduction of so-called chubby core adzes, as well as shaft-hole hatchets and mace heads (Eymundsson et al. 2018; Reitan 2022). Furthermore, recent investigations in south-eastern Norway has revealed what has been interpreted as integrated settlement systems consisting of sites with different functions, as opposed to the homogeneous sites that are to characterise the EM (Berg-Hansen et al. 2022; Solheim 2013; Solheim and Persson 2016).

While there appears to be a high diversity of dwelling structures from the MM in Norway, including some that are reminiscent of those from the EM (e.g. Granados 2023), substantial sunken dwelling-structures dated to the MM have also been identified (Berg-Hansen et al. 2022; Bjerck 2008; Fretheim 2017:220; Mjærum 2018; Solheim and Olsen 2013). The higher investment of time and resources that these dwelling structures represent has been taken by many to indicate an increased residential focus on the area in which they were built (e.g. Åstveit 2009; Berg-Hansen et al. 2022; Bjerck 2008; Fretheim et al. 2016; Solheim and Persson 2016).

Furthermore, the MM sees an increased exploitation of inland and mountain regions (Boaz 1999; Indrelid 1994; Persson 2009, 2018; Selsing 2010), and it has been suggested that a separate inland population is established in this period in south-eastern Norway (Damlien and Solheim 2018). The exploitation of red deer, reindeer and especially elk appears related to these inland sites – a practice that is suggested to be firmly established around 6500 BCE (Mjærum 2018). The comparatively low number of EM sites in the inland areas of Eastern Norway should also be seen in light of the fact that the ice sheet did not melt entirely until probably around 8000–7500 BCE (Mangerud and Svendsen 2022:65), and that environmental conditions conducive of a larger elk population with stable migratory routes was established after c. 7000 BCE (Mjærum 2018:188). However, Boaz (1999:132–133) has argued that human occupation in these inland regions followed some time after productive biotopes were already established in parts of this area, and therefore that this delay mainly reflects cultural factors rather than environmental ones.

Stable isotope data from human remains dating to the Norwegian Mesolithic is published for two sites. One individual is from the Viste cave in western Norway, dated to around 6200–6000 BCE (Schulting et al. 2016), and for between two and five individuals found at Hummervikholmen in southern Norway, dated to between c. 8200–7000 BCE (Skar et al. 2016). The δ^{15}N for these individuals are the highest measured for any Mesolithic individuals in Scandinavia, and indicate a heavy reliance on higher-trophic marine resources such as marine mammals and piscivorous fish (Schulting et al. 2016; Skar et al. 2016; Solheim 2020). However, as the isotopic evidence is limited, and isotope analysis of human remains from Huseby Klev (c. 8500–7500 BCE) and Uleberg (c. 5500 BCE) in western Sweden indicate the inclusion of terrestrial species in the diet (Lidén et al. 2004), it is not clear how representative these results are for the Mesolithic in Norway as a whole (see Solheim 2020).

Furthermore, while there are several taphonomic factors that might bias the preservation of faunal material, this material does appear to offer support for changes in the resource base from the EM to the MM. In their review of the osteological material from MM sites in western Sweden and south-eastern Norway, Mansrud and Persson (2018) find support for a comparatively broad-spectrum resource-base in the MM that includes the exploitation of fish, birds and both terrestrial and marine mammals. While fish and marine mammals appears to have constituted the main components of the diet, terrestrial species could have constituted parts of the diet while also providing raw-materials for the production of clothes and tools.

While a wide exploitation and specialisation towards fishing has traditionally been argued to be a characteristic of later Mesolithic phases and be related to an increase in sedentism, finds of fish hooks and assemblages associated with a dominating abundance of fish remains has pushed back this date to the MM (e.g. Bergsvik and David 2015; Boethius 2018a; Boethius et al. 2020; Mjærum and Mansrud 2020; Ritchie et al. 2016). Whether indications of extensive exploitation of fish can be pushed even further back in time remains to be determined, but given the taphonomic bias and challenges with archaeological recovery that impacts the detection of fish bone (e.g. Boethius 2018a, 2018b), it is not unthinkable that the antiquity of extensive fishing in the Norwegian Mesolithic remains underestimated (Bergsvik and Ritchie 2020:240).

Unlike the genetic changes and changes in lithic technology that are believed to be more abrupt around the transition to the MM, Berg-Hansen et al. (2022) argue that other aspects, such as the transition to different settlement patterns and an increase in the use of non-flint material, is a more gradual process. This highlights the fact that while it appears relatively established that migration events resulted in pervasive changes to the Mesolithic societies in south-eastern Norway around the transition to the MM, a lot remains to be understood concerning the process and timing by which this happened, and the consequences it had at the societal level – thus highlighting the complexities that are associated with migratory events (e.g. Anthony 2023). Moves to challenge the established chronological framework, such as that proposed by Reitan (2016, 2022), can potentially help in an endeavour to untangle these developments, and accepting that different societal processes might operate and be recognisable at differing temporal and spatial scales is also imperative in this regard.

2.2.3 The Late Mesolithic (6300–3900 BCE)

The LM is in many respects seen as a period in which the societal developments towards semi-sedentism and social differentiation that several authors have argue begun in the the MM, intensify and become firmly established (e.g. Bjerck 2008:104–105; Fuglestvedt 2018:16–17).

The period sees an increase in the use of local non-flint material, especially represented by the Nøstvet core adze, and a few sites interpreted as specialised adze-production sites date from this period (Eigeland and Fossum 2014; Glørstad 2011). The western Swedish equivalent to the Nøstvet phase is denoted Lihult, and, as with preceding periods, these are now considered to represent the same phenomena (Glørstad 2011). However, in Reitan's (2016, 2022) re-evaluation of the material, he has not found indications that the typological indicators that are to be clear markers of the Nøstvet phase occur earlier than around 5600 BCE. Furthermore, and as a potential counterpoint to the gradual intensification of societal traits that are first introduced in the MM, the transition to the classic Nøstvet material record appears to represent a clear and relatively sudden typological break (Reitan 2022).

The transition to the LM phase entitled Kjeøy, occurring around 4600–4500 BCE (Table 2.1), is indicated by the re-introduction of flint projectile points, as well as a change in the production techniques of adzes and a reduction in their number (Reitan 2022). Based on changes in lithic technology (Eigeland 2015), and possible fluctuations in relative population numbers (Nielsen 2021a), it has been suggested that new people have migrated to the coastal areas of south-eastern Norway from the south in this period. The Kjeøy phase and its relation to the preceding periods must, however, be considered relatively poorly understood as there has historically been limited material available, and as the phase has not received the same amount of focused research as other Mesolithic phases (Damlien et al. 2021:100).

Taken as a whole, the LM sites in Eastern Norway are argued be characterised by an increased variation in size, artefact inventories and topographical location (Lindblom 1984), which includes several sites that are interpreted as the result of repeated stays of a longer duration (Glørstad 2010). Furthermore, the period has also been argued to be characterised by an increase in social differentiation and the establishment of territories within the region (Fuglestvedt 2008, 2018; Glørstad 2010:160–165; Jaksland 2001:119–210; see also Boethius et al. 2020).

There is evidence for increased use of inland and mountain regions in the LM (e.g. Damlien et al. 2021), and the most substantial Mesolithic dwelling structures in south-eastern Norway are found in inland regions and date to this period. These are represented by semi-subterranean housepits, associated with large accumulation of fire-cracked rocks, which in sum is taken to indicate their use in the winter season (e.g. Boaz 1999:143–146).

However, also inland utilisation appears to demonstrate fluctuations that are possibly better accommodated by Reitan's (2022) alternative chronology. Based on excavations in Rødsmoen and Dokkfløy in the inland region of south-eastern Norway, Boaz (1999) suggested that a significant peak in inland activity was reached around 6000 BCE. This is followed by a considerable drop until a second peak occurs around the onset of the Neolithic, c. 4000 BCE. This development has largely been confirmed by Selsing (2010) in a comprehensive evaluation of the data available from the mountain regions of Southern Norway, and by Persson (2018) who also included sites from the more recent Gråfjell project in Hedmark (Stene 2010). These developments thus roughly correspond to an increased inland activity in Reitan's Pecked Adze Phase, followed by a drop and lower inland activity in the Nøstvet Adze phase and Transverse Arrowhead Phase. Although this fluctuation has been given several possible explanations (as discussed by Persson 2018), Boaz (1999) related it to the establishment of more clearly separated inland and coastal settlement, where a specialised Nøstvet adaptation in the coastal areas led to a cessation of seasonal movement to the interior.

Increased territoriality has in part also been related to the not previously mentioned material category of rock art. Rock art is present from the EM in northern Norway (e.g. Gjerde 2021), but the LM marks the onset of what Fuglestvedt (2018:17) terms 'the great wave' of rock art in Norway. Furthermore, in Eastern Norway, rock art does not appear to be introduced before c. 5700 BCE (Fuglestvedt 2018:42–46; Glørstad 2010:216–233), thus roughly corresponding to the onset of Reitan's Nøstvet Adze Phase. While there are some challenges associated with the dating of rock art, this dramatic increase cannot reasonably be ascribed taphonomic effects or investigatory biases, and can therefore be taken to represent a clear indication of cultural changes with the LM. This increase in rock art is often interpreted as an increase in ritual behaviour of a kind that establishes a firm attachment to their location in the landscape, in turn thus supporting the notion of an increased degree of territoriality (e.g. Glørstad 2002:32–33).

Although mobility is argued to generally decrease and territoriality increase with the LM, this is qualified by Glørstad (2010:97) who states that while expedient mobility in surrounding landscape appears to be reduced, better terms might be that mobility became more structured and regulated, as longer-distance contact- and mobility-networks appear to have been established at the same time. This is reflected by the occurrence of flint in inland regions where this would not have been available naturally. The same notion is also reflected in the work of Fuglestvedt (2018), who on the grounds of shared motifs in rock art from eastern, north-western and northern Norway has argued the case for wide-ranging contact-networks in the LM.

Related to the increased evidence for ritual behaviour is also the only secure grave-find from the Mesolithic in south-eastern Norway, represented by an inhumation grave containing a single individual from the site Brunstad in Vestfold (Reitan et al. 2019; Schülke et al. 2019). Due to the poor preservation of the bones, neither ^{14}C-dating nor stable isotope analysis of the bones was successful. However, contextual information and dates from relating features date the grave to c. 5900 BCE. The grave was found as part of a site complex of three sites on what would have been an island in the Mesolithic. The sites were interpreted as the result of repeated visits between c. 6400–5600 BCE.

In western Norway, Bergsvik (1995, 2001) found that large LM sites associated with the accumulation of thick organic deposits were located close to good fishing locations along straits, and in combination sees this as an indication of an increased degree of sedentism and territoriality towards the later parts of the Mesolithic (see also Bergsvik 2006:149–150, 168–171). Furthermore, zooarchaeological evidence from rock shelters appear to indicate an increased specialisation towards fishing in the LM (Ritchie et al. 2016), and Bergsvik et al. (2016) argue that a shift towards sedentism in western Norway occurs around 6100 BCE. While the same kind of sites with extensive organic deposits located along straits have not been discovered in south-eastern Norway – possibly due to investigatory and taphonomic factors – a similar development has been suggested for this region. Glørstad (2010) argued that larger LM sites appear to have been situated at locations with an especially good access to marine resources, and Lindblom (1984) linked a similar argument to the location of the LM sites in fjords and the inner archipelago. It is thus possible that practices of settlement patterns and resource exploitation, introduced with a decrease in residential mobility in the MM, is intensified through the LM.

2.2.4 The end of the Mesolithic

Around 4000 BCE, agriculture is introduced in southern Scandinavia with the Funnel Beaker Culture, with direct agricultural evidence extending as far north as Bohuslän in Western Sweden on the border to present-day Norway (e.g. Sørensen 2014). While evidence for agriculture from the Early and Middle Neolithic in south-eastern Norway is sporadic and uncertain (e.g. Solheim 2021), other dimensions of the archaeological record clearly demonstrate influence from bordering agricultural societies, represented by artefacts such as pottery, polished flint axes, as well as a few megalithic dolmens in the Oslo fjord region (e.g. Østmo 2007). The nature of this transition and the role of the potential agricultural traces have been widely discussed. In many respects the first part of the Neolithic is viewed as a continuation of Mesolithic settlement patterns and subsistence base, but the changes in material culture indicate wide-ranging contact-networks and potentially internal developments that nonetheless appear to represent a significant societal shift (discussed by e.g. Glørstad 2012; Glørstad, Solheim, et al. 2020; Nielsen et al. 2019; Nielsen 2021b; Nyland et al. 2023; Østmo 1988; Prescott 1996, 2020; Solheim 2021). Reitan (2022) suggests that from a typological point of view, the transition to the Neolithic should be defined by the introduction of pottery and polished axes, rather than the currently weak indications of agricultural practices, and therefore sets the end of the Mesolithic in south-eastern Norway to 3900 BCE. This therefore also means that term Neolithic, when used to denote end of the Mesolithic in a Norwegian setting, does not imply the fundamental economic and societal changes with a wide adoption of agriculture that the term typically connotates in other parts of the world (called an 'artifactually defined Neolithic' by Rowley-Conwy 1993:350; recently discussed by Nyland et al. 2023).

2.3 Chapter summary

The above presentation has outlined the general environmental setting and overarching cultural developments that are believed to have characterised the Mesolithic in south-eastern Norway. The larger scale developments are of main interest to this thesis, where the main dimensions that have been deemed of central importance is the economical basis of these societies, associated land-use and settlement patterns, and demographic factors such as population size and migratory events. The next chapter will outline a more explicit analytical framework for how these dimensions can be understood theoretically and approached empirically, and especially how they can potentially be reflected in archaeological data such as site frequency, lithic assemblages and the position of the sites in the landscape.

Chapter 3

Analytical background

The last chapter outlined the environmental and archaeological background for the thesis. This chapter presents underlying analytical concepts that have motivated the research questions asked and the methods employed in the undertaken studies. The first part of the chapter outlines some issues that are fundamental to archaeology in general, pertaining to dimensions such as the quality and resolution of the empirical data, chronological frameworks and cultural taxonomies, and presents some methodological and conceptual ways in which these can be contended with. The last part of the chapter moves on to consider dimensions and characteristics of hunter-gatherer societies that are often considered to be of central importance for understanding the variation that has existed among these societies. The section on hunter-gatherers thus pertains more directly to what cultural historical dimensions the thesis attempts to elucidate.

3.1 The quality of the archaeological record

Underdetermination and equifinality are two related concepts that concern the degree to which empirical evidence can be drawn on to adjudicate between competing explanations. Equifinality pertains to the case where different processes have the same empirical result, while underdetermination pertains to the case where the available empirical evidence can be the result of different processes (e.g. Okasha 2016:66–70; Perreault 2019:1–2; Psillos 1999:162–182). The degree to which this occurs therefore impacts the hope we have of ever choosing between competing explanations, and is especially pertinent for archaeology as we deal with a fragmented empirical record fraught with various systematic and un-systematic biases that impact the quality of our data, in turn leading to the underdetermination of potential explanations.

Due to underdetermination, the quality of the data available to us is consequently fundamental for knowing what questions we can and cannot hope to answer about the past (see Perreault 2019). Lower quality data will lead to averaging and smoothing, where for example a reduced temporal resolution can lead to chronological smearing that hides smaller scale oscillations and variability (Bailey 2007; Daems et al. 2023; Stern 1994). The same principle extends to the spatial scale, where a lower empirical coverage means that answers to questions pertaining to processes operating at the scale of individuals, sites or smaller regions might not be empirically tractable, and a larger view might be necessary to bring into view a process of interest, thus determining what processes we can hope to unveil. Furthermore, this issue also pertains to what Perreault (2019) terms the dimensionality of the data, that is, the features that can and have been recorded for a set of observations – for example stable isotope characteristics of human remains. Loss or otherwise reduced dimensionality can here result in a reduction of variability and richness, impacting for example the perceived characteristics of artefact assemblages.

Furthermore, loss and mixing can sometimes be more subtle effects than complete absence of data, which can potentially be more easily recognised. Moreover, effects such as loss, mixing of past events and analytical lumping will most likely not impact the quality of the data in a uniform way. Taphonomic loss is likely to be more severe the further back in time one moves (Surovell et al. 2009) and follow from geographically contingent environmental impact on preservation. Analytical biases following for example from disciplinary interests or what geographical areas have been subjected to archaeological investigation will also skew our impression of the past (Binford 1964). Mapping the spatial and temporal quality of the archaeological record is thus critical for knowing what past processes we would be able to discern, and by extension what kind of archaeology we can hope to do. For these reasons, a central aim of this thesis is to contribute to mapping the data available from the coastal Mesolithic of south-eastern Norway.

3.1.1 Digital and computational archaeology

Given the large amounts of data that have been and continue to be generated by Norwegian Mesolithic archaeology, contending with this data at even the most basic level necessitates the use and development of computational methods designed to handle this, in the words of Bevan (2015), 'data deluge'. Furthermore, most of the data generated by archaeology today is to varying degrees digital in nature, legacy data is increasingly being digitised, and digital tools are used at all levels of archaeological practice. Therefore, digital and computational methods are fundamental and intrinsic to modern archaeology, irrespective of the scale we are operating on. As Morgan and Eve (2012:534) have stated: 'we are all, whether we like it or not, digital archaeologists'.

Given this dependency on computational and digital methods, it has been argued that it is not enough for archaeologists to passively employ these technologies or to critically assess their development from afar. Archaeologists have to become active, informed and reflective participants in the development of new technologies, and in the assessment and creative application of those that already exist (Llobera 2011). As the philosopher of technology Ihde (2004) has argued, it is necessary to some degree to 'go native' (cited by Huggett 2015:88). All four papers of this thesis can be said to contribute to this through the exploration, development and open dissemination of methods and technologies for the purposes of handling data and casting this as evidence for understanding the Mesolithic of south-eastern Norway.

There can be merit to an exploratory accumulation and systematisation of the available data in its own right, both to get an overview of the processes we can hope to explain, and as it can reveal patterns in archaeological investigation and categorisation as well as help identify, and potentially average out erroneous data points or idiosyncratic and random variation (see e.g. Cooper and Green 2016; Hamilton and Tallavaara 2022). However, more data will not by itself offer any meaningful insight. Discussing this in the context of so-called 'big data' in archaeology, Huggett (2020) states that 'digital data not only offer possibilities but may also constrain actions, they limit as well as enable, and this may not always be recognized in the thrill of the revolutionary discourses surrounding Big Data and the lack of a proper data gaze.' While seeing data as given, free of influence from our preconceptions is a well-known fallacy and a long held criticism in archaeology, several authors have expressed concerns with the degree to which developments in digital technology may lead to an over-enthusiasm that neglects the messy, fragmentary and complex nature of archaeological data, and that this can lead to fetishisation of digital data following from its availability, tractability and often elegant-seeming results (see e.g. Hacıgüzeller 2012; Huggett 2020; Solli 2007).

While large amounts of data do not offer a way to side-step the fundamental issues with archaeological evidence, there is nonetheless decidedly value to evaluating data at multiple scales. Not only can this reveal patterns and processes that operate at some scales and not at others, but different scales of perspective can also feed back to each other and reveal biases or inconsistencies. Furthermore, by drawing on for example Kuhn (1970) and the later work of Galison (1997), several authors have argued that the development and employment of digital and computational tools by itself impacts the fundamental practice of doing archaeology (Grosman 2016; Schmidt and Marwick 2020) – an effect that extends beyond the scale these methods can operate on. Active, informed participation and sharing of digital and computational tools is therefore likely to advance archaeology by leading to a situation where 'familiar objects are seen in a different light and are joined by unfamiliar ones as well' (Kuhn 1970:111).

This promise is of course also dependent on the context and ways in which data has been recorded and been made available (Cooper and Green 2016; Huggett 2014). A central issue with digital data is therefore to avoid naive empiricisms and to offer transparency with regards to its creation, manipulation, handling and finally with how it is cast as evidence. This will allow ourselves and others to assess how these steps might influence the arguments that are made. The ways in which these issues are attempted to be tackled in the context of this thesis will be laid out in more detail in Chapter 4.

3.2 Chronology, cultural taxonomy and modifiable analytical units

The study area of this thesis, situated within south-eastern Norway, is for the most part believed to have followed a similar trajectory in terms of overall cultural-historical developments and expressions of material culture through the Mesolithic. At least within the analytical detection limit that has characterised the field thus far. What has been of greater concern is the temporal transition between the occurrence of cultural taxonomic elements within the region. In Norwegian Mesolithic research more widely, however, the question of both regional variation in material culture and its timing has led to discussions of whether a concept known as 'chronozones' has any merit as a framework for systematising the archaeological material. This is a concept that has remained marginal in archaeology as a whole, but is used by several practitioners in Norwegian Mesolithic archaeology (e.g. Bjerck 2008; Breivik et al. 2018; Fretheim 2017; Fuglestvedt 2018; Nyland 2016; Skar and Breivik 2018), and is related to fundamental issues faced within archaeology.

The concept originates in a paper by Bjerck (1986), in which he attempts to tackle the distinction between the archaeologically defined cultures of Fosna and Nøstvet in the context of Western Norway. Instead of an ever-continued nuancing of these terms as more variation and idiosyncrasies are encountered in the archaeological record, Bjerck (1986:117–119) instead suggests a division of the Mesolithic period into a series of time-intervals denoted chronozones, originally at a resolution of 500 years, which he argues could facilitate a pan-Scandinavian framework for approaching the Mesolithic (Bjerck 2008:72–73). The concept of chronozones is taken from the geosciences, where the term is used to denote stratigraphic layers that formed over the same specific time-span on a regional or world-wide scale, known from geochronological units such as for example the Preboreal, Boreal and Atlantic time-intervals (e.g. Salvardor 1994:83–85). Bjerck's motivation for adapting this to archaeology is to form a framework that is neutral with respect to cultural variation across space and time. He argues that traditional archaeological units of analysis, typically denoted by terms such as cultures or techno-complexes that are discretely delineated in time and space, has led to an artificial partitioning of the archaeological material that is less open to gradual temporal change and spatial variation – an issue that has been contended with by many archaeologists through the years (e.g. Butzer 1982:279–320; Childe 1956:121–125; Clark 2009; Reynolds and Riede 2019; Roberts and Vander Linden 2011; Smith 1992). Bjerck argues that the use of neutral 500-year time-intervals will reduce the degree to which analyses will overemphasise homogeneity within, and exaggerate differences between such analytical units. To further illustrate the issues Bjerck (1986) attempted to tackle, it is useful with a detour via the concepts of the Modifiable Areal Unit Problem (MAUP), as taken from the field of geography (e.g. Harris 2006), and its recently coined temporal equivalent, the Modifiable Temporal Unit Problem (MTUP, Bevan and Crema 2021).

3.2.1 The MAUP and MTUP

The scale problem, as its often called, is central to geographical research. This follows from the scale that is chosen in the necessary generalisation of continuous phenomena, the dependency of this generalisation on the density of sampling points, and the variable spatial scales that different phenomena operate across (Harvey 1968). Some central implications Haggett (1970) identifies in relation to this is the *scale coverage problem*; related to the choice of variable sampling designs and intensities for undertaken studies, the *scale linkage problem*; the problem of comparing results captured at one spatial scale with those captured at another, and the *scale standardisation problem*; the issue of how data that have been captured on varying spatial scales are adjusted to a common scale (Harris 2006:46). Extending on the last problem, Haggett (1970:177–179) shows how adjusting the boundaries used to delineate the originally retrieved data can have substantial consequences for any basic comparisons of the occurrence of phenomena within these units, which is the issue that underlies the MAUP.

The MAUP is defined by Heywood et al. (2002:8) as 'a problem arising from the imposition of artificial units of spatial reporting on continuous geographical phenomenon resulting in the generation of artificial spatial patterns' and is an issue that underlies most if not all analyses that draw on areal data (Harris 2006:48). A common example from archaeology is the areal unit of the site, the delineation of which typically follows some notion of concentration of artefacts. However, the density of artefacts over a landscape can be conceived of as a continuous phenomenon, and so its definition will always be modifiable and subject to choice, whether it follows from some kind of statistical procedure or a more intuitive definition (e.g. Dunnell and Dancey 1983; Hodder and Orton 1976:17–19; Thomas

1975). The same problem extends to the smaller scale, such as with the definition of site features based on the concentration of charcoal, and up in scale, such as to the definition of archaeological cultural areas. How these units are defined will impact the most basic comparison between them. Given the arbitrariness and potential variation that might exists in the aggregation procedures underlying our areal units, it is therefore always a danger that discovered patterns could simply be artefacts of the aggregation technique.

These issues can also be extended to the temporal dimension, which Bevan and Crema (2021) have recently demonstrated in the context of archaeology by illustrating how periodisation involving lumping and splitting of phenomena within disjoint time-intervals have analytical consequences that remain under-appreciated within the discipline (see also Crema 2015). First, employing strict cut-offs between temporal units – units that often also vary in their duration – has major implications for comparison between these units, and can, as Bjerck (2008:73) also notes, lead to an artificial and inadvertent overemphasis of the transition between these. Basic operations such as comparing counts will be biased by variable duration of these units, and the position of breaks between them can be highly influential to the appearance of the frequency distribution of events over time.

Building on Crema and Kobayashi (2020), Bevan and Crema (2021) further define three types of uncertainty associated with this archaeological practice. The first is *phase-assignment uncertainty* – how certain can we be that a given phenomenon can be ascribed to a given phase. The degree to which this varies between different material categories means that it can be difficult to compare their frequency across archaeological phases. As was found in the third paper for this thesis (Roalkvam 2022), the occurrence of formal tool types at the Mesolithic sites in the study appears to be greater further back in time. This as opposed to younger sites, which are to a larger extent dominated by generic debitage that can be more difficult to assign to a specific phase. This can have implications for how many sites are ascribed earlier periods, and, by extension, could impact a comparison between phases. The second pertains to the *within-phase uncertainty*, the degree to which the occurrence of various phenomena have an equal likelihood of occurrence throughout an archaeological phase. For example, in typological discussions for the Norwegian Mesolithic, the occurrence of different artefacts types is in practice typically treated as having a uniform frequency of occurrence within a given time-span. The final dimensions Bevan and Crema (2021) highlight is the *phase boundary uncertainty*, which pertains to the start and end points of the archaeological phases themselves. As these are typically defined by a complex interplay of multiple cultural phenomena, they are seldom meant to operate on the scale of individual years but will in practice often be operationalised as such.

3.2.2 Archaeological chronozones

While possible methodological ways around these issues are presented in the works cited above, neither the MAUP nor the MTUP have any clear solutions, and the magnitude of their impact will depend on the given research question and accompanying analytical scale. However, their formulations arguably form a better frame for understanding these issues than the concept of chronozones. I argue here that chronozones can instead obfuscate the distinction between the temporal and the spatial scale, and that of culturally taxonomic artefact classification (see e.g. Dunnell 1971; O'Brien and Lyman 2002; Reynolds and Riede 2019; Riede et al. 2022). Bjerck (1987) states that typology obviously has its place as a culturally responsive framework for classifying artefact variation over time and space. Here I understand typology to be meant in a wide sense, pertaining both to the act and result of classifying artefacts, and its potential role as a dating method (see references above and e.g. Berg 2021:59–65; Gräslund 1987; Sørensen 2015, for discussions concerning the typology term). By ignoring this cultural dimension, chronozones, on the other hand, are supposed to facilitate comparisons across taxonomically inferred boundaries in space and time.

In her comment to Bjerck's paper, Skar (1987:35) notes that geological chronozones couple pan-regional stratigraphic layers with the calendar scale, but that there are no equivalent pan-regional archaeological phenomena that equally consistently correspond to a section of the calendar scale. As Bjerck (1987:40) further underscores in his response, archaeological chronozones are therefore not, unlike typological frameworks, meant to be culturally responsive, but are to represent a neutral temporal scale, typically instantiated as 500-year intervals. However, as Østmo (1987) and Mikkelsen (1987) note in their comments to Bjerck's original paper, this purpose is already fulfilled by the calendar. If the stratigraphic information related to a specific time-interval is removed from the geological chronozone, only 'chrono' remains. Similarly, if the archaeological chronozone is not meant to hold any culturally responsive component, only the time-scale remains.

As a culturally independent scale, the calendar scale will always be preferable to the that of chronozones. Not only because it is firmly established, but also because it already allows for more variation in the temporal resolution associated with different phenomena to be systematised, and allows for their duration and uncertainty of occurrence to span a wider range of aggregative time-units (cf. Reitan 2022:187). The ability to shift and readjust the temporal resolution depending on the phenomena one is attempting to align and contrast is important as 'different timescales bring into focus different sorts of processes, requiring different concepts and different sorts of explanatory variables' (Bailey 1987:7; 2007).

In replying to this critique, Bjerck (1987:40) states that questioning the need of chronozones when we already have the calendar is like asking 'Do we need the term “month” when we have numbered days?'. This would seem to imply that chronozones, like the month, is to be of a predefined duration, at least within any individual study, and that variable duration and temporal uncertainty of different phenomena to be analysed must be collapsed into these aggregative units. Another issue is also if the terminology used with chronozones is better than simply stating what time-intervals we are dealing with. For example, Bjerck (2008) uses the term Middle Mesolithic (MM) to denote the three chronozones MM1, 8000–7500 BCE; MM2, 7500–7000 BCE; and MM3, 7000–6500 BCE. A reader coming across 'MM3' instead of '7000–6500 BCE', or some other more neutral name, therefore has to keep in mind that this simply refers to this specific time-interval. The term Middle Mesolithic should be entirely disregarded, as it is in this use meant to be devoid of any cultural meaning.

One could perhaps change terminology to something that doesn’t have as many cultural and research historical connotations as the Middle Mesolithic, but it strikes me as altogether unnecessary to do this via the chronozone, as this is simply solved by establishing a reference frame only using the calendar scale in the first place. If one wants to use a time-scale of 500-year intervals it would in my mind be better to simply define this independently of the now inflated discussion of chronozones, not least because I believe the discussions of the concept demonstrates that its use can lead to unnecessary confusion – if not for practitioners, then likely for readers.

In their comments to the original paper by Bjerck (1986), Østmo (1987) and Mikkelsen (1987) deem chronozones an unnecessary and complicating concept. Commenting on these critiques, Nyland (2016:53–56) states that both Østmo and Mikkelsen make their comments considering typological frameworks for Mesolithic south-eastern Norway, but that neither address the issue of the geographical coverage that these have. However, this is first and foremost an empirical issue rather than something to be solved by new terminology, and clearly not by the chronozone, which is a concept meant to be culturally unresponsive.

Drawing on an example given by Nyland (2016:55); if the question is if central Norway falls within the same cultural sphere as south-eastern Norway, understood to be determined by comparable material culture, then this is dependent on two dimensions, assuming the problem of the initial delineation of these two regions has been resolved. The first is an evaluation of the degree to which characteristics of archaeological material in the two regions is considered to be similar, according some criteria. The second pertains to the timing of the occurrence of this material. To establish this necessarily demands temporal data that is independent of the typological framework itself, or possibly by reference to some principle of seriation with the uncertainty that this entails (e.g. Dunnell 1970). If a set of artefact types occurs in both central Norway and south-eastern Norway, this could lead one to suggest that a similar kind of cultural expression is common to the two regions. If independent temporal data associated with this material, such as radiocarbon dates, additionally indicates that there is a temporal synchroneity between their occurrence, then this would lead one to conclude that this cultural expression appears to occur simultaneously – within some level of temporal certainty. Depending on the magnitude of artefactual and temporal evidence for this coincidence, this could then lead one to apply this typological framework as a dating method in the case that one excavates a site in either region and discovers material of the type in question. A continuous adjustment and evaluation of the reliability of the identified cultural affinity and the derived typological dating frame will of course be necessary, but it will have to be founded on material culture and the position of their occurrence on the calendar scale. This also pertains to the co-occurrence of various archaeological evidence and their wider cultural implications, for example whether or not some artefact type tends to be associated with agricultural activity. If either region lack artefactual or temporal data, then either the nature or the timing of cultural affinity cannot be resolved. The concept of chronozones cannot overcome these issues, and, I think, is more likely to confuse them.

I therefore agree with Østmo (1987) and Mikkelsen (1987) in that the concept of chronozones represents an unnecessary complication. Although some of these complications follow from misunderstandings of the original proposition (as pointed out by Bjerck 1987:40; Nyland 2016:55), this only underscores that the concept sometimes leads to the muddling of several spatial, temporal and culturally taxonomic issues. These are therefore arguably best handled by reference to already well-established terminology, and by the use of modern methods that allows for the formal definition and handling of fuzzy and uncertain categorisation in the aggregation of data, both on the scale of material culture, time and space (e.g. Bayliss et al. 2007; Bevan and Crema 2021; Crema 2012; Fusco and Runz 2020; Leplongeon et al. 2020; Matzig et al. 2021; Riede et al. 2019; Shennan et al. 2015).

The misunderstandings and the amount of ink now spent discussing chronozones also means that invoking archaeological chronozones carries with it the necessity to clarify how one intends to use it, which can be circumvented by avoiding the term altogether. Furthermore, as a term suggested for use in Pan-Scandinavian Mesolithic research, I believe this idiosyncratic terminology will also unnecessarily divorce the field from discussions of the same issues within archaeology more widely, while also making the field less accessible to outsiders, more difficult to couple with adjacent disciplines, and possibly lead to confusion with the geological chronozone. It is therefore unclear what the concept now provides beyond what well-established archaeological and colloquial terminology already covers, perhaps apart from making us aware of these universal archaeological issues.

3.2.3 Radiometric and archaeological dating methods

Rather than being based on predefined discrete time-intervals beyond the calendar scale, the analyses undertaken in the papers for this thesis largely rely on absolute dates from radiocarbon- and shoreline dating. These two methods can be denoted radiometric and archaeological dating methods, where the first category is based on a process of radioactive decay and the second is based on some regularity in human behaviour leading to predictable variation over time. In the case of shoreline dating, this follows from the proclivity of people to have continuously settled close to the shoreline throughout the Norwegian Mesolithic, where the coupling of this with the calendar scale follows from the timing of shifts in the relative sea-level. However, a note should also be made on the fact that radiometric dating is never purely based on a steady process of radioactive decay. Apart from interpretations to do with the calibration, reliability and sampling context of a radiometric date, this also has to be seen in light of other chronological information and the wider archaeological context (Wylie 2017). As with the process of shoreline displacement, the cessation of radiocarbon uptake in an organism also requires an interpretative step to be meaningfully associated with a cultural event of archaeological interest.

It is important to underscore that given the scarcity of radiocarbon dates, and the relative low resolution of shoreline dates, typological frameworks responsive to temporal variation in material culture can most decidedly offer valuable chronological insights, even though this is not directly integrated in the studies undertaken for this thesis. Furthermore, while the analyses are done here using dating methods that largely operate irrespective of archaeological periodisation, the results are frequently narratively and informally associated with general cultural developments believed to characterise the Mesolithic of south-eastern Norway, as roughly outlined in Chapter 2. This is predominately done in an approximate manner with reference to what are best viewed as temporally and spatially fuzzy frameworks and is based on the underlying logic that frequent co-occurrence of a range of material expressions in time and space, as suggested by others, reflects some level of meaningful cultural cohesion. This also means that the term culture is used in a loose archaeological sense and is not presumed to equate to a people or a unified unit in terms of language, genetics, or social structures (see e.g. Roberts and Vander Linden 2011 for thorough discussions of the culture term as used in archaeology; and e.g. Riede et al. 2019 for perspectives that can be taken to challenge the rather naive view taken here). While it appears reasonable to assume that such cohesion has largely resulted from the same cultural factors within the geographically limited area of south-eastern Norway through the Mesolithic, it is also worth noting that empirical correspondence can be driven by other factors. This includes cases where people have arrived at the same technology fulfilling the same purpose in disjoint regions of time and space, known as cultural convergence (e.g Mesoudi 2011:36–37), as well as cases where the same material expression has occurred across a range of different cultural and environmental settings to fulfil different purposes (as has been argued to be the case with slotted bone tool technology in Northern Europe, Manninen, Asheichyk, et al. 2021) – effectively an example of equifinality.

Finally, it is worth commenting on the concept of non-linear time and temporality as it has been approached within archaeology and the humanities more widely. In an influential paper, Ingold (1993) makes the distinction between chronology, history and temporality. Chronology is here defined as a sequence of regular time intervals in which events have occurred. History is defined as a series of events that can be aligned relative to each other by their occurrence within chronological intervals. These are thus sterile and homogeneous sequences, largely detached from a social reality. Temporality, on the other hand, pertains to how people perceive the flow of time and their own position within it, relative to both past and future. However, as Bayliss et al. (2007) point out, it is hard to see how the nature of temporality and the subjective and societal experience of time can be investigated without first establishing the sequence and duration of events on the calendar scale. To repeat Vankilde (2007:22) as quoted in the introductory chapter: 'Chronology is the backbone of social interpretation.' (see also e.g. Holdaway and Wandsnider 2008). Focus is in this thesis therefore directed towards chronology and history (in Ingold's understanding) rather than temporality, as there are fundamental questions pertaining to the chronology of the Norwegian Mesolithic that remain unanswered. Improving our tools for establishing the chronology of events and its associated uncertainty can lay a critical foundation for future investigations of Mesolithic temporality and other non-linear conceptions of time (see e.g. Lucas 2021; Nielsen et al. 2021).

3.3 Hunter-gatherers

The concept of hunter-gatherers here functions as a foundational heuristic model from which to derive empirical avenues to be explored, and to propose possible causal drivers behind any observed patterns (cf. Warren 2022:29). Hunter-gatherers or foragers are useful but fuzzy and not unproblematic synonyms that are typically, but not exclusively, used to denote societies that have a diet based on non-agricultural produce (Kelly 2013). In the introduction to the seminal book *The Lifeways of Hunter-Gatherers: The Foraging Spectrum*, Kelly (2013:4) states that he aims at providing his readers with 'some knowledge of the variation that exist among foragers and some idea of what accounts for it'. Thus, while comprehensive in scope, Kelly (2013) is also very explicit in the limitations of his review and states that while the hunter-gatherer term can be a useful heuristic and analytical unit for human societies, it carries no explanatory weight by itself (Kelly 2013:22). The societal variation among more recent hunter-gatherer societies is immense, and as foraging has constituted the predominant life-way for humanity for 99% of its existence, the variation that can be expected among past hunter-gatherer societies is comparatively vast (e.g. Cummings 2013:33; Singh and Glowacki 2022).

With the *Man the Hunter* conference in 1966, the so-called nomadic or generalised forager model was established, in which hunter-gatherer societies was seen as small and nomadic, characterised by being egalitarian, non-territorial, non-storing and low-violence (Lee and DeVore 1968). As a response to the oversimplifying generalised foraging model, several authors pointed to examples of hunter-gatherers that deviated significantly from this model. As a consequence, several interrelated concepts were introduced as means with which to understand these deviations (e.g. Testart 1982; Woodburn 1982; see Grier et al. 2006; Kelly 2013:241–268; Lane 2014), of which forager complexity has been especially influential to archaeology (Price and Brown 1985a). In this understanding, societal complexity among foragers can include reduced residential mobility, increased population size and density, economic intensification, specialisation, and storage of resources, technological ratcheting involving increased number of artefact components and production steps, control of resources and territories, increased inter-group trade and conflict, elaboration of ceremonies and ritual behaviour, and increased social inequality with hierarchical differentiation in decision-making power (e.g. Arnold 1996; Cummings 2013:55–74; Jeffrey and Lahr 2020; Kelly 2013:241–242; Price and Brown 1985a; Zvelebil 1998).

It is, however, important to note that complexity and simplicity are not value judgements concerning what constitutes a 'better' or 'worse' kind of societal organisation, nor does it entail that simple (sometimes termed generalised) foraging societies are easier to understand than those viewed as more complex. Furthermore, the distinction between simple and complex foragers should not be understood as a discrete dichotomy. The different components of what is often associated with degree of complexity is best conceived of not as a check-list, but rather as a complex web of interrelated societal variables that are merely collapsed under the complexity term. Different components of this concept will be variably relevant in any given context (e.g. Cummings 2013) and these components can be variably related to societal complexity as conditions, consequences and causes for its emergence, permanence or lack thereof (Arnold 1996; Price and Brown 1985b). Following from issues such as those listed above, some authors have deemed the complexity term inappropriate (e.g. Kelly 2013:242; Warren 2005). However, I believe it can still inform some, but certainly not all features of hunter-gatherer societies that are of interest to elucidate, as long as care is taken to avoid a search for complexity in itself – which can lead one to force the empirical record to accord with some idealised expectation of what characterises complex hunter-gatherers. Rather than searching for complexity, a better goal is to identify how and in what ways a society is more or less characterised by explicit dimensions of forager complexity (see Warren 2005:75), and realise that employing this heuristic model reduces the variation we can hope to discern to the idealising confines of the model (Cummings 2013:74).

With increased concern for the diversities that exist among hunter-gatherers, researchers have, at least from the 1980s, increasingly focused on the immense variation that has been demonstrated and can be expected among both extant and past hunter-gatherers (e.g. Arnold 1996; Arnold et al. 2016; Kelly 2013; Lewin 1988; Price and Brown 1985b; Singh and Glowacki 2022). As a consequence, this thesis attempts to balance some insights from hunter-gatherer studies more widely, with an open and exploratory perspective. While preconceptions of hunter-gatherer societies necessarily dictates some of the analytical avenues taken and influence the type of questions that are asked, the aim is to map variation in the dimensions of interest and have idiosyncrasies of the archaeological record from coastal south-eastern Norway dictate the conclusions that are reached.

A further underlying issue with employing hunter-gatherers as a heuristic category with which to approach the material, are ways in which the history of research into such societies might inadvertently dictate how the data is treated. For example, a unilineal socio-evolutionary perspective was a fundamental influence at the inception of the research into hunter-gatherers (e.g. Kelly 2013:4–7). While such views are deemed a grossly inappropriate reference frame today, it can be difficult to fully grasp and account for ways in which this influences the fundamental categories we operate with, however divorced they may now appear. Related concerns have also been voiced in Norwegian Mesolithic research, where for example Åstveit (2014) is vary that a view of EM societies as highly mobile and LM societies as more sedentary might, at least in part, follow from an implicit view of prehistory as characterised by a continuous trajectory towards increased societal complexity. This implicit view might have forced us to cast the material traces available to us to meet these expectations.

Calls for more directed attempts at unveiling how such research-historical conditions might influence how we conduct Mesolithic research have recently been voiced (Elliott et al. 2022; Elliott and Warren 2023). While it is beyond the scope of this thesis to contribute much in the way of bringing these influences and their consequences to light, the next chapter will outline a framework that is employed in an attempt to clarify the evidential logic that underlies the undertaken studies. Hopefully, this can contribute to making evident where such biases might have influenced any analytical choices and the conclusions that are reached.

3.3.1 Hunter-fisher-gatherers

One implication of the defining economic characteristic of hunter-gatherers appears to be a case where environmental variation represents a considerable factor in structuring cultural variation. Environmental variability has been frequently shown to impact central aspects of forager societies, such as economy, population dynamics and mobility patterns, which in turn can be interrelated with virtually all dimensions of these societies (e.g. Binford 1990; Bird and Codding 2008; Hoebe et al. 2023; Jørgensen 2020a; Kelly 2013; Morgan 2009; Ordonez and Riede 2022).

However, while it appears to be the case that variables such as temperature and precipitation dictate general variability among prehistoric and historic hunter-gatherers, this has to be qualified. First of all, while this appears to be the case *in general*, it can hardly be assumed to apply uniformly to any individual case (see references above and e.g. Arponen et al. 2019; Johnson 2014). Understanding precisely what consequences variation in any single environmental variable has in any given case, if any, will be complicated by both the societal and environmental systemic wholes that respond to this variation, with some systems being more or less robust to such perturbations, depending also on the time-scale over which it operates and can be recognised archaeologically. While for example drought could intuitively be taken to represent a societal challenge, this certainly need not be the case. Drought might very well present more opportunities for resource exploitation than it eliminates (Arponen et al. 2019:5–6 with further references), illustrating the point that any systemic variation, environmental or societal, can represent both threat and opportunity to systemic wholes, and simultaneously represent threat and opportunity to different parts of the systems.

The further delineation of this thesis to focus on coastal areas has some further implications for what can be expected to be variables of concern for understanding the structure of the societies dealt with, indicated by the header of this section which includes the term 'fishers'. Hunter-fisher-gatherers is a term used by some scholars to underscore the economic significance of the utilisation of aquatic resources to some hunter-gatherer groups (Cummings 2013:22–24). The term is generally meant to be used in an inclusive fashion, and can in addition to fishing thus also pertain to the exploitation of other marine resources such as marine mammals, shellfish and seabirds. Given the concentration of Mesolithic sites in the coastal areas of Norway, and the relative importance of marine resources that can be assumed from this, the term hunter-fisher-gatherer has been preferred by several scholars working with the material (e.g. Bergsvik and Hufthammer 2009; Mansrud and Persson 2018).

One reason that the coastal setting is of importance is that environments with a rich and stable access to resources has been argued by many authors to be more likely to support semi-sedentary, hierarchical foragers with higher population densities. This is found to commonly be associated with concentrated marine resources (e.g. Keeley 1988; Singh and Glowacki 2022; Smith and Codding 2021), which are associated with a higher net productivity and ecological stability, with coastal areas representing ecotones that give rise to multiple niches conductive of species diversity (e.g. Yesner et al. 1980). However, as with the role of other environmental conditions for impacting the social structure of hunter-gatherers, important variation exists within these general trends. As a consequence, Jeffrey and Lahr (2020) have argued that there has been a tendency of oversimplifying and reducing the adaptational diversity among foragers utilising aquatic resources, reminiscent of the earlier oversimplifications of hunter-gatherers in general (see also Bailey and Milner 2002; Erlandson 2001). As this study is limited to studying the developments within the coastal region of south-eastern Norway, it is not in a position to inform the question of how coastal adaptation might be conductive of other societal configurations than terrestrial adaptation. It can, however, potentially illuminate regionally internal variation in coastal adaptation over time.

A note should be made on the fact that in the literature the terms *coastal adaptation* and *coastal resource use* are sometimes taken to imply different and quite specific things (see e.g. Faulkner et al. 2021; Marean 2014; Will et al. 2019). Coastal resource use is in this understanding seen as something that is conducted sporadically or occasionally, and that has limited transformative feedback effects on the life-ways of the societies in question. Conversely, coastal adaptation involves a degree of coastal engagement and commitment that has an altering effect on these societies. I do not use the terms in this manner here. The conceptual distinction is certainly an important one, especially as marine exploitation is believed to potentially, but not necessarily (e.g. Erlandson 2001), lead to technological ratcheting and increased societal complexity. However, these quite specific connotations of the terms stand in danger of leading to misunderstandings for readers that have another understanding of adaptation, which need not be defined by some threshold in the intensity of coastal engagement. One response to the specifics of a given coastal habitat might for example be movement and extended use of terrestrial resources, which would fall within a more inclusive definition of adaptation to a given coastal environment. While the above division might have merit in some analytical settings, the dependence on marine resources is arguably better understood along a continuum that I believe this distinction might unnecessarily dichotomise.

3.3.2 Land-use and mobility patterns

As it is fundamental for subsistence search, mobility patterns is considered defining of hunter-gatherer societies (e.g. Kelly 2013:77–113; Singh and Glowacki 2022). Important characteristics related to land-use and mobility patterns is the range of movement, its frequency, the degree to which movement ranges are territorially defined, where in the landscape movement and occupation occurs, the degree to which this is related to different kinds of activities, and the degree to which these aspects varies annually, with the seasons or other temporal frequencies. Furthermore, as mobility operates at the level of individuals, the degree to which people have moved as individuals or in groups, and what kinds of people have moved is ultimately also collapsed within the mobility term (Kelly 1992). From an archaeological perspective, however, occupational duration is often considered the most important dimension of hunter-gatherer mobility (Grove 2009). This follows both from the structuring effect this has on the activities carried out by members of these societies, from its frequent correlation with a range of other indicators of societal complexity, and from the expectation that occupational duration should be reflected in characteristics of the available archaeological material. However, the role of occupational duration as either a potential pre-requisite, cause or mere covariate with other dimensions of societal complexity cannot be assumed for any given case, and is also likely to play into a complex web of interrelated societal feedback effects.

One of the most central models with which to approach past hunter-gatherer mobility follows from Binford's (1980) distinction between foragers and collectors. Foragers are generally characterised by higher residential mobility, involving the movement of all members between residential bases, while collectors are associated with a higher degree of logistic mobility, involving the temporary excursion of task-groups from more permanent residential bases to fulfil specific tasks. Binford (1980) argued that foragers are more common in environmentally homogeneous regions, while collectors are more common in regions exhibiting temporal and spatial variation in available resources.

The mid-latitude coastal setting of this thesis could thus have some general implications for what might be expected in terms of mobility patterns. Based on historically known hunter-gatherers, Binford (1990) has argued that a semi-nomadic mobility pattern dominate in higher latitude settings. This involves a reduction in residential mobility in the winter months, where settlements are established close to stable resource patches or stored foods, and foragers utilising aquatic resources will, in general, be characterised by highly logistical mobility patterns. Furthermore, Binford (1990) also argued that in higher latitude settings there is generally a lower dependence on plant foods, and a tendency for this to be replaced by the exploitation of aquatic resources, rather than terrestrial hunting and trapping. The exploitation of aquatic resources such as fish and marine mammals can in turn have implication for technological complexity, where a dependency on elaborate boating and catching technologies can follow from the challenges posed by hunting aquatic resources (e.g. Arnold 1995; Kelly 2013:127).

Lane (2014) has argued that while there is a general consensus on the heuristic value of the forager/collector distinction, he also underscores that these are the extreme ends of a continuum, as Binford (1980) also originally contended, and that most forager populations have mobility patterns that fall somewhere between these extremes. While it might very well be the case that that higher latitude hunter-fisher-gatherers are generally associated with a higher logistical as opposed to residential mobility patterns, the degree to which this has been the case and might have varied throughout the coastal Mesolithic of south-eastern Norway must still be considered undetermined. While classic treatments of hunter-gatherer mobility such as that of Binford (1990) do touch on the issue of aquatic hunter-gatherers, it has been argued that they often underestimate the implications of aquatic adaptation, and crucially the implications this has for these models to meaningfully track mobility patterns that involve traversing intricate coastlines and voyages to offshore islands using water-going vessels (see Ames 2002; Rowley-Conwy and Piper 2017; Yesner et al. 1980). However, despite the important nuances that might be subsumed within the forager–collector continuum, especially when applied to hunter-fisher-gatherers, Ames (2002) maintains its heuristic value. Consequently, the forager–collector continuum and occupational duration are aspects of mobility that are in focus for this thesis. This is the direct concern of Paper 3, which attempts to illuminate these dimensions by drawing on the composition of the lithic inventories associated with sites in the study area (Roalkvam 2022). However, as outlined above, there are still a host of dimensions to mobility that are not captured by this framework and which decidedly warrant future investigation.

3.3.3 Responses to sea-level change

In most areas of the world, post-glacial sea-level change has involved inundation of vast areas that were previously inhabited. For Europe alone, Bailey et al. (2020:2) give the estimate that around 2.5 million km^2 have been submerged following the Last Glacial Maximum, which equates to c. 40% of the present landmass. This has undoubtedly led to the destruction of vast amounts of archaeological material, and offers a considerable challenge to the retrieval of what archaeological material remains, and for efforts to reconstruct the past landscape in the impacted areas. This has been argued to have led to a reluctance on the part of archaeologists to contend with this challenging material, and to have resulted in an underestimation of the role that marine adaptation has played throughout prehistory (Bailey and Milner 2002).

As was presented in Chapter 2, unlike most areas of the world the study area for this thesis has been subject to a continuous and at times dramatic post-glacial relative sea-level fall. While methodological developments, new material and willingness to confront the issues posed by post-glacial relative sea-level rise have improved greatly in recent decades (see e.g. Bailey et al. 2020), the potential insight that can be gleaned from areas such as south-eastern Norway is therefore immense. This follows from the fact that the material has not been subject to the destruction and erosion that can follow from marine transgressions, and from the fact that retrieval of the material is comparatively easy, given that it is today located on dry land and has not been buried in thick layers of marine sediments. Mesolithic sites in the region are generally located at elevations that have historically not been impacted by the expansion of infrastructure or agriculture, and the sites are typically detectable through test-pit surveys that commonly encounter the material from c. 10–30 cm below the surface. While this has come at the cost of preservation of organic material, which is typically poor in the acidic Norwegian soils, it does, at the same time, offer a virtually unprecedented potential for mapping the distribution of a large number of sites through the relatively easily recovered lithics. Furthermore, while the reconstruction of past sea-level change is hefted with some challenges, these areas have not been impacted by the deposition of marine sediments following their emergence from the sea, which means that the landscape inhabited by Mesolithic populations is also comparatively easy to reconstruct.

Depending on its magnitude, sea-level change can impact not only the habitational suitability of any individual location, but can have far-reaching effects that impact shoreline morphology, drainage systems and oceanic circulation, in turn having a wide range of potential effects on the prehistoric societies that inhabited these areas (e.g. Åkerlund 1996; Astrup 2018; Groß et al. 2018; Vaneeckhout et al. 2012). While the at times dramatic sea-level change would have required a response from human populations residing in the impacted areas, it is by no means given that these would have negative societal effects. In fact, areas impacted by sea-level change can become increasingly attractive for hunting, fishing and gathering precisely because of these factors. Conneller et al. (2016), for example, argue that the rapidly changing coastal landscape associated with the isolation of the Channel Islands from the mainland made these especially attractive for settlement by Mesolithic populations. As with any environmental change, how sea-level change impacts the population of any given area will thus depend on a wide range of factors pertaining to the amplitude of shoreline displacement, the topographic setting, and the nature of the environmental and societal systems that respond to these changes (see references above and Barnett et al. 2020).

Sea-level regression would have had the consequences that present-day fjords would have been wider in prehistory, and other fjords, straits and waterways that are closed off today would have been present. In south-eastern Norway, the sea-level regression has impacted the shoreline morphology in various ways and at various scales. At the larger scale, the Oslo fjord itself would have been a larger bay in the early Holocene, which would, for example, have had consequences for the first human migration extending along the Norwegian coast (Glørstad 2016). Comparatively, the closing of specific straits, the forming of peninsulas by islands being connected to the mainland, or the emergence of islands from the sea might have had important consequences at a more local scale (see e.g. Mjærum 2022). Furthermore, with the emergence of land from the sea, the transition from oceanic, to littoral to terrestrial environments means that the coastal areas would have been characterised by a process of ecological change that continued also well after an area emerged from the sea (Åkerlund 1996:79; Wren et al. 2020).

Beyond impacting the physical and environmental conditions of the areas that these societies inhabited, a central premise for Norwegian Stone Age archaeology has been that people have continuously settled on or close to the shoreline throughout the Mesolithic (e.g. W. C. Brøgger 1905). This has typically been related to resource exploitation, as well as travel and communication by boat. The degree to which this settlement pattern has been constant through the Mesolithic has fundamental societal implications, given the commitment to coastal adaptation such a settlement pattern can be assumed to reflect. However, it also underlies a method known as shoreline dating. Given the premise that sites were in use when located close to shoreline, it follows that a reconstruction of the trajectory of relative sea-level change can be drawn on to assign approximate date to when the sites were in use, based on their altitude relative to the present sea-level. Shoreline dating provides a valuable dating tool that allows us to date sites where typological indicators or radiometric dates are not available, and is fundamental to the chronological framework that underlies our understanding of the Norwegian Mesolithic. The first paper of this thesis involves a more principled evaluation of the relationship between sites and sea compared to what has been done in the past (Roalkvam 2023a), and the results of this analysis were then used to develop a more formalised method for shoreline dating that is made available as an R package through the second paper of the thesis (Roalkvam 2023b).

3.3.4 Palaeodemography

Palaeodemography or the study of temporal and spatial variation in the size and structure of past populations is a fundamental problem for archaeology (e.g. Drennan et al. 2015; French et al. 2021; Kintigh et al. 2014; Shennan 2000). This follows from the fact that demography is a central factor in processes such as genetic diversification, social network structure and scaling, as well as technological innovation and accumulation – human culture is in large part determined by human interaction, which is dependent on population density.

For example, the Late Glacial and early Post Glacial colonisation attempts of southern Scandinavia is characterised by a repeated sequence of technological loss which Riede (2009) has related to demographic dynamics, drawing on Henrich's (2004) model for reduction in technological complexity with demographic collapse (see also Premo and Kuhn 2010). However, when considering the potential role of population increase or decline for societal change, it is important to consider the wider context in which these developments operate. This can be illustrated by the distinction between population density and population pressure which Keeley (1988) emphasises. Population pressure is the combined effect of population density and available critical resources. Unless there is a catastrophic demographic collapse, increased population pressure can bring about changes to socio-economic complexity as an adaptational response, for example by economic intensification or diversification, storage or exchange, or with an increase in mobility (Halstead and O'Shea 1989) – population decline is therefore not necessarily or uniformly associated with reduction or increase in societal complexity (Collard, Ruttle, et al. 2013; Riede 2014). Understanding the consequences of changes in population dynamics and population structure is thus also dependent on knowledge of the nature and scale of the demographic development, as well as factors such as economic organisation and corresponding environmental carrying capacity. As a result, the role and potential feedback effects between population dynamics and other societal dimensions is contested in the literature (see e.g. Collard, Buchanan, et al. 2013; Currie and Meneganzin 2022; Read and Andersson 2020; Vaesen 2023), and Collard et al. (2016) have cautioned that population characteristics should be considered *potential* explanatory variables for observed cultural change. It cannot be assumed *a priori* that population structure determines observed cultural variation, or that it does so in a uniform way, and so it is important that such explanations are compared, contrasted and variably included in a range of potential explanatory frameworks.

A central question in the reconstruction of population dynamics among past hunter-gatherers is related to what is known as the forager population paradox (Blurton Jones 2016). This follows from the difference between the population growth rates among recent hunter-gatherer populations, which have been found to have an annual growth rate of around 1–3 %, and those that must have characterised prehistoric hunter-gatherer populations. Gurven and Davison (2019) give the example that with a growth rate near 1% per annum, a population of 100 would reach close to modern population numbers of 7.5 billion in under 2000 years. Some processes must therefore have led to the near stationary population numbers throughout evolutionary history, which Gurven and Davison (2019) argue is likely the result of oscillating cycles of population booms and busts (see also Chamberlain 2009). By contrasting archaeological population proxies with ethnographic and historical estimates, Tallavaara and Jørgensen (2021) have demonstrated how the scale over which these oscillations operate likely imply that common archaeological population proxies only puts us in a position to track average population size over the relative long term. This in turn has implications for the kind of questions we can hope to answer concerning variable population growth rates and their consequences (e.g. Brown 2017; Sibly and Hone 2002), and has to be kept in mind if archaeologically recognisable population changes are to be contrasted with other forms of cultural or environmental variation over time (Tallavaara and Jørgensen 2021).

Inferences concerning demographic developments in Norwegian Stone Age archaeology have traditionally been done by drawing on possible archaeological correlates such as the number and density of artefacts and sites (Olsen and Alsaker 1984; Østmo 1988). Following developments in prehistoric demographic modelling more widely (e.g. Crema 2022; Crema and Bevan 2021; Shennan et al. 2013; Timpson et al. 2014), such efforts have in recent years been directed towards analysing the summed probability distributions (SPDs) of ^{14}C-dates (e.g. Jørgensen et al. 2020; Lundström 2023; Nielsen et al. 2019; Nielsen 2021a; Solheim 2020; Solheim and Persson 2018). Modelling population dynamics by use of SPDs is based on the underlying logic that more people will have resulted in deposition and later retrieval of more dateable material (also known as the dates-as-data approach, after Rick 1987). However, there are a series of methodological and conceptual issues with this procedure, some of which have been dealt with, and others which are integrated into the methodology and need to be accounted for when interpreting any results (see recent review by Crema 2022).

One fundamental methodological issue follows from procedure of summing probabilities. Several authors have pointed to the fact that this operation entails a collapse of both the frequency of events and their uncertainties, thus rendering the final SPD difficult to interpret and not suitable for direct analysis (Blackwell and Buck 2003; Carleton et al. 2018; Crema 2022; Timpson et al. 2021). Another issue pertains to the underlying logic that there is a direct connection between the magnitude of material that ends up being dated and the number of people responsible for this, and the degree to which this relationship is stable over longer periods of time and across economic and cultural systems (e.g. Freeman et al. 2018; Surovell et al. 2009).

While various solutions and ways to contend with these issues have been proposed (cf. Crema 2022), their magnitude and relevance can be difficult to properly assess for any given context without also drawing on additional data that can inform the corresponding developments of other relevant factors. Consequently, what both critics and proponents of the approach appear to agree upon is the importance of contrasting a range of population proxies while also accounting for other variables that might impact these (e.g. Attenbrow and Hiscock 2015; Palmisano et al. 2017, 2021; Rick 1987; Timpson et al. 2015; Torfing 2015). The fourth and final paper for this thesis therefore compares the frequency distribution of shoreline and radiocarbon dates over time, both of which have previously been compared for the purposes of modelling past population dynamics in Fennoscandia (Jørgensen et al. 2020; Solheim and Persson 2018; Tallavaara and Pesonen 2020). This was done both to devise a methodology for using the newly developed method of shoreline for this purpose, and with the substantive goal of starting to unpack and understand how these proxies relate and what underlying factors could be driving their relationship.

3.4 Chapter summary

The first part of this chapter has outlined how fundamental problems relating to the resolution of the archaeological record in the dimensions of time, space and material culture has been contended with in the literature and how these are approached in this thesis. The second part of the chapter outlined some of the factors that are typically viewed as central for understanding past hunter-gatherer societies, and that dimensions related to mobility patterns, responses to sea-level change and demographic developments are the ones primarily dealt with in this thesis.

Preconceived notions of what has characterised hunter-fisher-gatherer societies will at some level necessarily impact how the material under study is interrogated. This follows both from what research questions are deemed central, and because these notions will have impacted how the material has been retrieved and recorded. These notions are therefore to some degree inescapable influences on any research into the Norwegian Mesolithic. However, in the next chapter I will argue how this should not lead to epistemic despair.

Chapter 4

Model-based archaeology

Over the years, several works have purported the benefits of a model-based archaeology (e.g. Clarke 2015[1972]; Wylie 2002:91–96), which has especially gained a footing within various strands of computational, ecological and evolutionary archaeology (see e.g. Barton 2013; Brughmans 2021; Gonzalez-Perez 2018; Graham 2020; Kohler and van der Leeuw 2007; Lake 2015; Nakoinz 2018; Romanwoska 2015; Steele and Shennan 2009; Winterhalder and Smith 1992:12–16). The goal of the next two chapters is two-fold. First I will elucidate what defines or can define a model-based scientific approach, and in the following chapter I will demonstrate how this can form a useful framework for archaeological inquiry by drawing on examples from the papers of this thesis.

Central to the present chapter are four problem areas in the understanding scientific models, as identified by Frigg and Hartmann (2018): 1) The ontological: what are models? 2) The semantic: what do models represent? 3) The epistemological: how do we learn with models? And 4) what consequences do the use of models have for overarching principles such as scientific realism, reductionism and explanation?

One fairly common understanding of models simply entails seeing them as a set of simplifications or assumptions concerning real-world phenomena (e.g. Barton 2013:154). Any representation could thus be considered a model whether it is generated physically, digitally, verbally, simply imagined, or is construed in a natural or formal language. Scholars arguing the case for model-based archaeology often start out by making the point that whether we acknowledge it or not, we always employ such abstractions when attempting to understand past reality (Kohler and van der Leeuw 2007:4; Lake 2015:7). The infinite complexity of reality means that any description of it has to be a simplification, and even if we were able to, a complete rendition of reality would not be a worthwhile endeavour in its own right. A perfect reconstruction of reality would be a tautology, which without perspective offers neither insight nor understanding (Slingerland

and Collard 2012:14–19; Yarrow 2006:77). Put differently, whether we understand archaeology as tasked with providing explanation, understanding, or interesting narratives about the past, any demand for more nuance, for its own sake, would be a refutation of theory (see Healy 2017).

These are, however, universal scientific points, variations of which have been made under diverse headings of archaeological theory (see e.g. Clarke 1978:13–16; Hodder 1999:67; Kristiansen 2004:98–99), and which extend far beyond the scientific endeavour, captured by what the artist Derek Jarman (2000:320, see Figure 4.1) described as the 'intellectual imperative of abstraction'. It would thus follow that if the term model is taken to denote all generalisations or abstractions of reality, which in its ubiquity would include any description or explanation, it is not given why this would have to be dealt with within a comprehensive model-based archaeology. The arguments in favour of a distinct model-based archaeology tend to follow from *how* this necessary simplification should be embraced, and in turn handled. What this entails can be foreshadowed here by invoking the classic quote from Box (1979:2): 'All models are wrong but some are useful'. But if all models are wrong, what is their epistemic value? To begin to answer this question, the above view of models, simply seeing them as abstractions, will be accepted for now without regard for their demarcation to data, theory and hypotheses.

4.1 Confronting beliefs with data

Smith (2015:18; 2017:522) has stated that one of the most central questions we can ask about our archaeological arguments is 'How would you know if you are wrong?'. Archaeological explanation often takes the form of what Binford (1981) termed a *post hoc* accommodative argument. This involves first gathering and categorising the data of interest, often using variables chosen by convention and convenience, and then building an explanation around any discerned patterns (Clark 2009:29). This data-dredging or pattern-searching approach is argued to constitute a limited inferential framework for a couple of reasons.

First, what among the virtually infinite aspects of the material available to us is considered interesting will always be determined by our beliefs concerning the processes that have resulted in their manifestation. What characteristics of the material is recorded and drawn on to organise it will dictate what patterns one can hope to reveal. As Popper (1989:46) framed it, without an underlying theory, how would we know what to look for? If one follows what has been done conventionally, without taking any explicit stance towards this, one will be dependent on how others have conceived of what questions are of interest and how these can be answered. Furthermore, this accommodative process can never falsify our argument, and Smith (2015:19) likens it with 'the farmer who paints bulls-

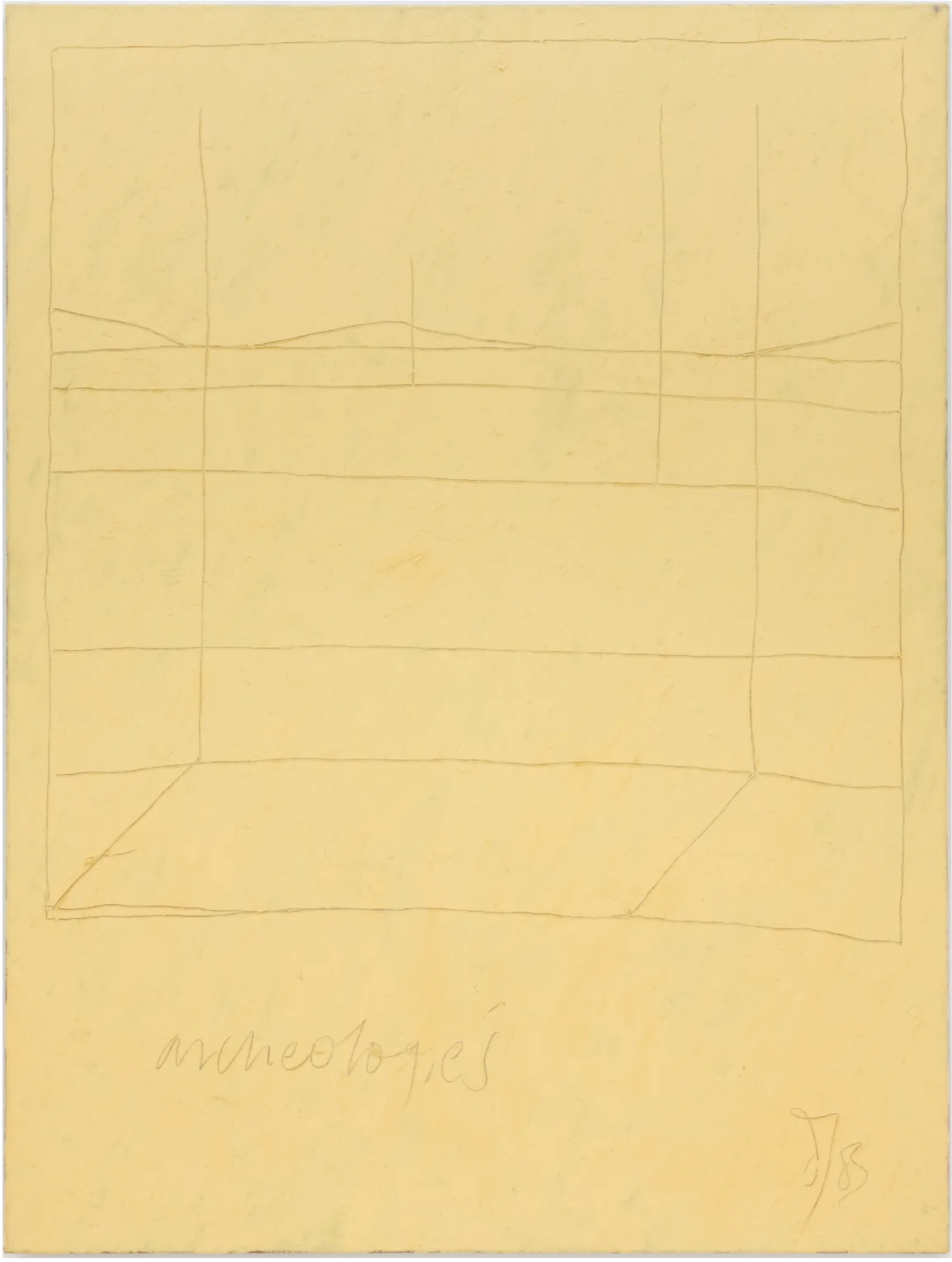

Figure 4.1: Derek Jarman, *Untitled (Yellow Painting - Archeologies)*, 1983. Oil on canvas, 134.6 x 101.6 cm.

eyes around the bullet holes in his barn in order to show his superior shooting skills.' *Post hoc* accommodative arguments can provide the identification of empirical patterns with respects to the employed units of analysis, which in turn can form the basis for social and behavioural hypotheses. But Binford (1981:85) has argued that such arguments can at best be 'treated as provocative ideas in need of evaluation'. Clark (2009:29) states that a necessary next step is to derive empirical implications of this hypothesis, which can be evaluated against a part of the archaeological record that is independent from the material originally used to derive it (also Barton 2013). Subsequent testing thereby provides an opportunity to reveal if one's accommodative belief is wrong.

The explicit testing of archaeological explanations was assertively introduced to the discipline with processualism, which argued that archaeology should adopt the explanatory goals of positivist social sciences. How this was to be done first follows from the standard processual view on what the archaeological material represents. Here, material culture was seen as an integrated part of – and the result of – total, multidimensional cultural systems (e.g. Binford 1962). As such, theories concerning how all aspects of cultural systems would influence and manifest in the material record should be conceived. Central to this is that the archaeological material represents an objective, albeit complex empirical record that reflects empirical causes, irrespective of our beliefs about what these causes are. The empirical material will in this processual understanding therefore offer a direct link back to this systemic whole. Archaeological material is representative of the multidimensional causal chain from cultural system to the archaeological record. The goal was therefore to develop theories concerning the prehistoric systemic whole and what processes have influenced the remnants available to us, which were then to be tested by drawing on the hypothetico-deductive approach. Furthermore, drawing on the deductive-nomological or covering-law framework, as taken from the logical positivist/empiricist view of Hempel (e.g. 1965), the ultimate goal was to establish laws pertaining to the conjunct occurrence of certain types of material remains with certain types of societal systems, irrespective of time and place.

It should be noted here that the programme of logical positivism, and the more mature logical empiricism (although see Uebel 2013 on this distinction), were far more nuanced that what they are often given credit for in the archaeological literature concerned with establishing why these views were misguided (Gibbon 1989:8–60). This is equally true for the over-simplified presentation that is given here. However, this can in part be justified with reference to the naive versions of these programmes that were adopted by positivist social science and archaeology at the time (Gibbon 1989:91–117).

According to Hempel (1965:231–243), the goal of science is to establish laws that are deductively valid, of the kind given by the classic example *All men are* *mortal / Socrates is a man / Therefore, Socrates is mortal.* If the premises are true, then the conclusion will always be true. However, when adapted to archaeology, the proposed laws were so banal that Flannery (1973) stated that attempts at adopting Hempelian empiricism 'has produced some of the worst archaeology on record' (see Smith 2022). The search for deterministic covering laws for societal systems was therefore abandoned by most practitioners. Furthermore, whether an argument is deductively valid or not is not dependent on whether the premises are true. If it happens to be true that all men are mortal and Socrates is a man, then the deductively valid argument is said to be sound. Determining whether the premises are true of the world depends on non-deductive reasoning. A deductively derived test that successfully corresponds with data only supports the hypothesis inductively, a point that appears to have been lost on early processualists (Chapman and Wylie 2016:27). However, giving up on the search for covering laws and deductive certainty need not entail that hypothetico-deductive testing is misguided, and more modest goals of confronting beliefs pertaining to specific contexts or research questions with data is, I will argue, still very much a viable goal.

4.1.1 Confirmation

Within a classic hypothetico-deductive system, an initial goal is to derive as many empirical implications of an explanation as possible. These implications are then to be tested by comparing these implications to actual observed data. Drawing on Carnap's (1936:425) 'gradually increasing confirmation', this entails that each time a model matches the data, the confidence that the model is true is increased. If, on the other hand, the model fails, it can be discarded as untrue. This should thus lead to the continual rejection of false models, and move us ever closer to, but not necessarily to, the actual model of reality. Although certainly an enticing prospect, there are problems related to this approach, irrespective of any goals of establishing covering laws.

A fundamental issue for hypothetico-deductivism, and scientific inference as a whole, follows from Hume's problem of induction (e.g. Ladyman 2002:31–61). As an empiricist, all knowledge about the world was for Hume derived from sensory perception. Any reasoning that extend beyond observation, past or present, is based on cause and effect. However, since we can never observe a causal connection between events, the conjoined occurrence of observations is all we have to draw on. As there is no logical necessity for regularity in patterns to hold beyond what we can observe, there is no logical foundation for inductive reasoning – there is no logical connection between the observable and unobservable. While we might observe the sun rise every day, there is no logical contradiction in believing it will not rise tomorrow. Hume held that while inductive reasoning will continue to be fundamental to science, and our every-day lives, it therefore has no logical justification. Following from the problem of induction, an issue for hypothetico-deductivism therefore pertains to the value of testing a hypothesis, and whether with successful tests our belief in the hypothesis should increase.

The logical empiricist attempts at working around the problem of induction and establishing a logical justification for confirmation was never successful, and a move to stating our beliefs in probabilistic terms never dissolved this fundamental issue. Central here is what is known as the paradoxes of confirmation (e.g. Sprenger 2023), of which Hempel's (1965:12–20) own raven paradox is a classic example (see Goodman 1984:59–83 for the so-called new problem of induction). If the hypothesis is that all ravens are black, this is logically equivalent to the statement that if something is not black it is not a raven. If we were to observe a black raven, this is evidence in support of the hypothesis. The paradox follows from the second statement: Given their logical equivalence, the observation of a green apple would be evidence in support of the hypothesis. Paradoxically then, we can study ravens by looking at apples. While problems of confirmation such as this are simple, they have proven difficult to resolve and a logically sound justification for confirmation is yet to be agreed upon (e.g. Godfrey-Smith 2003:39–56).

4.1.2 Falsification

One of the most influential contentions with the issue of testing is found with Popper and his concept of falsificationism. Popper, also a sceptic of induction, held that the problems of induction cannot be resolved. However, this is not of concern, as science in fact progresses not with confirmation but with falsification. In an attempt at demarcating science from non-science, Popper (e.g. 1989:33–66) stated that a theory can only be considered scientific if it has the potential to be refuted by observation. A theory that is compatible with all empirical variation is unscientific. The test of a hypothesis should be aimed at falsifying it, not confirming it, and an hypothesis that is not proven false should simply be subjected to even more stringent and elaborate tests. It is with each new rejection of an hypothesis that science progresses and we learn something about the world. Although it will inevitably be falsified, a good theory for Popper is therefore one that is bold, risky and corresponds with the world in surprising ways. There are, however, further issues related to the fundamental prospect of confronting our beliefs with data.

As insight from complex systems theory demonstrates, sensitivity to initial conditions can lead both different causes to produce similar empirical results, and similar causes to produce different empirical results (Premo 2010; van der Leeuw 2004:121). This reflects the problems of equifinality and underdetermination, as presented in the last chapter, where several explanations can agree on the empirical data, but disagree on the underlying causal mechanisms. This follows from the ubiquity of measuring error and the sensitivity of complex systems to minute variation. One classic example in this regard is the complex system of the weather, which can only be reliably predicted a few days into the future. Human behavioural and societal systems are often far more complex than that of the weather. Consequently, this renders the prospects of empirical confirmation or falsifiability weakened, and preference among different, even contradictory explanations can often not hope to be based on observable data. In the case of archaeology, explanatory models are additionally faced with our generalisations of an already sparse and fragmented archaeological record, further increasing the likelihood that several explanations account equally well and are underdetermined by the data at hand. However, underdetermination and sensitivity to initial conditions can also impact the assumptions underlying an explanation. To show how this is an issue we can draw on what is known as the Duhem problem (after Duhem 1954[1914]), or the Duhem-Quine thesis (following Quine 1953, and the holistic theory of testing; Psillos 1999:164), which states that nothing is necessarily learned from rejecting an hypothesis on the grounds of a test.

Drawing on Hvidsten (2014:184–187), we may postulate a simple model holding that mechanism A, under assumption B, implies C. In a test in which A occurs, it would in a hypothetico-deductive understanding increase our belief in the model if we could then reliably measure that C is true. In the case of Popper, the model is simply yet to be falsified. If, on the other hand, C is not true, this would imply that either A or B are untrue. We would not, however, be able to derive logically which of A and B are untrue. This would perhaps not appear to be an immediate reason for concern. As long as one aspect of the model is untrue, the model is untrue, and should be rejected. The problem is that we know that models always contain a multitude of untrue assumptions. Drawing on the classic quote from Box (1979) above and the earlier discussion on abstraction, all models involve subsuming the virtual infinite complexity of reality and thus cannot work without an equal amount of untrue assumptions that could impact a test (a point made in the context of archaeology by Salmon 1975).

In exemplifying the Duhem problem, Ladyman (2002:77–78) gives the example of testing Newtonian gravitational theory by observing the travel of a comet. The theory of gravity alone does not provide a prediction for this path. It also depends on factors such as the mass of the comet, the mass of other objects in the solar system, and their relative positions, velocities and initial positions, as well as Newton's other laws of motion. If the test was to fail, this failure can follow from an untrue hypothesis, but also from a misspecification of an assumption that is subsumed in the test – such as background conditions, measurement error, and initial conditions of the system. The Duhem-Quine thesis holds that any theory can be saved from refutation by adjusting its auxiliary assumptions (Psillos 1999:165).

At some level a decision of whether the explanation has in fact been interfaced with observation is therefore needed. As stated by Ladyman (2002:80), 'falsification is only possible in science if there is intersubjective agreement among scientists about what is being tested.' While a severely complicating issue for falsificationism, as Popper also recognised, his proposition still holds if it is qualified by stating that for a hypothesis to be scientific, it has to have the potential to be refuted by some kind of observation. The challenge is determining what kind of observation this is (Godfrey-Smith 2003:66).

Drawing on this issue with testing and falsificationism, several authors have argued that these logical inferential schemas do not capture how science has actually progressed. This view can be related to naturalism, which can be conceived of as a perspective where philosophy of science should not be concerned with establishing universal, logically justified formalistic schema for how science should be conducted at remove from the scientific enterprise itself. In a naturalistic view, philosophy of science should rather draw on and be a continuation of scientific ideas themselves (Godfrey-Smith 2003:149–162). While formalistic logic can provide some important insights on what *can* constitute good components of strategies for scientific inquiry, such as aspects of Poppers falsificiationism, the scientific undertaking has been argued to be a far messier enterprise, where attempts at establishing a universal logical inferential foundation is doomed to fail. As a practical example, the orbit of Mercury was not properly accounted for by Newtonian gravitational theory. While this was known for many years, it was not until Einstein's theory of gravity that this orbit was correctly predicted (Ladyman 2002:89). Despite being unable to predict the orbit of Mercury, and thus being falsified, this did not cause the abandonment of Newton's theory of gravity.

Examples illustrating this point can easily be found in archaeology as well. For example, when new dates that dramatically push back the earliest human occupation in the Americas have been presented over the years (e.g. Holen et al. 2017; Parenti et al. 1991, 2018), these have often been met with scepticism as related to their veracity, and geological and other non-anthropogenic alternative explanations have been proposed (e.g. Agnolín and Agnolín 2023; Braje et al. 2017; Magnani et al. 2019). How convincing an explanation is and what causes it to be abandoned thus clearly depends on more than data alone, not least because data is more than a simple binary category that is either observed/not observed. What data is accepted, what it is understood to represent, and if it is adequately confronted with a hypothesis is in part dependent on a decision by the person who observes and the wider research community. What we observe should to some degree dictate what we believe about the world. However, the examples above demonstrate that stringent empiricism is untenable and is not in fact how scientific insight is achieved.

4.2 Instrumentalism and scientific realism

Arguments such as those presented above have in sum rendered suspect a unidimensional absolute demand for adherence to observable data and presents a significant challenge to the prospect of testing our beliefs about the world. This realisation also underlies common understandings of the virtues of a model-based archaeology, in which a search for the true model of the world should be abandoned. Rather than assessing the correspondence between model and the world, the concern is rather with assessing the degree to which the mechanisms of concern correspond with the world (Kohler and van der Leeuw 2007). However, if we are to concede to the fact that all models are wrong, how can we ever trust model-based inference?

In a classical instrumental understanding, the goal of science should be the prediction of phenomena that matter (e.g. Hausman 1998:187–190), a view famously forwarded by Friedman (2008[1953]). Whether prediction is achieved through the use of models that build on true causal mechanisms or not is irrelevant. As long as the predictions of the model has a satisfactory correspondence with the empirical variation of interest, it is deemed a success. This view is therefore compatible with the constraining realisation that all models are wrong, both because the truth of postulated causal mechanisms in and of itself does not matter, and because of the resulting relaxed demand for accordance with total empirical variation – degree of empirical correspondence determines the choice between models.

Related views have also been advanced within archaeology. The clearest example can be found in the domain of archaeological 'predictive' modelling, concerned with understanding where archaeological sites are located in the landscape (e.g. Verhagen and Whitley 2012). These studies have sometimes focused on identifying where sites are located in the present-day landscape, irrespective of past motivations, so as to potentially reduce costs of land-development, or to help guide archaeological surveys in large areas where a complete coverage of the landscape is not possible. The concern then is knowing where sites are and are not located, not why.

However, one of the criticisms forwarded towards instrumentalism is that if the ultimate goal is manipulation of relevant variables for the improvement of society, this will depend on uncovering true causal mechanisms. While mere prediction depends on stable correlation, control necessitates causality (Hausman 1998:190). As Elster (2015:18) puts it, explanation demands causation, and causation can never be revealed solely through prediction (see also Gibbon 1989:49). One way to conceive of causality is as dependent on a time-ordered counter-factual condition (e.g. Lewis 1974; Morgan and Winship 2015:4–6; but see also Pearl 2009), simply stated as A causes C if when A occurs then C occurs, and if A does not occur then neither does C. Instrumentalism and a focus on prediction and stable correlation can therefore never hope to explain social phenomena (see also Lake 2015:23–24). Of course, causal explanation does not necessarily have to be the main concern for archaeology. One could argue that academic interest in causal explanation should not always be the guiding principle behind archaeological inquiry but rather, for example, that mitigating costs associated with land-development or assembling interesting and poetic, albeit more speculative narratives about the past can be more important goals. My view in this context, as stated in the introduction to the thesis, follows from a form of realist understanding, where scientific inquiry is as a strategy by which we try to confront theoretical constructs with empirical observation, aimed at aligning our beliefs as reliably as possible with what is true (Godfrey-Smith 2003:161), where the ultimate aim is to answer why something we believe to be true has occurred.

Scientific realism has been the dominating perspective in philosophy of science for decades (Preston 2013:7), and so an enormous range of different realist positions exists (e.g. Psillos 1999). At its core, scientific realism is typically taken to entail the philosophical stance that there exist real observable and unobservable entities and properties, and that claims concerning the veracity of either dimension cannot be set apart (Gibbon 1989:142–172; Psillos 1999; Wylie 2002:97–105). The goal is to reveal these truths, where truth typically follows a commonsensical definition of being determined by what is the case, and not, for example, what we believe to be true or what is most beneficial (Ladyman 2002:157–158; see also Malnes 2012:19–30). Regardless of whether or not it is possible to ever achieve, the goal of the realist is to reveal true, or approximately true (Psillos 1999:261–279), yet unobservable causal mechanisms that generate and shape the flux of observable phenomena. Scientific realism thus combines causal explanatory goals with ontological theses concerning the existence of observables and unobservables, and epistemological postulates on the possibility of gaining evidence for unobservables (Hausman 1998:191).

In a realist view, even the most careful empirical approach depends on theoretical assumptions that will determine what hypotheses are deemed relevant, what evidence empirical data are believed to represent, and how these are evaluated against hypotheses (Wylie 2002:100). With the early post-processual critique of processualism, Hodder (1984) argued that objective data is never tested against separate independent theories. These theories already underlie and determine how the archaeological material is recorded – there is no theory-free data. To the realist, however, the realisation that we might view the world differently does not take away from the belief that we inhabit a common reality that exists and is true independently of what we think about it (Godfrey-Smith 2003:174). Shanks and Tilley (1987:111) stated that 'there is literally nothing outside of theory' as archaeologists, according to Hodder (1983:6) simply 'create facts' (cited by Wylie and Chapman 2015:6), echoing Shapin and Schaffer (1985:355): ‘it is ourselves and not reality that is responsible for what we know.’ This, however, is a false dichotomy. As human knowledge is a part of reality, not something outside of it, it is better to understand human knowledge as the result of both ourselves and the world (Godfrey-Smith 2003:132; see also Hodder 1999:51–52). By extension, and by drawing on Fodor (1984), Godfrey-Smith (2003:158–162) states that it is not enough to say that observation is theory-laden. The challenge is determining what theories influence observation, how they do so, and how reality manifests in observation.

As an extension of this view, the form of feminist empiricist perspective advocated by Longino (e.g. 1990) through her ‘contextual empiricism’ follows from treating the social group as the foundational scientific unit. What constitutes a good explanation in a field of research is determined by the varying views and non-coercive consensus that is reached on these issues at the level of the research community. As we view the world differently, what ideas are brought to bear on an issue, and a decision of whether a theory has been adequately interfaced with data will thus follow from the diversity of that community. This is thus related to aspects of Mill’s (2018[1859]) 'marketplace of ideas' (e.g. Gordon 1997) and Feyerabend’s (1970) 'proliferation of ideas' as scientific virtues (Godfrey-Smith 2003:114). While there is a danger of simplistic generalisations of how, for example, sex differences influences how one views the world (Longino 1990:187–188), a healthy state for a research community would thus be one where a multiplicity of marginalised and privileged groups are represented.

4.3 What are models?

Building on the above, we can return to the issue of scientific models. While the classic hypothetico-deductive framework in a sense sees every model as a truth-candidate, they are for advocates of a model-based archaeology instead often understood as ‘pieces of machinery that relate observations to theoretical ideas’ (Clarke 2015[1972]:1). A similar view can be found with Morrison and Morgan’s (1999) view of ‘models as mediators’, where a model is a concrete or explicit representation of observables and theoretical beliefs and allows for a confrontation between these two dimensions. This is very much in line with the model as envisaged by Kohler and van der Leeuw (2007), who sees them as constructions that have similarities with, but exist independently of the target systems that they are to represent. Models are constructions used to draw further inferences about the reality they are to represent and are construed on the basis of what mechanisms we believe shaped the observables available to us. The hope is that when confronted with the world, the mechanisms of the model that the researcher is interested in correspond with those of the target system.

To explicate the concept of models as mediators, it can be useful to think in terms of an epistemological hierarchy, extending from observations to high-level theory. In a Mertonian view (Merton 1968), this extends from day-to-day working hypothesis of what data represents, to middle-range theories that act as bridging concept for casting these within more comprehensive high-level social theories (e.g. Raab and Goodyear 1984; Smith 2015:22; see also Lucas 2015 for nuances on this). High-level theories can in this view be understood as 'overall perspectives from which one sees and interprets the world' (Abend 2008:179), with examples frequently encountered in archaeology being practice theory, cultural evolutionary theory, and so on. Popper (1989) was concerned with establishing how Marxism and Freudian psychoanalysis were unscientific, as they are compatible will all empirical variation. However, Godfrey-Smith (2003:71) holds that attempts at determining whether Marxism is scientific or not is a mistake. Rather, a given instantiation of Marxism – a Marxist model in the view taken here – should risk exposure to observation and have the potential to be falsified in a given context. One way to see models is thus as bridging concepts representing concrete instantiations of abstract theories, and as machinery for casting data as evidence to be confronted with these theoretical constructs.

In a realist conception of models, these can thus be seen as analytical tools, the purpose of which is to provide a concrete representation of the researchers beliefs, used to isolate or create a closed and credible surrogate system where causal mechanisms are allowed to work without impediment from surrounding noise (see e.g. Cartwright 2009; Mäki 2009; Sugden 2000; Sugden 2009 for discussion and variations on this). The aim, according to Cartwright (2009), is to reveal the capacities and differential contributions of unimpeded causal effects within such an idealised structure. However, this does not mean that the causal contribution is necessarily stable outside the surrogate system. In an open target system, the complex interplay of several causal mechanism can render the contribution from the modelled causal effects completely transformed, compared to their role in an idealised surrogate system (Gibbon 1989:150). Although stable correlations can point to the possible existence of a causal relationship, the relevance of the realist study of capacities, unlike positivist regularities, does not presuppose closed target systems (Groff 2004:12–16). Positivism can be seen as necessitating a closed system with regular conjunctions between events, such that an event of type A is always followed by an event of type B (Gibbon 1989:149). Cartwright (2009) contends that even though the realist surrogate system is credible, in the sense that the mechanisms could conceivably occur and result in the phenomena in question, the system is almost always different from all real cases in ways that matter. Drawing on the oft-invoked *ceteris paribus* statement – all other things are in fact not equal (cf. Cartwright 1983:44–77) – all models are wrong. The confrontation of model and data can therefore never avoid the problems of induction, and the question of interest then is not whether the model is true or false, but if the model resembles the world in the relevant dimensions, given its purpose (Clarke and Primo 2007:747; Kohler and van der Leeuw 2007:3).

For all the ambiguities nested in the above account of what can be taken to constitute models, a central element is the view that they are constructed and explicit representations of our beliefs. Precisely this is also central to the contention that one of the most important aspect of model-based approaches follow from their explorative side (Aydinonat 2007; Hausman 1992:77; Premo 2010). This results both from the assembly process itself, and from subsequent probing and manipulation of the model (Morrison and Morgan 1999). In the initial construction of a representation of theory and data, the researcher is forced to concretise their assumptions and beliefs. This will likely lead to the adjustment of inconsistencies, the discovery of additional theoretical implications or relevant empirical patterns and increase the opportunity for explicit handling and reporting of uncertainty. Through stringent and explicit aggregation of model features, further theoretical and empirical consequences are also likely to be revealed. Thus, in its construction, the model will already have provided valuable insights, regardless of its future archaeological life-span.

Following its construction, further insight can be achieved through direct manipulation of model parameters and assumptions (Morrison and Morgan 1999:32–35). This holds the potential of revealing additional causal propensities and limitations that are difficult to reveal by passive study of the model, and can reveal how sensitive it is to such adjustments (Gibbard and Varian 1978; Premo 2010). It has been argued that the potential of mathematical and computational models to stringently and coherently aggregate a multitude of mechanisms, and allow these to dynamically interact over time means that these can reveal unnoticed or counter-intuitive aggregate effects (Aydinonat 2007; Lake 2014, 2015), in effect generating new evidence that could not be discerned otherwise (Wylie 2017). The same exploratory potential is then extended by any attempts at evaluating the correspondence between model and target system, and by the involvement of an audience that comments, criticises, dismisses or helps align model and target system (Mäki 2009).

This explorative side of models can also be related to the realist concern with explanation, and not merely emulation and prediction, which has been emphasised by several advocates of model-based archaeology (e.g. Lake 2015:23–24; Premo 2005, 2010). An emulative adjustment of model parameters until the model acquires an adequate fit to the original data under study, followed by an assessment of the ability of the model to predict independent data, could result in a sufficient result from an instrumental view. However, the issues of equifinality and underdetermination underlies a view in which emulation of a process that accounts for the empirical variation of interest is not an satisfactory inferential aim if the goal is to reach true explanations of the past. As multiple processes could likely account for the empirical patterns under study, mere emulation does not inform what and how many competing explanations could be viable alternatives, and does not provide any basis for evaluating the probability that a proposed explanation should have resulted in the observed outcome. Consequently, an experimental approach has been advocated, in which a range of competing models are to be compared with an aim to assess their sensitivity to perturbations and parameter inclusion, exclusion and adjustments (see Lake 2015). Some structuring principles that can underlie such an experimental approach, and what criteria can be drawn on to adjudicate between competing models, can be approached with reference to the concepts of explanatory power and inference to the best explanation.

4.4 Inference to the best explanation

So far induction has here been used to denote all non-deductive reasoning and been exemplified by what is sometimes termed its enumerative or statistical form. That is, induction as the repeated observation of conjoined phenomena. However, other forms of non-deductive inference exist. Archaeology is often concerned with explaining singular or infrequent events, and not generalisations where an appeal to enumerative induction is possible. Clearly then, other lines of reasoning can be drawn on to arrive at and choose between alternative explanations. One such form of inference has been variably labelled abduction, explanatory inference or inference to the best explanation (Godfrey-Smith 2003:39–44; Harman 1965; Lipton 1991). Lipton (1991:58) formulates this mode of inference simply as 'Given our data and background beliefs, we infer what would, if true, provide the best of the competing explanations we can generate of those data.' (Fogelin 2007:604). Scientific realists often lean on this mode of inference to provide a way around the problems of induction and underdetermination (Psillos 1999:162–182), and this has been argued to constitute a good and often inadvertently employed framework for archaeological inquiry (e.g. Campanaro 2021; Fogelin 2007).

Fogelin (2007) argues that despite the theoretical differences that exists among archaeologists, inference to the best explanation is often the logic underlying their conclusions. For example, he demonstrates how when providing an explanation for smudge pits, a common archaeological feature in Eastern United States, Binford (1967) draws on ethnographic analogy to arrive at an explanation that is better than any alternative explanations he can muster (Fogelin 2007:611–612). Despite using deductive-nomological language, Binford never independently tests any deductively derived hypothesis, and he arrives at his conclusion, Fogelin (2007:612) argues, because it is the explanation among the alternatives that corresponds with the widest breadth of relevant empirical data. Similarly, Hodder (1991), after having abandoned his most relativistic stance, adopts what he terms a 'guarded objectivity' through an appeal to hermeneutics. This starts with the context of the archaeologists themselves and their pre-existing beliefs and underlying theories, which is opposed to the context of the people responsible for the archaeological material available to us. By moving back and forth between such context and trying to cast our data in the light of these, the goal is to adjust an interpretative whole until the two contexts coalesce. The process is thus one of iteratively fitting empirical pieces within an interpretative whole, that is at the same time adjusted by these pieces. In this framework 'We measure our success in this enmeshing of theory and data (our context and their context) in terms of how much of the data is accounted for by our hypothesis in comparison to other hypotheses.' (Hodder 1991:8). This is arguably also an appeal to inference to the best explanation (Fogelin 2007:612–614).

Central here is, as above, that hypotheses have been argued to be best evaluated when comparing them to the ability of substantive competing alternatives to fulfil the same purpose, and not just their negation, the null-model (e.g. Perreault 2019:1–22; Smith 2015; Wylie 2002:95). Pitching alternatives against each other will lead away from a pure search for corroborative evidence for a single hypothesis, and will, following from Chamberlin's (1897) 'method of multiple working hypotheses', help the researcher avoid 'a pressing of the theory to make it fit the facts and a pressing of the facts to make them fit the theory' (Chamberlin 1897:843; see also Betts et al. 2021; Platt 1964). This thus avoids one of the dangers of emulation and *post hoc* accommodative arguments, which has been argued to lead to explanatory complacency and personal attachment to individual explanations (Smith 2015; see also Elster 2015:12).

However, if one arrives at hypotheses that account for the data equally well, that is, they are underdetermined, then other criteria will dictate what is the best choice among them. These are often termed theoretical virtues, which when combined is to capture the explanatory power of a hypothesis (Psillos 1999:171). A first criteria pertains to explanation, where a realist would hold that a hypothesis that makes claims about what has caused an empirical pattern will be given preference over an hypothesis that does not. If a locational model says that sites tend to be located close to rivers, and another explains this with reference to a specific kind of resource exploitation practice, then the second hypothesis would be given preference. Apart from the realist goal of explanation, this follows from the additional empirical implications this causal explanation holds, thus potentially increasing its explanatory breadth and increasing its falsifiability. From a

Popperian view, it is riskier. Other and interrelated virtues pertain to coherence with established theories, the power of an explanation to unify multiple theories in a unified whole, the consilience of multiple lines of evidence, lack of *ad hoc* explanatory features, and ability to generate novel predictions (Psillos 1999:171). Simplicity is also often held to be one such theoretical virtue (Fogelin 2007; also discussed by Lake 2015), although it is not necessarily clear why truth should be simple rather than complex (Godfrey-Smith 2003; see also Sober 2015).

4.5 Evidential scaffolding

Theoretical discussions in archaeology have often framed the field as situated at extremes of positivism and relativism, or humanistic and scientific ideals, harking back to Snow's (1959) distinction between 'The Two Cultures' in western academia (e.g. Earle and Preucel 1987; Sørensen 2017). However, Chapman and Wylie (2016) and others (see below and Fogelin 2007 above) have argued that this perspective does not inform how archaeology has in fact progressed, nor that it constitutes a good reference frame for understanding how to do good archaeology. This is not to say that these discussions cannot hold important points for elucidating the nature of our inferential frameworks, or that theoretical stances do not influence what questions are deemed of interest and how the material record is approached. Rather, this then in a sense naturalistic argument is that these discussions are over-simplified, hyperbole and largely unrepresentative of an archaeology that generally progresses by drawing on a far more complex and eclectic web of theoretical and philosophical influences (see also e.g. Hegmon 2003; Johnson 2006; Pearce 2011; Pétursdóttir and Olsen 2018; Preston 2013). Therefore, the extremes of insisting on trying to establish deductively certain knowledge or a whole-sale rejection of the possibility of ever moving beyond speculation does not represent an adequate reference frame for understanding what constitutes good archaeology, how to conduct it, nor how consensus and synthesis on claims about the past have been arrived at.

Given the realisation that we lack an infallible logical foundation with which to establish explanations, Chapman and Wylie (2016) speak for an iterative epistemological process where a temporary scaffolding for how data is cast as evidence by drawing on multiple methodologies and lines of reasoning is continuously adjusted, extended and reassembled. Crucially, these scaffolds are to be subjected to critical reflexivity, but be grounded in domain-specific norms of what constitutes evidence, so as to tackle what Binford (1981:21) presented as the challenge of 'how to keep our feet on the "empirical" ground and our heads in the "theoretical" sky.' (Chapman and Wylie 2016:8). They further draw on Norton (2003) to argue that progression in science has been achieved mainly through the domain-specific development of robust reference frames for grounding further inference, not through the development of increasingly sophisticated universal inferential schemas (Chapman and Wylie 2016:39).

By drawing on Toulmin (1958:213), who argues that we should 'abandon the ideal of analytic argument' and the goal of deductive certainty, a central component of Chapman and Wylie's (2016:36–37) argument is illustrated by a quote from Toulmin (1958:248):

> 'The proper course for epistemology is neither to embrace nor to armour oneself against scepticism, but to moderate one's ambitions – demanding of argument and claims of knowledge in any field not that they should measure up against analytic standards but, more realistically, that they shall achieve whatever sort of cogency or well-foundedness that can relevantly be asked for in that field.'

Important here is therefore that there is no universal recipe for inferential adequacy, but that inference is domain specific. What we can hope to achieve is that our inferences are credible, but this limitation should not entail a regress into wholesale scepticism. The goal is to arrive at beliefs that are more reasonable to trust than doubt, without demanding that they should be infallible and beyond critical scrutiny.

Building on the theoretical plurality of archaeology, and echoing the point made by Godfrey-Smith (2003) referenced above, Chapman and Wylie (2016:41–43) argue that theory-ladenness will differentially impact what archaeologists consider evidence. Some biophysical observations will be relatively transferable between contexts, and their role as archaeological evidence less integrated with theoretical preconceptions. Inferences to do with symbolic behaviour are less transferable as they will be less secure, and more contingent on the given cultural context and the evidential scaffolding supporting them to be considered evidentially adequate. However, this does not mean that symbolic behaviour is in any sense more off-limits than for example chronological inferences that draw on radiometric dating. Neither can reach deductive certainty, and their role as evidence for past events is simply differentially dependent on the warrants and assumptions that underlie them (Chapman and Wylie 2016:42).

While the inferential virtues outlined in the section above can constitute some guiding principles for how to arrive at good explanations, Chapman and Wylie (2016) hold that these cannot be schematically and universally brought to bear on archaeological explanation. Different questions will necessitate different evidence, and different evidence will necessitate different warrants. What Wylie (Chapman and Wylie 2016; 2017) has held as a central component of evidential scaffolding is that these should be robust and draw on multiple lines of evidence. In his review of Chapman and Wylie (2016), Currie (2017a) likens this with the view of Cartwright (2015) who prefers arguments that are 'short, stocky and tangled' over elegant and tidy arguments that are 'tall and skinny'. That is, at the price of complication, a diverse and broad evidential foundation is more secure than an elegant but fragile chain of evidential premises (see also Bayliss and Whittle 2015; Currie 2017b).

4.6 Quantitative archaeology and models

The understanding of archaeological inquiry outlined above need not be cast within a model-based understanding. The term model has been noted to increasingly involve aspects that were previously seen as a domain of theory (Preston 2013:10), and aspects of their role as conceived of here also relate to and cannot necessarily be set apart from other concepts for bridging data and beliefs, such as hermeneutics, Mertonian middle-range theory and evidential scaffolding. Furthermore, it has also been argued that models are best understood as a separate and distinct kind of reasoning (Godfrey-Smith 2009) and that models should not be conflated with all kinds of 'representational vehicles' (Godfrey-Smith 2003:186–189).

However, despite its ambiguities, I still believe the model term offers a sensible way of thinking about the issues dealt with in thesis. It forces a view where explanations are cast as fallible explicit constructs, which are thus both more easily interrogated, and are less likely to lead to explanatory complacency. Furthermore, this concretisation and fallibility is also very much compatible with the ideals of open science. Precise and explicit constructs of our beliefs as interrogative machinery lends itself well to a transparent and cumulative research endeavour as these are more readily communicated and disseminated.

Furthermore, this view also directly maps on to developments in statistics, where a model-based framework has been argued to constitute a better and increasingly more dominating framework than the traditional null-hypothesis significance testing (NHST) approach, which has dominated much of the discipline for the last century or so (e.g. Burnham and Anderson 2002:1–22; McElreath 2020:1–17; Rodgers 2010). To briefly run through this argument, the epistemological basis for NHST starts with assuming a null hypothesis under which chance alone has generated the data, or that there is no meaningful difference between two compared groups beyond that which chance has caused. If under some statistical model the observed data is found to be unlikely to be in compliance with this null hypothesis, then the alternative hypothesis, that of the researcher, is favoured. Many authors have pointed to the severe limitations of this approach over the years (e.g. Cohen 1994; Rozeboom 1960) – a critique that has garnered renewed vigour with the replication crisis that has impacted large swathes of the social sciences (e.g.

Nuzzo 2014; Wasserstein and Lazar 2016).

Some of the central issues include that rejecting the null hypothesis does not give logical support to the alternative, nor does failing to reject the null give logical support to the null. Multiple random or neutral processes can be responsible for the data, and data inconsistent with chance can be the result of multiple non-random processes – a decision concerning the rejection of the null therefore gives limited, if any, explanatory insight. This follows from what is considered the backwards logic of NHST, as it evaluates the probability of the data given the hypothesis, not the probability of the hypothesis given the data. The probability therefore does not concern the veracity of the hypotheses themselves. Additionally, a large enough sample size will always lead to a rejection of the null (Cohen 1994). As Tukey (1991:100) put it 'the effects of A and B are always different – in some decimal place – for any A and B. Thus asking "Are the effects of A and B different?" is foolish'. Statistical significance is not equivalent to substantive significance, as the magnitude of the probability associated with a NHST test does not necessarily have any bearing on the size, importance, or lack thereof, of a substantive effect. Furthermore, this kind of dichotomised view of significant/non-significant is argued to often be equated to the truth of an hypothesis, and once a result is reached, subsequent substantive interpretations can quickly extend beyond what the significance test itself warrants (see Crema 2022; Timpson et al. 2021 on this point in the context of demographic modelling in archaeology).

Some measures to counteract these issues is an increased focus on estimation and fuller reporting of statistical power, effect-sizes and confidence intervals, as well as a focus on explicating the processes we believe underlie the data. This is argued to be facilitated by a model-based statistical understanding, an understanding that Rodgers (2010:1) argues underlies a 'quiet methodological revolution' in statistics. He illustrates the concept by example of the arithmetic mean of a distribution (Rodgers 2010:4). Under the NHTS this is typically denoted as a descriptive statistic. In a modelling understanding, the mean can instead be conceived of as one of many possible mathematical models for the data, with the mean being a representation of the central tendency of a distribution. The shift to a model-based perspective leads to the questions of whether this model achieves what the researcher is interested in, and whether it does so better than its reasonable competitors, which in the case of the mean could be the median (Rodgers 2010). Put differently, the map is never the territory, but a highly abstract model such as the subway map can prove very useful for the purposes of commuting, and more useful for commuting than a topographic map (Clarke and Primo 2007:742). Echoing the point made above, we should therefore not evaluate our models against a null model, its negation, we should instead cast it against alternative models for fulfilling the same purpose.

The importance of estimation and model evaluation over significance testing has also been promoted in archaeology over the years (e.g. Buck et al. 1996; Cowgill 1977), and a concern with multi-model inference and model comparison is increasingly evident in the literature (e.g. Crema and Shoda 2021; DiNapoli et al. 2021; Eve and Crema 2014; Jørgensen 2020b; Timpson et al. 2021). In a similar vein to Rodgers (2010), Kohler and van der Leeuw (2007:3) have argued that a drift towards model-based inference has also been quietly happening in archaeology. Furthermore, given the view that the goal is to compare the explanatory power of viable alternatives, not focus on building and corroborating single monolithic explanations, this model-based view is also compatible with Fogelin's (2007) argument that in practice, abduction is the form of reasoning that underlies most archaeological inference, whether this is acknowledged or not.

4.7 Chapter summary

In closing, the model-based understanding outlined here builds on the realisation that data is influenced both by the world and what we believe about it, and that the fallible beliefs we have about the world are built by entire research communities over time. Furthermore, this model-based understanding not only involves the recognition of the necessity of simplification, but is, to repeat Jarman (2000:320), to 'embrace the intellectual imperative of abstraction'. As fallible constructs, the goal is to arrive at a model that is better than any competitors we can muster, not ones that are deductively certain. By extension, a model-based approach is therefore concerned with being transparent and precise in the arguments and assumptions that are being made, and therefore represents a strategy that both helps the modeller clarify their inferential framework to themselves, and facilitates critical engagement by others. Furthermore, as was indicated towards the end of this chapter, casting our questions in this light is also directly compatible with a wealth of techniques in quantitative research more broadly, in which an increasingly model-based understanding recognises and helps handle and make explicit the subjectivity, ambiguity and uncertainty in our proposed explanations (e.g. Flora 2018; McElreath 2020). In the next chapter, each paper of the thesis will be presented in light of the perspectives presented here.

Chapter 5

Modelling the Norwegian Mesolithic

The last chapter laid out the foundation for what can constitute components of a model-based archaeology. This chapter will explore some ways in which casting the papers of the thesis in this light can help elucidate assumptions and further lines of inquiry associated with the arguments and empirical patterns identified in the papers.

The central empirical patterns and modelling efforts for the papers are presented in Figure 5.1. These are presented in simplified form to represent a point of departure for this chapter. A range of ambiguities, nuance and questions concerning the reliability of the results are presented in more detail below.

Figure 5.1A gives the gamma distribution describing the vertical relationship between Mesolithic sites and the contemporaneous shoreline in the study region. This underlies the method for shoreline dating that is proposed in Paper 1 and 2. Figure 5.1B presents the variation in what is termed a curation index derived in the third paper. Higher values on this index is suggested to reflect a higher degree of residential mobility. The logistic model in Figure 5.1C describes the temporal frequency distribution of radiocarbon dates within the study area, which is proposed to mainly reflect overall population dynamics. Figure 5.1D presents an exponential model fit to the summed probability of shoreline dates from the study area. The model is rejected, meaning that although it was the best of the explored alternatives, it does not adequately capture this development. Albeit somewhat provisionally, the temporal distribution of shoreline dated sites is suggested to be influenced by population density but be most heavily determined by variation in mobility patterns.

In the following, the evidential foundations and inferential leaps that underlie the archaeological claims made in the papers are first explicated by presenting each paper using an evidential argument schema (Chapman and Wylie 2016; Toulmin

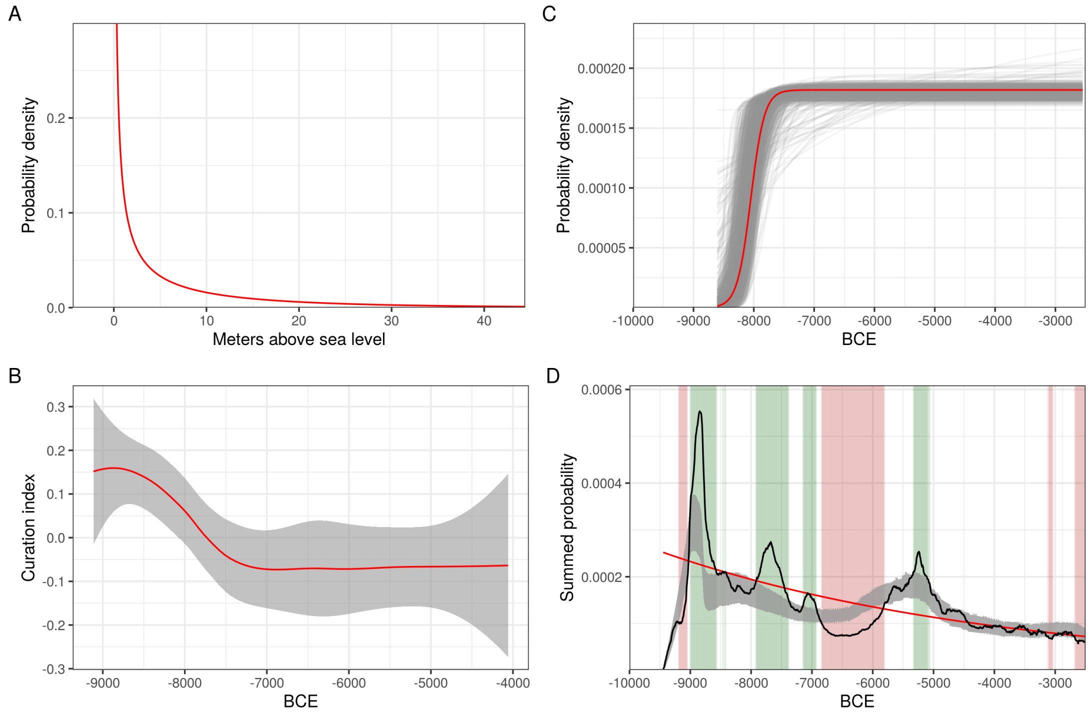

Figure 5.1: Models derived in the papers of the thesis. For clarity in the figures, the data underlying the models are left out. This is with the exception of for D, as this model was rejected as adequately explaining the data. A) The gamma distribution used to describe the likely elevation of sites older than 2500 BCE above the contemporenous sea-level within the study area (Paper 1 and 2). B) The average of 1000 LOESS curves and 95% confidence intervals fit to the curation index that is used to characterise lithic inventories within a subsection of the study area (Paper 3). C) Logistic model (red line) fit by maximum likelihood (ML) and 1000 samples from the joint posterior parameter distribution derived through Markov chain Monte Carlo sampling (grey lines, see Timpson et al. 2021), describing the summed probability distribution of radiocarbon dates from within the study area (Paper 4). D) The rejected exponential function (red line) fit by ML describing the summed probability distribution of shoreline dates (black line) within the study area (Paper 4). Deviations from the 95% critcal envelope derived from the exponential model through Monte Carlo simulation is given a red colour for negative deviation and green for positive.

1958). Subsequently, a causal model for the main components of each paper is presented in the form of directed acyclic graphs (DAGs, e.g. Morgan and Winship 2015; Pearl 2009). These outline some substantive explanations that I believe might underlie the patterns that are observed in each paper, with the purpose of identifying some implications and avenues along which the results can be further interrogated in the future. First, therefore, the concepts of evidential argument schemas and graphical causal models are given a brief presention.

5.1 Evidential argument schema

The presentation of each paper below starts with laying out an evidential argument schema for the central evidential claims being made in the papers. The purpose of this is to clarify the argument being made, highlight central and potential objections and uncertainties, ways in which the study account for these, and ways in which this could be further investigated and improved in future studies. The components of the argument schemas are presented in Figure 5.2.

Following Toulmin (1958), 'warrants' are here understood as bridging concepts that allows one to move from observed data to substantive evidential claim. Warrants are in themselves claims that 'license the inference from facts to conclusions' (Chapman and Wylie 2016:34) that therefore also depend on underlying substantive, domain-specific arguments. All claims, including warrants, can in turn be challenged by 'rebuttals', which represent potential exceptions or objections to the claims being made. To maintain the inferential claim, rebuttals can in turn be answered with additional theoretical support and evidence, termed 'backing'.

Some adjustments to this framework have been made here. First, I have added the category 'potential backing'. These are meant to indicate steps that might be taken in future studies to further accommodate rebuttals and strengthen the belief that the warrants hold. Secondly, drawing on Chapman and Wylie (2016:176), the category 'deflection' indicates cases where I argue that rebuttals can be disregarded due to an assumed limited impact and relevance. That is, in these cases the rebuttals are not met with additional backing. Finally, the category 'qualifiers' from Figure 5.3 is not included, as there were as of yet no grounds on which to properly assess the strength of the evidential claims being made in the papers.

In the presentation of the papers below, these schemas will not be complete, but draw on what I view as the most central components of the arguments. Further nuances and caveats can be found in prose in the papers themselves, while the data and code published with each paper also offer further sources that can be scrutinised for additional underlying assumptions and potential inconsistencies (see Section 1.4).

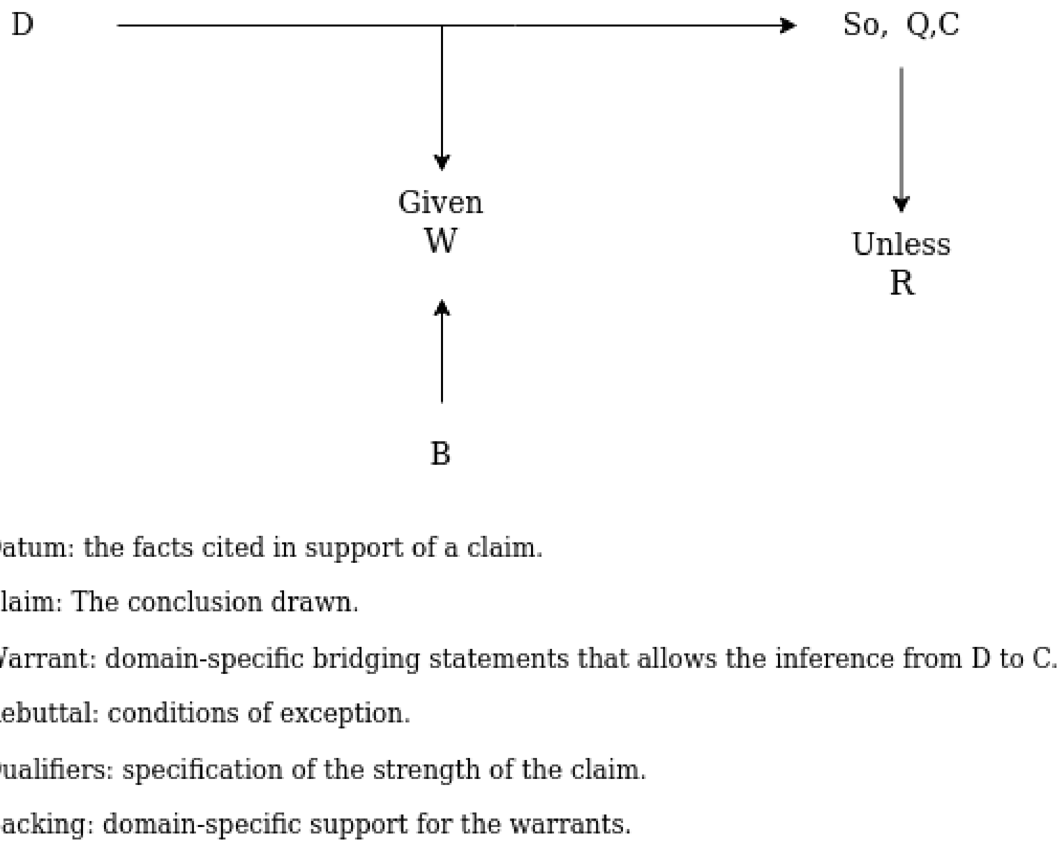

Figure 5.2: Outline of Toulmin's argument schema. The figure is redrawn from Chapman and Wylie (2016:fig.1.1) which is in turn based on Toulmin (1958:94–145).

5.2 Directed acyclic graphs

The second part of the presentation of each paper involves constructing a causal graph that explicate what I believe are the main proximal causal drivers behind the patterns that were observed in each study. As was outlined conceptually in Chapter 4, building comprehensive theories of what we believe underlie a data generating process is central both to meaningfully treat the data, test explanations, and offers a clear path for establishing alternative explanatory frameworks which can be compared and contrasted.

The presentation draws on structural causal modelling, which originated with Pearl (see Pearl 2009; and Pearl and Mackenzie 2018 for an accessible introduction), through the use of causal graphs in the form of directed acyclic graphs. While causal graphs in various forms have a long history of use in archaeology (see e.g. contributions in Clarke 2015[1972]; and Jørgensen 2020b; Kelly 2013; Price and Brown 1985b), the more principled framework of structural causal modelling has seen limited application in the discipline while being increasingly applied in the social sciences more generally (see e.g. Elwert 2013; Greenland et al. 1999; Huntington-Klein 2022; McElreath 2020; Morgan and Winship 2015; Pearl 2009; Rohrer 2018). As the causal graphs presented here are only meant to be cautious suggestions that can potentially structure future studies and accommodate further discussion, their full potential is far from being utilised.

First, it is necessary to establish some foundational premises and terminology. The goal of structural causal modelling is to allow the correlative and associative relationships that can be assessed by use of statistical tools to inform the causal effects that might exist between variables. A blind inclusion of all and as many covariates as one can come up with, without taking an explicit stance towards causation, stands in danger of undermining any drawn conclusions. This follows from the fact that the complete causal web will dictate what variables will have to be controlled for, that is, holding their effect constant either through sampling design or statistical control, and which variables would introduce bias if they are controlled. This is demonstrated through the use of DAGs below.

DAGs represent a specific kind of causal graph, where the term 'directed' refers to the rule that causal effects cannot be bi-directional – that is, causes points to effects. 'Acylic' refers to the rule that no directed path can form a closed loop. To illustrate the concept, a series of basic causal relationships are represented as DAGs in Figure 5.3. While many details have been left of this presentation, all DAGs, irrespective of their complexity, can be constructed and analysed using the basic relationships of chains X → Y → Z (and the condensed X → Y), forks X ← Z → Y, and inverted forks X → Z ← Y (Elwert 2013:249), all which are represented in Figure 5.3.

The direction of the arrows (edges) in the model illustrates what variables (nodes) have a causal effect on other variables. An arrow going directly between two variables means that there is a direct effect. X is therefore said to have a direct causal effect on Y in Figure 5.3A. In other words, X causes Y. Treating Y as the dependent response variable and X as the independent explanatory variable in a statistical treatment would in this case be able to provide an estimate of the causal effect of X on Y.

In Figure 5.3C, X has a direct effect on Y, but as Z impacts both, Z is a confounding variable. That is to say, part of the impact of X on Y may simply be the result of Z affecting both, thus distorting the causal relationship between X and Y if Z is not controlled for. In Figure 5.3D, both X and Y cause Z. Z is therefore said to be a collider. Here, controlling for Z would lead to a distortion of the association between between X and Y. This is because controlling for a common outcome of two variables can introduce a spurious association between the variables, known as collider or endogenous selection bias (Elwert 2013:250; see e.g. Griffith et al. 2020 for an intuitive example). In Figure 5.3B, part of the effect of X on Y goes through Z, which is therefore said to be indirect, mediated by Z. Controlling for Z would in this case block the causal pathway and could lead to an underestimation of the magnitude of the causal effect of X on Y. While there might be situations in which it could be of interest to isolate the effect that remains after accounting for the mediating variable (Baron and Kenny 1986; Hayes 2009), it has been demonstrated that this kind of mediation analysis stands in danger of introducing endogenous selection bias (Elwert 2013:264). A rule of thumb is therefore to not control for mediating variables.

It might seem disconcerting that DAGs cannot readily accommodate cycles or feedback-loops. While frameworks for directly accommodating this do exist (White and Chalak 2009), Morgan and Winship (2015:80) recommend a focus and willingness to first attempt to establish empirically tractable directed graphs in most settings. This follows from the fact that the future cannot cause the past, and so what might appear to represent feedback effects will generally be an issue of temporal resolution (Elwert 2013:249; Greenland et al. 1999). One solution when employing DAGs can thus be to take repeated measures at multiple time-points which can then be added as individual nodes in the model, such that, for example, increasing population density following an initial phase of colonisation might initially lead to a reduction in residential mobility, and reduction in residential mobility could then cause a further increase in population density at a later time-point. Thus, with increased temporal resolution, DAGs can accommodate such complex situations (Rohrer 2018:30). An inability to establish the time-order of effects, either empirically or theoretically, means that certain causal questions might be out of reach for a fragmented archaeological record of variable quality (see Section 3.1).

Explicating the causal processes and relationships that we believe underlie our explanations is critical for the construction of study designs and statistical models that correctly account for the causal relationships between variables, as not doing so stands in danger of severely distorting our findings. Provided the variables can be sensibly operationalised, DAGs offer a precise statement of how the interrelation between variables should be modelled statistically or how a sampling design should be structured so as to correctly estimate causal influences while removing the effects of non-causal associations that distort these estimates. Furthermore, causal modelling and the explicit formulation of what mechanisms we believe underlie the data generating process make DAGs an effective tool for clarifying research questions, for explicating relevant concepts, for identifying assumptions underlying an explanation, and for deriving testable implications of an explanation.

It is, however, important to note here that the DAGs presented below are highly speculative and have limited theoretical specification. They are presented in a purely qualitative manner, lacking information about the direction, strength and shape of proposed causal relationships, as well as their operationalisation. Furthermore, as they represent a first iteration, they are only meant to be tenuous suggestions that can potentially pave the way for exploring these issues. This will first involve the challenging task of establishing if and how the variables can be reliably measured, which reflects the fundamental issue of measurement and how archaeological data can be cast as evidence for past events. While the DAGs presented here will undoubtedly be proven to be inadequate in a myriad of ways, I still believe in the benefits of attempting to explicate our suggested explanations in this manner, as they can provide a starting point for further analysis, and for iterative refinement as our understanding grows.

5.3 Modelling the relationship between Mesolithic sites and the prehistoric shoreline

In the first paper of this thesis I have proposed a method for shoreline dating Mesolithic sites on the Norwegian Skagerrak coast, based on an empirically derived model of the relationship between the sites and the prehistoric shoreline (Roalkvam 2023a). This was based on simulating the distance between sites and the shoreline using 66 ^{14}C-dated sites and local reconstructions of shoreline displacement. The ^{14}C-dates operate as evidence for site-use that is independent of the position of the shoreline at the time, effectively offering a way to test and quantify the long-held belief that coastal Stone Age sites in Norway were located by the shoreline. The study found the sites to typically be located on or close to the shoreline up until some time just after 4000 BCE, when a few sites are located further inland

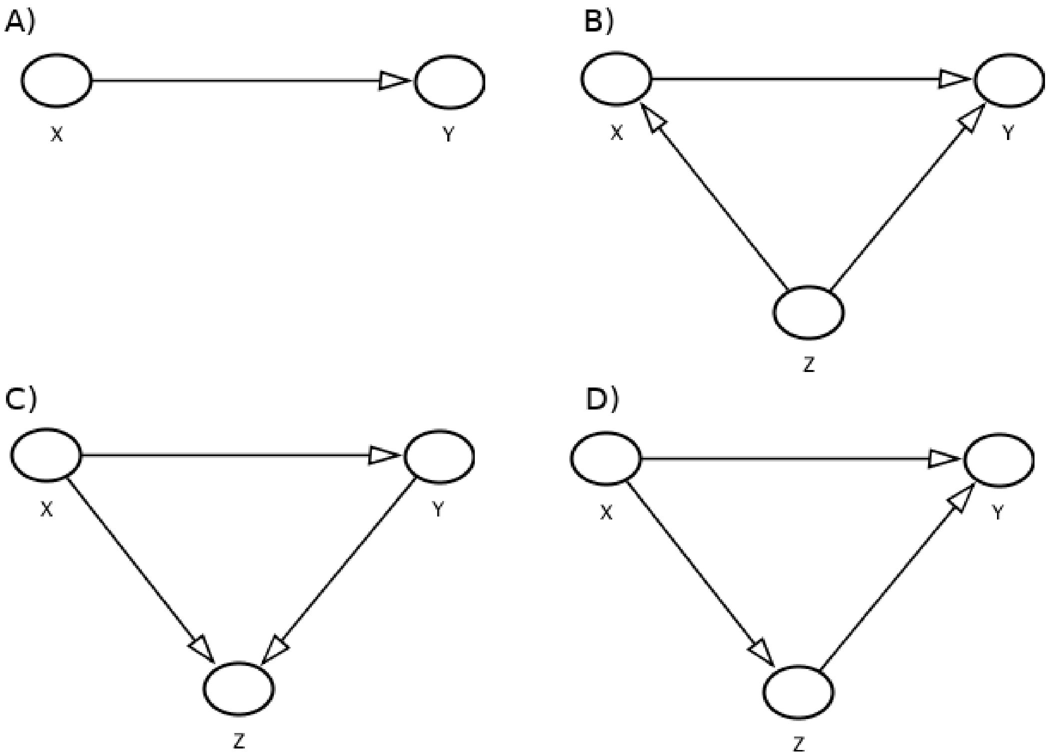

Figure 5.3: Basic patterns of causal relationships represented as directed acyclic graphs. A) Direct effect of X on Y. B) The effect of X on Y is confounded by Z. C) The effect of X and Y collide at Z. D) Part of the effect of X on Y is indirect, mediated through Z.

from the shoreline. At around 2500 BCE there is a clear break, and the sites are from this point on situated further from and at variable distances from the shoreline. Building on these findings, the likely elevation of sites dating to earlier than 2500 BCE were, in aggregate, found to be reasonably approximated by the gamma function given in Figure 5.1A. This is the model that forms the foundation of the proposed method for shoreline dating, which is released as an R package with the second paper of the thesis (Roalkvam 2023b).

The evidence and arguments underlying the study are presented as an argument schema in Figure 5.4. This centres on six major warrants that are necessary foundations for the evidential claim to hold. The first of these, Warrant 1, pertains to the radiocarbon dates from the sites and whether these correspond to the typological indicators in the lithic inventory of the sites, or should for some other reasons be disregarded as not being related to the occupation of the sites. For Paper 1, this choice was largely based on following the discretion of the archaeologists who have undertaken the excavations. Excluding the dates viewed as unrelated to the occupation of the sites substantially increased the degree to which sites were found to have been located by the shoreline, and thus functions in support for the evidential claim. A potential concern could be that the close association between coastal sites and the shoreline is a fundamental premise in Norwegian Stone Age archaeology, and might therefore have impacted how deviating dates are treated in the excavation reports. A brief presentation of the dates and the arguments for why they are believed to correspond or not to the use of each site is provided in the supplementary material to the paper (Backing 1.3). While I believe this procedure to be adequate and the interpretations in the excavation reports to generally be sensible, it might be a worthwhile improvement to instead predefine a set of evaluation criteria for the quality and relevance of the ^{14}C-dates if a similar study was to be undertaken in the future (Potential backing 1.4, following e.g. Pettitt et al. 2003; Seitsonen et al. 2012). This would reduce the number of *ad hoc* assessments of the radiocarbon dates.

A related point that is not included in the schema that is worth commenting on is how several radiocarbon dates from a single site were treated. Dates not intersecting at 99.7% probability were seen as representative of unrelated occupation events. Intersecting dates were then modelled using the OxCal (v.4.4, Bronk Ramsey 2021) function Boundary, and then summed using the Sum function. However, the procedure of summing dates is argued by some authors to be difficult to justify statistically, and procedures for defining the likely start, span and end-dates for occupational phases might be more sensible (e.g. Blackwell and Buck 2003). Furthermore, typological indicators in the assemblages could also have been explicitly included in the modelling of the dates (e.g Bronk Ramsey 2009; Buck et al. 1996).

Warrant 2 pertains to the geological reconstructions of shoreline displacement and the interpolation between these to the analysed sites (the displacement curves are presented in Section 2.1.2). This is a necessary premise for it to be possible to evaluate the correspondence between site-use and the sea. While the geological curves are used directly, there are some uncertainties associated with these that are not accounted for. This follows from the expert knowledge that underlies the compilation of the curves, meaning that some variation between them could simply follow from which experts have conducted the geological studies. While there exist more principled methodologies for reconstructing relative sea-level change, which could potentially reduce or be used to assess some of this subjectivity (e.g Ashe et al. 2019), this is beyond my geological know-how and the scope of this thesis (Deflection 2.4). Furthermore, the procedure for interpolating the trajectory of shoreline displacement to locations between the isobases of the curves was done using inverse distance weighting (IDW). IDW does not account for increased uncertainty as one moves further away from the isobases, and is dependent on how the distance to the isobases is weighed and how many of the isobases are used to inform the interpolation to each location. A host of different interpolation methods exist (e.g. Conolly 2020) which, along with the impact of adjusting the parameter settings for the IDW, would be worthwhile to explore (Potential backing 2.3).

Warrant 3 concerns how the site limits are defined. As was outlined in Section 3.2.1, site limits involves the arbitrary delineation of continuous phenomena represented by the distribution of archaeological artefacts in the landscape. Furthermore, the distribution of artefacts need not represent the entire area making up the activity areas of past inhabitants at a site location. For example the landing area for boats, which presumably has relevance for the location of a site relative to the sea (see also below), can hardly be assumed to be directly reflected in artefact distributions. Deflection 3.2 states that while all of these are valid points, I believe the distances considered means that these dimensions will have limited influence on the final results.

Warrant 4 pertains to the digital terrain model (DTM) that is used when adjusting the sea-level to its position in the Mesolithic. While erosion and modern disturbances has impacted the DTM, this was attempted to be accounted for by using a 10 m resolution DTM that is a down-sampled version of the 1 m version provided by the Norwegian Mapping Authority (Authority 2018), and by manually defining and interpolating the elevation values over especially problematic areas such highways and quarries. While I believe this to have been largely successful, this cannot be guaranteed (Rebuttal 4.3). However, if there are individual cases were this is not true, I believe the overall results to still hold. The future inclusion of a larger sample could also be a way to mitigate such problems.

Warrant 5 states that for the modelling efforts to hold, the precise details of how the distance between site and shoreline was measured is a central component.

This pertains both to how the shoreline and the site limits (see Warrant 3) are defined (Rebuttal 5.1), and what methods were used for the measuring of the distances (Rebuttal 5.2). Central aspects here is that the displacement curves used to define the position of the shoreline represent the mean sea-level. For the definition of the site limits, Deflection 3.2 from above is relevant also here, while Potential backing 5.5 suggests that both including an estimate of the tidal range and potentially exploring the definition and uncertainty associated with the delineation of the site limits could be worked into the simulation procedure.

When it comes to the measured distances, the main measure, which also underlies the proposed method for shoreline dating, is the vertical distance between the elevation of the shoreline and the lowest point on the site polygons. In addition to this, measures for the distance between the horizontally closest points on the site and the shoreline, as well as the topographic distance (that is, the distance when accounting for the slope of the terrain) between the sites and the horizontally closest points were also taken. Especially the last measure entails some simplification. Measuring the topographic distance to the horizontally closest points means that this does not necessarily identify the topographically closest points, which is a more computationally expensive operation. Furthermore, identifying the topographically shortest path between these points is also dependent on the choice of least cost path algorithm (e.g. Herzog 2013). Again, however, I believe that the distances considered means that the assumptions and inferential leaps that this warrant requires will have a limited impact on the findings (Deflection 5.3).

The last warrant, Warrant 6, pertains to the treatment of the data following the simulations. This was done by fitting an array of standard models to the univariate distribution of vertical elevation distances between sites and shoreline, and selecting the gamma as the best model by use of the Akaike information criterion (AIC) and Bayesian information criterion (BIC). Given the fairly limited consideration of competing univariate models and the lack of probability estimates for the model parameters, the study can ultimately be considered part of a procedure of modular model construction, where this study represents a first step (e.g. Buck et al. 1996; Gelman et al. 2020).

Finally, the study does not involve any consideration of what factors have caused the distribution of elevation values, which is also reflected by the use of univariate models. In one way this can therefore be viewed as an instrumental model as the *reason* for the location of the sites has not been considered explicitly. The concern is directed towards prediction not explanation. By combining the present altitude of a site, its likely elevation above the shoreline when it was in use, as informed by the gamma function, and local shoreline displacement curves, this model makes it possible to assign a probabilistic absolute shoreline date to coastal sites in the region. While the model and derived method can be viewed as

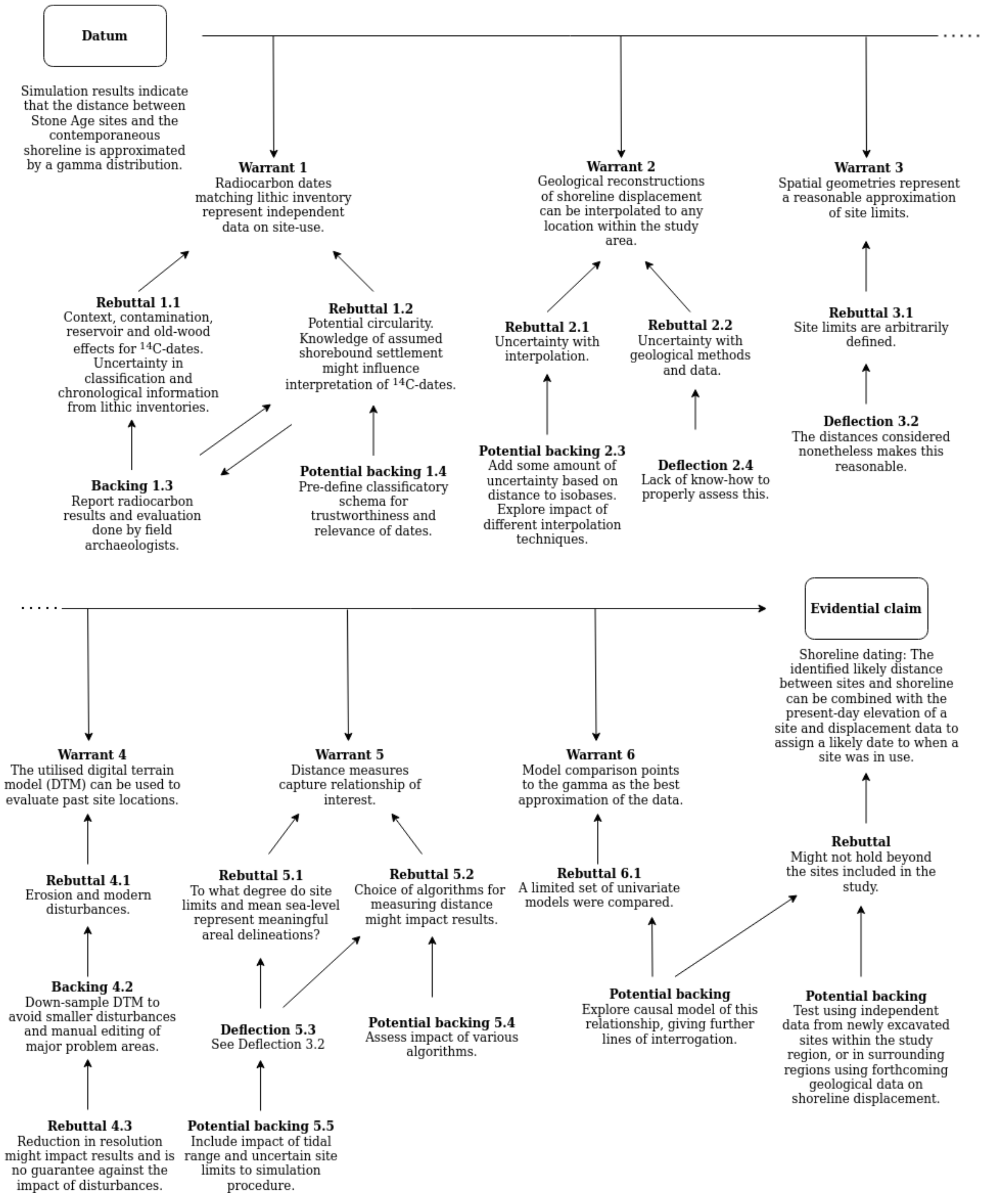

Figure 5.4: Argument schema for Paper 1 and 2.

a instrumental dating tool, it is determined by the proclivity for sites to be located on the shoreline. As such, it likely to be tightly integrated with both overarching cultural developments, as well as behaviour at the site level. By extension, the multitude of factors that can have shaped the site-sea relationship on the large and small scale, both temporally and spatially, offers a challenging causal web of possible interacting effects. Having first derived this instrumental model, however, this gives opportunity both to further test its correspondence with other empirical data, and explore and expound underlying theoretical assumptions and implications. To this end, I have constructed a suggestion for a causal model concerning what could be the determining factors for the vertical distance between coastal Mesolithic sites and the shoreline in south-eastern Norway (Figure 5.5).

5.3.1 Causal model for the site-sea relationship

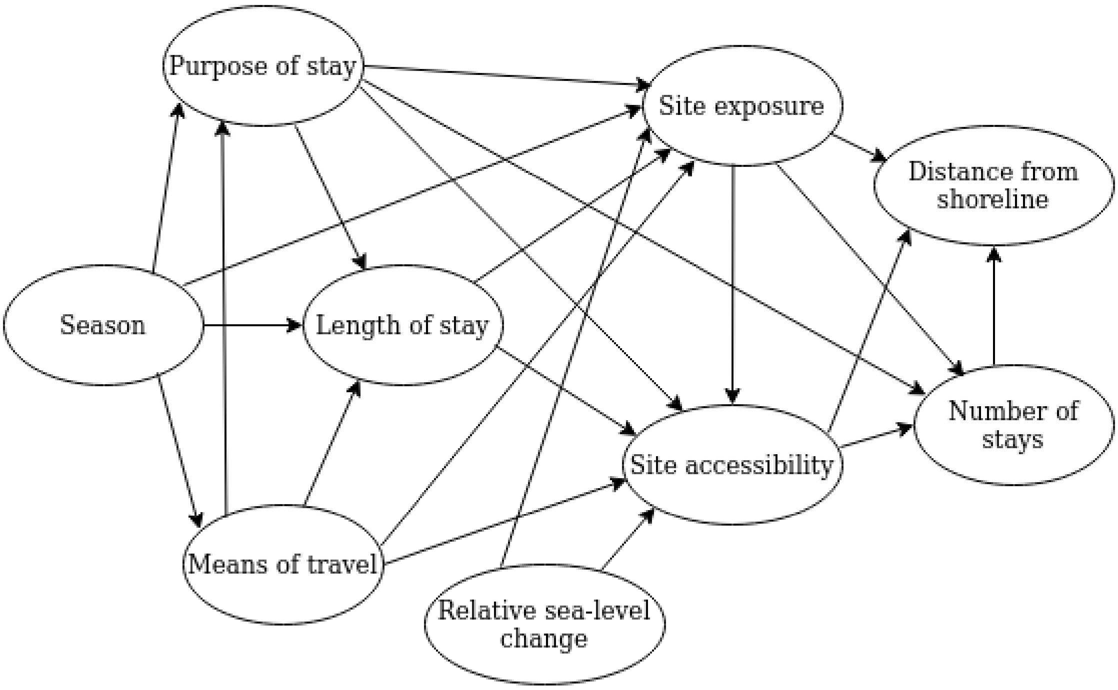

Figure 5.5: Suggested causal model for the drivers behind the relationship between site location and the prehistoric shoreline in Mesolithic south-eastern Norway.

An immediately obvious aspect of the suggested model is that the effect of all variables for the the site-sea relationship is mediated through the variables site exposure, pertaining to the exposure of the location to wind and wave action; site accessibility, concerning access to and from the site; and the number of stays at the site. Consequently, these also represent some of the strongest causal assumptions in the model, as the presence of arrows in causal graphs merely point to a possible causal relationship. The strongest claims of knowledge in a causal graph rather stems from missing arrows (Elwert 2013). Removing arrows can be based on either theory or data, meaning that some of the suggested relationships in the DAG could be proven to be of little to no relevance in future empirical studies or theoretical discussions.

A likely important factor for how exposed and accessible people accepted a site location to be is the purpose of the visit to the site. The purpose of the visit is therefore given a direct effect on exposure and accessibility. For example, is the site meant to be used as a stop to rest and repair tools, to be used as a hunting camp or a location from where to acquire raw materials for tool-production? Is it a base-camp for the entire residential group from where further forays are made, or is it meant to be a meeting place for several groups?

The purpose of the stay is likely also to impact the length of the stay, which in turn might have implications for how close to the shoreline the site is established. A longer stay could for example mean that the site would have to be more withdrawn from the shoreline, so as to make sure storm surges do not reach the site. The length of stay is not given a direct effect on the distance to the shoreline, as sites in the region are interpreted to not having been in used for more than, at most, a few months at a time (e.g Glørstad 2010). This means that the shoreline regression would have been negligible within the time-span of any individual stay.

Means of travel is also included in the model. Most travel in the coastal region is assumed to have been done by boat in this period, which means accessibility to the site from the sea is likely to be of concern, as well the ability to safely beach and store the boats. However, what kind of boats that were in use does remain a point of discussion (see e.g. Glørstad 2013 with comments; Schmitt 2013), and could have implications for these dimensions. Furthermore, some travel was also likely done by foot (see e.g. Bjerck et al. 2016; Pettersson and Wikell 2018; Schülke 2023). This could for example be from a base-camp to a site close by for gathering and processing resources, where the need for the carrying capacity offered by boats might not have been necessary. Travel by foot, or by skis or sledge in the winter-timer, for example in connection with the hunting and processing of resting seal that are not disturbed by approaching people, or species of seal that predictably utilise breathing holes in the ice could also be an alternative (see Bjerck et al. 2016). Not having to land boats could presumably have implications for the degree and in what ways a site location could be exposed and accessible.

The season could also have implications for how often one had to establish camp, and possibly led to a reduction of mobility in colder periods (cf. Binford 1990). The season might also influence the kinds of dwelling structures that were necessary to erect, and likely determines the kinds of resources that were exploited, thus potentially impacting the purpose of the stay. The season is also believed to have implications for the degree of wind and wave-action at a location, thus affecting the exposure of the site to the elements, and impacting accessibility. Finally, the season presumably also has implications for the means of travel, for example by reducing the potential use of boats and enabling travel on the ice. Season is therefore given a direct effect on all of these variables.

The full period of time over which a site was is in use could presumably be influenced by relative sea-level change by the determining the frequency of revisits. Depending in part on the topography, relative sea-level change could make a location increasingly less attractive due to a reduced accessibility to and from the site or by impacting its exposure. In periods characterised by more a stable sea-level, on the other hand, a single location would have retained any strategic or beneficial position over a longer time-span, allowing for repeated visits over a longer period. Relative sea-level change is therefore given an indirect effect on the distance to the shoreline, mediated by accessibility, exposure and number of stays. However, these are presumably not the only factors determining the number of times a place could be revisited. Following for example from an investment into more substantial dwelling structures or due to some other factors that might elevate its importance (see e.g. Glørstad 2010:97–102; Schülke 2020), it would seem plausible that such factors could counterbalance, to a degree, the adverse effects of relative sea-level change on the attractiveness of a site location. This is indicated by the the direct effect of purpose of visit on number of visits.

Some variables and nuance that have been left out of the model are worth commenting on. The weather is for example likely to impact many of these factors, but is near, if not entirely impossible to determine archaeologically. Furthermore, the purpose of a stay is here indicated using a single variable, but a stay need not, or perhaps likely did not, have a single purpose. A simple example might be a case where multiple kinds of resources were to be exploited from a site. A possible alternative would be to operationalise these as individual variables, where for example the magnitude of seal-hunting and the gathering of hazelnuts to be done from the site is kept as separate variables. These would in turn likely be determined by factors such as the density of these resources in the landscape, their caloric return, their cost in terms of handling-time and -energy, and the potential prestige associated with hunting or sharing a specific resource (see e.g. Kelly 2013).

Furthermore, the entire picture is also further complicated by other latent variables that are left out of the model. Social structure, overarching mobility patterns, territoriality, group size and composition, as well as religious beliefs could all impact land-use, site-structure and ultimately how sites were positioned relative to the sea. The proposed causal model thus pertains, as was noted above, to what can be termed proximal causes.

Nonetheless, I still believe the model forms a reasonable starting point from where to potentially improve the baseline model, and that it has the potential to reveal some important causal determinants for the site-sea relationship. A central challenge is of course how these factors are to be operationalised and determined archaeologically. The exercise of setting up the causal model is still useful in its own right, if not simply by forcing its author to think through and concretise what elements they believe are important and how these are related, but it also forms a framework that dictates how these variables would have to be handled analytically.

A central challenge for the proposed model is thus how the different variables can be measured. For example, determining the season for when a site was in use is possibly an insurmountable challenge in many cases, but some avenues for investigation exist. The most immediate line of evidence is drawing on faunal and vegetational material. Depending on what resources were exploited, this could make it possible to discern in what season the sites were in use (e.g. Boethius et al. 2020; Mikkelsen 1978). Furthermore, Solheim and Persson (2016) speculated whether what they identified as a predominance of fish remains on sites located in outer coastal areas, as opposed to terrestrial faunal material at sites in inner coastal areas, could reflect seasonal movement patterns (see also Bergsvik et al. 2020). As bone is typically poorly preserved in the acidic Norwegian soils, this is a challenging line of evidence to draw on, but if this could be shown to consistently correspond to other site features such as their location, this could possibly be extended to sites where bone is not preserved.

Similarly challenging is determining the means of travel. While boats can be reasonably be assumed to have been the main means of transportation throughout the Mesolithic in the coastal region, some controversy surrounds what kinds of boats were in use (e.g. Glørstad 2013, with comments), and it has been suggested that sledges and skis could have been used in inland areas (see Sørensen et al. 2013). Although the relevance of this variable is therefore not certain, and these suggestions remain speculative, one line of reasoning could again be to examine the topographic location of the site in an attempt to reveal if this can be found to be related to the means by which the sites were reached.

When it comes to measuring the length of stay, it was suggested in the third paper of this thesis (Roalkvam 2022), as presented in more detail below, that aspects of the lithic inventories reflect the duration of stays at the sites under study. Assessing the distance between site and shoreline when accounting for these measures could therefore offer a way forward in this regard. The length and purpose of the stays are likely to be tightly integrated, but the analysis of lithic inventories offer a clear possibility for approaching these issues.

Exposure is one of the variables in the suggested causal models where a range of analytical avenues exist. The exposure of Mesolithic sites was investigated in Roalkvam (2020) by using viewshed analysis to estimate visibility, and the estimation of wind-fetch to measure exposure to wave-action. A third potential way to handle exposure could be to devise a method for estimating the distance from the site to the outer-most coastal feature to evaluate their location within the wider landscape (see Section 2.2.1). Although all of these measures have seen limited or no previous application in Norwegian archaeology, they offer clear ways forward with which to investigate these issues.

Accessibility is another challenging variable to operationalise that has not been explored much in the literature. Good landing places for boats are often pointed to in excavation reports and in the literature. Common defining features of this appears to be a gentle slope towards the prehistoric shoreline, which can readily be explored in a geographical information system, as well as the degree to which the surroundings of a site forms a natural harbour by being less exposed to winds and wave-action (e.g. Bjerck 1990; Nummedal 1923; Pettersson and Wikell 2018). Drawing on the methods suggested for estimating the exposure a site, its accessibility could therefore also conceivably be measured.

While multiple occupational phases as suggested by ^{14}C-dates were included in the analysis for Paper 3, the number of stays at the sites was not treated explicitly when deriving the method for shoreline dating. Both radiocarbon dates and lithic inventories can provide information on the number of visits (e.g. Åstveit and Tøssebro 2023), and a possible approach could be to stratify the measure of distances from site to shoreline by inferred phases of occupation in future studies.

As it stands the most readily operationalised explanatory variables of the model is therefore the duration of the stays at the site, their exposure to surrounding landscape – and potentially the accessibility to the sites and the number of occupational phases. To conclude, this exercise has demonstrated some of the value of suggesting an explicit causal model, and has laid out some potential avenues for further interrogating the issue of the relationship between coastal Mesolithic sites and the contemporaneous shoreline.

5.4 Modelling the technological expediency of Mesolithic assemblages

The third paper of this thesis (Roalkvam 2022) was aimed at exploring methods for handling lithic assemblages associated with the large number of excavated Mesolithic sites in the region, which can range in size from a few hundred to several thousands artefacts. The 55 sites chosen for analysis were excavated as part of four large excavation projects undertaken by the Museum of Cultural History in the last two decades, and were located within a constrained geographical area. This means that the excavations were carried out using similar excavation methods and that the classification of the artefact inventories followed similar guidelines. This choice of sample was aimed at reducing the amount of variation in the assemblages that could follow simply from investigatory and classificatory differences, as well as from variable access to raw materials when the sites were in use. The analysis focused on two analytical avenues. The first of these was to evaluate the chronological development in the occurrence of artefact categories over time, which in large part appears to coincide with previous suggestions in the literature. The second line of investigation was aimed at exploring methods for tracking variation in mobility patterns based on the composition of lithic inventories, which is the part of the analysis that is in focus here.

In terms of chronological fixing of the occupation of the sites, this was based either on radiocarbon dates or shoreline dates in combination with typological indicators. As this study was undertaken before Paper 1 and 2, the newly proposed method for shoreline dating had not yet been developed. This means that the dates informed by shoreline displacement and typological indicators were accepted as they are given in the original excavation reports. In addition to this, only radiocarbon dates seen as relevant for the occupation of the sites in the reports were considered.

The evidential claim of the paper is that the forager–collector continuum, as outlined in Section 3.3.2, is captured by variables taken from the Whole Assemblage Behavioural Indicators (WABI, see Clark and Barton 2017). This involves the assumption that the abundance of available resources and knowledge of their sources impacts the degree of retouch that has been done on the lithics constituting the assemblages, where retouch is taken to represent efforts to extend the use-life of lithics by rejuvenating edges and re-purposing tools. Following this logic, higher mobility will lead to a greater necessity to conserve lithics in anticipation of more uncertain and less predictable circumstances. Lower degree of mobility, on the other hand, should affect the organisation of lithic technology by leading to more predictable surroundings, distribution of resources and what tasks that will have to be performed. This is assumed to lead to a reduced necessity for conservation and re-purposing of lithics. The different forms of technological organisation that is to result from these situations is denoted by the terms curation and expedience, which, following from their dependence on on mobility patterns, are to reflect the forager–collector continuum. The central empirical correlates of technological curation is high degrees of retouch and low overall density of lithics, with the reverse being defining for technological expediency.

The analysis undertaken for the paper was exploratory, meaning that a range of variables in the assemblages that have previously been associated with mobility patterns were included in the undertaken principal components analysis to assess their ability to explain the variation in the data. The findings confirmed that the proportion of non-flint material in the assemblages increases through the Mesoltihic, as has been noted by numerous authors over the years (e.g. Reitan 2022; Solheim 2017b), and which has been argued to be an indication of decrease in residential mobility through the Mesolithic of south-eastern Norway (Glørstad 2010:181; Jaksland 2001:112). Furthermore, this development conforms with the expectations of the WABI by showing an overall decrease in the proportion of secondarily worked lithics and an increase in the volumetric density of lithics on the sites over time.

To further explore the nature of this development, while also accounting for the temporal uncertainty associated with the dating of the sites, the two WABI variables were combined into a 'curation index'. This was done by min-max normalisation, adjusting the variables to take on values between 0 and 1. The volumetric density of lithics was then made negative, as higher values is to indicate a lower degree of curation, and the mean was then taken for the two variables for each site to find their value on the curation index. A simulation was then performed to account for the temporal uncertainty associated with the developments in this curation index over time. For each simulation run, the date of a site was drawn from their associated date ranges, either uniformly in the case where the site were dated by reference to shoreline displacement and typology, or, where these were available, by drawing the year weighted by the sum of the posterior density estimates of radiocarbon dates. For each simulation run, a locally estimated scatterplot smoothing (LOESS) curve was fit to the data to capture the overall developments in the curation index. The average LOESS curve from 1000 simulation runs is given in Figure 5.1B.

The necessary warrants underlying the study are presented in the argument schema in Figure 5.6. The first warrant pertains to the issue of whether the artefact inventories have been consistently categorised across excavation reports. The support for this can initially be found in the sample of sites that was chosen for the study, which was aimed at being likely to have artefact inventories that were categorised using similar methods. To add to this, the key variables of the WABI, namely proportion of secondarily worked lithics and volumetric density of lithics, are both variables that have had the same definition for decades (cf. Helskog et al. 1976). Consequently, while the sample itself makes this rebuttal likely to be of less concern, part of the value of the WABI is that these variables lend themselves well to studies of legacy data where more modern classificatory schemas have not been used (Backing 1.3, Clark and Barton 2017). However, some ancillary expectation of the WABI were not found to correspond to the suggested developments. This especially pertains to the role of cores. One expectation of the WABI is that unexhausted cores is likely to be more frequent in assemblages characterised by a

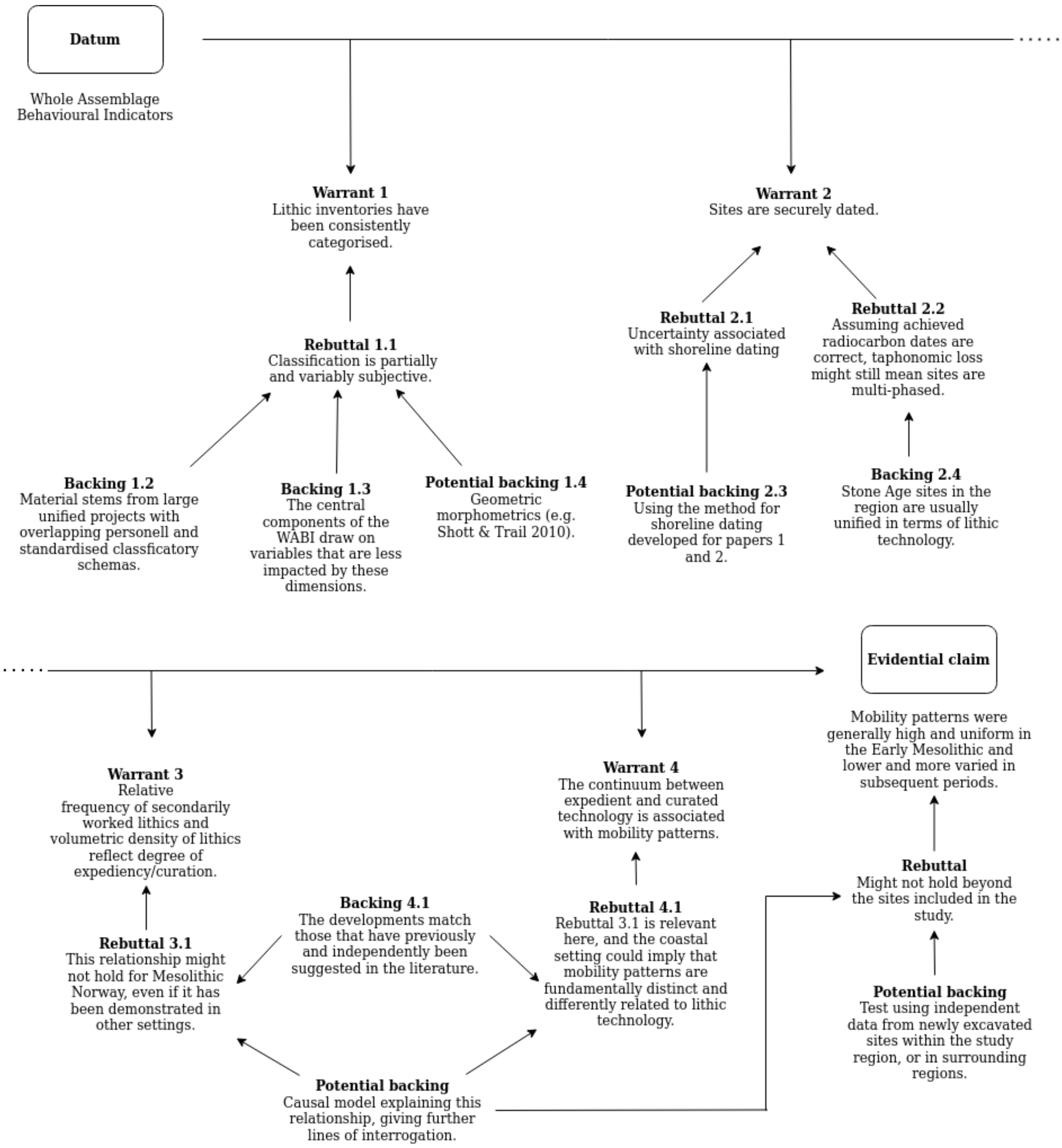

Figure 5.6: Argument schema for Paper 3.

lower degree of mobility, but no clear chronological patterning could be identified in the frequency of cores in the assemblages. However, this could be related to the fact that these are often not classified beyond being categorised as cores, and so a more in-depth analysis might reveal different patterns related to dimensions such as the exhaustion of the cores. While the analysis of cores need not employ this methodology, this point can be related to Potential backing 1.4 in the argument schema, where a more principled analysis of the artefact inventories by the use of geometric morphometric is suggested (see e.g. Matzig et al. 2021; Shott and Trail 2010).

Warrant 2 concerns the chronological control for the accumulation of the lithic assemblages. 17 of the 55 sites were associated with radiocarbon dates which were seen as relevant to the occupation of the sites in the original reports. Multiple dates from a single site were then treated by use of the Boundary and Sum functions in OxCal, and so the same points as those discussed for radiocarbon dates in relation to Paper 1 in Section 5.3 are also relevant here. More critical is the fact that as Paper 3 was written before Paper 1 and 2, the newly developed method for shoreline dating was not applied. Instead, the shoreline dates were taken directly from the reports. In Paper 1 I found that previous applications of shoreline dating generally corresponded with the start dates of the ones achieved with the newly proposed method, but previous application have tended to overestimate the precision of the dates (Roalkvam 2023a:11–15). This can in part follow from the fact that the excavation reports also draw on typological information and not only shoreline dating, thus constraining the achieved date. However, this has always been done in an informal manner and so it is difficult to assess the degree to which the precision achieved in the reports can be justified (Rebuttal 2.1). The chronological control could therefore be somewhat exaggerated for Paper 3, and a clear point of improvement would be to undertake the study using the new method for shoreline dating (Potential backing 2.3).

Warrant 3 and 4 can be treated in unison here, as they concern whether the curated–expedient continuum is meaningfully captured by the variables of the WABI, and whether this in turn reflects the forager–collector continuum as originally devised by Binford (1980). As is indicated by the title of the paper *Exploring the composition of lithic assemblages in Mesolithic south-eastern Norway*, the paper is explicitly exploratory. This means that it was aimed at identifying empirical patterns and suggest some potential explanations for their occurrence. The study thus decidedly entailed *post hoc* accommodative argumentation (see Section 4.1), as the explanations were construed following the identification of the empirical patterns. These patterns correspond to those that could be expected from the main components of the WABI, with previous suggestions for the development of mobility patterns through the Mesolithic of south-eastern Norway, and with the corresponding increased use of non-flint material through the period (Backing 4.1). The relevance of the WABI for tracking mobility patterns based on lithic assemblages has been explored and substantiated over a range of different contexts in Eurasia – ranging in temporal coverage from the Pleistocene to the Holocene, and by drawing on assemblages associated with both Neanderthals and anatomically modern humans (e.g. Barton et al. 2013, 2018; Clark and Barton 2017; Riel-Salvatore et al. 2008).

However, as a first attempt at employing these measures in the context of Mesolithic Scandinavia, and, as was noted in Section 3.3.2, following from the coastal setting that might have implications for the applicability of the collector–forager continuum, both the reliability of Warrant 3 and 4, and, by extension, the the main evidential claim of the paper should be explored and tested in a range of ways (Rebuttal 3.1 and 4.1). First, given the explorative and accommodative analytical framework, additional testing of the framework using independent data would be fruitful both to assess the strength of the evidential claim, and has the potential to reveal nuances that were not captured in the study undertaken for Paper 3. Furthermore, given the developments in mobility patterns that this framework is believed to capture, drawing on other variables that are believed to be related to these developments should also be explored. A fruitful first step to achieve this is to set up a causal model, a suggestion for which is presented in Figure 5.7.

5.4.1 Causal model for the expediency of lithic assemblages

The causal model that underlies the relationship between lithic inventories and residential mobility is fairly straightforward in that it posits that higher residential mobility leads to a higher degree of expedient technological organisation. This follows indirectly from the assumption that a reduction in mobility leads to a better predictability of raw material availability and allows for its accumulation if sites are occupied for a longer duration. With increased occupational duration, the tasks that will have to be carried out are also believed to more predictable than in a situation of high mobility, where changing and more unpredictable circumstances will lead to a more curated technology. In the model, residential mobility is therefore given a direct effect on all the variables underlying the curated–expedient continuum. This relationship is effectively an instantiation of that which has been proposed by Barton and collegues in other context (e.g. Barton and Riel-Salvatore 2014; Clark and Barton 2017), where properties of the lithic assemblage functions as indicator variables for the underlying causal drivers.

An addition to the model that is more specific to the Norwegian Mesolithic follows from the role of non-flint material. It was found in Paper 3 that an increase in the use of non-flint material occurs over time. As mentioned above, it has previously been suggested that this reflects an increased familiarity with local surroundings, and that this is related to a decrease of residential mobility. In the paper it was found that the overall development in the curation index was robust to removing non-flint material from the data set. However, as the use of non-flint material is generally associated with a higher abundance of debitage per secondarily worked artefact, this procedure did markedly increase the curation values for some individual sites. The effect of non-flint material can therefore potentially be more significant and skew the measure in other contexts.

An important assumption concerning the role of non-flint material in the suggested causal model is that there is no direct effect between choice of raw material and technological expediency. The assumption is thus that raw material only impacts the empirical indicator variables for technological expediency without directly impacting the fundamental technological strategy itself. However, it is possibly premature to remove this arrow of effect, as it is a proposition that would benefit from further substantiation, including an assessment of the degree to which choice of material might impact raw material predictability. Furthermore, excavations in areas such as Aust-Agder, located south of the study area of Paper 3, have found that quartz is often a more dominating part of the assemblages in this region (e.g. Reitan and Sundström 2018). Thus, while the overall developments were robust to the effect of excluding non-flint material for the sample of assemblages considered for Paper 3, it is not clear that this relationship necessarily holds in areas with a different availability of various raw materials. Consequently, the question of the spatial stationarity of the relationship between non-flint material and expediency is relevant, irrespective of whether this is thought to be of direct causal relevance for technological organisation or for the adjustment of its indicator variables.

Finally, while the sample of sites chosen for Paper 3 was aimed at reducing the confounding effects of investigatory and classificatory differences that might exist between excavations, it is possible that with an extension of the study to include a larger sample, nodes representing such effects should be included in the causal model.

In the exploratory setting of Paper 3, the relevance of the WABI was mainly arrived at based on their correspondence with overall developments in mobility patterns and use of non-flint material that has previously been proposed in the literature. However, a proper evaluation of the causal model presented in Figure 5.7, and a clarification of the potential role of the curated–expedient continuum for tracking mobility patterns will depend on comparing it with other, properly operationalised variables that have been suggested to be of relevance to the same developments. One way forward in this regard is represented by the the findings of the fourth paper of this thesis.

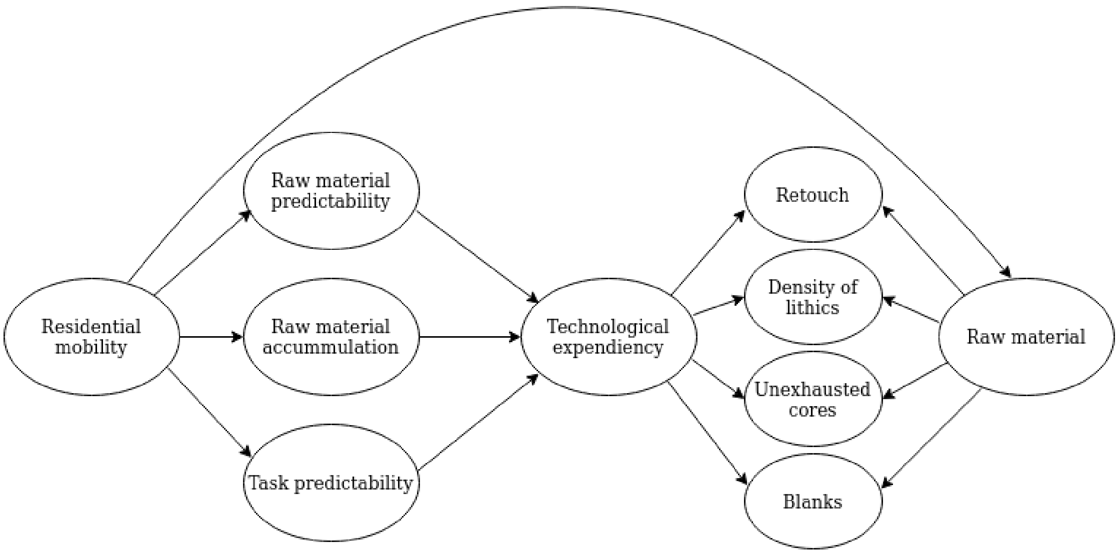

Figure 5.7: Suggested causal model for the drivers behind the relationship between mobility patterns and the composition of lithic inventories.

5.5 Modelling demographic developments through the Mesolithic

The fourth and final paper of the thesis is written in collaboration with Steinar Solheim and has been uploaded as a pre-print before it is to be submitted to a journal for publication. The paper contrasts two proxies that have often been drawn on to model relative population density in Fennoscandia, namely radiocarbon and shoreline dates (e.g. Solheim and Persson 2018; Tallavaara and Pesonen 2020). These are analysed by way of summed probability distribution of radiocarbon dates (RSPD), and, drawing on Paper 1 and 2, the summed probability distribution of shoreline dates (SSPD) from within the study area.

The study was based 310 ^{14}C-dates. The procedure of summing these start by combining multiple dates from a single site that fall within 200 ^{14}C-years of each other to account for cases were the investigatory context or research interests might have impacted the number of radiocarbon dates, thus potentially biasing the frequency of dates. This procedure therefore effectively reduces the sample of dates by weighting these site-phases equally in subsequent analysis. Undertaking this procedure reduced the effective sample from 310 dates to 134 sites phases for the final RSPD. To account for the possible fluctuations in the RSPD that could follow from sampling error or wiggles in the calibration curve, an exponential, logistic and uniform model were then fit to the RSPD and the distribution of dates that could be expected if the development followed these models were simulated 10,000 times to achieve a critical envelope of expected values given each null model (for details, see e.g. Crema 2022; Crema and Bevan 2021; Shennan et al. 2013; Timpson et al. 2014; Timpson et al. 2021). Of these models, the logistic development was found to be the best alternative, and the simulation procedure confirmed that the available data could be expected under this model.

The same procedure was then adapted to the sample of shoreline dated sites, consisting of 820 surveyed sites and 101 excavated and previously shoreline dated sites. This gave a total of 921 sites for the final SSPD. Given that the dating procedure does not treat the possibility of multiple site-phases explicitly, the SSPD is the sum of performing a single shoreline date for each site. The same three base models as those used for the RSPD were then fit to the SSPD. In the employed method for shoreline dating, the local trajectory of relative sea-level change effectively fulfils the same purpose as the calibration curve does in the handling of radiocarbon dates. Consequently, the dates that were simulated to characterise the expected development under each null model for the SSPD was here based on the distribution of observed sites in the study region and the trajectory of shoreline displacement associated with these site locations. All standard models could be rejected for the SSPD, with the exponential model being identified as the best alternative. This indicates an overall decrease in sites over time, but given that the model could be rejected and given the deviations from the simulation envelope evident in Figure 5.1D, this does not adequately capture the distribution of the data.

As can be seen from Figure 5.1C and D, the temporal distribution of the proxies thus follow different trajectories. Given the overall reduction in mobility that has been argued to occur through the Mesolithic (see Chapter 2), we suggested that the mismatch could reflect a case where the frequency of shoreline dated sites is more heavily influenced by mobility patters than population density, and that the reverse is true for the RSPD. However, as the main focus of the paper was to establish a method for handling and assessing the summed probability of shoreline dates, these discrepancies were given a purely narrative treatment in the paper. This is reflected in the argument schema in Figure 5.8, which pertains both to the methods used for assembling the RSPD and SSPD, and the potential substantive implications these might have.

The first warrant in the schema pertains to the included sample of surveyed sites, which is taken from the national heritage data base Askeladden, maintained by the Norwegian Directorate for Cultural Heritage (Norwegian Directorate for Cultural Heritage 2018). As is pointed out in Rebuttal 1.1, these records and associated spatial geometries are of widely varying quality and the site records were originally created for the purposes of cultural resource management – the reliability of any individual record for research purposes can therefore not be readily assumed.

To accommodate this we employed a scoring system going from 1–6, pertaining to the quality of the site records and the degree to which the spatial geometries could reasonably be assumed to reflect the position and spatial extent of the sites (Backing 1.2). This system was originally used in Roalkvam (2020). While we employed a single cut-off for the quality of the site records when determining what sites to include in the study, it would also be possible to explore the implications of adjusting this exclusion criteria to further evaluate the robustness of any observed patterns.

The second warrant concerns the degree to which shoreline dating is a reliable method for dating coastal Stone Age sites. While its application for Paper 4 extends beyond the original sample used to derive the method (Rebuttal 2.1), the shoreline dated sites for Paper 4 are all taken from within the same study region as the one used in Paper 1, giving some support for an assumption that it holds for the analysed sites (Backing 2.2). The reliability of the application of shoreline dating for the purposes of Paper 4 is nonetheless premised on the argument schema for Paper 1 and 2, and would therefore clearly benefit from any additional evidential support that would follow from handling the rebuttals related to these papers (Potential backing 2.3).

The third necessary warrant for the comparison between the SSPD and RSPD to be meaningful is that the radiocarbon dates included in the RSPD stems from reliable anthropogenic contexts. The radiocarbon data is provided in the repositories for the paper, where the context has been noted, also making it possible for others to assess this. However, as for Paper 1, the use of a predefined auditing system for evaluating the reliability of the dates would be beneficial, following for example Pettitt et al. (2003; implemented by e.g. Riede and Edinborough 2012).

The fourth warrant concerns the treatment of the two SPDs once these had been assembled. This was done using standard approaches for the RSPD (see e.g. Crema and Bevan 2021; Timpson et al. 2014), with the exception of using maximum likelihood estimation for fitting the three compared null models to the data, and for comparing their performance using the Bayesian information criterion. This was done using the recently developed methodology of Timpson et al. (2021; see also Crema 2022; Crema and Shoda 2021). For the SSPD, a bespoke methodology had to be developed to account for idiosyncrasies of the dating method when simulating the distribution of dates that could be expected under the three null models, but this draws heavily on the framework used with ^{14}C-dates. The main adjustment involves accounting for the distribution of the sites within the study area relative to the direction of the isobases. Given that the shoreline displacement varies along a south-west/north-east gradient (see Section 2.1.2), the distribution of sites will have implications for the frequency of sites that could be expected under each null model. By accounting for the distribution of sites, the variable relative sea-level change in the study area is reflected in the achieved simulation envelopes.

Although adjustments to the algorithms used for shoreline dating and for simulating the critical envelopes could follow from future developments of the method for shoreline dating, the main rebuttal to Warrant 4 follows from the fact that all three standard models could be rejected as explaining the data in the SSPD. The simulation envelope associated with a rejected null model only address the failure of the data to accord with the null model of choice, and, following from the use of a 95% critical envelope, 5% of these deviations could be expected to occur by chance without it being possible to ascertain which 5% this pertains to. The deviations do therefore not give any statistical justification for interpreting the deviations themselves, and only represent deviations of a potentially substantively interesting nature. Put differently, the model does not explain the data, and the deviations merely indicates temporal regions where the data deviate from an erroneous model. Consequently, there is a danger of over-interpretation and placing too much analytical weight on these deviations, which has been argued to often be the case (Timpson et al. 2021).

The fifth warrant pertains to the degree to which the frequency of radiocarbon dates reflect population numbers. This is based on the fundamental premise that more dateable material from a given time-interval is a reflection of more people responsible for depositing this material. This is known as the dates-as-data approach, as suggested by Rick (1987). Some issues that have been argued to potentially confound this premise is taphonomic loss (e.g. Surovell et al. 2009), sampling error (Timpson et al. 2014), different cultural or economical practices that could result in variable output of dateable material irrespective of population density (e.g. Freeman et al. 2018), and investigatory biases that could impact the number of radiocarbon dates that are carried out for specific contexts or time-intervals (see e.g. Crema 2022 and Section 3.3.4). Some methodological solutions have been presented to account for such biases, such as adjustments to account for taphonomic loss, sample selection that is likely to derive from populations with similar economic and technological systems, and methods for weighting multiple radiocarbon dates from the same context to reduce investigatory bias. However, without independent evidence for the connection between RSPDs and population dynamics for a given context, an inferential leap is nonetheless necessary (Rebuttal 5.2). An approach that many authors therefore agree can make such inferences more robust is to compare the agreement between multiple population proxies (e.g. French et al. 2021; Palmisano et al. 2017), which is the fundamental motivation for undertaking the comparison between the frequency of radiocarbon and shoreline dates in Paper 3.

As a consequence of the mismatch between the two proxies, the sixth warrant pertains to the degree to which this discrepancy can be accounted for by mobility patterns that more heavily impacts the SSPD. The earliest part of the Mesolithic is in the SSPD indicated to be associated with a larger number of sites, but lacks a signal in the RSPD, leading to the hypothesis that this is the result of colonising groups characterised by low population numbers and high mobility. The subsequent drop in the SSPD was then seen in association with migratory events from the east, believed to lead to a reduction in residential mobility and reduction in the number of sites. The conclusion of this drop corresponds to the first signal in the RSPD, which rapidly grows before it plateaus in the first centuries after 8000 BCE. This plateau also corresponds to a positive deviation in the SSPD, which we in combination suggest is an indication of a population increase that is reflected in both proxies. As the logistic model fit to the RSPD then remains stable for the remainder of the period, one possibility is that the subsequent fluctuations in the SSPD follows from variation in mobility patterns that have no bearing on population density. However, it is also possible that the relatively small sample of radiocarbon dates hides fluctuations that match those in the later parts of the SSPD. It is thus an open question if the degree to which the proxies respond to and reflect population density and mobility patterns is stable throughout the Mesolithic, and if other variables might impact these (Rebuttal 6.2). Unpacking this will not least depend on also including independent measures for mobility patterns (Potential backing 5.3), but will benefit from drawing on multiple interrelated variables explicated by means of a causal graph (Potential backing 6.3).

5.5.1 Causal model for demographic developments

The fourth paper can thus be said to mainly provide a methodological framework for assembling and assessing the summed probability distribution of shoreline dated sites. With a comparison with the RSPD, this led to the development of some hypotheses pertaining to the relationship between the variables. This is presented as a DAG in Figure 5.9. It is important to underscore that given the narratively fashioned and highly speculative explanation for the patterns and divergent relationship between the proxies, the DAG presented here extends far beyond that which has been substantiated empirically and remains fairly unspecified in terms of the processes underlying it. Exploring and adjudicating between potential explanations will ultimately depend on drawing on the other variables in the DAG, and that adequate temporal and spatial resolution allows these to be meaningfully compared and contrasted.

The most proximal causes to the frequency of ^{14}C-dates and frequency of shoreline dated sites is suggested to be population numbers, mobility patterns and investigatory factors. Not indicated in the DAG is that it is hypothesised

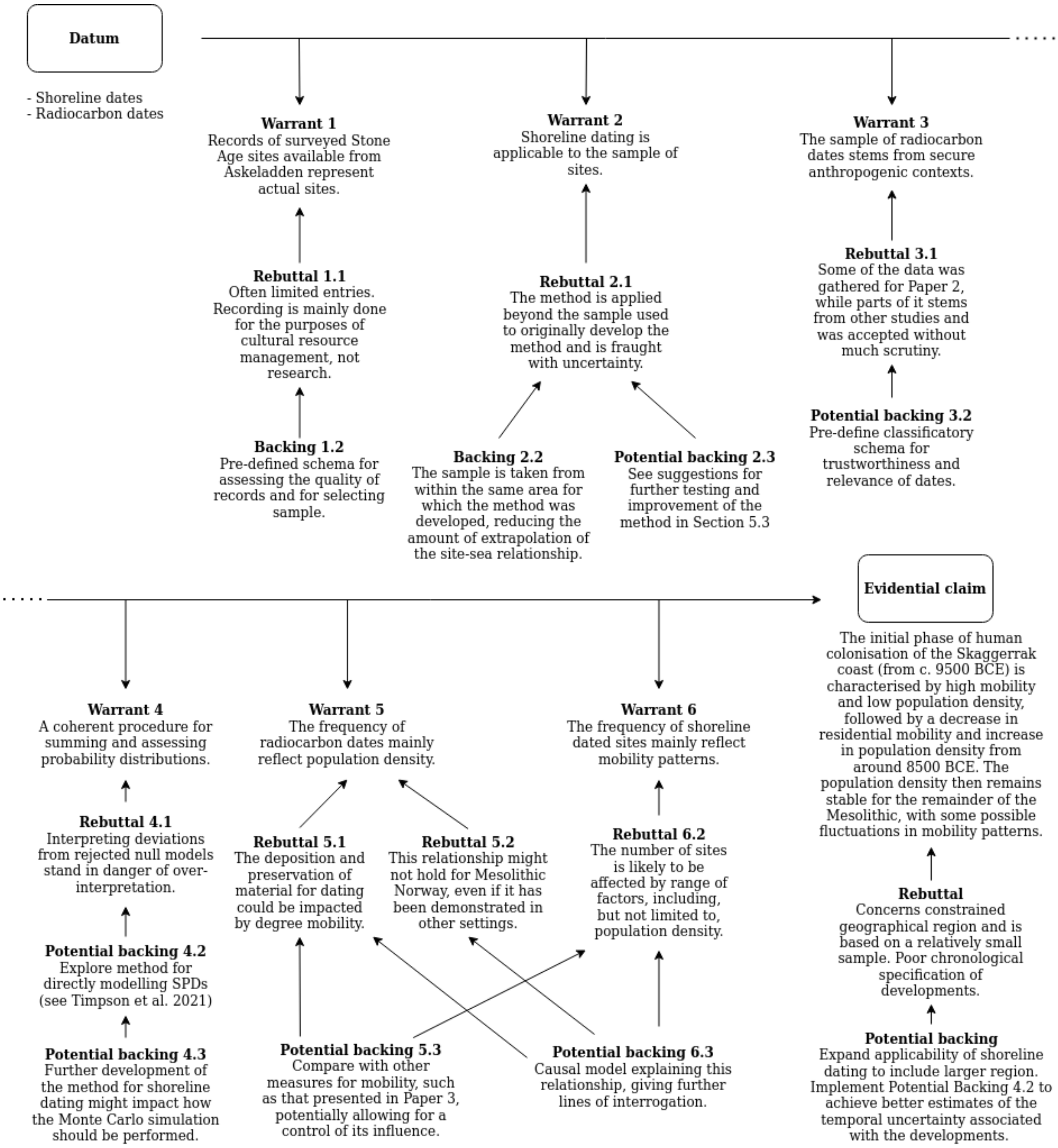

Figure 5.8: Argument schema for Paper 4.

that the frequency of shoreline dated sites is more heavily influenced by mobility patterns than population numbers. Furthermore, while the influence of mobility on the frequency of radiocarbon dates is thought to be small compared to population numbers, the absence of radiocarbon dates from the earliest parts of the Mesolithic, where we know people were present, would indicate that this is a non-zero effect. The node representing investigatory factors, on the other hand, is meant to pertain both to the range of ascertainment biases that are frequently discussed in the literature on RSPDs (e.g. Crema 2022; Rick 1987; Shennan et al. 2013) and those that might influence the frequency of shoreline dated sites that can be assigned certain time intervals. The binning of ^{14}C-dates, as mentioned above, is one way to try to reduce the influence of such ascertainment biases for the number of radiocarbon dates. However, as Crema (2022) has noted, this does lead to a case where focus is slightly shifted to being directed towards counts of the occupation of sites, rather than purely the number of radiocarbon dates. This shift in what is being counted could have implications for what underlying processes the analysis can unveil. When it comes to the SSPD, which is based on the shoreline dating of surveyed and excavated sites, a pertinent question would be if certain elevations are more intensely surveyed than others, which could bias the SSPD. Evaluations done by Persson (2014) and Solheim (2017b) found that different elevations were generally surveyed with equal intensity (Solheim and Persson 2018:340). However, as these only pertain to two fairly recent survey projects, a more principled evaluation of the degree to which this has been the case, also for earlier projects, would be beneficial to ascertain the degree to which such biases might influence any findings. The same also extends to whether certain elevations have been more intensely targeted by the expansion of infrastructure, which is the main determinant for where archaeological surveys are undertaken.

The purely narrative treatment of mobility patterns in the paper focused on the degree of residential mobility, which, following from Paper 3 and the suggestion of previous research, was argued to be reduced around 8500–8300 BCE. This has been suggested to follow from migratory events involving an influx of people from the east around the transition to the Middle Mesolithic c. 8300 BCE (see Section 2.2.2). Following this, if the results from Paper 3 are assumed to be trustworthy and applicable to the study area for Paper 4, this would indicate that degree of residential mobility then remains stable for the remainder of the Mesolithic. The fluctuations in the SSPD following the transition to the 7th millennium BCE was could therefore be related to other aspects of mobility, such as seasonal and territorial movement between inland and coastal areas (see Section 2.2.3).

Another central element in the DAG is the direction of the effect indicated between mobility patterns and population density. This follows from the empirical patterns that were indicated by the data. The dramatic drop in the SSPD appears to be followed by the first signal and increase in the RSPD, which culminates with a corresponding positive deviation in the SSPD. These developments are hypothesised to follow from the confounding effects of migratory events that lead to a reduction in residential mobility and increased population density. Given that the logistic model fit to the RSPD is stable following this, despite fluctuations in the SSPD, there are as of yet no direct empirical grounds on which to claim that there is any causal effect between the variables following this initial phase. A negative deviation in the RSPD from the logistic model around 6400 BCE does correspond to a negative deviation in the SSPD, but the deviation in the RSPD has to be disregarded given the failure to reject the logistic model – at least given the present data and modelling efforts. A potential, albeit highly speculative suggestion was nonetheless forwarded with the suggestion that this deviation could follow from an increase in inland utilisation at the expense of the coastal areas in this period (see also Section 2.2). With an increased resolution and size of the employed data set it is likely that the relationship between mobility patterns and demographic developments are best represented by series of nodes, reflecting the likely complex web of feedback effects that operate between residential mobility and population density (e.g. Jørgensen 2020b; Kelly 2013:209–213).

The suggested DAG also includes a node for environmental conditions. No direct consideration of this was made in the paper and the node is likely to represent a more complex web of interacting effects with factors such as oceanographic developments, precipitation and temperature changes having frequently been demonstrated to be of relevance for demographic developments in past hunter-gatherer populations (e.g. Hoebe et al. 2023; Jørgensen 2020a; Lundström 2023; Ordonez and Riede 2022). The rate of relative sea-level change is included as its own variable in the DAG as it was suggested in the paper that the rate of sea-level change might induce changes to settlement patterns without having any direct influence on population numbers. The rate of relative sea-level change can be directly derived from the displacement curves and can therefore readily be drawn on in future studies. Albeit somewhat limited, there do exist data for variation in other environmental dimensions through the Mesolithic of south-eastern Norway (see Solheim et al. 2020 with further references), and data for variation in sea-surface temperature is also available for the the mid- to late Holocene of Skaggerrak (Polovodova Asteman et al. 2018). In sum, these offer some potential potential avenues for exploring these issues further. Furthermore, if the framework from Paper 3 can be expanded upon and given a more solid evidential foundation, as also indicated in Potential backing 5.3 in Figure 5.8, this can be potentially be used to assess the SPDs while controlling for variation in mobility patterns.

The DAG presented for the fourth paper is clearly the less complete and most speculative of the ones present in this chapter. Several of the postulated mech-

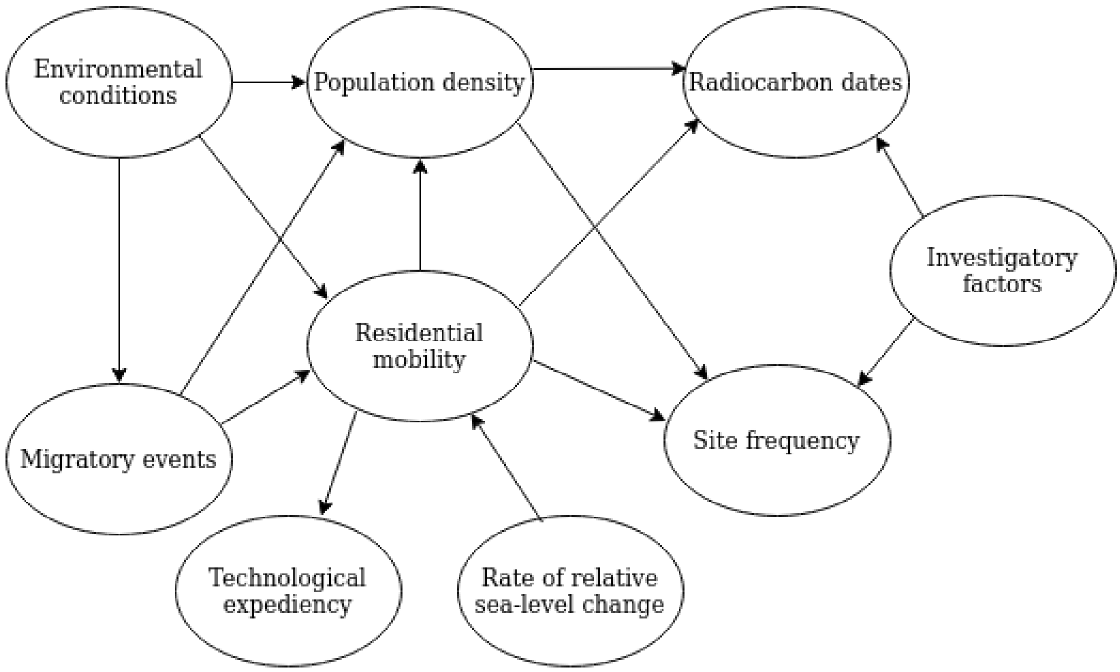

Figure 5.9: Suggested causal model for the drivers behind the frequency of radiocarbon dates and shoreline dated sites through the Mesolithic of south-eastern Norway.

anisms are likely missing mediating and potentially confounding variables that could be critical for properly understanding these relationships, and the question of temporal resolution is also critical following from the potential feedback effects that have been suggested to exists between several of these variables. The model nonetheless outlines an array of possible relationships to explore, all of which have some potential albeit uncertain avenues for fruitful operationalisation.

5.6 Chapter summary

This chapter has laid out the arguments and evidential claims that underlie each of the four papers of the thesis. Furthermore, developing explicit hypotheses have been argued by many to reduce accommodative argumentation, thereby reducing research bias, increasing reproducibility and potentially facilitate a move towards unveiling causality (see last chapter and e.g. Betts et al. 2021; Platt 1964). Consequently, the chapter also presented suggestions for causal graphs pertaining to the empirical patterns identified in the papers, aimed at offering some potential avenues for future research. While future studies will undoubtedly lead to the adjustment of these models, having explicitly laid these out can help focus and direct avenues of criticism and further research efforts, irrespective of the life-span of the models.

Chapter 6

Concluding remarks

Any attempt at describing or explaining the past involves imposing abstractions that will necessarily hide variation and idiosyncrasies that could prove to be both important and interesting. Quantification is one system of representation that allows stringent reporting and handling of uncertainty, while providing comparability and analytical feasibility for large amounts of data across multiple scales. Furthermore, the material that has been and continues to be generated by archaeology is getting increasingly vast, and any attempts at getting a basic overview, let alone draw inferences concerning past societal systems, require frameworks designed to handle this flood of information. Consequently, at the cost of reducing the archaeological record to the logic of numbers, quantification offers the potential to yield insights that are simply not achievable by other means.

Shennan (1988:1) quotes Colin Renfrew has having stated that 'the days of the innumerate are numbered'. However, Kristiansen (2004:80) later stated that quantitative methods were 'disastrously out of fashion' in archaeology. This picture has changed considerably since 2004 (e.g. Kristiansen 2014), and increased enthusiasm for such approaches need to be continuously tempered by a concern for the answers they can hope to answer, the nuances that they might subsume, and the intricacies involved with critically employing such methods in an informed manner. However, the potential of quantitative and computational approaches is arguably far from having being sufficiently utilised in Norwegian archaeology.

This thesis has shown some of the advantages quantitative methods can have. Through the four papers of the thesis, focus has in part been directed towards exploring and deriving methods that can be used to meaningfully handle the increasingly massive material associated with the Norwegian Mesolithic. In one sense, therefore, the thesis can be considered to have contributed to fundamental descriptive and exploratory tasks related to the first overarching research question posed in the introduction (see Section 1.2): i) What is the extent and quality of the archaeological record from Mesolithic Norway? However, as the second research question implies, the answer to this also have clear substantive implications: ii) What consequences does this have for our disciplinary agenda and for our understanding of the Norwegian Mesolithic? As is made clear both through the papers and this introductory text, the elucidated patterns can be directly related to societal dimensions such as patterns of settlement, mobility and demographic developments – all of which have been heralded as fundamental to our understanding of past hunter-gatherer societies.

Furthermore, the project was conducted within a framework of open science with all underlying data, text, and code being shared with the thesis. This was done both to allow others to assess the inner workings of the arguments being made, to extend methods and data to other contexts or research questions, and, in keeping with an epistemic modesty laid out in Chapter 4, to facilitate critical engagement. In the same vein, Chapter 5 laid out what I believe are the fundamental inferential steps taken in each of the papers, and presented the main findings of each paper as concrete hypotheses, instantiated as causal graphs. In presenting the central arguments and inferential leaps taken, the hope is both to facilitate and motive critical engagement, and pave the way for pursuing these issues in future research. Providing all underlying data and code, and laying out arguments and hypotheses as explicitly as possible is both a challenge in terms of attempting to expound what processes might have generated the data, and risky, in the sense that any mistakes, blind-spots or omissions will be easier to identify. However, at the price of putting academic pride at risk, there can be little doubt about the disciplinary benefits of clarity and transparency.

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Papers

Paper 1

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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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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ABSTRACT

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

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 created 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; Gjerde, 2021; Løken, 1977; Nordqvist, 1995; Schmitt et al., 2009; Sognnes, 2003; Tallavaara and Pesonen, 2020; Wikell et al., 2009).

The close association between Stone Age settlements in the northern parts of Scandinavia and shifting prehistoric shorelines was proposed at the end of the 19th century (De Geer, 1896), and was first applied as a dating method at the turn of the century (Brøgger, 1905; Hollender, 1901). Shoreline dating has been fundamental to Norwegian Stone Age archaeology ever since (e.g. Berg-Hansen, 2009; Bjerck, 1990, 2008a; Breivik, 2014; Johansen, 1963; Mansrud and Persson, 2018; Mikkelsen, 1975a; Mjærum, 2022; Nummedal, 1923; Olsen and Alsaker, 1984; Shetelig, 1922; Solheim et al., 2020; 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 number of surveyed sites that only contain generic lithic debitage that could hail from any part of the period, and as the conditions for the preservation of organic material is typically poor in Norway, dating with reference to shoreline displacement is often the only and most precise method by which one can hope to date the sites. Shoreline dating is consequently

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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 Fennoscandian 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 here is to quantify the degree to which the assumption of shore-bound settlement holds through the Stone Age in a relatively well sampled portion of Scandinavia, and in turn have this quantification inform the development of a formalised method for shoreline dating. As presented in more detail below, this problem involves the combined evaluation of three major analytical dimensions. One is the questions of when the sites were in use, the second pertains to the reconstruction of the contemporaneous sea-level, and the third follows from the fact that the relation between site and shoreline is inherently spatial. Taking inspiration from studies that have integrated various sources of spatio-temporal uncertainty through Monte Carlo simulation (e.g. Bevan et al., 2013; Crema et al., 2010; Crema, 2012, 2015; Yubero-Gómez et al., 2016), a similar approach is adopted here and adapted to post-glacial sea-level change and the Stone Age settlement of southern Norway.

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 isostasy. Eustatic sea-level is understood to be 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). Isostasy, on the other hand, pertains to adjustments in the crust to regain gravitational equilibrium relative to the underlying viscous mantle caused by mass loading and unloading, which occurs with glaciation and deglaciation. These effects 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 Fig. 1), the isostatic rebound has caused most areas of Norway to have been subjected 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 faster towards the centre of the ice sheet relative to the distal aspects. Thus, there is differential glacio-isostatic impact to a site's location depending on its relation to the ice sheet's centre of mass, leading some areas on the outer coast to 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 phases that are difficult to disentangle (e.g. Hagen, 1963; Reitan and Berg-Hansen, 2009). Transgression phases, on

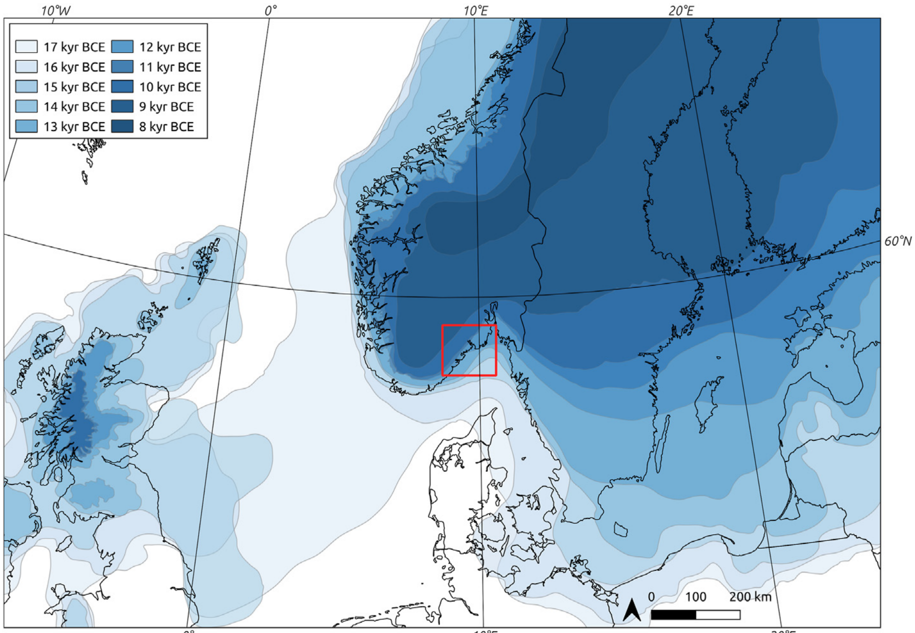

Fig. 1. Deglaciation at 1000-year intervals from c. 17–8 thousand years (kyr) BCE. The study area defined later in the text is marked with a red outline (deglaciation data from Hughes et al., 2016, but see also Romundset et al., 2019 in relation to the study area). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the other hand, can lead to complete destruction of the sites, bury them in marine sediments, or in the outermost periphery, submerge them (Bjerck, 2008a; Glørstad et al., 2020). Transgression can therefore lead to a hiatus in the archaeological record for certain sub-phases in the impacted areas despite the fact that there were likely coastal settlements during the inferred hiatuses. 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, 1957, 1983; Romundset et al., 2018; Sørensen, 1979). This makes the region especially useful for evaluating the assumption of a shore-bound settlement pattern over a long and continuous time span.

The method of shoreline dating has been met with scepticism as related to the fundamental premise that most sites would have been consistently shore-bound, it has been characterised as a relative dating method for sites located within a constrained geographical area, or it has been argued to offer no more than an earliest possible date for when a site could have been in use (see review by Nordqvist, 1999). The most common application in Norway has arguably been to use shoreline dating to provide an approximate date for the occupation of the sites, often in combination with other dating methods (see for example chapters in Glørstad, 2002, 2003, 2004; Jaksland, 2001; Jaksland, 2012a, 2012b; Jaksland and Persson, 2014; Melvold and Persson, 2014a; Reitan and Persson, 2014; Reitan and Sundström, 2018; Solheim, 2017; Solheim and Damlien, 2013 and below). Recently the method has also been used independently to date a larger number of sites to get a general impression of site frequency over time. This is done by aggregating point estimates of shoreline dates in 100-, 200- or 500-year bins (Breivik, 2014; Breivik and Bjerck, 2018; Fossum, 2020; Mjærum, 2022; Nielsen, 2021; Solheim and Persson, 2018; see also Jørgensen et al., 2020; Tallavaara and Pesonen, 2020). In his review, Nordqvist (1999) argues that there can be little doubt concerning the general applicability of the method—what is less clear is the level of reliability and chronological resolution that it can offer (see also Johansen, 1963, 1997; Mikkelsen, 1975b:100).

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

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

One of the more extensive evaluations of the relationship between archaeological radiocarbon dates and RSL-change was done by Solheim and colleagues (Breivik et al., 2018; Solheim, 2020), who compared 102 radiocarbon dates from 29 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 86.3% of the dates (Solheim, 2020:48). However, where there was a discrepancy, the main occupation of the sites is 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 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}C-dates. The evaluation of the relevance of radiocarbon dates to settlement activity will here therefore be entirely dependent upon 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 mass functions plotted against local shoreline displacement curves based on the elevation of the site (e.g. Åkerlund et al., 1995; Åstveit, 2018; Berg-Hansen et al., 2022; Solheim, 2020; see also Bjerck, 2008b; Kleppe, 1985; Ramstad, 2009). This approach has a couple of limitations. First, 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; Rosenvinge et al., 2022). 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 the conclusion supports the 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 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 identifying 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 (Fig. 2). This area has newly compiled displacement curves for Skoppum in Horten (Romundset, 2021), Gunnarsrød in Porsgrunn (Sørensen et al. in press; Sørensen et al., 2014a,b), Hanto in Tvedestrand (Romundset, 2018; Romundset et al., 2018), and Bjørnebu in Arendal (Romundset, 2018).

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

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

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

Three of the sites have been associated with agriculture, either directly or in the form building structures. The first is Nordby 1 at which the ^{14}C-dates are associated with a Late Neolithic long-house (Gjerpe and Bukkemoen, 2008). The Middle Neolithic phase at Kvastad A2 (Stokke and Reitan, 2018) and Late Neolithic phase at Nauen A (Persson, 2008) are both directly related to farming activities. Both of these sites also have radiocarbon dates and lithic inventory associated with Mesolithic forager activities. Following from the expected deviance from the settlement patterns that are

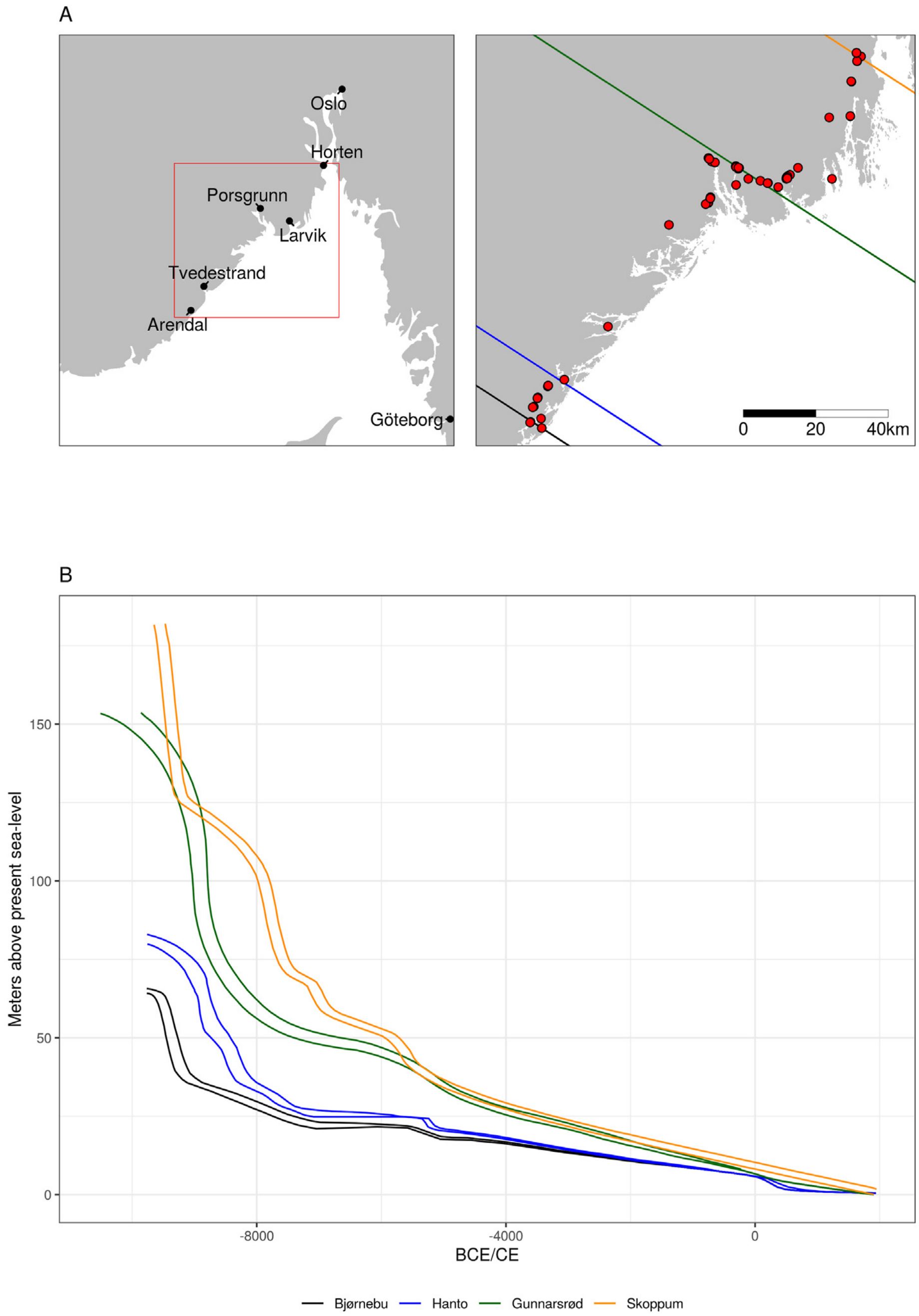

Fig. 2. A) Location of the study area and the distribution of the 66 analysed sites relative to the isobases of the displacement curves. The isobases have a direction of 327° (Romundset et al., 2018, although see Sørensen et al., 2014a). B) Displacement curves. Note the increasing steepness of the curves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

to characterise forager sites, these agricultural phases are highlighted in the analysis below. Finally, Nielsen (2021) has recently suggested that Early and Middle Neolithic features from the otherwise younger sites Bratsberg (Wenn, 2012) and Larønningen (Røberg, 2012) could be related to early agricultural activity in the Oslo fjord region. Due to the uncertain and somewhat speculative nature of this suggestion, these are omitted here.

The elevation data used for the analysis is a digital terrain model (DTM) freely available from the Norwegian Mapping Authority (Norwegian Mapping Authority, 2018; https://hoydedata.no). The 10 m resolution DTM was used rather than the higher-resolution 1 m version, both because this resulted in considerably less processing time and because the higher resolution elevation model is more vulnerable to smaller-scale modern disturbances. The 10 m resolution DTM of the study area is a down-sampled version of the 1 m version and has a height accuracy with a systematic error of 0.1 m (Norwegian Mapping Authority, 2018). All data and R programming code (R Core Team, 2021) required to run the analyses, as well as the derived data are freely available in a version-controlled repository at https://doi.org/10.17605/osf.io/7f9su, organised as a research compendium following Marwick (2017; Marwick et al., 2018).

4. Methods

Shoreline dating is based on the spatial relationship between two phenomena, occupation of sites and shoreline displacement, each associated with temporal uncertainty. The first task was therefore to ascribe a likely date and associated degree of uncertainty to these dimensions. To take account of the gradient in the isostatic rebound, the trajectory of shoreline displacement was first interpolated to each site location based on the distance to the isobases of the displacement curves, using inverse distance weighting (e.g. Conolly, 2020; Conolly and Lake, 2006:94–97). This was done for each year along the entirety of the curves, weighting the interpolation by the squared inverse of the distances. The result of this process is shown for an example site in Fig. 3. For 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 their date ranges intersected at 99.7% probability, meaning these were effectively taken to be associated with the same occupation event, here termed settlement or site phase. In the case where there are multiple dates believed to belong to a single settlement phase, these were modelled using the Boundary function in OxCal and then summed using the Sum function. Multiple phases at a single site were treated as independent of each other.

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

Armed with a likely date range for the occupation(s) of each site, an estimated trajectory of RSL 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 weighted by the posterior probability distribution of a given occupation phase of a site (Fig. 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 5 cm. 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

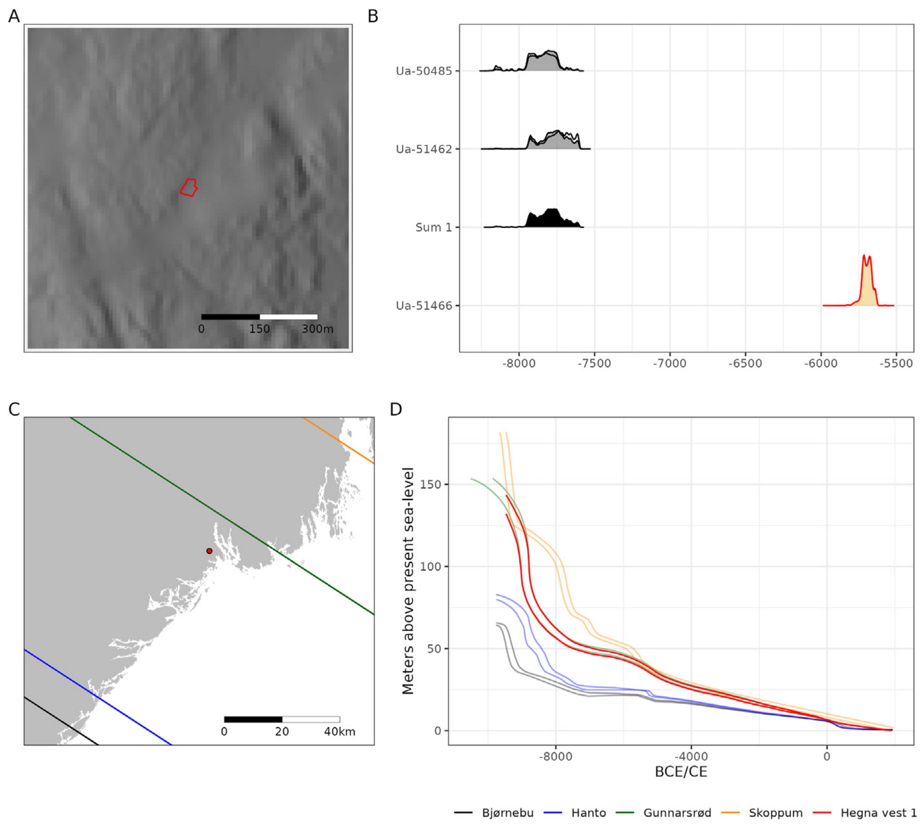

Fig. 3. Example site Hegna vest 1 (Fossum, 2017). A) Location of the site on the edited 10 m resolution DTM. The red outline is the site limit. B) Radiocarbon dates associated with the site. Fill colour indicates what dates are assumed to belong to the same settlement phase. Multiple dates are modelled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

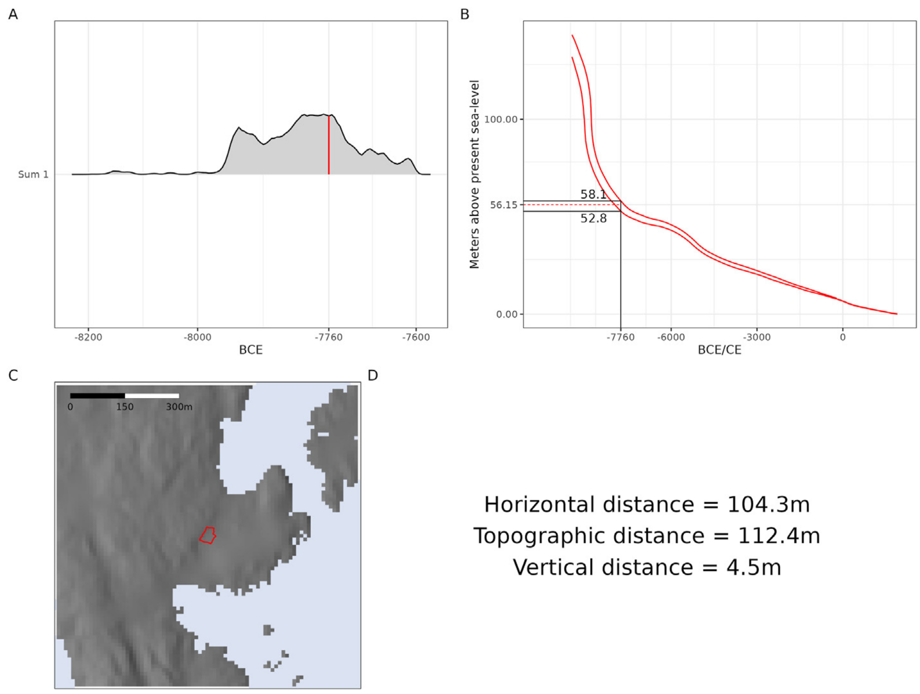

Fig. 4. Example of a single simulation run on the site Hegna vest 1. A) The simulation starts by drawing a single year, weighted by the posterior probability distribution. B) This then corresponds to an elevation range on the interpolated displacement curve. A single elevation is drawn uniformly from this range using 5 cm 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.

measuring the distance while taking into account the slope of the terrain on the DTM. This was done using the topoDistance package for R (Wang, 2019). The topographic distance was measured between the points on the site and sea polygons that were identified as being the closest when measured horizontally. Because it is measured as the shortest topographic path between the horizontally closest points, this means that the distance does not necessarily match the closest topographic distance if the entirety of the polygons had been considered. Not finding the topographically closest points significantly reduced the computational cost of the analysis, and is deemed unlikely to have a considerable impact on the results, given the distances considered. The shortest topographic path was found using the Moore neighbourhood of eight cells (e.g. Conolly and Lake, 2006:253; Herzog, 2013).

In the case where the sea polygons intersect the site polygon, all distance measures were set to zero. In the case that the sea polygons completely contain the site, the horizontal and topographic distance measures were made negative, and the vertical distance was instead measured to the highest point on the site polygon. While it is safe to assume that an archaeological site was not occupied when it was located below sea-level, a negative result can reflect the inherent uncertainty in this procedure, and might also help identify discrepancies in displacement data or radiocarbon dates. Negative values were therefore retained except 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 (Fig. 5). The choice of 1000 simulation runs follows from an evaluation of when the mean distances between site and shoreline converged when running 5000 iterations of the simulation on the site Hovland 5 (cf. Crema et al., 2010:1125). This evaluation is presented in the supplementary material. Hovland 5 was chosen for this assessment as it has an imprecise age and is located in area of quite complex topography (Mansrud and Koxvold, 2013).

5. Simulation results

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

Another immediately striking result is the apparent deviation from the shoreline towards the end of the Stone Age. Of the results from after 2500 BCE, which are associated with 8 sites, only one has simulation results for vertical distance that includes zero. The highest simulated vertical distance among these is 56.5 m and the median is 12.9 m. Furthermore, some deviation from the shoreline is evident from just after 4000 BCE as well. Of the 21 sites associated with the period between 4000 and 2500 BCE, two sites have all vertical distance results above 25 m. However, the median vertical distance of the results from this period is only 4.3 m, indicating that

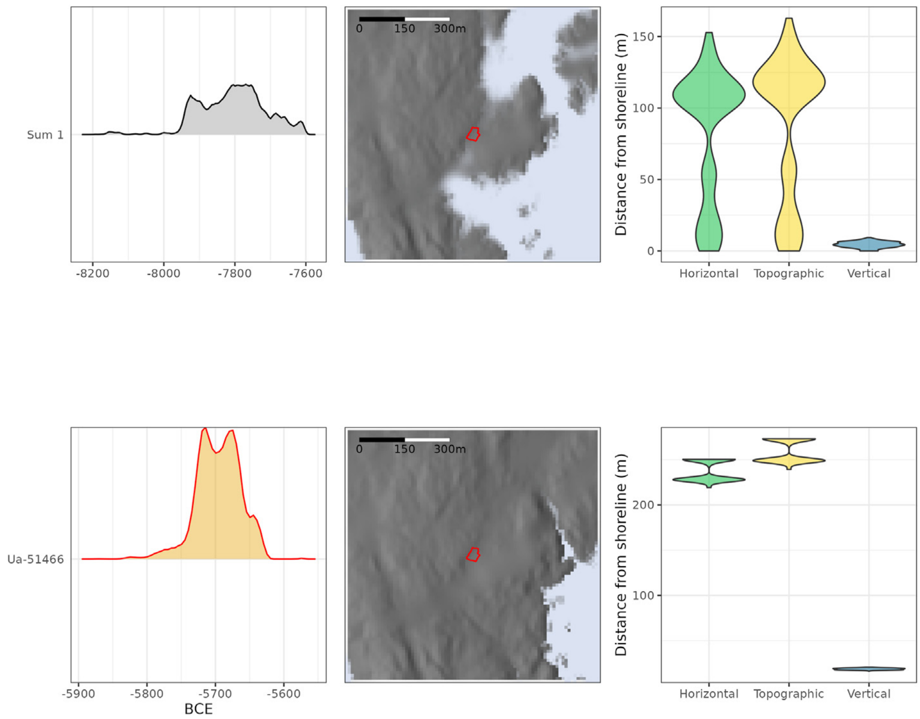

Fig. 5. The result of 1000 simulation runs for each of the two groups of dates on the site Hegna vest 1. The leftmost column of plots shows the calibrated radiocarbon probability distribution from where dates were drawn during simulation. The centre column displays the result of simulating the raised sea-level 1000 times. The more opaque the colour appears, the more times the sea-level was simulated in that location. The rightmost column shows violin plots of the different distance measures across all simulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

while some sites have a markedly withdrawn location, most are still situated close to the shoreline. The chronological smearing following from the uncertainty in the ^{14}C-dates means that while the results cannot be used to directly inform discussions that deal with the century scale around these chronological transitions (e.g. Prescott, 2020; Solheim, 2021), the findings are nonetheless in clear agreement with the general chronological developments suggested in the literature.

The negative values around 8000 BCE originate from the sites Løvås 1, 2 and 3. Berg-Hansen et al. (2022:644) made a similar observation in their assessment of the correspondence between shoreline displacement and radiocarbon dates from these sites. The sites are recently excavated, well-dated and are situated in a relatively undisturbed area of the landscape (Berg-Hansen et al., 2022; Reitan and Hårstad, 2022). While there could 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 an upper constraining limit for the sea-level, as they would not have been in use when located under water. It therefore seems that the Løvås sites represent a case where the archaeological material indicates a slight discrepancy in the geologic reconstruction of shoreline displacement in the area.

Accepting that shoreline dating appears to lose utility around the transition to the Late Neolithic, as indicated by the clear deviation in site location from the shoreline after this, the results from Fig. 6B are presented again in Fig. 7A, 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 sites and shoreline for the pre-Late Neolithic is given by the median distance of 4 m, while 95% of the values fall within the range 0–18 m. That is, for 95% of the cases, the shoreline was simulated to be situated on or less than 18 m below the site location. While these values remain the same when only the Mesolithic dates are included (Fig. 7B), the mean and standard deviation are slightly constrained. Furthermore, while the median for horizontal and topographic distance is only 10 m across all plots in Fig. 7, the relative magnitude of the statistics for dispersion is greater than what it is 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.

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

The performance of the models was then compared by means of the Akaike information criterion (AIC) and the Bayesian (or Schwarz) information criterion (BIC). The AIC and BIC evaluate the degree to which the models fit to the data, while penalising for the number of model parameters to avoid over-fitting (e.g. Burnham and Anderson, 2002; for applications in archaeology see e.g. Eve and Crema, 2014; Timpson et al., 2021). As lower values point to

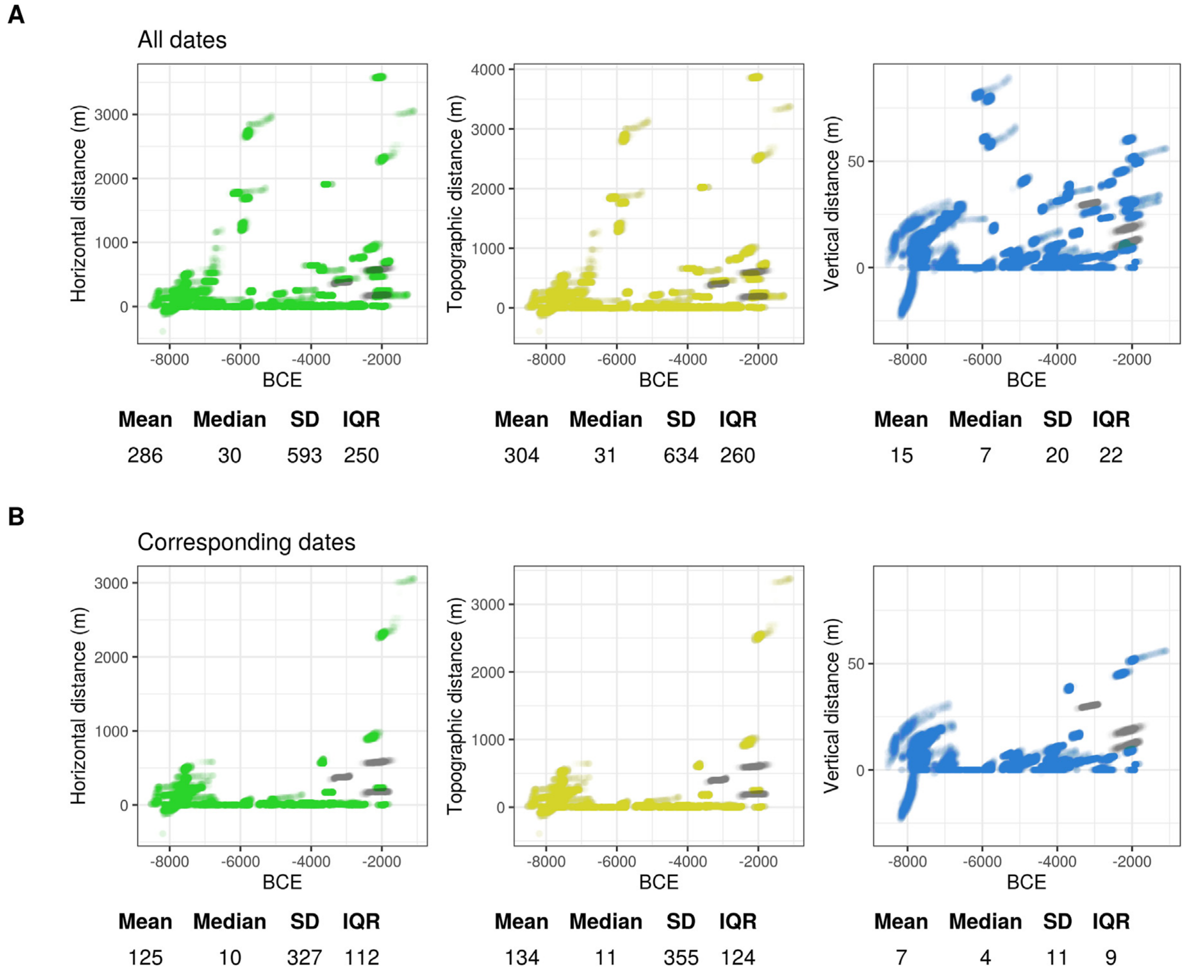

Fig. 6. The result of running the analysis across all sites. Each data point is plotted with some transparency, meaning that the more intense the colour, the more often those values occurred. Results associated with agricultural activities are plotted in grey. The first row A) shows the result of including all dates to the Stone Age, including those seen as otherwise unrelated to the main occupation of the sites (66 sites and 166 site phases). The second row B) shows the result of excluding these (resulting in 51 sites and 69 site phases). The table under each plot lists some corresponding statistics for central tendency and dispersion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a better model, it is evident from both the AIC and BIC that the gamma is the best among the candidate models. It is worth noting that this could have benefited from a more sophisticated treatment of the zero-values. This is because these are likely to be a mix of both exact zeros, the case when there is an actual intersection between site and sea, and, although probably to a far lesser extent, zeroes that result from the case when the distance between site and sea is below the detection limit due to the employed methods and the resolution of the spatial data (e.g. Dunn and Smyth, 2005; Helsel, 2005). In conclusion, however, the gamma appears to represent a reasonable approximation of the data. If one accepts this, the probability density function for the gamma distribution can be used to characterise the vertical distance between sites and the shoreline and be used to inform a method for shoreline dating that takes this into account.

6. Shoreline dating

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

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

where α is the shape and σ the scale of the distribution, and $\Gamma(\alpha)$ denotes the gamma function. This can then be coupled with the trajectory of relative sea-level change to find the corresponding calendar date T for the occupation of the site. This is defined by a discrete uniform probability mass function (Ud) on the calendar scale 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:

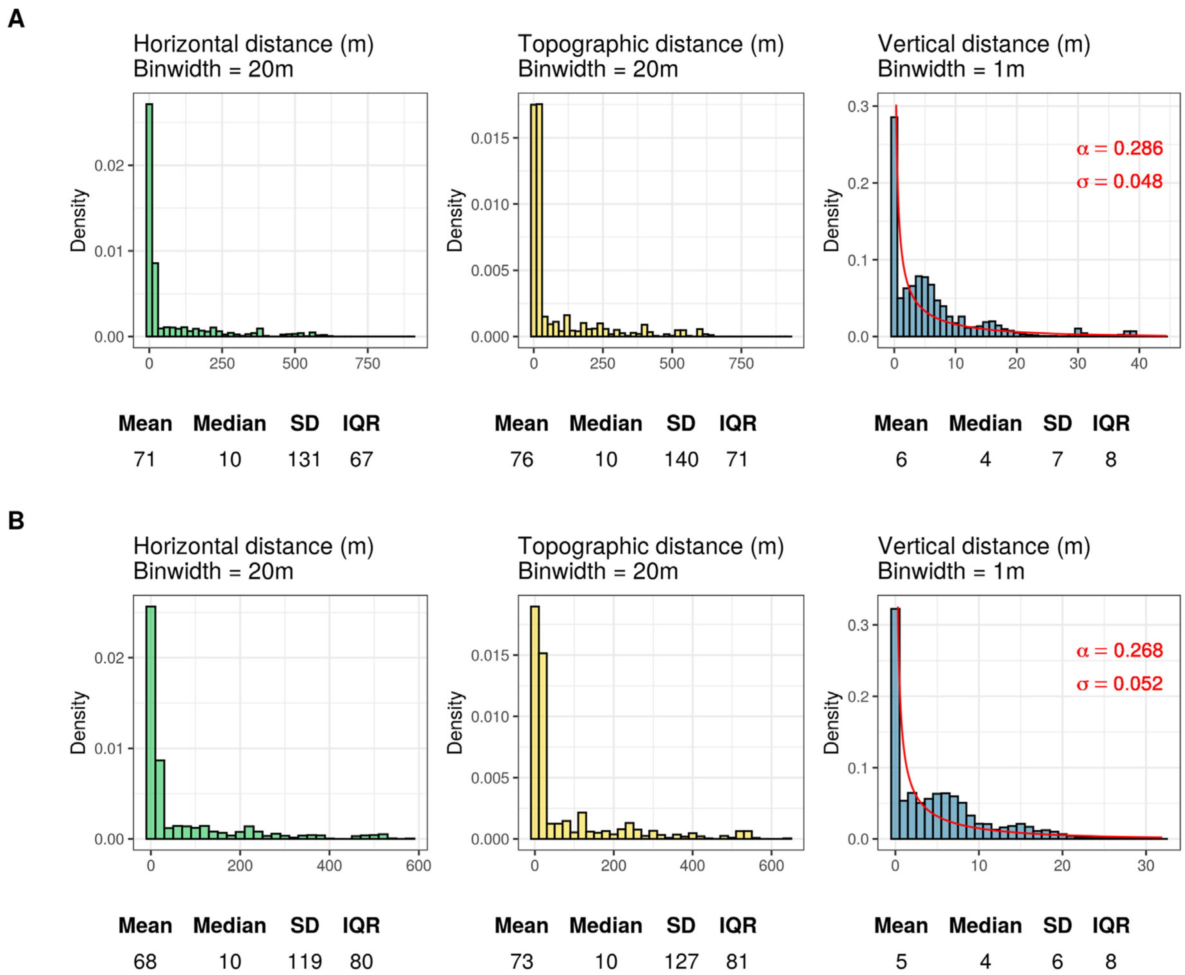

Fig. 7. Histograms showing the simulated distance from the shoreline using radiocarbon dates corresponding to the site inventories. Negative values have been set to zero. A) Simulated results older than 2500 BCE (50 sites and 66 site phases) and B) simulated results older than 4000 BCE (43 sites and 51 site phases). Note that the cut-off is done based on the calendar year associated with each distance value. Consequently, sites and site phases are only completely excluded if the entire posterior probability of the radiocarbon dates falls later than the cut-off. Furthermore, the superimposed gamma distributions have been fit when adding a constant of 0.001 to the distance values and have been cut off on the y-axis for visualisation. The gamma distribution in A forms the basis for the analysis to follow, but a version has also been fit to the vertical distances in B to further illustrate the difference between the distributions.

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

Model	Parameters	AIC	BIC
Gamma	Shape (α) = 0.286 Scale (σ) = 0.048	230,247	230,229
Log-normal	Mean of the logarithm (μ) = −0.647 SD of the logarithm (σ) = 3.926	268,082	268,064
Power law	Exponent (k) = 1.16	274,052	274,043
Exponential	Rate (λ) = 0.168	348,484	348,475
Logistic	Location (μ) = 4.698 Scale (σ) = 3.558	415,322	415,304

$$p(T|E-D) = Ud\left[T_{l|E-D,} T_{u|E-D}\right] \tag{2}$$

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:

$$p(T|E-D) = p(T|E-D)p(E-D) \tag{3}$$

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

$$p(T|E) = \sum_D p(T|E-D)p(E-D) \tag{4}$$

An example of an implementation of the outlined approach is given in Fig. 8, where $\alpha = 0.286$ and $\sigma = 0.048$. These are the parameters for the gamma distribution identified when considering all pre-Late Neolithic simulation results (Fig. 7A) and are the parameters used in all applications of the proposed method that follow below. For the numerical implementation, D is here stepped through as a sequence of increments of 0.001 m, which, following from the adjustment of the values for fitting the compared models, starts from 0.001 m. The gamma distribution is stepped through in its cumulative form, where the probability from the previous 0.001 m step is subtracted from the probability at the current step. This probability is then divided equally across the individual calendar years in the range between the lower and the upper limit of the displacement curve at the current 0.001 m step. The probability mass function that is the resulting shoreline date is the sum of performing this procedure on all possible 0.001 m values of D,

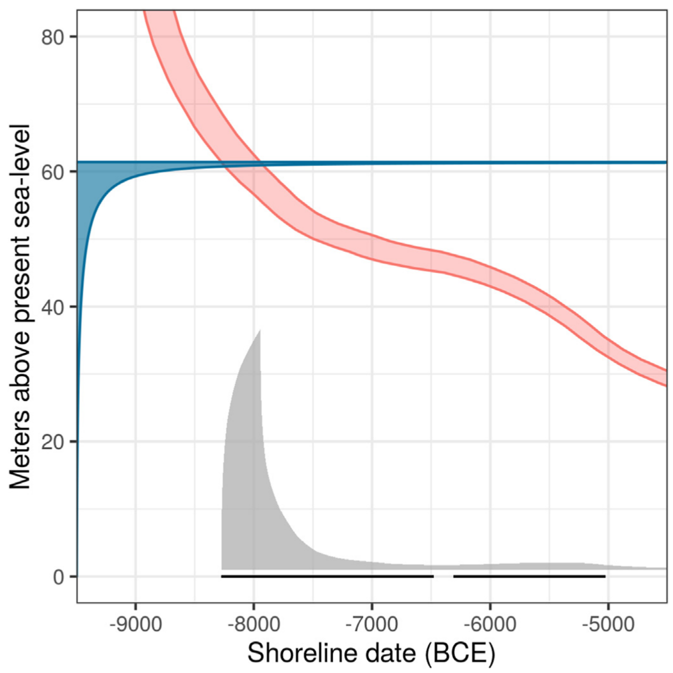

Fig. 8. Shoreline dating of Hegna vest 1. The mean elevation of the site polygon is used to inform E in the dating of the site. The gamma distribution in blue on the y-axis extends the full range of possible values for $E - D$ and has the parameters $\alpha = 0.286$ and $\sigma = 0.048$ (see Fig. 7A). The red envelope marks the shoreline displacement curve interpolated to the site location. The resulting shoreline date in grey is underlined with the 95% HDR in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

which, in practice, is down to and including $E - D = 0.001$ or when 99.999% of the gamma distribution has been stepped through.

To evaluate the outlined procedure, it is used to shoreline date the sites from where the method was derived to check if the resulting shoreline dates correspond to the radiocarbon dates associated with the sites (Fig. 9). The Late Neolithic sites are also included here for illustrative purposes, even though these have not informed the gamma parameters in use. 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 variation in elevation over the site limits. The synchroneity between radiocarbon and shoreline dates was then evaluated using the method presented by Parnell et al. (2008). Here, 100,000 age samples drawn from the probability mass function of each shoreline date were subtracted from 100,000 age samples drawn from the corresponding probability mass function of the modelled ^{14}C-dates. The resulting range of the 95% highest density region (HDR, Hyndman, 1996) was then checked to see if it crosses zero, in which case the dates are considered to be in agreement (Fig. 10). When excluding the earliest occupation phase at Gunnarsrød 5, the deviation of which is to be expected based on issues with the DTM (see above), the shoreline date corresponds to the radiocarbon dates in 64 out of 68 cases (93%). Only including dates modelled to be older than 2500 BCE with 95% probability, i.e. older than the Late Neolithic, improves this to 60 out of 62 cases (97%). When only including dates older than 4000 BCE with 95% probability, i.e. only Mesolithic site phases, the success rate is further increased to 49/49 (100%).

7. Re-dating previously shoreline dated sites

To further explore the implementation for shoreline dating presented above, 87 excavated and shoreline dated Stone Age sites within the study area where ^{14}C-dates are not available or these are not believed to date the main occupation of the sites have been subjected to the outlined approach (Fig. 11). The resulting dates are compared to those originally proposed in the excavation reports for the sites (the numerical results are available in the supplementary material). 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. As all of the included sites have been excavated after the turn of the millennium, and the wide adoption of GNSS technology, the reported elevations should be trustworthy.

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

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

With these considerations in mind, the results also indicate that shoreline dating has at times been applied with an exaggerated degree of precision. While the implications of a more stable RSL-change for shoreline dating are well known, this also appears to be somewhat under-appreciated in the practical implementation of the method. The results indicate that the spatial and temporal contingency of the method is better captured by the implementation suggested here, as is illustrated by the variation in the range of the 95% HDRs for the dates. In some cases the proposed method provides a relatively precise date and in others the HDR 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 dates (cf. Fig. 2B). However, as some of the 95% HDRs extend well beyond major chronological divisions, even into the Iron Age, it is also clear that some of these could be severely and securely constrained with only cursory reference to typology. While this would be trivial in some cases, the nature and uncertainty inherent to the method still means that this is arguably an exercise that should be explicitly performed. This also points to the possibility of drawing on other temporal data to further improve the precision of the dates that can be achieved with shoreline dating.

Not least following from the fact that relatively few ^{14}C-dates older than c. 8000 BCE associated with anthropogenic activity have been achieved in Norway (Åstveit, 2018; Damlien and Solheim, 2018; Kleppe, 2018), the shoreline dating of the earliest sites is

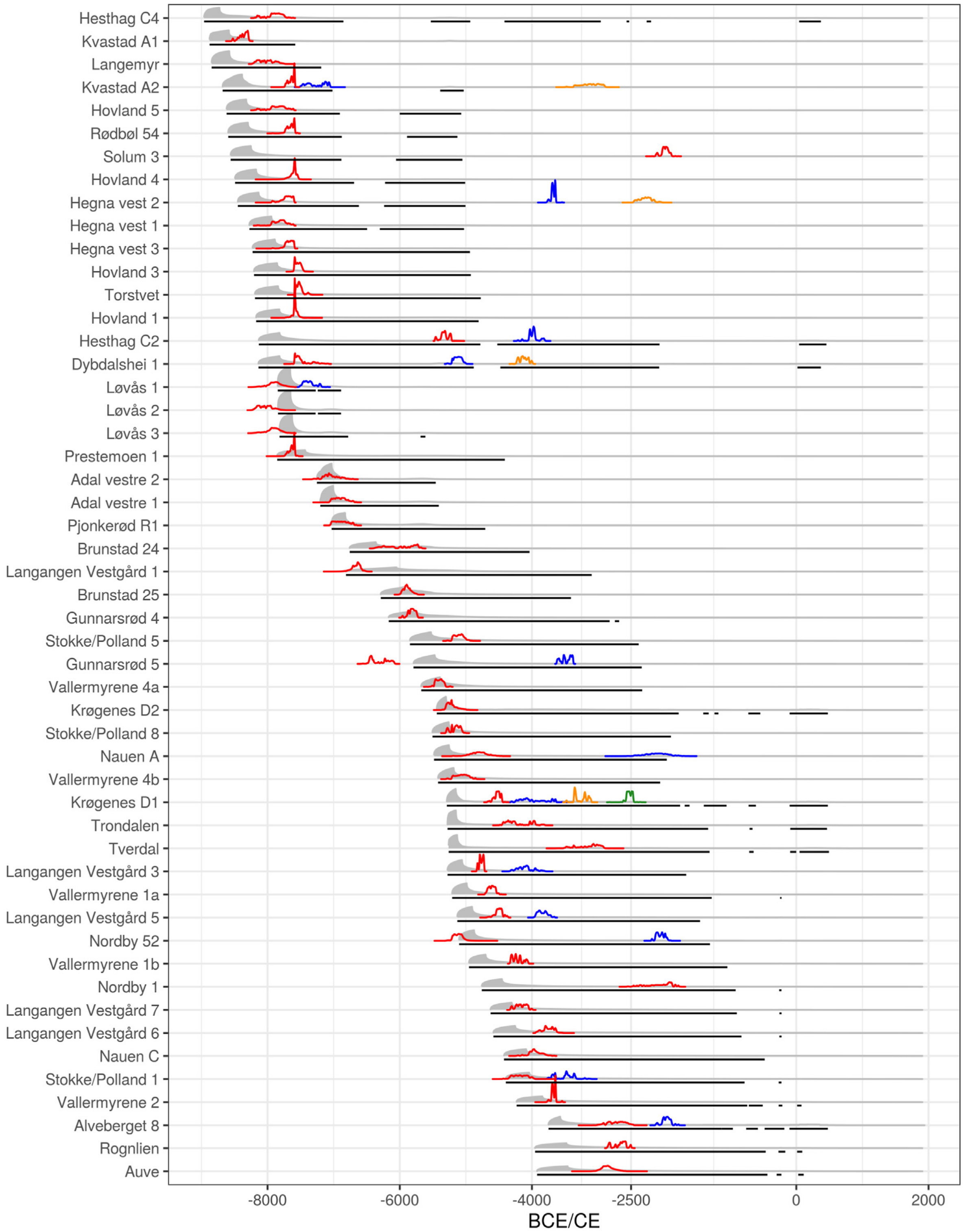

Fig. 9. The result of backwards shoreline dating the 51 sites with radiocarbon dates corresponding to the artefact inventory using the method proposed here. The shoreline dates are plotted in grey and underlined with the 95% HDR in black. These are plotted against the modelled radiocarbon dates, which are given colour from oldest to youngest occupation phase for each site, defined by non-intersecting dates at 99.7% probability. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

essential for understanding the pioneer settlement and the initial colonisation of the Scandinavian peninsula (e.g. Bang-Andersen, 2012; Berg-Hansen, 2018; Breivik, 2014; Fuglestvedt, 2012; Glørstad, 2016). The shoreline dated Preboreal 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 use of the sites would have been

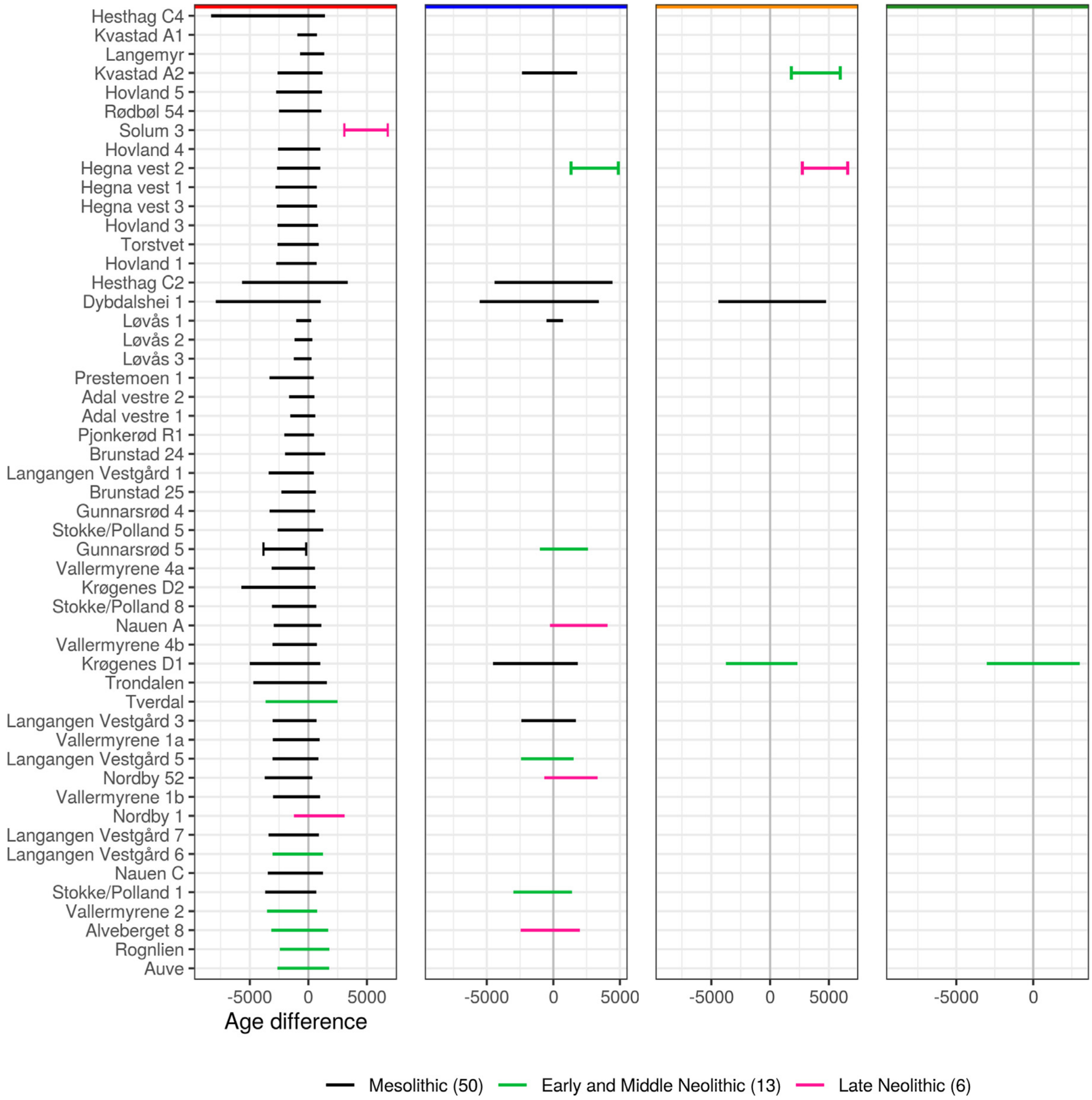

Fig. 10. Evaluation of the agreement between the shoreline dates and radiocarbon dates given in Fig. 9. When the range of the 95% HDR for age difference crosses zero, the shoreline and radiocarbon dates are considered to be in agreement. Line segments with vertical bars indicate that the HDR does not 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 Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

difficult after the sea retreated any significant distance from their location due to accessibility. 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 Fig. 12A. The sites have been dated using what Jaksland (2014) gives as the lowest elevation of finds at each site.

The small discrepancies between the achieved results mainly follow from the fact that a slightly updated version of the local displacement curve is applied here (Sørensen et al. in press; cf. Sørensen et al., 2014a). 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 his 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 do not overlap. This information is not integrated in the approach outlined here, but it could justify further reducing 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 suggested that additional temporal data could be combined with the method to improve its precision. Drawing on Jaksland (2014), this example instead highlights the fact that the spatial nature of the method means that a consideration of the surrounding terrain and other sites can also help to increase the precision of the method if this can be used to exclude certain RSLs as unlikely for when a site was in use. One potential way to do this

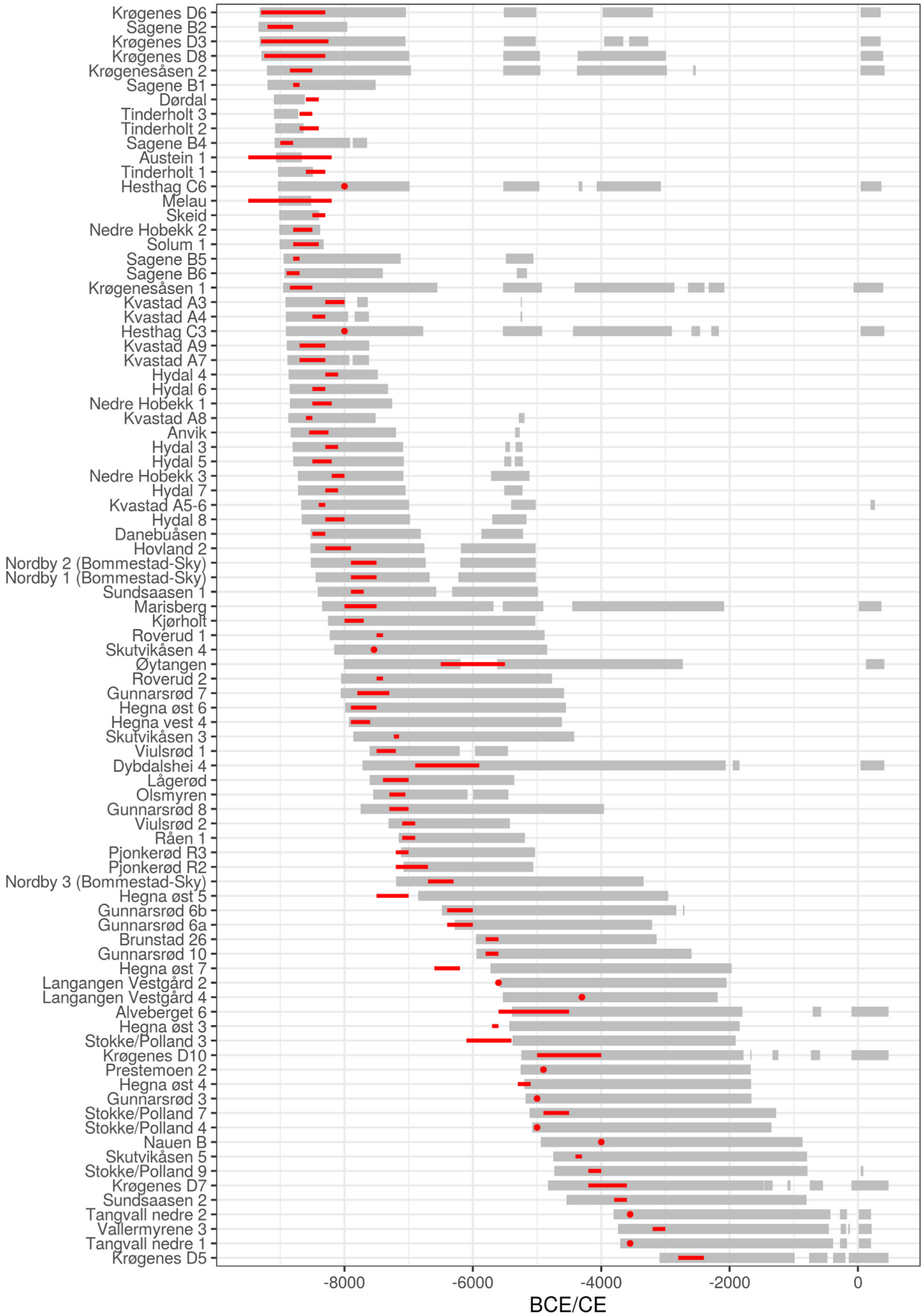

Fig. 11. Re-dating 87 excavated and previously shoreline dated sites in the study area without radiocarbon dates or with radiocarbon dates that do not correspond to the artefact inventories. The 95% HDRs in grey are compared to the dates originally proposed by the excavation reports in red. For clarity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

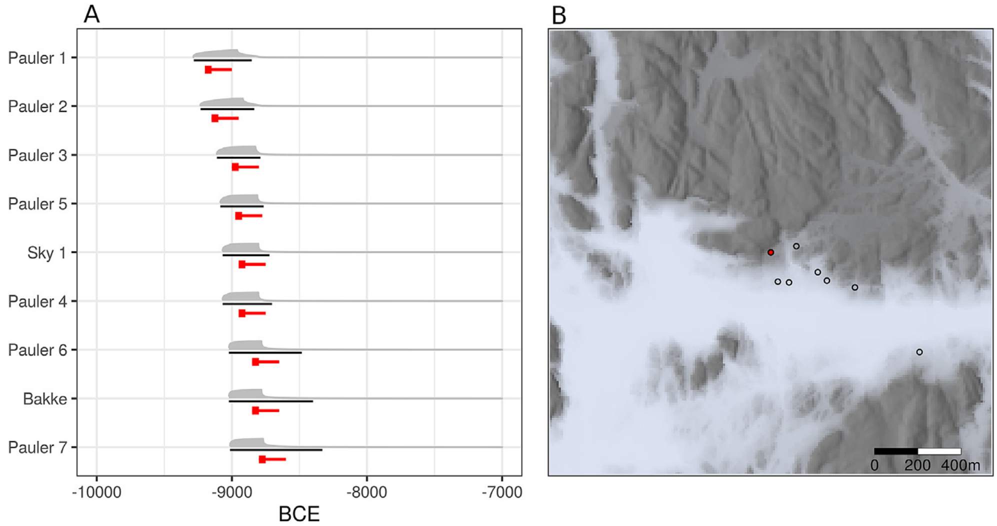

Fig. 12. Shoreline dating of the Brunlanes sites using site altitudes provided by Jaksland (2014:tab.4). A) The result of applying the approach to shoreline dating outlined above. The shoreline date in grey is underlined with the 95% HDR in black. Dates provided by Jaksland (2014) are plotted in red. 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be through the analysis of phosphate concentrations in soils, which has the potential to offer insights on the likely position of the shoreline when a site was in use (Ilves and Darmark, 2011). This has been done in the Baltic Sea region (e.g. Broadbent, 1979; Ilves and Darmark, 2011; Sundström et al., 2006), but has yet to provide reliable results in Norway (e.g. Melvold and Persson, 2014b; Viken, 2018). The identification of other physical traces of shore formation processes and the deposition of beach sediments in relation to archaeological material also holds similar potential (e.g. Bondevik et al., 2019). Finally, another 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 Fig. 12B, followed for example by a visual evaluation of the topography or by evaluating the distance and steepness of the slope to the shoreline. If such methods are developed further, it could conceivably be possible to exclude certain elevations as unlikely for the position of the shoreline when the site was in use. Such approaches would make less of an impact for the Brunlanes sites, where the 95% HDRs are already quite constrained, but could considerably improve the precision of the method in cases where RSL-change has been less severe (cf. Fig. 11).

8. Concluding remarks

The most significant finding of this paper is a confirmation of previous research into the relation between coastal Norwegian Stone Age sites and the prehistoric shoreline. This is indicated by the close proximity of sites and the shoreline until the transition to the Neolithic at c. 4000 BCE, after which a few sites are situated some distance from the sea, followed by a more decisive break at the transition to the Late Neolithic at c. 2500 BCE. This development is in clear agreement with the literature. Furthermore, based on the quantitative nature of these findings, an initial formulation of a refined method for the shoreline dating of pre-Late Neolithic Stone Age sites has been proposed. Apart from taking the distance between sites and the isobases of the displacement curves into consideration when dating the sites, this involves accounting 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 gamma distribution with a shape of 0.286 and scale of 0.048 (Fig. 7A) to characterise this relationship. Furthermore, while this remains to be formalised and explored further, it was also demonstrated how the method could potentially be improved by including more information on both the topographic location of the sites and other temporal data. To the degree that making such a distinction is useful, this could be derived from assessments of both a qualitative and quantitative nature, with Bayesian inference forming a natural framework for integrating such considerations (e.g. Buck et al., 1996; Otarola-Castillo et al., 2023). As the precision of the method is 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, the impact of such additional information will also vary.

Future investigations and radiocarbon dates from Stone Age sites in the region can not only be used to further evaluate 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. For example, from Fig. 7 it is clear that the Mesolithic sites have generally been located closer to the shoreline than the later sites. It was not attempted to explore this further here, given the constrained sample size and the accuracy that was achieved with the parameters in use. However, the future addition of more data might give justification for using different models or parameter settings when dating sites from certain time intervals. Furthermore, following from its behavioural nature, it is also likely that dimensions such as the nature and purpose of visits to the sites will have implications for how close to the shoreline the sites were located. This is illustrated here by the site phases associated with agricultural activity, marked in Fig. 6, which were all found to be located some distance from the sea. A wide range of different behavioural dimensions could potentially provide nuance to how the method should be applied.

Other factors related to the topographic location of the sites could also be similarly explored. This for example pertains to the exposure of sites to wave action, which is likely to have been of concern (Roalkvam, 2020), and which presumably has implications for how close to the shoreline people settled. This is also related to the fact that while the mean sea-level is used for dating the sites, a consideration of the tidal range and potential impact of storm surges could also have implications for the location of a site relative to the shoreline, depending on the topography (Bondevik et al., 2019; Helskog, 1978). The potential of exploring such dimensions was also hinted at here with the estimation and cursory treatment of the horizontal and topographic distance to the shoreline. If patterns related to such locational patterns can be discerned and unpacked, this will not least be useful for improving the shoreline dating of sites which have only been surveyed and where little information beyond their location is available. A mention should also be made here of the fact that catastrophic events such as tsunamis might also be of relevance (e.g. Blankholm, 2020; Nielsen, 2020; Nyland et al., 2021). Evidence for the impact of tsunamis in the Stone Age has not been identified in south-eastern Norway as of yet (see Romundset et al., 2015:398; cf. Romundset et al., 2018; Sørensen et al., 2014a), and might therefore not be of direct relevance to the coastal settlement in the region. However, the outburst flood resulting from the catastrophic drainage of the glacial lake Nedre Glomsjø around 8500–8000 BCE (Høgaas and Longva, 2019), located in Mid-Norway some 230 km north of present-day Oslo, could have had consequences for how the coast was utilised (Solheim et al., 2020:9).

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

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

As the nature of the relationship between sites and sea is likely to vary temporally and geographically (e.g. Nyland, 2020), the proposed implementation and parametrisation of shoreline dating cannot be expected to be directly applicable elsewhere. When this is combined with the fact that the rate of RSL-change also varies geographically and temporally (e.g. Svendsen and Mangerud, 1987), this means that the accuracy and precision of the method will also vary. However, the methodological framework used to evaluate the relationship between sites and sea is readily extendible to other regions of northern Scandinavia where reliable data on shoreline displacement is available, thus making such extensions feasible. Furthermore, the simulation approach used to integrate multiple sources of spatio-temporal uncertainty was used here to inform the question of the distance between sites and the shoreline. However, this method and general framework 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 shoreline, and the uncertainty inherent to this reconstruction.

Contributions

Isak Roalkvam: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and programming scripts used for the analysis is openly available in a online repository at https://doi.org/10.17605/osf.io/7f9su

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2022.107880.

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Corrigendum to “A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast” [Quaternary Science Reviews 299C (2023) 107880]

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When this paper was originally published, there was a notational error in the parameters for the gamma distributions. The gamma can be parametrised with either a ratio or a scale parameter, with the ratio being the inverse of the scale. While the ratio was used for the computations, this was erroneously stated to be the scale in the paper. All places where a value for the scale is provided (Tab. 1, Fig. 7 and pages 10, 11 and 15), this is correct if 1 is divided by the provided value. For the proposed method for shoreline dating, the scale is therefore not 0.048 but 1/0.048, or 20.833 when rounded to the third decimal. This error only occurred in the description of the findings and the proposed method. Code, results and visualisations are unaffected.

The author would like to apologise for any inconvenience caused.

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Paper 2

shoredate: An R package for shoreline dating coastal Stone Age sites

shoredate: An R package for shoreline dating coastal Stone Age sites

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Summary

As a result of glacio-isostatic rebound, large regions of Fennoscandia have undergone a process of relative sea-level fall following the retreat of the Fennoscandian Ice Sheet. Furthermore, coastal Stone Age sites in the region appear to have been predominantly located on or close to the shoreline when they were in use. Based on their altitude relative to the present-day sea-level, this can be combined with a reconstruction of past relative sea-level change to assign an approximate date to when the sites were in use. This method, called shoreline dating, has been used in the region since the early 1900s (e.g. Brøgger, 1905) and is still widely applied today (e.g. Manninen et al., 2021; Solheim & Persson, 2018).

Statement of need

`shoredate` is an R package developed for shoreline dating Stone Age sites on the coast of south-eastern Norway, based on local geological reconstructions of past relative sea-level change. Drawing on an empirically derived estimate of the likely elevation of the sites above sea-level when they were in use, the method for shoreline dating implemented in the package was recently published in Roalkvam (2023). No open-source software with which to perform shoreline dating currently exists. The only closed-source software available is `sealev` from the University of Tromsø, Tromsø Geophysical Observatory (https://www.tgo.uit.no/sealev/, see Møller, 2003), which can provide non-probabilistic point estimates of shoreline dates based on data last updated in 2002.

`shoredate` is aimed at providing researchers and students dealing with the coastal Stone Age of the region with tools for performing and handling shoreline dates. This complements software for handling radiocarbon dates and other sources of temporal data, such as the R packages `rcarbon` (Crema & Bevan, 2021), `bchron` (Haslett & Parnell, 2008), `oxcAAR` (Hinz et al., 2021), `kairos` (Frerebeau, 2022) and `ArchaeoPhases` (Philippe & Vibet, 2020), as well as closed-source software such as `OxCal` (Bronk Ramsey, 2009).

Shoreline dating is frequently applied in the research and cultural resource management sectors in Norway, both to plan archaeological investigations and for establishing temporal frameworks with which to analyse the archaeological material. Case-studies employing `shoredate` are currently being undertaken. Furthermore, future archaeological material can be drawn on to further test the method as it is implemented here, and potentially lead to adjustments in how it should be applied in a given setting.

Spatial and temporal coverage

As the method of shoreline dating is dependent on reliable reconstructions of relative sea-level change, the package was developed to be applied in the coastal region between Horten in the north east to Arendal in the south west (Figure 1). Geologically derived displacement curves from this region have recently been published for Skoppum in Horten (Romundset, 2021), Gunnarsrød in Porsgrunn (Sørensen et al., 2023), Hanto in Tvedestrand (Romundset et al., 2018) and Bjørnebu in Arendal (Romundset, 2018). The spatial coverage of `shoredate` will be extended to surrounding areas as forthcoming data on shoreline displacement becomes available. Furthermore, although the direct applicability of the method in other regions remains undetermined, suggestions and examples of how such extensions can be achieved is included in the documentation for the package.

Following from the latest start date among the geological displacement curves, 9469 BCE marks the lower temporal limit of the package within the spatial limit in south-eastern Norway. The oldest verified anthropogenic activity in Norway currently dates to around 9300 BCE (Glørstad, 2016). In Roalkvam (2023) it was found that sites in the region tend to be located at more variable distances from the shoreline after c. 2500 BCE. This therefore marks the upper temporal limit for shoreline dating in the region.

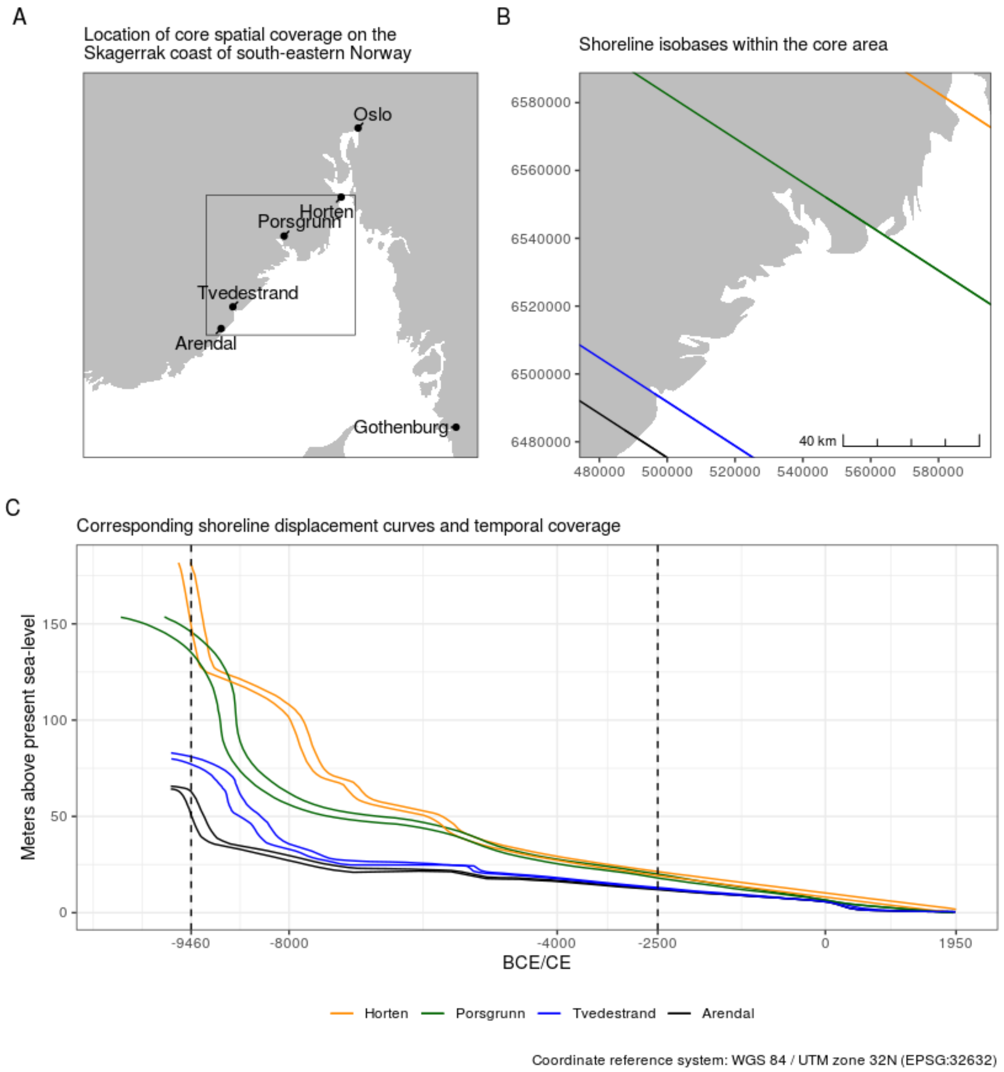

Figure 1: The spatial and temporal coverage for which the package was developed. A) The location of the spatial coverage in south-eastern Norway. B) The location of the isobases that represent contours along which the shoreline displacement has followed the same trajectory. C) The displacement curves corresponding to the isobases, where the temporal limits are marked with dashed lines.

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Example of base functionality

To date a site, its elevation above present sea-level must be provided when running the function `shoreline_date()`. This can be done by either manually specifying the site elevation, or by providing an elevation raster of class `SpatRaster` from the `terra` package (Hijmans et al., 2022) from where this is derived. Unless a pre-compiled curve is provided, the trajectory of shoreline displacement at the location of the site is then interpolated under the hood with the function `interpolate_curve()`, using inverse distance weighting when `shoreline_date()` is called. This is based on the distance between the site and the isobases of the displacement curves. To perform this interpolation, the site geometry has to provided as a spatial object of class `sf` from the `sf` package (Pebesma, 2018).

Figure 2 shows the location of an example site, plotted by passing it to `target_plot()`. Figure 3 displays the result of running the command `interpolate_curve()` on the example site, and plotting the resulting interpolated displacement curve with `displacement_plot()`. Finally, Figure 4 shows the result of dating the example site with `shoreline_date()` when manually specifying that the site is situated at 58.8m above present sea-level. The resulting date is plotted with the function `shoredate_plot()`.

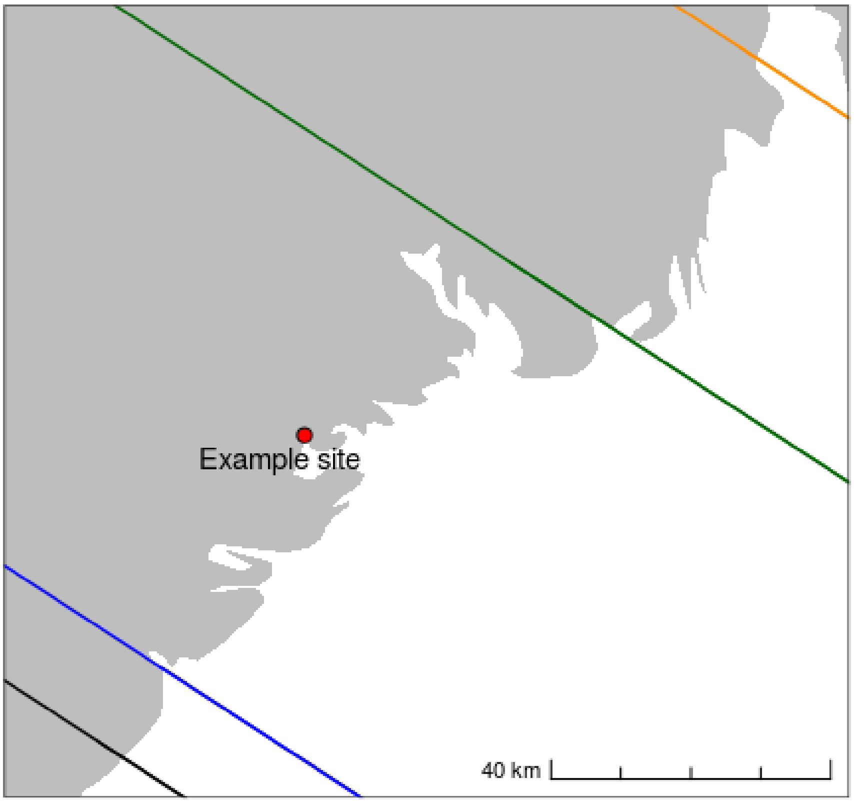

Figure 2: The location of the example site relative to the isobases of the displacement curves. The base map is a simplified light-weight map of the region.

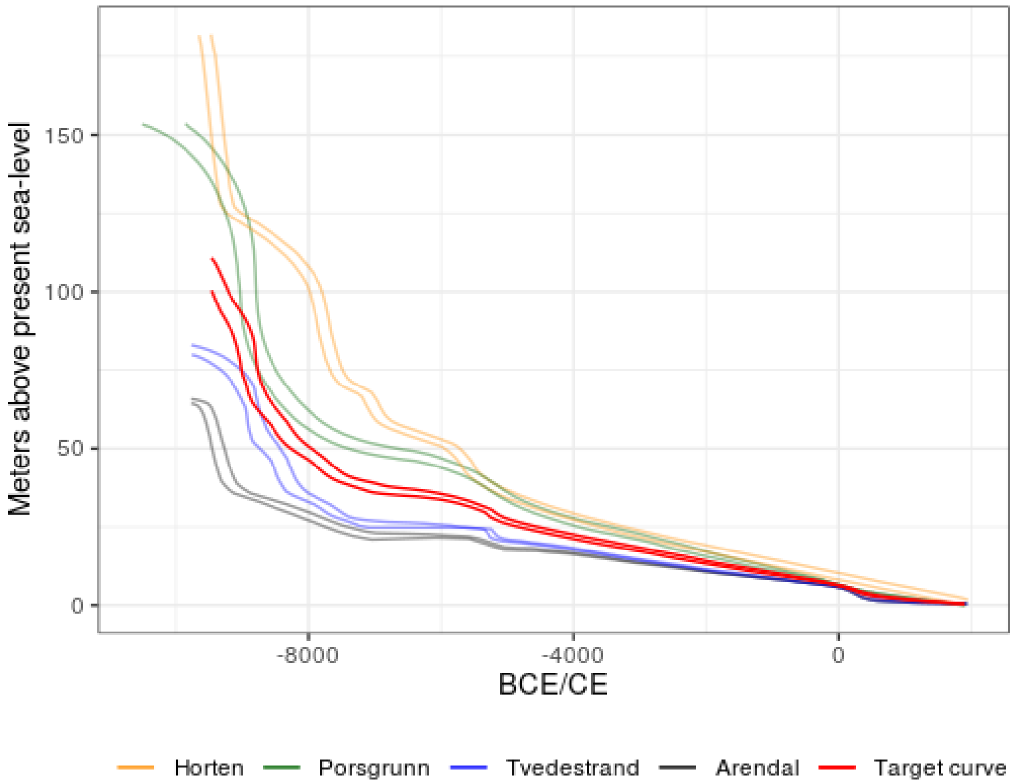

Figure 3: The curve interpolated to the example site by means of inverse distance weighting. This is based on the distance between the site and the isobases of the geological displacement curves.

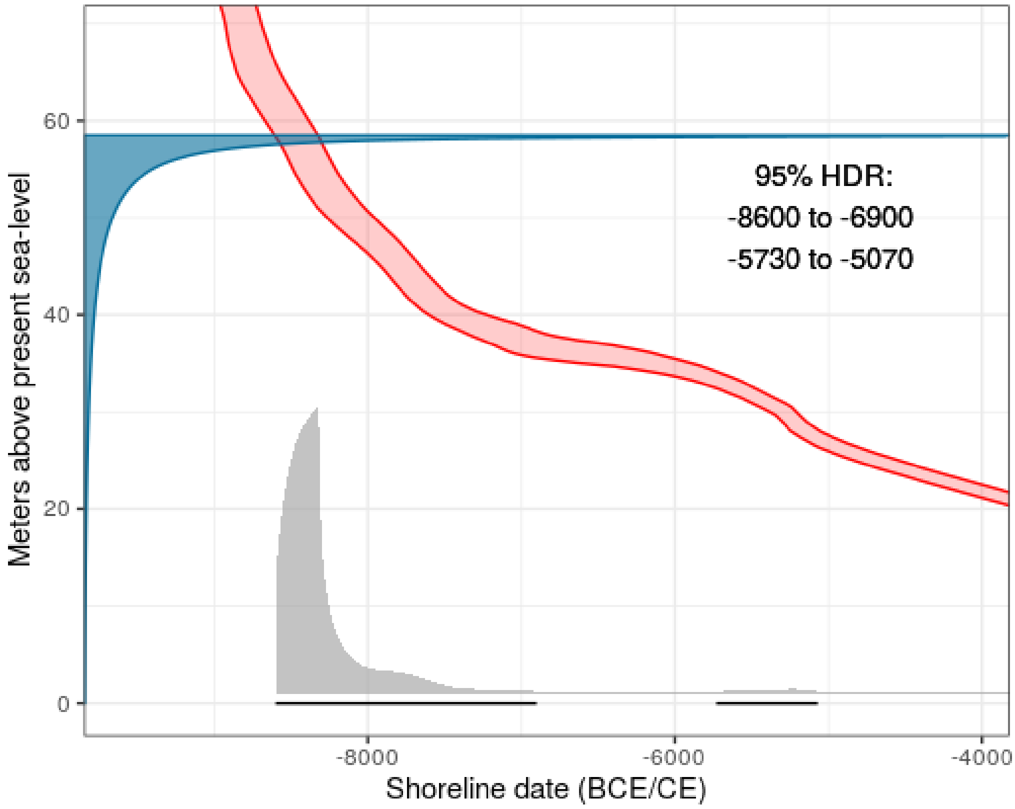

Figure 4: The resulting shoreline date for the example site. The blue gamma distribution on the y-axis indicates the likely elevation of the site above sea-level when it was occupied. The red envelope is the interpolated shoreline displacement curve for the site location. The resulting shoreline date in grey is the result of transferring the probability from the gamma distribution to the calendar scale by coupling it with the displacement curve. The date is underlined with the 95% highest density region (HDR) in black.

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Paper 3

Exploring the composition of lithic assemblages in Mesolithic south-eastern Norway

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Exploring the composition of lithic assemblages in Mesolithic South-Eastern Norway

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ABSTRACT

This paper leverages multivariate statistics to explore the composition of 54 Mesolithic assemblages located in south-eastern Norway. To provide analytical control pertaining to factors such as variable excavation practices, systems for artefact categorisation and raw-material availability, the sites chosen for analysis have all been excavated relatively recently and have a constrained geographical distribution. The assemblages were explored following two strains of analysis. The first of these entailed the use of artefact categories that are in established use within Norwegian Mesolithic archaeology, while the other involved drawing on measures that have been linked directly to land-use and mobility patterns associated with lithic assemblages more widely. The findings pertaining to the established artefact categories largely reflect the temporal development previously reported in Norwegian Mesolithic research. Furthermore, the chronological trends associated with variables taken from the so-called Whole Assemblage Behavioural Indicators (e.g. Clark and Barton, 2017), originally devised for characterising Palaeolithic assemblages in terms of associated mobility patterns, also align with the development previously proposed in the literature. This provides an initial indication that these measures are applicable in a Norwegian Mesolithic setting as well, setting the stage for a more targeted and rigorous model evaluation outside this exploratory setting. Furthermore, this finding supports the notion that these measures can offer a powerful comparative tool in the analysis of lithic assemblages more generally.

1. Introduction

This study employs multivariate exploratory statistics to analyse lithic assemblages associated with Mesolithic sites located in south-eastern Norway. This is done to identify latent patterns and structure in the relationship between the assemblages, with the ultimate aim of identifying behaviourally induced variation in their composition across time. However, the composition of the assemblages can be expected to be determined by a multitude of factors (e.g. Dibble et al. 2017; Rezek et al. 2020), ranging from the impact of natural formation processes, to various and intermixed behavioural aspects such as purpose, duration, frequency and group sizes at visits to the sites. The assemblages are also likely to be impacted by variation in lithic technology, artefact function, use-life and discard patterns, as well as procurement strategies and access to raw materials. Finally, analytic and methodological dimensions relating to survey, excavation and classification practices are also fundamental to how the assemblages are defined. Consequently, the analysis conducted here is done from an exploratory perspective, where all of these factors should be seen as potential contributors to any observed pattern. In an attempt to limit the influence of some potentially confounding effects, the material chosen for analysis has a constrained geographical distribution, and stems from recent investigations that have employed comparable methods for excavation and classification within larger unified projects.

Even though each individual assemblage can have been impacted by an virtual infinitude of effects that might skew an archaeological interpretation, this does not preclude the applicability of inductive analyses aimed at revealing overarching structure in the data without imposing overly complex analytical frameworks that attempt to account for these particularities (Bevan 2015). Structure that can be revealed from considering all of the assemblages in aggregate can constitute a step in an iterative analytical chain that ultimately aims to tease apart the multitude of factors that have shaped the composition of the assemblages. This would in turn give analytical access to the organisation of lithic technology and variation in past behaviour, adaptation and demographic development (see for example Andrefsky 2009; Barton et al. 2011; Binford 1979; Dibble et al. 2017; Rezek et al. 2020). The most immediate danger of the approach outlined here is rather to be overly naive in the causal significance and cultural importance that is ascribed to any identified pattern. As such, the main aim of this analysis is to compare the results with findings reported in previous literature concerned with the Mesolithic in southern Norway and have the generation of new hypotheses as a possible outcome. To this end, the analysis follows two analytical avenues. The first involves an analysis of

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the assemblages using the classification of the artefacts done for the original excavation reports. The second involves an analysis of the assemblages in light of the so-called Whole Assemblage Behavioural Indicators (e.g. Clark and Barton, 2017) and other factors that have been employed to align properties of lithic assemblages with land-use and mobility patterns.

2. Archaeological context and material

The Early Mesolithic, or Flake Axe Phase, is defined as lasting from c. 9300–8200 BCE (Table 1), and is set to start with the first recorded human presence in Norway (Damlien and Solheim 2018). Previous research has typically proposed that the Early Mesolithic is characterised by a relatively high degree of mobility, and low variation in site types and associated mobility patterns (e.g. Bjerck 2008; Breivik and Callanan 2016; Fuglestvedt 2012; Nærøy 2018; but see Åstveit 2014; Viken 2018). Around the transition to the subsequent Middle Mesolithic or Microlith Phase at c. 8200 BCE, pervasive changes in blade and axe technology occur (Damlien 2016; Eymundsson et al. 2018; Solheim et al. 2020), which in turn has been associated with changes in population genomics and related migration events hailing from the Eurasian steppes (Günther et al. 2018; Manninen et al. 2021). The Microlith Phase is defined as lasting until around 7000 BCE, which is followed by the Pecked Adze Phase, characterised by a more dominating presence of non-flint macro tools and associated production waste in the assemblages (Reitan 2016). The next typological transition at c. 5600 BCE signifies the onset of the Nøstvet Adze Phase. While previously defined as having a slightly longer duration, the Nøstvet Phase has traditionally been seen as representing the onset of more varied settlement systems and stable mobility patterns (e.g. Jaksland 2001; Lindblom 1984). In recent years it has been suggested that the transition to a decrease in mobility and more varied land-use patterns can be traced back to the Middle Mesolithic (Solheim and Persson 2016). The subsequent Transverse Arrowhead Phase (c. 4500–3900 BCE) is characterised by a dramatic decrease in axe finds, and the introduction of new flint projectiles (Reitan 2016). It has recently been suggested that a dispersal of people from southern Scandinavia into southern Norway takes place in this period (Eigeland 2015:379; Nielsen 2021), which could follow after a preceding population decline at c. 4300 BCE (Nielsen 2021; cf. Solheim 2020; Solheim and Persson 2018).

A defining characteristic of the Norwegian Mesolithic is that a clear majority of the known sites are located in coastal areas (e.g. Bjerck 2008). Furthermore, these coastal sites appear to predominantly have been located on or close to the contemporary shoreline when they were in use (Åstveit, 2018; Breivik et al. 2018; Møller 1987; Solheim 2020). In south-eastern Norway, this pattern is combined with a continuous regression of the shoreline, following from isostatic rebound (e.g. Romundset et al. 2018; Sørensen 1979). The fairly rapid shoreline displacement means that the sites tend not to have retained their strategic or ecologically beneficial shore-bound location for long periods of time (cf. Perreault 2019:47). Consequently, the shore-bound settlement,

Table 1
Chronological framework. Glørstad's (2010) divison of phases reflects the more traditional framework, to which Reitan (2016) has recently suggested considerable changes.

Glørstad (2010)	
Early Mesolithic, Fosna Phase	9500–8200 BCE
Middle Mesolithic, Tørkop Phase	8200–6300 BCE
Late Mesolithic, Nøstvet Phase	6300–4600 BCE
Late Mesolithic, Kjeøy Phase	4600–3800 BCE
Reitan (2016)	
Flake Axe Phase	9300–8200 BCE
Microlith Phase	8200–7000 BCE
Pecked Adze Phase	7000–5600 BCE
Nøstvet Adze Phase	5600–4500 BCE
Transverse Arrowhead Phase	4500–3900 BCE

combined with the rapid shoreline displacement has resulted in a relatively high degree of spatial separation of cumulative palimpsests, to follow the terminology of Bailey (2007), while the reconstruction of the trajectory of relative sea-level change allows for a relatively good control of when these accumulation events occurred. In other parts of the world, a higher degree of spatial distribution means that while the physical separation of material can help delineate discrete events, this typically comes at the cost of losing temporal resolution as any stratigraphic relationship between the events is lost (Bailey 2007).

The 54 coastal sites chosen for analysis here have a relatively limited geographical distribution (Fig. 1A). The sites were excavated as part of four larger excavation projects that all took place within the last 15 years (Jaksland and Persson 2014; Melvold and Persson 2014; Reitan and Persson 2014; Solheim 2017a; Solheim and Damlien 2013). The sites included in the analysis consist of all Mesolithic sites excavated in conjunction with the projects that have assemblages holding more than 100 artefacts. The institution responsible for these excavations was the Museum of Cultural History in Oslo. This has led to a considerable overlap in the archaeological personnel involved, and comparable excavation practices across the excavations. Furthermore, with these projects, major efforts were made to standardise how lithic artefacts were to be classified at the museum (Koxvold and Fossum 2017; Melvold et al. 2014). As a result, this should reduce the amount of artificial patterning in the data incurred by discrepancies in the employed systems for categorisation (cf. Clark and Riel-Salvatore 2006; Dibble et al. 2017).

The lithic data analysed here is based on the classification of the site assemblages done for the original excavation reports, and consists of 48 debitage and tool types. These represent artefact categories that have been used consistently across the reports. Consequently, sub-categories that have only been used in the classification of some inventories have been omitted. This for example pertains to what blanks have been used for the production of formal tools, which has only been noted in some of the reports. Furthermore, the artefact data have been divided into flint and non-flint materials. Flint does not outcrop naturally in southern Norway, and is only available locally as nodules that have been transported and deposited by retreating and drifting ice (e.g. Berg-Hansen 1999). This means that the distribution and quality of flint has been impacted by a diverse set of climatic and geographical factors (Eigeland 2015:46). Thus, while flint is treated as a unified category here, the variability in quality could have been substantial. Furthermore, the various non-flint raw materials that have been lumped together have quite disparate properties, where fine-grained cryptocrystalline materials are often used as a substitute or supplement to flint, while other, coarser materials are usually associated with the production of axes and other macro tools. Given this differentiated use, these raw-material properties are expected to be reflected in the retained debitage and tool categories. An important benefit of combining all of the non-flint materials is that this reduces the dependency on whether or not these have been correctly and consistently categorised for the reports (cf. Frivoll 2017). Finally, while factors such as landscape changes through shoreline displacement can have led to variable raw-material availability at the analysed sites, for example by impacting accessibility by means of watercraft, the relatively constrained geographical distribution of the sites hopefully counteracts some environmentally given sources of variation.

3. The analysis of lithic assemblages

Studies concerned with chronological changes in the composition of lithic assemblages in southern Norway have typically had a focus on morphological variation among artefacts (e.g. Ballin 1999; Bjerck 1986; Reitan 2016) or been concerned with technological processes associated with certain sub-categories of the site inventories, such as the production of blades or axes (e.g. Berg-Hansen 2017; Damlien 2016; Eymundsson et al. 2018; Solheim et al. 2020). Studies that have involved

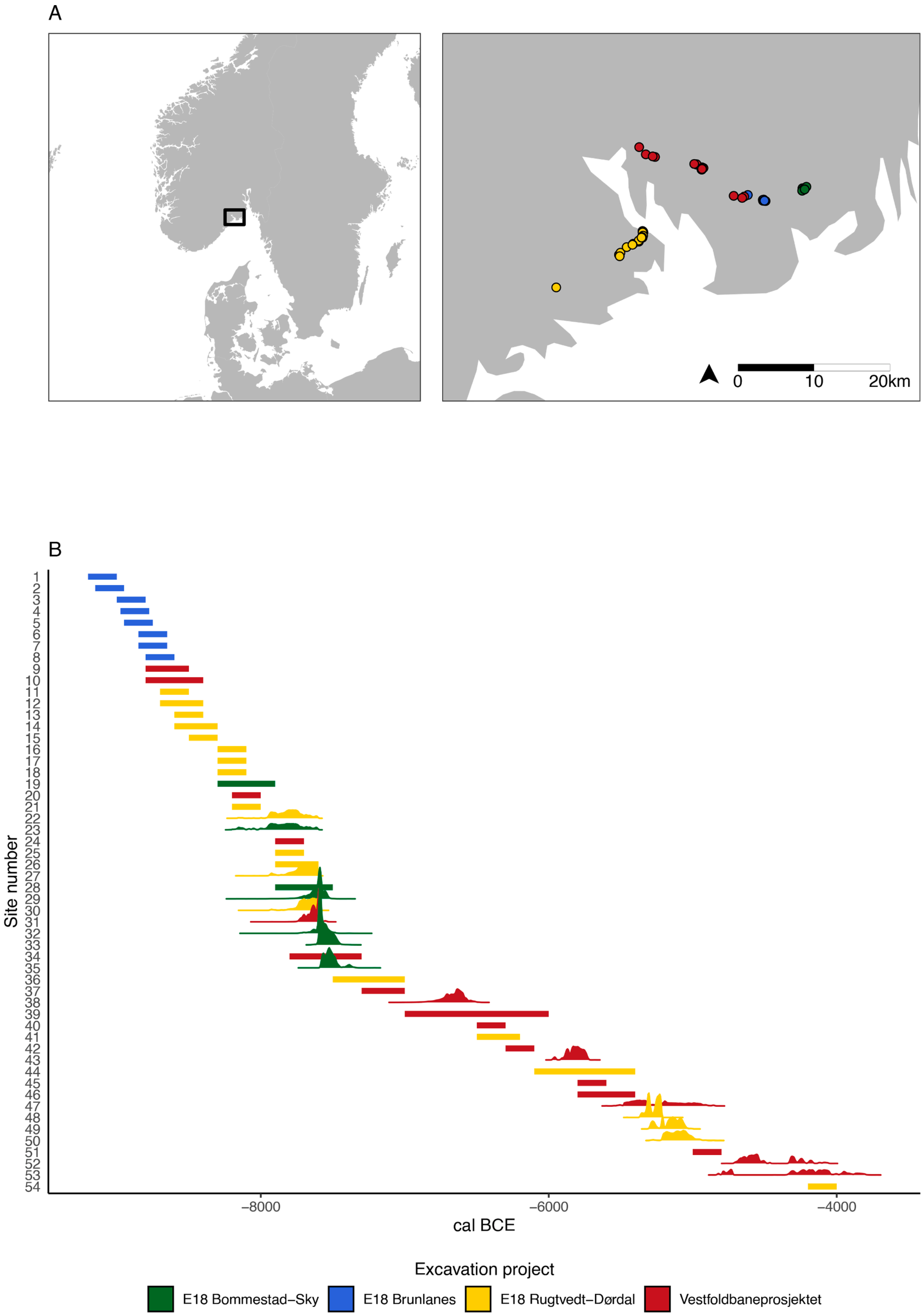

Fig. 1. A) Spatial and B) temporal distribution of the sites chosen for analysis. Radiocarbon age determinations are given as the sum of the posterior density esimates. Solid lines indicate that the site has been dated with reference to relative sea-level change and typological indicators. These follow the original reports. Site numbers match those provided in Table 2.

entire assemblages have either been concerned with general compositional traits such as relative frequency of various tool types and raw-materials (e.g. Breivik 2020; Breivik and Callanan 2016; Reitan 2016; Viken 2018), or involved extremely in-depth studies of technological organisation associated with a handful of assemblages (e.g. Eigeland 2015; Fuglestvedt 2007; Mansrud and Eymundsson 2016). These studies are, however, based on non-quantitative or uni- and bivariate methods, leaving the weighting of the many variables for the final interpretations unclear. To my knowledge, only a single study dealing with the composition of Mesolithic assemblages in southern Norway has involved the use of a multivariate quantitative framework, which was employed to structure the analysis of eight Middle Mesolithic assemblages (Solheim 2013; see Glørstad 2010:145–146 for a spatial application). In sum then, previous studies have typically either been limited to a small number of sites, to a subset of the inventories, to morphological characteristics, or to methods that are difficult to scale and consistently balance in the comparison of a larger number of artefact categories and assemblages.

The aim of the first of part of the analysis conducted here is to evaluate the degree to which the composition of the assemblages align

Fig. 2. Aggregation of variables for the correspondence analysis. The column on the left shows the variables as originally compiled. The column on the right shows how these have been aggregated for the analysis.

with earlier studies that have employed more informal methods. This therefore assumes that the artefact categories employed in Norwegian Stone Age archaeology are, at least to a certain extent, behaviourally meaningful. However, the approach taken is also partially informed by the so-called Frison effect (Jelinek 1976), which pertains to the fact that lithics studied by archaeologists can have had long and complex use-lives in which they took on a multitude of different shapes before they were ultimately discarded. Several scholars have built on this to argue that morphological variation in retouched lithics from the Palaeolithic cannot be assumed to predominantly be the result of the intention of the original knapper to reach some desired end-product, but rather that what is commonly categorised as discrete types of artefacts by archaeologists can instead in large part be related to variable degrees of modification through use and rejuvenation (e.g. Barton 1991; Barton and Clark 2021; Dibble 1995). Artefact categories believed not to be internally consistent and categorically exclusive have therefore been collapsed for the analysis (Fig. 2), as their contribution as discrete analytical units could potentially be misleading. An underlying assumption of the largely intuitively determined aggregation procedure is therefore effectively that the retained categories represent artefact categories that have fulfilled different purposes or are related to different technological processes. While aggregating artefact categories in this manner could subsume important variation, it does also reduce the possibility that any conclusions are not simply the result of employing erroneous units of analysis.

However, for the most part we lack even a most basic understanding of what any individual lithic object in an assemblage has been used for (Dibble et al. 2017). For example, a vast amount of artefacts defined as debitage are likely to have fulfilled the function of tools, and both debitage and formal tool types could have had various different purposes and had a multitude of shapes throughout their use-life. This has major implications that the above-outlined analysis does not take properly into account, rendering it difficult to align any identified pattern with specific behavioural dimensions. As a consequence, the second part of the analysis employs a suite of measures developed for the classification of lithic assemblages with these inferential limitations in mind (Barton et al., 2011; Clark and Barton, 2017, and below). The logic behind these measures are founded on an understanding of technology as being organised along a continuum ranging between curated and expedient (Binford 1973, 1977, 1979). An expedient technological organisation pertains to the situational production of tools to meet immediate needs, with little investment of time and resources in modification and rejuvenation, resulting in high rates of tool replacement. Curated technological organisation, on the other hand, has been related to manufacture and maintenance of tools in anticipation of future use, the transport of these artefacts between places of use, and the modification and rejuvenation of artefacts for different and changing situations.

However, following not least from the ambiguous definition first put forward by Binford (1973), the theoretical definition of curation, its archaeological correlates, and behavioural implications have been widely discussed and disputed (e.g. Bamforth 1986; Nash 1996; Shott 1996; Surovell 2009:9–13). Still, that the distinction can offer a useful analytical point of departure if clearly and explicitly operationalised seems more or less agreed upon, and some dimensions of the concept are generally accepted. For example, although precisely how it is measured may vary, the empirical correspondent to a curated technological organisation is typically defined by high degrees of retouch, as this is commonly seen as a means of realising the potential utility of a tool—or extending its use-life—by the repeated rejuvenation and modification of edges (e.g. Bamforth 1986; Dibble 1995; Shott and Sillitoe 2005).

One concrete operationalisation of the terms has been forwarded by Barton (1998) and collegues (e.g. Barton et al., 1999, 2011, 2013; Barton and Riel-Salvatore, 2014; Clark and Barton, 2017; Riel-Salvatore and Barton, 2004, 2007; Villaverde et al., 1998), who through a series of studies have shown that the relationship between volumetric density of lithics and relative frequency of retouched artefacts in lithic assemblages have a consistent negative relationship across a wide range of chronological and cultural context, ranging from Pleistocene and Holocene assemblages in Europe and Asia, to assemblages associated with both Neanderthals and modern humans (Barton et al. 2011; Riel-Salvatore et al. 2008). This relationship is taken to reflect degree of curation, and is in turn mainly to follow from the accumulated nature of land-use and mobility patterns associated with the assemblages (Barton and Riel-Salvatore 2014). Furthermore, the relationship between curated and expedient technological organisation has been related to the continuum defined by Binford (1980) between residentially mobile foragers and logistically mobile collectors (Clark and Barton, 2017; Riel-Salvatore and Barton, 2004; see also Bamforth 1986; Binford 1977). Residential mobility involves the relatively frequent movement of entire groups between resource patches throughout the year, while logistic mobility entails the use of central base-camps that are moved less often and from where smaller task-groups venture on targeted forays to retrieve specific resources. A higher degree of logistic as opposed to residential mobility thus also involves a wider range of site types and associated mobility patterns (Binford 1980).

Furthermore, in this model, higher degree of mobility would mean a higher dependency on the artefacts and the material people could bring with them, and dimensions such as weight, reliability, repairability, and the degree to which artefacts could be manipulated to fulfil a wide range of tasks are therefore assumed to have been factors of concern. From this it follows that the empirical expectation for short-term camps is a curated technological organisation with higher relative frequency of retouched artefacts, and a lower overall density of lithics (Clark and Barton, 2017). More time spent in a single location, on the other hand, is assumed to lead to better control of raw-material availability and to allow for its accumulation. This should in turn lead to a more expedient technological organisation with reduced necessity for the conservation of lithics and extensive use of retouch. The empirical expectation for lower degree of mobility is therefore relatively high density of lithics, a low relative frequency of retouched artefacts, as well as a higher number of unexhausted cores and unretouched flakes and blades. These variables and underlying logic constitute what has been termed Whole Assemblage Behavioural Indicators (WABI, Clark and Barton, 2017), and is the main framework adopted here.

As these measures are argued to predominantly be determined by land-use and mobility patterns, relative frequency of chips and relative frequency of non-flint material are also included in the analysis, as these measures have also been linked to mobility patterns (e.g. Bicho and Cascalheira 2020; Kitchel et al. 2021) and are of central importance to Norwegian Stone Age archaeology (e.g. Breivik et al. 2016; Reitan 2016)—the use of local non-flint material has been taken to indicate reduced mobility and increased familiarity with local surroundings (Glørstad 2010:181; Jaksland 2001:112).

4. Methodology

The exploratory approach taken here means that a wide range of combinations and transformations of variables has been explored to identify patterning in the data. While only parts of this process can sensibly be reported upon, all data and employed R programming scripts (R Core Team 2020) are freely available as a research compendium at https://osf.io/ehjfc/, following Marwick et al. (2018), allowing readers to explore and scrutinise the data and the final analytical choices made (Marwick 2017).

The 54 analysed sites have been dated by reference to relative sea-level change, typology and/or radiocarbon dates (Table 2). Date ranges for sites based on shoreline displacement and typology are taken from the original reports and follow the evaluation done by the original excavators. Where radiocarbon age determinations believed to be associated with the lithic material are available, these have been calibrated using the IntCal20 calibration curve (Reimer et al. 2020) and

Table 2
Analysed sites. The column for dating method lists whether the sites have been dated with reference to shoreline displacement and typology, or by means of radiocarbon dating. Reported start and end dates are given as years cal BCE.

no	Site name	Dating method	Reported start	Reported end
1	Pauler 1	Shore/typo	9200	9000
2	Pauler 2	Shore/typo	9150	8950
3	Pauler 3	Shore/typo	9000	8800
4	Pauler 5	Shore/typo	8975	8775
5	Pauler 4	Shore/typo	8950	8750
6	Pauler 6	Shore/typo	8850	8650
7	Bakke	Shore/typo	8850	8650
8	Pauler 7	Shore/typo	8800	8600
9	Nedre Hobekk 2	Shore/typo	8800	8500
10	Solum 1	Shore/typo	8800	8400
11	Tinderholt 3	Shore/typo	8700	8500
12	Tinderholt 2	Shore/typo	8700	8400
13	Dørdal	Shore/typo	8600	8400
14	Tinderholt 1	Shore/typo	8600	8300
15	Skeid	Shore/typo	8500	8300
16	Hydal 3	Shore/typo	8300	8100
17	Hydal 4	Shore/typo	8300	8100
18	Hydal 7	Shore/typo	8300	8100
19	Hovland 2	Shore/typo	8300	7900
20	Nedre Hobekk 3	Shore/typo	8200	8000
21	Hydal 8	Shore/typo	8200	8000
22	Hegna vest 1	Radiocarbon	8000	7800
23	Hovland 5	Radiocarbon	8000	7700
24	Sundsaasen 1	Shore/typo	7900	7700
25	Hegna øst 6	Shore/typo	7900	7700
26	Hegna vest 4	Shore/typo	7900	7600
27	Hegna vest 2	Radiocarbon	7900	7550
28	Nordby 2	Shore/typo	7900	7500
29	Hovland 4	Radiocarbon	7900	7500
30	Hegna vest 3	Radiocarbon	7800	7600
31	Prestemoen 1	Radiocarbon	7700	7600
32	Hovland 1	Radiocarbon	7700	7400
33	Hovland 3	Radiocarbon	7650	7450
34	Gunnarsrød 7	Shore/typo	7800	7300
35	Torstvet	Radiocarbon	7500	7100
36	Hegna øst 5	Shore/typo	7500	7000
37	Gunnarsrød 8	Shore/typo	7300	7000
38	Langangen Vestgård 1	Radiocarbon	6800	6600
39	Gunnarsrød 2	Shore/typo	7000	6000
40	Gunnarsrød 6b	Shore/typo	6500	6300
41	Hegna øst 7	Shore/typo	6500	6200
42	Gunnarsrød 6a	Shore/typo	6300	6100
43	Gunnarsrød 4	Radiocarbon	6000	5800
44	Stokke/Polland 3	Shore/typo	6100	5400
45	Gunnarsrød 10	Shore/typo	5800	5600
46	Langangen Vestgård 2	Shore/typo	5800	5400
47	Vallermyrene 4	Radiocarbon	5500	5200
48	Hegna øst 2	Radiocarbon	5350	5200
49	Stokke/Polland 8	Radiocarbon	5300	5200
50	Stokke/Polland 5	Radiocarbon	5300	5000
51	Prestemoen 2	Shore/typo	5000	4800
52	Vallermyrene 1	Radiocarbon	4700	4100
53	Langangen Vestgård 3	Radiocarbon	4350	4000
54	Stokke/Polland 9	Shore/typo	4200	4000

subjected to Bayesian modelling using OxCal v4.4.4 (Bronk Ramsey, 2009) through the oxcAAR package (Hinz et al. 2021) for R. The only constraint imposed for the modelling of the dates was that the dates from each site are assumed to represent a related group of events through the application of the Boundary function (Bronk Ramsey, 2021). The resulting posterior density estimates were then summed for each site.

The first part of the analysis involves employing the method of correspondence analysis (CA), using the lithic count data as classified for the original excavation reports (e.g. Baxter 1994; Shennan 1997). As this part of the analysis partially draws on the above-mentioned Frison effect, several artefact categories have been collapsed for the CA. A version of the CA using the original artefact categories, as well as some additional configurations and ways to aggregate the variables are also available in the supplementary material to the paper.

Following the WABI and other factors associated with mobility patterns, as presented above, the variables employed in the second part of the analysis are relative frequency of secondarily worked lithics (RFSL), defined as the proportion of the assemblages constituted by retouched or ground lithics; volumetric density of lithics (VDL), defined as the total number of artefacts divided by total excavated m^3 as taken from the original reports; relative frequency of chips, defined as the proportion of artefacts with size < 1 mm; relative frequency of cores, the proportion of all artefacts classified as cores in the original reports; relative frequency of blanks, here defined as the proportion of all artefacts classified as flakes, blades, micro-blades or fragments; and finally relative frequency of non-flint material. Following Bicho and Cascalheira (2020), the analysis is done using principal components analysis (PCA), leading to a shift in focus from the relative composition emphasised by the CA, to having more weight placed on patterning in the most abundant occurrences (Baxter 1994:71–77).

A note should also be made on the fact that a few variables that are sometimes invoked for the classification of sites in terms of associated mobility patterns are omitted here (e.g. Bergsvik 1995:116; Bicho and Cascalheira 2020; Breivik et al. 2016). For the assemblage data itself this especially pertains to diversity in tool-types (Canessa 2021), which has been omitted in light of the above-metioned Frison effect. Number of features on the sites has also been disregarded as taphonomic loss is likely to have led to a chronological bias in their preservation. Similarly, the number of activity areas, effectively number of artefact clusters, however defined, has also been disregarded. This follows most notably from the fact that the impact of post-depositional processes at Stone Age sites in Norway is arguably understudied (Jørgensen 2017). This pertains for example to bio-turbation in the form of three-throws, which can have a detrimental effect on the original distribution of artefacts, and which can be expected to have impacted several of the sites treated here (Darmark 2018; Jørgensen 2017).

5. Results

The general impression from the CA is that a chronological dimension accounts for a substantial amount of patterning in the data (Fig. 3). This is indicated by the general transition across the colour scale in the row plot (Fig. 3B), as well as the horseshoe curve or Guttman effect evident in the column plot (Fig. 3A, Baxter 1994:119–120; Lockyear 2000). The fact that the two first dimensions of the CA accounts for as much as 80.53% of the inertia or variance also means that the structure of the data is well-represented in the plots and that these therefore are likely reflect true patterning in the data.

The column plot reveals that the earliest sites are characterised by the flint artefact categories microburins, projectiles, as well as flint macro tools and associated debitage. These assemblages are also to a larger extent characterised by core fragments, both in flint and non-flint materials, rather than cores. The non-flint material on the earliest, or among the earliest sites, appears to be centred around the production of projectiles, as both projectiles and non-flint blades are important constituents of the assemblages at these sites. The first dimension, which is pulling some of the later sites towards the right of the plot, is mainly defined by macro tools and associated debitage in non-flint materials that are negatively correlated with more flint dominated assemblages.

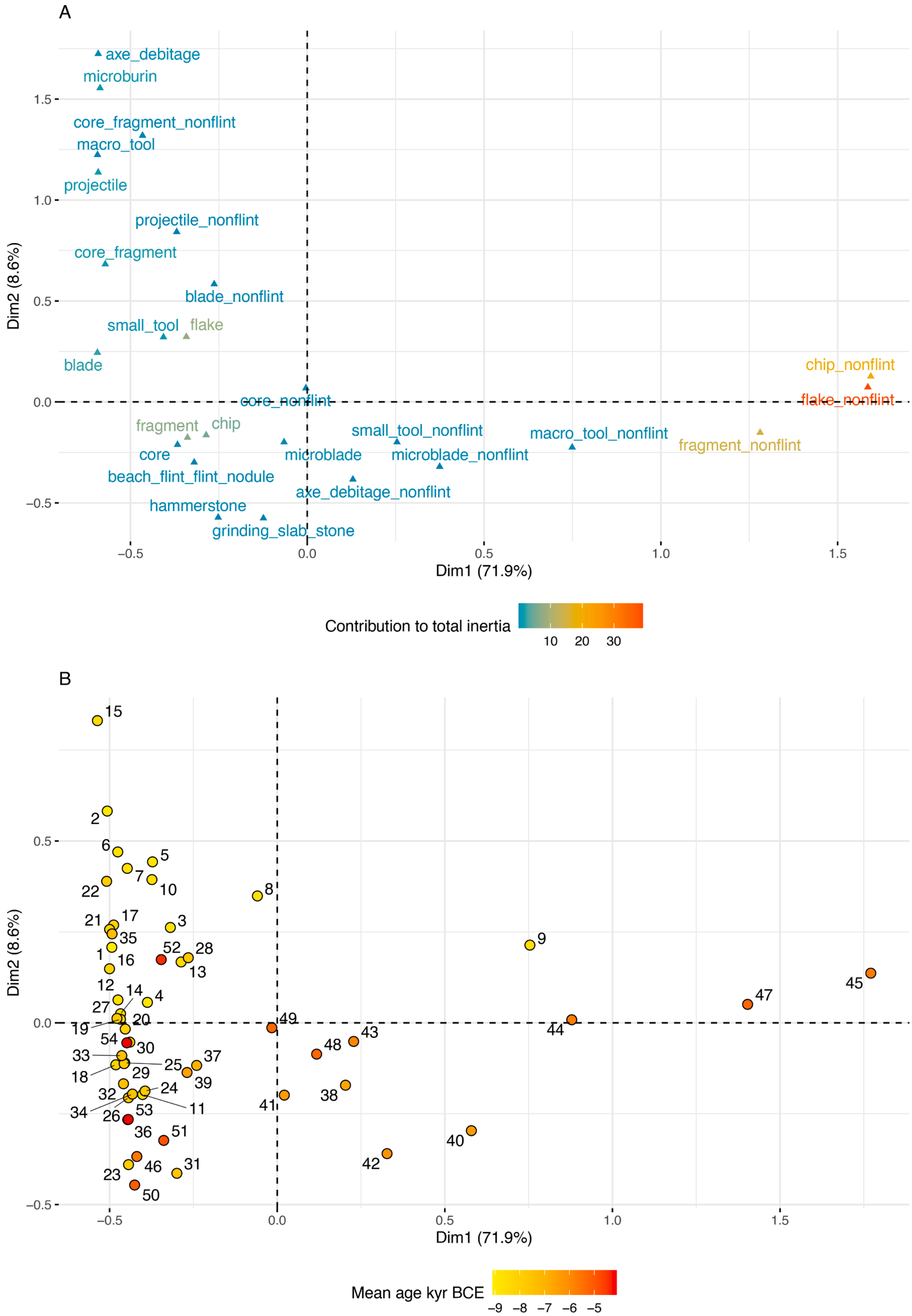

Fig. 3. Correspondence analysis using the artefact count data. A) Column plot (variables), B) Row plot (sites). Points close together are more similar. By evaluating how the variables are distributed on the column plot it is possible to say how these define the two axes, in turn making it possible to relate the distribution of the sites in the row plot to the variables. As these are symmetrical plots, only general statements concerning the interrelation between the rows and the columns across the two plots can be made.

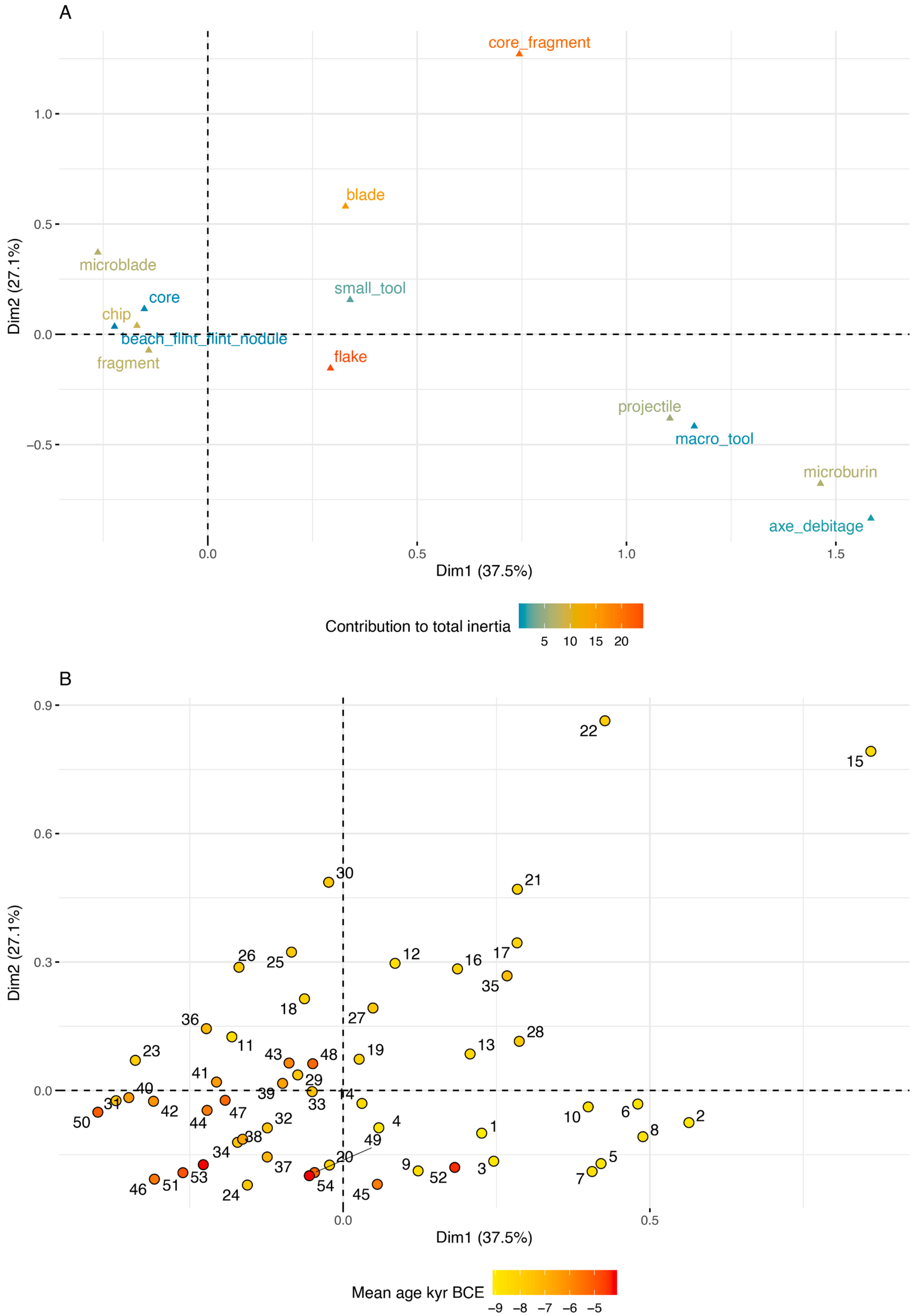

Fig. 4. Correspondence analysis using the flint data. A) Column plot, B) Row plot.

Site number 9, Nedre Hobekk 2, located in the upper right quadrant of the row plot represents a somewhat curious case in that it is an early assemblage characterised by axe production in metarhyolite (Eigeland 2014). However, the site had been quite heavily impacted by modern disturbances that could have impacted the lithic material and which could explain its position as an outlier in the plot. Finally, although the sample size is quite strained and the discussion of finer chronological points might not be warranted, the first dimension does appear to be of of less importance for the absolute latest sites, as indicated by their location to the left of the plot.

As most of the variation in the data is accounted for by the dominating non-flint material in later assemblages, this suppresses and makes it difficult to discern patterns in the flint data. A second CA was therefore performed, excluding the non-flint material (Fig. 4). While not as substantial, there is clear temporal patterning in the flint data as well. This is most marked for the earliest sites which are pulled away from the main cluster, as projectiles, microburins, macro tools and debitage from their production characterises these sites. Slightly younger sites appear more impacted by core fragments and blades. The temporal transition in the main cluster is not as marked, but clearly present, and is driven by a

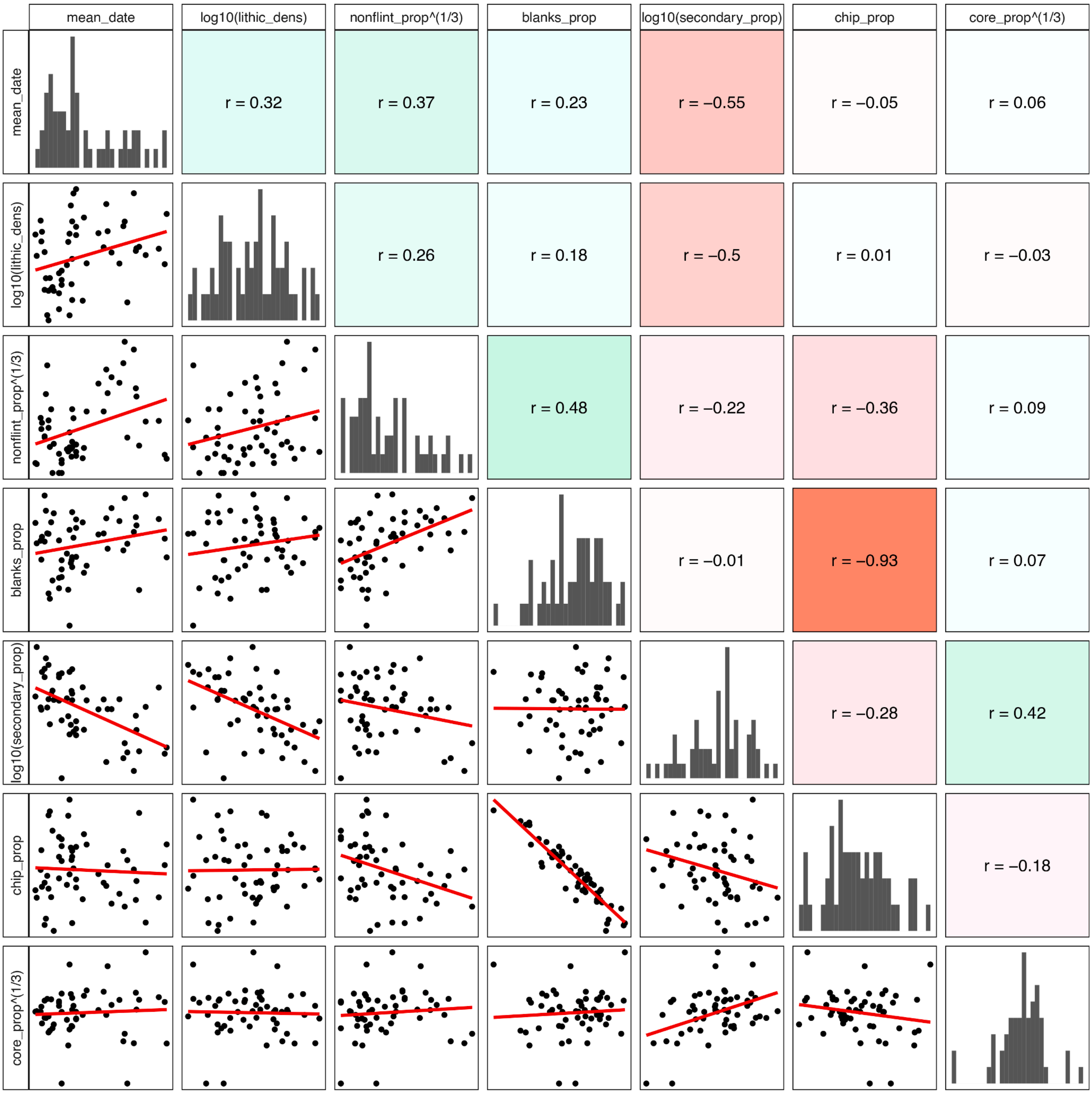

Fig. 5. Correlation matrix showing transformation of skewed variables for the PCA. The mean age of the sites has also been included to visualise overall temporal trends. Cells below the diagonal display the bivariate distributions with a fitted OLS-regression. The cells above the diagonal display and are coloured by the corresponding Pearson's correlation coefficient.

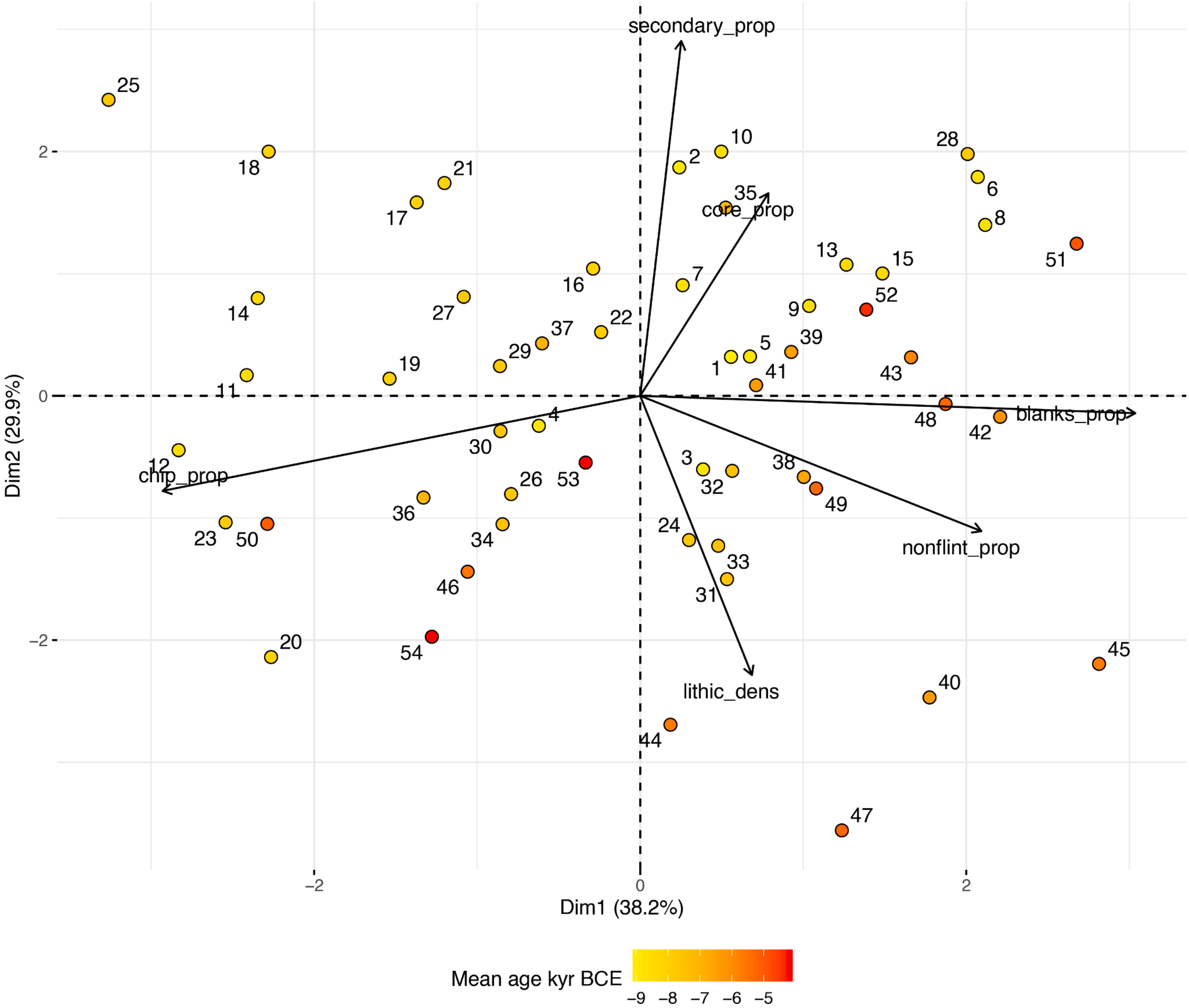

Fig. 6. PCA biplot resulting from analysing variables that have been related to mobility patterns. Note that details on the transformation of the variables has been left out of the plot for clarity, but follow those given in Fig. 5.

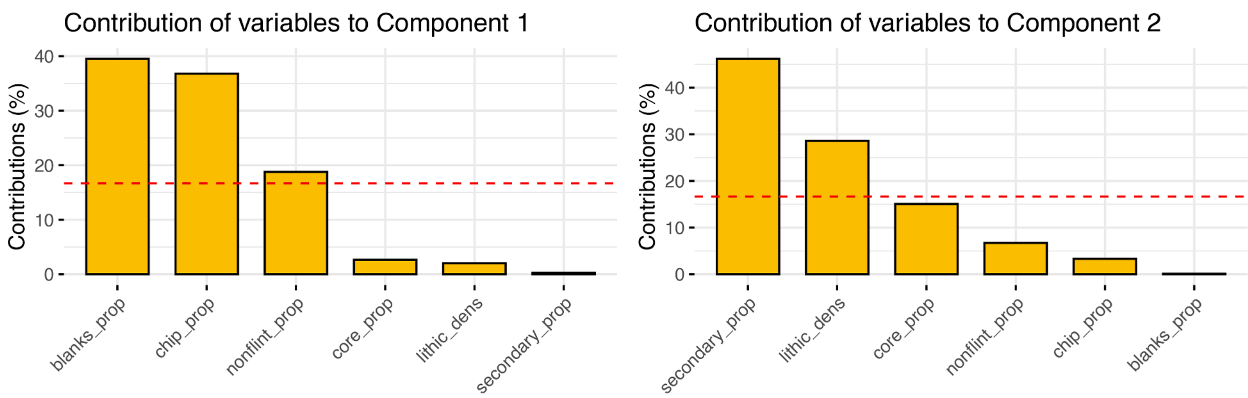

Fig. 7. Contribution of variables to the first two components of the PCA. The dotted red line indicates the expected contribution from each variable given a uniform distribution of impact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

larger proportion of blades, flakes and small tools in the earliest assemblages of the cluster, which is opposed to chips, fragments and partly micro-blades.

Moving on to the PCA of measures that have been linked to mobility, some of the variables with severely skewed distributions were initially transformed (Fig. 5). Fig. 6 displays the resulting PCA. There is a general temporal transition from the upper left to the bottom right of the plot. The second dimension is mainly defined by a negative correlation between the VDL and RFSL (Fig. 7). Almost orthogonal to this is the strong negative correlation between relative frequency of chips and blanks. While there is a slight tendency for blanks to be more associated with younger sites, frequency of chips appears to be largely independent of time. However, this almost suspiciously strong negative correlation can perhaps have a practical explanation. Seeing as the frequency of non-flint material is positively correlated with blanks and negatively correlated with chips (Fig. 5), one explanation to this pattern could be that smaller non-flint pieces are simply more difficult to identify and separate from naturally fragmented stone during excavation and classification. This could conceivably have led to an over-representation of blanks as compared to chips in assemblages with a high proportion of non-flint material. While this is not necessarily the entire explanation, this does make it difficult to place much analytical weight on this pattern. Relative frequency of cores is not especially impactful in the PCA, and appears to be independent of the temporal dimension as well. That is not to say that cores may not be indicative of or related to mobility patterns, but to get at this may require further analysis beyond their simple classification as cores (Kitchel et al. 2021).

Thus, while the relative frequency of blades and cores does not appear to meet the expectations of the WABI, it is difficult to say to what degree this is caused by idiosyncrasies in the Norwegian system for classification of lithics and properties of the lithic material itself. The relationship between VDL and RFSL does correspond to the model and follows a clear temporal trend that is also correlated with the increased use of local raw material. Thus, if the relationship between VDL and RFSL is accepted as a proxy for curation, and is related to land-use and mobility patterns, these findings would be in line with previous research into the Mesolithic of Norway, indicating that earlier sites are associated with higher degree of mobility than sites from later phases (e.g. Bergsvik 2001; Bjerck 2008; Glørstad 2010; Jaksland 2001). To explore this proposition further, these two variables are subjected to more detailed scrutiny below.

There is a strong negative correlation between the two variables (r = -0.5) and a general tendency for younger sites to be associated with a higher VDL and a lower RFSL than older sites (Fig. 8A). The linear correlation is stronger between the mean site age and RFSL (r = -0.51), than between mean site age and VDL (r = 0.22). Variable non-flint availability and workability has also been suggested to potentially impact these dimensions (cf. Manninen and Knutsson 2014), but while the negative correlation is slightly less marked when only the flint data is considered (r = -0.4), the general pattern is the same (Fig. 8B). The relationship between mean site age and relative frequency of secondarily worked flint is even stronger (r = -0.57), but as indicated by the more spread out distribution along the x-axis, the volumetric density of flint is not temporally contingent (r = 0.1). As was also indicated by the CA, this follows from the fact that non-flint materials make up a higher share of the assemblages for some of the later Mesolithic sites, and is a point returned to below where the temporal dimension of the relationship between VDL and RFSL is explored further.

To get more directly at this temporal trend, a curation index based on VDL and RFSL was devised by first performing a min–max normalisation of the two variables, scaling them to take on values between 0 and 1. The value for artefact density was then made negative to reflect its relationship with degree of curation. The mean was then found for each site on these two normalised values. To account for the temporal uncertainty associated with the dating of the sites, a simulation-based approach was also adopted (e.g. Crema 2012; Orton et al. 2017). A LOESS curve was fit to the curation index and site age for each simulation run, where the age of each site was drawn as a single year from their respective date ranges as provided in Fig. 1. For sites with radiocarbon age determinations the dates were drawn from the summed posterior density estimates, while ages for sites dated with reference to relative sea-level change and typology were drawn uniformly from the associated date range (Fig. 9). This simulation was repeated 1000 times. Disregarding the edge-effects at either end of the plot, the general tendency is a relatively high degree of curation among the earlier sites, followed by a marked drop around 8000 BCE. This has stabilised by around 7000 BCE and remains stable for the rest of the Mesolithic. The variation in degree of curation is also markedly higher after 8000 BCE. Fig. 9B displays the result of running the same procedure on the flint data. The general pattern follows the same trajectory, but the result for some individual sites is noticeably different.

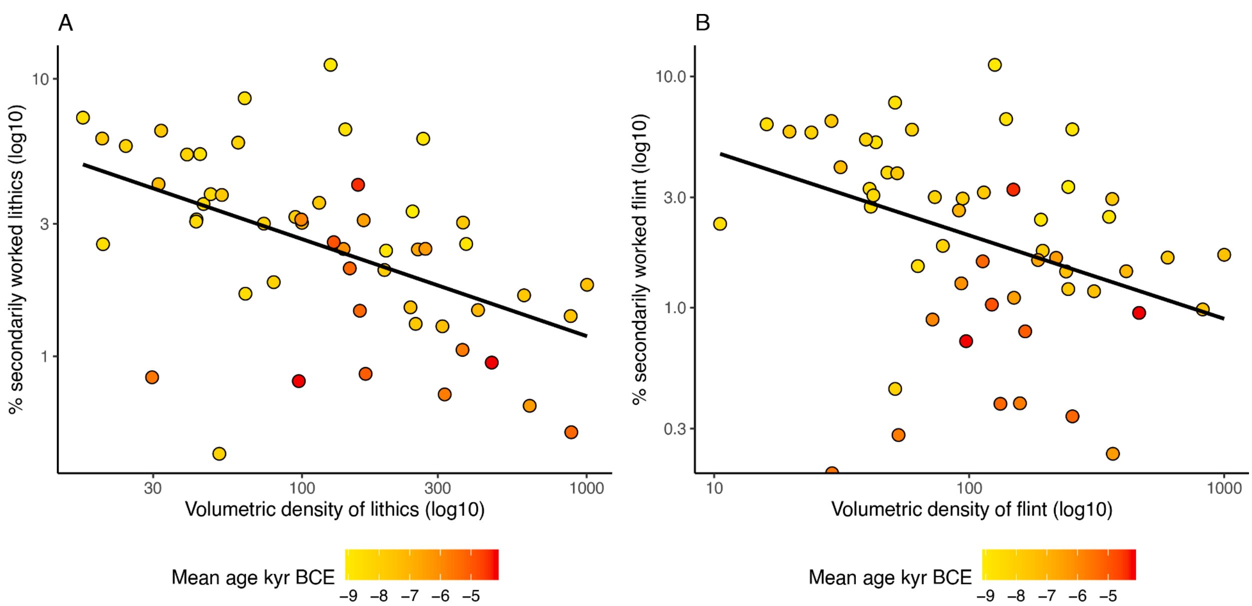

Fig. 8. Relative frequency of secondarily worked lithics plotted against the volumetric density of artefacts for A) All lithics (r = −0.5), B) Flint (r = −0.4). The logarithm is taken to base 10 on all axes.

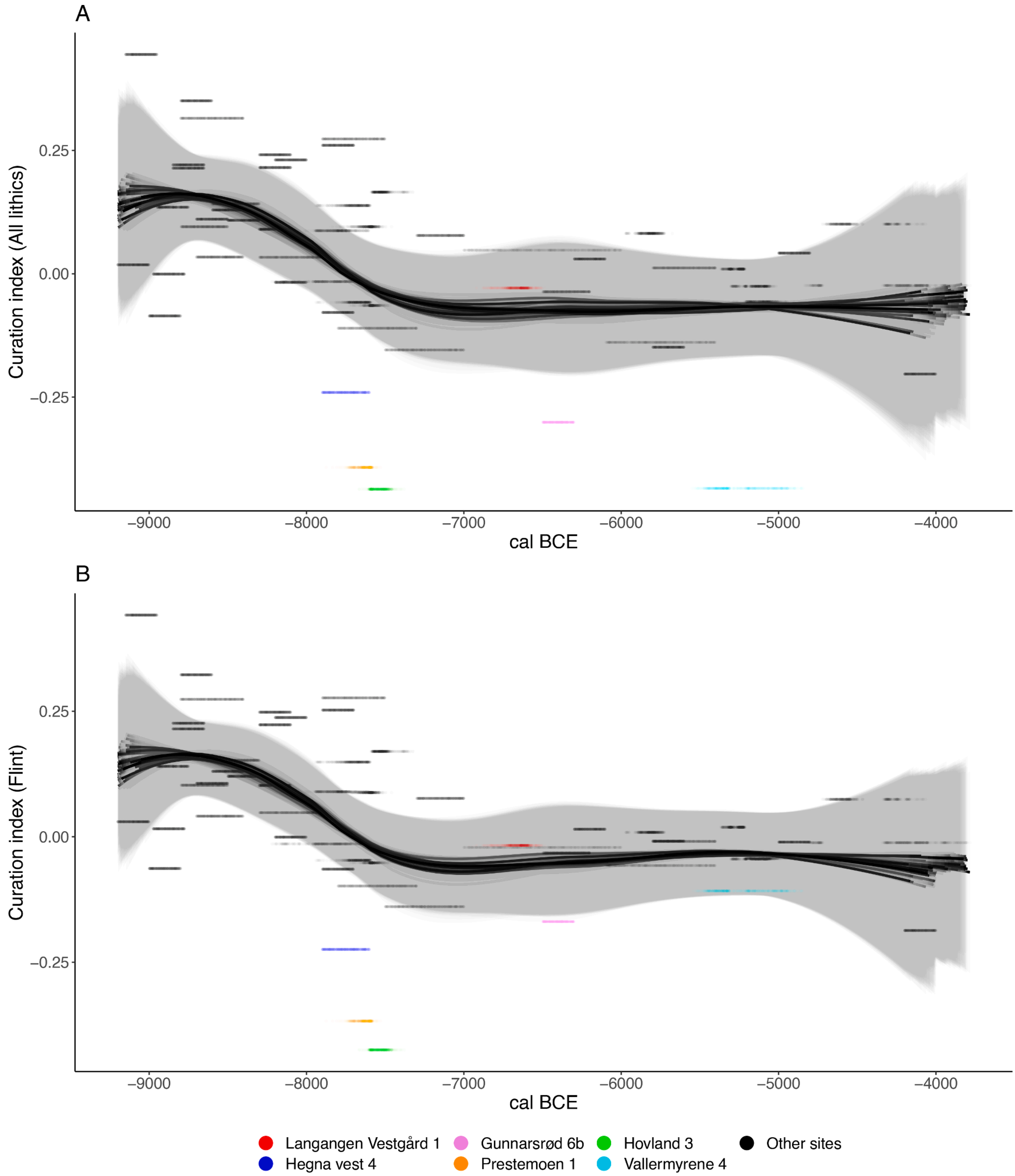

Fig. 9. Temporal variation in the curation index for A) All lithics, and B) Flint. The temporal uncertainty is handled by means of a simulation approach where the site ages are drawn from their respective age determination probability density functions given in Fig. 1B. A LOESS curve has been fit to the distribution for each of the 1000 simulation runs. Each simulation run is plotted with some transparency. Sites mentioned in the text are given colour.

6. Discussion

The results of the CA appear to align well with previous research (e.g. Solheim 2017b, with references). In the flint material the earliest sites are separated from the rest primarily based on the presence of macro tools, microburins, projectiles, and, for slightly younger sites, core fragments and blades (cf. Bjerck 2017; Breivik et al. 2018; Damlien and Solheim 2018; Fuglestvedt 2009; Jaksland and Fossum 2014). The importance of the latter two can be associated with the blade technology that is introduced with the Middle Mesolithic, characterised by blade production from conical and sub-conical cores with faceted platforms that involves the removal of core tablets and rejuvenation flakes

(Damlien 2016). When it comes to the non-flint material, projectiles are to a larger extent a property of the earlier sites than later ones. The use of metarhyolite for the production of axes is present at some earlier sites in addition to the previously mentioned Nedre Hobekk 2, and the production of non-flint hatchets and core axes is introduced in the Microlith Phase (Eymundsson et al. 2018; Jaksland and Fossum 2014; Reitan 2016). However, in agreement with the literature, this is evidently not as prominent a part of these assemblages.

The flint material of the later sites is to a larger extent characterised by micro-blades, which corresponds to the transition to micro-blade production from handle cores (e.g. Solheim et al. 2020). A more fragmented flint material, as indicated by the relative importance of flint chips and fragments, is also a previously noted property of some later Mesolithic, as well as early Neolithic sites (e.g. Fossum 2017; Stokke and Reitan 2018). The most defining material for the later sites, however, is non-flint macro tools and associated debitage, which is dominating some of these assemblages. It was noted above that this material does not seem to impact the latest sites, which would indicate that specialised axe production sites disappear towards the end of the Mesolithic, a notion that would be in line with previous suggestions (e.g. Glørstad 2011; Reitan 2016).

One implication of the fact that the employed artefact categories are so clearly capturing a temporal component could be that the aggregation of artefact categories might have been overly conservative. However, it is also evidently clear, in the words of Kruskal (1971:22), that 'time is not the only dimension.' The results of the CA do most certainly correspond to more pervasive cultural change than a purely typo-chronological development of artefact morphology, which is also made evident by some significant deviances from the overall pattern. Unpicking and aligning these patterns with any specific behavioural and technological dimensions using the coarse CA results is, however, another task entirely. This follows most clearly from the fact that for the most part we do not know what individual lithic objects in the assemblages have been used for, leaving the behavioural and social significance of the employed units of analysis unclear. The results of the CA can, however, be used in conjunction with the part of the analysis that has attempted to get at more specific behavioural dimensions to nuance or explain discrepancies in this data.

The curation index has relatively high values until some time before 8000 BCE, before it drops and stabilises around 7000 BCE. This pattern is evident in both the flint data and when all lithics are treated in aggregate. Furthermore, the increased variation in degree of curation after around 8000 BCE could indicate that these sites were associated with a more varied mobility pattern. The five sites that have values on the curation index below c. -0.25 could in this perspective have predominantly functioned as base-camps within a logistic settlement pattern. That these assemblages reflect stays of a longer duration was suggested for all five sites in the original reports (Carrasco et al., 2014; Eigeland and Fossum, 2017; Persson, 2014; Solheim and Olsen, 2013), with the exception of for Vallermyrene 4, which was argued to be a specialised axe production site, not necessarily associated with lower degrees of mobility (Eigeland and Fossum 2014). This highlights a possible issue pertaining to raw-material variability, as the coarse non-flint material used for the production of axes generally results in a relatively large amount of waste per produced tool, possibly skewing the curation index when compared to assemblages dominated by flint. Referring back to the CA, the difference is most marked for the sites in the later part of the Mesolithic where non-flint material become more dominating parts of the assemblages. As can be seen in Fig. 9B, the degree of curation is markedly higher for both Gunnarsrød 6b and Vallermyrene 4 when the non-flint material is excluded, although they remain more expedient than that of contemporary assemblages. Thus, the degree of expediency for assemblages dominated by non-flint might be somewhat exaggerated when the non-flint material is included, while its exclusion would likely lead to its underestimation. One possible approach could be to weigh the curation index by the proportion of non-flint material in the assemblages. This is not explored further here, however, as the overall tendencies appear robust to this effect.

Another case also worth commenting on is Langangen Vestgård 1, which, on the grounds of an overall large number of artefacts and the possible presence of a dwelling structure was argued to reflect a more permanent site location in the original report (Melvold and Eigeland 2014). However, the relatively high value on the curation index could mean that the site reflects the aggregation of stays which predominantly have been of a comparable duration to those on contemporary sites, while the possible dwelling structure, if taken as an indication of longer stays, could in this perspective represent a remnant from one or a few visits of longer duration that constitute a smaller fraction of the use-life of the site as a whole (cf. Barton and Riel-Salvatore 2014).

While there are certainly nuances in the material that might lead one to question the applicability of the VDL and RFSL measures for any individual site, the overall pattern for curation does appear robust. The curation index is relatively high and uniform until some time before 8000 BCE. This corresponds well with the view that the Early Mesolithic is characterised by a high and uniform degree of mobility. This is followed by a marked increase in expedience, which has stabilised by around 7000 BCE. Again, this corresponds well with the employed chronological framework. Referring back to the demographic changes that are to take place around this transition, the Microlith phase could thus represent a period where migrating people and new living practices were propagating through societies in south-eastern Norway—a process that in light of the curation data would have concluded around 7000 BCE.

The curation index then remains stable for the rest of the Mesolithic. This suggests that the transition to mobility patterns traditionally ascribed to the Nøstvet Phase can indeed be traced back to the Microlith Phase (cf. Solheim and Persson 2016). The continued stability of the curation index could also indicate that the demographic changes suggested to take place in the Transverse Arrowhead Phase are not related to major shifts in land-use and mobility patterns. However, it is worth highlighting the strained sample size for the later parts of the Mesolithic, which could mean that the effect is simply missed.

As it stands, the main hypotheses resulting from the present analysis would be that settlement patterns in the earliest parts of the Mesolithic were characterised by relatively high and uniform degrees of mobility, which then drop before levelling off at around 7000 BCE. These then remain stable throughout the rest of the period, despite variation pertaining to other aspects of the lithic inventories, as evidenced by the CA. The fall in curation levels and parallel increase in variation would seem to correlate well with a transition from a predominantly residential to logistical settlement system (Binford 1980). This indicates, in turn, that the measures represent an empirical link between technological organisation and economic behaviour and mobility patterns (Riel-Salvatore and Barton, 2004).

7. Conclusion

The results of the CA align well with results of previous research in south-eastern Norway, indicating that meaningful chronological patterning is associated with the employed artefact categories. These tendencies are already well-established when it comes to the formal tool types and some debitage categories, but have been given less focus in light of entire assemblages. Precisely what behavioural implication the development in the occurrences of the tool and debitage categories have are less clear, but appears to follow a different and more complex development over time than that of curation, as operationalised here.

The temporal trends associated with the curation index corresponds surprisingly well with trajectories of cultural development previously suggested in the literature, and does therefore, in my view, suggest that shifts in land-use and mobility patterns are the main drivers behind this empirical pattern—in line with the framework of Barton et al. (2011). Another perspective would be that this is not surprising at all (cf. Kuhn and Clark 2015:14), and that the previously demonstrated relevance of these measures across a wide range of contexts points to their pervasive relevance for the organisation of lithic technology, and, therefore, that there should be little reason to think Mesolithic south-eastern Norway should be any different. However, the conclusion that these these measures apply to and appear to capture the dimensions of interest in a relatively controlled empirical setting, reached by means of an exploratory analysis can only constitute a first analytical step. As Elster (2015:12) has pointed out, the human mind seems to have a propensity to settle for an explanation that *can* be true, as soon as this has been reached. This, however, can only constitute the absolute minimum of what is required of a proposed explanation. Subsequent steps should be to probe and challenge this explanatory framework, also in light of alternative hypotheses (e.g. Clark 2009:29–30; Perreault 2019:1–22). The empirical relationship does nonetheless hold great potential for large scale comparative studies in Mesolithic Scandinavia and beyond. Furthermore, the curation index was here simply narratively associated with the most immediate chronological trends emphasised in the literature concerned with the Mesolithic of south-eastern Norway. The explicit quantification does, however, offer the possibility to conduct formal comparisons with a wide range of environmental, demographic and cultural dimensions across multiple scales of analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Paper 4

Comparing summed probability distributions of shoreline and radiocarbon dates from the Mesolithic Skagerrak coast of Norway

Comparing summed probability distributions of shoreline and radiocarbon dates from the Mesolithic Skagerrak coast of Norway

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Abstract

By developing a new methodology for handling and assessing a larger number of shoreline dates, this paper compares the summed probability distribution of radiocarbon dates and shoreline dates along the Skagerrak coast of south-eastern Norway. Both measures have previously been compared to elucidate demographic developments in Fennoscandia, but these have not been based on probabilistic methods for shoreline dating. The findings indicates a largely diverging development of the two proxies through the Mesolithic. The number of shoreline dated sites undergoes some process of overall decrease through the period, while the radiocarbon data is characterised by a lacking signal in the earliest parts of the period and then undergoes a logistic growth that quickly plateaus and remains stable for the remainder of the period. Although the precise nature of this discrepency will require further substantiation, we tentatively suggest that while not devoid of a demographic signal, the number of shoreline dated sites is heavily influenced by mobility patterns. Conversely, we also suggest that the lacking signal in the radiocarbon data for the earliest part of the Mesolithic is in part the result of mobility patterns, but that the radiocarbon data more directly reflects population dynamics.

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1 Introduction

Variations in population patterns are regarded as important drivers and potential outcomes of cultural variation, and are thus of critical importance to our understanding of past human societies (e.g. French et al., 2021; Shennan, 2000; Shennan and Sear, 2021). During the last decade, the frequency distribution of radiocarbon dates has become the preferred proxy for archaeologists studying prehistoric population dynamics (Crema, 2022; French et al., 2021; Shennan et al., 2013), owing in part to the fact that radiocarbon dates represent the most temporally and spatially widespread archaeological data available for studying past population densities (Bird et al., 2022). This has also been the case for Norwegian Stone Age archaeology (Bergsvik et al., 2021; Jørgensen et al., 2020; Lundström, 2023; Nielsen, 2021a; Nielsen et al., 2019; Solheim, 2020; Solheim and Persson, 2018; see also Persson, 2009).

The potentially immense value of insights into past population dynamics, combined with the ubiquity of radiocarbon dates and the relative ease with which these can now be processed within what has been termed a dates-as-data methodology (Rick, 1987) has undoubtedly contributed to the popularity of the approach. Several limitations and forms of criticism have, however, been directed at these procedures. Some of the objections are of a methodological nature, while others pertain to the underlying logic and the degree to which there is likely to be a constant and direct connection between the frequency of ^{14}C-dates and population dynamics (e.g. Attenbrow and Hiscock, 2015; Carleton and Groucutt, 2021; Torfing, 2015; Ward and Larcombe, 2021). What appears to be agreed upon by practitioners and critics alike is that radiocarbon dates are best analysed in this manner when compared and contrasted to other proxies for past population dynamics, and other variables that might impact these (Attenbrow and Hiscock, 2015; Bevan et al., 2017; Crombé and Robinson, 2014; French et al., 2021; Palmisano et al., 2021, 2017; Rick, 1987; Williams, 2012). In this paper, we report on and begin to unpack the relationship between two measures that have been linked to relative population size in the context of the Mesolithic Skagerrak coast in south-eastern Norway, namely the summed probability distribution of calibrated radiocarbon dates (RSPD) and the summed probability distribution of shoreline dated sites (SSPD). We discuss how the data compare with each other as well as how they can potentially be drawn on to understand cultural historical developments in the region through the Mesolithic, c. 9500–4000 BCE.

2 Background

Following the retreat of the Fennoscandian Ice Sheet, large parts of the post-glacial landscape of Northern Scandinavia has been characterised by dramatic isostatic uplift that has led to a net sea-level fall throughout the Holocene, despite eustatic sea-level rise (e.g. Mörner, 1979; Steffen and Wu, 2011). The majority of Mesolithic sites along the Norwegian Skagerak coast are interpreted as having been shore bound or located close to the contemporaneous shoreline at their time of use. Thus, as coastal foragers in this region appear to have predominantly settled on or close to the contemporaneous shoreline during early and mid-Holocene, this can be utilised to assign an approximate date to the sites. This is done by coupling the present-day altitude of the sites with reconstructions of past shoreline displacement – a method known as shoreline dating. Shoreline dating has a long tradition of use in Fennoscandian archaeology (Brøgger, 1905; Hollender, 1901), and is especially useful for dating the large number of surveyed archaeological sites where temporal data that often follow with an excavation, such as radiocarbon dates or typological indicators in artefact inventories, are not available. A series of studies have suggested that shoreline dated sites can be used as a proxy to study temporal variation in population density (Jørgensen et al., 2020; Mjærum, 2022; Solheim and Persson, 2018; Tallavaara and Pesonen, 2020).

Previously, the frequency of shoreline dated sites has been evaluated by finding point estimates of shoreline dates that are aggregated in somewhat arbitrary bins of 200 or 500 years (e.g. Fossum, 2020; Mjærum, 2022; Solheim and Persson, 2018; Tallavaara and Pesonen, 2020), or by the use of disjoint time-intervals of variable duration (Berg-Hansen et al., 2022), which could cause issues when comparing the relative counts across these units (Bevan and Crema, 2021). However, the point-based estimates do not consider the uncertainty in the distance between the sites and the contemporaneous shoreline, nor the impact the variability in the rate of sea-level change has on the precision of the dates that can be achieved with the method. In a recent study, Roalkvam (2023a) has presented a probabilistic method for shoreline dating that takes these parameters into account, thus setting the stage for a more refined investigation of the relationship between the frequency of ^{14}C-dates and shoreline dated sites. The parametrisation of the method was based on simulating the distance between 66 sites with ^{14}C-dates and the prehistoric shoreline along the Skagerrak coast in the region between Horten municipality in the north-east to Arendal municipality in the south-west (see map in Figure 1). The results of the analysis indicates that the sites tend to have been located close to the shoreline until just after 4000 BCE when a few sites become more withdrawn from the shoreline (see also Nielsen, 2021b), followed by a clear break around 2500 BCE, at which point shoreline dating appears to lose its utility. Thus, this geographical and temporal limit are also used for this study.

The present study is decidedly exploratory. While some thoughts concerning the relationship between the variables underlie the analysis, these could not be instantiated as concrete hypotheses. Rather, we explore the data by using a set of standard models to begin to unpack patterns and grasp the relationship between the variables. The dates-as-data approach is dependent on there being a link between how prehistoric people generated material that become ^{14}C samples and population dynamics. The sum of shoreline dated sites, on the other hand, is determined by site frequency, and its use as a population proxy is therefore dependent on there being a connection between site count and population density. If a comparison of these proxies do not, or only partially correspond, it is thus an open question what factors have impacted either distribution to cause this discrepancy, and which measure, if any, reflects true population dynamics. The issue will therefore initially demand an open and exploratory approach where a multitude of explanatory and confounding effects can be drawn on to suggest explanations of any observed pattern.

2.1 Population dynamics and summed probabilities

To what degree the radiocarbon record is determined by past population numbers might vary geographically and chronologically, based on variation in investigatory and taphonomic factors (Bluhm and Surovell, 2019; Surovell et al., 2009), as well as cultural processes within prehistoric populations. One example of the latter is the difference that might exist between farmer and forager populations, where Freeman et al. (2018) have suggested that an increased per capita energy consumption introduced with farming means that ^{14}C-dates should not be weighted equally when making relative population estimates across such populations. Similarly, while site counts have also been invoked for the analysis of past population dynamics, these are likely to be impacted by factors such as land-use and mobility patterns, and settlement nucleation and dispersion, as well as variation in archaeological investigations and what has been taken to constitute a site (Drennan et al., 2015, pp. 16–20; Palmisano et al., 2017). However, these could be considered theoretical issues that have implications for how fluctuations in these proxies should be interpreted, and possibly weighted differently by factors such as those mentioned above. Before any such fluctuations are given any substantive interpretation, however, there is a host of methodological issues that have to be considered (see Crema, 2022 for a recent review).

The most critical of these follows from the fact that the summation of the probabilities associated with the dates for SPDs is not a directly coherent statistical procedure. This is because the summed probabilities can no longer been seen as probabilities, but rather represent the combination of events and chronological uncertainties, making the two indistinguishable, and rendering the interpretation of the resulting sum difficult (Blackwell and Buck, 2003; Crema, 2022). As Timpson et al. (2021, p. 2) put it: 'the SPD is not *the* single best explanation of the data, nor even *a* single explanation of the data, but rather a conflation of many possible explanations simultaneously, each of which is mired by the artefacts inherited from the calibration wiggles.' The SPD is not a model. It is the combined representation of a range of possible explanations for the data – the frequency of dated events combined with the variable uncertainty associated with these (Carleton and Groucutt, 2021). This means that a direct visual inspection of SPDs can be misleading, that they cannot be directly analysed to draw inferences on population dynamics, and that they cannot be directly compared to other time-series data (Carleton et al., 2018; Crema, 2022; Timpson et al., 2021). While this problem cannot be entirely resolved, a range of approaches have been developed in an attempt to work around this issue.

The most commonly applied of these is a null-hypothesis significance testing approach by means of Monte Carlo simulation, first introduced by Shennan et al. (2013) and later expanded upon by Timpson et al. (2014) and Crema and Bevan (2021). This works by comparing the observed RSPD with a series of simulated RSPDs, generated from a null model. These null models are typically a uniform, exponential or logistic distribution. These are chosen *a priori* with reference to common long-term population dynamics and are typically parametrised by fitting the models by means of least-squares or, given recent methodological developments (Timpson et al., 2021), maximum likelihood estimation (MLE). The result from these simulations is then used to create a 95% critical envelope representing the null model. The proportion of the observed RSPD that falls outside the simulated envelope (i.e. positive or negative divergence of the observed SPD from the fitted null model), is then used to estimate a global p-value indicating whether the null model can be rejected. In the case that it can, the portions of the observed RSPD that falls outside this envelope can subsequently be interpreted as representing potentially meaningful demographic events, relative to the null model. However, care has to be taken in how these are interpreted. First, this follows from the fact that 5% of the deviations from the critical envelope can be expected to be random, and there is no way to know which deviations this pertains to. Secondly, for example, an exponential null model fit to the data is only one of an infinite set of exponential models with different growth rates that could be used. While a model fit by means of MLE will likely have a reasonable growth rate, and by extension exclude many other exponential fits as likely to explain the data, this can be difficult to determine. Finally, the p-value only indicates whether the null model as a whole can be rejected as an explanation of the data, and it does not provide statistical justification for inferring whether local deviations themselves are meaningful demographic signals (Crema, 2022; Timpson et al., 2021).

The procedure outlined above represent the standard approach in efforts to model population dynamics based on RSPDs. This can be helpful for getting an impression of the overall developments of population proxies, and it is an especially useful first step in the treatment of shoreline dated sites, as few assumptions concerning this overall development could be made. However, it is worth underscoring that deviations from these rejected null models do not in themselves give statistical justification for the interpretation of any local deviations, nor a subsequent direct analysis of the SPDs themselves.

3 Methods and data

Sites surveyed by means of test-pitting between Horten and Arendal were initially retrieved from the national heritage database Askeladden (Norwegian Directorate for Cultural Heritage, 2018), totalling at 1299 records. The records were then manually reviewed and given a quality score based on the criteria in Table 1, indicating the degree to which the spatial location and extent of the sites is believed to be represented by the geometries available in the database (see also Roalkvam, 2020). All sites with a quality score of 4 or worse were excluded from further analysis. Any sites situated at elevations that result in a shoreline date earlier than 9465 BCE were then excluded. This marks the latest start-date among the employed displacement curves, and no sites in the region have yet been conclusively verified to have an older date than around 9300 BCE (Glørstad, 2016). Data on excavated sites was originally compiled for Roalkvam (2023a) and has been compared with site data as listed in Damlien et al. (2021) and Nielsen et al. (2019). Only excavated sites with available spatial data in Askeladden or local databases at the Museum of Cultural History of the University of Oslo were included in the analysis. The 102 excavated sites in the dataset without relevant ^{14}C-dates that were originally shoreline dated in the excavation reports were included in the SSPD along with the retained surveyed sites. This gave a total of 921 shoreline dated sites in the final SSPD.

The borders of the municipalities within which the shoreline dated sites are located were used to limit the radiocarbon sample. Radiocarbon dates were taken from Roalkvam (2023a) and an unpublished data set collated by Solheim and Kjetil Loftsgarden for the Museum of Cultural History. Dates done on food crusts were then excluded due the issue of marine reservoir effects (Nielsen et al., 2019, p. 83). Following both from the point made by Freeman et al. (2018) concerning the comparison of radiocarbon dates from populations with different economic modes, as noted above, and from the fact that shoreline dating appears less reliable after 4000 BCE and appears to loose its utility c. 2500 BCE, the Mesolithic is the main focus of this analysis. Consequently, probabilities falling later than 2500 BCE were excluded from the analysis, leading to a final sample of 310 ^{14}C-dates. Probabilities falling after 4000 BCE, and the first possible small-scale introduction of agriculture in south-eastern Norway, were retained to account for edge-effects but these results should be treated with care for the reasons noted above.

All analyses done in this study were performed using the R programming language (R Core Team, 2020). Underlying data and programming code used for the paper is available in a version-controlled online repository at https://doi.org/10.17605/osf.io/fqwt5. This is structured as a research compendium following Marwick et al. (2018), to allow for reproducibility of the results (see also Marwick, 2017). Analysis of the ^{14}C-dates were done using the R packages *ADMUR* (Timpson et al., 2021) and *rcarbon* (Crema and Bevan, 2021). The R package *shoredate* was used for performing and handling the shoreline dating of sites (Roalkvam, 2023b), and re-purposed code from both *ADMUR* and *rcarbon* for subsequent Monte Carlo simulation and model comparison.

3.1 Summed probability of calibrated radiocarbon dates

To account for investigatory bias that can result from variable sampling intensity between sites, the summing of radiocarbon dates with *ADMUR* starts with binning dates from the same sites that fall within 200 uncalibrated ^{14}C years of each other when measured from the mean ^{14}C age. All dates are then calibrated

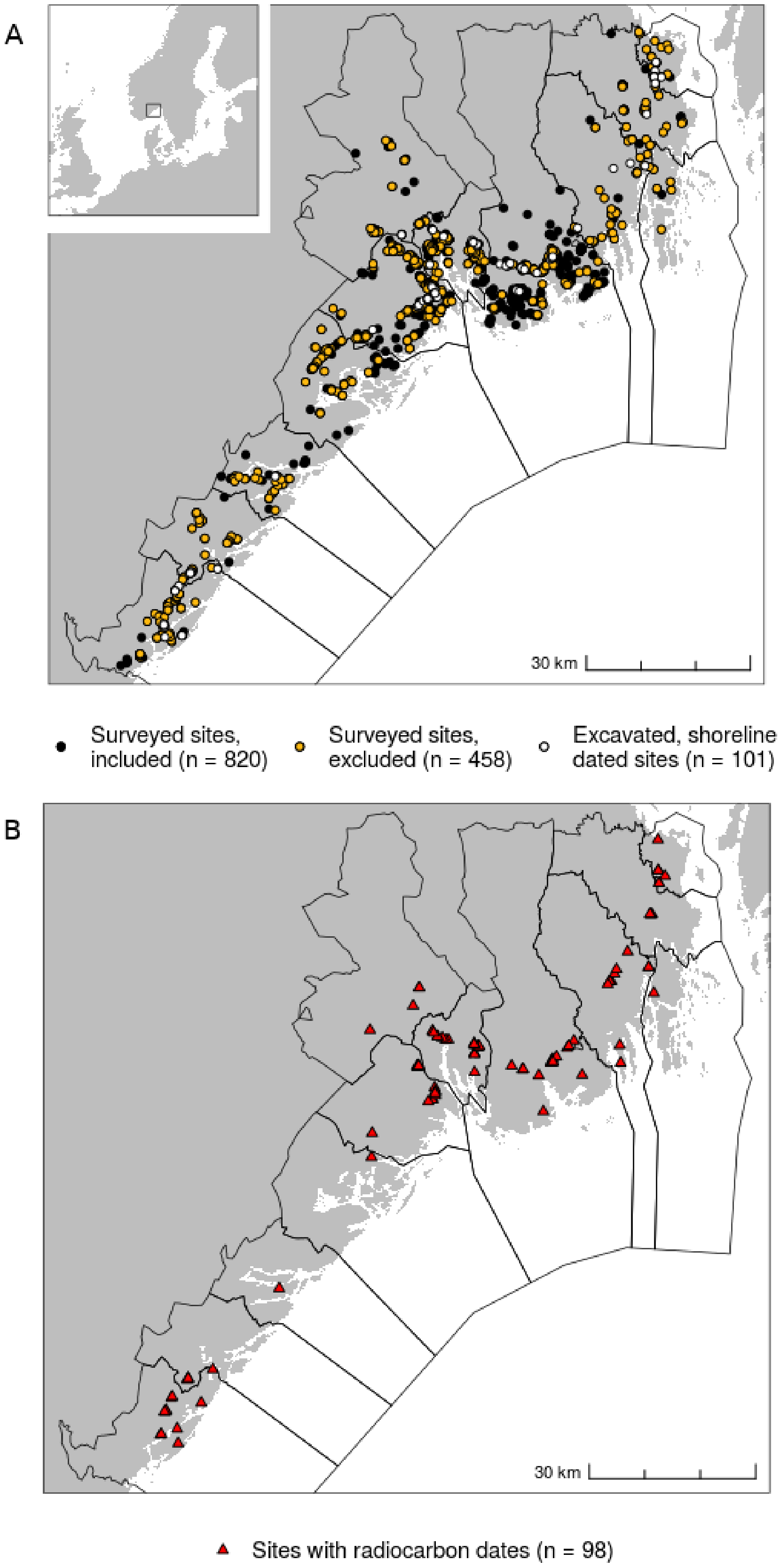

Figure 1: A) Map displaying the location of the study area and shoreline dated sites. Black lines indicate the borders between municipalities. The surveyed sites included in the analysis are the ones given a quality score of 3 or higher using the framework in Table 1. B) The distribution of radiocarbon dates employed in the study.

Table 1: Quality scoring of site records of surveyed sites retrieved from the national heritage database Askeladden. The scoring system was first used in Roalkvam (2020).

Definition	Quality	Count
Site delineated by use of a GNSS-device, or a securely georeferenced record. Extensive database entry.	1	353
Secure spatial data. Slight disturbance of the site or somewhat lacking database record.	2	340
Secure spatial data. Damaged site, such as outskirts of a quarry, and/or very limited database entry.	3	148
Surveyed by archaeologists. However, the database entry is extremely limited/unclear, the site geometry is only given as a point or small automatically generated circle, and/or finds are from the topsoil of a field.	4	165
Likely site but uncertain spatial information. Typical example is recurring stray finds in a field or other larger area.	5	124
Single stray find or unverified claims/suggestions of possible site.	6	169

using a resolution of 5 years and normalised to sum to unity. The RSPDs for each site-phase are summed to achieve the final SPD, which is in turn normalised. All calibrations were performed using the IntCal20 calibration curve (Reimer et al., 2020).

The final RSPD was subjected to the standard null-hypothesis testing approach through Monte Carlo simulation, as introduced above (see Shennan et al., 2013; Timpson et al., 2014), by fitting an exponential, logistic and uniform model to the observed RSPD. Following Timpson et al. (2021), the model parameters were identified by MLE search with *ADMUR*, using the differential evolution optimization algorithm *DEoptimR* (Brest et al., 2006). The Monte Carlo simulations were then performed using the *SPDsimulationTest()* function from *ADMUR*. For each model, a series of individual calendar years are drawn from the model distribution, with replacement, the number of which equals the number of bins in the observed RSPD. These are then ‘uncalibrated’ to a single value on the ^{14}C scale and a random error from among the observed errors is added to the date. These are then calibrated back to the calendar scale and finally summed. Here, this procedure was repeated 10000 times for each null model. The 2.5 and 97.5 quantile of the resulting summed probability for each year across all simulations are then retrieved to create the 95% critical envelope with which to compare the observed RSPD. The degree to which the observed RSPD deviates from the simulations is used to calculate a global p-value, indicating whether the null model under consideration can be rejected.

3.2 Summed probability of shoreline dated sites

Summing the probability of the shoreline dated sites and the model-fitting procedures followed the same structure as that for radiocarbon dates and was partly based on re-purposed programming code from *rcarbon* and *ADMUR*. However, idiosyncrasies in the dating method did necessitate some adjustments. To illustrate this, the procedure for shoreline dating a single site, as suggested in Roalkvam (2023a), is provided in Figure 2 and outlined below.

Four geological reconstructions of shoreline displacement in the region lays the foundation for the method as implemented here (Figure 2B). These shoreline displacement curves are from Horten (Romundset, 2021), Porsgrunn (Sørensen et al., in press, 2014a, 2014b), Tvedestrand (Romundset et al., 2018; Romundset, 2018) and Arendal (Romundset, 2018), each associated with a shoreline isobase along which the trajectory for relative sea-level change has been the same (see Svendsen and Mangerud, 1987, and map in Figure 2A). The first step in the dating procedure is to interpolate the shoreline displacement to the site to be dated. This is done by inverse distance weighting (e.g. Conolly, 2020), where the relative sea-level change is interpolated to the location of an archaeological site based on its distance from the isobases of the geological displacement curves.

With an estimated trajectory of shoreline displacement at the site to be dated, the elevation of the site can be drawn on to find a likely date for when it was in use, under the assumption that it was in use when located on or close to the shoreline. Figure 2C indicates where the mean elevation of the polygon representing the example site intersects the interpolated displacement curve. As it can reasonably be assumed that a site was not in use when located under water, this effectively represents a *terminus post quem* (TPQ) date. However, TPQ dates that do not account for the likely distance between site and sea when the site was in use limits the further inferential steps that can be taken. Furthermore, the common practice of adding a constant error or binning point-estimates of shoreline dates, as mentioned above, does not consider that the rate of shoreline displacement varies both spatially and temporally, and therefore introduces bias to the result on both the spatial and temporal scale, while also overestimating the precision of the method in most cases.

This last point can be illustrated by finding the range between the upper and the lower limit of the four geological displacement curves for every meter from the marine limit and down to elevations that do not give an earliest date younger than 2500 BCE. This gives a mean TPQ range of 276 years with a standard deviation of 156 years across all four displacement curves, with this range varying significantly over time and between curves.

The analysis in Roalkvam (2023a) found that site phases ^{14}C-dated to before 2500 BCE have a likely elevation above sea-level that can be reasonably approximated by a gamma distribution with shape = 0.286 and scale = 20.833. This is incorporated in the procedure for shoreline dating used for this study (Figure 2D). When performing this dating procedure, the gamma distribution is sequentially stepped through and transferred to the calendar scale by uniformly distributing the probability across the years in the range between the lower and upper limit of the interpolated displacement curve. This procedure thus gives the shoreline date of a site when accounting for the likely elevation of the site above sea-level when it was in use (see Roalkvam, 2023a for details). Given that the shoreline displacement curves have no inversions and should therefore before commutative (cf. Weninger et al., 2015, p. 545), each shoreline date is normalised to sum to unity before being summed. To reduce the computational cost of the simulation procedures to follow below, the gamma distribution is here stepped through at increments of 0.1 m and the calendar scale is kept at a resolution of 5 years.

The implications of different approaches to shoreline dating and summing the results are illustrated in Figure 3. In Figure 3A the sites to be shoreline dated are plotted according to their elevation. Due to the variable rates of shoreline displacement within the study region, the same elevation does not necessarily equate to the same date, and so this does not directly inform us about their temporal distribution. For example, as the trajectory for sea-level regression is more pronounced towards the north-east, the same elevation at a location to the south-west implies a younger date compared to one situated further north-east.

When the frequency distribution of shoreline dates has been investigated in the past, this has typically involved finding point-estimates of dates by either using the mean of the displacement curves, or by taking mean of the TPQ dates for each site (as illustrated in Figure 2C). As outlined above, these point-estimates are then typically aggregated in bins of 200 or 500 years. This approach is illustrated in Figure 3B. The SSPD resulting from using the probabilistic method of shoreline dating, given in Figure 3C, demonstrates that accounting for the site-sea relationship gives a substantially different result compared to the more traditional approach, which is indicated by the shifts in the positions of peaks and troughs in the distribution after c. 8000 BCE.

In the same way as with an RSPD, the SSPD cannot be directly interpreted as reflecting the intensity of sites over time, due to the summation issues introduced above. Furthermore, similar to how characteristics of the calibration curve can introduce bias to the RSPD, the same is true for the SSPD, where the local trajectory of relative sea-level change effectively functions as the calibration curve for each site. As the shoreline displacement curves are interpolated to the sites based on their location along a south-west/north-east gradient, each site is effectively associated with a unique shoreline displacement curve, provided they are not located on exactly the same isobase. With analogy to the radiocarbon methodology, this would be equivalent to each radiocarbon date being associated with a unique calibration curve. As it would be computationally prohibitive to interpolate the shoreline displacement trajectory for each date to be simulated in the Monte Carlo procedure, one shoreline displacement curve was initially interpolated to the centre of each of a series of 2 km wide line segments running perpendicular to the shoreline gradient between the extremes of the distribution of sites. These intervals were assigned a weight based on how the density of observed sites is distributed among them (Figure 4).

The Monte Carlo simulations with the SSPD is based on drawing a sample of calendar dates from the observed date range in the SSPD, equalling the number of shoreline-dated sites, where the probability of drawing any 5-year interval is determined by the null model of choice. This is equivalent to the sampling method *calsample*

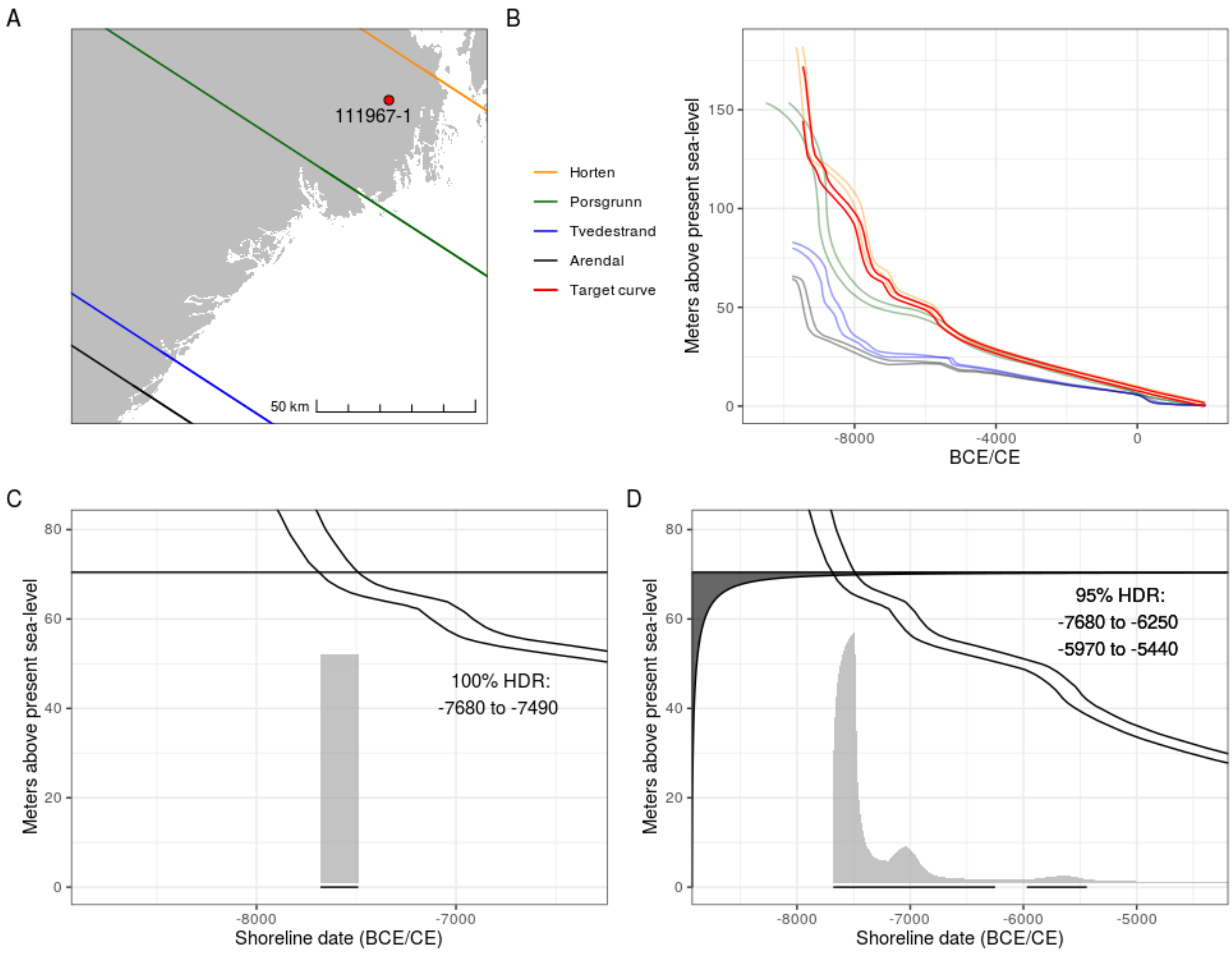

Figure 2: A) The location of an example site (Askeladden ID 111967-1) relative to the isobases of the displacement curves. B) The geologically derived shoreline displacement curves for the region and the curve interpolated to the example site. C) The black line on the y-axis represents the elevation of the site. This crosses the interpolated displacement curve at 7680 and 7490 BCE, which thus in practice gives an estimate of when the location of the site emerged from the sea and represents a *terminus post quem* date for the site. D) The shoreline dating approach used for this study, where the gamma function on the y-axis describes the likely vertical relationship between the shoreline and the site when it was in use.

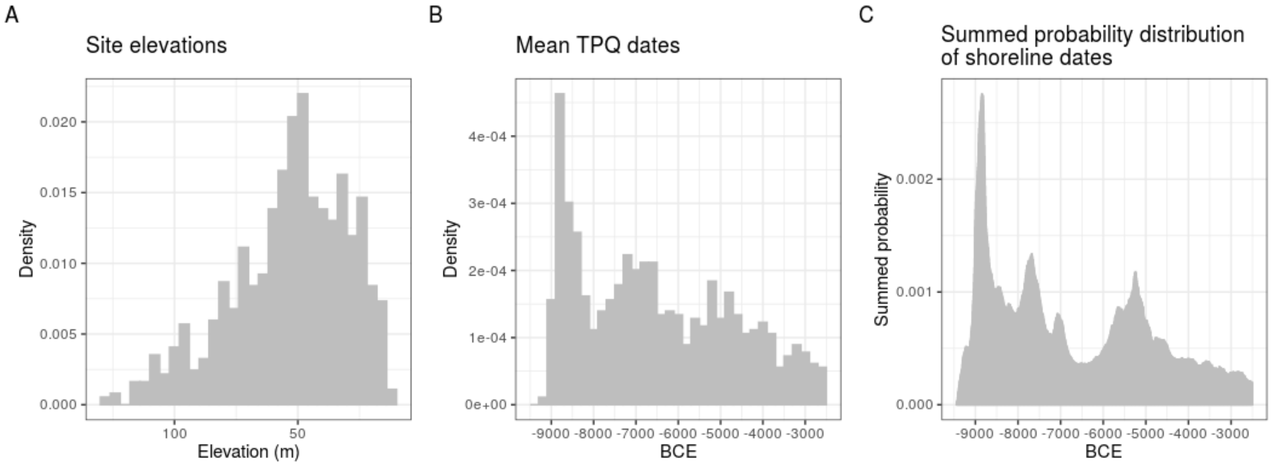

Figure 3: A) The distribution of the shoreline dated sites (n = 921) by altitude above present sea-level. The binwidth is 4 m. B) The mean of *terminus post quem* dates for the sites, plotted with a binsize of 200 years, reflecting the common approach to summing shoreline dates. C) The result of instead summing the probability of the shoreline dates achieved with the method employed here, which accounts for the likely distance between sites and shoreline. The binwidth is 5 years, following the resolution used with the dating procedure.

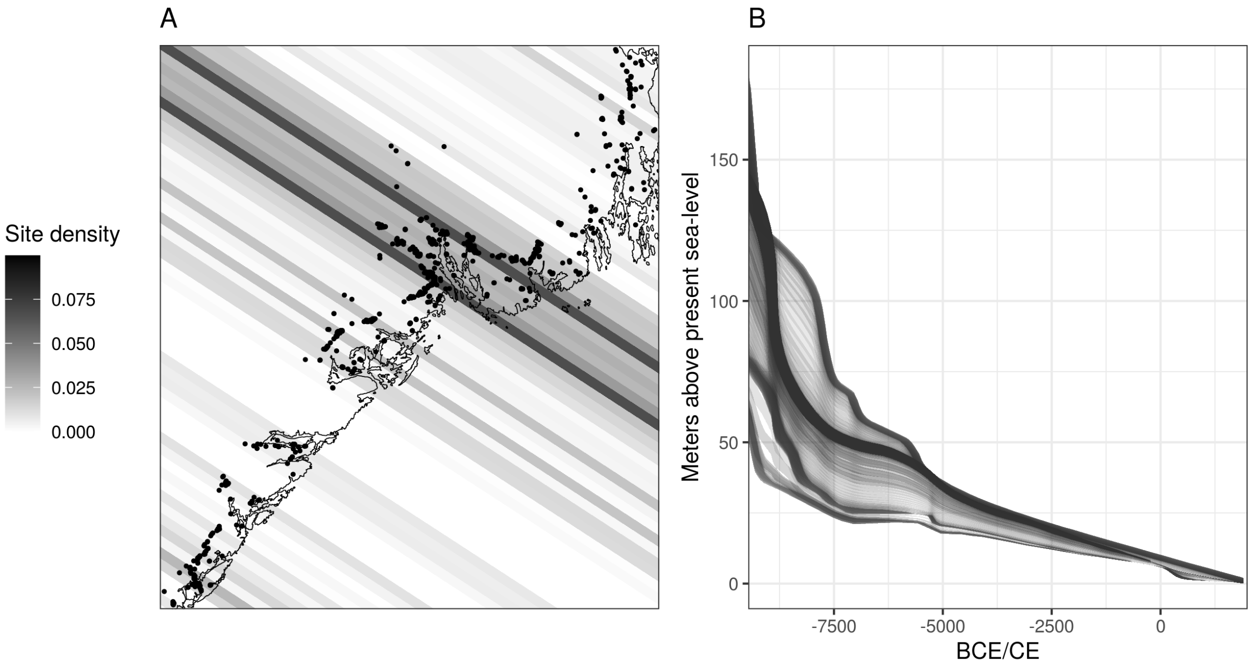

Figure 4: A) Density of included surveyed sites and excavated sites dated by means of shoreline dating (n = 921) as distributed across 2 km wide line segments that run perpendicular to the shoreline gradient. B) The displacement curves interpolated to the centre of each segment for use in the Monte Carlo simulations below.

from *rcarbon* (Crema and Bevan, 2021). Each sampled date is then assigned one of the pre-interpolated displacement curves, the probability of which is weighted by the density of observed sites within each 2 km interval. The calendar date is 'uncalibrated' – to follow the RSPD terminology – to an elevation range from which a single elevation value is drawn with uniform probability between the lower and upper limit of the displacement curve at that calendar year, using intervals of 5 cm. As shoreline dating is here done with a gamma distribution with the same parameters across all sites, there is no equivalent of the error term for ^{14}C-dates that determine the shape of the Gaussian distribution associated with the ^{14}C age. Consequently, the elevation value retrieved by 'uncalibrating' the shoreline date was shoreline dated using the displacement curve for the relevant 2 km interval with the same gamma distribution for all samples. Having dated the number of samples equalling the number of shoreline-dated sites, these were then summed, and the entire process repeated a total of 10000 times. The 97.5% highest and 2.5% lowest summed probability at each interval of 5 years across all simulations was then retrieved to create the 95% critical envelope, and the global p-value found in the same manner as for the RSPDs. This was done using re-purposed code from *ADMUR*.

3.3 Comparing model performance

For each dating method, the relative performance of the exponential, logistic and uniform models was compared. This was done by finding the overall relative log-likelihoods of the models using the *loglik* function from *ADMUR*. For any given model, this involves finding the scalar product between the probability of each shoreline date against the probability of the null model, and in the case of the ^{14}C-dates, each site-phase. The overall model likelihood is the product of these individual probabilities and is not, critically, found by using the values of the final SPD (Crema, 2022; Timpson et al., 2021). From these likelihoods, the Bayesian (or Schwarz) information criterion (BIC) was then found for each model. This penalises the models for the number of parameters in use to avoid over-fitting, and provides a measure for the relative performance of the models.

4 Results

The results of the Monte Carlo simulations are given in Figure 5, displaying the deviations from the simulation envelopes and the corresponding global p-values. The comparison of the models based on BIC scores is given in Figure 6.

For the RSPD, the logistic model achieved a p-value of 0.072, and could therefore not be rejected (Figure 5E). As is also indicated by the BIC values of the compared models, the logistic model represents the best explanation of the data, and the failure to reject the model means that the data could be expected under this logistic development. This is characterised by a rapid growth from the start of the RSPD, around 8500 BCE, which plateaus at around 7500 BCE and then remains stable for the remainder of the period.

All of the standard models could be rejected for the SSPD. Of the contrasted models, the BIC values indicate that the exponential model is the best candidate. Its negative direction indicates that some overall process of reduction in the frequency of shoreline-dated sites occurs over time, while the rejection of the model and clear deviations from the exponential pattern indicates that this model does not account for the entire development (Figure 5A). Some significant deviations occurs with the model over-predicting the frequency of sites in the period from c. 9200–9000 BCE, followed by a significant positive peak just after 9000 BCE, lasting until around 8500 BCE. The process of decline is then interrupted by positive deviations at 7900–7400, and with a smaller deviation around 7000 BCE. This is closely followed by a negative deviation between c. 6800 and 5800 BCE. Finally, a positive deviation occurs again around 5300–5000 BCE. While all of the above deviations should also be viewed with caution, questions concerning the reliability of shoreline dating after 4000 BCE (cf. Roalkvam, 2023a) and the small magnitude of the negative deviations that occur around 3000 BCE means that these are disregarded in the discussion to follow.

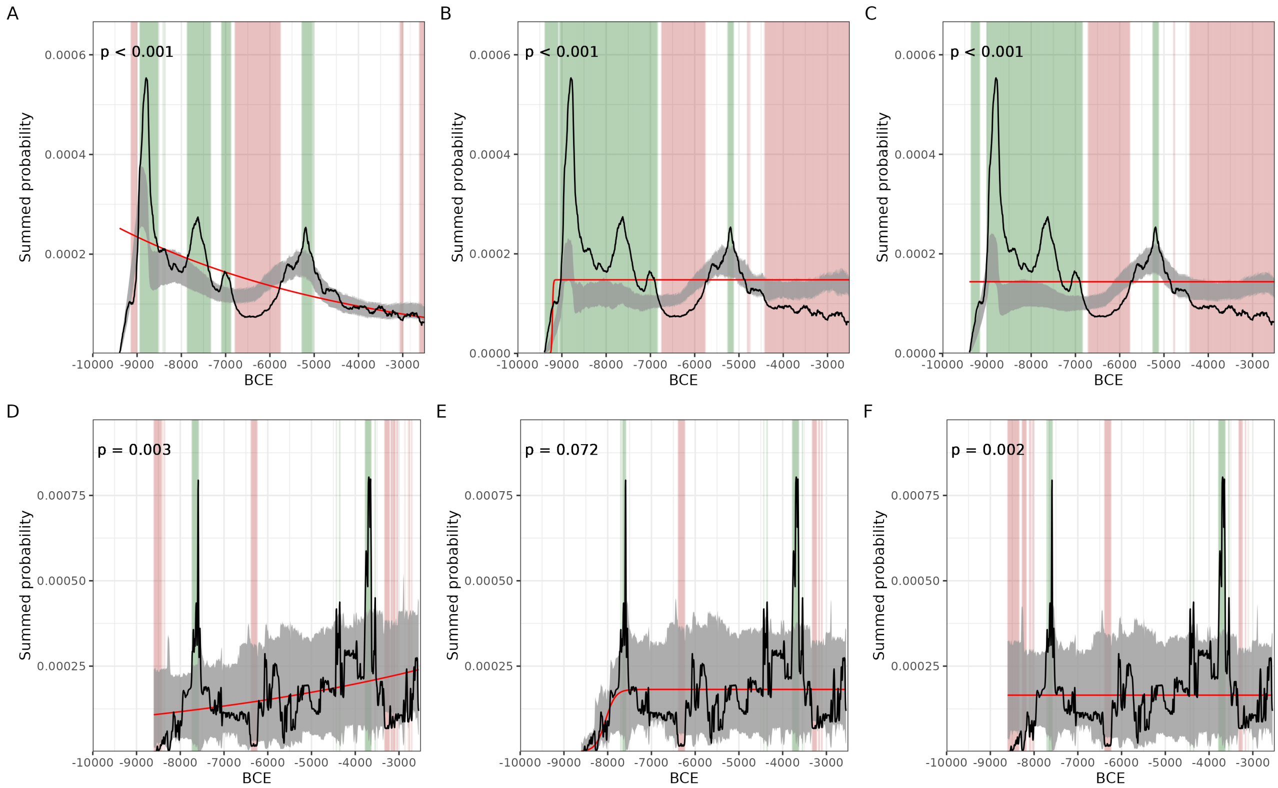

Figure 5: Monte Carlo simulation for shoreline and radiocarbon dates. A) Summed probability of shoreline-dated sites (n = 921) compared to an exponential null model. B) SSPD compared to a logistic null model. C) SSPD compared to a uniform null model. D) Summed probability of calibrated radiocarbon dates (n = 310, bins = 134) compared to an exponential null model. E) RSPD compared to a logistic null model. F) RSPD compared to a uniform null model.

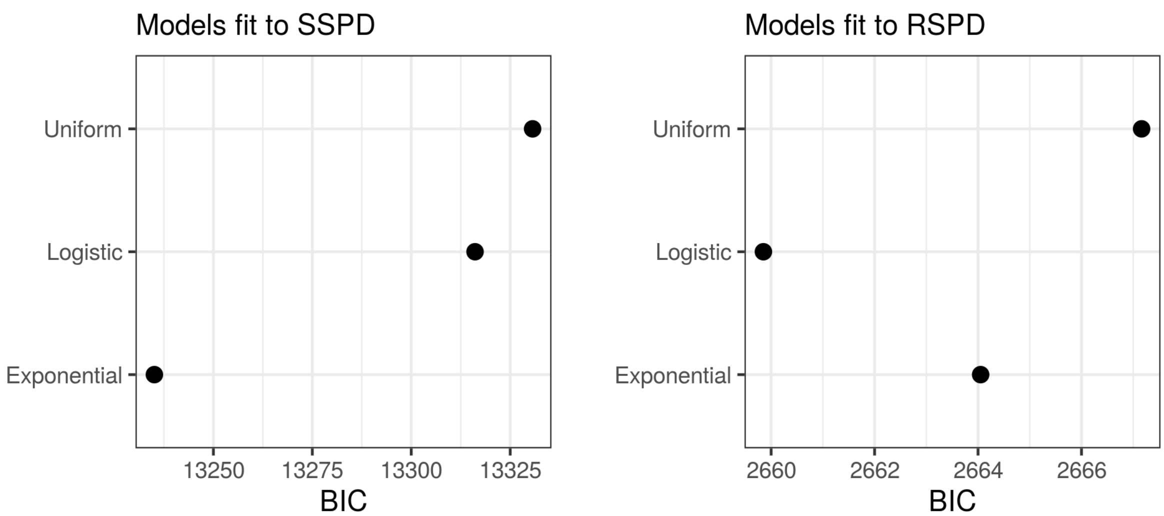

Figure 6: Bayesian information criterion for the models fit to the SPDs. Lower values indicate a better model.

5 Discussion

Although there are generally few ^{14}C-dates from the earliest part of the Mesolithic in Norway (e.g. Åstveit, 2018; Breivik and Bjerck, 2018; Kleppe, 2018; Solheim and Persson, 2018), it is established that Stone Age sites in southern Norway date to the period from before the earliest ^{14}C-dates in the study area for this paper, and at least from as far back as around 9300 BCE (e.g. Damlien and Solheim, 2018; Glørstad, 2016). While the SSPD achieved here starts from c. 9500 BCE, the RSPD shows no evidence of human activity until c. 8500 BCE. What has caused the lack of ^{14}C-dates from this earliest period has been given many possible explanations through the years. These range from taphonomic loss to diverse environmental and/or cultural factors, such as the use of shrubs or rapidly deteriorating seal blubber as fuel for burning, or a preference for consuming raw, dried or fermented food (see Bjerck, 2017; Damm, 2022). A possible lack of reliable access to firewood has also been seen as possible contributor to this pattern, although evidence for the early presence of forested landscapes, at least in the southern parts of the country, has now rendered this a less favoured hypothesis (Solheim and Persson, 2018; cf. Damm, 2022; Sørensen et al., 2014a). While taphonomic and ecological factors are likely part of the picture, we view it as probable that the rapid growth at the start of RSPD and the magnitude of the SSPD in the period preceding this suggest that cultural and demographic factors are central drivers behind this pattern.

The considered models also indicate that after the initial jumps of each proxy, some process of decrease in shoreline dated site frequency occurs throughout the Mesolithic, contrasted by a general stationary frequency of ^{14}C-dated material. Following from what is generally held to be a reduction in residential mobility from the earliest to the later parts of the Mesolithic (e.g. Bang-Andersen and Bjerck, 2005; Bjerck, 2008, pp. 103–105; Fuglestvedt, 2018, pp. 16–17; Lindblom, 1984), an immediate explanation of this mismatch could be that the SSPD is more heavily impacted by variation in land-use and mobility patterns, while the RSPD mainly reflects population numbers.

A common interpretation of the Early Mesolithic in Norway is that the population was small but highly mobile, reflected in large numbers of short-lived sites along the coast (e.g. Bjerck, 2017, 2008; Fuglestvedt, 2012). This is commonly seen in relation to homogeneous lithic technology over large swathes of the Scandinavian Peninsula in this period, and what is believed to have been a rapid colonisation of the Norwegian coastline (e.g. Bang-Andersen, 2012; Bjerck, 2009; Fuglestvedt, 2012). High mobility has been seen as necessary both to maintain demographic viability among colonising groups, and for it to be possible to maintain this technological uniformity over large areas (Rowley-Conwy and Piper, 2017; also discussed by Berg-Hansen, 2018). The initial peak in the SSPD could thus be congruent with a process of rapid colonisation of the Norwegian coast, coupled with a high degree of mobility, leading to the overall high site-count in the earliest period. The lacking signal in the RSPD for the first settlement period could in this view reflect mobility patterns characterised by short occupational duration and corresponding pyrotechnology based on small, short-lived fires (cf. Damm, 2022) and low population numbers.

Following this earliest phase of rapid increase in shoreline dated sites, there is a drop from this initial peak, starting from around 8800 BCE, concluding around 8500 BCE and remaining within the simulation envelope until c. 7900 BCE. It has previously been suggested that a change in mobility patterns occurs sometime around 8500–8000 BCE, involving a reduction in residential mobility (e.g. Damlien and Solheim, 2018; Roalkvam, 2022). Furthermore, both genetic data and technological analyses of lithic inventories indicate that the initial phase of human colonisation from the south is followed by an influx, and possible mixing of people from the east around the same time (Günther et al., 2018; Manninen et al., 2021). If this narrative is coupled with the data observed here, these migratory events could appear to result in a relatively sudden drop in site-count as indicated in the SSPD, which in turn could be related to a change in mobility patterns. The end of this drop also roughly corresponds to the first ^{14}C-dates in the RSPD around 8500 BCE, leading to the logistic growth that plateaus in the first centuries after 8000 BCE. The logistic growth in the RSPD reaches its plateau in the same time-interval as a positive deviation in the SSPD from the exponential model – an increase that was also noted by Berg-Hansen et al. (2022) – which could indicate that a demographic signal is reflected in the frequency of shoreline dated sites as well.

Subsequently, the SSPD deviates negatively from the exponential null model from c. 6800 to c. 5800 BCE. This is followed by a positive deviation in the last centuries before 5000 BCE. These developments should possibly be seen in relation to simultaneous developments in the inland areas of southern Norway. The negative deviation in the SSPD appears to correspond to an increase in inland activity, which is to take place in the period from c. 6700–5900 BCE and reach its peak around 6200–6000 BCE (Boaz, 1999; Persson, 2018; Selsing, 2010). Boaz (1999) related this to an economic reorganisation, involving a more focussed exploitation of the interior and a reduction in the utilisation of coastal areas. This period is followed by a marked reduction in inland activity, lasting until c. 4500–4000 BCE (Persson, 2018, p. 204), the onset of which thus corresponds to the end of the negative deviation in the SSPD at c. 5800 BCE and the positive deviation from c. 5300–5000 BCE. Boaz (1999) associated this period of decrease in inland activity to the onset of the classic Nøstvet phase, which is now believed to commence in the middle of the 6th millennium BCE (Reitan, 2022). The Nøstvet period is argued to be characterised by an increase in specialised coastal adaptation that also coincides with what Fuglestvedt (2018, p. 17) has been termed 'the great wave' of rock art in Norway, starting from around 5700 BCE in south-eastern Norway (Fuglestvedt, 2018, pp. 42–46; Glørstad, 2010, pp. 216–233). The onset of the classic Nøstvet thus roughly corresponds with the positive deviation in the SSPD around the later parts of the 6th millennium BCE.

A recent study by Manninen et al. (2023), which considers a larger inland area of northern Scandinavia than the above-referenced studies, found a corresponding increase in inland activity starting from the earliest parts of the Mesolithic that lasted until c. 6000 BCE. However, after this the population dynamics indicated by the radiocarbon record is found to have been characterised by a cessation of growth, rather than the clear decrease suggested by the regional studies in southern Norway. Consequently, properly relating the developments in the coastal region to inland developments and their relevance to each other will benefit from an integrated approach that also explicitly considers the spatial dimension without invoking predefined analytical regions (cf. Crema et al., 2017).

Following from the divergence between the proxies, assessing the suggested and possibly varying influence of demographic developments and mobility patterns on the measures will remain speculative without drawing on additional variables that can control for such confounding effects. Following from the stationarity of the logistic model of the RSPD after c. 7500 BCE, it is possible that fluctuations in the SSPD reflect variation in mobility patterns that are unrelated to demographic developments. There does appear to be a negative deviation from the logistic null model in the RSPD corresponding to the one in the SSPD just before 6000 BCE. However, the logistic model could not be rejected for the RSPD, and so it is inappropriate to interpret any deviations from the Monte Carlo envelope and place any analytical weight on the deviations in the RSPD, at least given the present data. While it is possible that the fairly limited sample of ^{14}C-dates has led to an underestimation of this deviation, there is, additionally, no indications in the RSPD of an increased demographic signal in the period just before 5000 BCE (see also Solheim and Persson, 2018). A related point that is also worth making here is that the overall demographic trends that the modelling efforts can hope to identify are likely to have been subject to smaller scale demographic fluctuations that simply cannot be ascertained given the available data and its resolution (cf. Tallavaara and Jørgensen, 2021), and which impacts the comparison of the two proxies following both from the different resolutions of the dating methods and the sample sizes underlying the SPDs.

Given the presence of people and corresponding signal in the SSPD before the start of the RSPD, and the suggested relevance of mobility patterns for the lacking signal in the RSPD in this earliest period, neither proxy is presumably devoid of influence from population density or mobility patterns. This is also given support by the correspondence between the logistic growth in the RSPD and the positive deviation in the SSPD in the first centuries of the 8th millennium BCE. However, properly assessing this relationship and the degree to which it has held constant throughout the period will, as mentioned, depend on independent data that track the developments of the other factors that have been suggested to be of relevance to the behaviour of the two proxies.

Another relevant point to mention here is that the relative sea-level change is effectively built into the Monte Carlo simulations, much in the same way as the Monte Carlo simulation method used with radiocarbon dates account for fluctuations in the calibration curve (e.g. Crema, 2022). The simulation envelopes therefore pertain to the frequency of shoreline dated sites that could be expected under the null models, given the distribution of sites in the study area (Figure 4A), the corresponding local trajectories of relative sea-level change (Figure 4B), and a constant relationship between sites and shoreline described by the gamma function employed for the dating procedure (Figure 2D). Beyond uncertainties to do with the dating method itself, and by extension also the generation of the Monte Carlo envelope, it is also conceivable that variation in rates of sea-level change has impacted settlement patterns beyond that which could be directly expected under these null models. An increased movement instantiated by increased rates of relative sea-level change could result in the transition to a settlement pattern involving more frequent moves than that which could be expected under a constant adjustment to the shoreline. If this is the case, the proxy would still reflect the degree of occupational duration, but this could be a response to the rate of relative sea-level change rather than other cultural and societal dimensions such as migratory events or adjustments to other environmental developments. Directly accounting for variation in the rate of sea-level change could thus prove important for properly assessing the substantive implications of the fluctuations in this proxy.

Finally, analogous to investigatory biases that might impact the frequency of radiocarbon dates from certain time-intervals, for example resulting from targeted sampling directed towards certain periods of interest, the distribution of sites over different elevations in the landscape might be influenced by survey practices. In evaluating two larger survey projects within the present study region, Persson (2014) and Solheim (2017) found that the test-pitting was generally conducted in a comparable degree across elevations, but that altitudes equating to shoreline dates towards the end of the Stone Age might be under-represented (also Solheim and Persson, 2018, p. 337). Moving forward, similar investigations conducted in a more comprehensive manner will be important for properly evaluating the impact investigatory factors might have on the distribution of shoreline dated sites over time. This will also benefit from directly accounting for the elevation at which residential and commercial infrastructure development has been undertaken, as this generally dictates where surveys are undertaken, while also relating this to the topographic characteristics of the landscape.

6 Conclusion

This paper has presented a new methodology for assembling and assessing the sum of a larger number of shoreline dates. This was done by employing the probabilistic method for shoreline dating presented in Roalkvam (2023a), and by drawing on analogous procedures in the treatment of the temporal frequency distribution of radiocarbon dates (Crema, 2022; Crema and Bevan, 2021; Timpson et al., 2014). The result of employing this methodology was then compared to radiocarbon dates from within the same area, to begin to assess the relationship between the two data types.

The main results were that the RSPD is consistent with the logistic model fit to the data. This is characterised by a rapid logistic growth from the start of the RSPD, which plateaus and remains stationary from the first centuries after 8000 BCE. This is contrasted to the shoreline dates, the development of which were better described by a function of exponential decay. While this indicates that some process of decline in the number of shoreline dated sites has occurred over time, the model was rejected as an adequate description of the SSPD. Some of the deviations from the model were then narratively explored to suggest some possible reasons for these deviations. However, given the lack of a model that adequately describe the data, and the informal treatment of these deviations, these should be viewed as suggestions that represent potential lines for further interrogation.

While it appears that the SSPD and RSPD are differentially impacted by population density, and, we cautiously suggest, the SSPD is more heavily influenced by land-use and mobility patterns, this suggestion and the nature of the discrepancy between the proxies clearly requires further investigation. This is also relevant for the treatment of RSPDs in Scandinavia more broadly, as we suggested that mobility patterns have relevance for the kind of pyrotechnologies that were utilised in the first period of human occupation in the region, and that the technologies utilised largely explain the absence of radiocarbon dates from this earliest period. The degree and stability with which mobility patterns might have impacted the radiocarbon record from later periods, potentially as mediated by pyrotechnology, remains unclear, and could prove important for properly isolating a demographic signal in the radiocarbon data – a point that has also been made in other contexts (Crombé and Robinson, 2014; Hiscock and Attenbrow, 2016, p. 219).

Some further lines of inquiry could be to draw on lithic technology and tool-kit diversity as a function of population size and density (e.g. Berg-Hansen, 2018; Collard et al., 2013; Riede, 2014; Solheim et al., 2020), and mobility patterns that can potentially be inferred from the composition of lithic assemblages (e.g. Barton and Riel-Salvatore, 2014; Clark and Barton, 2017; Preston and Kador, 2018; Roalkvam, 2022), which is potentially also influenced by variable rates of relative sea-level change. In terms of mobility patterns, focus was directed here towards residential movement and occupational duration; but other dimensions relating for example to seasonal and territorial mobility, as reflected in the discussion of inland activity, could also prove to be important. In the same vein, environmental conditions, constraints and developments beyond relative sea-level change also represent a range of factors that can have implications for these dimensions, and will consequently be of future importance to unpack the relationship between the proxies (e.g. Hoebe et al., 2023; Jørgensen et al., 2020; Lundström, 2023; Ordonez and Riede, 2022). To account for the confounding effects these might have, a more principled and comprehensive evaluation of how investigatory practices might impact the SPDs would also be beneficial. While certainly also pertinent for the RSPD, this has generally been considered more extensively for radiocarbon data than for shoreline dated sites. Furthermore, aligning the complex web of causes and effects that these different lines of evidence potentially represent will also benefit from a more direct modelling of the development in the SSPD, rather than simply basing the analysis on deviations from a rejected null model (cf. Timpson et al., 2021). Finally, mapping and contrasting these developments across a larger region will not only offer a larger sample size, which is especially limited for the ^{14}C-data employed here, but could also provide important contextualisation for the observed development (see e.g. Lundström et al., 2021; Manninen et al., 2023; Solheim and Persson, 2018) and potentially reduce the impact of idiosyncratic investigations that might impact the present SPDs inordinately (see e.g. Crema, 2022; Hoebe et al., 2023; Rick, 1987).

Seeing as the implemented method for shoreline dating was recently developed and has been subjected to limited evaluation and testing, there are still considerable uncertainties and limitations associated with its application. While we believe the approach represents an improvement over previous implementations, the results should therefore be considered a cautions first exploration of the implications of employing a probabilistic method for shoreline dating when evaluating large scale trends in the temporal frequency distribution of coastal sites in the region.

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Appendix

The following sections holds supplementary material published with the papers. Note that all data, code, text and figures underlying the papers, this synopsis and the supplementary material is available through the online repositories listed in Section 1.4.

Supplementary material, Paper 1

Supplementary material to the paper ‘A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast’

Isak Roalkvam

12 November, 2022

Contents

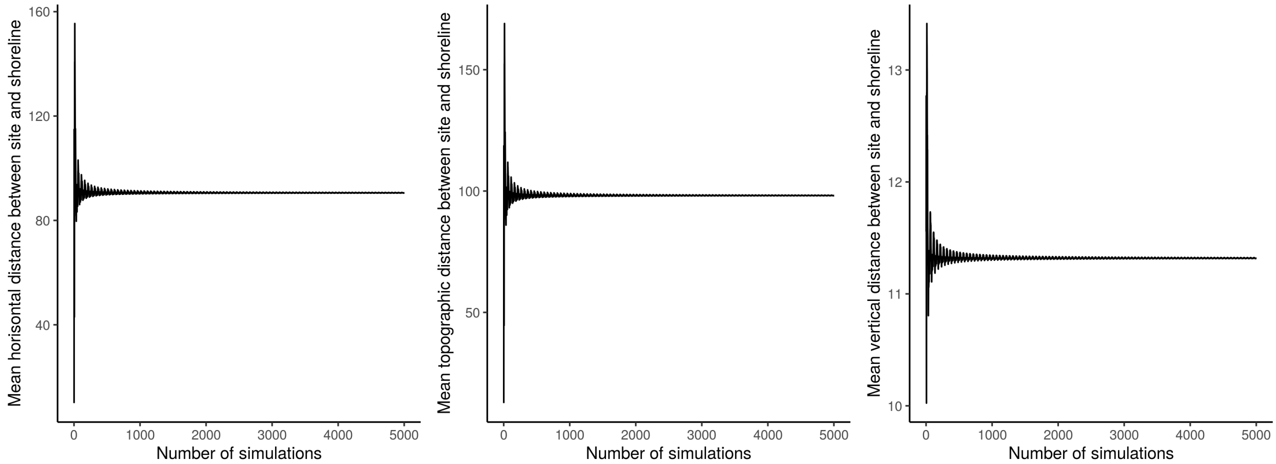
0.1 Contents

This document presents the sensitivity analysis performed for informing the number of simulation runs in the analysis of each site, the analysis of each individual site, the evaluation of different for models for characterising the results, and the results of re-dating previously shoreline dated sites. All underlying and derived data are available in the online repository for the paper at https://osf.io/7F9SU

0.2 Sensitivity analysis

The first figure shows the result of a test run for the site Hovland 5, where the simulations were run 5000 times to identify when the means for the different distance measures converged. This was used to inform the use of 1000 simulation runs for the subsequent analysis of the other sites, as the means appear to have stabilised sufficiently by this point. Hovland 5 was chosen because the site only has a single ^{14}C-date, giving an uncertain age, and because it is located in an area of the landscape where the landscape results in quite large variability on the distance measures.

Test-run on Hovland 5 to inform number of simulation runs



0.3 Site analyses

The presentation of simulation results for each individual site also has some additional notes pertaining to edits to the DTM, treatment of ^{14}C-dates and other relevant information. The sites are presented in alphabetical order.

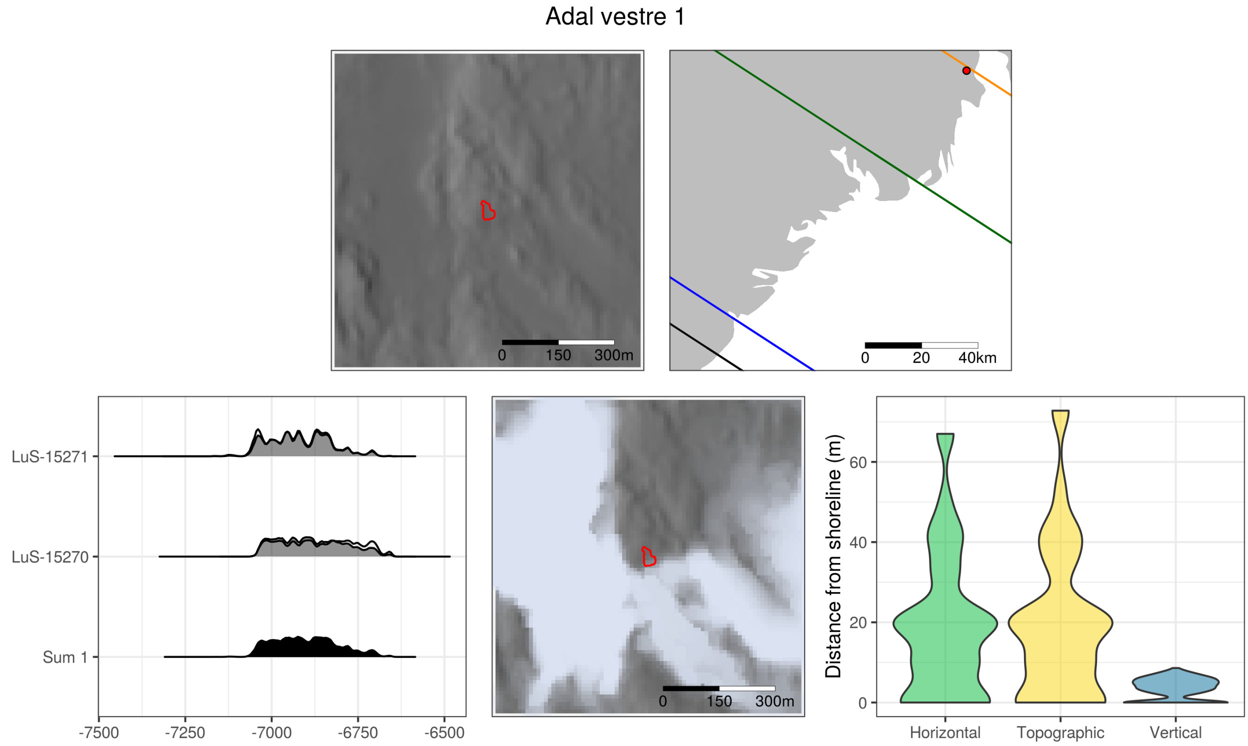
Stone Age sites for which no spatial data was readily available are Frebergsvik A–C (Mikkelsen 1975), Nedre Holtan (Glørstad 1998; Sjurseike 1991), Rugtvedt (Odgaard 1994), Tangen (Glørstad 2005), and Torsrød (Østmo 1976). These sites are therefore not included in the analysis. Furthermore, Nielsen (2021) has recently interpreted features from the otherwise younger sites Bratsberg and Larønningen as possibly related to farming activity in the Early Neolithic. However, given the limited number of features, the lack of any artefacts directly related to these, and the therefore somewhat speculative nature of this suggestion, the sites are kept out of the analysis here.

The first plot on the first row for each site shows all calibrated radiocarbon dates from the Stone Age associated with the site (see analysis/data/raw_data/radiocarbon.csv for all dates, including those falling outside of the period). The fill colour of the radiocarbon dates indicates whether they are interpreted as belonging to the same phase, and each sum indicates that multiple dates for a phase have been modelled using the Boundary function and then summed using OxCal. Each phase is assumed to be independent of other phases. A red outline indicates that the date(s) were not seen as related to the artefact inventory in the original report. The second plot on the first row displays the site location in the present day landscape on the edited DTM (i.e. highways and railways impacting the adjusted sea-level have been removed, and elevation values are interpolated from the surroundings; see main text and analysis/script/03dtm_edit.R). The third plot on the first row shows the site location within the study area relative to the isobases of the shoreline displacement curves in use.

Subsequent rows for each site then show the simulation results. The first plot on these rows shows the probability density function from which site dates were drawn during simulation. The second plot shows the result of the simulation runs, where the intensity of the colour indicates the number of times the sea was simulated to be present at any given location. The third plot displays a violin plot of the measured distances between site and shore-line across all simulation runs.

Table 1: Adal vestre 1

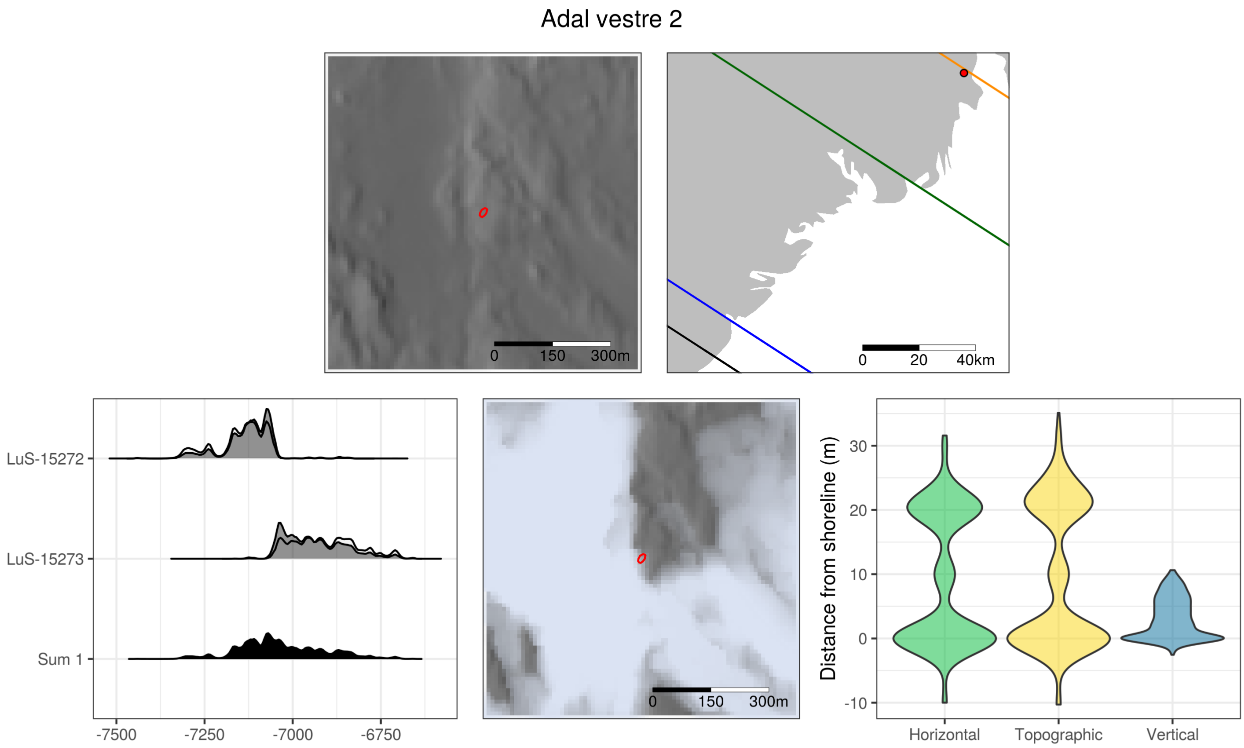
ID	^{14}C BP	Error	Material	Context
LuS-15264	665	35	Spruce (Picea)	Possible post hole (ID 4050)
LuS-15265	770	35	Pine (Pinus)	Possible post hole (ID 4050)
LuS-15266	1885	35	Pine (Pinus)	Fireplace (ID 6032)
LuS-16260	3255	35	Confier (Coniferae indet.)	Cooking pit/fireplace (ID 11485)
LuS-15268	2445	35	Pine (Pinus)	Cooking pit (ID 11508)
LuS-15269	1020	35	Birch (Betula)	Cooking pit (ID 11508)
LuS-15270	7950	45	Hazel (Corylus), nutshell	Cooking pit/fireplace (ID 11521)
LuS-15267	2250	35	Hazel (Corylus), nutshell	Cooking pit/fireplace (ID 11556)
LuS-15271	8020	45	Hazel (Corylus), nutshell	Quadrant (574x401ySW, layer 2/3)



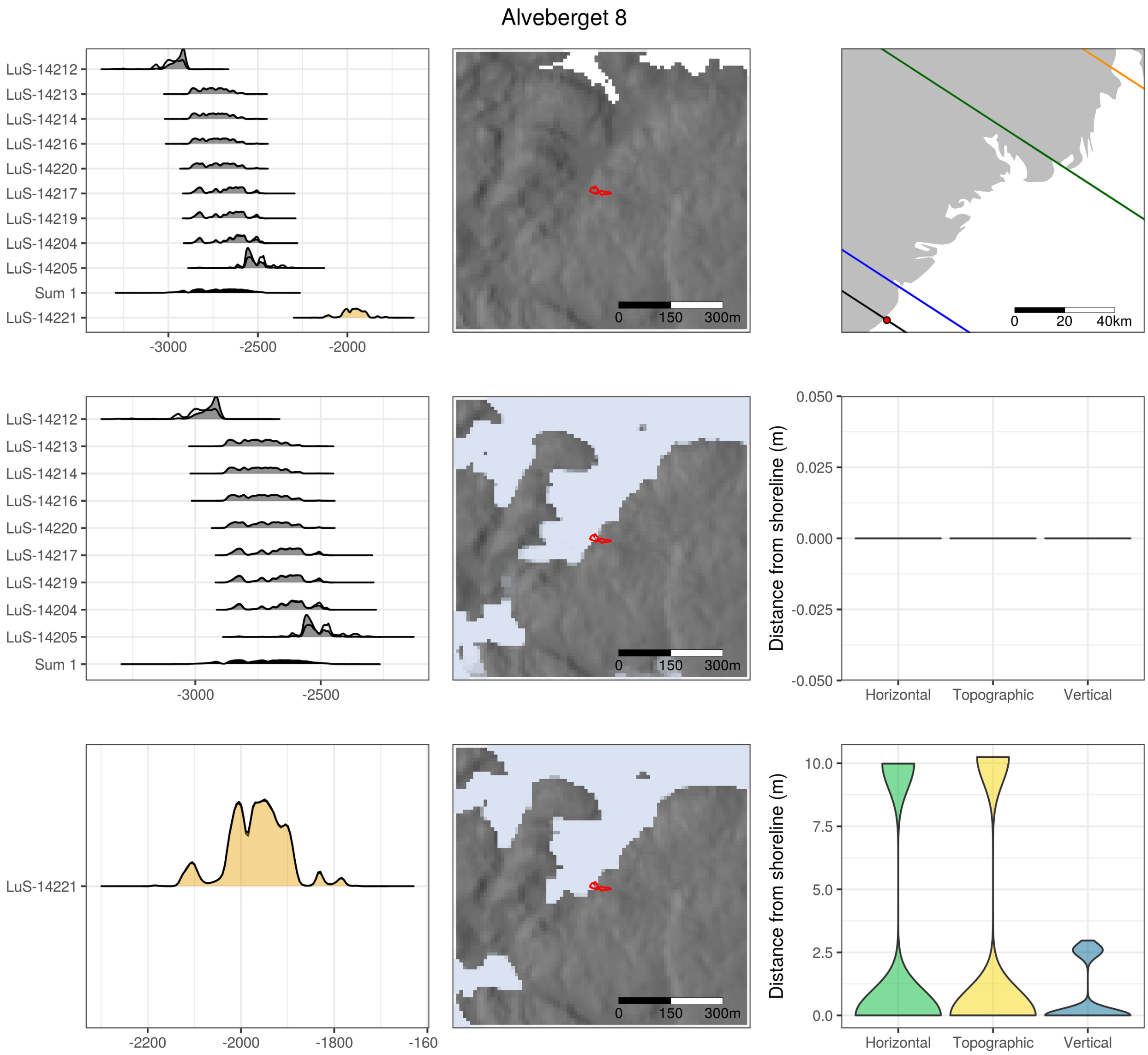
The single-phased lithic inventory matches the radiocarbon dates to the Middle Mesolithic at Adal vestre 1 (Granados 2022). The site is situated close to a field, but this does not appear to have resulted in any relevant changes to the terrain.

Table 2: Adal vestre 2

ID	^{14}C BP	Error	Material	Context
LuS-15272	8140	45	Hazel (Corylus), nutshell	Cooking pit/fireplace (ID 10036)
LuS-15273	8000	45	Hazel (Corylus), nutshell	Cooking pit/fireplace (ID 10051)



The artefact inventory from Adal vestre 2 is single-phased and matches the ^{14}C-dates (Granados 2022). The site has a similar location in the present day landscape to that of Adal vestre 1 (above) with no apparent indications of relevant impact to the DTM from modern activities.



The artefact inventory at Alveberget 8 matches the radiocarbon dates (Mansrud and Berg-Hansen 2021). The site is located in an undisturbed area of the DTM.

Table 3: Alveberget 8

ID	^{14}C BP	Error	Material	Context
LuS-14212	4360	40	Pome fruit tree (Pomoideae)	Profile bench (ID 1600)
LuS-14213	4165	40	Alder (Alnus)	Profile bench (ID 1600)
LuS-14214	4155	40	Pine (Pinus)	Profile bench (ID 1600)
LuS-14216	4145	40	Alder (Alnus)	Profile bench (ID 1750)
LuS-14220	4130	40	Alder/birch (Alnus/Betula)	Square (253x351y, layer 8)
LuS-14217	4095	40	Alder (Alnus)	Profile bench (ID 1537)
LuS-14219	4090	40	Oak (Quercus)	Profile bench (ID 2502)
LuS-14204	4070	40	Alder (Alnus)	Profile bench (ID 1306)
LuS-14205	3975	40	Alder (Alnus)	Fireplace (ID 1752)
LuS-14221	3605	40	Linden (Tilia)	Square (253x347y, layer 8)
LuS-14211	3500	40	Willow/aspen (Salix/Populus)	Profile bench (ID 1600)
LuS-14201	3480	40	Hardwood	Profile bench (ID 1770)
LuS-14210	3280	40	Alder (Alnus)	Profile bench (ID 1600)
LuS-14208	3095	40	Alder/hazel (Alnus/Corylus)	Profile bench (ID 1306)
LuS-14200	2950	40	Linden (Tilia)	Fireplace (ID 1332)
LuS-14209	1750	40	Hazel (Corylus)	Profile bench (ID 1600)
LuS-14203	1690	40	Hazel (Corylus)	Profile bench (ID 1770)
LuS-14215	1690	40	Hazel (Corylus)	Profile bench (ID 1750)
LuS-14206	1670	40	Hazel (Corylus)	Profile bench (ID 1306)
LuS-14202	1215	40	Alder/birch (Alnus/Betula)	Profile bench (ID 1770)
LuS-14207	1190	35	Hazel (Corylus)	Profile bench (ID 1306)
LuS-14218	1175	35	Hazel (Corylus)	Profile bench (ID 2504)

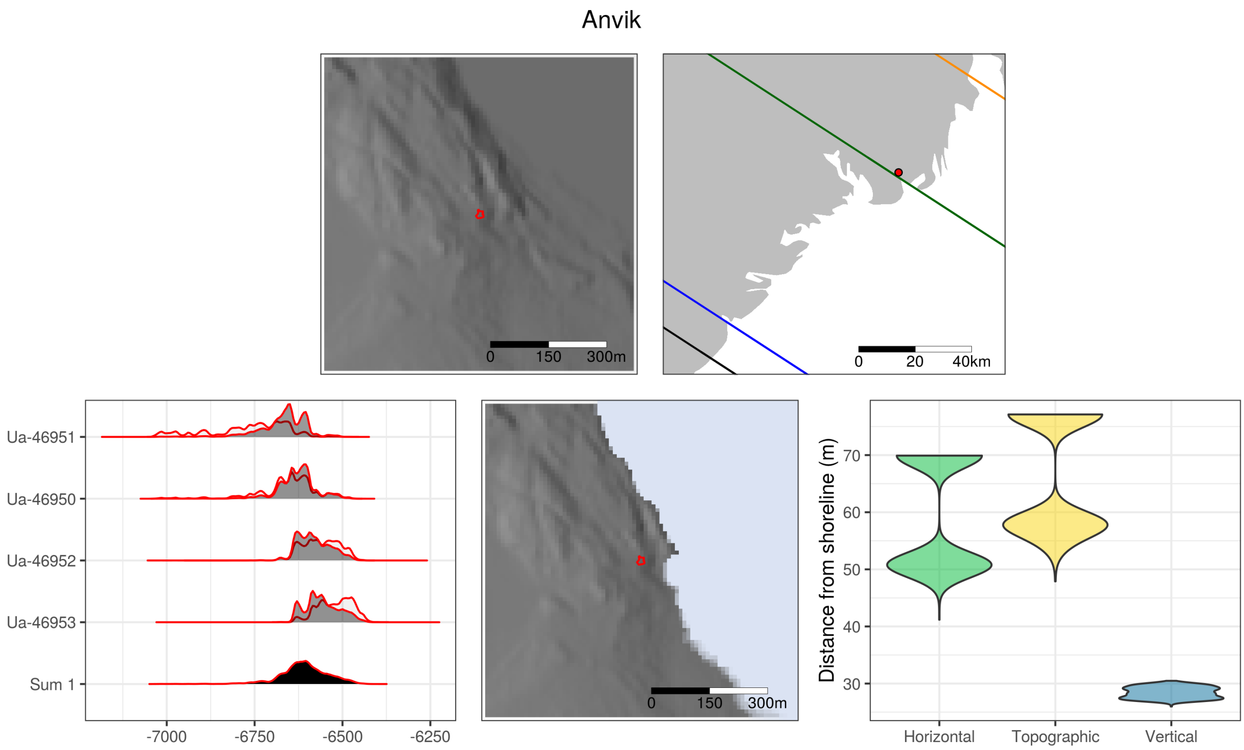
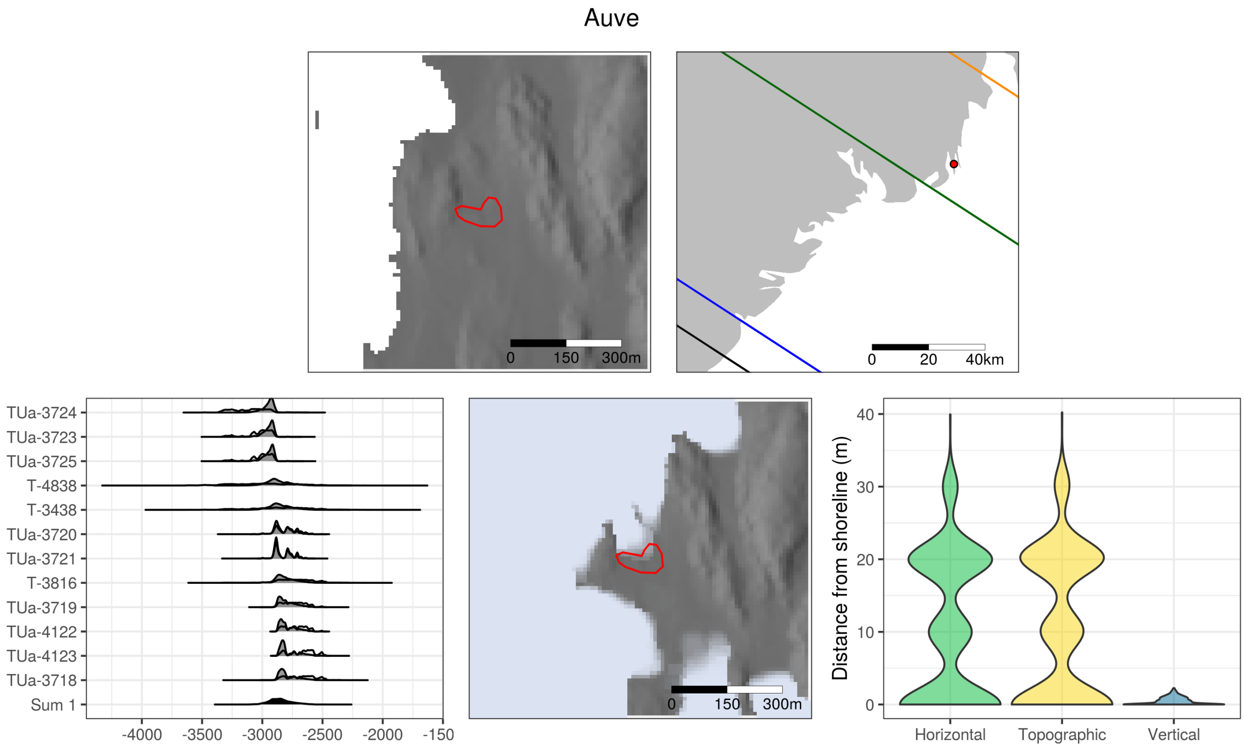


Table 4: Anvik

ID	^{14}C BP	Error	Material	Context
Ua-46950	7818	49	Hazel (Corylus), nutshell	Fireplace (ID 10520)
Ua-46951	7875	52	Willow (Salix)	Fireplace (ID 10520)
Ua-46952	7744	49	Willow (Salix)	Fireplace (ID 10520)
Ua-46953	7678	49	Pine (Pinus)	Fireplace (ID 10520)

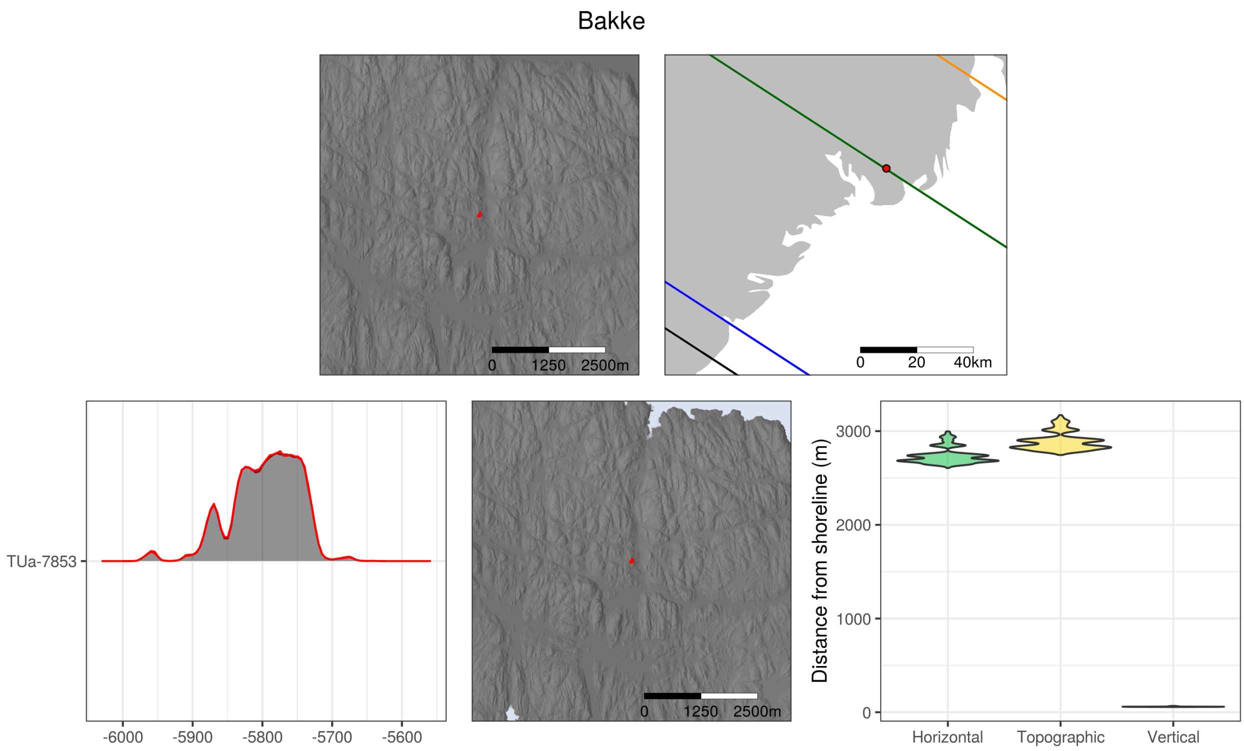
Anvik (Eymundsson 2014a) is situated by the highway and a smaller road. Neither appear to impact the simulation results. The dated fireplace is not seen as related to lithic material, which is believed to hail from the latest part of the Early Mesolithc (c. 8500-8250 BCE).



The site limit for Auve was drawn manually based on the description in the publication of the site and the site geometry available in the national heritage database Askeladden (Norwegian Directorate for Cultural Heritage 2018). The site is located in and around an intersection of the road, parts of the area has been levelled and farmed, and an area to north-west of the site has reportedly been affected by land-slides (Østmo 2008:16–29), but the extent of this is difficult to ascertain based on maps of the area. As the simulation results appear reasonable (see also map in Østmo 2008:Figure 142), nothing was done to try to correct for these factors.

Table 5: Auve

ID	^{14}C BP	Error	Material	Context
TUa-3716	1640	40	Pine/rowan/birch (Pinus/Sorbus/Betula)	Sand layer
TUa-3717	1215	70	Willow/pine/hazel (Salix/Pinus/Corylus)	Sand layer
TUa-3722	130	65	Pine/birch (Pinus/Betula)	Sand layer
TUa-3724	4420	80	Pine/birch (Pinus/Betula)	Square (ID AE21)
T-3437	3570	160	Pine (Pinus)	Excavation unit, unknown
TUa-3723	4365	55	Willow/pine (Salix/Pinus)	Square (ID AC22)
TUa-3719	4150	55	Willow/deciduous/pine (Salix/Decid. indet./Pinus)	Square (ID R9)
T-4838	4330	190	Elm/willow/linden/pine (Ulmus/Salix/Tilia/Pinus)	Excavation unit, unknown
T-3438	4240	160	Pine (Pinus)	Excavation unit, unknown
TUa-3721	4240	45	Willow/hazel/pine/birch (Salix/Corylus/Pinus/Betula)	Square (ID W14)
TUa-3720	4230	60	Deciduous (Decid, indet.)	Square (ID W12)
T-3816	4150	110	Pine/aspen (Pinus/Populus)	Excavation unit, unknown
TUa-3725	4355	55	Birch/pine (Betula/Pinus)	Square (ID AC22)
TUa-4122	4130	40	Deciduous/pine (Decid, indet./Pinus)	Square (ID S11)
TUa-3718	4095	70	Willow/pine/birch (Salix/Pinus/Betula)	Square (ID Q11)
TUa-4123	4090	45	Birch/willow/pine (Betula/Salix/Pinus)	Square (ID Z17)
T-3436	3570	160	Pine (Pinus)	Excavation unit, unknown



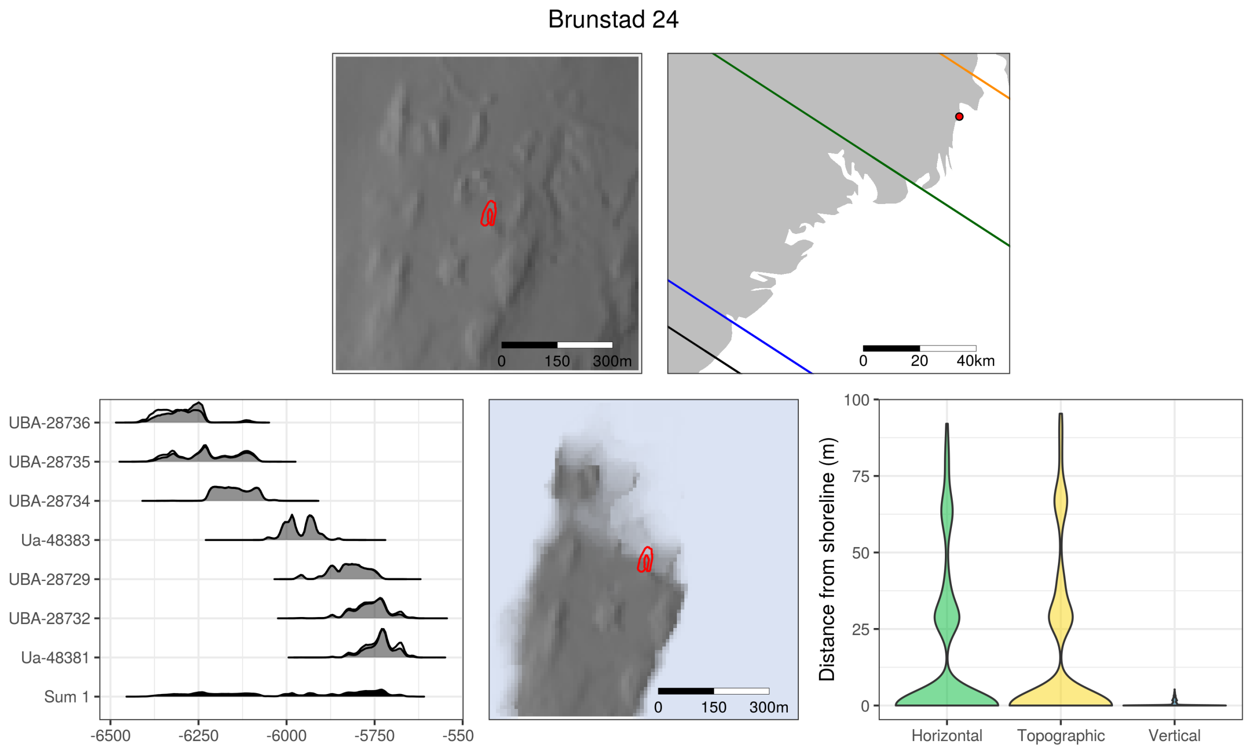
The radiocarbon date to the Stone Age is not related to the site inventory at Bakke, which is distinctly Early Mesolithic in character (Nyland and Amundsen 2012).

Table 6: Bakke

ID	^{14}C BP	Error	Material	Context
TUa-7852	2115	30	Birch (Betula)	Fireplace (ID 2)
TUa-7853	6915	40	Birch (Betula)	Fireplace (ID 2)

Table 7: Brunstad 24

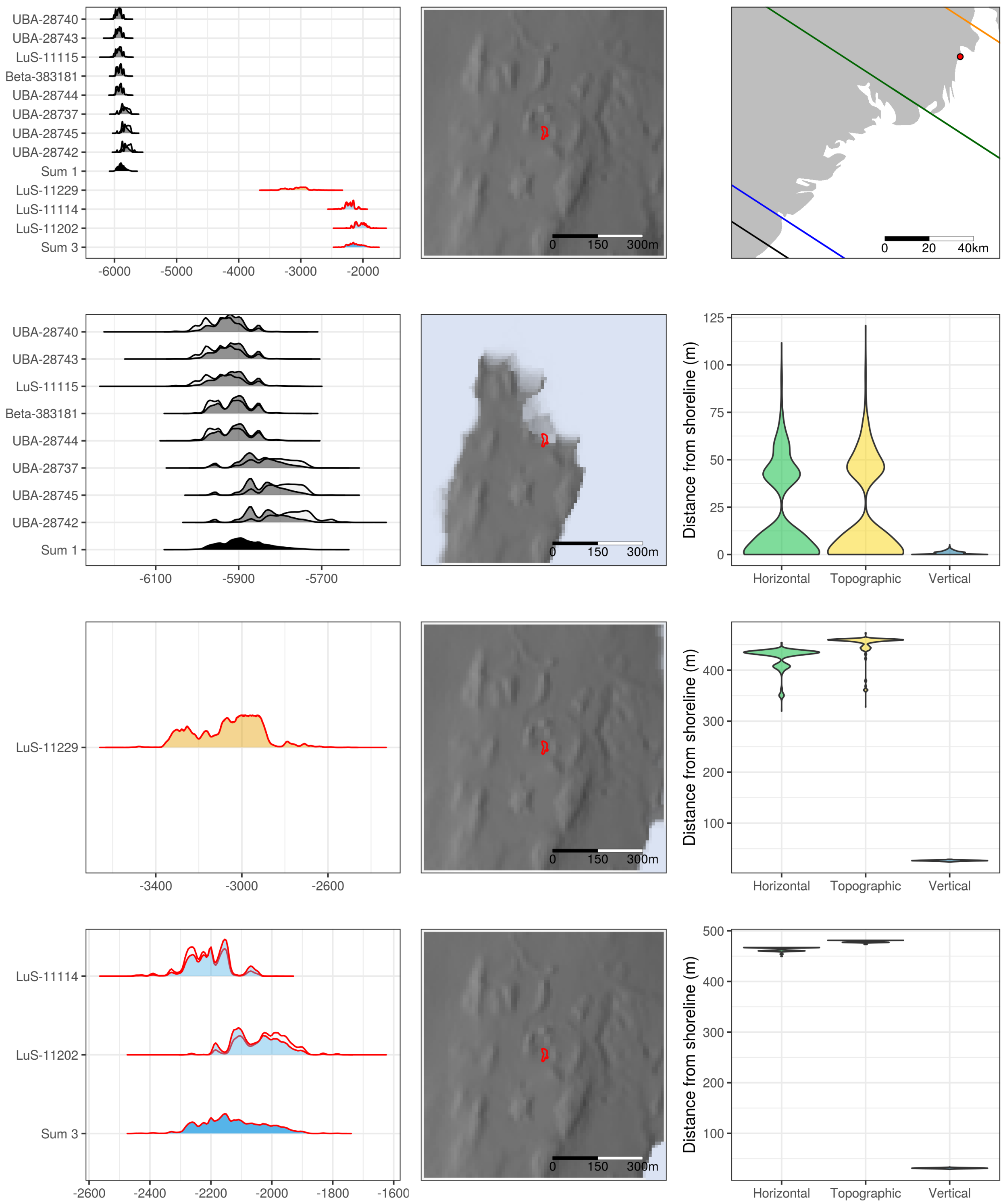
ID	^{14}C BP	Error	Material	Context
UBA-28736	7439	39	Hazel (Corylus)	Cooking pit (ID 4990)
UBA-28735	7374	45	Hazel (Corylus)	Cooking pit (ID 4979)
UBA-28734	7285	37	Deciduous (Decid, indet.)	Cooking pit (ID 4967)
Ua-48383	7090	35	Hazel (Corylus)	Quadrant (50x54yNE, layer 3)
UBA-28729	6948	35	Aspen/willow (Populus/Salix)	Cooking pit (ID 2574)
UBA-28732	6873	43	Beech (Fagus)	Cooking pit (ID 4200)
Ua-48381	6850	35	Birch (Betula)	Quadrant (50x54yNE, layer 2)
Ua-48384	2715	30	Ash (Fraxinus)	Cooking pit (ID 2000)
Ua-48382	2646	30	Oak (Quercus)	Quadrant 50x50x10 cm (50x54y NE, layer 3)
UBA-28728	2460	26	Ash (Fraxinus)	Cooking pit (ID 2000)
UBA-28730	2403	26	Hazel (Corylus)	Cooking pit (ID 3934)
UBA-28733	2250	27	Linden (Tilia)	Cooking pit (ID 4362)
UBA-28731	2240	27	Hazel (Corylus)	Cooking pit (ID 4010)



Typological indicators in the lithic inventory from Brunstad 24 matches the ^{14}C-dates (Danielsen et al.

2018). The footprint of a large building structure covering a large part of the site from the south required editing of the DTM. Apart from that the landscape appears relatively undisturbed. 8 fragments from a pot could potentially correspond with the ^{14}C-dates to the Late Bronze Age and Early Iron Age, but given their uncetain nature and the limited number of sherds, this was disregarded here.

Brunstad 25

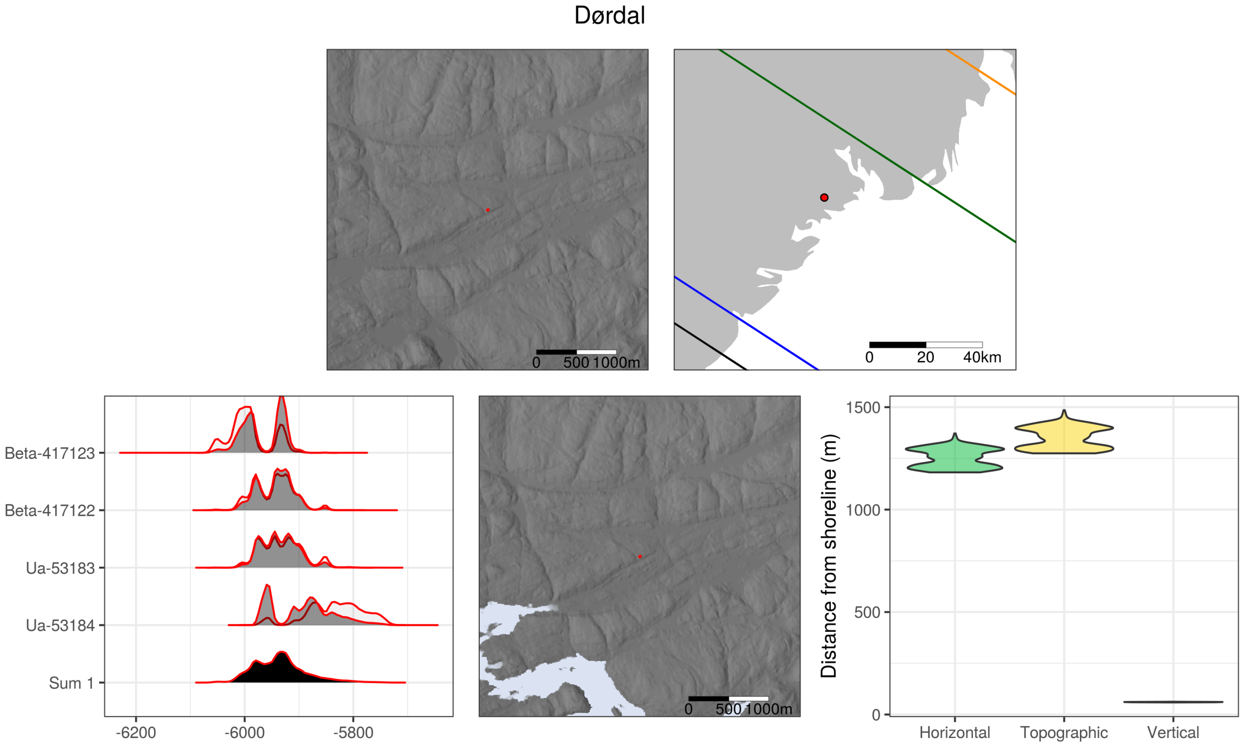


As with Brunstad 24 (above), the artefact inventory from Brunstad 25 matches the radiocarbon dates (Reitan and Solberg 2018a), and the building structure covering the southern part of the site had impacted the DTM

Table 8: Brunstad 25

ID	^{14}C BP	Error	Material	Context
LuS-11202	3645	50	Unburnt bone, human, skull	Grave (ID 2400)
LuS-11114	3790	35	Unburnt bone, human, skull	Grave (ID 2400)
LuS-11229	4370	95	Unburnt bone, human, right femur	Grave (ID 2400)
LuS-11115	7060	45	Maple (Acer)	Grave, layer 8 (ID 2400)
Beta-383181	7030	30	Charcoal, not determined	Grave, layer 5 (ID 2400)
UBA-28737	6943	44	Aspen (Populus)	Grave, layer 6/7 (ID 2400)
UBA-28740	7067	37	Aspen (Populus)	Cooking pit (ID 3185)
UBA-28743	7057	38	Hazel (Corylus), nutshell	Fireplace (ID 4663)
UBA-28744	7032	34	Eml (Ulmus)	Floor layer? (ID 4604)
UBA-28745	6920	37	Deciduous (Decid, indet.)	Cooking pit (ID 4895)
UBA-28742	6886	47	Alder/hazel (Alnus/Corylus)	Cooking pit (ID 3783)
UBA-28739	2749	27	Alder (Alnus)	Post hole (ID 2429)
UBA-28738	2715	28	Alder (Alnus)	Post hole (ID 2409)
UBA-28741	2659	26	Hazel (Corylus)	Post hole (ID 3737)

and had to be removed.



The ^{14}C-dates from two fireplaces at Dørdal are not related to the lithic inventory, where there are no typological indicators pointing the Late Mesolithic. The report suggest that the results might reflect a contamination through a natural process of some sort (Solheim et al. 2017).

Table 9: Dørdal

ID	^{14}C BP	Error	Material	Context
Beta-417122	7070	30	Pine (Pinus)	Fireplace (ID 1134)
Ua-53184	6956	31	Pine (Pinus)	Fireplace (ID 1134)
Beta-417123	7120	30	Pine (Pinus)	Fireplace (ID 792)
Ua-53183	7050	31	Pine (Pinus)	Fireplace (ID 792)

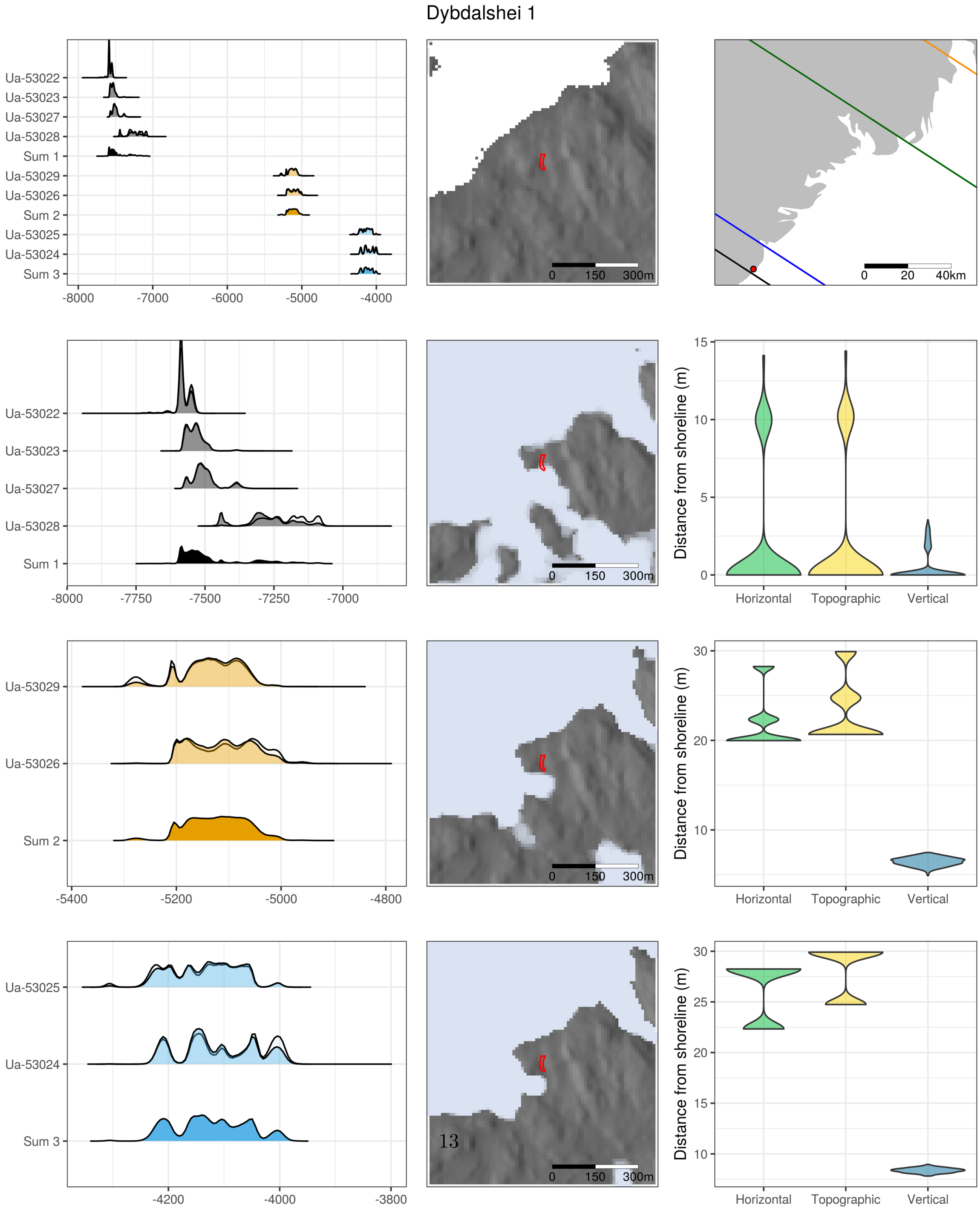


Table 10: Dybdalshei 1

ID	^{14}C BP	Error	Material	Context
Ua-53022	8566	36	Willow (Salix)	Cooking pit (ID 501)
Ua-53023	8462	36	Pomoideae (Malinae)	Cooking pit (ID 519)
Ua-53027	8422	36	Pomoideae (Malinae)	Cooking pit (ID 545)
Ua-53028	8199	35	Pomoideae (Malinae)	Cooking pit (ID 556)
Ua-53029	6202	32	Birch (Betula)	Cooking pit (ID 566)
Ua-53026	6150	32	Alder (Alnus)	Cooking pit (ID 537)
Ua-53025	5310	31	Aspen (Populus)	Cooking pit (ID 531)
Ua-53024	5262	31	Oak (Quercus)	Cooking pit (ID 526)

Table 11: Dybdalshei 2

ID	^{14}C BP	Error	Material	Context
Ua-53030	3868	30	Pine (Pinus)	Cooking pit (ID 650)

Dybdalshei 1 was subject to a very limited excavation (Granum and Schülke 2018), and the lack of data might therefore lead one to question whether or not the site actually represent a settlement area. Furthermore, what little lithic material was retrieved is too generic to offer any typological support to the radiocarbon dates of the dated cooking pits. Nonetheless, the site and the ^{14}C-dates are still treated the same way as the other sites. This is based on the agreement between the ^{14}C-dates ans the spatial relation between the lithic artefacts and the features, which offers some additional support to the notion that the cooking pits represent remnants from visits in the Mesolithic.

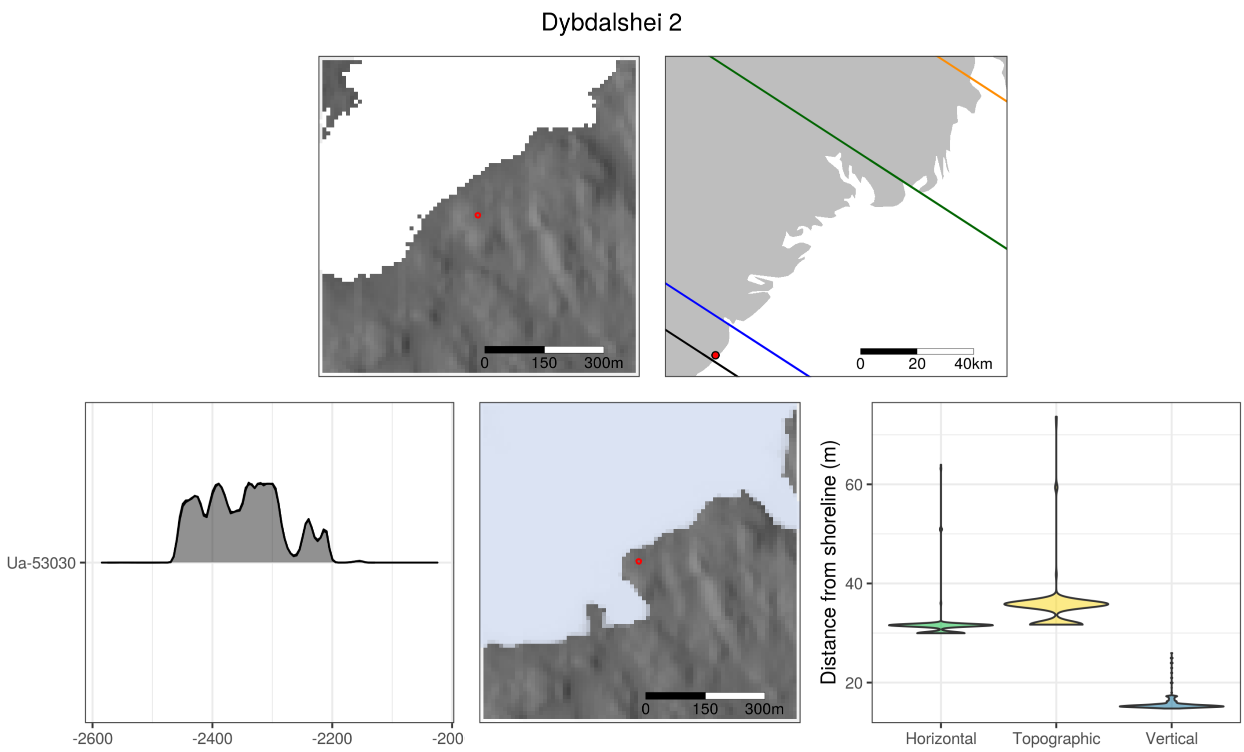
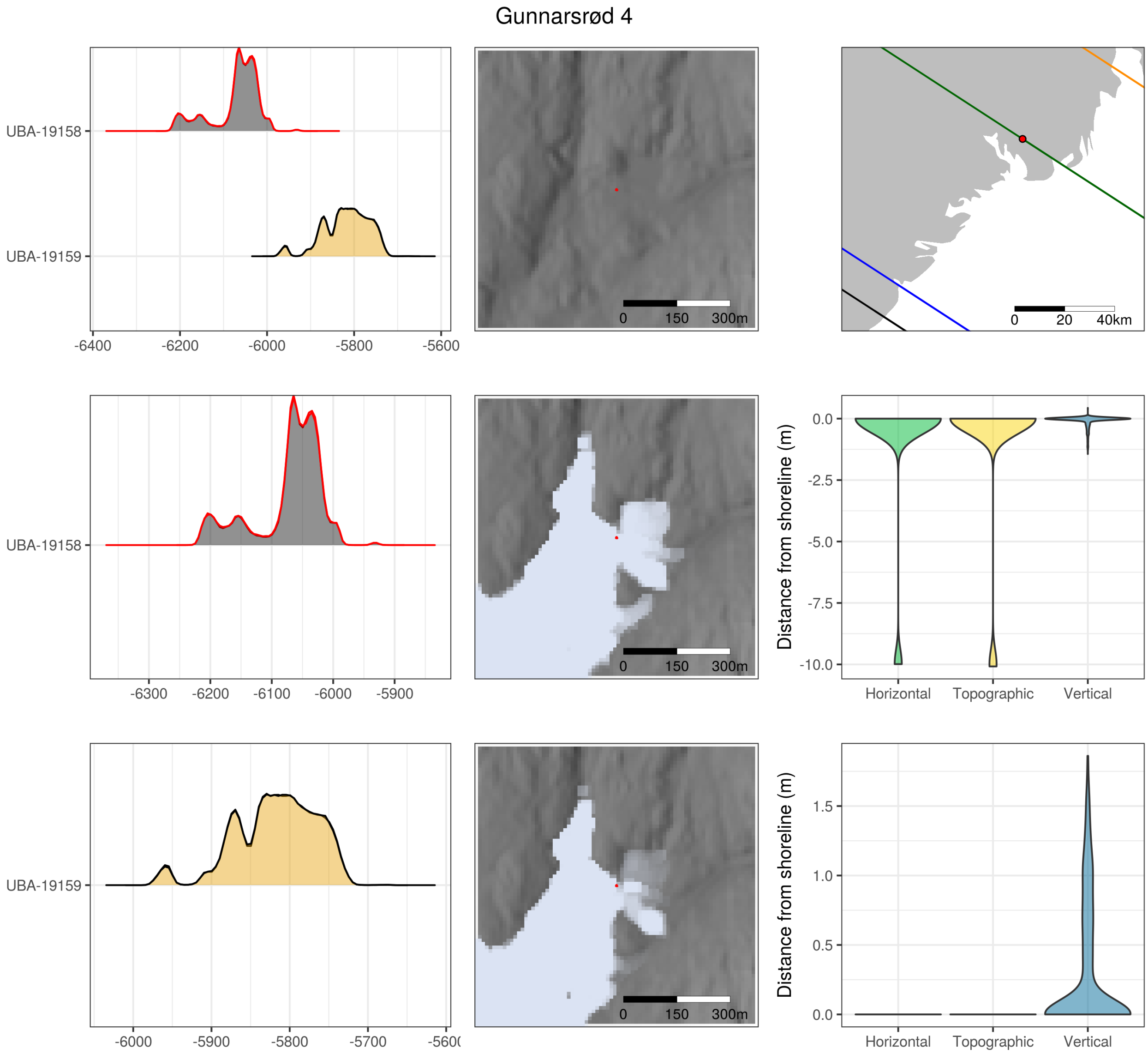


Table 12: Gunnarsrød 4

ID	^{14}C BP	Error	Material	Context
UBA-19134	2396	24	Hazel (Corylus)	Fireplace (ID 100000)
UBA-19159	6941	36	Birch (Betula)	Cultural layer, top (ID 100002)
UBA-19158	7210	38	Pine (Pinus)	Cultural layer, bottom (ID 100002)

The situation on Dybdalshei 2 is similar to that on Dybdalshei 1 (above, Granum and Schülke 2018), but with only a single date from a single feature and no lithics, the site is not included in subsequent analysis.



The rock-shelter site Gunnarsrød 4 (Reitan 2014a), and Gunnarsrød 5 (below), were situated close to where the railway runs today, and therefore required editing of the DTM. Based on maps from the report, this appears to have given adequate, although not perfect results (Reitan 2014a:Figure 14.7.1). The date from the bottom of the cultural layer was seen as possibly impacted by old-wood effect, a notion that is in line with the simulation results, as this date would have the site located beneath the sea-level (Reitan 2014a).

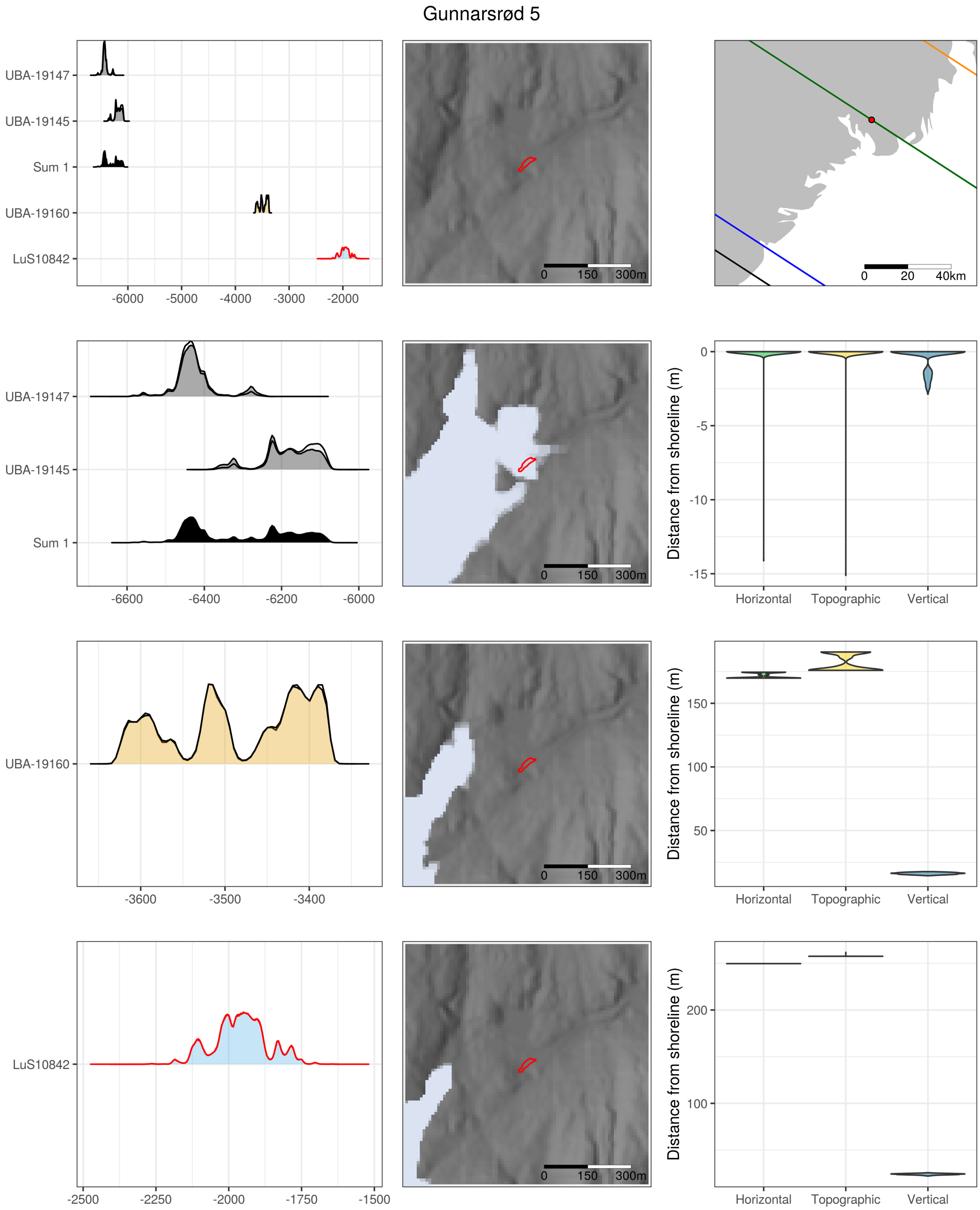
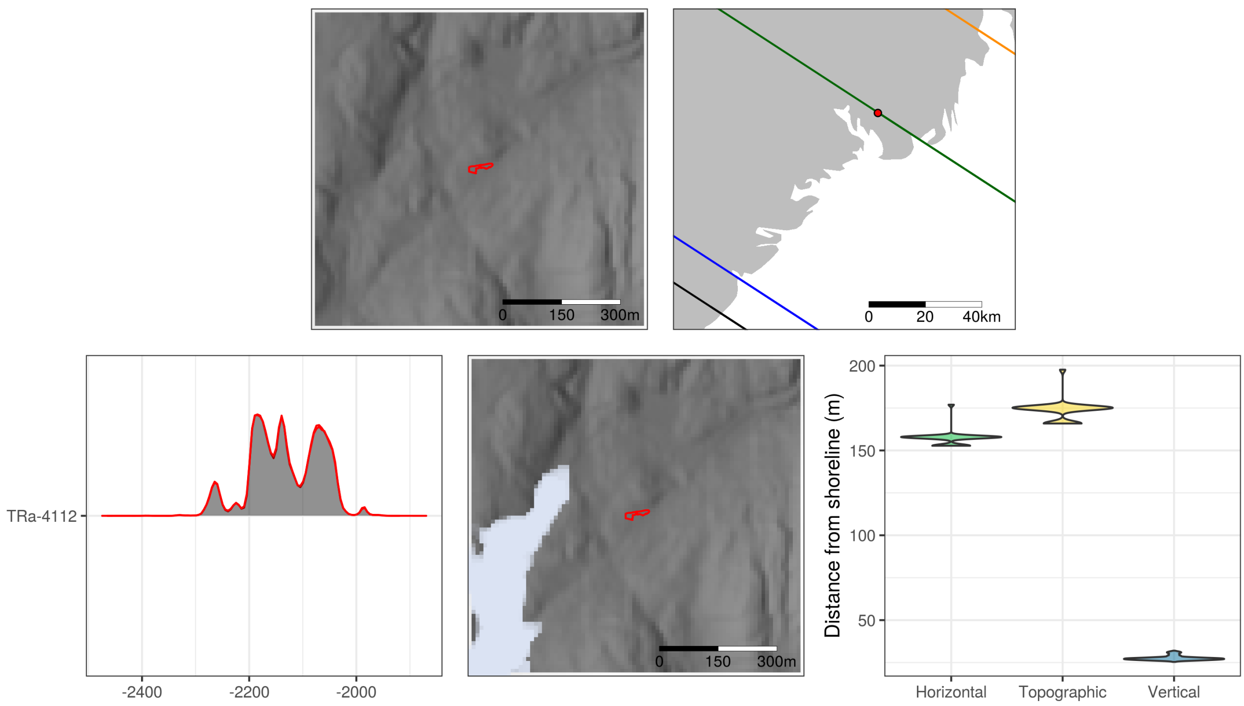


Table 13: Gunnarsrød 5

ID	^{14}C BP	Error	Material	Context
UBA-19147	7582	47	Hazel (Corylus), nutshell	Fireplace (ID 1206)
UBA-19145	7336	38	Birch (Betula)	Undefined feature (ID 1420)
UBA-19160	4716	31	Hazel (nutshell)/birch (Corylus/Betula)	Pit with pottery (ID 1519)
LuS-10842	3600	60	Soot extracted from pottery sherd	Pit with pottery (ID 1519)
UBA-19146	168	29	Birch (Betula)	Disturbance (ID 1085)

The location of Gunnarsrød 5 is today situated at the exit of a railway tunnel. The construction of the tunnel entrance has lead to a removal of parts of what used to be a hill on which the site was situated (Reitan 2014b). While the editing and interpolation of the DTM appears to give reasonable results for the rest of the flatter marsh area where the railway runs today (see also Gunnarsrød 4, above), the site itself would have been situated slightly higher. This has likely led to the negative values on the distance measures. In combination, the simulation results and the site map in the report (Reitan 2014b:Figure 9.1) indicate that the site would not have been situated any significant distance from the shoreline. The negative values have therefore been set to zero for the final aggregative analysis. A note can also be made on the date that is seen as unrelated to the artefact inventory. This is from charcoal from a pit with ceramics which had a far younger date. The date was therefore interpreted as the result of contamination of some kind.

Gunnarsrød 6a



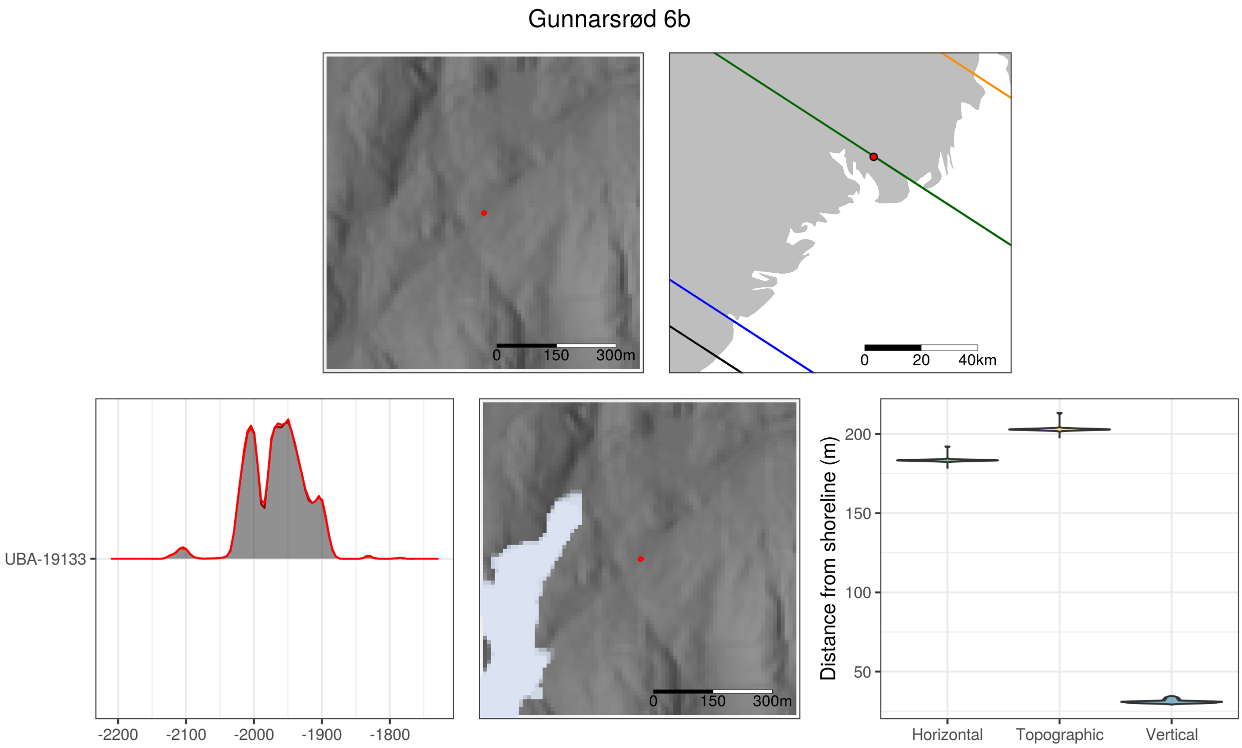
The ^{14}C-date to the Neolithic from Gunnarsrød 6a is not related to the lithic inventory on the site, which is clearly Mesolithic (Carrasco et al. 2014).

Table 14: Gunnarsrød 6a

ID	^{14}C BP	Error	Material	Context
TRa-4112	3735	35	Birch/ash (Betula/Fraxinus)	Cooking pit/fireplace (ID 600)
UBA-19130	2369	24	Birch (Betula)	Charcoal layer
UBA-19131	1330	27	Hazel (Corylus), nutshell	Square (965x46y, layer 4)
UBA-19132	883	23	Hazel (Corylus), nutshell	Quadrant (969x49ySE, layer 3)

Table 15: Gunnarsrød 6b

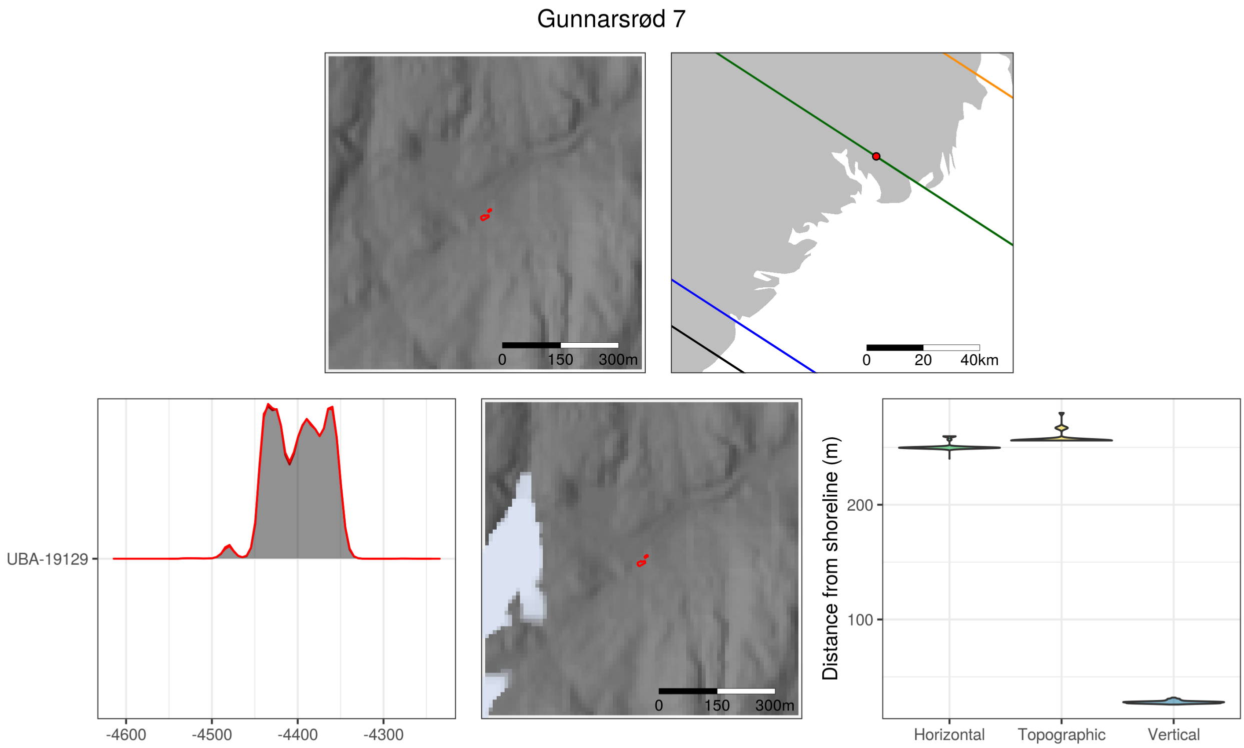
ID	^{14}C BP	Error	Material	Context
TRa-4113	335	25	Pine (Pinus)	Undefined feature (ID 1313)
UBA-19133	3608	25	Hazel (Corylus), nutshell	Squares (917x626y, 916x626y, layer 5)



As with Gunnarsrød 6a above, the ^{14}C-date to the Neolithic from Gunnarsrød 6b is not related to the Mesolithic inventory on the site (Carrasco et al. 2014).

Table 16: Gunnarsrød 7

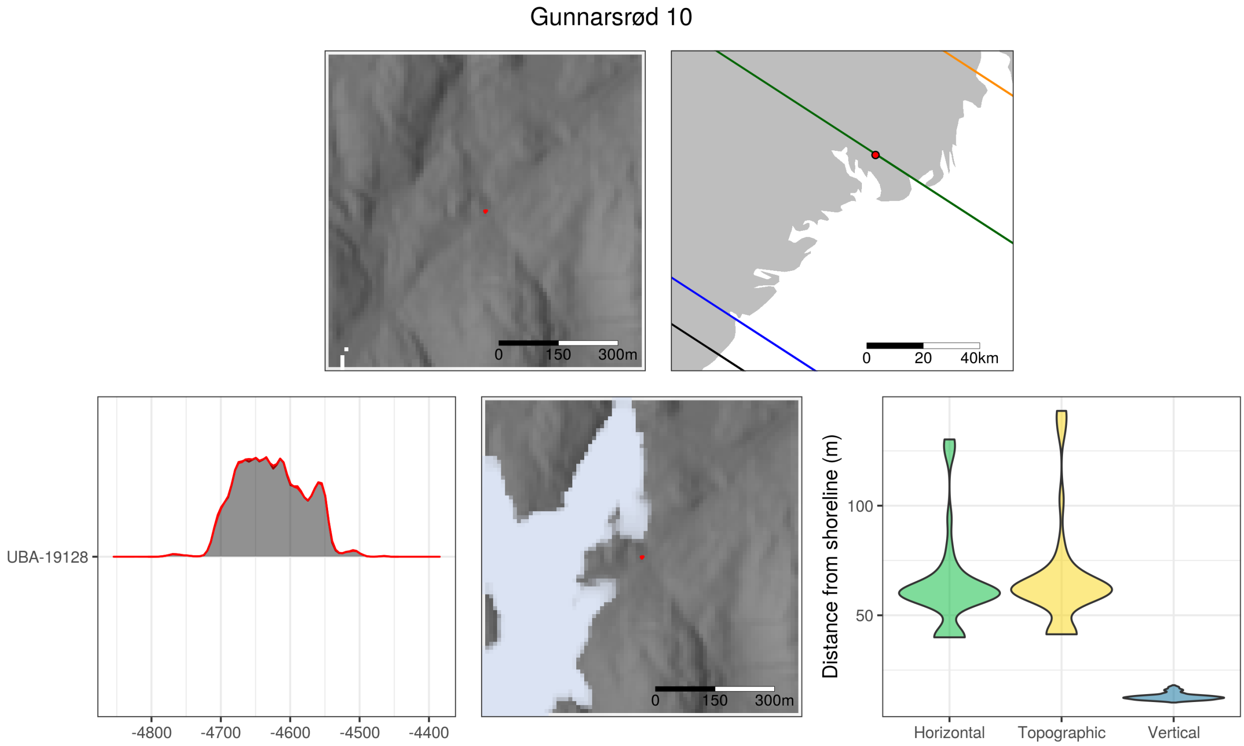
ID	^{14}C BP	Error	Material	Context
UBA-19129	5563	30	Birch (Betula)	Undefined feature (ID 1000)
UBA-19162	1697	26	Birch/oak (Betula/Quercus)	Undefined feature (ID 1016)



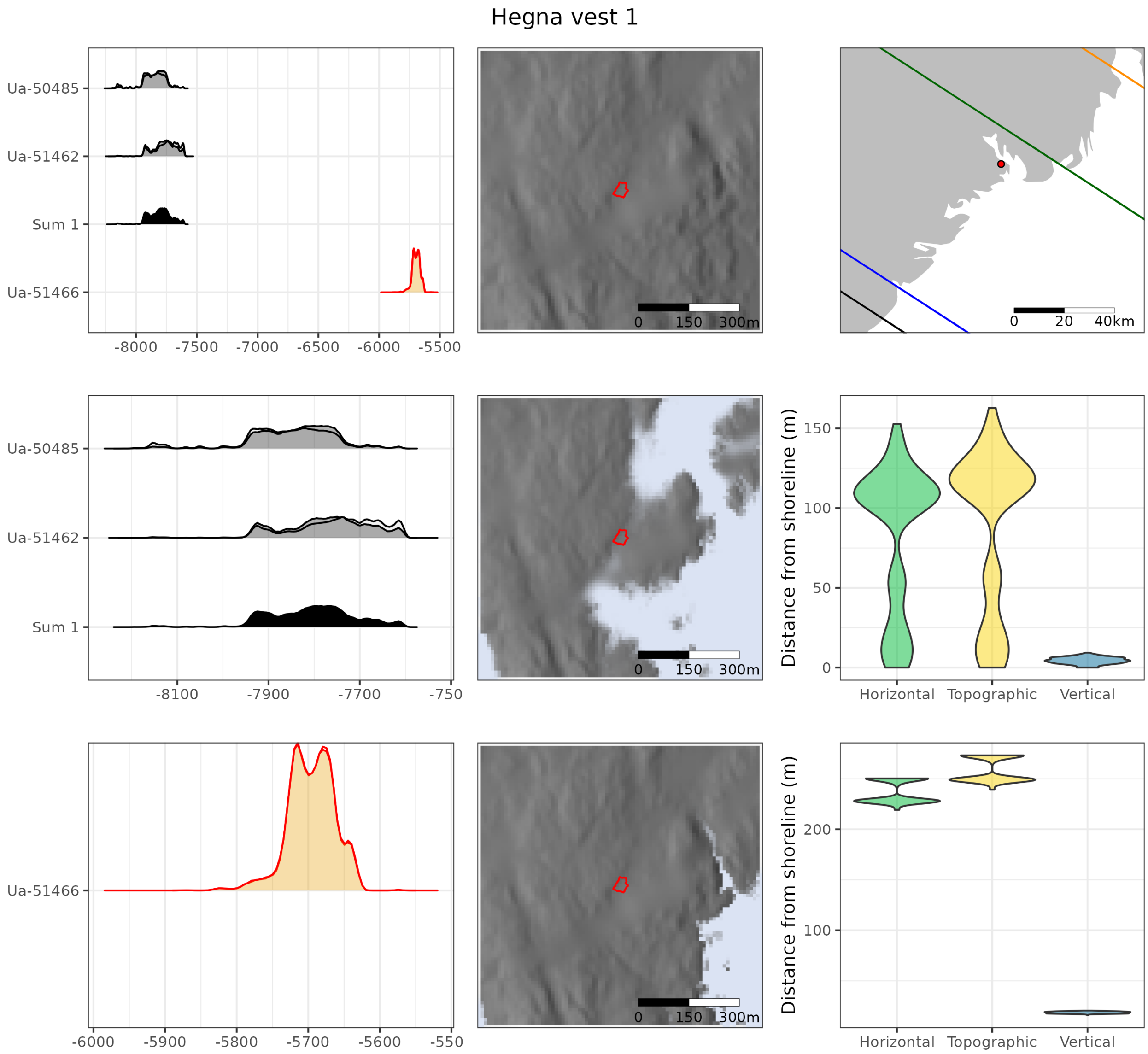
The lithic inventory from Gunnarsrød 7 is of a Middle Mesolithic character and does not match the ^{14}C-dates (Fossum 2014a).

Table 17: Gunnarsrød 10

ID	^{14}C BP	Error	Material	Context
UBA-19128	5778	31	Birch (Betula)	Fireplace (ID 100001)



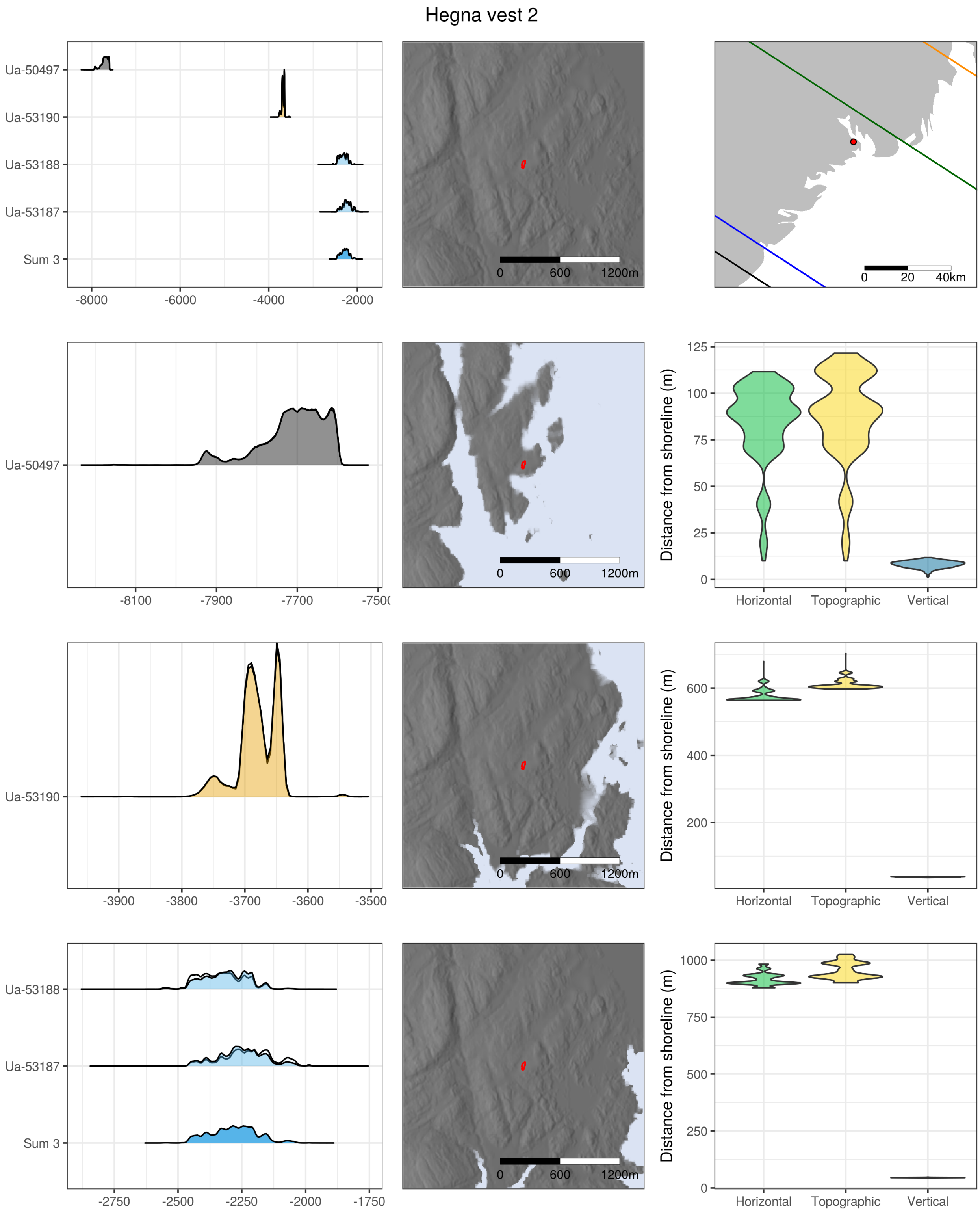
Based on the location of Gunnarsrød 10 on a steep ledge indicating a shore-bound location, and the site inventory, the ^{14}C-date is not believed to be related to the main occupation of the site (Reitan and Fossum 2014).



Example site from the main text. Hegna vest 1 has been visited multiple times throughout prehistory. The lithic inventory is distinctly Middle Mesolithic and Neolithic in character, with some finds that might be even younger. This is also reflected in the pottery finds, which are deemed to be from the Bronze Age–Early Iron Age. The ^{14}C-date to the Late Mesolithic is therefore considered unrelated to the main occupation of the site, as it cannot be related to any elements of the site inventory (Fossum 2017a). The highway runs right by Hegna vest 1 and has been removed. This seem successful in that it doesn't appear to impact the simulated sea-levels.

Table 18: Hegna vest 1

ID	^{14}C BP	Error	Material	Context
Ua-50485	8788	34	Aspen/willow (Populus/Salix)	Fireplace (ID 14834)
Ua-51462	8732	40	Willow (Salix)	Fireplace (ID 9819)
Ua-51466	6816	36	Willow (Salix)	Undefined feature/three throw (ID 100079)
Ua-51461	3318	32	Alder (Alnus)	Undefined feature (ID 9807a)
Ua-50484	2831	24	Ash (Fraxinus)	Cooking pit (ID 14417)
Ua-51467	2724	34	Hazel (Corylus), nutshell	Undefined feature (ID 11663)
Ua-51463	2670	33	Birch (Betula)	Undefined feature (ID 11663)
Ua-51460	2667	33	Alder (Alnus)	Stone packing/fireplace (ID 9725)
Ua-51465	2474	33	Hazel (Corylus)	Undefined feture (ID 15034)
Ua-50472	2440	24	Pine (Pinus)	Fireplace (ID 9642)
Ua-50475	2225	28	Aspen (Populus)	Cooking pit (ID 10127)
Ua-50482	2215	21	Hazel (Corylus)	Undefined feature (ID 14324)
Ua-50483	2197	21	Hazel (Corylus)	Undefined feature (ID 14383)
Ua-50486	2186	23	Hazel (Corylus)	Undefined feature (ID 100078)
Ua-50473	2186	21	Birch (Betula)	Fireplace (ID 9659)
Ua-50480	2186	23	Aspen (Populus)	Cooking pit (ID 14280)
Ua-50481	2178	24	Aspen (Populus)	Cooking pit (ID 14298)
Ua-50477	2174	27	Birch (Betula)	Undefined feature (ID 11767)
Ua-50479	2154	23	Hazel (Corylus)	Cooking pit (ID 14637)
Ua-51464	2124	33	Birch (Betula)	Undefined feature (ID 11683)
Ua-50476	2118	30	Birch (Betula)	Undefined feature (ID 100077)
Ua-51468	2063	33	Hazel (Corylus), nutshell	Undefined feature (ID 15034)
Ua-50474	1702	22	Birch (Betula)	Cooking pit (ID 9745)
Ua-50478	1685	20	Birch (Betula)	Cooking pit (ID 11828)
Ua-50487	971	26	Birch (Betula)	Fireplace (ID 11707)



As with Hegna vest 1 (above), Hegna vest 2 has been used throughout prehistory. This includes the Middle Mesolithic, the Neolithc, the Bronze Age and the Early Iron Age. The ^{14}C-dates are believed to be related to

Table 19: Hegna vest 2

ID	^{14}C BP	Error	Material	Context
Ua-50497	8708	38	Pine (Pinus)	Cooking pit (ID 11906)
Ua-53190	4900	30	Burnt bone, mammal	Square (523x346y)
Ua-53188	3863	57	Burnt bone, beaver (Castor)	Undefined feature (ID 11546)
Ua-53187	3789	60	Burnt bone, Sus/Canis	Undefined feature (ID 11546)
Ua-50494	3337	27	Pine (Pinus)	Undefined feature (ID 11546)
Ua-51469	3121	31	Ash (Fraxinus)	Undefined feature (ID 9029)
Ua-51470	3085	31	Ash (Fraxinus)	Concentration of stones (ID 9057)
Ua-53189	3083	29	Burnt bone, mammal	Undefined feature (ID 11546)
Ua-53191	3079	28	Burnt bone, sheep/goat (Ovis/Capra)	Square (523x346y)
Ua-50499	2659	25	Aspen (Populus)	Cooking pit (ID 11954)
Ua-50490	2239	25	Aspen (Populus)	Fireplace (ID 9238)
Ua-50493	2216	23	Hazel (Corylus)	Cooking pit (ID 8903)
Ua-50496	2203	27	Birch (Betula)	Cooking pit (ID 9181)
Ua-50495	2193	23	Birch (Betula)	Undefined feature (ID 9002)
Ua-50492	2190	23	Birch (Betula)	Undefined feature (ID 8940)
Ua-50498	2188	24	Hazel (Corylus)	Cooking pit (ID 11926)
Ua-50500	2180	22	Birch (Betula)	Cooking pit/ditch (ID 11975)
Ua-50491	2168	28	Pine (Pinus)	Cooking pit/fireplace (ID 9261)
Ua-50488	1810	23	Alder (Alnus)	Cooking pit (ID 9181)
Ua-50489	1781	24	Hazel (Corylus)	Cooking pit (ID 9211)

the site activities (Fossum 2017b). Hegna vest 2 is located where the highway runs today. This was removed, which appears to have been successful in relation to the simulation results.

Hegna vest 3

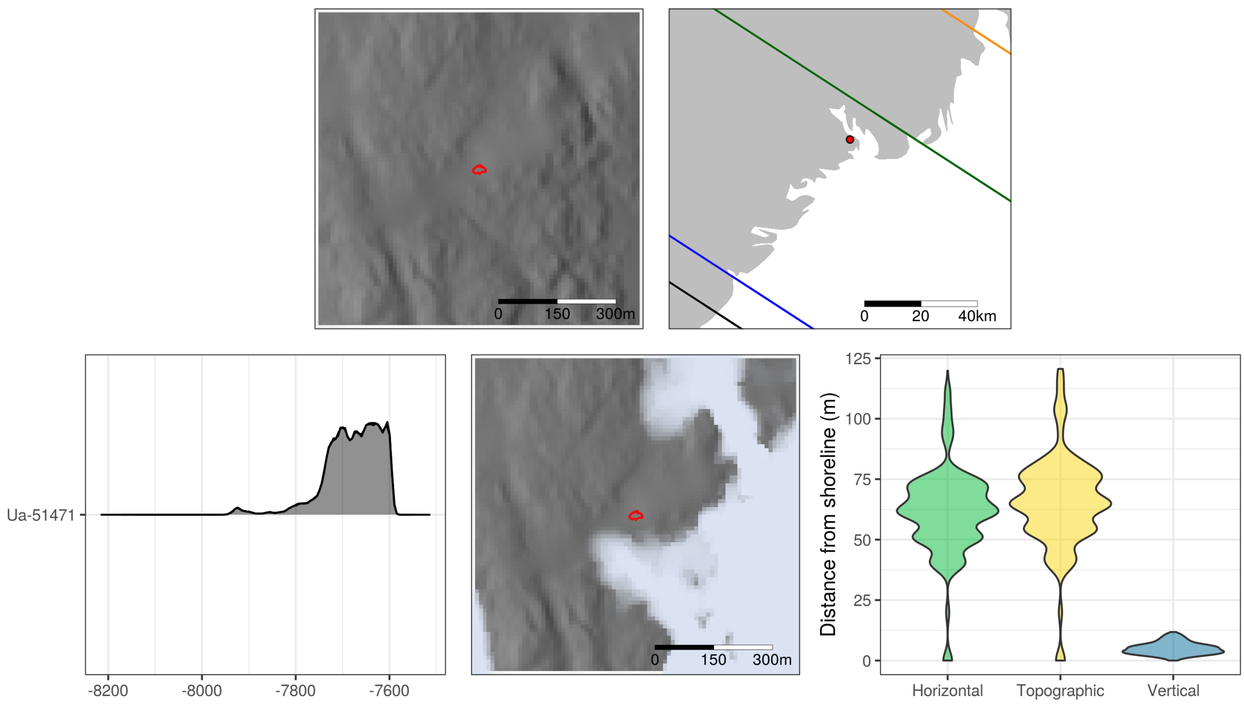
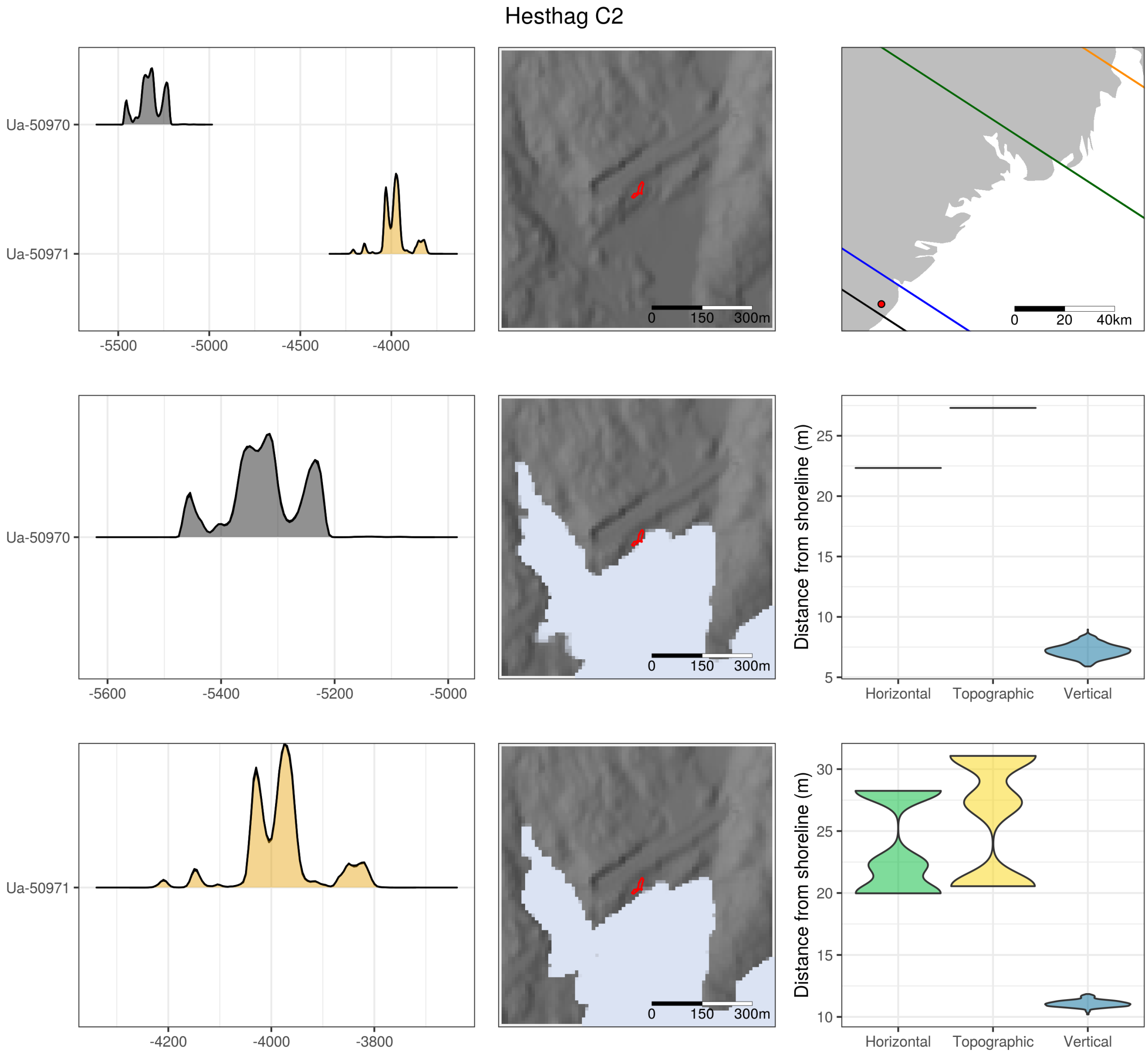


Table 20: Hegna vest 3

ID	^{14}C BP	Error	Material	Context
Ua-51471	8679	39	Aspen/willow (Populus/Salix)	Cooking pit (ID 11620)

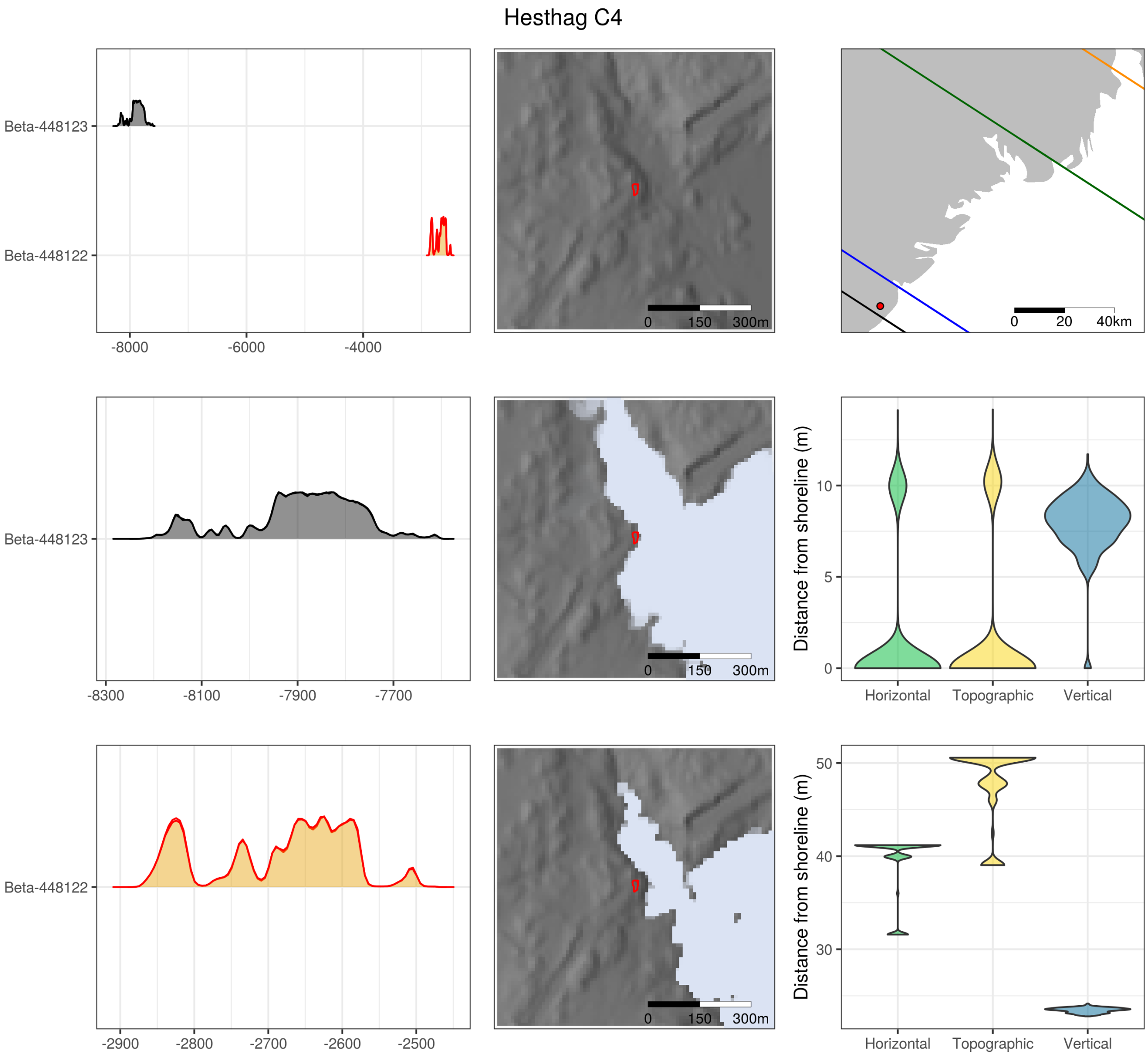
Along with Hegna vest 2 (above), Hegna vest 3 was situated where the highway runs today. The highway has been removed, and it would seem successfully so, as related to the sea-level adjustments. The ^{14}C-date to the Middle Mesolithic fits well with the lithic inventory (Eigeland and Fossum 2017a).



Hesthag C2 has seen repeated use, as evidenced both by ^{14}C-dates and the artefact inventory (Viken 2018a). While only a few finds can be typologically dated to the Late Mesolithic, these were deemed substantial enough to trust the two ^{14}C-dates to the period (Viken 2018a:271). No editing of the DTM was necessary.

Table 21: Hesthag C2

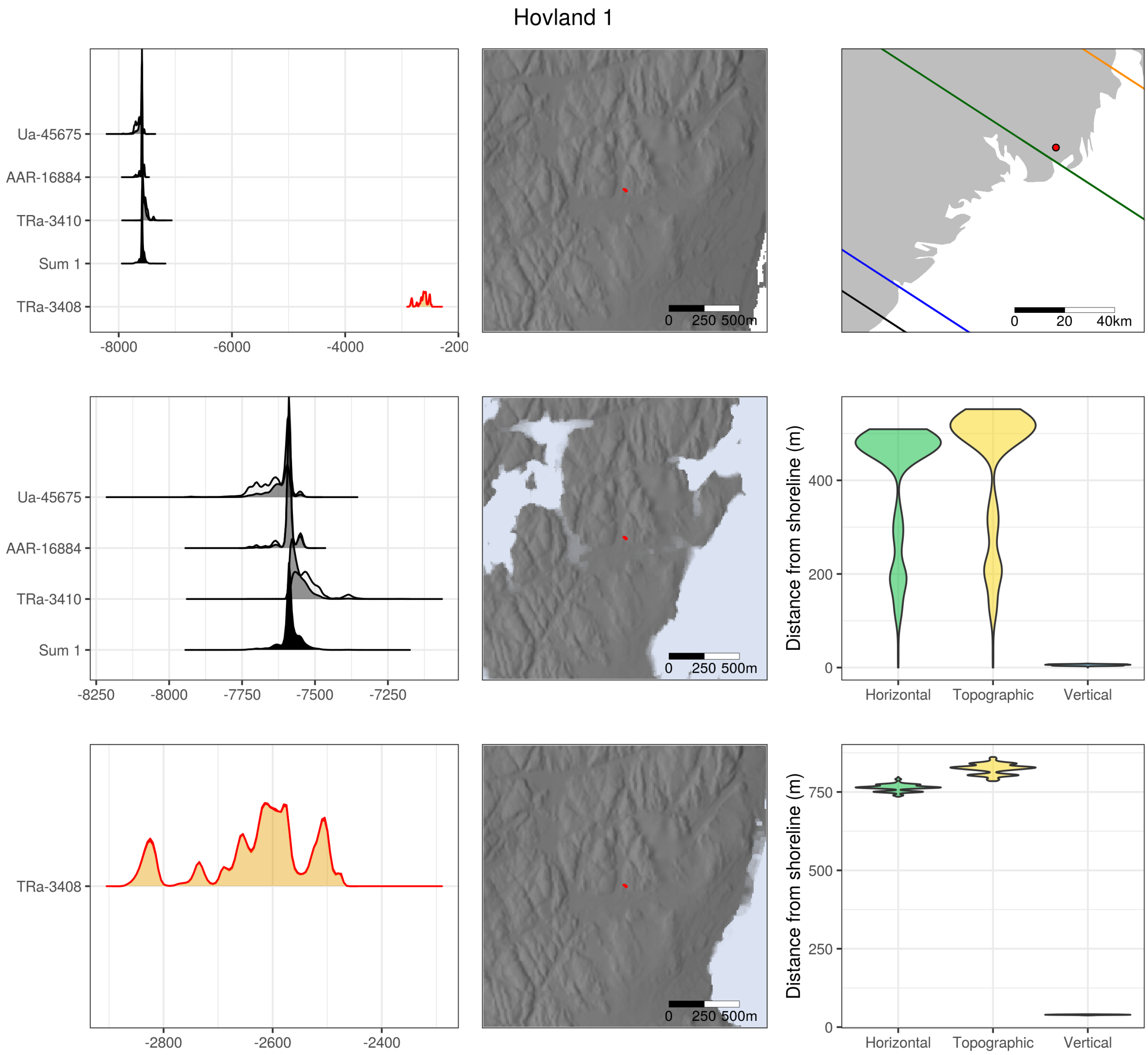
ID	^{14}C BP	Error	Material	Context
Ua-50970	6351	45	Oak (Quercus)	Fireplace (ID 2726)
Ua-50971	5172	44	Hazel (Corylus)	Fireplace (ID 2736)
Ua-50972	2182	30	Birch (Betula)	Fireplace (ID 4049)
Ua-50984	2143	32	Hazel (Corylus)	Cooking pit (ID 5366)
Ua-50973	1977	30	Birch (Betula)	Fireplace (ID 4063)
Ua-50974	1866	31	Birch (Betula)	Fireplace (ID 4224)



Typology and radiocarbon date match, and there are no modern disturbances in the vicinity of Hesthag C4 (Viken 2018b). The second ^{14}C-date is a reference date of charcoal from a context believed not be anthropogenic.

Table 22: Hesthag C4

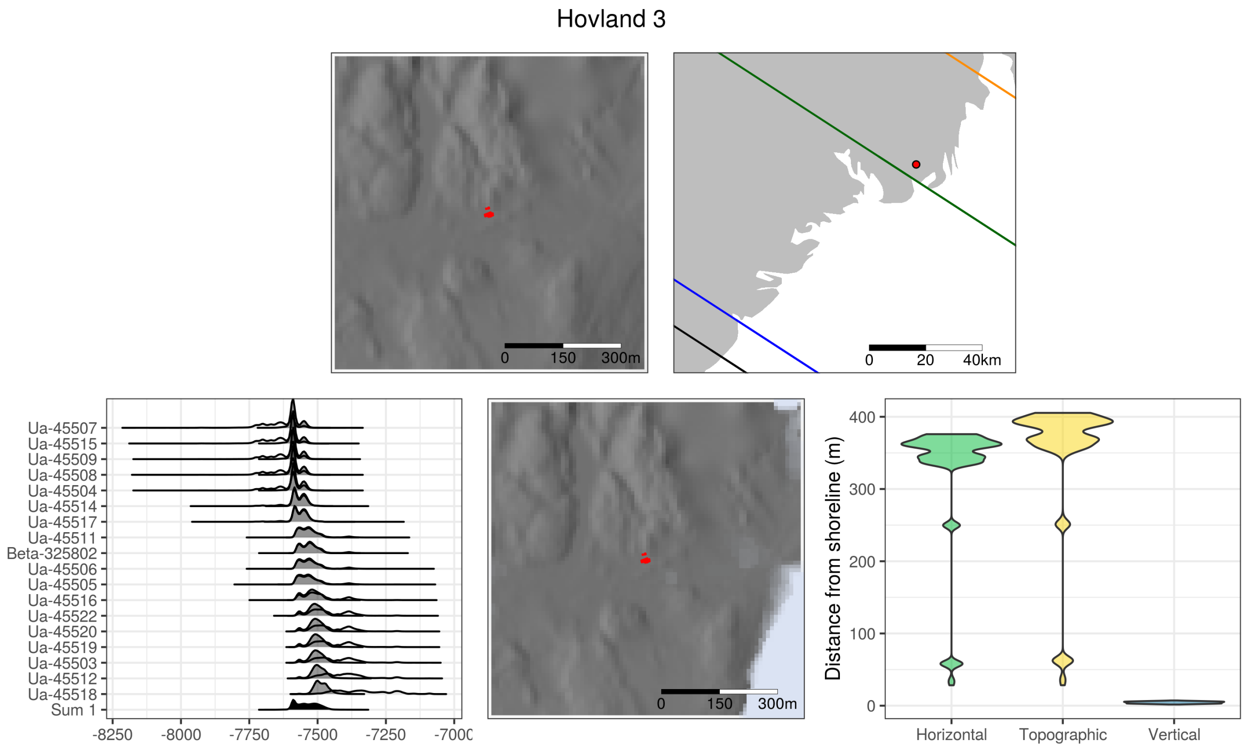
ID	^{14}C BP	Error	Material	Context
Beta-448123	8800	40	Pine (Pinus)	Cooking pit (ID 41178)
Beta-448122	4100	30	Birch (Betula)	Quadrant (993x863yNW)



It was noted in the report that it is uncertain how close to the shoreline Hovland 1 would have been situated, based on the ^{14}C-dates (Olsen 2013a). The earliest dates match the lithic inventory. The later date is the only indication of activity from the Early Bronze Age/Early Iron Age. The site is not located far from the highway, which was also edited for the analysis of Hovland 1 and 4, as well as Torstvet (see below). It could be noted that all of the Hovland sites and Torstvet (sites from the E18 Brunlanes project) are located a relatively short vertical distance from the sea, but the terrain makes this result in quite high horizontal and topographic distances.

Table 23: Hovland 1

ID	^{14}C BP	Error	Material	Context
TRa-3410	8465	55	Hazel (Corylus)	Cooking pit (ID 4)
Ua-45675	8623	50	Aspen/willow (Populus/Salix)	Cooking pit (ID 4)
AAR-16884	8582	33	Birch resin (Betula) on microblade	Quadrant (172x159ySW, layer 2)
TRa-3408	4070	35	Hazel (Corylus), nutshell	Square (158x164y, layer 2)
TRa-3409	2435	35	Hazel (Corylus)	Cooking pit (ID 2)



Hovland 3 is securely dated both typologically and radiometrically (Solheim and Olsen 2013). The site located right by the highway, but this appears to have been successfully removed.

Table 24: Hovland 3

ID	^{14}C BP	Error	Material	Context
Ua-45507	8609	54	Birch (Betula)	Post hole (ID 13)
Ua-45515	8606	50	Hazel (Corylus), nutshell	Quadrant (99x66yNE, layer 2)
Ua-45509	8594	48	Birch (Betula)	Post hole? (ID 17)
Ua-45508	8591	50	Rowan (Sorbus)	Post hole (ID 14)
Ua-45504	8584	49	Birch (Betula)	Undefined feature (ID 24)
Ua-45514	8552	50	Rowan (Sorbus)	Dwelling structure (0-5 cm)
Ua-45517	8540	51	Hazel (Corylus), nutshell	Dwelling structure (10-15 cm)
Ua-45505	8467	53	Rowan (Sorbus)	Undefined feature (ID 23)
Ua-45511	8465	48	Birch (Betula)	Undefined/ditch/post hole (ID 18)
Ua-45506	8458	48	Rowan (Sorbus)	Cooking pit (ID 21)
Beta-325802	8450	40	Hazel (Corylus), nutshell	Quadrant (100x66yNE, layer 3)
Ua-45516	8428	50	Hazel (Corylus), nutshell	Dwelling structure (0-5 cm)
Ua-45522	8398	49	Hazel (Corylus), nutshell	Undefined/ditch/post hole (ID 18)
Ua-45520	8387	47	Hazel (Corylus), nutshell	Dwelling structure (30-35 cm)
Ua-45519	8383	47	Hazel (Corylus), nutshell	Dwelling structure (25-30 cm)
Ua-45503	8376	51	Birch (Betula)	Cooking pit (ID 25)
Ua-45512	8348	47	Birch (Betula)	Post hole (ID 7)
Ua-45518	8291	48	Hazel (Corylus), nutshell	Dwelling structure (20-25 cm)
Ua-45523	3423	34	Hazel (Corylus), nutshell	Post hole (ID 8)
Ua-45521	2674	32	Hazel (Corylus), nutshell	Stone packing (ID 15)
Ua-45502	2408	34	Hazel (Corylus)	Fireplace (ID 5)
Ua-45501	2188	33	Hazel (Corylus)	Fireplace (ID 27)
Ua-45510	1833	30	Birch (Betula)	Fireplace (ID 11)
Ua-45513	1334	30	Birch (Betula)	Quadrant (101x67ySW, layer 3)

Table 25: Hovland 4

ID	^{14}C BP	Error	Material	Context
Ua-45500	8747	64	Burnt bone	Quadrant (93x46yNW, layer 2)
Ua-45499	8630	49	Hazel (Corylus), nutshell	Quadrant (90x45ySW, layer 2)
Ua-45493	8568	51	Birch (Betula)	Cooking pit (ID 6)
Ua-45494	8526	52	Birch (Betula)	Fireplace (ID 1)
Ua-45495	3534	34	Hazel (Corylus)	Fireplace (ID 8)
Ua-45496	3016	32	Hazel (Corylus)	Fireplace (ID 10)
Ua-45497	2327	32	Hazel (Corylus)	Cooking pit (ID 14)
Ua-45492	2090	32	Birch/hazel (Betula/Corylus)	Fireplace (ID 3)
Ua-45498	1751	31	Hazel (Corylus), nutshell	Quadrant (101x59yNE, layer 2)

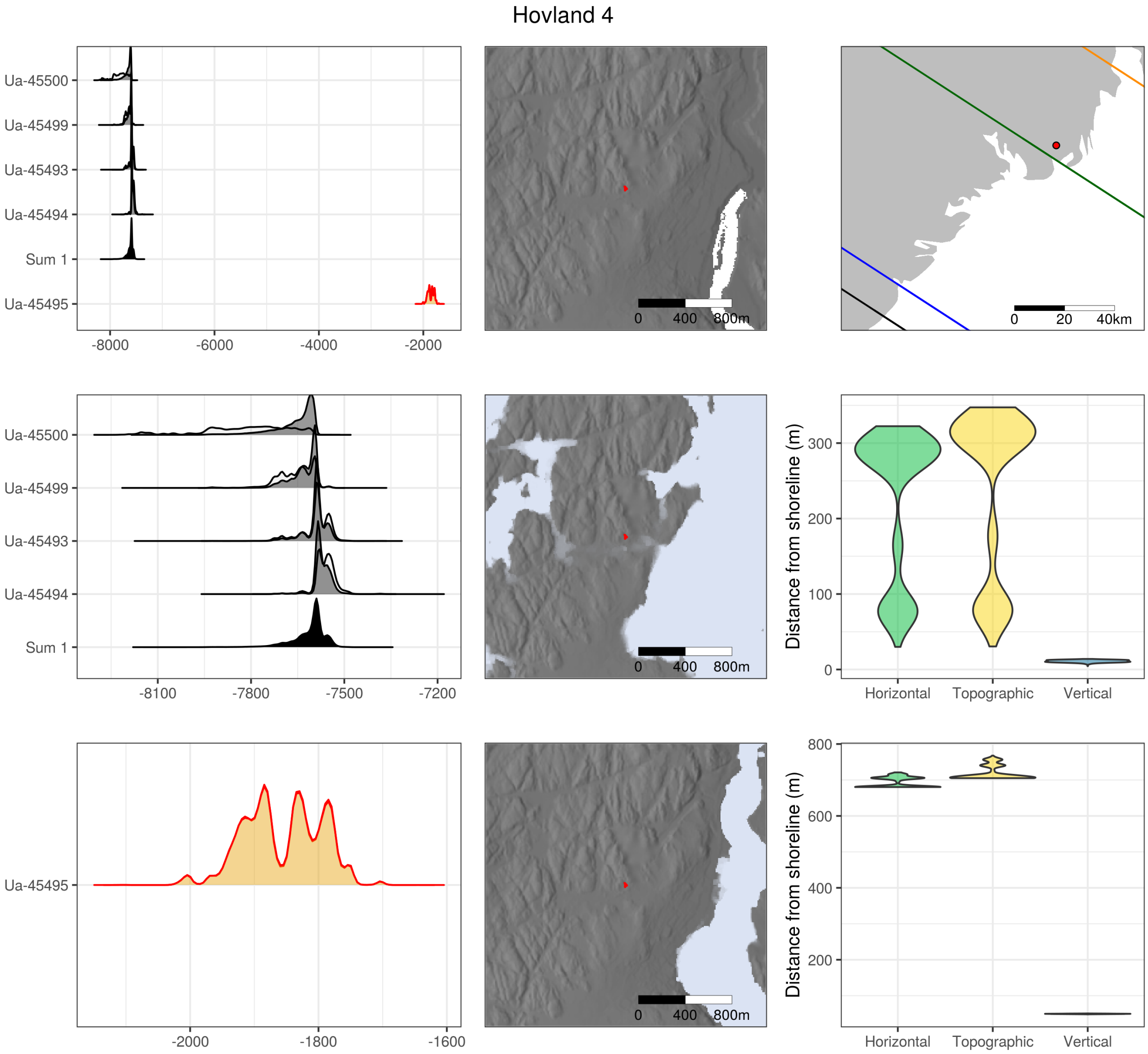
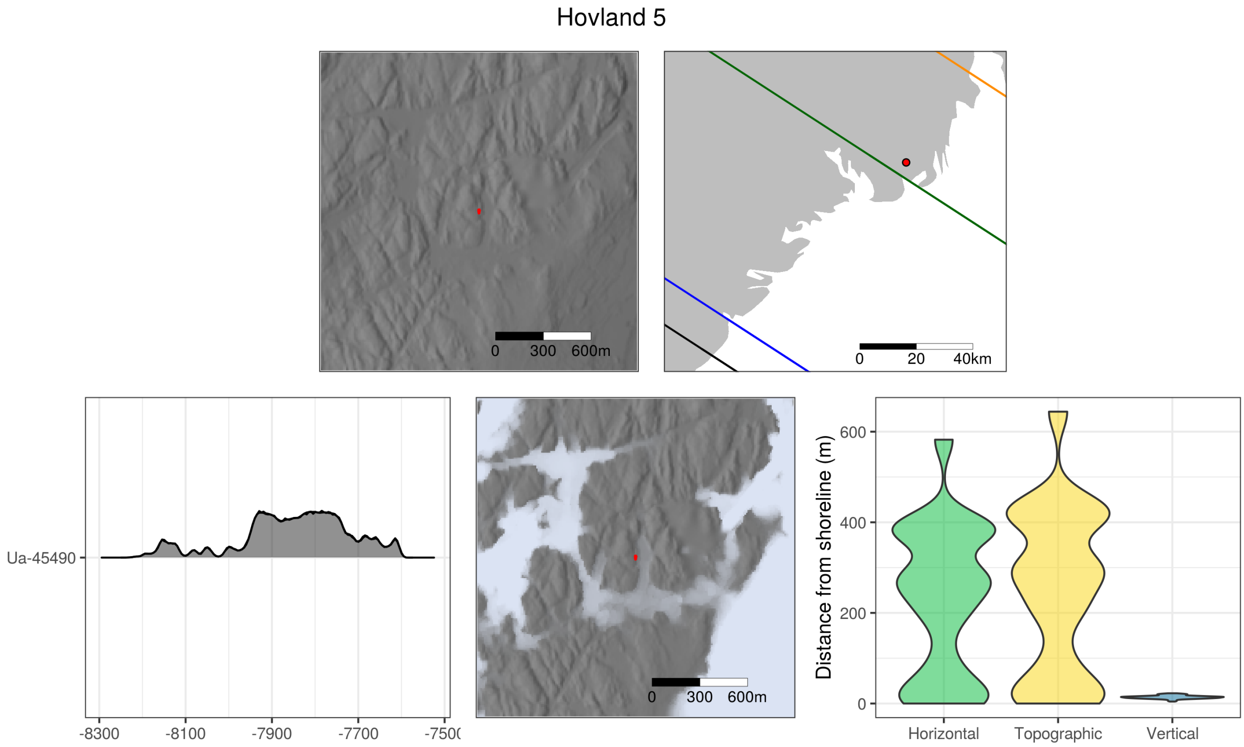


Table 26: Hovland 5

ID	^{14}C BP	Error	Material	Context
Ua-45490	8775	52	Hazel (Corylus), nutshell	Quadrant (66x104ySE, layer 2)
Ua-45491	2674	34	Hazel (Corylus), nutshell	Quadrant (67x104ySE, layer 1)

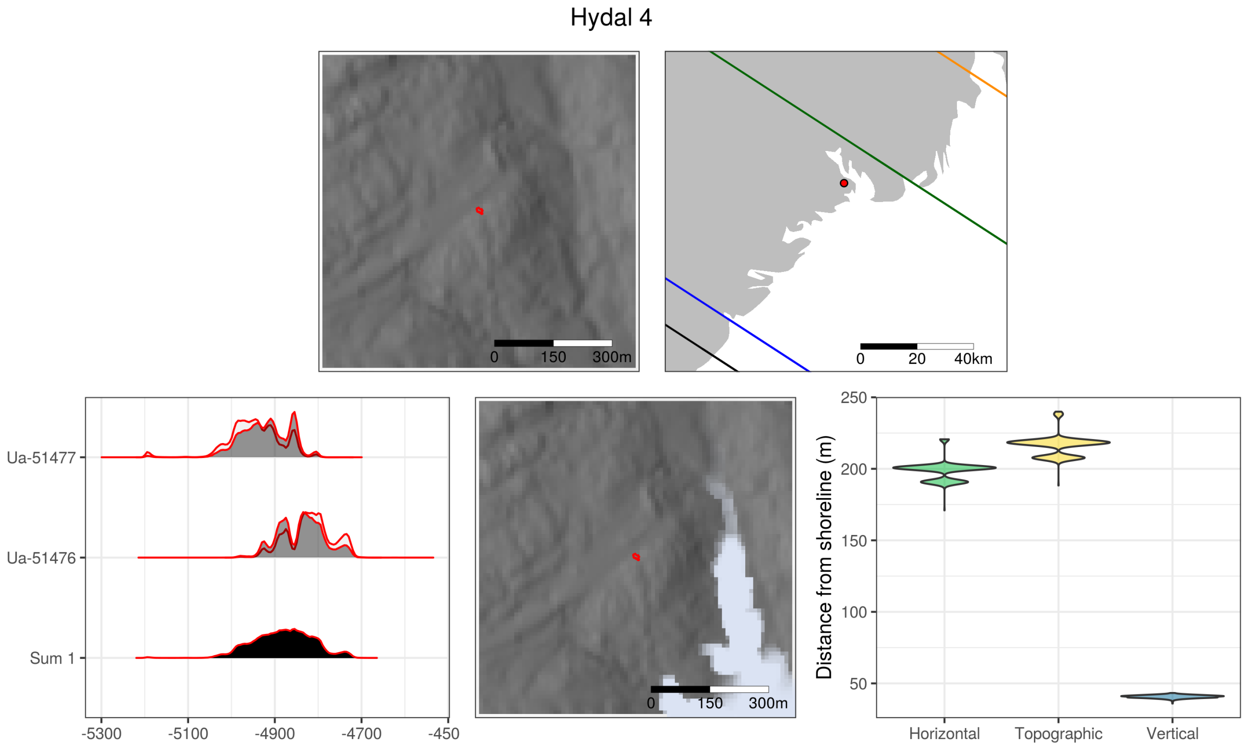
Hovland 4 is well-dated both typologically and with ^{14}C-dates to the Mesolithic (Mansrud 2013a). It has a similar location to that of Hovland 3 (above), and editing of the highway seems to have been successful.



Hovland 5 is situated more withdrawn from the highway than the other Hovland sites (above), and the DTM did therefore not require any editing. The site only has a single ^{14}C-date to the Stone Age, but this does match the typological indicators of the assemblage (Mansrud and Koxvold 2013).

Table 27: Hydal 4

ID	^{14}C BP	Error	Material	Context
Ua-51475	2064	33	Willow (Salix)	Grave, urn (ID 5442)
Ua-51476	5944	35	Oak (Quercus)	Fireplace (ID 5459)
Ua-51477	6049	36	Hazel (Corylus), nutshell	Square (107x604y, layer 2)
Ua-51478	2361	29	Burnt bone, human	Grave, urn (ID 5442)



The lithic inventory from Hydal 4 is distinctly Middle Mesolithic in character, and therefore does not match the ^{14}C-dates to the Late Mesolithic (Koxvold 2017a). The simulation of the sea-level does not appear impacted by any modern disturbances.

Krøgenes D1

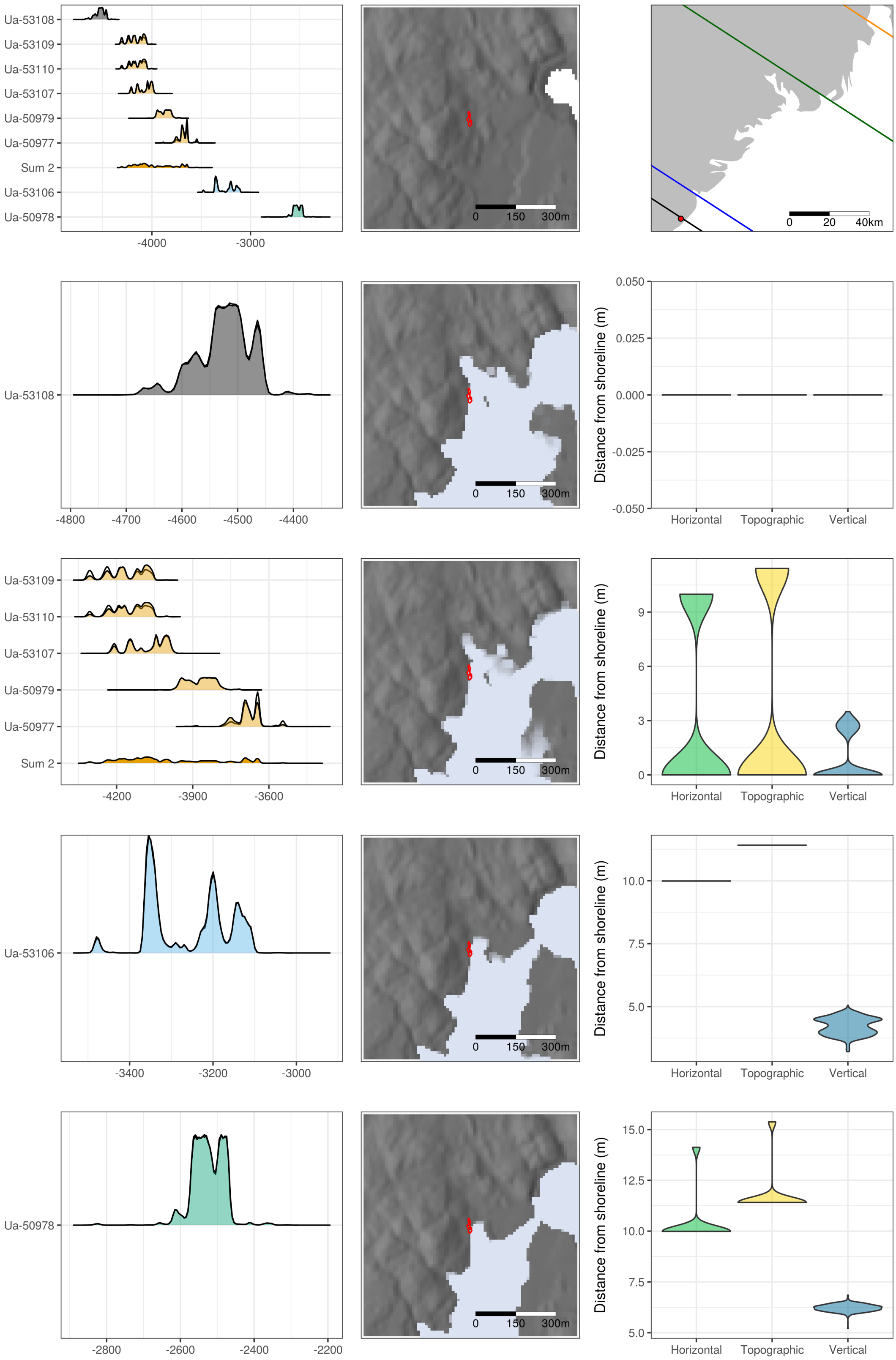

Ua-53108
Ua-53109
Ua-53110
Ua-53107
Ua-50979
Ua-50977
Sum 2
Ua-53106
Ua-50978
-4000
-3000
0
150
300m
0
20
40km
Distance from shoreline (m)
Horizontal
Topographic
Vertical

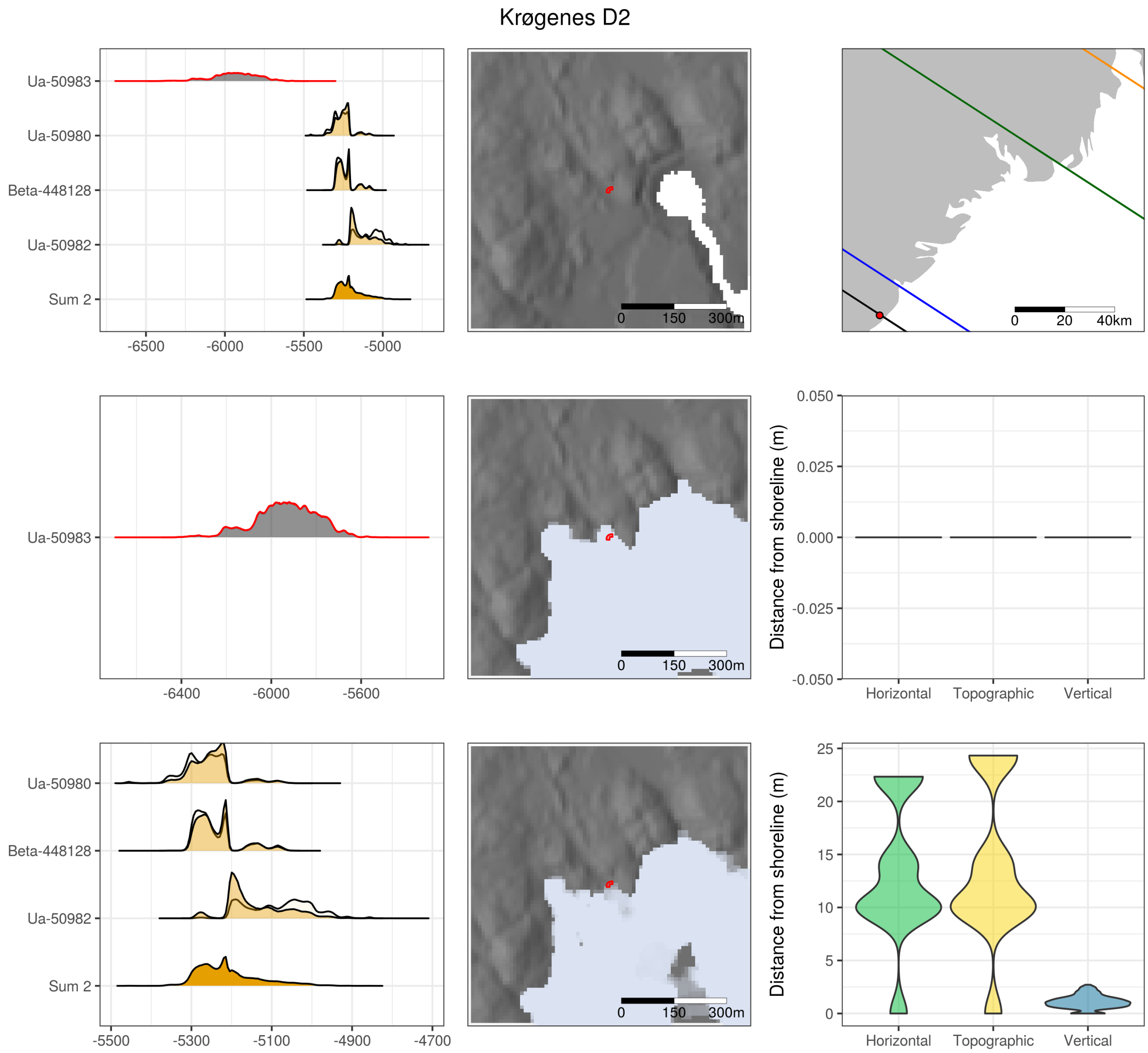
Table 28: Krøgenes D1

ID	^{14}C BP	Error	Material	Context
Ua-53108	5694	32	Ash (Fraxinus)	Cooking pit/fireplace (ID 204387)
Ua-53109	5351	31	Pine (Pinus)	Cooking pit/fireplace (ID 207098)
Ua-53110	5334	31	Pine (Pinus)	Cooking pit/fireplace (ID 207811)
Ua-53107	5249	31	Birch (Betula)	Posthole? (ID 204397)
Ua-50979	5082	40	Willow/alder (Salix/Alnus)	Ditch (ID 204424)
Ua-50977	4883	40	Willow/alder (Salix/Alnus)	Cooking pit/fireplace (ID 204413)
Ua-53106	4559	31	Pine (Pinus)	Ditch (ID 203549)
Ua-50978	4005	34	Ash (Fraxinus)	Cooking pit/fireplace (ID 206352)
Ua-50975	1641	30	Ash (Fraxinus)	Cooking pit/fireplace (ID 203533)

All ^{14}C-dates from Krøgenes D1 are believed to be related to use of the site, which has been reused multiple times over a long time-span (Reitan and Solberg 2018a). This is evidenced by the artefact inventory as well. To what degree the different dates are related to different or the same settlement phases is difficult to ascertain, but is here, as with for the rest of the sites, simply based on grouping dates overlapping with 99.7% probability. The site is situated around 100 meter from a road to the south, but this does not appear to impact simulation results, which is therefore left unedited in the DTM.

Table 29: Krøgenes D2

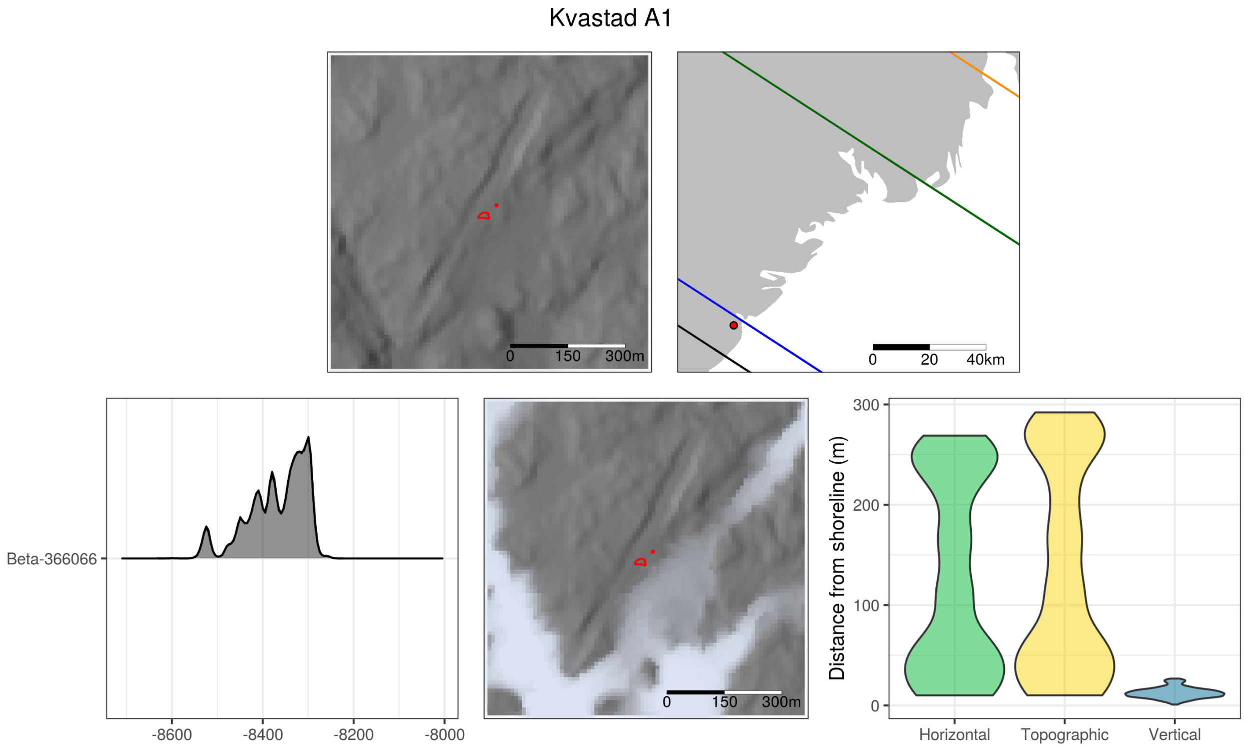
ID	^{14}C BP	Error	Material	Context
Ua-50983	7059	143	Pine (Pinus)	Stone packing (ID 206735)
Ua-50982	6132	45	Pine (Pinus)	Cultural layer (ID 206712)
Beta-448128	6260	30	Alder (Alnus)	Cultural layer (K2, sample ID 3102)
Ua-50980	6297	44	Pine (Pinus)	Cultural layer (ID 206712)
Ua-50981	3379	34	Birch (Betula)	Sand layer (ID 206652)
Beta-448127	1760	30	Hazel (Corylus)	Cultural/Cultivation layer (K1, sample ID 3646)



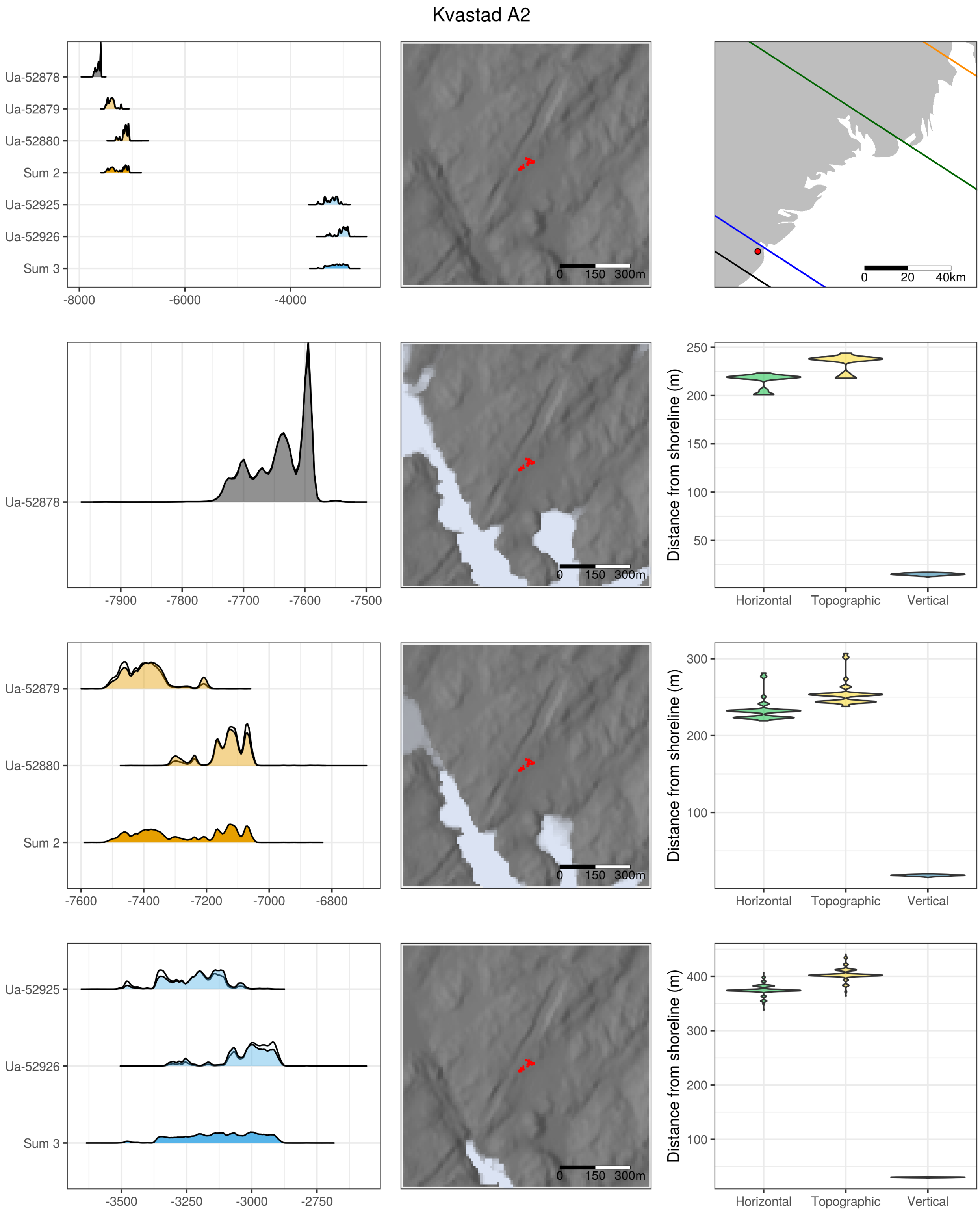
Dates match the artefact inventory of Krøgenes D2, with the exception of the oldest date which is not seen as relevant for the main occupation of the site, in part also due to the large error (Mansrud et al. 2018). The site location is similar to that of Krøgenes D1 (above), and did not require any editing of the DTM.

Table 30: Kvastad A1

ID	^{14}C BP	Error	Material	Context
Ua-53920	2400	30	Yew (Taxus)	Fireplace (ID 1108)
Ua-53921	2388	29	Indet.	Fireplace (ID 1108)
Ua-53918	2249	29	Alder (Alnus)	Fireplace (ID 1108)
Ua-53917	2176	29	Birch (Betula)	Fireplace (ID 1108)
Ua-53919	2164	29	Indet.	Fireplace (ID 1108)
Ua-52872	2264	27	Birch (Betula)	Fireplace (ID 1108)
Beta-366066	9150	40	Pine (Pinus)	Test pit (ID 20993)



^{14}C-date and lithic inventory at Kvastad A1 correspond with a date to the end of the Early Mesolithic (Stokke et al. 2018). The highway to north of the site is clearly visible on the DTM, but does not impact the simulation results.



The two find areas at Kvastad A2 are predominantly Mesolithic (to the south-west) and Neolithic (to the north-east) but were treated in combination here as one Mesolithic date was from the Neolithic area (Stokke

Table 31: Kvastad A2

ID	^{14}C BP	Error	Material	Context
Ua-52878	8625	35	Pine (Pinus)	Fireplace (ID 57753)
Ua-52879	8339	35	Pine (Pinus)	Fireplace (ID 57995)
Ua-52880	8130	34	Coniferous (Conif. indet.), cone seed scale	Undefined feature (ID 54075)
Ua-52925	4551	56	Hulless barley (Hordeum vulgare var. nudum)	Fireplace (ID 54643)
Ua-52926	4351	55	Emmer (Hordeum vulgare var. nudum)	Fireplace (ID 54643)
Ua-52875	3464	28	Hulless barley (Hordeum vulgare var. nudum)	Fireplace (ID 54643)
Ua-52876	3477	28	Oat (Avena sp.)	Fireplace (ID 54643)
Ua-52877	3470	29	Oat (Avena sp.)	Fireplace (ID 54643)
Ua-52874	3431	28	Oat (Avena sp.)	Cultivation layer (ID 53485)

Table 32: Kvastad A4

ID	^{14}C BP	Error	Material	Context
Ua-52887	2395	27	Ash (Fraxinus)	Cooking pit (ID 153273)
Ua-52882	809	26	Oak (Quercus)	Fireplace (ID 150637)
Ua-52886	1100	26	Pine (Pinus)	Trench profile (ID 153311)
Beta-366067	8760	40		Test pit (ID 21410)

and Reitan 2018a). There is also a late Neolithic element in the lithic inventory that is not reflected in the ^{14}C-dates. As with Kvastad A1 (above) the highway runs north of the site, clearly visible on the DTM, but does not impact the simulation results.

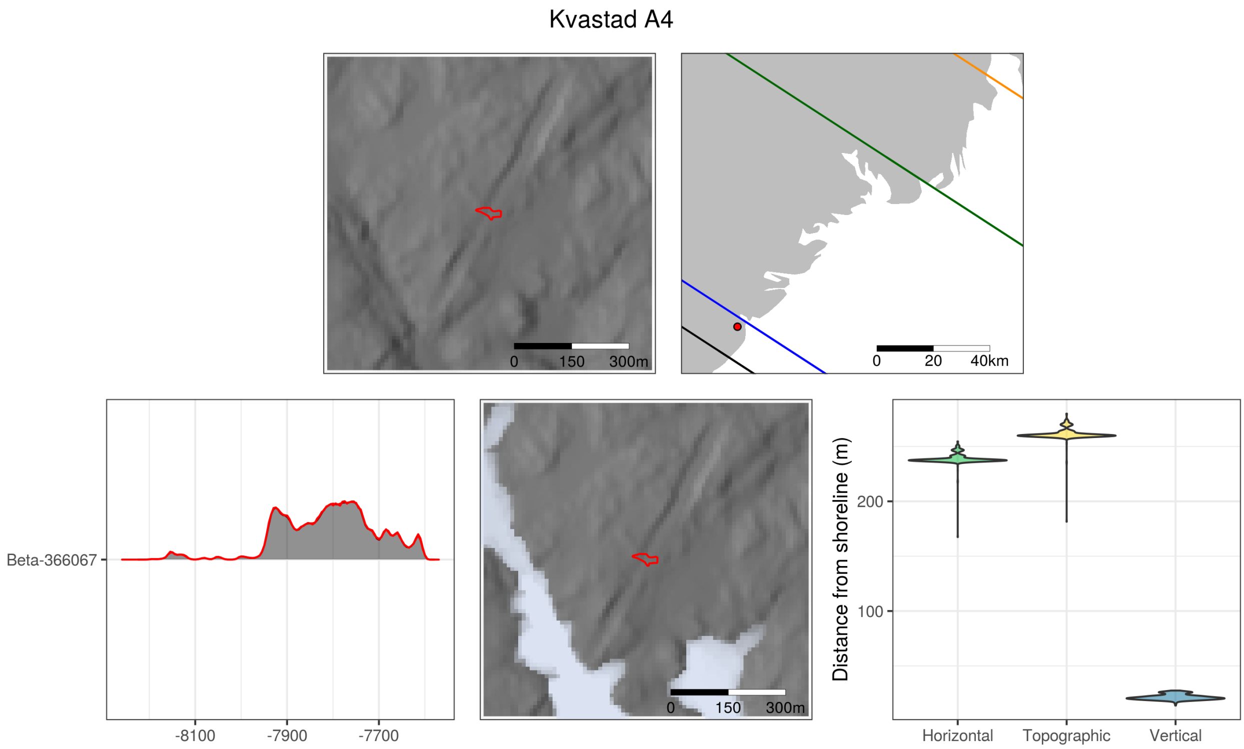
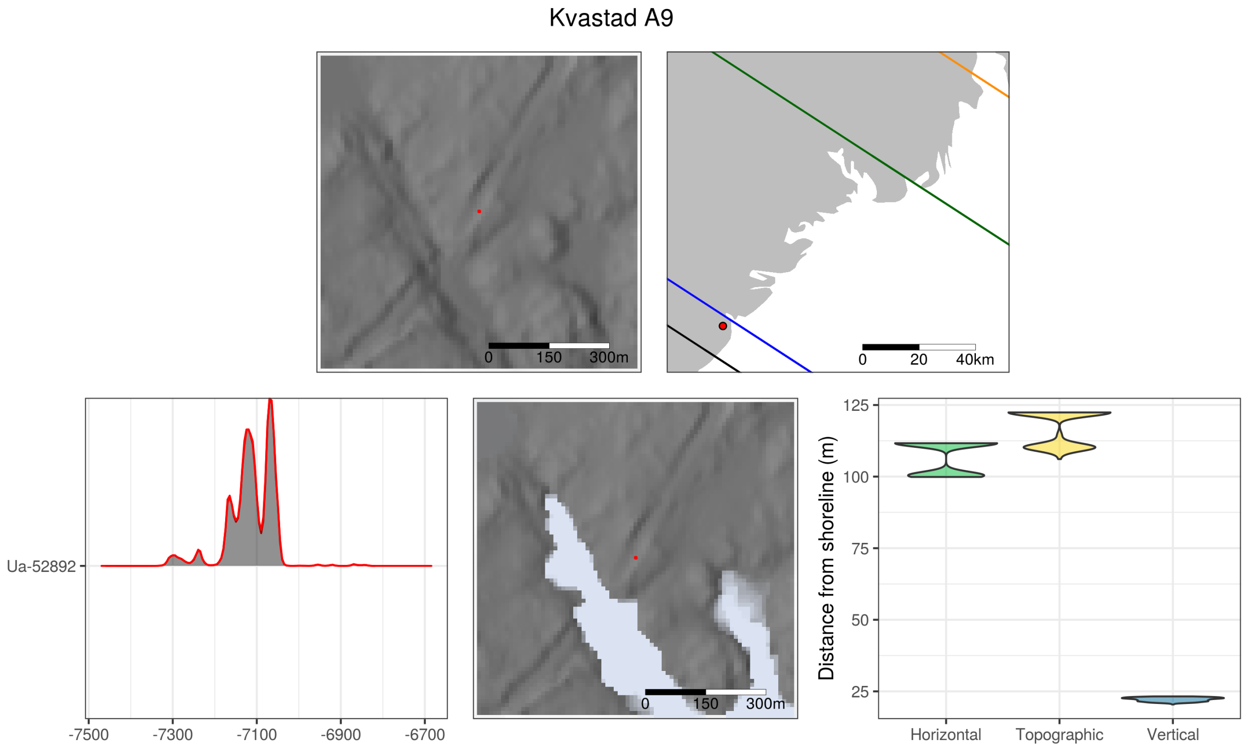


Table 33: Kvastad A9

ID	^{14}C BP	Error	Material	Context
Ua-52891	2476	27	Oak (Quercus)	Fireplace (ID 400076)
Ua-52892	8119	34	Pine (Pinus)	Stone packing (ID 400159)
Ua-52893	3187	28	Pine (Pinus)	Fireplace (ID 400180)

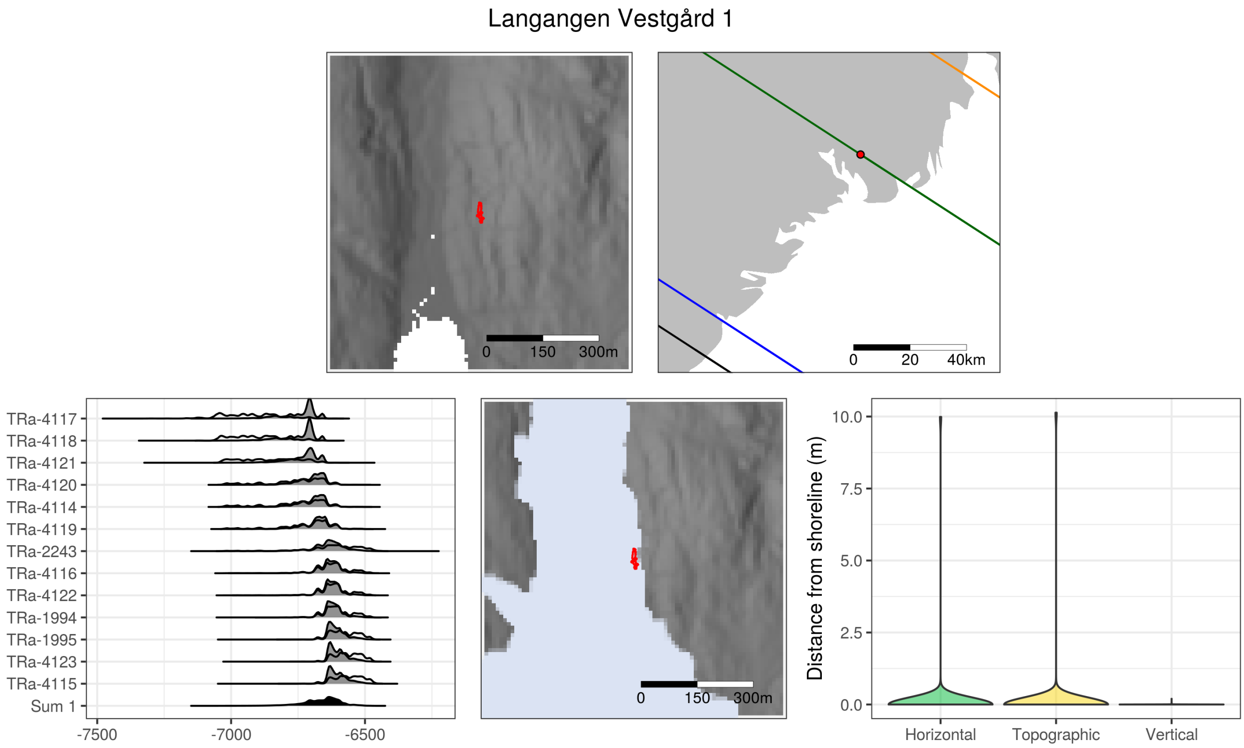
While there are a few elements of the lithic inventory from Kvastad A4 that could be related to the late Middle Mesolithic ^{14}C-date, it is not related to the main visits to the site, which are Early Mesolithic in character (Darmark et al. 2018). The highway runs over the site today, but this is not relevant for the shore-line reconstruction done here.



The Stone Age date from Kvastad A9 is not related to the Early Mesolithic assemblage (Darmark 2018a). The highway running by the site does not seem relevant to the simulation results.

Table 34: Langangen Vestgård 1

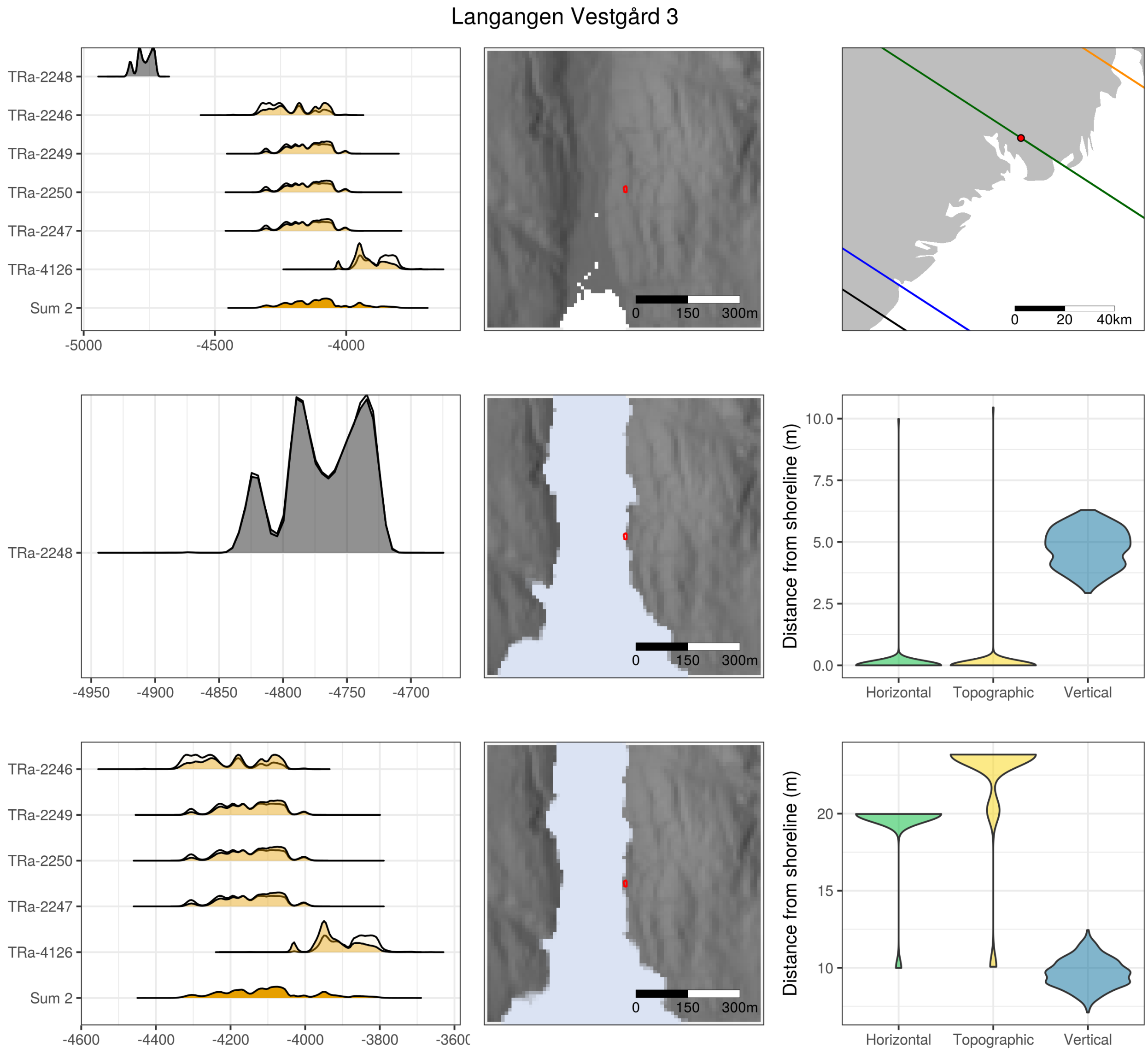
ID	^{14}C BP	Error	Material	Context
TRa-1994	7785	40	Burnt bone	Quadrant (579x937ySW, layer 2)
TRa-1995	7760	40	Burnt bone	Quadrant (580x938yNE, layer 2)
TRa-2243	7780	70	Pine (Pinus)	Floor layer (ID 1)
TRa-4114	7870	45	Birch/rowan (Betula/Sorbus)	Cooking pit (ID 3600)
TRa-4115	7740	45	Hazel (Corylus)	Cooking pit (ID 3601)
TRa-4116	7800	45	Hazel (Corylus)	Cooking pit (ID 4044)
TRa-4117	8030	55	Pine (Pinus)	Cooking pit (ID 4286)
TRa-4118	8005	45	Willow (Salix)	Undefined feature (ID 6)
TRa-4119	7850	45	Birch/hazel (Betula/Corylus)	Undefined feature (ID 8a)
TRa-4120	7875	45	Hazel (Corylus)	Undefined feature (ID 13)
TRa-4121	7945	45	Birch/willow (Betula/Salix)	Undefined feature (ID 12)
TRa-4122	7795	40	Burnt bone	Quadrant (583x929yNE, layer 1+2)
TRa-4123	7745	35	Burnt bone	Quadrant (589x931yNE, layer 2)



Langangen Vestgård 1 is a securely dated site with both ^{14}C-dates and typology (Melvold and Eigeland 2014). No modern disturbances appear relevant for the sea-level adjustment.

Table 35: Langangen Vestgård 3

ID	^{14}C BP	Error	Material	Context
TRa-2245	1080	30	Birch (Betula)	Cooking pit (ID 1640)
TRa-2246	5400	55	Pine (Pinus)	Cooking pit (ID 1600)
TRa-2247	5325	50	Pine (Pinus)	Cooking pit (ID 1600)
TRa-2248	5910	10	Pine (Pinus)	Cooking pit (ID 1664)
TRa-4126	5095	40	Pine (Pinus)	Cooking pit (ID 1664)
TRa-2249	5325	45	Birch (Betula)	Cooking pit (ID 1700)
TRa-2250	5325	50	Birch (Betula)	Cooking pit (ID 1700)

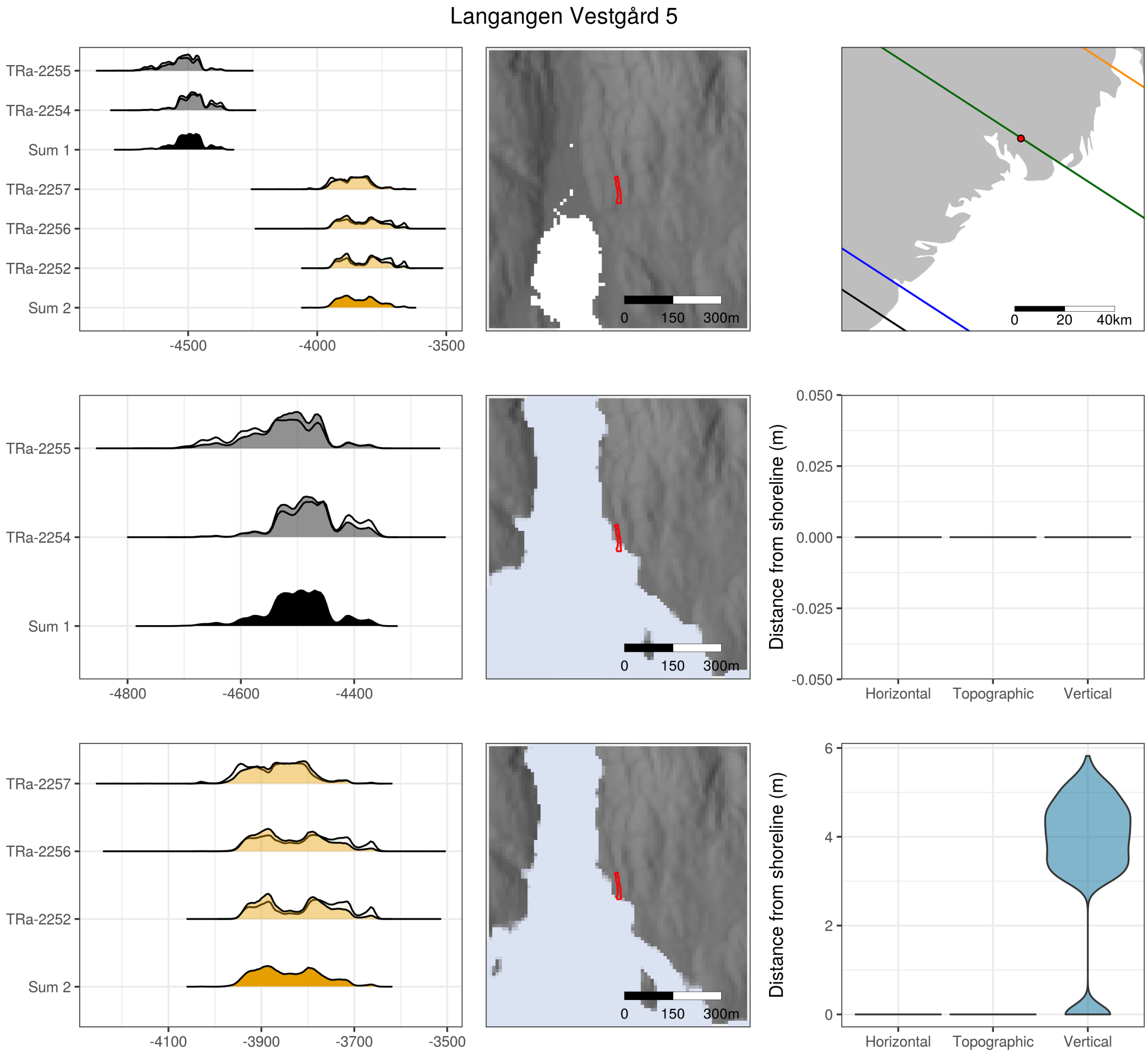


Typology of the site inventory from Langangen Vestgård 3 match the ^{14}C-date (Eggen 2014a). Typological indicators are too coarse to offer any insight on the division into two phases done here for the ^{14}C-dates (see

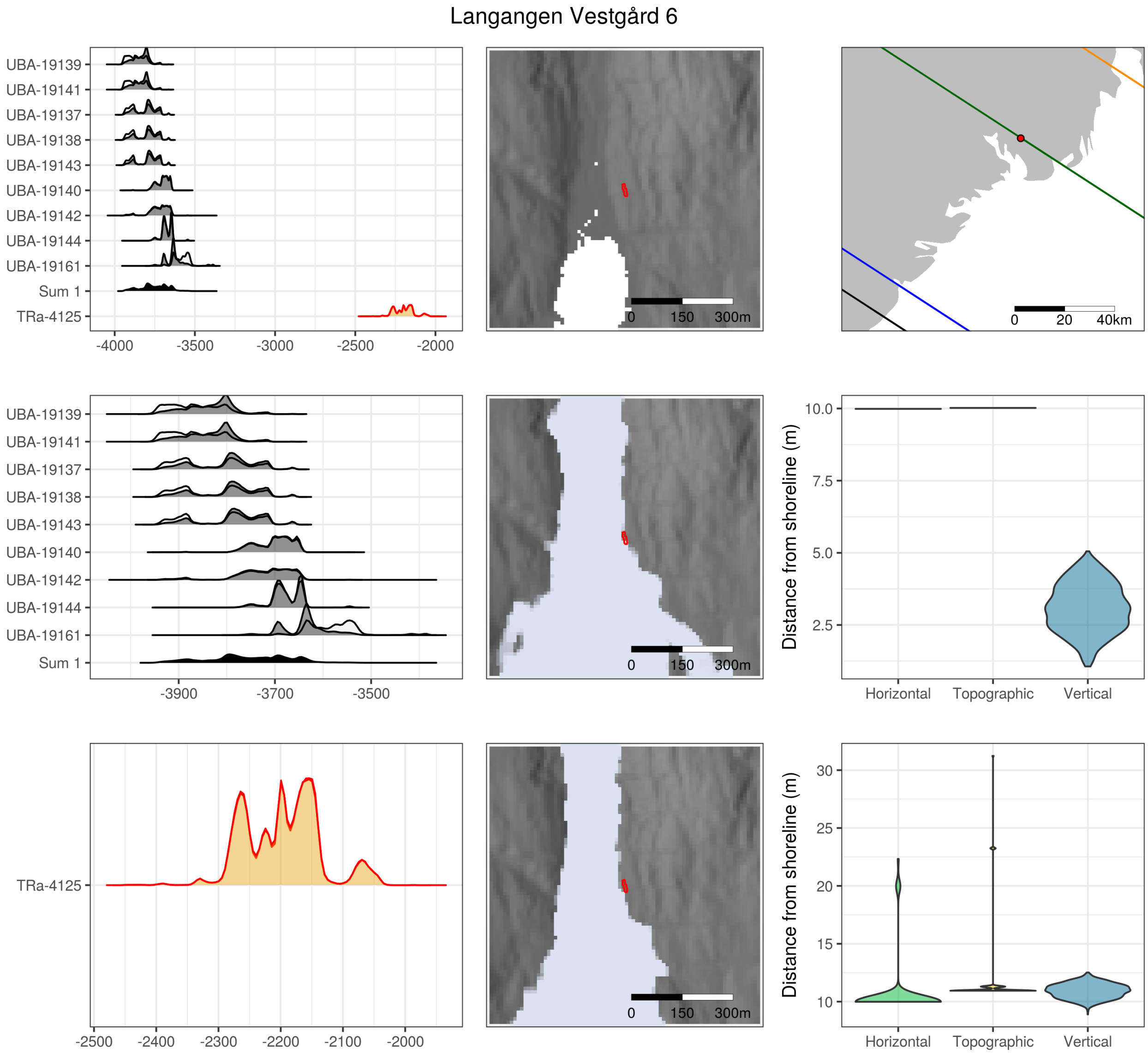
Table 36: Langangen Vestgård 5

ID	^{14}C BP	Error	Material	Context
TRa-2255	5695	50	Pine (Pinus)	Cooking pit (ID 2800)
TRa-2254	5645	45	Birch/willow (Betula/Salix)	Cooking pit (ID 2821)
TRa-2257	5085	50	Birch/linden (Betula/Tilia)	Cooking pit/fireplace (ID 395)
TRa-2256	5015	55	Birch/willow/rowan (Betula/Salix/Sorbus)	Cooking pit (ID 2300)
TRa-2252	5005	45	Birch/willow/rowan (Betula/Salix/Sorbus)	Cooking pit (ID 2329)
UBA-19135	3066	25	Birch (Betula)	Cooking pit? (ID 5316)
TRa-2253	2255	45	Birch/hazel/willow/rowan (Betula/Corylus/Salix/Sorbus)	Cultural layer? (ID 352)
UBA-19136	1819	26	Ash (Fraxinus)	Fireplace (ID 3369)
TRa-2251	1785	35	Birch/hazel (Betula/Corylus)	Fireplace (ID 350)
TRa-2258	1785	35	Birch/hazel (Betula/Corylus)	Charcoal/406x46ySWSE,layer 2 (ID 2328)
TRa-1996	100	30	Burnt bone, mammal (1.6g)	Quadrant (369x55yNW, layer 2)

main text). No editing of the DTM was necessary.



Langangen Vestgård 5. Typology match the ^{14}C-dates and a division into two settlement phases, one Late Mesolithic and one Early Neolithic (Reitan 2014c). No editing of the DTM deemed necessary.



Pottery and the lithic inventory of Langanven Vestgård 6 match ^{14}C-dates to the Early Neolithic (Reitan 2014d). Nothing in the artefact inventory could be related to the Late Neolithic date. The DTM did not require editing.

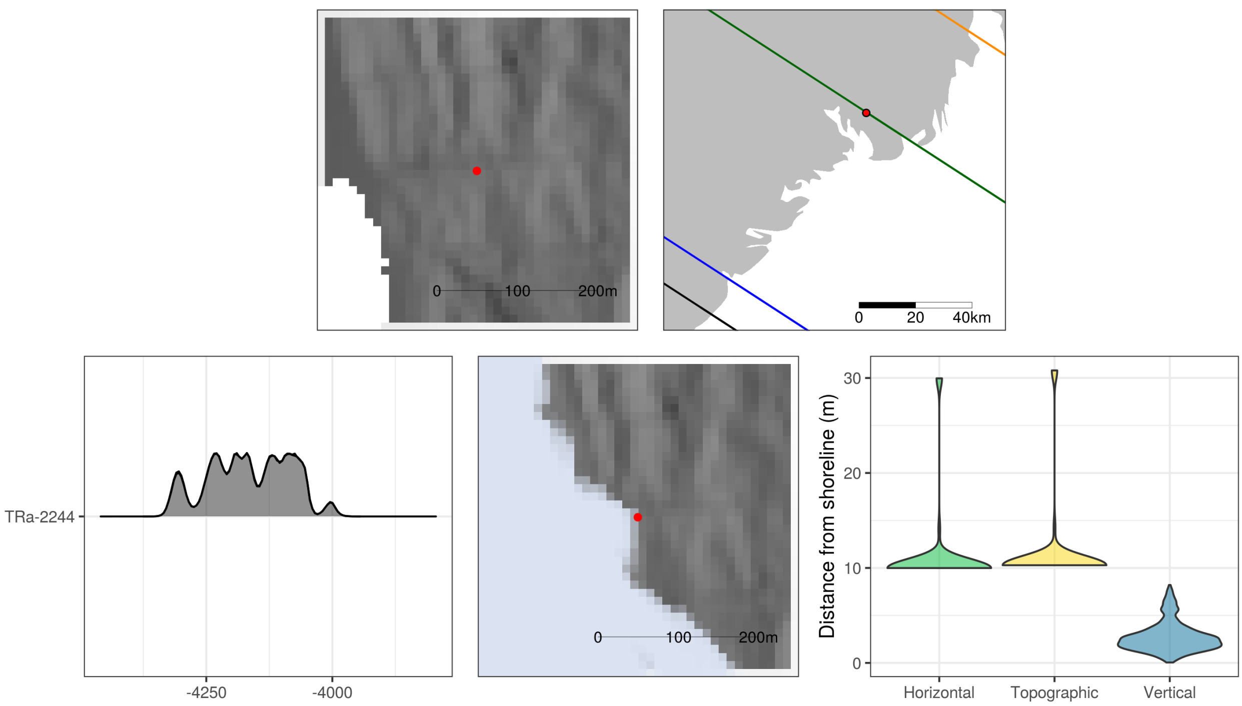
Table 37: Langangen Vestgård 6

ID	^{14}C BP	Error	Material	Context
UBA-19139	5057	28	Birch (Betula)	Cooking pit (ID 2045)
UBA-19141	5055	27	Birch/aspen (Betula/Populus)	Cooking pit? (ID 214)
UBA-19137	5021	28	Birch (Betula)	Cooking pit (ID 1732)
UBA-19138	5017	29	Birch (Betula)	Cooking pit (ID 2000)
UBA-19143	5010	27	Hazel (Corylus)	Cooking pit (ID 1886)
UBA-19142	4939	47	Birch/hazel (Betula/Corylus)	Undefined feature (ID 572)
UBA-19140	4931	31	Birch (Betula)	Fireplace (ID 1776)
UBA-19144	4891	31	Birch/willow (Betula/Salix)	Cooking pit (ID 163, east)
UBA-19161	4813	46	Birch (Betula)	Cooking pit (ID 2032)
TRa-4125	3775	30	Burnt bone, beaver (Castor)	Quadrant (61x890yNE, layer 1)

Table 38: Langangen Vestgård 7

ID	^{14}C BP	Error	Material	Context
TRa-2244	5335	50	Birch/willow (Betula/Salix)	Cooking pit (ID 214)

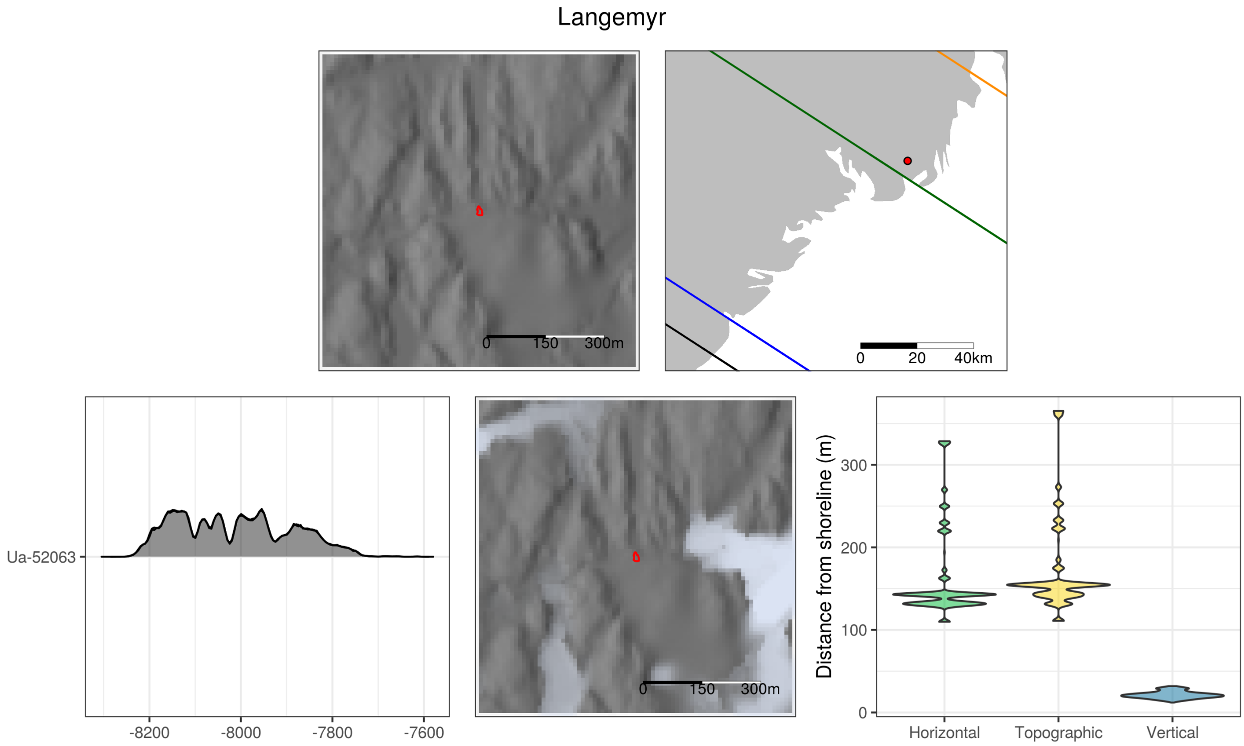
Langangen Vestgård 7



Langangen Vestgård 7 is represented by a cooking pit found on one of two terraces scattered with lithics that was not known and not originally part of the excavation project (Reitan 2014e). The site was therefore only investigated to a limited degree. However, the material does typologically match the ^{14}C-date.

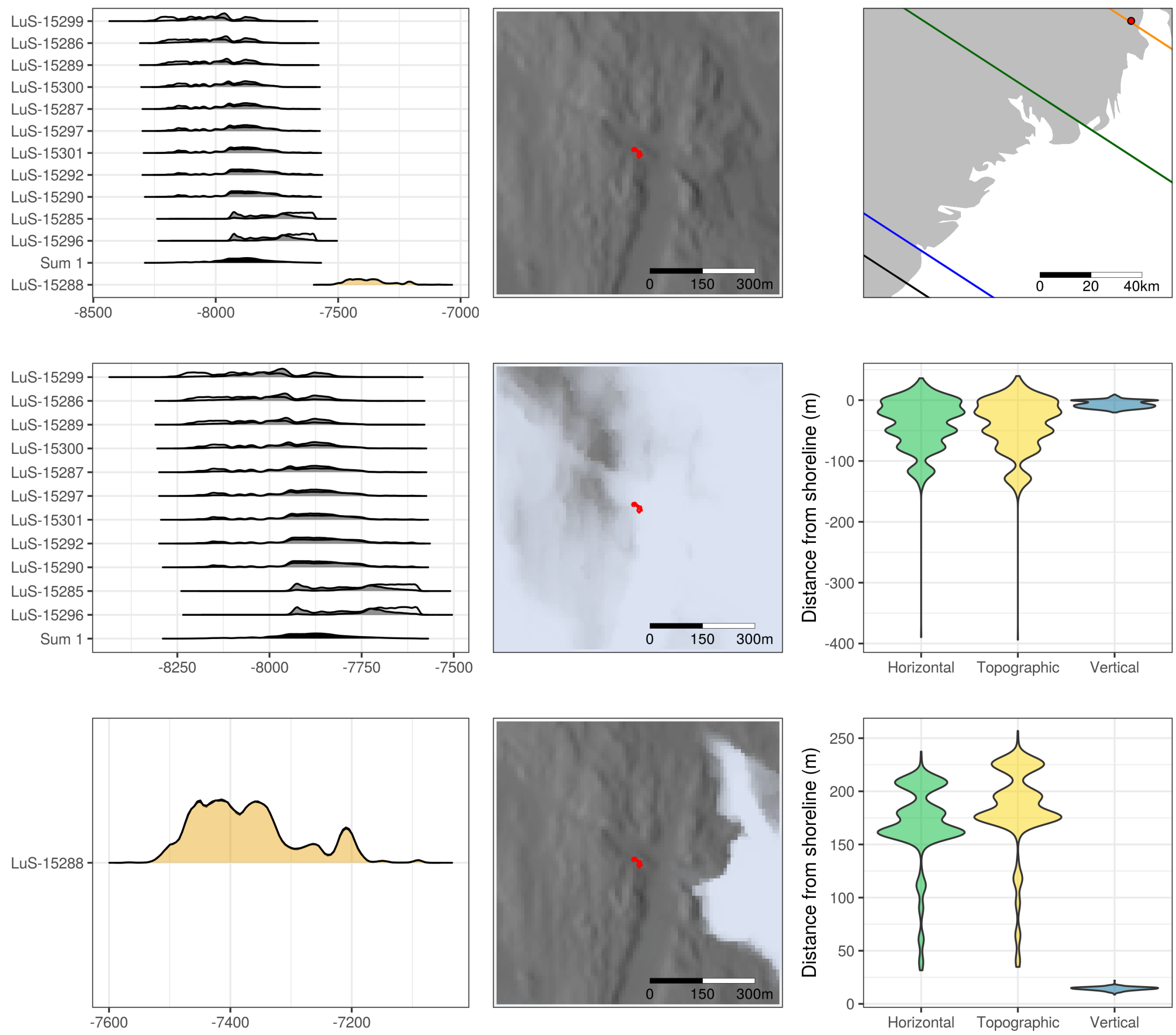
Table 39: Langemyr

ID	^{14}C BP	Error	Material	Context
Ua-52063	8853	43	Hazel (Corylus), nutshell	Quadrant (60x102y, layer 2)



Langemyr is typologically and radiometrically dated to the Middle Mesolithic (Koxvold 2018a). A construction area just south the site was removed. This is the same highway-project and raster editing that was done for some of the Hovland sites above.

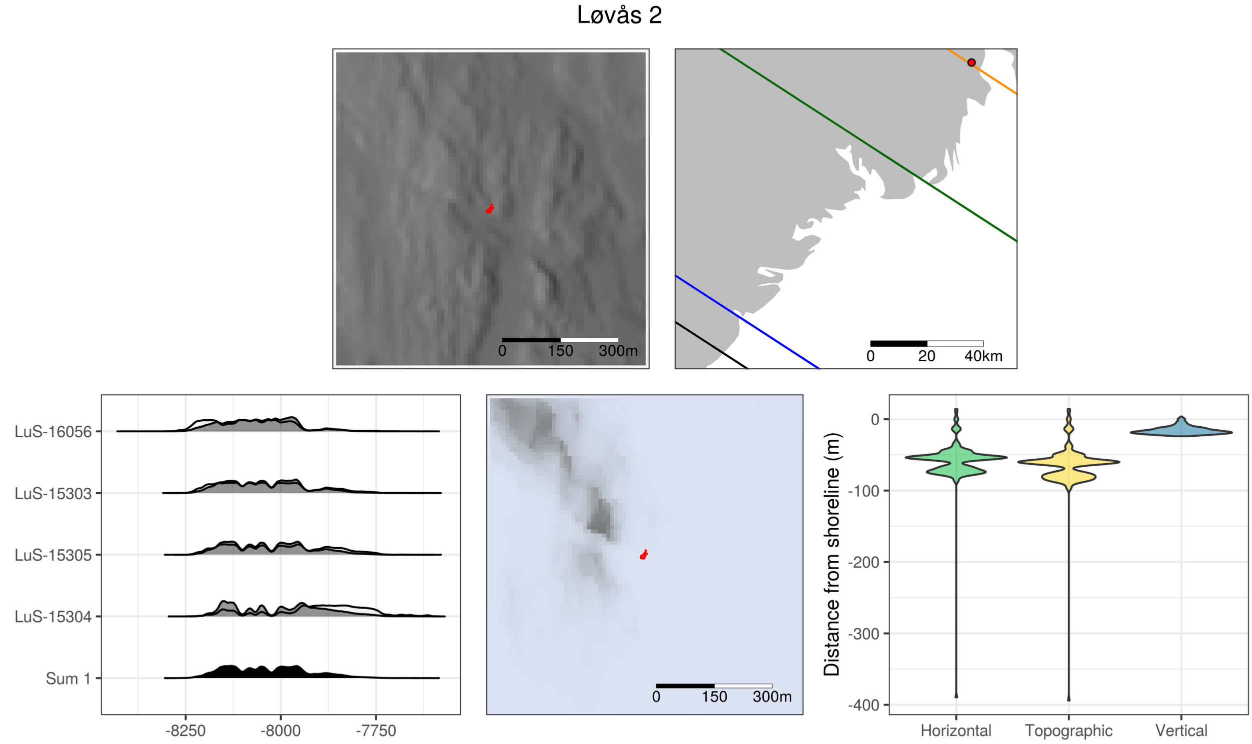
Løvås 1



The artefact inventory from Løvås 1 matches the radiocarbon dates (Reitan and Hårstad 2022). No editing of the raster appeared to be necessary. Interestingly only the Løvås sites were simulated to be situated beneath the sea-level. The typologically secure inventory combined with the many overlapping dates from various features does indicate that the issue is with the displacement curve and not the dating of the site (see also main text). Similar situation to that on Løvås 2 and 3 (below).

Table 40: Løvås 1

ID	^{14}C BP	Error	Material	Context
LuS-15299	8920	50	Hazel (Corylus), nutshell	Cultural layer (ID 50), sample (ID 100094)
LuS-15286	8880	45	Hazel (Corylus), nutshell	Cultural layer, dwelling structure? (ID 10693)
LuS-15289	8865	45	Hazel (Corylus), nutshell	Cultural layer, dwelling structure? (ID 10693)
LuS-15300	8840	45	Hazel (Corylus), nutshell	Cultural layer (ID 51), sample (ID 100097)
LuS-15287	8825	45	Hazel (Corylus), nutshell	Cultural layer, dwelling structure? (ID 10693)
LuS-15297	8815	45	Hazel (Corylus), nutshell	Fireplace (ID 26606)
LuS-15301	8805	45	Hazel (Corylus), nutshell	Cultural layer (ID 51), sample (ID 100108)
LuS-15292	8790	50	Pome fruit tree (Pomoideae)	Fireplace (ID 11838)
LuS-15290	8790	45	Pine (Pinus)	Fireplace (ID 11804)
LuS-15285	8690	45	Willow (Salix)	Fireplace (ID 8849)
LuS-15296	8675	45	Pine (Pinus)	Fireplace (ID 24085)
LuS-15288	8315	45	Willow (Salix)	Cultural layer, dwelling structure? (ID 10693)
LuS-15295	2220	35	Hazel (Corylus)	Fireplace (ID 24057)
LuS-15293	2205	40	Hazel (Corylus)	Fireplace (ID 21143)
LuS-15294	2190	40	Hazel (Corylus)	Fireplace (ID 21167)
LuS-15298	1570	35	Oak (Quercus)	Fireplace (ID 27064)
LuS-15291	875	35	Oak (Quercus)	Fireplace (ID 11818)
LuS-15302	500	35	Pine (Pinus)	Square (828x208y), sample (ID 100086)



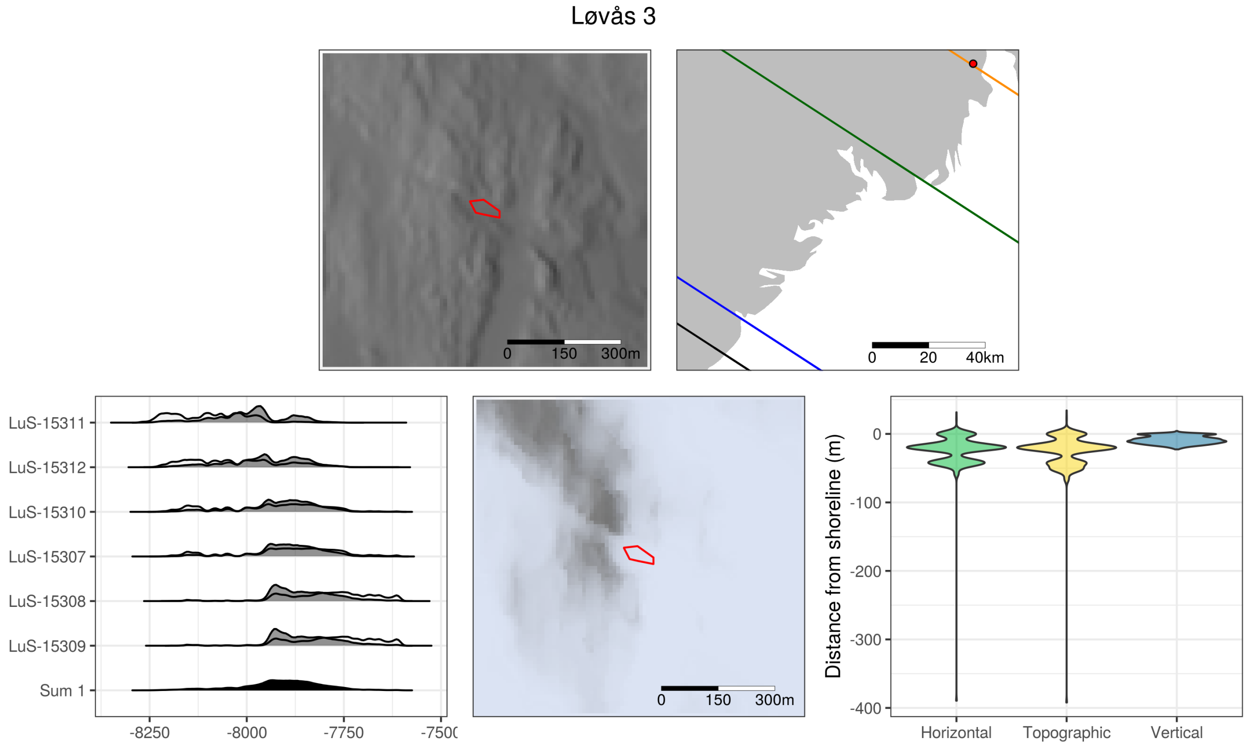
The artefact inventory from Løvås 2 matches the radiocarbon dates (Reitan and Hårstad 2022). Similar setting to that of Løvås 1 and 3 (above and below).

Table 41: Løvås 2

ID	^{14}C BP	Error	Material	Context
LuS-16056	8910	50	Burnt bone, reindeer (Rangiferus tarandus)	Square (913x202ySW, layer 1), sample (ID 100059)
LuS-15303	8870	45	Hazel (Corylus), nutshell	Square (915x203yNW, layer 2), sample (ID 100072)
LuS-15305	8850	45	Hazel (Corylus), nutshell	Square (914x203ySW, layer 2), sample (ID 100074)
LuS-15304	8805	45	Hazel (Corylus), nutshell	Square (913x206yNW, layer 2), sample (ID 100073)
LuS-15692	2355	35	Hazel (Corylus), nutshell	Square (916x208yNW, layer 1)
LuS-15690	2330	35	Hazel (Corylus), nutshell	Square (912x207yNW, layer 1)
LuS-15688	2220	35	Hazel (Corylus), nutshell	Square (911x205ySW, layer 1)
LuS-15306	2210	35	Willow (Salix)	Square (912x204yNW, layer 2), sample (ID 100075)
LuS-15689	2190	35	Hazel (Corylus), nutshell	Square (914x205ySE, layer 1)
LuS-15691	200	25	Hazel (Corylus), nutshell	Square (911x203yNW, layer 1)

Table 42: Løvås 3

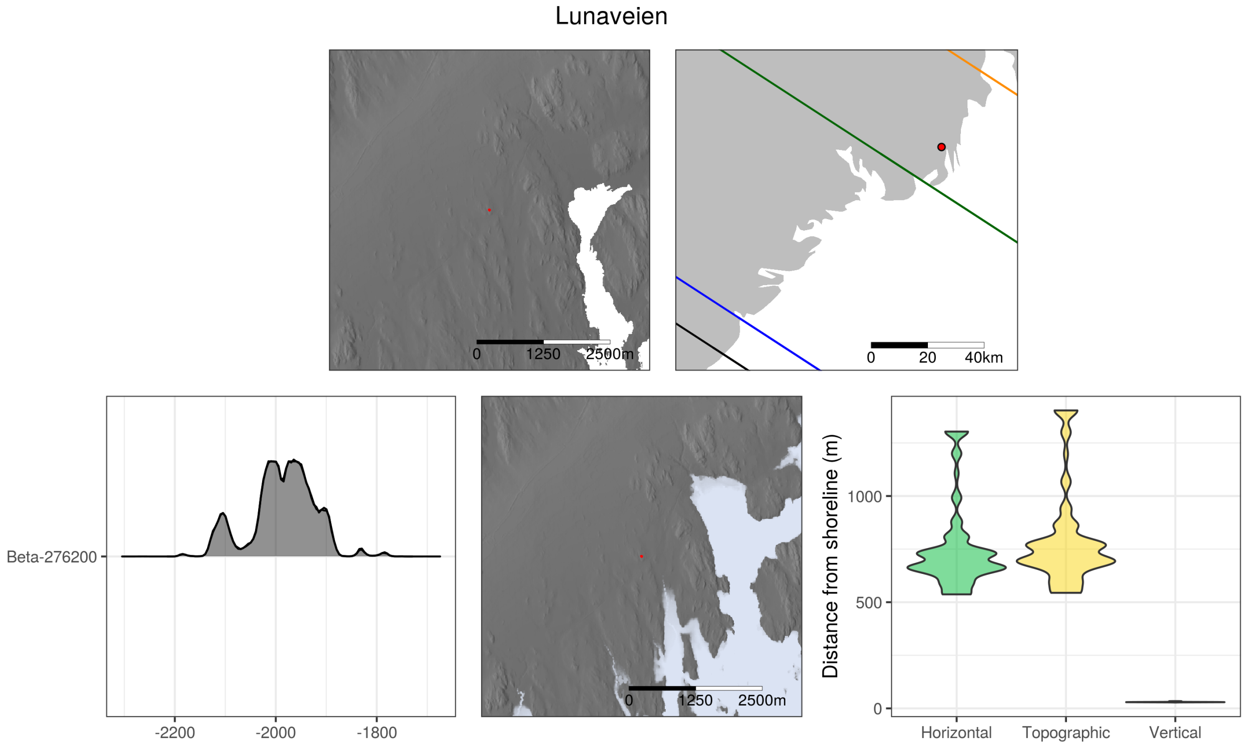
ID	^{14}C BP	Error	Material	Context
LuS-15311	8920	45	Hazel (Corylus), nutshell	Possible dwelling structure (ID 27142)
LuS-15312	8860	45	Hazel (Corylus), nutshell	Possible dwelling structure (ID 27142)
LuS-15310	8820	45	Hazel (Corylus), nutshell	Possible dwelling structure (ID 27142)
LuS-15307	8800	45	Pome fruit tree (Pomoideae)	Fireplace (ID 24176)
LuS-15308	8750	45	Aspen (Populus)	Fireplace (ID 24195)
LuS-15309	8745	45	Pome fruit tree (Pomoideae)	Fireplace (ID 24154)



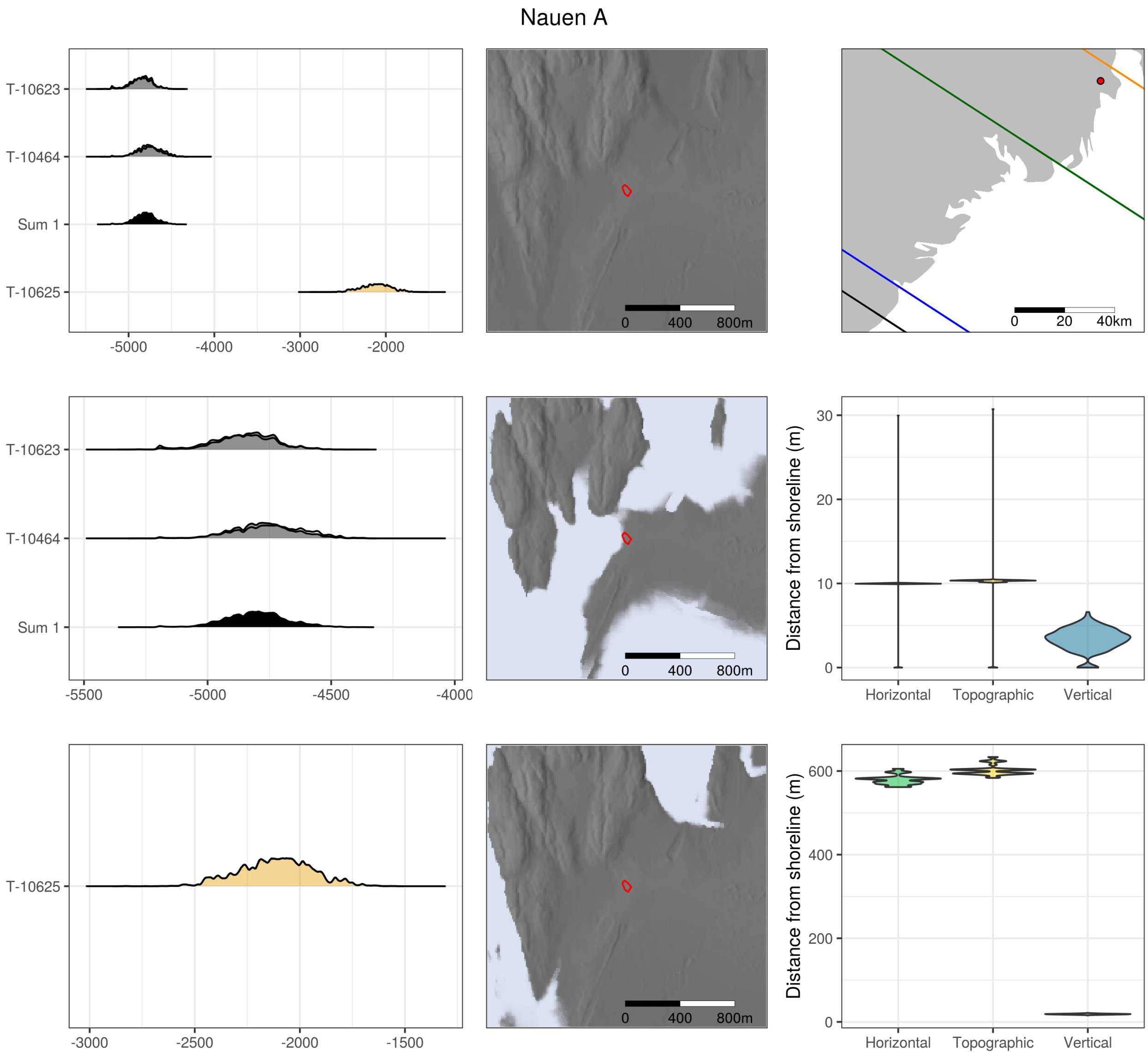
The artefact inventory from Løvås 3 matches the radiocarbon dates (Reitan and Hårstad 2022). Similar setting to that of Løvås 1 and 2 (above).

Table 43: Lunaveien

ID	^{14}C BP	Error	Material	Context
Beta-276197	1430	40	Birch (Betula)	Square (50x53y, layer 1)
Beta-276198	60	40	Pine (Pinus)	Square (50x50y, layer 1)
Beta-276199	1690	40	Birch (Betula)	Square (51x55y, layer 1)
Beta-276200	3620	40	Pine (Pinus)	Square (53x52y, layer 1)
Beta-278526	2350	40	Burnt bone	Square (50x50y, layer 2)
Beta-278527	2380	40	Burnt bone	Square (51x55y, layer 2)



Lunaveien is a grave cairn site, and the report states that it is unlikely that any of the finds relate to a settlement (Reitan 2010). The results have therefore been excluded from the aggregative analysis.



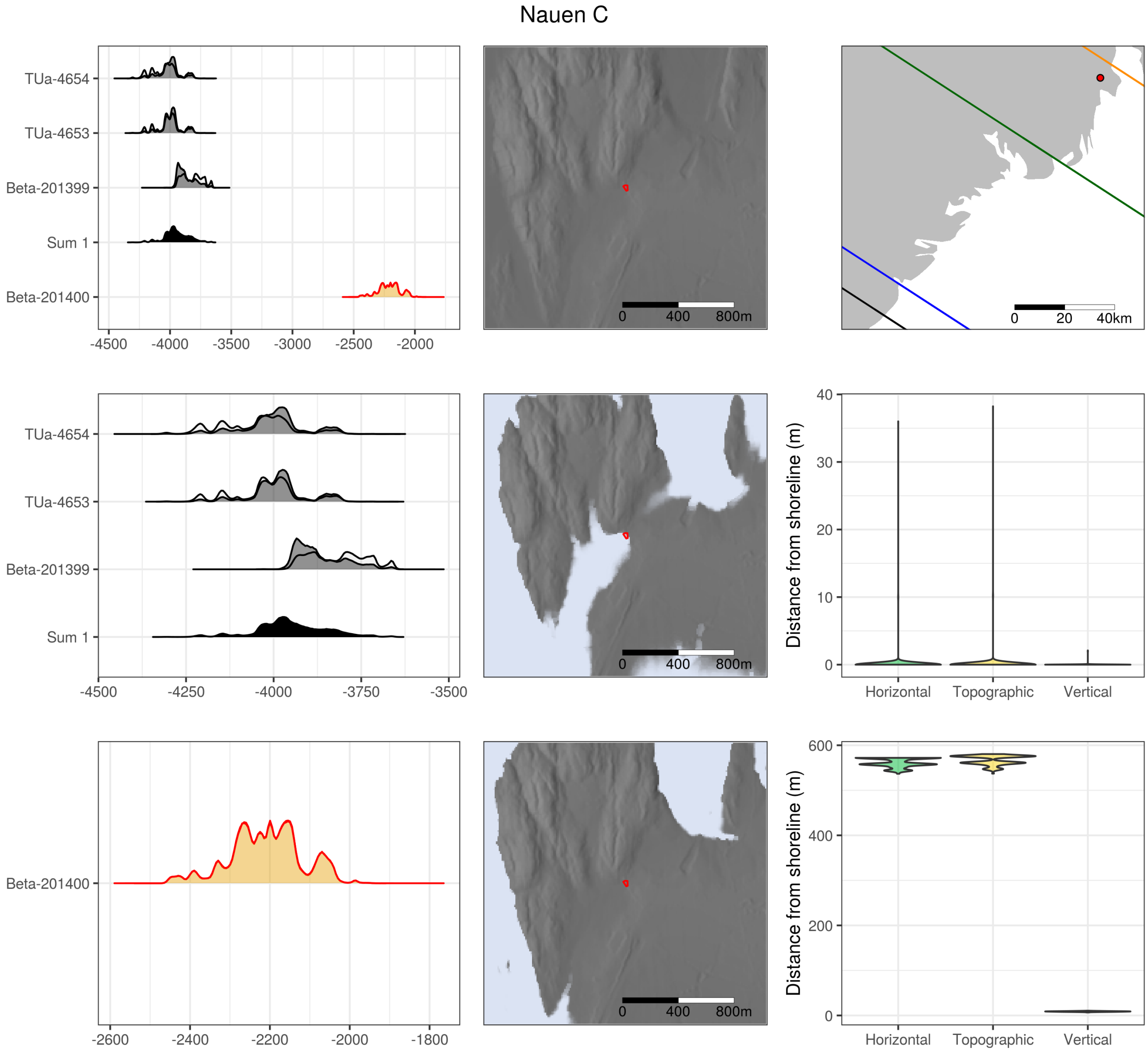
Typology of the lithic inventory on Nauen A points to a Late Mesolithic date (Persson 2008). The later date is seen as related to the establishment of a field for grazing or agriculture, which is also supported by younger dates that fall outside the analysis here. A section of the highway located a few hundred meters to the south was pre-emptively edited in the DTM. This does not appear to be relevant for the simulated sea-level.

Table 44: Nauen A

ID	^{14}C BP	Error	Material	Context
TUa-4651	3360	55	Charcoal, not specified	Undefined layer (ID 153)
Beta-204709	3020	50	Charcoal, not specified	Undefined layer (ID 156)
T-10907	1665	50	Charcoal, not specified	Unspecified
T-10463	1485	100	Charcoal, not specified	Unspecified
T-10908	1755	65	Charcoal, not specified	Unspecified
T-10622	2810	85	Charcoal, not specified	Unspecified
T-10623	5965	100	Charcoal, not specified	Unspecified
T-10624	3175	90	Charcoal, not specified	Unspecified
T-10464	5875	115	Charcoal, not specified	Unspecified
T-10625	3705	120	Charcoal, not specified	Unspecified
T-10626	875	100	Charcoal, not specified	Unspecified
T-10465	1005	155	Charcoal, not specified	Unspecified
T-10627	1000	90	Charcoal, not specified	Unspecified
T-10909	285	50	Charcoal, not specified	Unspecified
T-10628	1335	155	Charcoal, not specified	Unspecified
T-10629	1840	150	Charcoal, not specified	Unspecified
T-10466	635	150	Charcoal, not specified	Unspecified
T-10462	2925	80	Charcoal, not specified	Unspecified
T-10630	3595	110	Charcoal, not specified	Unspecified
T-10467	2235	80	Charcoal, not specified	Unspecified
T-10906	510	40	Charcoal, not specified	Grave (ID 2)
T-10906l	490	40	Charcoal, not specified	Grave (ID 2)
T-11050	2760	70	Charcoal, not specified	Concentration, stone? (ID 47)
TUa-4652	2765	35	Charcoal, not specified	Transect (ID 630)

Table 45: Nauen C

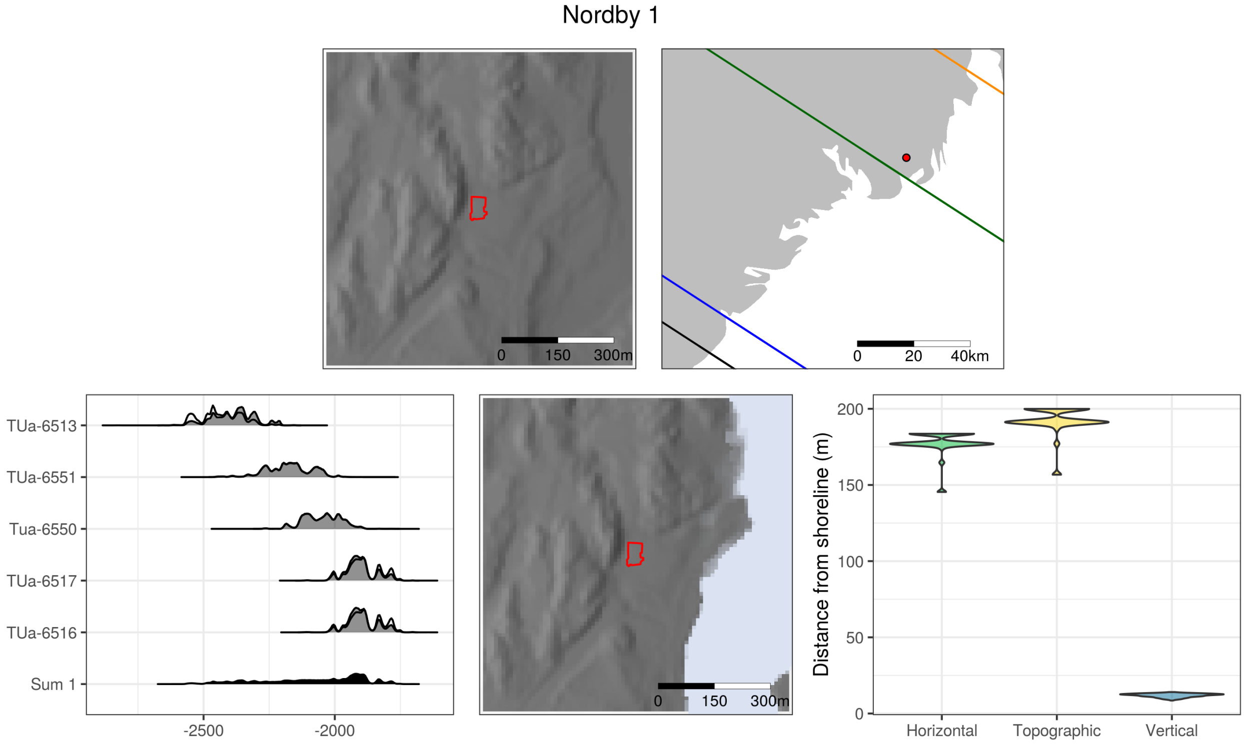
ID	^{14}C BP	Error	Material	Context
TUa-4653	5190	60	Charcoal, not specified	Unspecified
TUa-4654	5210	70	Charcoal, not specified	Possible tree throw (ID 2/4)
Beta-201399	5020	50	Charcoal, not specified	Possible tree throw (ID 2/4)
Beta-201400	3780	50	Charcoal, not specified	Possible tree throw (ID 2/4)
T-17050	3525	110	Charcoal, not specified	Possible tree throw (ID 2/4)
Beta-201401	2360	40	Charcoal, not specified	Undefined feature (ID 1)



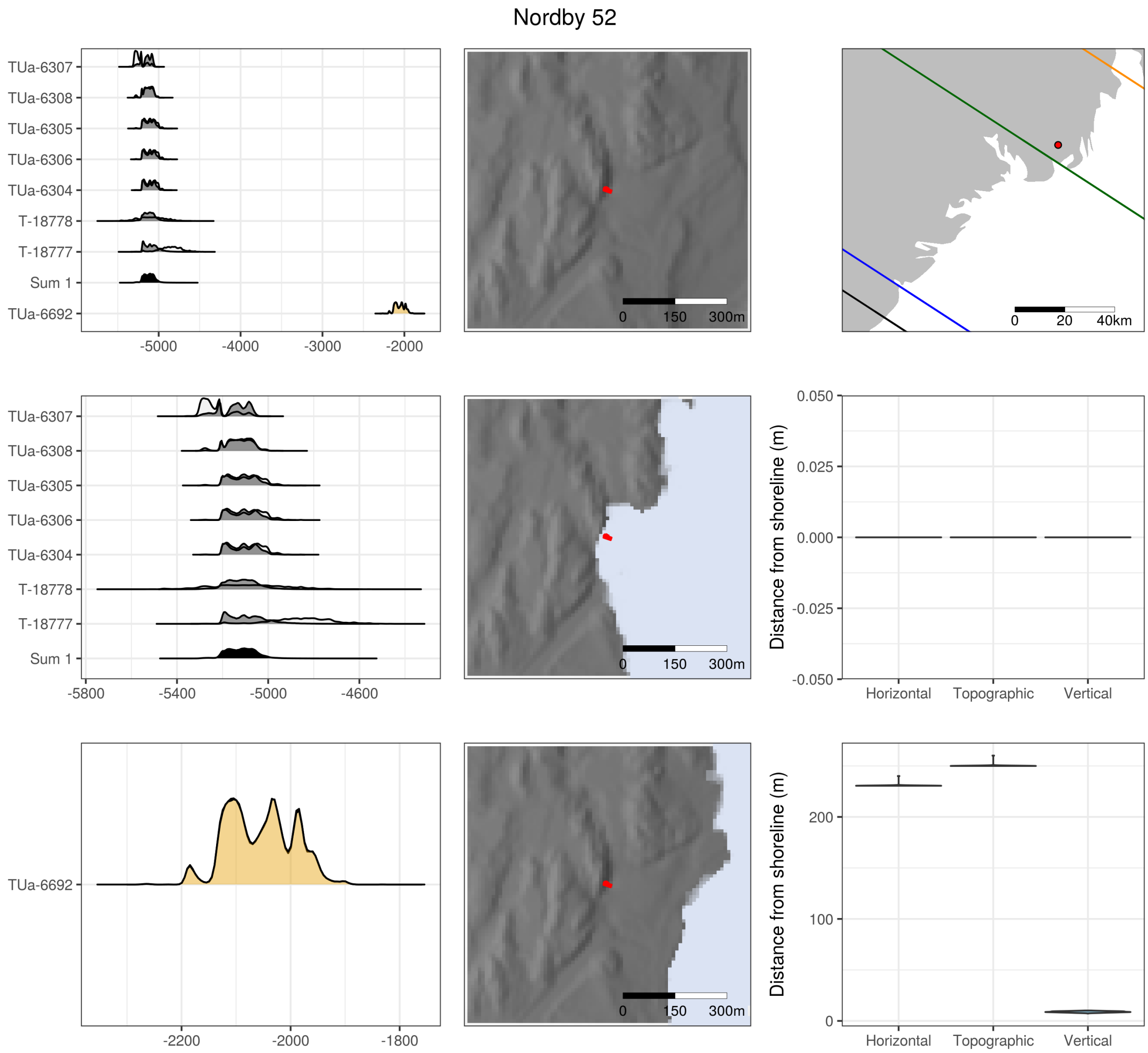
The typological indicators of the lithic inventory from Nauen C match the earliest dates (Persson 2008). As with Nauen A, above, the DTM was edited pre-emptively and does not appear to have been necessary.

Table 46: Nordby 1

ID	^{14}C BP	Error	Material	Context
TUa-6513	3945	45	Hazel (Corylus), nutshell	Post hole, house 4 (ID 35188)
Tua-6550	3665	45	Oak (Quercus)	Post hole, house 4 (ID 35191)
TUa-6555	2025	30	Plant remains, unspecified	Post hole, house 3 (ID 35082)
TUa-6511	1805	35	Barley (Hordeum vulgare)	Post hole, house 3 (ID 35081)
TUa-6556	1595	45	Charcoal, unspecified	Post hole, house 3 (ID 35036)
TUa-6551	3760	50	Deciduous (Decid, indet.)	Post hole, house 2 (ID 35086)
TUa-6558	3385	45	Oak (Quercus)	Post hole, house 2 (ID 35091)
TUa-6557	3340	45	Oak (Quercus)	Post hole, house 2 (ID 35099)
Beta-238363	3250	40	Cereal, unspecified	Post hole, house 2 (ID 35115, 35028)
TUa-6517	3555	35	Barley (Hordeum vulgare)	Post hole, house 1 (ID 35047)
TUa-6518	3465	35	Barley (Hordeum vulgare)	Post hole, house 1 (ID 35063)
TUa-6516	3550	35	Barley (Hordeum vulgare)	Post hole, house 1 (ID 35056)
Beta-234329	750	40	Birch (Betula)	Post hole, house 1 (ID 35047)
Tua-4412	940	50	Oak (Quercus)	Undefined feature (ID 35074)
Tua-6301	3300	25	Birch/ash (Betula/Fraxinus)	Undefined feature (ID 35064)
T-18774	740	75	Birch/hazel (Betula/Corylus)	Undefined feature (ID 35054)
Tua-6302	2575	25	Birch/ash (Betula/Fraxinus)	Cooking pit (ID 35141)
T-18773	845	75	Pine (Pinus)	Cooking pit (ID 35013)
T-18772	1925	100	Birch/hazel (Betula/Corylus)	Fireplace (ID 35006)



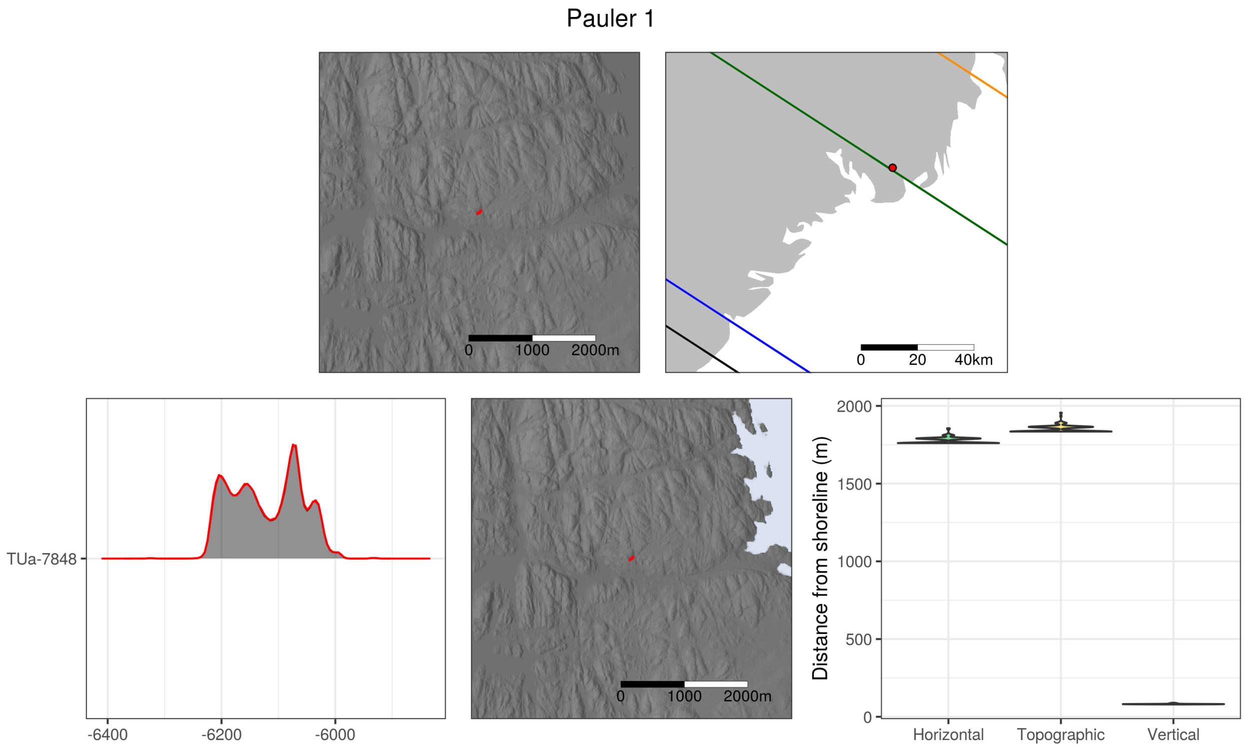
Nordby 1 is dated to the Late Neolithic, Bronze Age and Early Iron Age (Gjerpe and Bukkemoen 2008a) with long-house 4 dated to the Late Neolithic. Lithics and pottery finds support the ^{14}C-dates. The site located on what is today a highway which was edited also for Nordby 52 (below), but is not relevant for the sea-level reconstruction for Nordby 1.



Nordby 52 is a rock-shelter that has been visited throughout prehistory (Gjerpe and Bukkemoen 2008b). The site has a clear typological date to both of the Stone Age periods defined by the ^{14}C-dates treated here. The site is located by where the highway runs today (see also Nordby 1 above). Edit appears to have been successful.

Table 47: Nordby 52

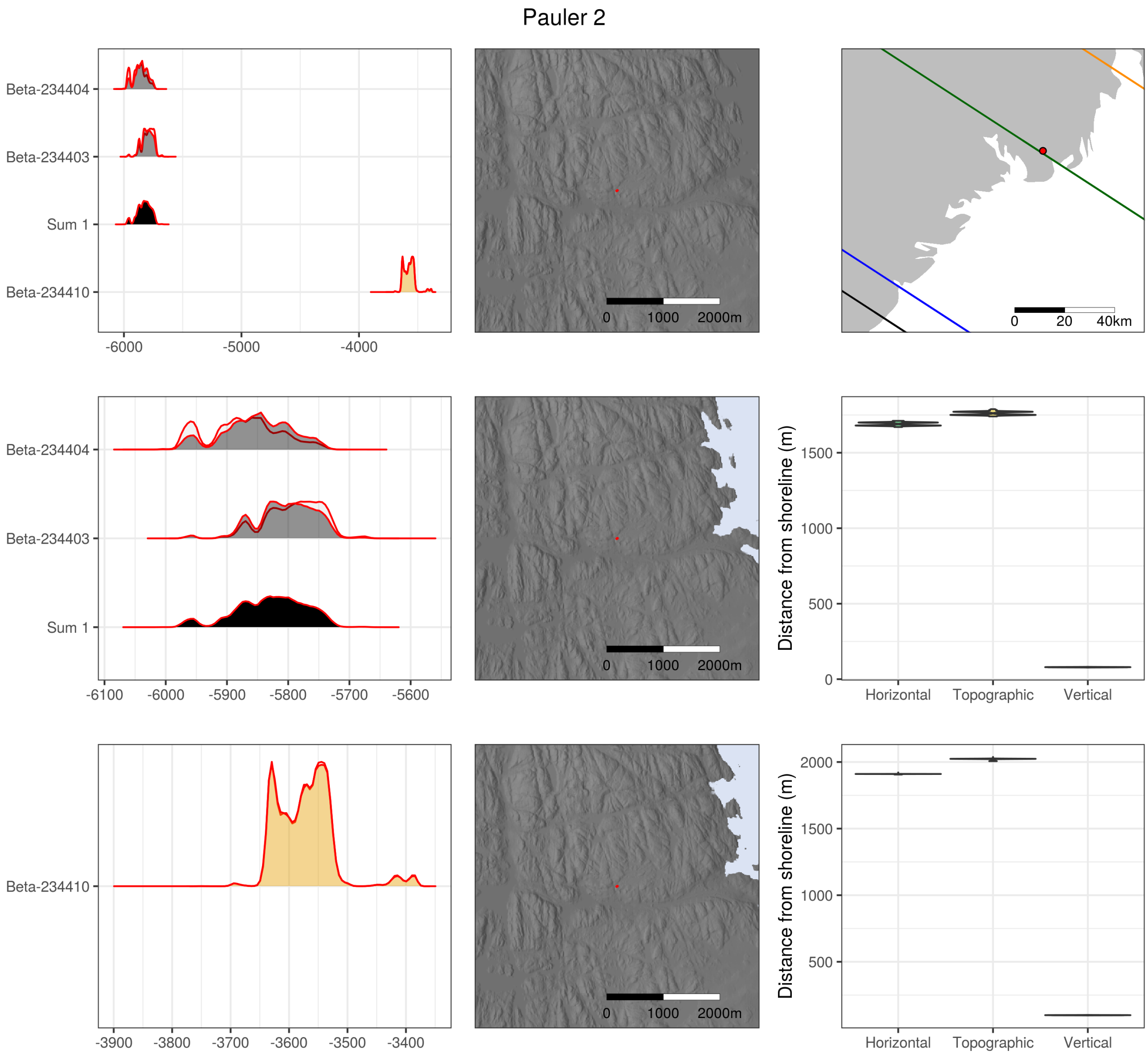
ID	^{14}C BP	Error	Material	Context
TUa-6308	6190	35	Charcoal, not specified	Fireplace? (ID 35136)
TUa-6307	6260	35	Charcoal, not specified	Fireplace? (ID 35185)
T-18777	5960	100	Charcoal, not specified	Fireplace (ID 35211)
TUa-6306	6140	40	Charcoal, not specified	Fireplace (ID 35212)
T-18778	6155	130	Charcoal, not specified	Cooking pit/fireplace (ID 35213)
TUa-6304	6140	35	Charcoal, not specified	Fireplace (ID 35215)
TUa-6305	6150	40	Charcoal, not specified	Fireplace? (ID 35216)
T-18775	2350	85	Charcoal, not specified	Fireplace (ID 35002)
T-18776	2490	105	Charcoal, not specified	Fireplace (ID 35125)
TUa-6303	610	25	Charcoal, not specified	Forge (ID 35217)
T-18779	505	75	Charcoal, not specified	Forge (ID 35217)
TUa-6694	3120	35	Burnt bone, harbour seal (Phoca vitulina)	Unspecified excavation unit
TUa-6692	3670	35	Burnt bone, mammal indet.	Unspecified excavation unit



Pauler 1 has a distinctly Early Mesolithic artefact inventory that is not related to the ^{14}C-dates (Schaller Åhrberg 2012).

Table 48: Pauler 1

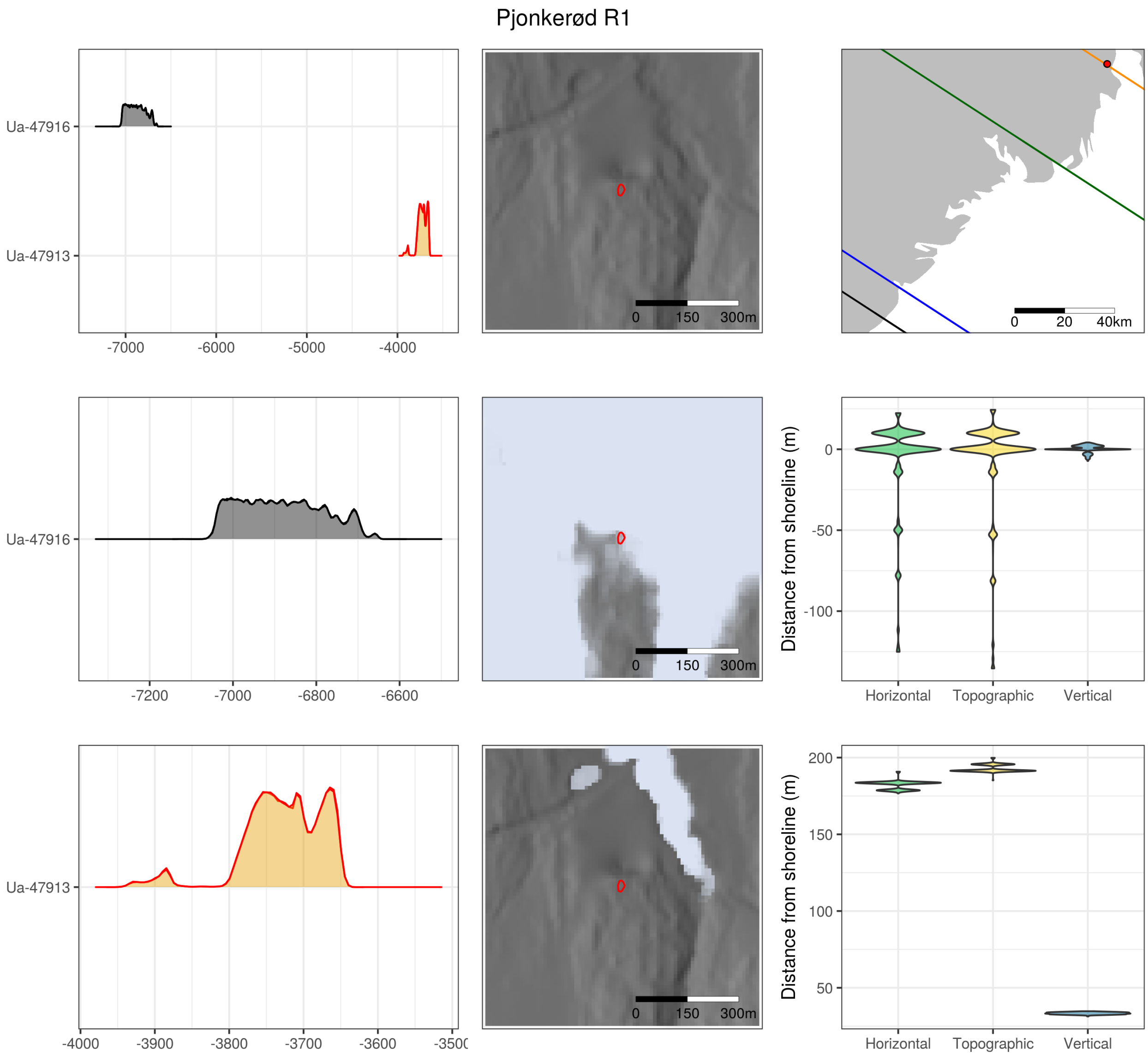
ID	^{14}C BP	Error	Material	Context
Beta-234411	3460	40	Pine (Pinus)	Fireplace (ID 1)
Beta-234412	910	40	Pine (Pinus)	Fireplace (ID 1)
Beta-234413	960	40	Birch (Betula)	Fireplace (ID 1)
Beta-234414	910	40	Deciduous (Decid, indet.)	Fireplace (ID 1)
TUa-7848	7245	45	Pine (Pinus)	Fireplace/Burnt root (ID 15)



As with Pauler 1 (above), Pauler 2 has a distinctly Early Mesolithic artefact inventory that is not related to the ^{14}C-dates (Nyland 2012a).

Table 49: Pauler 2

ID	^{14}C BP	Error	Material	Context
Beta-234403	6910	40	Hazel (Corylus), nutshell	Fireplace (ID 1)
Beta-234404	6990	40	Pine (Pinus)	Fireplace (ID 1)
Beta-234407	3260	40	Pine (Pinus)	Fireplace (ID 1)
Beta-234410	4800	40	Pine (Pinus)	Fireplace (ID 1)
Beta-234409	1440	40	Oak (Quercus)	Fireplace (ID 1)
Beta-234408	900	40	Birch (Betula)	Fireplace (ID 1)
Beta-234405	870	40	Birch (Betula)	Fireplace (ID 2)
Beta-234406	300	40	Pine (Pinus)	Fireplace (ID 2)



The lithic inventory from Pjonkerød R1 is consistent with the ^{14}C-date (Carrasco 2015). The site is situated

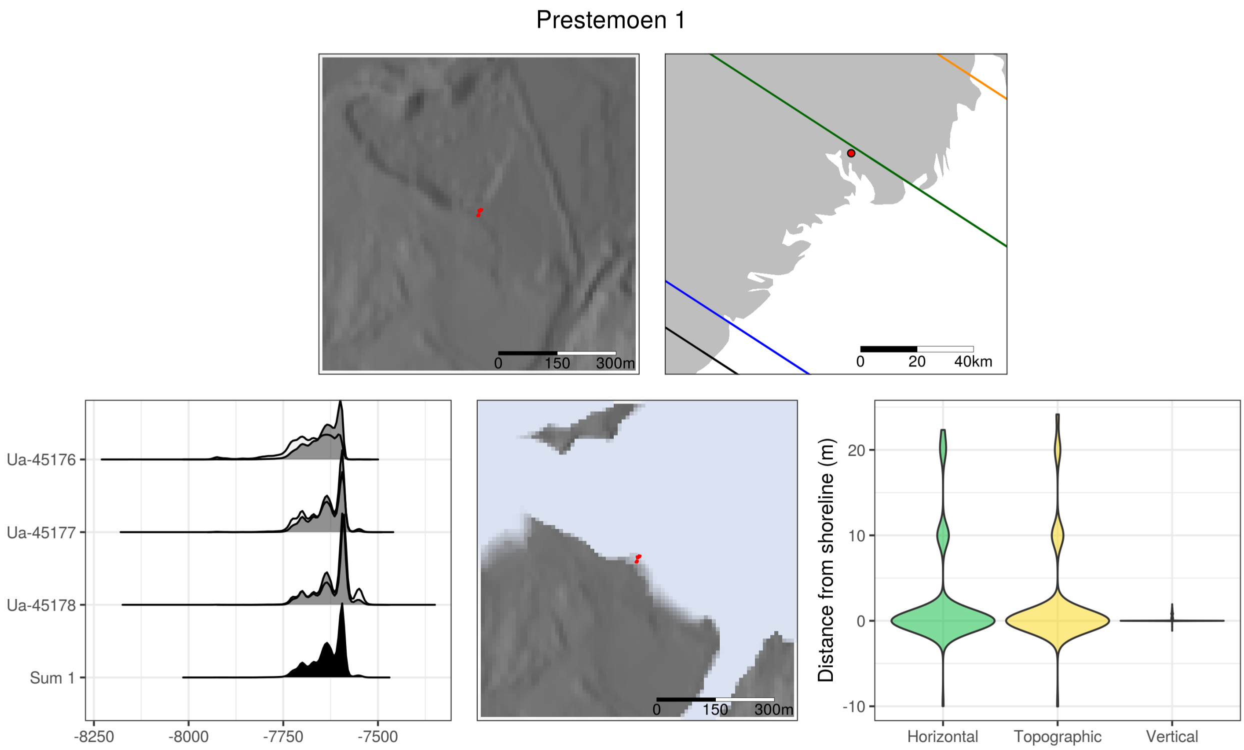
Table 50: Pjonkerød R1

ID	^{14}C BP	Error	Material	Context
Ua-47916	7970	44	Burnt bone	Quadrant 50x50x10 (112x51y NE, layer 2)
Ua-47914	3178	32	Pine (Pinus)	Undefined feature (ID 2001)
Ua-47915	3117	31	Pine (Pinus)	Cooking pit (ID 2002)
Ua-47917	1373	30	Oak (Quercus)	Cooking pit (ID 2007)
Ua-47913	4959	34	Pine (Pinus)	Undefined feature (ID 2001)

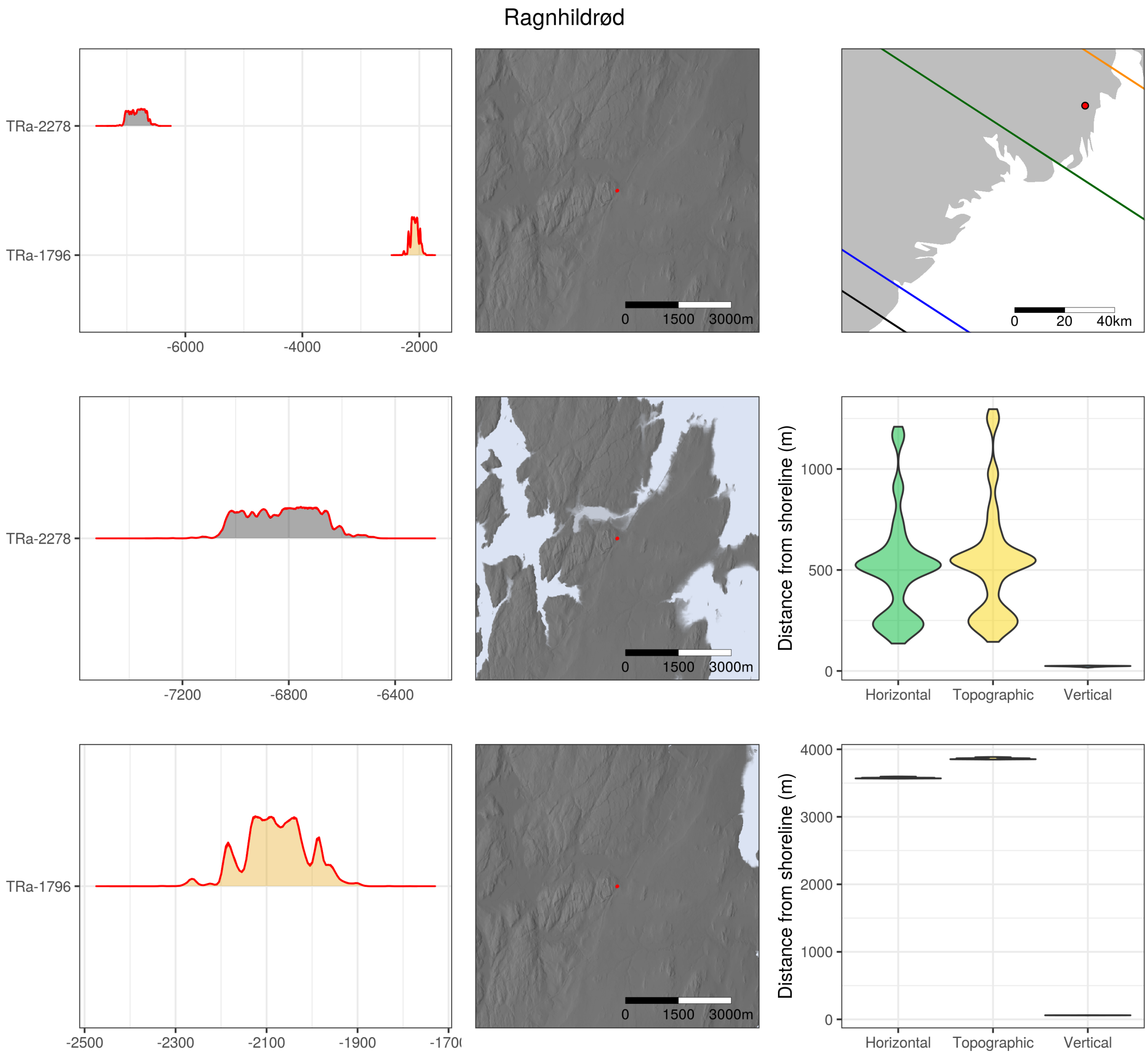
Table 51: Prestemoen 1

ID	^{14}C BP	Error	Material	Context
Ua-45176	8671	45	Hazel (Corylus), nutshell	Square (620x149y, layer 6)
Ua-45177	8620	45	Burnt bone	Square (620x149y, layer 6)
Ua-45178	8593	46	Hazel (Corylus), nutshell	Square (620x149y, layer 8)

by a large gravel pit today, which has been fairly successfully edited. However, as the few negative values in the results are likely to result from the interpolation process and the fact that this is a quite large area, as opposed to issues with the displacement curves or ^{14}C-dates, the negative values were forced to zero for the aggregative analysis.



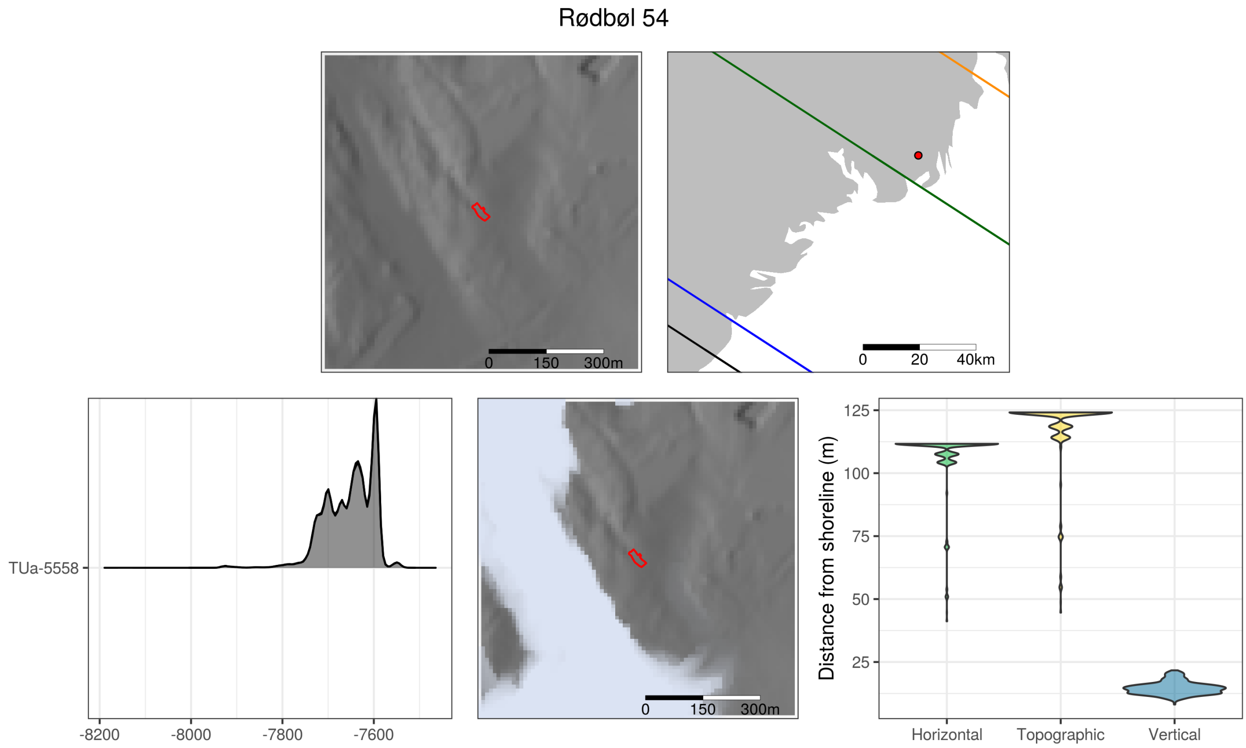
Prestemoen 1 has a lithic inventory consistent with the ^{14}C-dates (Persson 2014a). The site is situated by a gravel pit that is clearly visible on the DTM to the north-east of the site. This was not edited as it has not impacted the simulated distance between site and sea. The landscape surrounding the site would, however, have been very different in the Mesolithic (Persson 2014a:Figure 10.20).



The earliest ^{14}C-date, from an uncertain context, is argued to be younger and not match the typological indicators in the inventory from Ragnhildrød (Mjærum 2012:50, 71). The post-hole dated to the Late Neolithic/Bronze Age could be related to a single find of a pressure flaked object, but was not given much weight in the report (Mjærum 2012:76).

Table 52: Ragnhildrød

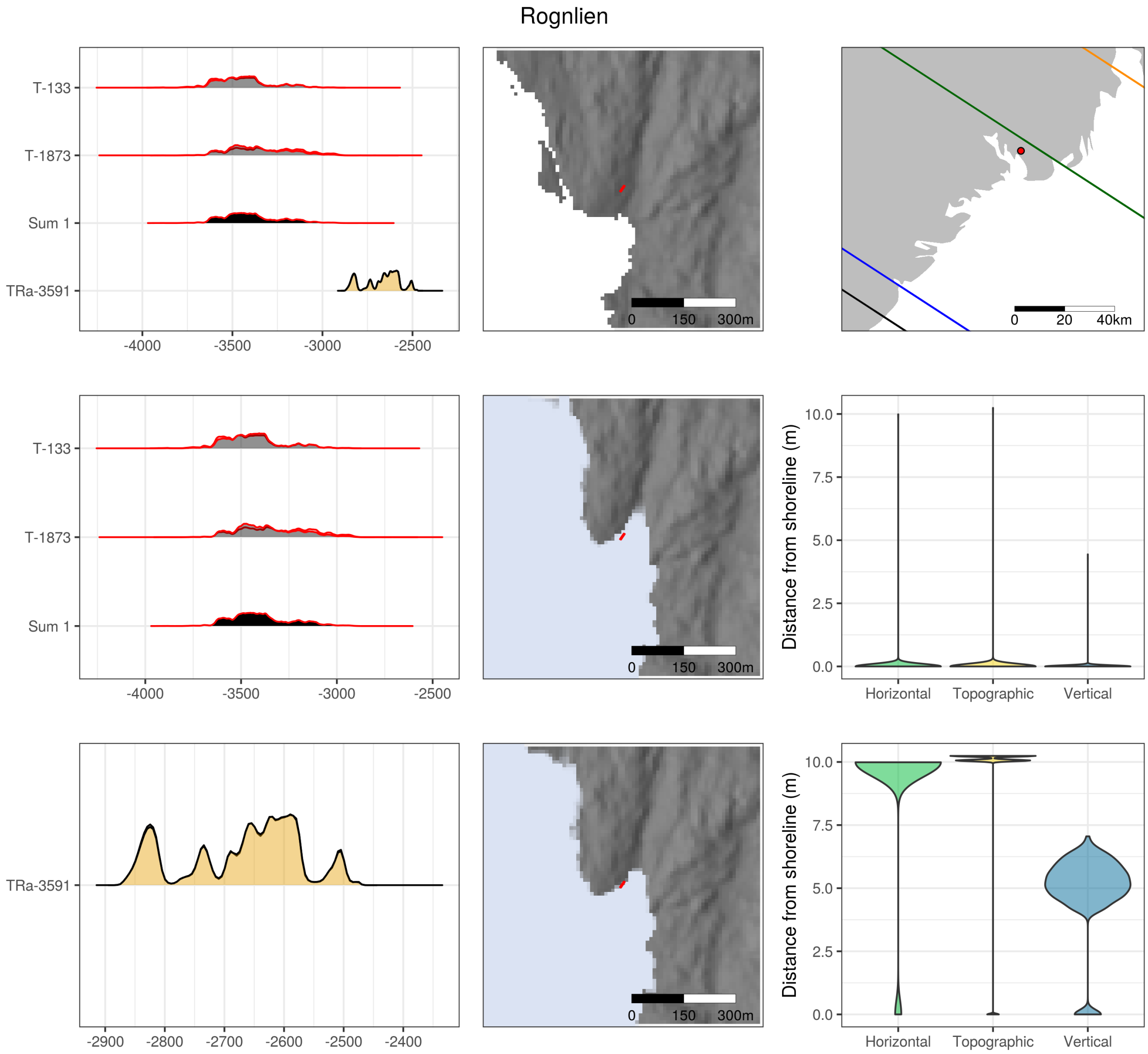
ID	^{14}C BP	Error	Material	Context
TRa-2278	7915	90	Oak (Quercus)	Layer, dwelling entry-way (ID 1351061)
TRa-1796	3690	45	Hazel (Corylus)	Post hole (ID 1350035)
UBA-17796	2926	22	Hazel (Corylus), nutshell	Post hole (ID 1350035)
TRa-1120	2325	40	Hazel (Corylus)	Cooking pit (ID 1350020)
TRa-1124	2285	35	Hazel (Corylus)	Cooking pit (ID 1351121)
UBA-17797	2275	28	Hazel (Corylus), nutshell	Cooking pit (ID 1351087)
TRa-1123	2225	55	Hazel (Corylus)	Fireplace (ID 1350026)
UBA-17800	2220	24	Hazel (Corylus)	Floor layer (ID 1351069)
TRa-1798	2195	40	Hazel (Corylus)	Cooking pit (ID 1351087)
TRa-1795	2190	30	Hazel (Corylus)	Cooking pit (ID 1350015)
TRa-1125	2185	45	Hazel (Corylus)	Outer wall ditch (ID 1351134)
UBA-17795	2170	43	Hazel (Corylus)	Cooking pit (ID 1350020)
TRa-1118	2140	40	Hazel (Corylus)	Cooking pit (ID 1350017)
TRa-1121	2130	40	Hazel (Corylus)	Fireplace (ID 1351071)
TRa-1799	1945	30	Hazel (Corylus)	Fireplace (ID 1351127)
TRa-1122	1660	45	Birch (Betula)	Fireplace (ID 1351057)
UBA-17799	1533	33	Hazel (Corylus)	Fireplace (ID 1351127)
TRa-1117	810	40	Beech (Fagus)	Fireplace (ID 1350004)



Lithic inventory match the ^{14}C-date from Rødbøl 54 (Mansrud 2008). The site is situated where the highway runs today, which required editing and which is deemed to have been successful.

Table 53: Rødbøl 54

ID	^{14}C BP	Error	Material	Context
TUa-5558	8630	45	Hazel (Corylus), nutshell	Fireplace (ID 20013)
TUa-6053	1770	30	Birch (Betula)	Fireplace (ID 20019)
T-18456	1715	55	Birch (Betula)	Cooking pit (ID 20057)
T-18454	1610	70	Birch/hazel (Betula/Corylus)	Cooking pit (ID 20005)



The first archaeological finds from Rognlien were done in the 1880s and, following some smaller investigations, was excavated by Ingstad (1970) in 1957. The site limit has been manually defined based on the description given in the publication and the spatial geometry of the site as defined in the database Askeladden (Norwegian Directorate for Cultural Heritage 2018). The manually defined limit could be slightly off, but should match the elevation of the site given in the publication (Ingstad 1970:26). The ^{14}C-dates from the original excavation

Table 54: Rognlien

ID	^{14}C BP	Error	Material	Context
T-133	4700	120	Charcoal, unspecified	Unspecified excavation unit
T-1873	4600	130	Charcoal, unspecified	Unspecified excavation unit
TRa-3591	4090	35	Burnt bone, elk (Alces alces)	Unspecified excavation unit

was not seen as contemporaneous with the lithic material on the site. Burnt elk bone from the original excavation was therefore recently subjected to radiocarbon dating and is believed to match the occupation of the site (pers.comm. Steinar Solheim, also provided in Stokke 2017:24). Given the 0m distance that the older dates give here, however, there does not appear to be grounds on which to reject the older dates based on sea-level change.

Sagene B1

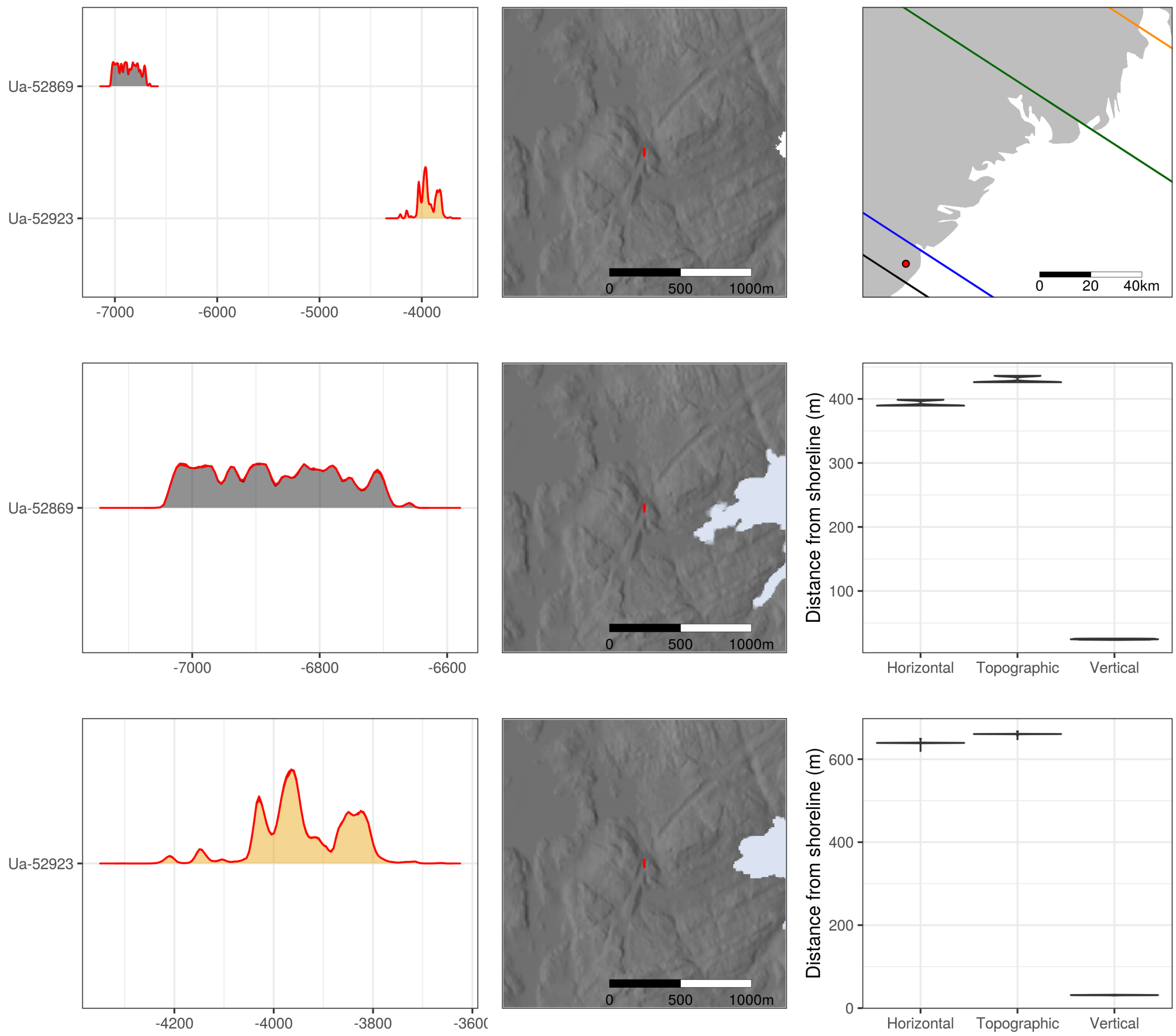


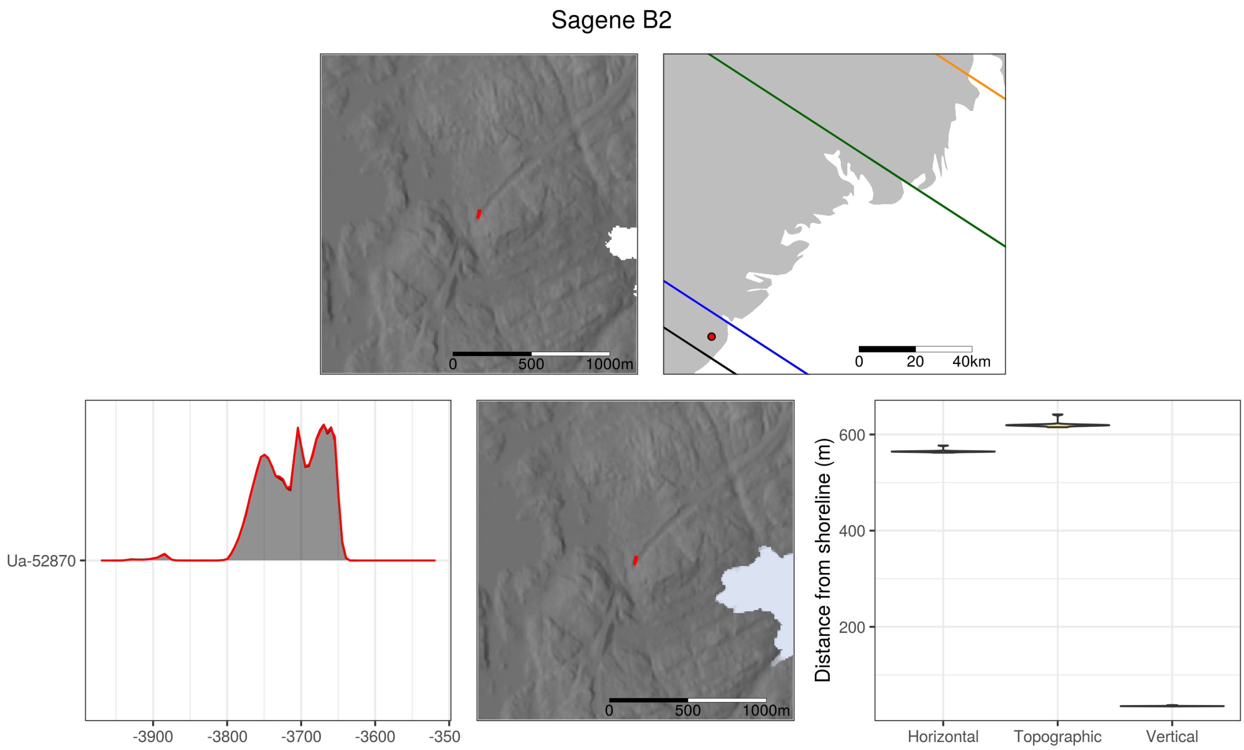
Table 55: Sagene B1

ID	^{14}C BP	Error	Material	Context
Ua-52869	7954	32	Pine (Pinus),	Post-hole (ID 456141)
Ua-52923	5150	58	Deciduous (Decid, indet.)	Post-hole (ID 456149)
Ua-52868	3352	27	Pine (Pinus)	Post-hole (ID 456132)
Ua-52866	2254	43	Ash (Fraxinus)	Fireplace (ID 454792)
Ua-52867	1766	47	Coniferous (Conif. indet.), cone seed scale	Floor layer (ID 451586)

Table 56: Sagene B2

ID	^{14}C BP	Error	Material	Context
Ua-52870	4946	29	Deciduous (Decid, indet.)	Tree throw (ID 503080)
Beta-411673	2640	30	Pine (Pinus)	Cooking pit (ID 500001)
Beta-411674	2460	30	Birch (Betula)	Cooking pit (ID 500001)
Ua-52924	1305	51	Coniferous (Conif. indet.), cone	Tree throw (ID 503080)

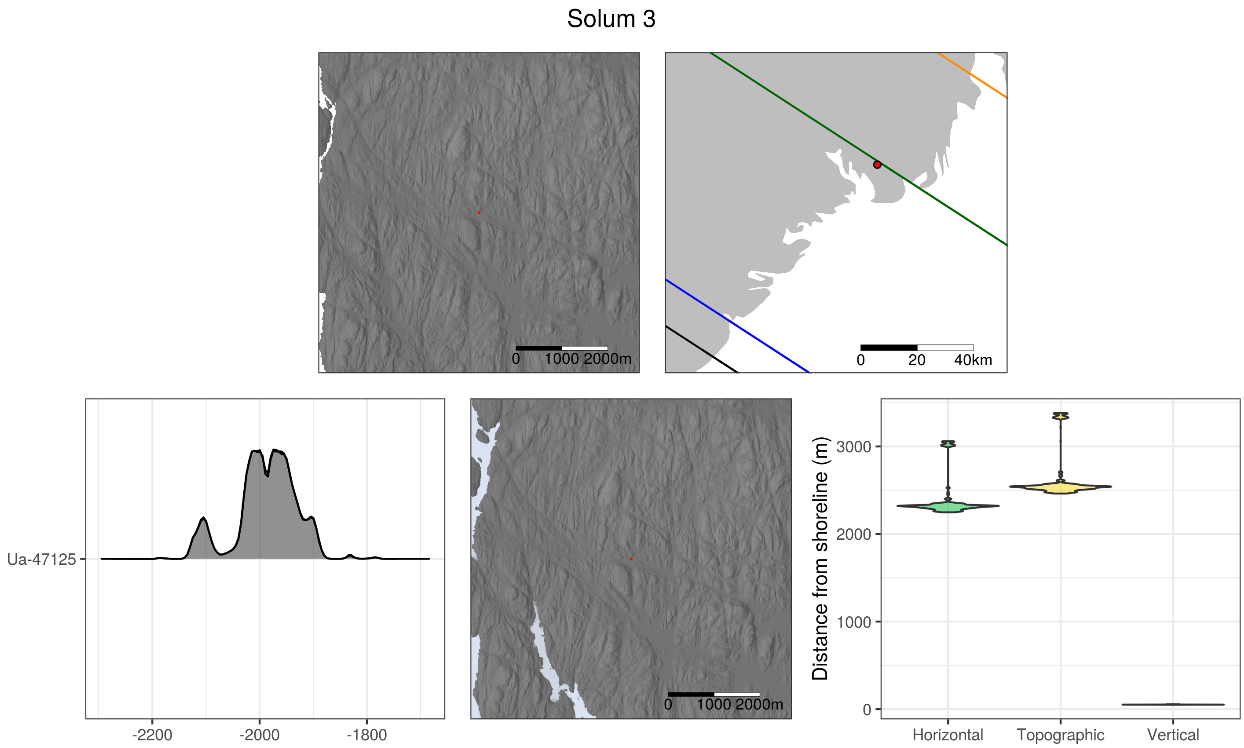
^{14}C-dates from Sagene B1 do not match the Early Mesolithic inventory of the site (Viken 2018c). The wide discrepancy of the dates from the the post-holes also led Viken (2018c) to suggest that these features might actually be non-anthropogenic and that they could instead be related to trees that have grown on the site.



The ^{14}C-dates from Sagene B2 do not match the clearly Early Mesolithic inventory of the site (Darmark 2018b).

Table 57: Solum 3

ID	^{14}C BP	Error	Material	Context
Ua-45179	3039	31	Hazel (Corylus)	Undefined feature/wooden construction (ID 350)
Ua-47125	3622	34	Burnt bone (1.4g)	Undefined feature/wooden construction (ID 350)



Solum 3 is a Late Neolithic and Early Bronze Age site, with ^{14}C-dates matching the lithic inventory (Fossum 2014b).

Table 58: Stokke/Polland 1

ID	^{14}C BP	Error	Material	Context
Ua-48259	5353	101	Hazel (Corylus)	Cooking pit (ID 22029)
Ua-48260	192	30	Spruce (Picea)	Charcoal clamp (ID 18176/22964)
Ua-48261	88	31	Spruce (Picea)	Cooking pit (ID 10537)
Ua-48264	4911	39	Elm (Ulmus)	Cooking pit (ID 18358)
Ua-48263	1514	30	Birch (Betula)	Undefined feature (ID 21259)
Ua-48262	4583	38	Willow (Salix)	Cooking pit (ID 22994)
Ua-48265	4667	39	Hazel (Corylus)	Undefined feature (ID 21238)
Ua-48266	1549	30	Birch (Betula)	Undefined feature (ID 15546)
Beta-359783	2960	30	Hazel (Corylus), nutshell	Tree throw (ID 1568)

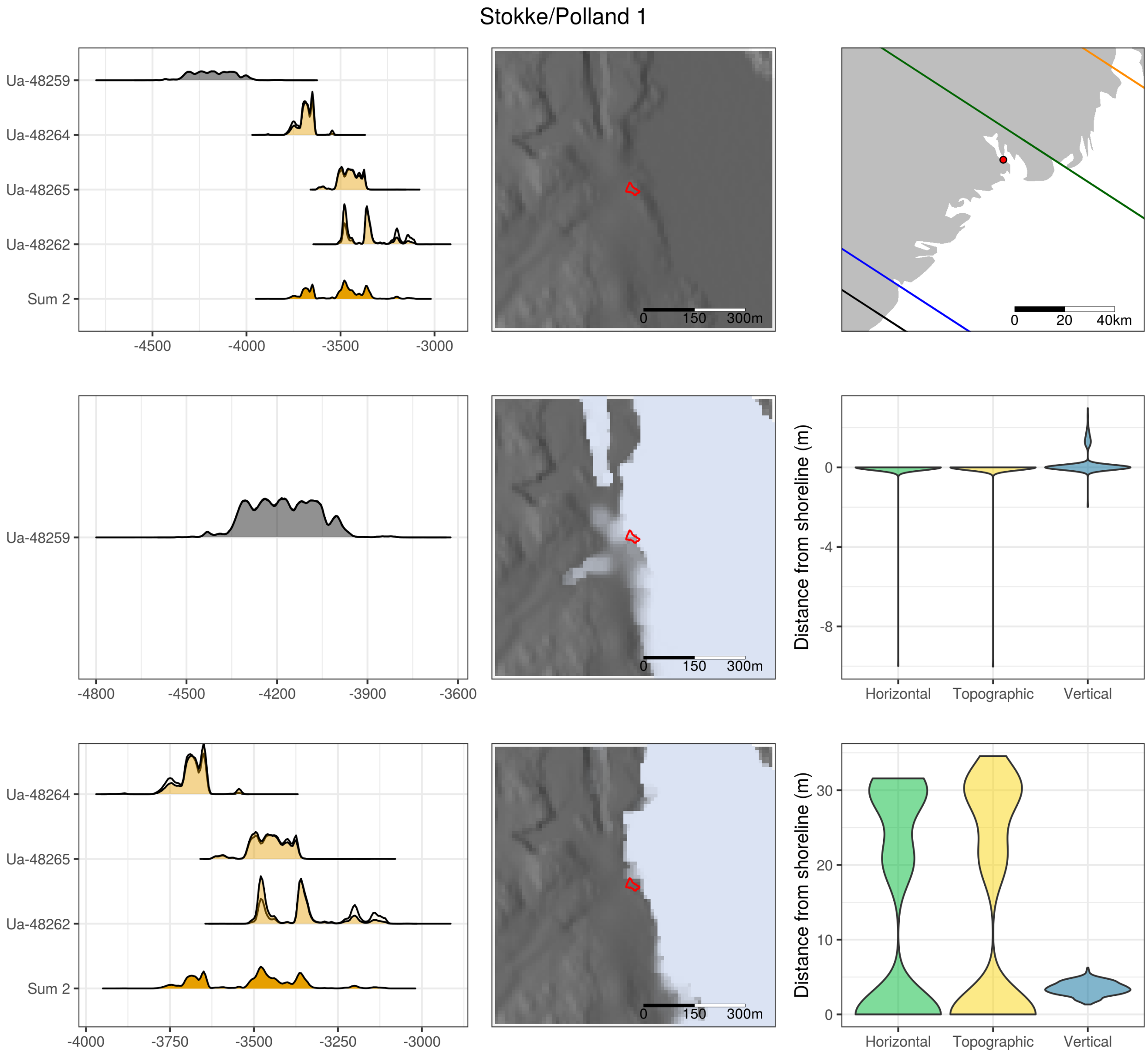
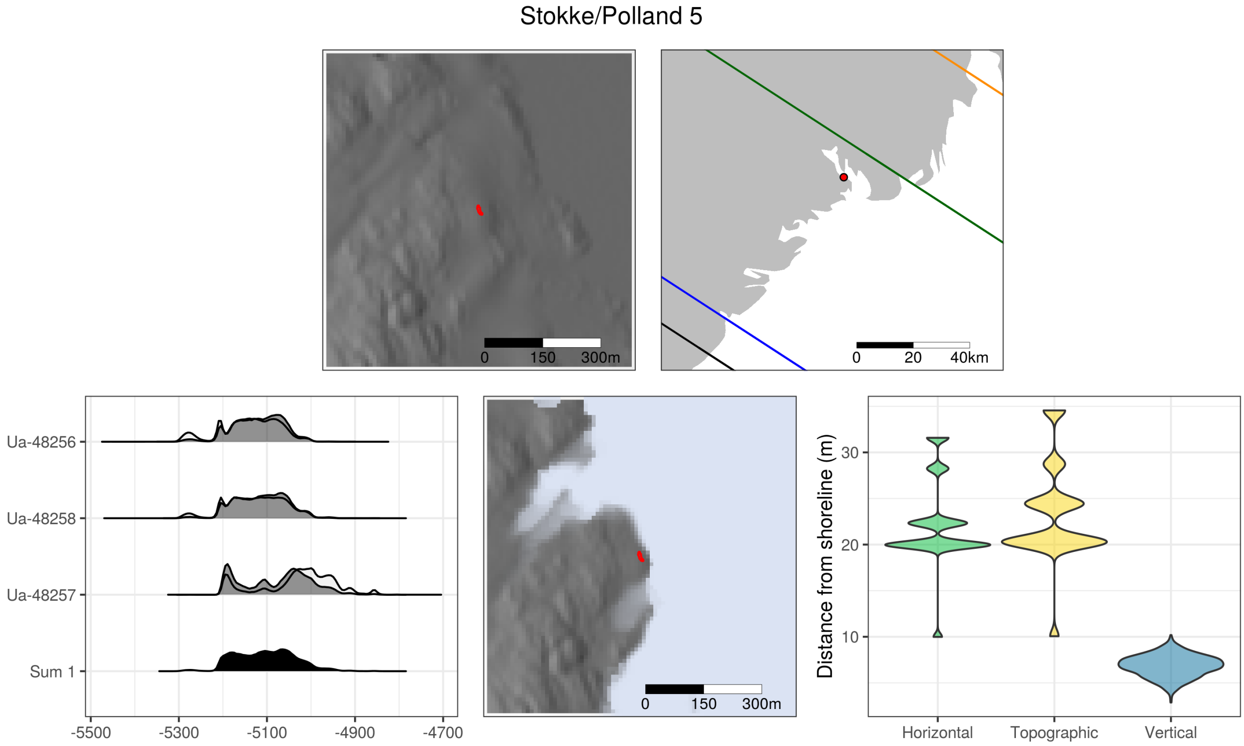


Table 59: Stokke/Polland 5

ID	^{14}C BP	Error	Material	Context
Ua-48256	6196	40	Alder (Alnus)	Cooking pit (ID 20345)
Ua-48257	6098	40	Pomoideae (Malinae)	Cooking pit (ID 20289)
Ua-48258	6177	42	Hazel (Corylus)	Cooking pit (ID 20270)

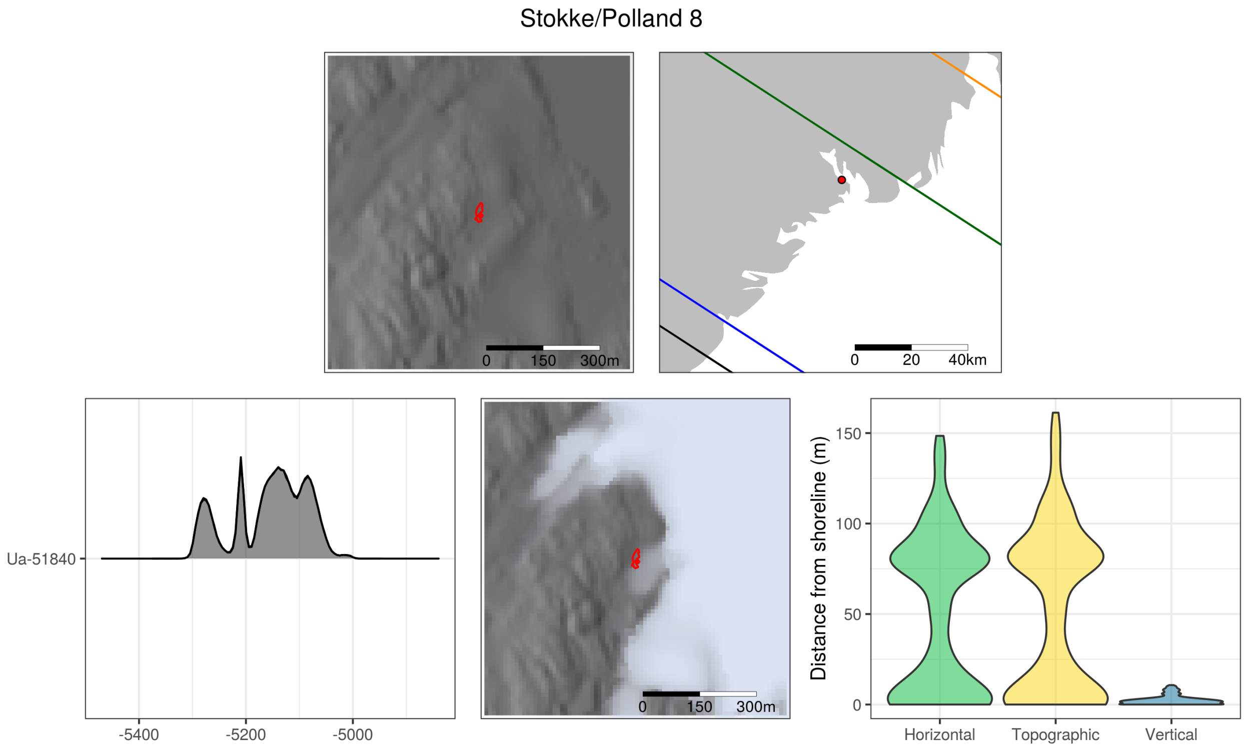
The artefact inventory from Stokke/Polland 1, containing both lithics and ceramics, indicates visits in the Late Mesolithic as well as the Early Neolithic (Koxvold 2017b). Date groups were therefore manually separated, even though they overlap at 99.7% probability. The site is located right by the highway to the east, which was edited for the other Stokke/Polland sites, but this does not appear relevant for the reconstruction of the sea-level at Stokke/Polland 1, which would have reached the site from the west.



The ^{14}C-dates matches the lithic inventory from Stokke/Polland 5 (Mansrud 2017). The site is located where the highway runs today. This appears to have been successfully edited. The excavated area is more extensive (field A–C in the report) than what is used as the site limit here, but the relation between the different areas is not clear. Field A, used as the site limit here, holds all the dated features.

Table 60: Stokke/Polland 8

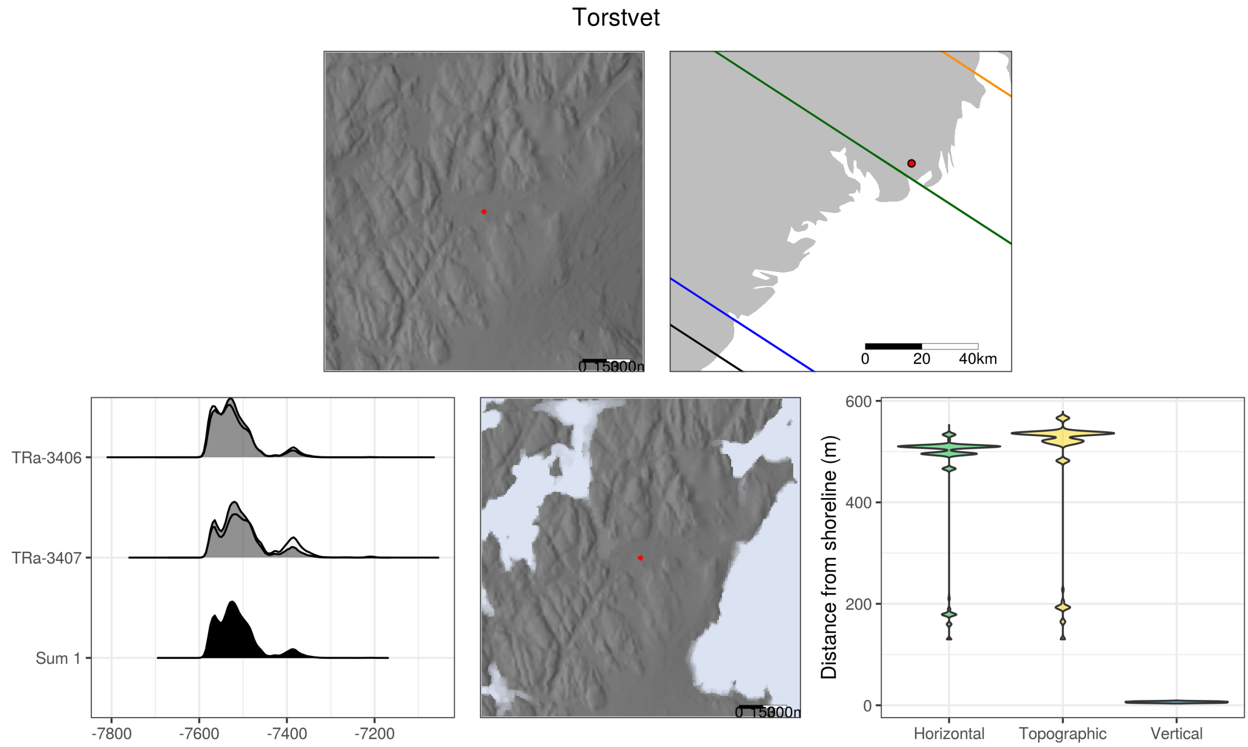
ID	^{14}C BP	Error	Material	Context
Ua-51840	6215	35	Birch (Betula)	Cooking pit/fireplace (ID 24210)



Stokke/Polland 8 have corresponding lithic inventory and ^{14}C-date (Fossum 2017c). The site is situated just east of where the highway runs today. This appears to have been successfully edited (cf. Fossum 2017c:Figure 28.3).

Table 61: Torstvet

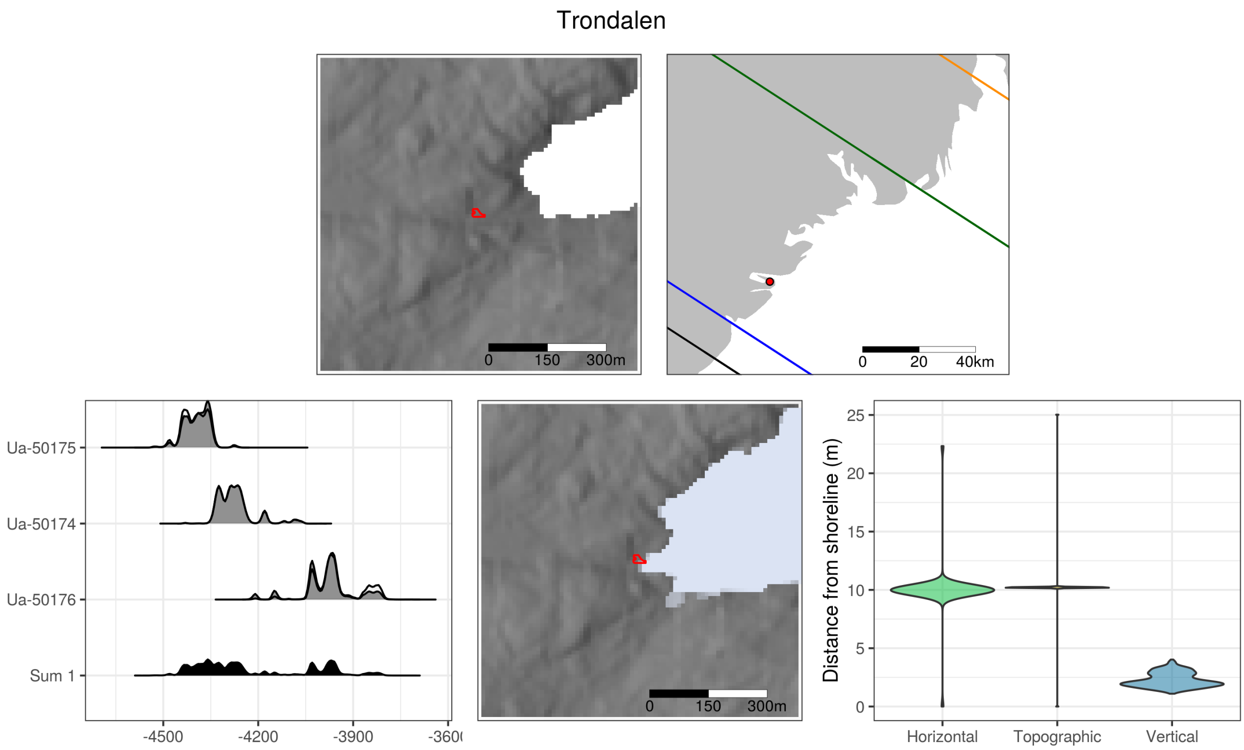
ID	^{14}C BP	Error	Material	Context
TRa-3406	8460	55	Hazel (Corylus), nutshell	Square (61x101y, layer 2)
TRa-3407	8425	55	Hazel (Corylus), nutshell	Square (61x102y, layer 2)
Ua-45677	2218	34	Birch (Betula)	Fireplace (ID 1)
TRa-3405	3090	30	Birch/willow (Betula/Salix)	Fireplace (ID 1)



Typology of lithics match the ^{14}C-dates from Torstvet (Mansrud 2013b). The site is located where the highway runs today. This appears to have been successfully edited, although there is a possibility that this has led to the sea-level being simulated sightly further away from the site than what would otherwise have been the case. However, as with he Hovland sites above, this appears to rather follow from the general topography of the landscape characterised by a low relief which makes the reconstruction more uncertain.

Table 62: Trondalen

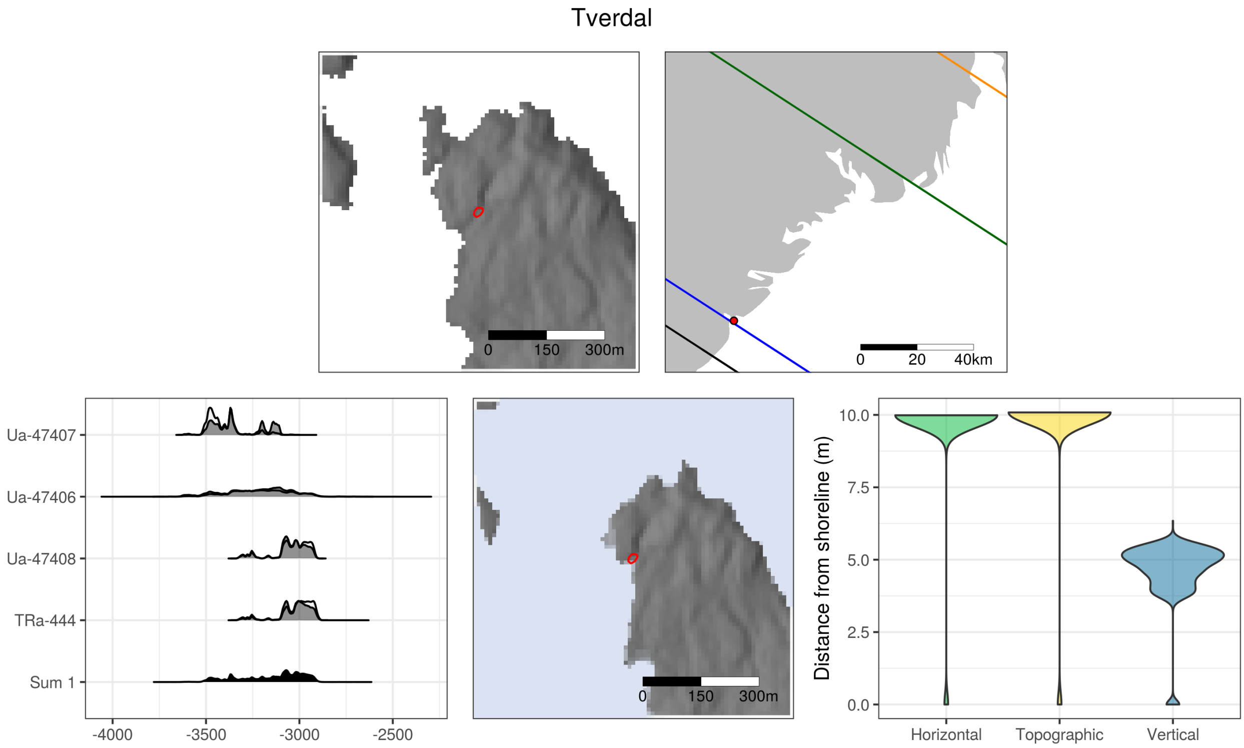
ID	^{14}C BP	Error	Material	Context
Ua-50174	5425	42	Hazel (Corylus)	Fireplace (ID 2)
Ua-50175	5557	43	Alder (Alnus)	Fireplace (ID 3)
Ua-50176	5156	44	Willow (Salix)	Cooking pit (ID 7)



^{14}C-dates match the typological indicators in the artefact assemblage at Trondalen (Mansrud 2018). No disturbances required editing in the DTM.

Table 63: Tverdal

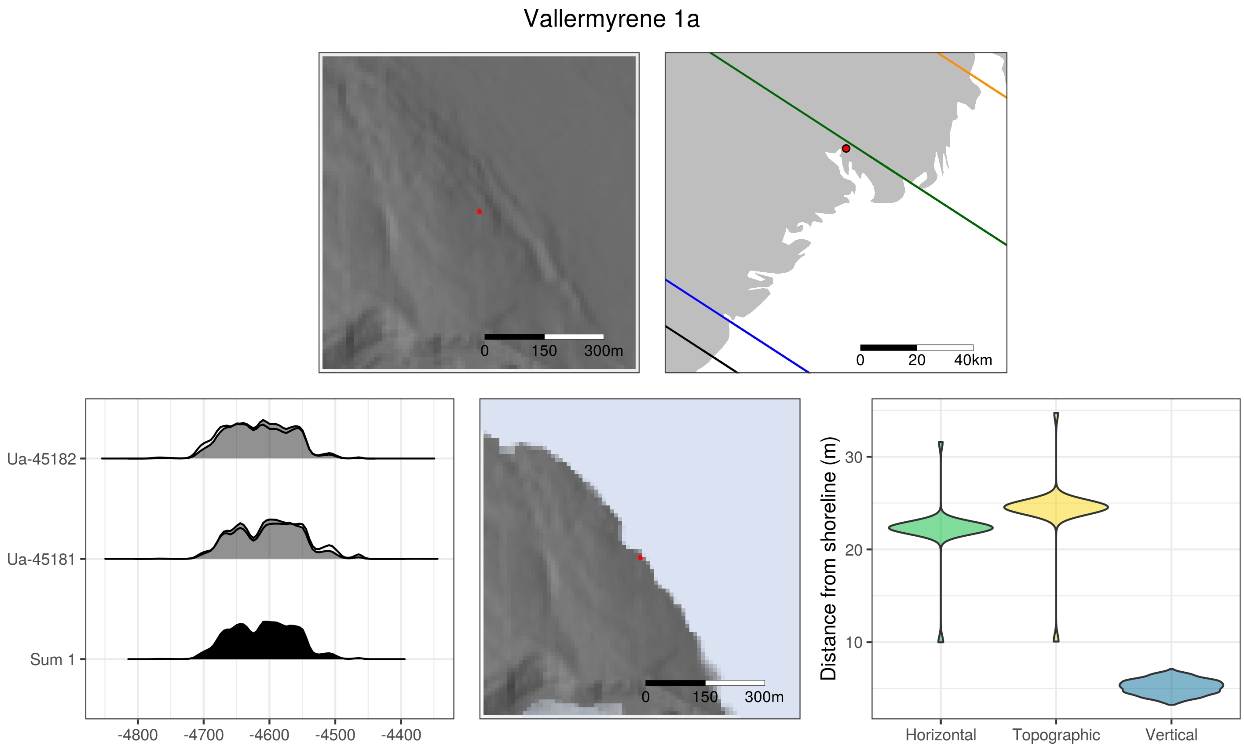
ID	^{14}C BP	Error	Material	Context
TRa-443	2480	35	Yew (Taxus)	Cultural layer, quadrant (16x10ySE)
TRa-444	4370	45	Birch (Betula)	Cultural layer, quadrant (14x10yNW)
TRa-445	2535	30	Birch (Betula)	Cultural layer, quadrant (16x10yNW)
TRa-446	2475	40	Yew (Taxus)	Cultural layer, quadrant (16x10ySW)
Ua-47406	4536	131	Dog (Canis familiaris)	Cultural layer, quadrant (16x10y)
Ua-47407	4622	48	Boar (Sus scrofa)	Cultural layer, quadrant (16x10y)
Ua-47408	4401	36	Mammal (Mammalia)	Cultural layer, quadrant (16x10y)



Tverdal is an unpublished site. Preliminary analysis indicates that radiocarbon dates and typological indicators match. The area surrounding the site appears relatively undisturbed by modern activity.

Table 64: Vallermyrene 1a

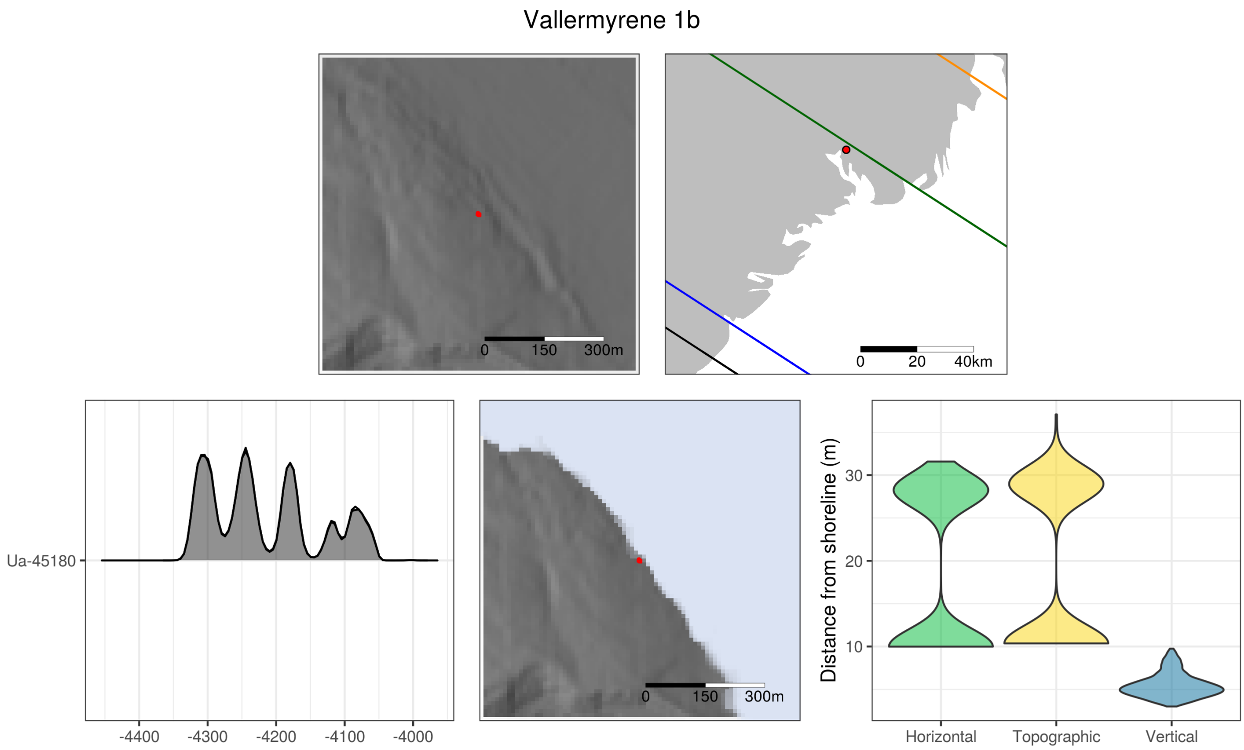
ID	^{14}C BP	Error	Material	Context
Ua-45182	5770	35	Pine (Pinus)	Fireplace (ID 322)
Ua-45181	5748	35	Pine (Pinus)	Cooking pit/fireplace (ID 301)



Vallermyrene 1 was divided into 1a and 1b based on elevation difference, typology and ^{14}C-dates (Reitan 2014f). Vallermyrene 1a is the oldest of the two. Although situated not that far from the railway, the area immediately surrounding the site has not been disturbed in a way that appears to impact the reconstruction of the past sea-level.

Table 65: Vallermyrene 1b

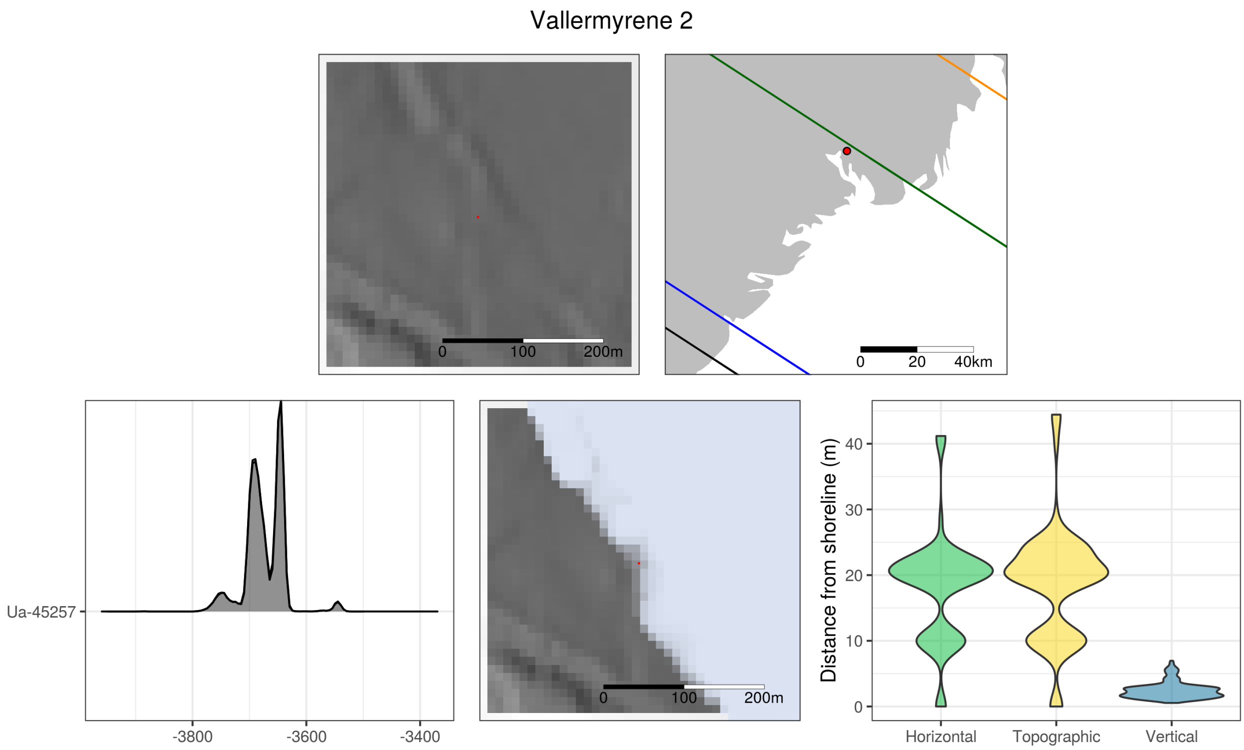
ID	^{14}C BP	Error	Material	Context
Ua-45180	5373	34	Birch (Betula)	Cooking pit/fireplace (ID 391)



Vallermyrene 1b is younger than Vallermyrene 1a (above), as indicated both by the radiocarbon date, typology and elevation (Reitan 2014f). The DTM did not require editing.

Table 66: Vallermyrene 2

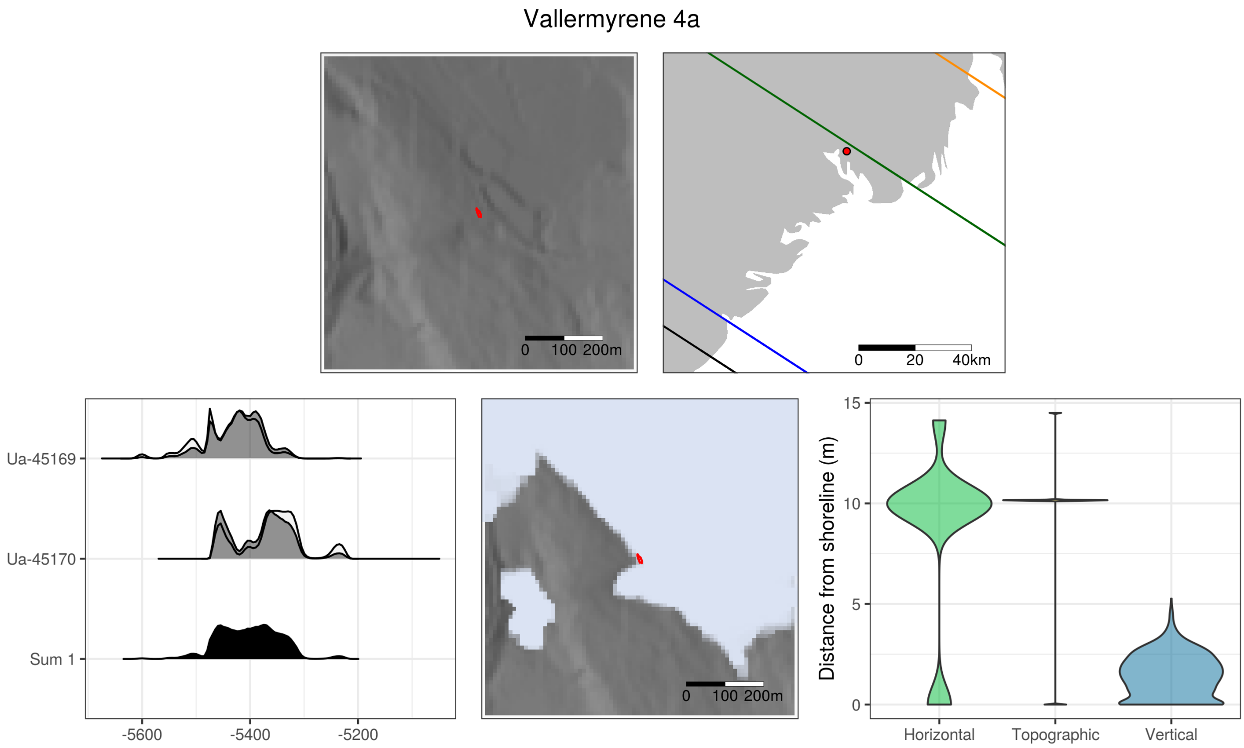
ID	^{14}C BP	Error	Material	Context
Ua-45257	4890	32	Hazel (Corylus)	Fireplace (ID 1017)
Ua-45253	3047	32	Birch (Betula)	Cooking pit? (ID 4026)
Ua-45258	2821	30	Willow (Salix)	Post hole? (ID 4455)
Ua-45251	2243	32	Willow (Salix)	Cooking pit (ID 350)
Ua-45256	2181	30	Birch (Betula)	Post hole (ID 2889)
Ua-45255	2156	30	Birch (Betula)	Cultivation layer (Profile in trench)
Beta-324757	2120	30	Hazel (Corylus)	Cultivation layer (611x554y)
Ua-45259	2009	30	Birch (Betula)	Cultivation layer (Profile)
Ua-45260	1942	30	Birch (Betula)	Post hole (ID 4210)
Ua-45249	1846	31	Birch (Betula)	Cooking pit (ID 545)
Ua-45248	1803	31	Birch (Betula)	Cooking pit (ID 437)
Ua-45252	1654	30	Birch/hazel/rowan (Betula/Corylus/Sorbus)	Undefined feature (ID 3351)
Ua-45254	1593	30	Pine (Pinus)	Post hole (ID 4468)
Ua-45250	1560	32	Birch (Betula)	Cooking pit/fireplace (ID 1043)



Vallermyrene 2 was a large site situated in a field (Reitan 2014g). The site has ^{14}C-dates and artefacts dating occupations at the site to multiple phases throughout prehistory, including the Bronze Age and phases up until the Viking Age. The Stone Age activity on the site was evidenced by 359 lithics and a fireplace dated to the Early Neolithic. Given it's uncertain extent, the site limit used here is defined by the fireplace.

Table 67: Vallermyrene 4a

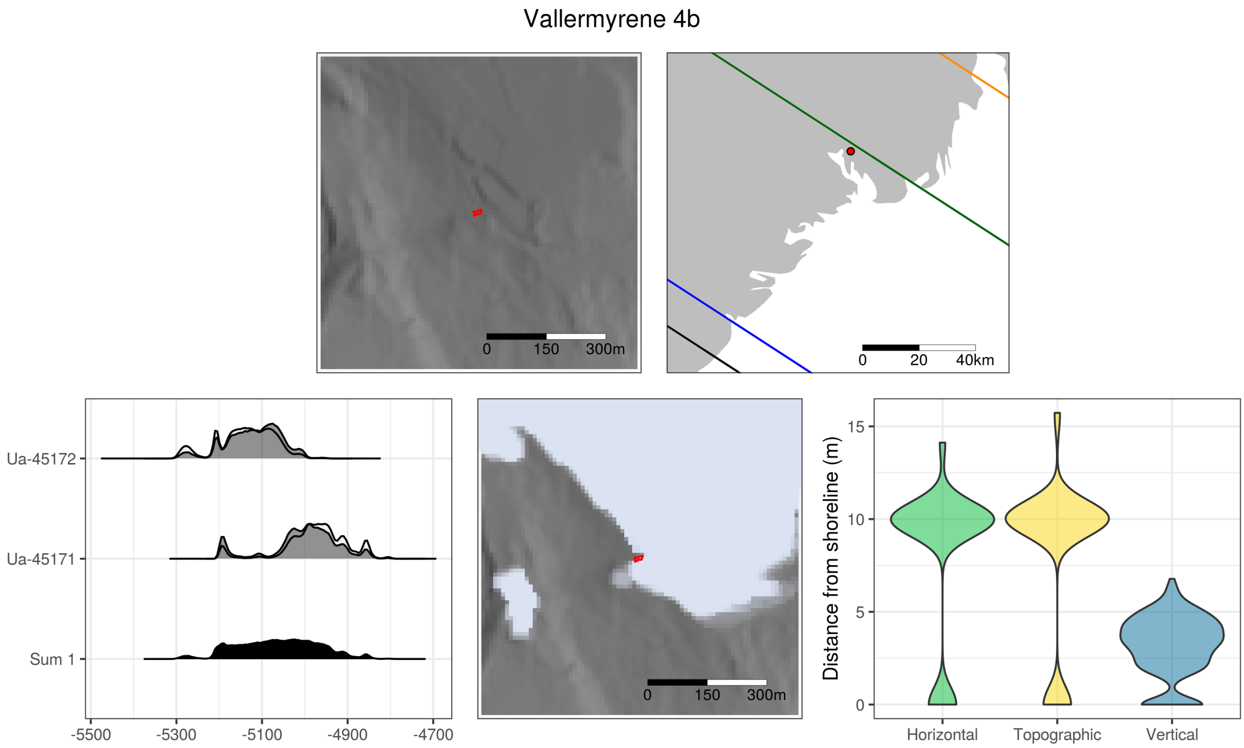
ID	^{14}C BP	Error	Material	Context
Ua-45169	6489	50	Burnt bone, mammal (0.5g)	Quadrant (894x242yNE, layer 1)
Ua-45170	6381	37	Burnt bone, mammal (1g)	Quadrant (892x243yNW, layer 3)



Vallermyrene 4 was, as with Vallermyrene 1 (above), divided into Vallermyrene 4a and 4b based on radiocarbon dates and differences in elevation (Eigeland and Fossum 2014). Typologically the sites are identical, and match the ^{14}C-dates. Vallermyrene 4a is the older of the two and was less disturbed by modern acitivity before the excavation. The railway runs just east and north-east of the site and had to be removed. In addition, what appears to be a gravel pit was located to the south-west. Both railway and gravel pit appear to have been adequately edited in the employed DTM.

Table 68: Vallermyrene 4b

ID	^{14}C BP	Error	Material	Context
Ua-45172	6197	40	Pine (Pinus)	Refuse/storage pit (ID 896)
Ua-45171	6067	41	Pine (Pinus)	Refuse/storage pit (ID 896)



Vallermyrene 4b is slightly younger than Vallermyrene 4a (above). Typology and radiocarbon dates match (Eigeland and Fossum 2014). The DTM was edited to remove the railway track running by the site and a gravel pit.

0.4 Model comparison and selection

Visualisation of the raw simulation results for vertical distances older than 2500 BCE, as well as the models fit for Table 1 in the main text. The table is also reproduced below. Note that the models have been fit when forcing negative values to zero and adding a constant of 0.001 to avoid zeroes. The data is presented with negative values set to zero in Figure 7A in the main text.

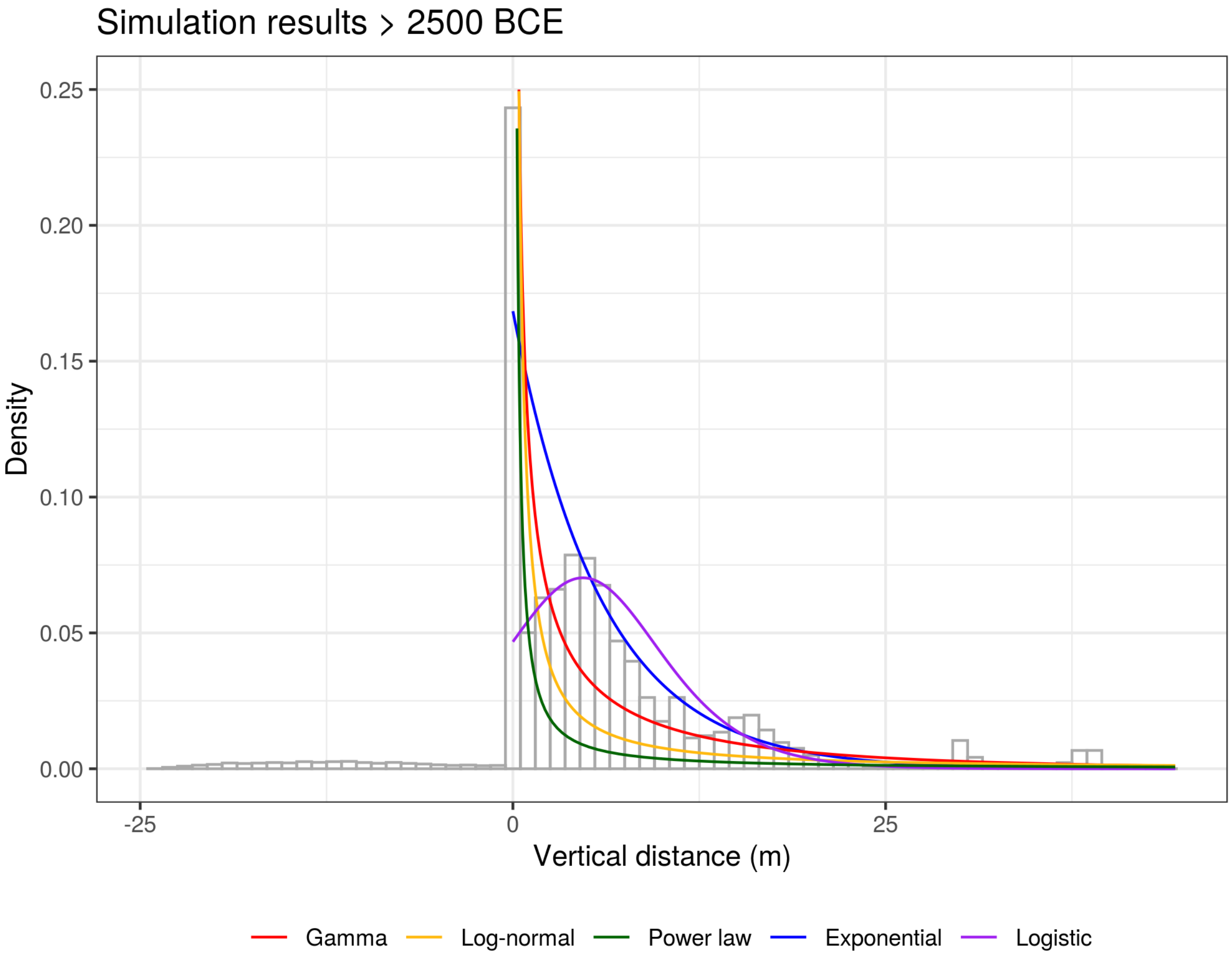


Table 69: Same as Table 1 in the main text. Model comparison using AIC and BIC. The models are listed in the order of performance.

Model	Parameters	AIC	BIC
Gamma	Shape (α) = 0.286 Scale (σ) = 0.048	230247	230229
Log-normal	Mean of the logarithm (μ) = -0.647 SD of the logarithm (σ) = 3.926	268082	268064
Power law	Exponent (k) = 1.16	274052	274043
Exponential	Rate (λ) = 0.168	348484	348475
Logistic	Location (μ) = 4.698 Scale (σ) = 3.558	415322	415304

0.5 Numerical result of re-dating

Table 70: The result of shoreline dating previously shorline dated sites using the method proposed here. The range of the 95% HDR is rounded to the nearest 10 years to reduce spurious precision.

	Site	Reported elevation	Reported date	95% HDR	Reference
1	Alveberget 6	17–23	5600–4500 BCE	5390 BCE–480 CE	Stokke 2021
2	Anvik	77–80	8550–8250 BCE	8840–5250 BCE	Eymundsson 2014
3	Austein 1	105–110	9500–8200 BCE	9070–8690 BCE	Matsumoto 2004
4	Bakke	98–98	8850–8800 BCE	9020–8450 BCE	Nyland & Amundsen 2012
5	Brunstad 26	46–50	5800–5600 BCE	5950–3340 BCE	Danielsen et al. 2018
6	Danebuåsen	70–75	8500–8300 BCE	8530–5190 BCE	Koxvold 2018b
7	Dørdal	100–101	8600–8400 BCE	9100–8650 BCE	Solheim et al. 2017
8	Dybdalshei 4	25–25	6900–5900 BCE	7720 BCE–470 CE	Granum & Schülke 2018
9	Gunnarsrød 10	43–44	5800–5600 BCE	5940–2590 BCE	Reitan & Fossum 2014
10	Gunnarsrød 3	35–36	5000–5000 BCE	5180–1640 BCE	Reitan 2014j
11	Gunnarsrød 6a	45–46	6400–6000 BCE	6280–2980 BCE	Carrasco et al. 2014
12	Gunnarsrød 6b	46–46.5	6400–6000 BCE	6480–3190 BCE	Carrasco et al. 2014
13	Gunnarsrød 7	55–59	7800–7300 BCE	8060–4460 BCE	Fossum 2014a
14	Gunnarsrød 8	52–54	7300–7000 BCE	7750–3890 BCE	Fossum 2014e
15	Hegna øst 3	37–39	5700–5600 BCE	5430–1910 BCE	Koxvold & Solheim 2017b
16	Hegna øst 4	34–36	5300–5100 BCE	5200–1530 BCE	Koxvold et al. 2016
17	Hegna øst 5	44–49	7500–7000 BCE	6850–3240 BCE	Havstein 2017b
18	Hegna øst 6	55–58	7900–7500 BCE	7990–4600 BCE	Havstein 2017a
19	Hegna øst 7	40–42	6600–6200 BCE	5720–2470 BCE	Koxvold et al. 2017
20	Hegna vest 4	54–57	7900–7600 BCE	7930–4200 BCE	Eigeland & Fossum 2017b
21	Hesthag C3	35–40	8000–8000 BCE	8910 BCE–370 CE	Reitan 2017
22	Hesthag C6	38–41	8000–8000 BCE	9040 BCE–370 CE	Reitan 2017
23	Hovland 2	65–70	8300–7900 BCE	8530–5010 BCE	Koxvold 2013a
24	Hydal 3	76–78	8300–8100 BCE	8810–5230 BCE	Koxvold 2017f
25	Hydal 4	80–80	8300–8100 BCE	8870–7430 BCE	Koxvold 2017a
26	Hydal 5	76–77	8500–8200 BCE	8800–7320 BCE	Koxvold 2016
27	Hydal 6	79–79	8500–8300 BCE	8860–7390 BCE	Koxvold 2017i
28	Hydal 7	73–74	8300–8100 BCE	8720–5150 BCE	Koxvold 2017g
29	Hydal 8	70–73	8300–8000 BCE	8670–5110 BCE	Koxvold 2017h
30	Kjørholt	59–63	8000–7700 BCE	8260–4950 BCE	Koxvold 2020b
31	Krøgenes D10	18–20	5000–4000 BCE	5250 BCE–480 CE	Stokke & Reitan 2018b
32	Krøgenes D3	38–42	9300–8250 BCE	9320 BCE–350 CE	Viken 2017d
33	Krøgenes D5	13–14	2800–2400 BCE	3090 BCE–480 CE	Reitan & Solberg 2018b
34	Krøgenes D6	40–40	9300–8300 BCE	9320 BCE–350 CE	Viken 2017b
35	Krøgenes D7	17–18	4200–3600 BCE	4830 BCE–480 CE	Stokke & Reitan 2018b
36	Krøgenes D8	39–39	9250–8300 BCE	9290 BCE–350 CE	Viken 2017a
37	Krøgenesåsen 1	34–35	8850–8500 BCE	8960 BCE–390 CE	Nielsen 2017
38	Krøgenesåsen 2	36–38	8850–8500 BCE	9210 BCE–410 CE	Nielsen 2017
39	Kvastad A3	56–58	8300–8000 BCE	8920–5240 BCE	Stokke & Bjørkli 2016
40	Kvastad A4	52–61	8500–8300 BCE	8910–5230 BCE	Darmark et al. 2018
41	Kvastad A5-6	46–49	8400–8300 BCE	8680–5050 BCE	Viken 2018d
42	Kvastad A7	54–54	8700–8300 BCE	8890–5210 BCE	Darmark 2015
43	Kvastad A8	50–55	8600–8500 BCE	8880–5180 BCE	Darmark 2017
44	Kvastad A9	54–55	8700–8300 BCE	8900–7620 BCE	Darmark 2018a
45	Lågerød	64–68	7400–7000 BCE	7610–5440 BCE	Eymundsson 2012
46	Langangen Vestgård 2	40–41	5600–5600 BCE	5580–2230 BCE	Eggen 2014c
47	Langangen Vestgård 4	39–41	4300–4300 BCE	5530–2330 BCE	Reitan 2014h
48	Marisberg	30–30	8000–7500 BCE	8350 BCE–370 CE	Mansrud & Carrasco 2018b
49	Melau	100–100	9500–8200 BCE	9030–8540 BCE	Matsumoto 2004
50	Nauen B	33–34	4000–4000 BCE	4940–750 BCE	Persson 2008
51	Nedre Hobekk 1	78–80	8500–8200 BCE	8850–7430 BCE	Eigeland 2014b
52	Nedre Hobekk 2	95–97	8800–8500 BCE	9020–8370 BCE	Eigeland 2014a
53	Nedre Hobekk 3	72–75	8200–8000 BCE	8730–5080 BCE	Fossum 2014d
54	Nordby 1 (Bommestad-Sky)	65–66	7900–7500 BCE	8450–5000 BCE	Olsen 2013b
55	Nordby 2 (Bommestad-Sky)	65–70	7900–7500 BCE	8520–5040 BCE	Koxvold 2013b
56	Nordby 3 (Bommestad-Sky)	49–49	6700–6300 BCE	7200–3730 BCE	Mansrud 2013c

57	Olsmyren	70–72	7300–7050 BCE	7550–5450 BCE	Hårstad 2021
58	Øytangen	32–34	6500–5500 BCE	8010 BCE–420 CE	Berge & Loftsgarden 2012
59	Pauler 1	127–130	9200–9150 BCE	9280–8840 BCE	Schaller Åhrberg 2012
60	Pauler 2	124–124	9150–9100 BCE	9230–8830 BCE	Nyland 2012a
61	Pauler 3	114–114	9000–8950 BCE	9110–8780 BCE	Amundsen 2012a
62	Pauler 4	108–111	8950–8900 BCE	9070–8730 BCE	Nyland 2012b
63	Pauler 5	110.5–110.5	8975–8925 BCE	9080–8750 BCE	Amundsen 2012b
64	Pauler 6	98–98	8850–8800 BCE	9020–8430 BCE	Jaksland 2012a
65	Pauler 7	95–95	8800–8750 BCE	9010–8340 BCE	Jaksland 2012b
66	Pjonkerød R2	62–62	7200–6700 BCE	7080–5040 BCE	Carrasco 2015
67	Pjonkerød R3	62–65	7200–7000 BCE	7120–5180 BCE	Carrasco 2015
68	Prestemoen 2	34–39	4900–4900 BCE	5260–1510 BCE	Persson 2014b
69	Råen 1	65–65	7100–6900 BCE	7160–5370 BCE	Hårstad 2021b
70	Roverud 1	59–62	7500–7400 BCE	8230–4920 BCE	Koxvold 2020a
71	Roverud 2	56–59	7500–7400 BCE	8050–4760 BCE	Koxvold 2020a
72	Sagene B1	48–55	8800–8700 BCE	9200–7540 BCE	Viken 2018
73	Sagene B2	55–58	9200–8800 BCE	9340–7960 BCE	Darmark 2018b
74	Sagene B4	53–55	9000–8800 BCE	9090–5220 BCE	Darmark 2018c
75	Sagene B5	45–47	8800–8700 BCE	8950–5070 BCE	Viken 2017c
76	Sagene B6	48–52	8900–8700 BCE	8940–5150 BCE	Darmark 2018c
77	Skeid	94–95	8500–8300 BCE	9020–8310 BCE	Nielsen & Solheim 2017
78	Skutvikåsen 3	54–55	7230–7150 BCE	7860–4200 BCE	Ekstrand 2013
79	Skutvikåsen 4	59–59	7540–7540 BCE	8160–4790 BCE	Ekstrand 2013
80	Skutvikåsen 5	30–31	4400–4300 BCE	4750–960 BCE	Ekstrand 2013
81	Sky 1	108–108	8950–8900 BCE	9070–8710 BCE	Amundsen 2012c
82	Solum 1	94–95	8800–8400 BCE	9010–8310 BCE	Fossum 2014c
83	Stokke/Polland 3	36–39	6100–5400 BCE	5380–1850 BCE	Fossum 2017c
84	Stokke/Polland 4	33–34	5000–5000 BCE	5080–1190 BCE	Mansrud & Carrasco 2018a
85	Stokke/Polland 7	33–35	4900–4500 BCE	5120–1350 BCE	Koxvold & Solheim 2017a
86	Stokke/Polland 9	29–31	4200–4000 BCE	4730–990 BCE	Fossum 2017e
87	Sundsaasen 1	62–66	7900–7700 BCE	8420–5010 BCE	Eggen 2014b
88	Sundsaasen 2	27–31	3800–3600 BCE	4540–850 BCE	Melvold & Persson 2014
89	Tangvall nedre 1	23–24	3550–3550 BCE	3700 BCE–200 CE	Stokke 2017
90	Tangvall nedre 2	23–25	3550–3550 BCE	3810 BCE–190 CE	Stokke 2017
91	Tinderholt 1	97–100	8600–8300 BCE	9040–8480 BCE	Koxvold 2017e
92	Tinderholt 2	104–107	8700–8400 BCE	9080–8680 BCE	Koxvold 2017d
93	Tinderholt 3	106–109	8700–8500 BCE	9100–8730 BCE	Koxvold 2017c
94	Vallermyrene 3	23–25	3200–3000 BCE	3740 BCE–210 CE	Reitan 2014i
95	Viulsrød 1	71–74	7500–7200 BCE	7610–5460 BCE	Reitan & Hårstad 2021b
96	Viulsrød 2	67–69	7100–6900 BCE	7310–5370 BCE	Reitan & Hårstad 2021b

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Supplementary material, Paper 2

The supplementary material for Paper 2 is PDF versions of HTML documents providing documentation for the R package *shoredate*. These can be viewed in their original interactive form on either the GitHub page for the package at https://github.com/isakro/shoredate, on the website of the package at https://isakro.github.io/shoredate/ or through the landing page for the package on CRAN: https://cran.r-project.org/package=shoredate.

Introduction to shoredate (README.rmd)

README.rmd

Isak Roalkvam

shoredate: An R package for shoreline dating coastal Stone Age sites

The package *shoredate* offers methods to shoreline date coastal Stone Age sites based on their present-day elevation and the trajectory of past relative sea-level change. Shoreline dating is based on the premise that coastal Stone Age sites in large parts of Fennoscandia were located on or close to the shoreline when they were in use. The package and method as implemented here was originally developed for the Norwegian Skagerrak coast in south-eastern Norway, based on an empirically derived estimate of the likely elevation of sites above sea-level when they were occupied (Roalkvam 2023).

While the package offers ways to extend and adjust the method for application in other areas, the ways and degree to which the procedures are directly applicable elsewhere is largely undetermined and likely to vary between contexts. Furthermore, such extensions are currently limited to regions that have been characterised by a monotonic trajectory of relative sea-level regression. Do also note that as the method is dependent on regularities in human behaviour, and as the Roalkvam (2023) study provides an initial formalisation of the method, it is hefted with unexplored uncertainties, also within the core area for which it was developed. In sum therefore, the dates achieved with the package should be treated with care.

Installation and loading

shoredate can be installed from CRAN with:

```
install.packages("shoredate")
```

The latest development version can be installed from GitHub using `devtools`:

```r
# install.packages("devtools")
devtools::install_github("isakro/shoredate",
                         build_vignettes = TRUE)
```

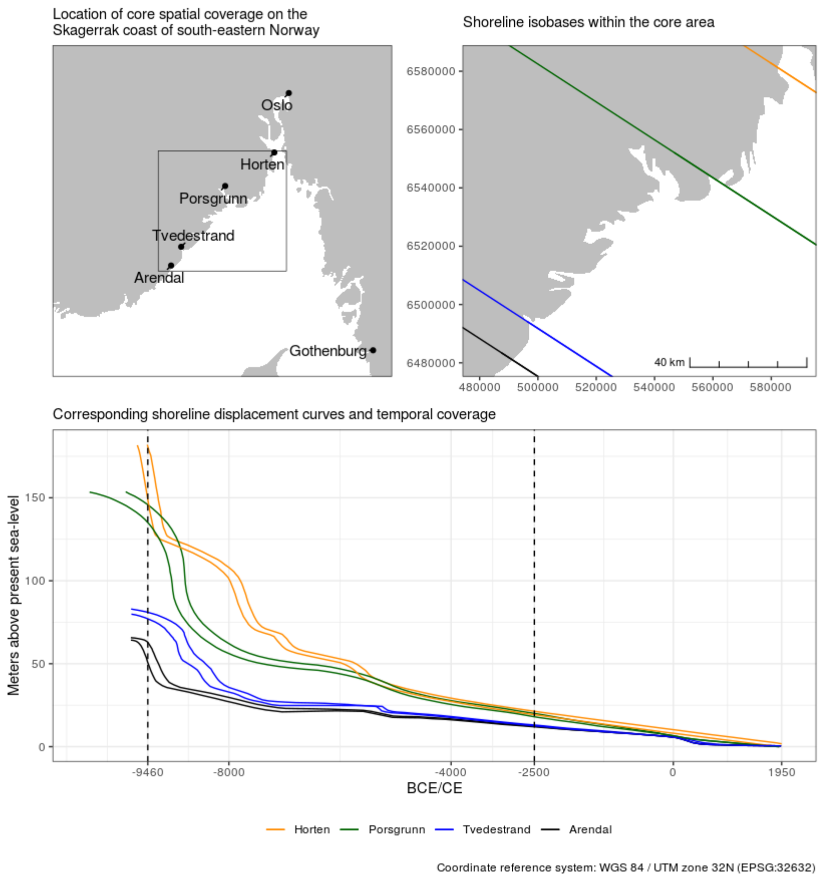
When it has been installed the package can be loaded:

```r
library(shoredate)
```

Geographical and temporal coverage

As the method of shoreline dating is determined by relative sea-level change, it is dependent on reliable geological reconstructions of this development. The method as outlined here was originally developed for the Skagerrak region of south-eastern Norway – extending from Horten in the north east to Arendal in the south west (see figure below). This region has newly compiled shoreline displacement curves for Horten (Romundset 2021), Porsgrunn (Sørensen et al. 2014; Sørensen et al. 2023), Tvedestrand (Romundset 2018; Romundset et al. 2018) and Arendal (Romundset 2018). The region also formed the study area for Roalkvam (2023), in which the method and its parameters were derived. The remainder of this document and the main vignette focuses on this area. It is, however, possible to adapt the procedures for application in other regions, which is outlined in the second vignette.

The first figure below shows the location of the spatial limit within which the method was originally derived. The shoreline isobases in the second figure represent contours along which the shoreline displacement has followed the same trajectory. These correspond to the displacement curves and place names in the third figure, which also indicates the temporal coverage of the method within the region.



As human occupation only occurred some time after the retreat of the Fennoscandian Ice Sheet, the currently oldest known sites in Norway are from around 9300 BCE (e.g. Glørstad 2016). Although no sites are yet known to be that old, the earliest possible age to achieve with *shoredate* in the Skagerrak region of south-eastern Norway is 9469 BCE, which marks the latest start date among the employed displacement curves. If a site has an elevation that implies a date older than this, it is returned as NA and a warning is given.

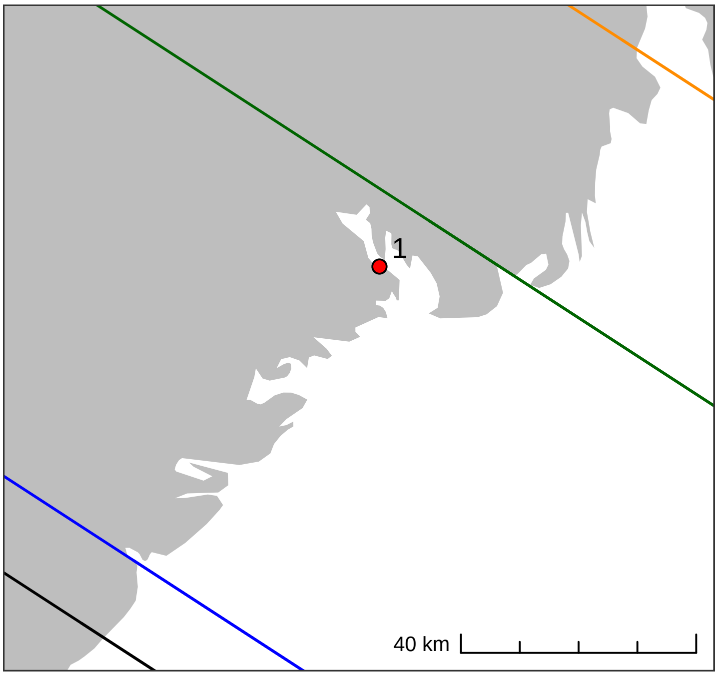
In Roalkvam (2023) it was found that sites in the study region tend to be located on or close to the shoreline up until around the transition to the Late Neolithic, c. 2500 BCE, which thus marks the upper limit for the applicability of the method in the region. A date that has a later start date than this is therefore returned as NA with a warning, with the default settings. The temporal range is indicated by the dashed lines in the plot above that displays the shoreline displacement curves. Additionally, if the probability of a date extends beyond 1950 CE (0 cal BP), thus indicating a site location below the present-day sea-level, this overshooting probability is cut off and the date is normalised to sum to unity.

Interpolating shoreline displacement to a site location

To shoreline date a site, a reconstruction of local shoreline displacement is necessary. There are currently four reliable geological displacement curves available from within the study area. Each of these is associated with a shoreline isobase, along which the trajectory of relative sea-level change has been the same. To find the local displacement curve, the curves are interpolated to a site location using inverse distance weighting, where the default is to weigh the interpolation by the square of the inverse distance between site and isobases.

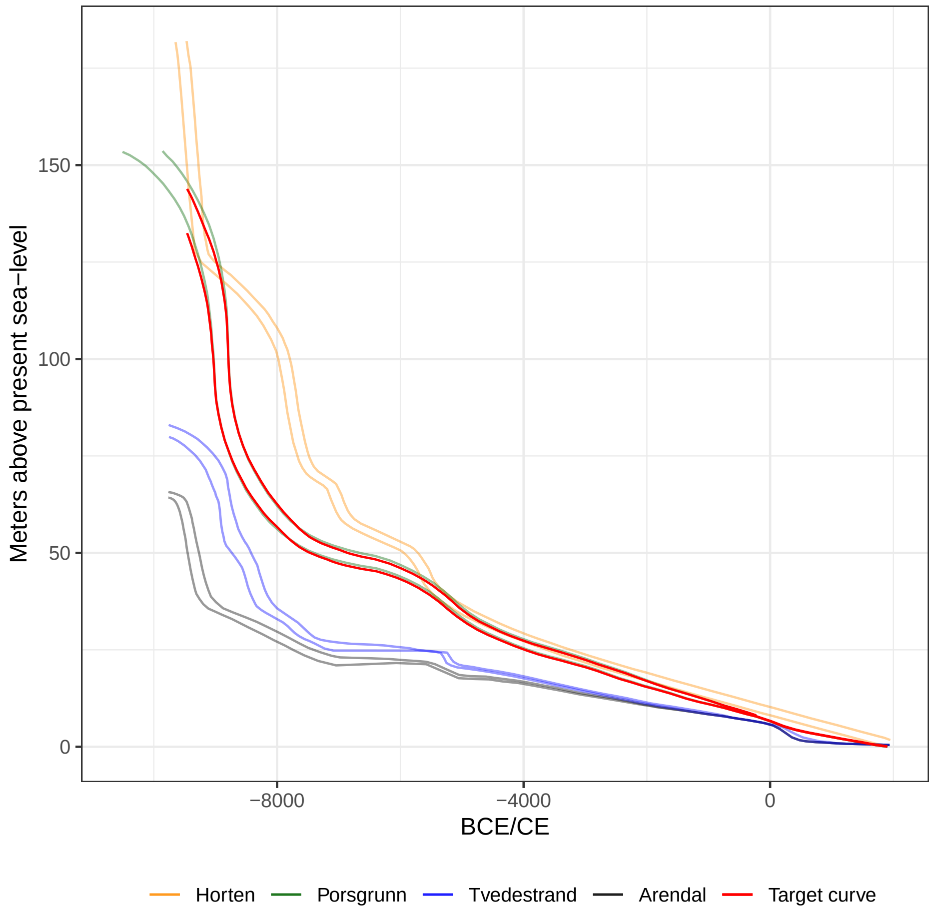
```r
# Create example point using the coordinate system required
# for the interpolation procedure:
# WGS84 / UTM zone 32N (EPSG: 32632)
target_point <- sf::st_sfc(sf::st_point(c(538310, 6544255)),
                           crs = 32632)

# Create a simple map showing the target location relative to the
# isobases of the displacement curves
target_plot(target_point)
```




```
# Interpolate shoreline displacement curve for
# the target location
target_curve <- interpolate_curve(target_point)

# Plot displaying the interpolated curve, reducing the opacity
# of the geological displacement curves
displacement_plot(target_curve, displacement_alpha = 0.4)
```



Unless a pre-compiled curve is provided, this interpolation is performed under the hood for each site when calling `shoreline_date()`, which is the function that performs the shoreline dating procedure.

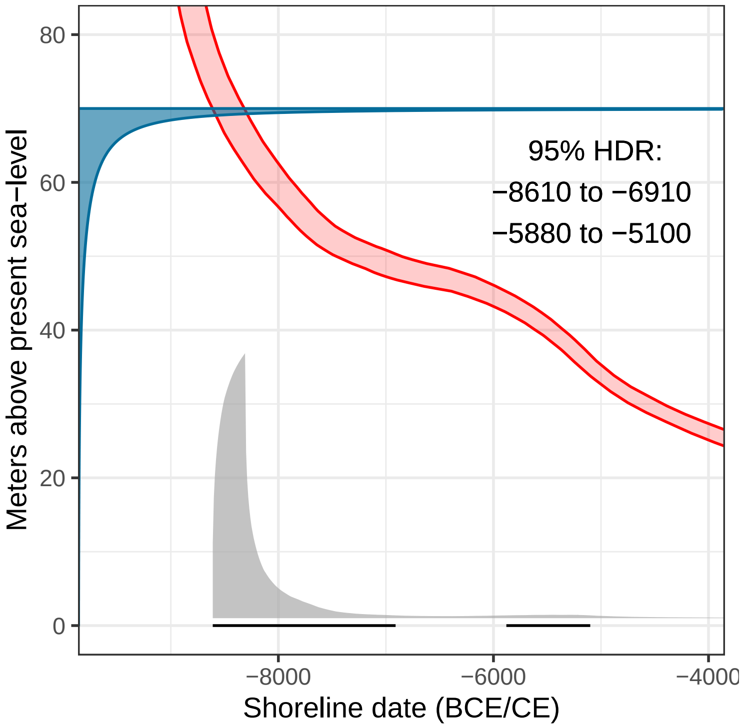
Shoreline dating a site

Below is a basic example outlining how to date a single site by manually specifying the site elevation. The default settings are used for the dating procedure and for plotting the resulting shoreline date.

```
# Using the example point from above and specifying
# it's elevation
target_date <- shoreline_date(site = target_point,
```

```
                                elevation = 70)

# Call to plot
shoredate_plot(target_date)
```



The blue gamma distribution on the y-axis represents the likely elevation of the site above sea-level when it was in use, which is described by an empirically derived gamma function with the parameters α (shape) = 0.286 and σ (scale) = 20.833. This starts from the elevation of the site. The red envelope is the shoreline displacement curve as interpolated to the site location. The probability from the gamma distribution is transferred to the calendar scale using the displacement curve. This gives the resulting shoreline date in grey, which is underlined by the 95% highest density region (HDR) in black (see Roalkvam 2023 for more details). By default, the shoreline date is normalised to sum to unity. The default resolution on the calendar scale is 10 years.

Calling the date object, which has the custom class `shoreline_date`, prints the name of the site, its elevation and the HDR:

```
target_date
#> ===============
#> Site:  1
#> Elevation:  70
#>
#> 95% HDR:
#> 8610 BCE-6910 BCE
#> 5880 BCE-5100 BCE
```

The first column of a data frame beyond the geometry of the spatial objects will be taken to represent site names. If no such column exist, the sites are simply numbered as they are passed to `shoreline_date()`.

Further documentation

The procedures outlined above have focused on the basic functions and default behaviours of the package when dating a single site in the area for which the package was originally developed. For further usage and a more detailed walk-through, see the main vignette by calling `vignette("shoredate")` or by accessing it on the website.

Furthermore, a second vignette which can be accessed with `vignette("extending-shoredate")` or viewed on the website, builds on the main vignette and outlines ways in which the package can be applied to other regions.

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Contributing

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Vignette 1: Guide to using shoredate (shoredate.rmd)

shoredate: Shoreline dating Stone Age sites on the Norwegian Skagerrak coast

Isak Roalkvam

Contents

1 Introduction

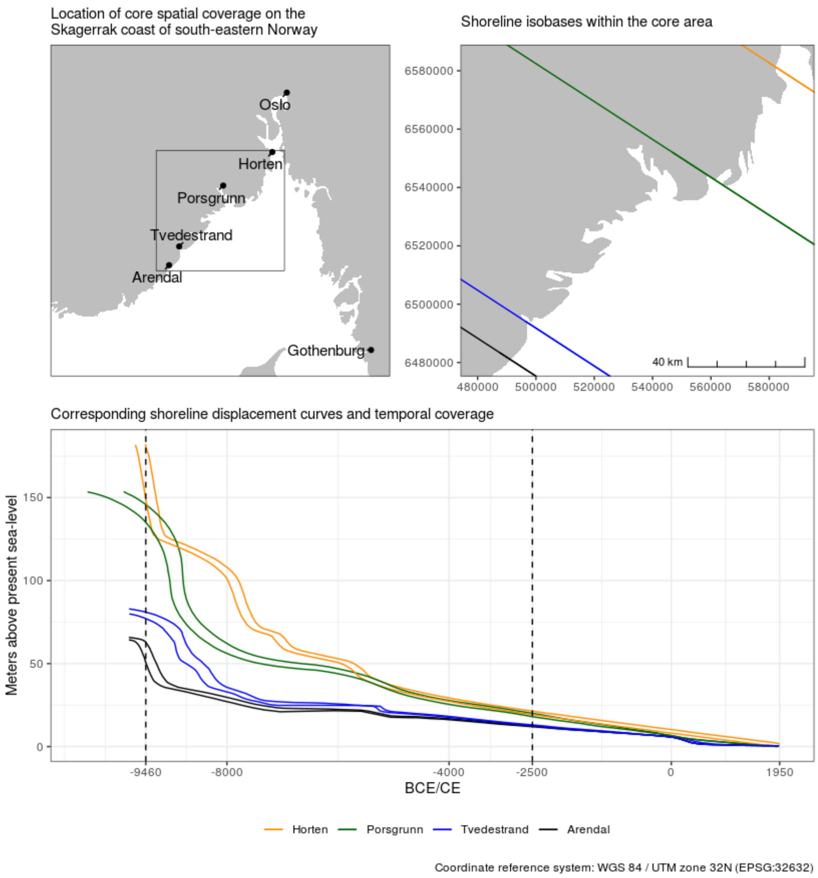
The concept of dating sites based on their present-day elevation with reference to past shoreline displacement has been an important tool for archaeologists in northern Scandinavia since the early 1900s (e.g. Brøgger 1905). This is based on the observation that Stone Age sites in the region tend to have been located close to the contemporaneous shoreline when they were in use. Furthermore, following the retreat of the Fennoscandian Ice Sheet, the isostatic uplift has been so severe that despite corresponding eustatic sea-level rise, the relative sea-level has been falling throughout prehistory in large parts of this region. Within any given area where this is the case, the general pattern is thus that older sites will be located at higher altitudes than younger sites.

This vignette describes the R package *shoredate* which provides tools for shoreline dating Stone Age sites located on the Norwegian Skagerrak coast using the approach presented in Roalkvam (2023). This is based on an empirical evaluation of the likely elevation of the sites above sea-level when they were in use, and the local trajectory of past relative sea-level change. Due to the geographical contingency of the method, and the dependency on geological reconstructions of shoreline displacement, the functionality of the package was developed for the purposes of dating coastal sites located in the region stretching from Horten county in the north east, to Arendal county in the south west. However, in the second vignette, ways in which the core functionality of the package could be applied in other areas of the world are presented.

1.1 Geographical and temporal coverage

Shoreline dating of Stone Age sites in northern Scandinavia is based on the premise that coastal sites within the region tend to have been located on or close to the shoreline when they were in use. By reconstructing the past trajectory of shoreline displacement, this thus allows us to ascribe an approximate date to when the sites were in use, based on their present-day elevation. The method is therefore dependent on local relative sea-level change and the likely elevation of the sites above sea-level when they were in use.

As the method is dependent on good geological reconstructions of shoreline displacement, the full functionality of *shoredate* is at present limited to being applicable in the region of south-eastern Norway between Horten in the north east to Arendal in the south west. This region has recently compiled shoreline displacement curves for Skoppum in Horten (Romundset 2021), Gunnarsrød in Porsgrunn (Sørensen et al. 2014a; Sørensen et al. *in prep*), Hanto in Tvedestrand (Romundset 2018; Romundset et al. 2018) and Bjørnebu in Arendal (Romundset 2018). This region also formed the study area for Roalkvam (2023), in which the specification of the method and the parameters used here were derived. The core spatial coverage of *shoredate* is indicated in the maps below.



Furthermore, human occupation in Norway only occurred some time after the retreat of the Fennoscandian Ice Sheet, and the oldest known sites are dated to around 9300 BCE (e.g. Glørstad 2016). 9469 BCE is the latest start date among the geologically derived displacement curves in the region, and thus marks the oldest possible age to achieve with *shoredate* here, although no sites are yet known to be that old. If a site has an elevation that implies a date older than the latest start date of the displacement curves, the date is returned as NA and a warning is given.

In the Roalkvam (2023) study it was found that sites tend to be situated at more removed and variable distances from the shoreline from around 2500

BCE. By default, this therefore marks the upper limit of the method, where dates with a start date after 2500 BCE are returned as NA.

1.2 Installing and loading *shoredate*

The package can be installed from CRAN:

```
install.packages("shoredate")
```

The development version of the package can be installed from the GitHub repository. This requires the `devtools` package. Note that the development version can be unstable.

```
# Uncomment and run to install devtools
# install.packages("devtools")

# Installation requires devtools
devtools::install_github("isakro/shoredate",
                         build_vignettes = TRUE)
```

When installed the package can be loaded.

```
library(shoredate)
```

2 Interpolating shoreline displacement to a site location

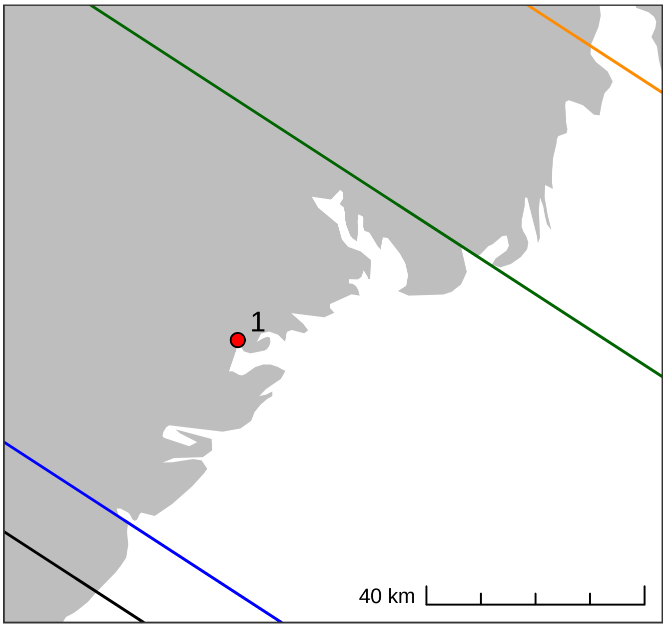
The function `shoreline_date()` forms the basis for *shoredate*, and is presented in more detail below. Unless a pre-compiled displacement curve is provided when calling `shoreline_date()`, the trajectory of shoreline displacement at the location of the sites to be dated is interpolated under the hood. This is based on the four different geological reconstructions of shoreline displacement along the Norwegian Skagerrak coat. Each of these displacement curves are associated with a shoreline isobase which indicates contours along which the relative sea-level change has followed the same trajectory. The variation in the rate of sea-level change is mainly determined by the degree of isostatic uplift, which is higher along a gradient than runs from the south west to the north east within the region. The shoreline displacement curve for any given location within the region is interpolated using the `interpolate_curve()` command, using inverse distance weighting, where the distance to the four isobases is weighted by the square of the inverse distances.

Note that spatial geometries representing sites to which `interpolate_curve()` is to be applied must be set to the coordinate reference system (CRS) WGS 84 / UTM zone 32N (EPSG:32632). Furthermore, a warning is given if one attempts to interpolate the trajectory for shoreline displacement at a site located outside the spatial extent outlined above. However, as there might still be use-cases where it could be useful to extrapolate the method outside this limit, the procedure is still performed (see the second vignette Applying shoredate to other regions for suggestions on how to apply the package to entirely different regions).

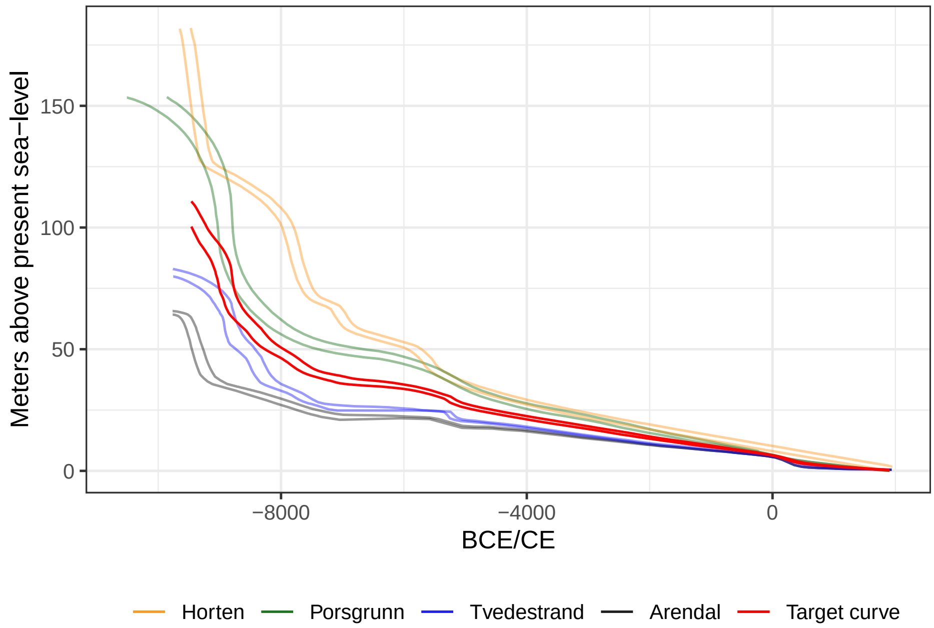
```
# Create example point using the required coordinate system
target_point <- sf::st_sfc(sf::st_point(c(517250, 6527250)),
                           crs = 32632)

# Interpolate the displacement curve
target_curve <- interpolate_curve(target_point)
```

To visualise the interpolated curve alongside the geological reconstructions, this can be passed to `displacement_plot()`. A simple map showing the location of one or more target sites relative to the isobases can also be displayed by using the command `target_plot()`.

```
target_plot(target_point)
```




```r
# The opactity of the geological displacement curves is
# reduced with displacement_alpha
displacement_plot(target_curve, displacement_alpha = 0.4)
```



3 Shoreline dating

The following section outlines how to perform shoreline dating and ways in which to visualise the results. Various parameters and helper-functions underlying the dating procedure are also presented, along with ways to manipulate these if one wishes to explore the sensitivity of the dates or believe other parameters than the defaults are more sensible in a given setting.

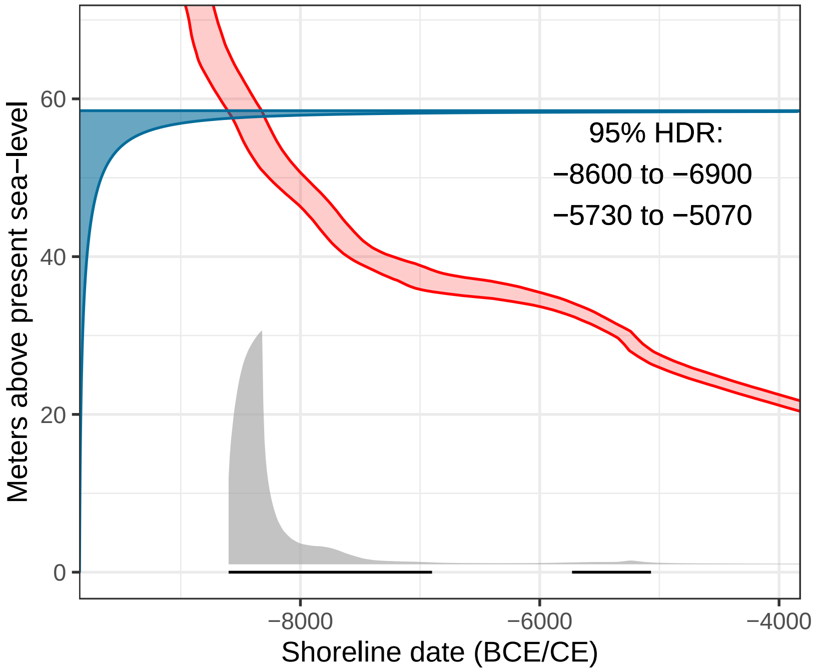
3.1 Dating a single site

To perform a basic shoreline date, a site has to be provided as a spatial `sf` object if the shoreline displacement is to be interpolated to its location. In a addition to this, the elevation of the site above the present sea-level has to be provided. This can either be done by manually specifying the elevation, or by providing an elevation raster (see below), in which case the elevation of the site will be derived from the raster, provided the site is given as a spatial object. In Roalkvam (2023) it was found that the vertical distance from the sites to the contemporaneous shoreline within the study region could be reasonably approximated by a gamma distribution. This forms the foundation for the implementation of shoreline dating in the package.

```
# Date the example point, manually specifying it's elevation
target_date <- shoreline_date(target_point, elevation = 58.5)
```

The results can then be plotted using the `shoredate_plot()` command:

```
shoredate_plot(target_date)
```



The blue gamma distribution on the y-axis indicates the likely elevation of the site above sea-level when it was in use, which is described by an empirically derived gamma distribution with the parameters shape $(\alpha) = 0.286$ and scale $(\sigma) = 20.833$. These parameters can be adjusted by specifying the values passed to `model_parameters` when calling `shoreline_date()`. The red envelope is the shoreline displacement curve as interpolated to the site location with `interpolate_curve()`, which is run under the hood if a curve is not provided to the `target_curve` argument of `shoreline_date()`.

Transferring the probability from the gamma distribution to the calendar scale using the displacement curve gives the resulting shoreline date in grey, which is underlined with the 95% highest density region (HDR) in black.

The coverage of the HDR can be adjusted with the `hdr_prob` parameter. The dating procedure involves stepping through the cumulative version of the gamma distribution, and at each step subtracting the probability at the previous step from the current one. The probability at each step is divided uniformly across the calendar years in the range between the lower and upper limit of the displacement curve. The default resolution on the calendar scale is 10 years, but this can be adjusted by specifying the `cal_reso` argument. The gamma distribution is stepped through using increments of 0.01m, which can be adjusted by using the argument `elev_reso`. By default, the resulting shoreline date is normalised to sum to unity.

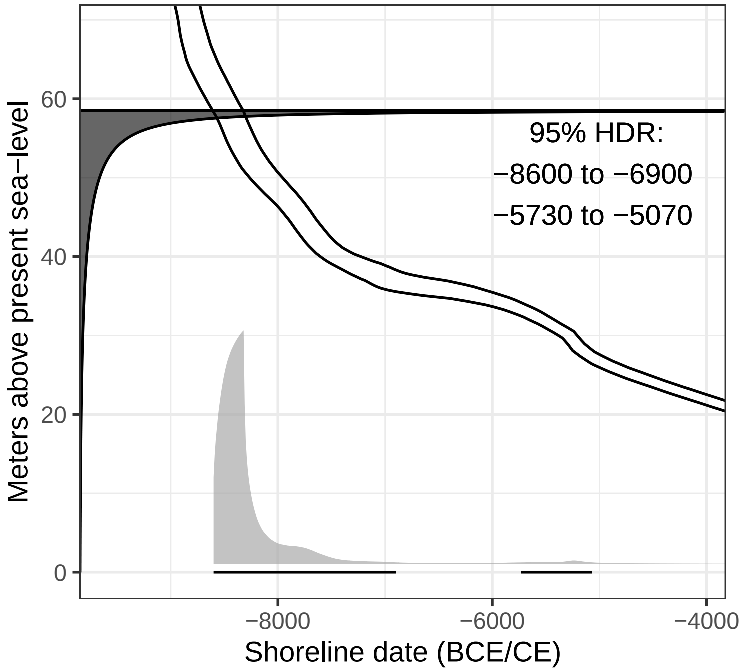
The function `shoreline_date()` returns an object of class `shoreline_date`. By calling the object the dates are printed to console, displaying site name, site elevation and the HDR of the date. Furthermore, the first column of a data frame beyond the `geom` column holding the `sf` geometry will be used as site names. If no such column is present, the sites will simply be numbered as they are passed to `shoreline_date()`.

```
target_date
```

```
## ===============
## Site:  1
## Elevation:  58.5
##
## 95% HDR:
## 8600 BCE-6900 BCE
## 5730 BCE-5070 BCE
```

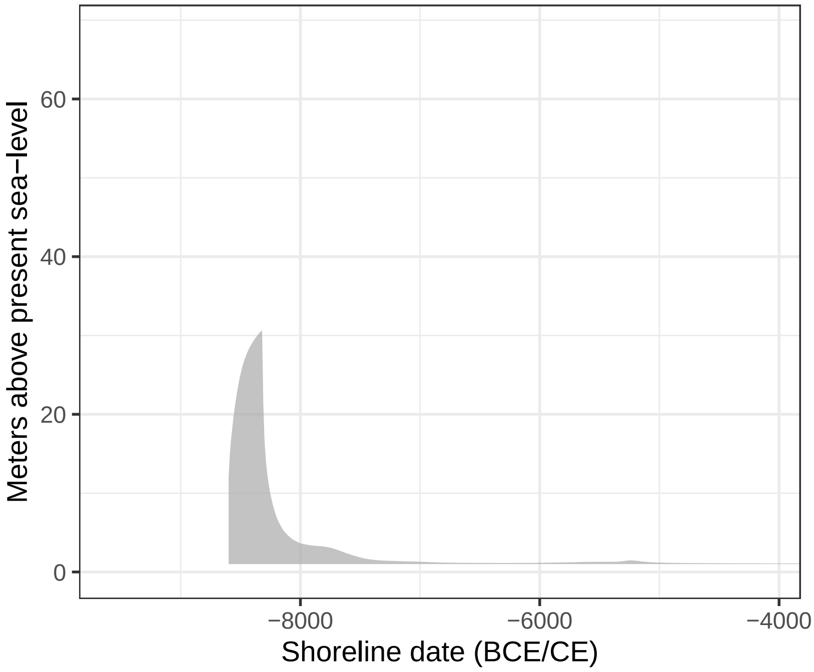
While a range of graphical parameters can be adjusted to change the appearance of the output plot, setting `greyscale = TRUE` offers a short-cut to plot a date in greyscale:

```
shoredate_plot(target_date,  greyscale = TRUE)
```



A more sparse version can also be plotted by specifying what elements are to be excluded from the plot:

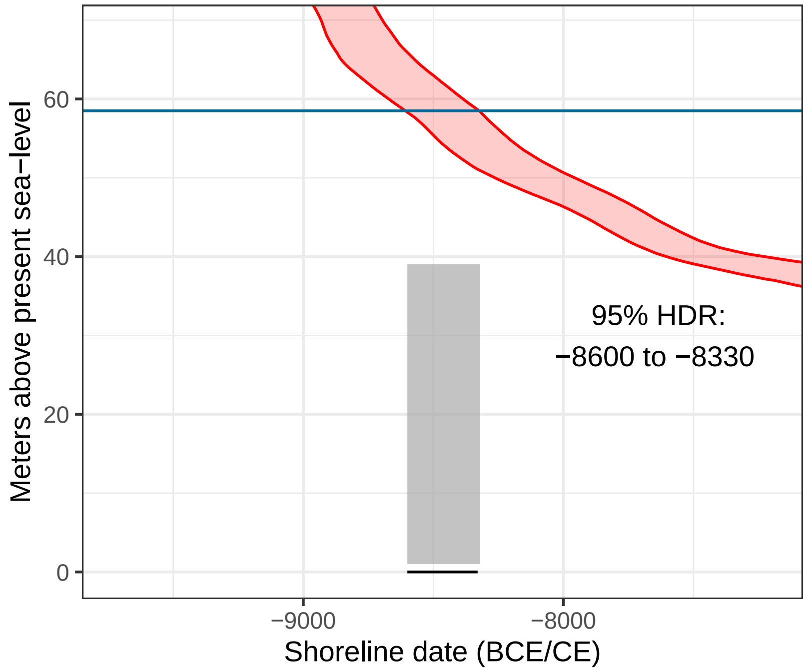
```
shoredate_plot(target_date, elevation_distribution = FALSE,
               displacement_curve = FALSE,
               highest_density_region = FALSE)
```



3.2 Finding the *terminus post quem* date

It is also possible to not account for the likely distance between the site and the shoreline. This is done by setting the `model` parameter to "none" when calling `shoreline_date()`. This thus effectively provides a *termnius post quem* date, the earliest possible date for when the site could have been in use, under the assumption that when the sea receded from the site location marks the earliest possible point in time for the occupation of the site.

```
# Date the example point, manually specifying it's elevation
tpq_date <- shoreline_date(target_point,
                           elevation = 58.5,
                           model = "none")

# Plot and adjust the position of the HDR label on the y-axis
shoredate_plot(tpq_date, hdr_label_yadj = 0.6)
```

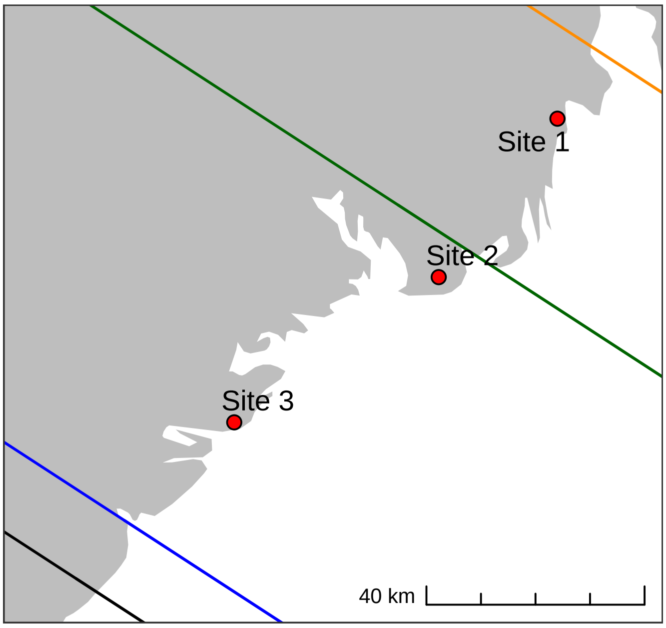


3.3 Dating multiple sites

As exemplified in the code chunks to follow, it is also possible to date multiple sites at once.

```
# Create multiple example points to be dated
target_points <- sf::st_sfc(sf::st_point(c(576052, 6567955)),
                            sf::st_point(c(554212, 6538835)),
                            sf::st_point(c(516599, 6512142)))

# Specify the correct CRS and make the points a sf data frame
# to be able to add the column below
target_points <- sf::st_as_sf(target_points, crs = 32632)

# Adding example site names
target_points$names <- c("Site 1", "Site 2", "Site 3")

# Create a plot showing the location of the points within the
# spatial limit
```

```
target_plot(target_points)
```



When dating multiple sites it can be useful to track the progress by setting `verbose = TRUE` to print the progress to console (this output is not reproduced here).

```
# Dating the target points, specifying the elevations in a
# vector of numeric values
target_dates <- shoreline_date(target_points,
                               elevation = c(68, 98, 73),
                               verbose = TRUE)
```

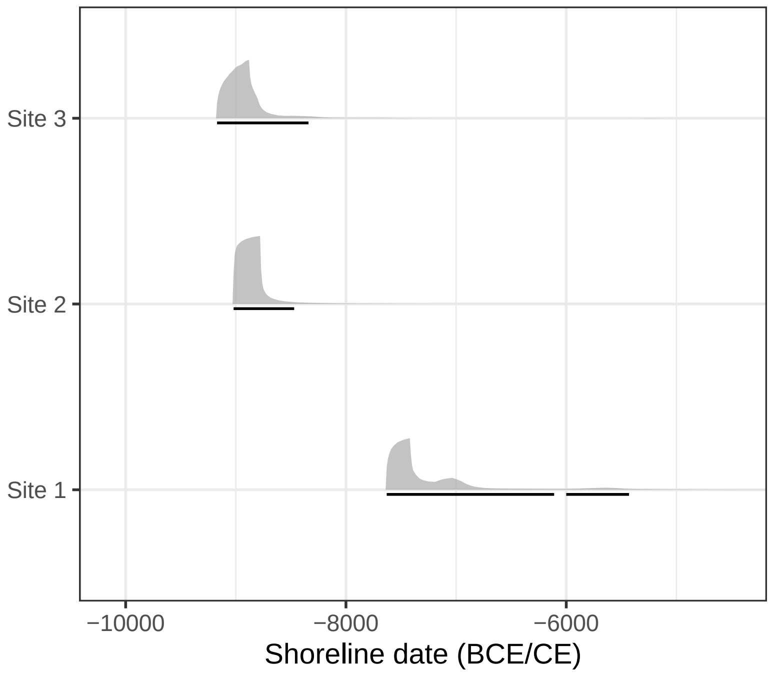
```
# Print results
target_dates
```

```
## ===============
## Site:  Site 1
## Elevation:  68
##
## 95% HDR:
## 7630 BCE-6110 BCE
## 6000 BCE-5430 BCE
```

```
## ===============
## Site:  Site 2
## Elevation:  98
##
## 95% HDR:
## 9020 BCE-8470 BCE
## ===============
## Site:  Site 3
## Elevation:  73
##
## 95% HDR:
## 9170 BCE-8340 BCE
```

The default behaviour when passing multiple dates to `shoredate_plot()` is to plot a series of individual plots. However, setting `multiplot = TRUE` collapses the dates on a single, more sparse plot. The sites are ordered from from earliest to latest possible start date for the occupation of the sites.

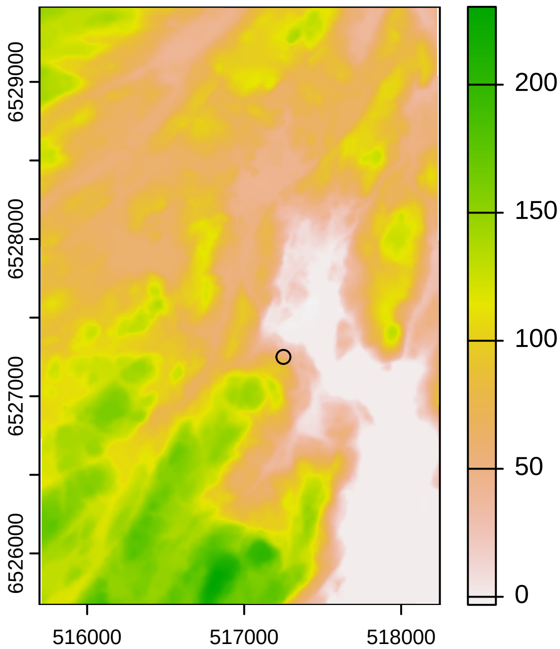
```
shoredate_plot(target_dates, multiplot = TRUE)
```



3.4 Using an elevation raster to find site elevations

The below code demonstrates how to find the elevation of one or more sites by passing a digital elevation model (DEM) to `shoreline_date()`. The example here uses data from Amazon Web Service Terrain Tiles, retrieved with the package `elevatr`. However, the best elevation data available for the study area can be retrieved freely from the Norwegian Mapping Authority at https://hoydedata.no/LaserInnsyn2/. To use this with *shoredate*, manually download a raster covering the location of the sites to be dated and read this in to R with `terra::rast()` before passing it to `shoreline_date()`.

```
# Reproject target_point for retrieving raster data
# with elevatr
target_wgs84 <- sf::st_transform(target_point, crs = 4326)

# Retrieve raster data
elev_raster <- elevatr::get_elev_raster(target_wgs84,
                                        z = 14,
                                        src = "aws")

# Make the retrieved raster a SpatRaster and re-project
# it to the correct coordinate system
elev_raster <- terra::project(terra::rast(elev_raster),
                              "epsg:32632")

# Plot the raster and target point for inspection
terra::plot(elev_raster)
plot(target_point, add = TRUE)
```



When a SpatRaster has been loaded into the R session this can be passed to shoreline_date() by specifying it in the elevation argument. This is then used to find the site elevations without having to provide these manually, as was done above. Note that if a site is represented by an object with a spatial extent (i.e. not a point feature) the default is to use the mean of the elevation on the raster. This can be changed with the elev_fun argument which accepts any function that can be passed to the fun argument in terra::extract() (see ?terra::extract).

```
raster_date <- shoreline_date(target_point,
                              elevation = elev_raster)

# Print to console
raster_date
```

```
## ===============
## Site:  1
## Elevation:  58.51383
##
## 95% HDR:
## 8600 BCE-6900 BCE
```

```
## 5730 BCE-5070 BCE
```

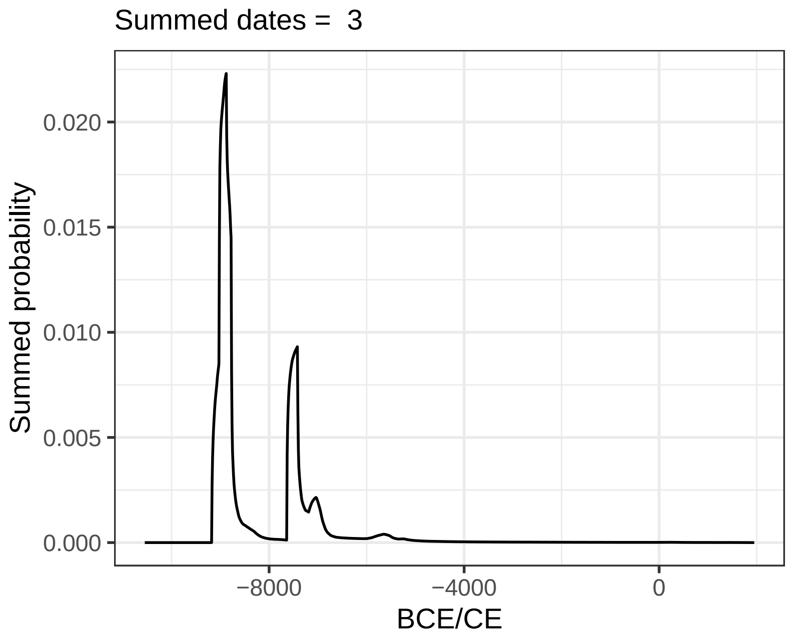
4 Summed probability distribution of shoreline dates

Using `sum_shoredates()` it is also possible to sum the probability of multiple shoreline dates to evaluate the temporal intensity of the dates, as is frequently done with calibrated radiocarbon dates (e.g. Crema and Bevan 2021). Do note that as this procedure involves collapsing the frequency of dates and their uncertainty, the interpretation of the resulting sum is not straightforward, as it's shape is determined not only by the number of sites but also the trajectory of shoreline displacement (see e.g. Bronk Ramsey 2017; Crema 2022 for perspectives and ways to approach this issue in the context of radiocarbon dates).

```
# Sum the three dates from above
summed_dates <- sum_shoredates(target_dates)
```

A simple line plot displaying the resulting summed probability can then be produced with `shoredate_sumplot()`.

```
shoredate_sumplot(summed_dates)
```



5 Direction of shoreline gradient

The direction of the shoreline gradient is specified by the isobases that run perpendicular to this gradient. When interpolating the displacement curve used for dating a site, the direction of these isobases defaults to 327°, following Romundset et al. (2018:180, fig.1). However, some authors operate with different isobase directions, with Sørensen et al. (2014:fig.2.2.3) using 338°. Furthermore, the direction of the uplift gradient might have varied throughout the Holocene (Sørensen et al. 2014:42–44).

5.1 Specifying different isobase directions

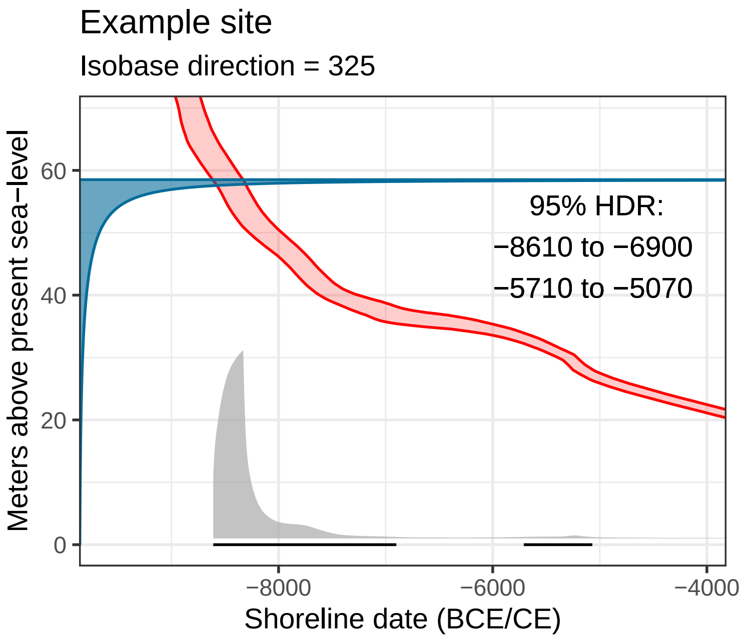
While the range of the typically employed isobase directions generally result in minor differences in the resulting shoreline dates, it is possible to specify other and multiple directions for these, and perform the shoreline dating using each individual direction. This can be useful either for evaluating the sensitivity of a date or if one believes there is reason suspect a different direction than the default in a particular case.

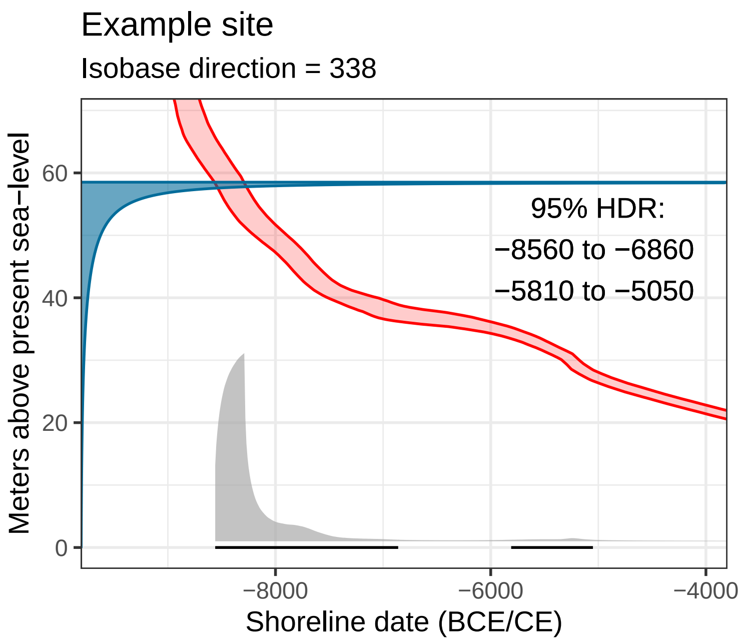
```r
# Add a name to the example site
target_point <- sf::st_as_sf(target_point, crs = 32632)
target_point$name <- "Example site"

# Using the same target point and elevation as above, but
# specifying two different directions for the isobases when
# dating
iso_date <- shoreline_date(site = target_point,
                           elevation = elev_raster,
                           isobase_direction = c(325, 338))

iso_date
```

```
## ===============
## Site:  Example site
## Elevation:  58.51383
##
## Isobase direction:  325
##
## 95% HDR:
## 8610 BCE-6900 BCE
## 5710 BCE-5070 BCE
##
## Isobase direction:  338
##
## 95% HDR:
## 8560 BCE-6900 BCE
## 5810 BCE-5070 BCE
```

In the call to plot it can then be specified that the direction of the isobases is printed with each date. Note that it is not possible use `multiplot` when having used multiple isobase directions when dating the sites. The following thus also shows the default behaviour when plotting multiple dates at once and not setting `multiplot = TRUE`.

```r
shoredate_plot(iso_date,
               site_name = TRUE,
               isobase_direction = TRUE,
               hdr_label_yadj = 0.35)
```


Example site
Isobase direction = 325
95% HDR:
−8610 to −6900
−5710 to −5070
Meters above present sea−level
Shoreline date (BCE/CE)
0
20
40
60
−8000
−6000
−4000


Example site
Isobase direction = 338
95% HDR:
−8560 to −6860
−5810 to −5050
Meters above present sea−level
Shoreline date (BCE/CE)
0
20
40
60
−8000
−6000
−4000

5.2 Sum the probability of dates across isobase directions

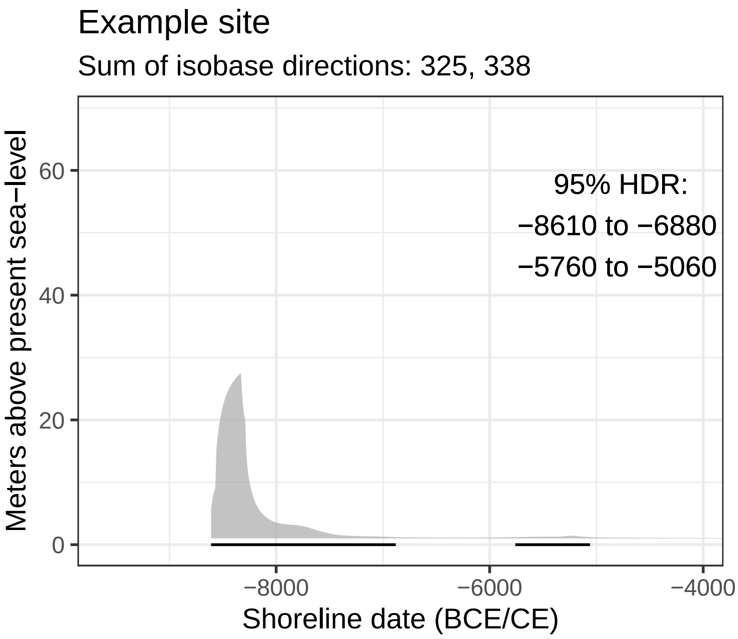
As an alternative to keeping the two shoreline dates of the site separate, the parameter `sum_isobase_directions` can be set to `TRUE` when calling `shoreline_date()` to sum the probability of the dates. Again, by default this is normalised to sum to unity.

```
sum_iso_date <- shoreline_date(site = target_point,
                               elevation = elev_raster,
                               isobase_direction = c(325, 338),
                               sum_isobase_directions = TRUE)

sum_iso_date
```

```
## ===============
## Site:  Example site
## Elevation:  58.51383
##
## Sum of isobase directions:  325 338
##
## 95% HDR:
## 8610 BCE-6880 BCE
## 5760 BCE-5060 BCE
```

This can then be passed to `shoredate_plot()`. Note that the interpolated displacement curves and the gamma distribution for the elevation of the site above sea-level is not included in the plot when summing the probability of dates across isobase directions.

```
shoredate_plot(sum_iso_date, site_name = TRUE,
               isobase_direction = TRUE)
```



6 References

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Crema, E. 2022. Statistical Inference of Prehistoric Demography from Frequency Distributions of Radiocarbon Dates: A Review and a Guide for the Perplexed. *Journal of Archaeological Method and Theory* 29:1387-1418. DOI: 10.1007/s10816-022-09559-5

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Romundset, A., Lakeman, T.R. and Høgaas, F. 2018. Quantifying variable rates of postglacial relative sea level fall from a cluster of 24 isolation basins in southern Norway. *Quaternary Science Reviews* 197:175e192. DOI: 10.1016/j.quascirev.2018.07.041

Sørensen, R, Henningsmoen, K.E. Høeg, H.I. and Gälman V. 2023. Holocen vegetasjonshistorie og landhevning i søndre Vestfold og sørøstre Telemark. In *The Stone Age in Telemark. Archaeological Results and Scientific Analysis from Vestfoldbaneprosjektet and E18 Rugtvedt–Dørdal*, edited by Persson, P. and Solheim, S., in press.

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Vignette 2: Extending shoredate (extending-shoredate.rmd)

Applying shoredate to other regions

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Contents

1 Introduction

While *shoredate* and the method underlying it has been developed for application in a constrained region of south-eastern Norway, it is possible to apply it to other areas. The following presents an example from Ørland in Trøndelag, Central Norway, for which a new displacement curve for the later parts of the Holocene has recently been published (Romundset and Lakeman 2019). Furthermore, all that is needed to use the main functions of the package is a shoreline displacement curve that describes the sea-level change at the location of a site to be dated, and an elevation value for that site. Consequently, it is in principle possible to extend the main functionality of the package to any region of the world in which the method is applicable, provided reliable data in a suitable format is available.

Some caveats and notes of caution should be added here. First of all the method will at present only work in regions which have experienced a monotonic non-increasing relative sea-level change. That is, regions with a continuous development of regressing or stable sea-levels. Furthermore, as the package was originally developed to be applied along the Skaggerrak coast of south-eastern Norway, not all of its functionality is applicable elsewhere. The function `interpolate_curve()` involves an increasing degree of uncertain extrapolation the further away from the spatial limit in south-eastern Norway one moves, and both `interpolate_curve()` and `create_isobases()` will fail with other coordinate reference systems than WGS 84 / UTM zone 32N (EPSG:32632).

Finally, the default method used for shoreline dating in the package is based on an empirically derived estimation of the relationship between coastal Stone Age sites and the contemporaneous shoreline in the Skagerrak region of south-eastern Norway. Consequently, the extent to which the same relationship characterises the site-sea relationship in other areas of Norway, and beyond, is therefore undetermined (a possible approach for assessing this relationship in other areas can be found in Roalkvam 2023). However, in regions characterised by a monotonically decreasing relative sea-level it can reasonably be assumed that the point in time when a location emerged from the sea defines the earliest possible date for when it could have been occupied. Consequently, another option is to use the method to find a *terminus post quem* date, as outlined in the main vignette, and further demonstrated below.

2 Applying *shoredate* in Ørland

2.1 Shoreline displacement curve for Ørland

Geologically derived displacement curves are in Norway often reported with a uniform probability between the lower and upper limit of the possible elevation of the sea-level over time. This is also the case for the displacement curve published for Ørland. At present, the required format for displacement curves to be used with *shoredate* is therefore a data frame with the columns `bce`, `upperelev`, `lowerelev` and `name`. Here, `upperelev` and `lowerelev` denote the highest and lowest possible elevation for the sea-level for each year BCE. Years BCE, defined by the column `bce`, should be given at an interval with equal or higher resolution than that which is desired for the resulting shoreline date. The probability between the upper and lower elevation limits are here assumed to be uniformly distributed.

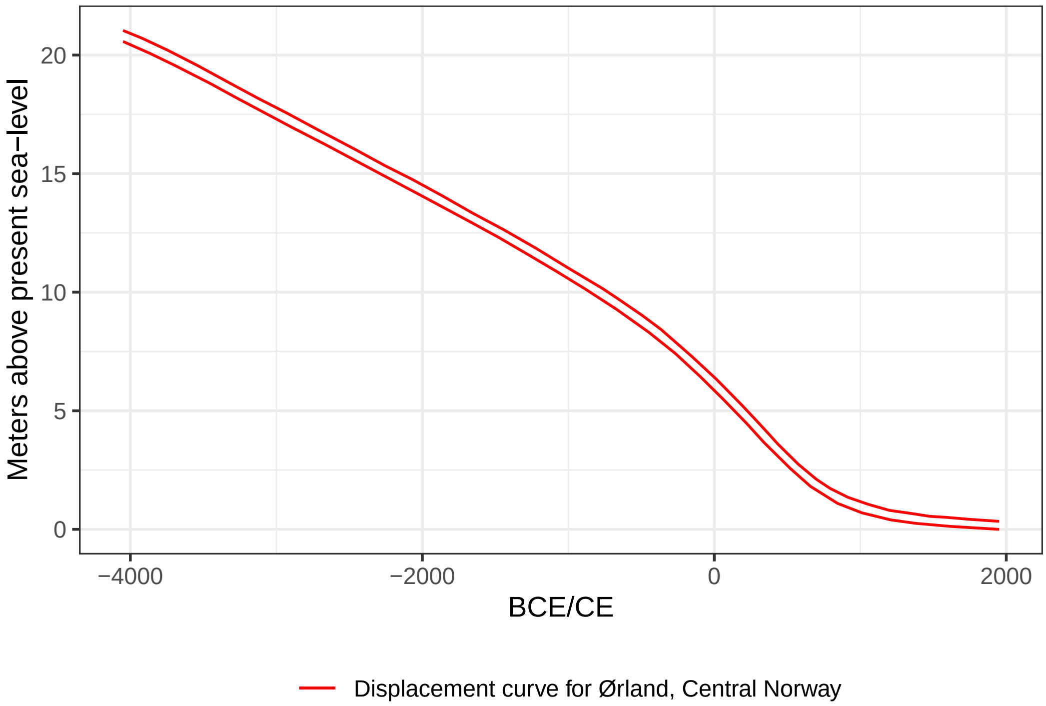
The displacement curve for Ørland is provided with *shoredate* and can be loaded with the following code:

```
# The packages ggplot2 and sf are explictly loaded here, instead of using the
# package::function() syntax with each function call below.
library(ggplot2)
library(sf)

# Load shoredate
library(shoredate)

# Load the displacement curve for Ørland
orland_disp <- get(load(system.file("extdata/orland_displacement_curve.rda",
                  package = "shoredate")))

# Print the last few rows of the Ørland displacement curve
tail(orland_disp)
```

```
##        bce upperelev lowerelev   name
## 5996 -4045  21.02450  20.55970 Ørland
## 5997 -4046  21.02702  20.56243 Ørland
## 5998 -4047  21.02954  20.56516 Ørland
## 5999 -4048  21.03206  20.56789 Ørland
## 6000 -4049  21.03458  20.57062 Ørland
## 6001 -4050  21.03710  20.57336 Ørland
```

This can then be plotted with `displacement_plot()`. The name is here adjusted with the argument `target_name` to something more informative, and the geologically derived displacement curves from south-eastern Norway are excluded by specifying the `displacement_curves` argument, as these are not of relevance here.

```
displacement_plot(target_curve = orland_disp,
                  target_name = "Displacement curve for Ørland, Central Norway",
                  displacement_curves = NA)
```



A note should be made that the Ørland curve was originally published with reference to the highest astronomical tide in the region (see Romundset and Lakeman 2019:66). To adjust this to mean sea-level, the difference in elevation between the highest astronomical tide and the mean sea-level has been been subtracted from the elevation values.

Furthermore, while variable uplift rates are also relevant for this area, this is not corrected for in this example. The example therefore focuses on the small area for which the curve was developed, where it can be assumed to be directly applicable. Functionality to adjust for variable displacement rates with *shoredate* is only accommodated for the Skagerrak area through the function `interpolate_curve()`. Thus, if similar adjustments are to made in other areas, this will at present therefore have to be done independently of *shoredate*, to which the adjusted curves can then be passed.

2.2 Creating maps of Ørland

Having loaded the displacement curve, this can then be directly used to shoreline date sites in locations where it applies, provided the elevation of the sites above present sea-level is known. First we will create a couple of fictitious site examples, each represented by a point, and maps of their location to demonstrate the extendibility of the `target_plot()` function.

```
# Create example sites
target_points <-  st_sfc(st_point(c(532719, 7065723)),
                         st_point(c(532896, 7066260)))

# Set CRS
target_points <- st_as_sf(target_points, crs = 32632)

# Add site names
target_points$name <- c("Example 1", "Example 2")
```

To create a map of where Ørland and these target points are located, one can adapt the `target_plot()` function. First, set up the geometries to be plotted:

```r
# Load in the limit of the spatial coverage in south-eastern Norway,
# which is provided with the package
senorway <- st_read(system.file("extdata/spatial_limit.gpkg",
                                package = "shoredate"), quiet = TRUE)

# Assign a name to this for the map legend
senorway$name <- "Skagerrak limit"

# Retrieve the first of the example points, to represent Ørland
orland <- target_points[1,]
orland$location = "Ørland"
```

Once this has been done we can use `target_plot()` to set up a plot. Setting `naturalearth_basemap` to TRUE downloads a world map from https://www.naturalearthdata.com/ using the `rnaturalearth` package. This is stored in a temporary folder and is deleted when the current R session is ended. The argument `naturalearth_zoom` specifies the amount of cropping that is done on this world map, with the provided targets as the focal point. The argument `crs_epsg` is here the same as the default, but is explicitly called to highlight that different coordinate reference systems can be used. Setting the argument `isobases` to NA means that the default isobases pertaining to south-eastern Norway are excluded from the plot. Finally, setting `target_labels` to FALSE excludes the labelling of the target points in the plot, which will instead be handled with a legend in the code to follow below.

```r
overview_map <- target_plot(targets = orland,
                      naturalearth_basemap = TRUE,
                      naturalearth_zoom = c(1000000, 1000000),
                      crs_epsg = 32632,
                      base_col = "black",
                      base_fill = "grey85",
                      isobases = NA,
                      target_labels =  FALSE)
```

```
## The legacy packages maptools, rgdal, and rgeos, underpinning this package
## will retire shortly. Please refer to R-spatial evolution reports on
## https://r-spatial.org/r/2023/05/15/evolution4.html for details.
## This package is now running under evolution status 0
```

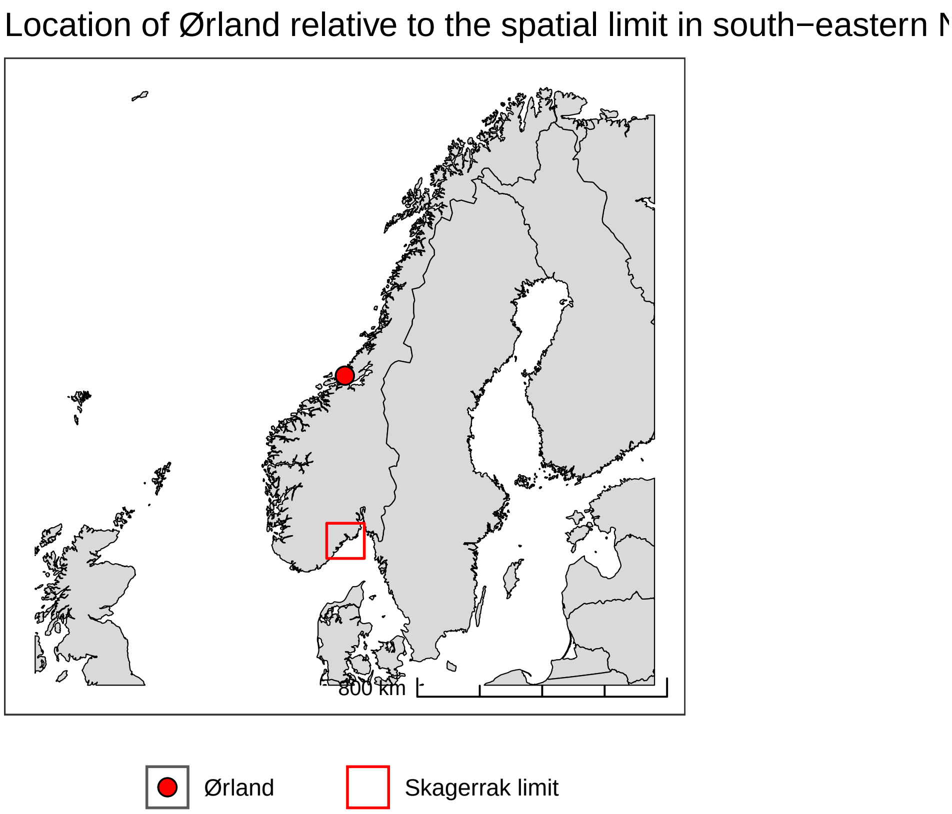
Having created a base plot, this can now be manipulated using other functions from the package `ggplot2`.

```r
overview_map <- overview_map +
        geom_sf(data = senorway, aes(col = name), fill = NA,
                    lwd = 0.5, show.legend = "polygon") +
        # Replotting the point for Ørland to add it to the legend
        geom_sf(data = orland, aes(fill = location),
                    col = "black", shape = 21,
                    size = 3, show.legend = "point") +
        scale_fill_manual(values = c("Ørland" = "red")) +
        scale_colour_manual(values = c("Skagerrak limit" = "red"),
                                guide = guide_legend(
                                           override.aes = list(shape = NA))) +
        theme(legend.position = "bottom",
              legend.title = element_blank()) +
        ggtitle(paste("Location of Ørland relative to the",
                      "spatial limit in south-eastern Norway"))
```

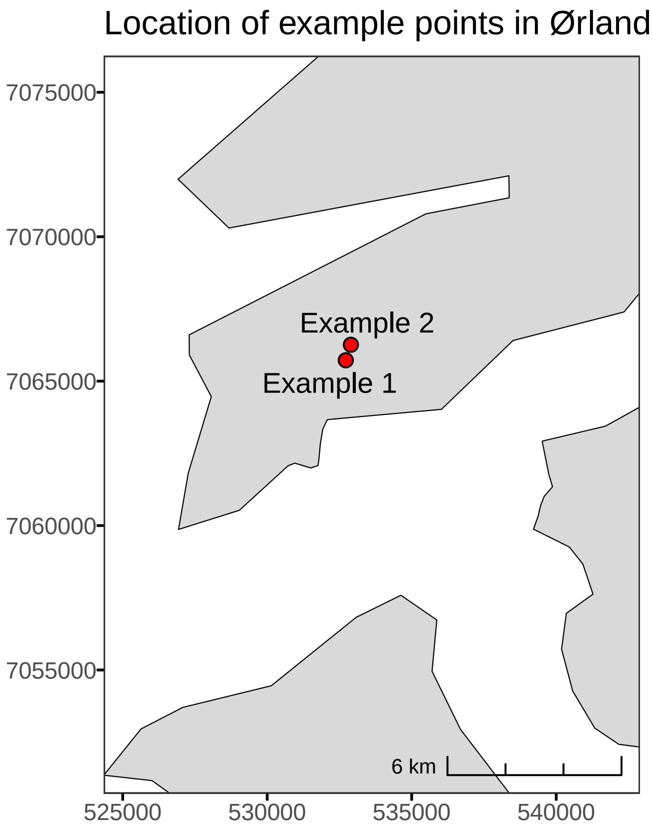
When the map displaying the location of Ørland is created, we can create a second map that shows the location of the example points, zoomed in at Ørland, which is located at the tip of the Fosen peninsula.

While the map is fairly simple, it can nonetheless be useful to perform this exercise to make sure everything looks as it should.

```
# Create basemap
examples_map <- target_plot(targets = target_points,
                            naturalearth_basemap = TRUE,
                            naturalearth_zoom = c(15000, 10000),
                            base_col = "black",
                            base_fill = "grey85",
                            isobases = NA)

# Add axis labels and ticks, which are not returned with target_plot()
examples_map <- examples_map +
      theme(
        axis.text.y = element_text(),
        axis.text.x = element_text(),
        axis.ticks = element_line()) +
      coord_sf(datum = st_crs(target_points), expand = FALSE) +
      ggtitle("Location of example points in Ørland")

# Call overview map
overview_map
```



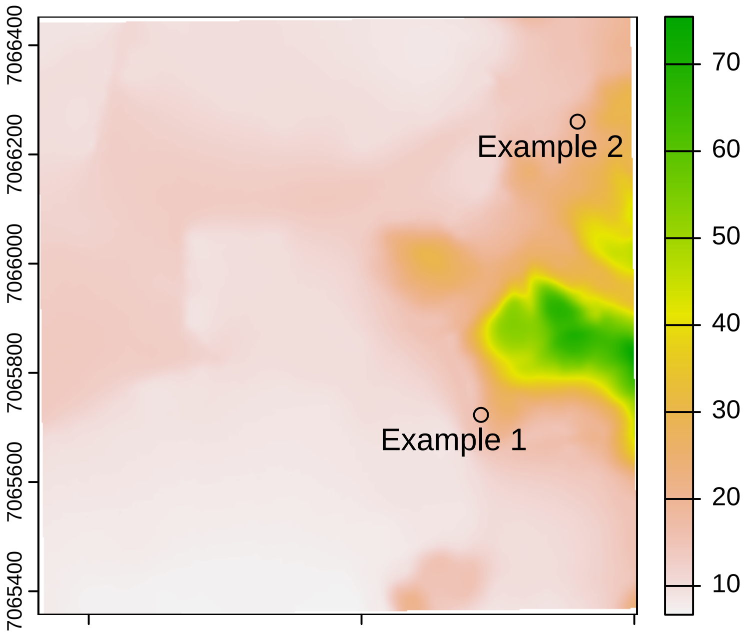

```
# Call map displaying the location of the example points
examples_map
```



2.3 Dating example sites in Ørland

For this example, a raster retrieved from Amazon Web Service Terrain Tiles is used for finding the elevation of the example sites. This follows the procedure that is outlined in the main vignette.

```
# Retrieve raster
target_wgs84 <- st_transform(target_points, crs = 4326)
elev_raster <- elevatr::get_elev_raster(target_wgs84, z = 14,
                                        verbose = FALSE, src = "aws")
elev_raster <- terra::project(terra::rast(elev_raster), "epsg:32632")

# Plot the raster and sites for inspection
terra::plot(elev_raster)
plot(target_points, col = "black", add = TRUE)
text(st_coordinates(target_points) - 50, labels = target_points$name)
```



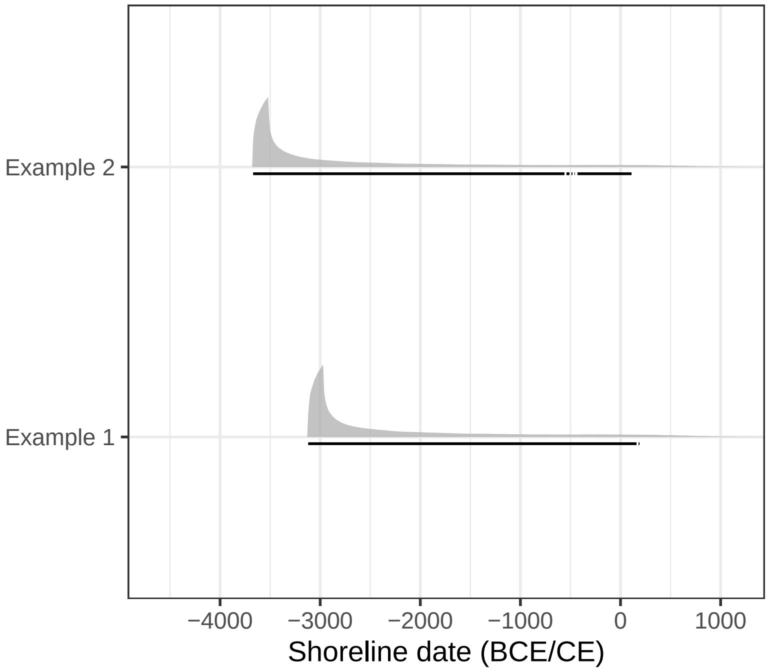
After the raster has been loaded we can find the elevation of the sites:

```
terra::extract(elev_raster, terra::vect(target_points))[, -1]
```

```
## [1] 17.74339 19.53946
```

This elevation is retrieved by `shoreline_date()` if the raster is passed to its `elevation` argument and the sites to be dated are provided as spatial geometries. However, to illustrate the point that all that is needed to use `shoreline_date()` is a displacement curve and knowledge of these elevations, the function is here called by only providing the displacement curve and providing a character vector with the name of the sites and a numerical vector with their elevations:

```
target_dates <- shoreline_date(sites = c("Example 1", "Example 2"),
                               target_curve = orland_disp,
                               elevation = c(17.7, 19.5))

# Plot the results
shoredate_plot(target_dates, multiplot = TRUE)
```



2.4 Finding the earliest possible date

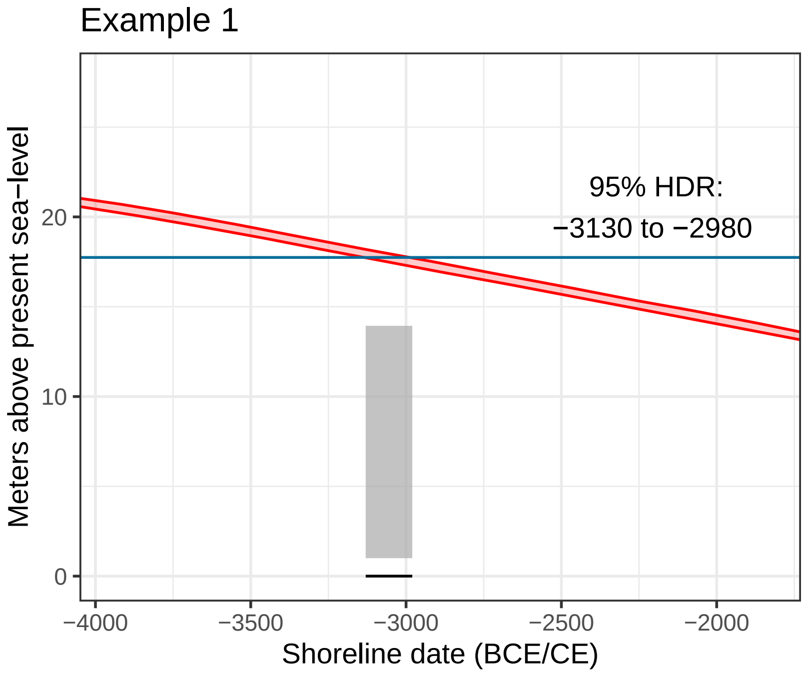
As mentioned, the above implementation assumes that the relationship between the sites and the shoreline is characterised by the same gamma function as that identified for sites in south-eastern Norway. At present, the only adjustment that is possible to do to this assumed relationship is changing the parameters for the gamma function when calling `shoreline_date()`, using the argument `model_parameters`.

However, as an alternative it is also possible to perform the dating procedure without accounting for any distance between the site and the contemporaneous shoreline. This is done by setting the parameter `model` to "none" when calling `shoreline_date()`. This thus effectively provides a *termnius post quem* date, under the assumption that the earliest possible date for when the site was in use is when the location of the site emerged from the sea.

While a *terminus post quem* date limits the further inferential steps that can be taken, it might be more appropriate to apply shoreline dating in this manner in regions where the relationship between sites and the shoreline is unknown. This can potentially also be extended to the dating of other phenomena such as rock art, or other cases where this relationship is less certain (see e.g. Sognnes 2003).

Furthermore, it could also be possible to reverse this logic in regions that have instead been subject to relative sea-level rise, where the date for when a location was inundated can provide a *terminus ante quem* date – the latest possible date for the use of a site. However, implementation of *shoredate* to regions which have experienced continuous or disjoint phases of relative sea-level rise remains to be developed.

```
# Finding the earliest possible date for the first example point
earliest_date <- shoreline_date(target_points[1,],
                                target_curve = orland_disp,
                                elevation = elev_raster,
                                model = "none")

# Call to plot
shoredate_plot(earliest_date, site_name = TRUE)
```



3 References

Roalkvam, I. 2023 A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast. *Quaternary Science Reviews* 299:107880. DOI: 10.1016/j.quascirev.2022.107880

Romundset, A. and Lakeman, T.R. 2019. Shoreline displacement at Ørland since 6000 cal. yr BP. In *Environment and Settlement: Ørland 600 BC – AD 1250: Archaeological Excavations at Vik, Ørland Main Air Base*, edited by Ystgaard, I. Cappelen Damm Akademisk, Oslo, pp. 51–67. DOI: 10.23865/noasp.89

Sognnes, K. 2003. On Shoreline Dating of Rock Art. *Acta Archaeologica* 74:189–209. DOI: 10.1111/j.0065-001X.2003.aar740104.x

Reference manual for shoredate (shoredate.pdf)

Package 'shoredate'

June 3, 2023

Type Package

Title Shoreline Dating Coastal Stone Age Sites

Version 1.1.0

Description Provides tools for shoreline dating coastal Stone Age sites. The implemented method was developed in Roalkvam (2023) <doi:10.1016/j.quascirev.2022.107880> for the Norwegian Skagerrak coast. Although it can be extended to other areas, this also forms the core area for application of the package. Shoreline dating is based on the present-day elevation of a site, a reconstruction of past relative sea-level change, and empirically derived estimates of the likely elevation of the sites above the contemporaneous sea-level when they were in use. The geographical and temporal coverage of the method thus follows from the availability of local geological reconstructions of shoreline displacement and the degree to which the settlements to be dated have been located on or close to the shoreline when they were in use. Methods for numerical treatment and visualisation of the dates are provided, along with basic tools for visualising and evaluating the location of sites.

Language en-US

License GPL (>= 3)

URL `https://github.com/isakro/shoredate`,
`https://isakro.github.io/shoredate/`

BugReports `https://github.com/isakro/shoredate/issues`

Encoding UTF-8

RoxygenNote 7.2.1

Imports ggplot2, ggrepel, ggridges, ggspatial, sf, terra, utils

Suggests covr, elevatr, rgdal, knitr, rmarkdown, testthat (>= 3.0.0), vdiffr, rnaturalearth

VignetteBuilder knitr

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NeedsCompilation no

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Depends R (>= 3.5.0)

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R topics documented:

`create_isobases` *Create isobases with different directions within the spatial coverage in south-eastern Norway*

Description

Function to create isobases for interpolating shoreline displacement curves within the spatial coverage in south-eastern Norway. This is done from the centre points of the supplied displacement curves. Isobases can also be created for multiple directions, which is useful for testing the sensitivity of dates to the direction of the isobases.

Usage

```
create_isobases(isobase_direction)
```

Arguments

`isobase_direction`
A numerical vector holding a single or multiple directions for the isobases.

Value

A simple feature holding the isobases represented as lines.

Examples

```
# Create isobases in a specified direction
isobases <- create_isobases(327)
plot(sf::st_geometry(isobases))

# Create isobases using different directions
isobases <- create_isobases(c(327, 338))

# Plot for visualisation
plot(sf::st_geometry(isobases))
```

---

displacement_plot *Plot shoreline displacement curves*

Description

Function for plotting shoreline displacement curves. Calling to plot without providing a target curve will display the four underlying geologically derived displacement curves.

Usage

```
displacement_plot(
  target_curve = NA,
  displacement_curves = c("Horten", "Porsgrunn", "Tvedestrand", "Arendal"),
  target_name = "Target curve",
  target_line = "solid",
  target_col = "red",
  target_alpha = 1,
 displacement_line = c(Horten = "solid", Porsgrunn = "solid", Tvedestrand = "solid",
    Arendal = "solid"),
 displacement_col = c(Horten = "darkorange", Porsgrunn = "darkgreen", Tvedestrand =
    "blue", Arendal = "black"),
  displacement_alpha = 1,
  greyscale = FALSE
)
```

Arguments

`target_curve` Data frame holding a shoreline displacement curve.

`displacement_curves`
: Character vector specifying which geologically informed displacement curves should be plotted. Accepted values are `c("Horten", "Porsgrunn", "Tvedestrand", "Arendal")`. All are included by default.

`target_name` Character value specifying the name that is given to the target curve, if provided. Defaults to `"Target curve"`.

`target_line` Character value specifying the line type that is used for the target curve, if this is provided. Defaults to `"solid"`.

target_col — Character value specifying the colour that is used for the target curve, if this is provided. Defaults to "red".

target_alpha — Numerical value specifying the alpha value that is used for the target curve, if this is provided. Defaults to 1.

displacement_line — Character vector specifying the line types that are used for the geological displacement curves to be plotted. Defaults to c("Horten" = "solid", "Porsgrunn" = "solid", "Tvedestrand" = "solid", "Arendal" = "solid").

displacement_col — Character vector specifying the colours that are used for the geological displacement curves to be plotted. Defaults to c("Horten" = "darkorange", "Porsgrunn" = "darkgreen", "Tvedestrand" = "blue", "Arendal" = "black").

displacement_alpha — Numerical value specifying the alpha value that are used for all of the geological displacement curves to be plotted. Defaults to 1.

greyscale — Logical value indicating whether the plot should be in greyscale or not. Defaults to FALSE.

Value

A plot displaying the underlying shoreline displacement curves and, if provided, a target curve.

Examples

```
# Empty plot for speed
displacement_plot(displacement_curves = "")
```

---

interpolate_curve — *Interpolate displacement curve to a target location within the spatial coverage in south-eastern Norway*

Description

Interpolate the trajectory of past shoreline displacement to a target location within the spatial coverage on the Skagerrak coast of south-eastern Norway. This based on the distance of the location to the shoreline isobases of the geologically derived displacement curves and is done using inverse distance weighting.

Usage

```
interpolate_curve(
  target,
  isobases = NA,
  power = 2,
  cal_reso = 10,
  verbose = FALSE
)
```

Arguments

`target`	A spatial target location to where the new displacement curve is interpolated.
`isobases`	4 spatial lines representing the shoreline isobases of the existing displacement curves. Multiple sets of 4 isobases with different isobase directions can be provided (see `create_isobases()`). Defaults to isobases with a direction of `327`.
`power`	A numerical value indicating the inverse distance power for IDW. Defaults to `2`.
`cal_reso`	A numerical value specifying the resolution to use on the calendar scale. Defaults to `10`.
`verbose`	Logical value indicating whether progress should be printed to console. Defaults to `FALSE`.

Value

Returns a list holding an interpolated displacement curve for each isobase direction. Each displacement curve is represented by a data frame with the columns `bce` where negative values indicate years BCE and positive CE, `lowerelev`, representing the lower limit for the elevation of the shoreline for each year. `upperelev`, the upper limit for elevation of the shoreline for each year, and `direction` which indicates the direction of the isobases used when interpolating the curve.

Examples

```
# Create example point using the required coordinate system
# WGS84 / zone UTM32N (EPSG: 32632)
target_point <- sf::st_sfc(sf::st_point(c(579570, 6582982)), crs = 32632)

# Interpolate shoreline displacement curve to the target point location,
# setting the resolution on the calendar scale to 2000 years for speed.
target_curve <- interpolate_curve(target_point, cal_reso = 2000)
```

`print.shoreline_date` *Print shoreline dates to console*

Description

Print the dates held in a `shoreline_date` object. Each date is printed with site name, elevation and highest density region. If the isobase direction is different or more are provided than the default, the directions and dates associated with these are printed separately.

Usage

```
## S3 method for class 'shoreline_date'
print(x, ...)
```

Arguments

`x`	Object of class `shoreline_date`.
`...`	Additional arguments.

Value

Print the site names, elevations, non-default isobase directions and HDRs contained in a `shoreline_date` object to console.

Examples

```
target_point <- sf::st_sfc(sf::st_point(c(538310, 6544255)), crs = 32632)

# Reduce date resolution with cal_reso and elevation_reso for speed
target_date <- shoreline_date(site = target_point,
                              elevation = 70,
                              elev_reso = 1,
                              cal_reso = 400)

# Print to console
target_date
```

---

shoredate_hdr *Find the highest density region of shoreline dates*

Description

Function to find 95% highest density region (HDR) for a provided shoreline date. Negative values denote years BCE while positive values denote CE.

Usage

```
shoredate_hdr(bce, probability, site_name, cal_reso, prob = 0.95)
```

Arguments

`bce`	A vector holding calendar years associated with a date.
`probability`	A vector holding the probability mass corresponding to each calendar year.
`site_name`	A vector holding the name of the site that has been dated.
`cal_reso`	Resolution on the calendar scale used when dating the site.
`prob`	A numerical value between 0 and 1 indicating the probability coverage of the HDR. Defaults to `0.95`.

Value

A list holding start and end points for segments of the highest density region of a shoreline date, the weighted mean date, the probability coverage and site name.

Examples

```
target_point <- sf::st_sfc(sf::st_point(c(538310, 6544255)), crs = 32632)

# Reduce date resolution with cal_reso and elevation_reso for speed
target_date <- shoreline_date(sites = target_point,
                              elevation = 80,
                              elev_reso = 1,
                              cal_reso = 400)

# shoredate_hdr() is already called under the hood with shoreline_date(),
# the result of which is printed when calling the shoreline_date object
target_date

# However, shoredate_hdr() can be applied separately by pulling the
# necessary data from the date
(shoredate_hdr(target_date[[1]][[1]]$date$bce,
               target_date[[1]][[1]]$date$probability,
               target_date[[1]][[1]]$site_name,
               target_date[[1]][[1]]$cal_reso))
```

`shoredate_plot` *Plot shoreline dates*

Description

Function for plotting shoreline dates along with associated metadata.

Usage

```
shoredate_plot(
  shorelinedates,
  date_probability = TRUE,
  elevation_distribution = TRUE,
  displacement_curve = TRUE,
  site_name = FALSE,
  parameters = FALSE,
  isobase_direction = FALSE,
  highest_density_region = TRUE,
  hdr_label = TRUE,
  multiplot = FALSE,
  date_col = NA,
  date_fill = "darkgrey",
  displacement_col = "red",
  displacement_fill = "red",
  site_elevation_col = "#046c9a",
  site_elevation_fill = "#046c9a",
  hdr_col = "black",
  hdr_label_xadj = 0.2,
```

```
  hdr_label_yadj = 0.3,
  greyscale = FALSE
)
```

Arguments

shorelinedates
: Object of class `shoreline_date`.

date_probability
: Logical value indicating whether the probability distribution of the shoreline date should be plotted. Defaults to `TRUE`.

elevation_distribution
: Logical value indicating whether the distribution describing the distance between site and shoreline should be displayed. Default is `TRUE`.

displacement_curve
: Logical value indicating whether the displacement curve should be displayed. Default is `TRUE`.

site_name
: Logical value indicating whether the name of the site should be printed in the header of the plot. Defaults to `FALSE`.

parameters
: Logical value indicating whether the parameters of the statistical function should be displayed. Default is `FALSE`.

isobase_direction
: Logical value indicating whether the direction of the isobases should be printed. Default is `FALSE`.

highest_density_region
: Logical value indicating whether the 95% highest density region should be displayed. Defaults to `TRUE`.

hdr_label
: Logical value indicating whether the numeric values for the highest density regions should be displayed. Default is `TRUE`.

multiplot
: Logical value indicating whether multiple dates should be plotted individually, or be collapsed into a single plot. The only other graphical option with `multiplot` set to `TRUE` is `highest_density_region`. Default is `FALSE`.

date_col
: Character value specifying the outline colour of the probability distribution of the shoreline date. Defaults to `NA`.

date_fill
: Character value specifying the fill colour of the probability distribution of the shoreline date. Defaults to `"darkgrey"`.

displacement_col
: Character value specifying the outline colour of the displacement curve. Defaults to `"red"`.

displacement_fill
: Character value specifying the fill colour of the displacement curve. Defaults to `"red"`.

site_elevation_col
: Character value specifying the outline colour of the distribution describing the likely distance between site and shoreline. Defaults to `"#046c9a"`.

site_elevation_fill
: Character value specifying the fill colour of the distribution describing the likely distance between site and shoreline. Defaults to `"#046c9a"`.

hdr_col — Character value specifying the colour of the line segment giving the highest density region of the shoreline date. Defaults to "black".

hdr_label_xadj — Numerical value between 0 and 1 specifying the position of the HDR label on the x-axis. Increasing the value moves the label further from the plot border. Defaults to 0.2.

hdr_label_yadj — Numerical value between 0 and 1 specifying the position of the HDR label on the y-axis. Increasing the value moves the label further from the plot border. Defaults to 0.3.

greyscale — Logical value indicating whether the plot should be in greyscale or not. If TRUE, overrides other colour parameters. Defaults to FALSE.

Details

`shoredate_plot()` returns a plot displaying the provided shoreline dates. A single plot is created for each date, where a range of settings can be adjusted to display or hide various parameters and results. Setting the parameter `multiplot` to `TRUE` returns a sparser version for multiple dates, where the only option is whether or not to display the highest density region in addition to each date. `multiplot` does not allow for multiple isobase directions. Negative values denote years BCE while positive values denote CE.

Value

Plot(s) displaying shoreline dates and associated metadata.

Examples

```
# Create example point with correct coordinate reference system
target_point <- sf::st_sfc(sf::st_point(c(538310, 6544255)), crs = 32632)

# Reduce date resolution with cal_reso and elevation_reso for speed
target_date <- shoreline_date(sites = target_point, elevation = 80,
                              elev_reso = 10,
                              cal_reso = 500)

shoredate_plot(target_date)
```

---

shoredate_sumplot — *Plot the summed probability distribution of multiple shoreline dates*

Description

Function to plot the sum of the probabilities of multiple shoreline dates as resulting from running `sum_shoredates()`.

Usage

```
shoredate_sumplot(shoredates_sum, sample_size = TRUE)
```

Arguments

shoredates_sum Object of class shoredates_sum.

sample_size Logical indicating whether or not to display the number of summed dates on the plot. Defaults to TRUE.

Value

A line plot showing the provided summed probability distribution.

Examples

```
# Create example points
target_points <- sf::st_sfc(sf::st_point(c(538310, 6544255)),
                            sf::st_point(c(538300, 6544250)))

# Set correct CRS
target_points <- sf::st_as_sf(target_points, crs = 32632)

# Reduce date resolution with cal_reso and elevation_reso for speed
target_dates <- shoreline_date(target_points,
                               elevation = c(65, 70),
                               elev_reso = 10,
                               cal_reso = 750)

# Find summed probability
target_sum <- sum_shoredates(target_dates)

# Call to plot
shoredate_sumplot(target_sum)
```

---

shoreline_date *Shoreline date*

Description

A function for shoreline dating Stone Age sites based on their present-day elevation, their likely elevation above sea-level when in use and the trajectory of past shoreline displacement. Details and caveats pertaining to the implemented method is given in Roalkvam (2023).

Usage

```
shoreline_date(
  sites,
  elevation = NA,
  elev_reso = 0.01,
  cal_reso = 10,
  isobase_direction = 327,
  sum_isobase_directions = FALSE,
```

```
  model = "gamma",
  model_parameters = c(0.286, 20.833),
  elev_fun = "mean",
  upper_temp_limit = -2500,
  target_curve = NA,
  hdr_prob = 0.95,
  normalise = TRUE,
  sparse = FALSE,
  verbose = FALSE
)
```

Arguments

`sites` Vector giving one or more site names, or, if displacement curves are to be interpolated, objects of class `sf` representing the sites to be dated. In the case of a spatial geometry, the first column is taken as the site name.

`elevation` Vector of numeric elevation values for each site or a an elevation raster of class `SpatRaster` from the package `terra` from where the elevation values are to be derived.

`elev_reso` Numeric value specifying the resolution with which to step through the distribution representing the distance between site and shoreline. Defaults to 0.01m.

`cal_reso` Numeric value specifying the resolution to use on the calendar scale. Defaults to 10.

`isobase_direction` A vector of numeric values defining the direction(s) of the isobases. Defaults to 327.

`sum_isobase_directions` Logical value indicating that if multiple isobase directions are specified in `isobase_direction` the results should be summed for each site using `sum_shoredates`. Defaults to FALSE.

`model` Character vector specifying the statistical model with which to model the distance from site to shoreline. Currently accepts either "none" or "gamma". Defaults to "gamma".

`model_parameters` Vector of numeric values specifying the parameters for the statistical model describing the distance between site and shoreline. Defaults to c(0.286, 20.833), denoting the shape and scale of the default gamma function, respectively.

`elev_fun` Statistic to define site elevation if this is to be derived from an elevation raster. Uses `terra::extract()`. Defaults to mean.

`upper_temp_limit` Numerical value giving the upper temporal limit. Dates with a start date after the limit are returned as NA. Defaults to -2500, i.e. 2500 BCE.

`target_curve` Data frame holding pre-computed shoreline displacement curve. This has to have the same or higher resolution on the calendar scale as that specified with `cal_reso`. `interpolate_curve()` will be run if nothing is provided to `target_curve`. Defaults to NA.

`hdr_prob`	Numeric value specifying the coverage of the highest density region. Defaults to 0.95.
`normalise`	Logical value specifying whether the shoreline date should be normalised to sum to unity. Defaults to TRUE.
`sparse`	Logical value specifying if only site name and shoreline date should be returned. Defaults to FALSE. Note that of the functions for further treatment, sparse dates are only compatible with `sum_shoredates()`.
`verbose`	Logical value indicating whether progress should be printed to console. Defaults to FALSE.

Value

A nested list of class `shoreline_date` holding the shoreline date results and associated metadata for each dated site for each isobase direction. The elements of each date is:

- `site_name` name of the site.
- `site_elev` elevation of the site.
- `date` data frame with the columns `bce` where negative values indicate years BCE and positive CE, as well as `probability`, which gives the probability mass for each year.
- `weighted_mean` the weighted mean date.
- `hdr_start` start values for the HDR ranges.
- `hdr_end` end values for the HDR ranges.
- `hdr_prob` probability level for the HDR.
- `dispcurve` data frame holding the displacement curve used for dating the site. This has the columns `bce`, giving years BCE/CE. `lowerelev`, the lower limit for the elevation of the shoreline for each year. `upperelev`, the upper limit for elevation of the shoreline for each year.
- `dispcurve_direction` direction of the isobases in use.
- `model_parameters` parameters for the statistical model.
- `modeldat` data frame holding the model distribution. The column `offset` denotes the vertical distance (m) from the shoreline, as specified by the `elev_reso` argument. `px` is the cumulative probability at each step of `offset`, and `probs` is the probability of each step found by subtracting the preceding value from each value of `px`.
- `cal_reso` resolution on the calendar scale.

References

Roalkvam, I. 2023. A simulation-based assessment of the relation between Stone Age sites and relative sea-level change along the Norwegian Skagerrak coast. *Quaternary Science Reviews* 299:107880. DOI: https://doi.org/10.1016/j.quascirev.2022.107880

Examples

```
# Create example point using the required CRS WGS84 UTM32N (EPSG: 32632)
target_point <- sf::st_sfc(sf::st_point(c(538310, 6544255)), crs = 32632)
```

```
# Date target point, manually specifying the elevation instead of providing
# an elevation raster. Reducing elev_reso and cal_reso for speed.
shoreline_date(sites = target_point,
               elevation = 80,
               elev_reso = 1,
               cal_reso = 400)
```

`sum_shoredates` *Sum the probability of multiple shoreline dates*

Description

Function for finding the summed probability distribution of multiple shoreline dates.

Usage

```
sum_shoredates(
  shoreline_dates,
  cut_off = -2500,
  cut_off_level = 1,
  normalise = TRUE
)
```

Arguments

`shoreline_dates`	Object of class `shoreline_date`.
`cut_off`	Calendar year specifying where dates should be cut off. Defaults to 2500 BCE.
`cut_off_level`	Numerical value between 0 and 1 indicating the probability mass that has to fall after the cut-off for a date to be excluded. Defaults to 1, retaining all dates.
`normalise`	Logical value indicating whether the probability sum of the dates should be normalised to sum to unity. Defaults to TRUE.

Value

List of class `shoredate_sum` holding the elements:

- `sum` data frame with the columns `bce` where negative values indicate years BCE and positive CE, as well as `probability`, which gives the probability mass for each year.
- `dates_n` number of dates that make up the sum after applying any specified cut-off. One date per site per isobase direction.

Examples

```
target_points <- sf::st_sfc(sf::st_point(c(538310, 6544255)),
                            sf::st_point(c(538300, 6544250)))
target_points <- sf::st_as_sf(target_points, crs = 32632)

# Shoreline date, reducing resoltuion on elevation and calendar scales for
# speed.
target_dates <- shoreline_date(target_points,
                               elevation = c(65, 70),
                               elev_reso = 10,
                               cal_reso = 500)

sum_shoredates(target_dates)
```

---

target_plot *Plot a map with target locations*

Description

Function to plot the centroids of sites to be dated and shoreline isobases of employed displacement curves on a basemap. Defaults to displaying a light-weight version of the spatial coverage in south-eastern Norway. However, spatial geometries covering other regions can also be provided or temporarily downloaded with the function.

Usage

```
target_plot(
  targets = NA,
  isobases = sf::st_read(system.file("extdata/isobases.gpkg", package = "shoredate",
    mustWork = TRUE), quiet = TRUE),
  basemap = sf::st_read(system.file("extdata/naturalearth_basemap.gpkg", package =
    "shoredate", mustWork = TRUE), quiet = TRUE),
  crs_epsg = 32632,
  naturalearth_basemap = FALSE,
  naturalearth_zoom = c(20000, 20000),
  target_labels = TRUE,
  scalebar = TRUE,
  scalebar_width = 0.4,
  scalebar_style = "ticks",
  scalebar_location = "br",
  base_fill = "grey",
  base_col = NA,
  target_shape = 21,
  target_col = "black",
  target_fill = "red",
  target_size = 2.25,
  isobase_line = c(Horten = "solid", Porsgrunn = "solid", Tvedestrand = "solid", Arendal
```

```
    = "solid"),
  isobase_col = c(Arendal = "black", Porsgrunn = "darkgreen", Tvedestrand = "blue",
    Horten = "darkorange"),
  greyscale = FALSE
)
```

Arguments

`targets` Objects of class `sf` representing the sites to be dated. The first column beyond geom is taken as site name.

`isobases` Spatial lines as object of class `sf` representing the shoreline isobases. Defaults to isobases with a direction of 327 within the spatial limit in SE Norway, but `create_isobases()` can be used to create isobases with other directions that can then be passed to `target_plot()`.

`basemap` Object of class `sf` representing a background map. Defaults to a light-weight basemap for the spatial limit in SE Norway.

`crs_epsg` Numeric value specifying the EPSG code of the coordinate reference system (CRS) to be used. Geometries with a different CRS will be re-projected. Defaults to 32632, which is WGS 84 / UTM zone 32N (EPSG:32632).

`naturalearth_basemap`
Logical value specifying if a background map should be downloaded to be used as a basemap. Downloaded files are stored with `base::tempdir()` and deleted when the R session is closed. If `TRUE`, overrides the `basemap` argument. Defaults to `FALSE`.

`naturalearth_zoom`
A vector of two numerical values specifying the amount of cropping that is done around provided `targets` when `naturalearth_basemap` is set to `TRUE`. Be aware of whether a projected or geographical CRS is specified in `crs_epsg`. Defaults to `c(20000, 20000)`.

`target_labels` Logical value specifying whether the targets should be labelled in the plot. Takes the first column beyond the one holding the geometries to represent names. If this is not present the targets are labelled by row number. Defaults to `TRUE`.

`scalebar` Logical specifying whether a scale bar should be added to the plot. Defaults to `TRUE`.

`scalebar_width` Numerical value specifying the width of the scale bar by passing it to the `width_hint` argument of `ggspatial::annotation:scale()`. Defaults to `0.4`.

`scalebar_style` Character value specifying the style of the scale bar by passing it to the `style` argument of `ggspatial::annotation:scale()`. Defaults to `"ticks"`.

`scalebar_location`
Character value specifying the location of the scale bar on the plot by passing it to the `location` argument of `ggspatial::annotation:scale()`. Defaults to `"br"`.

`base_fill` Character value specifying the fill colour of the basemap. Defaults to `"grey"`.

`base_col` Character value specifying the outline colour of the basemap. Defaults to `NA`.

`target_shape` Numerical value specifying the point shape that represent the centroids of the targets. Defaults to `21`.

target_col
: Character value specifying the colour parameter for the points that represent the centroids of the targets. Defaults to "black".

target_fill
: Character value specifying the fill parameter for the points that represent the centroids of the targets. Defaults to "red".

target_size
: Numerical value specifying the size of the points that represent the centroids of the targets. Defaults to 2.25.

isobase_line
: Vector of character values specifying the linetype that is used to represent the isobases of the geologically derived displacement curves. Defaults to c("Horten" = "solid", "Porsgrunn" = "solid", "Tvedestrand" = "solid", "Arendal" = "solid").‘

isobase_col
: Vector of character values specifying the colours used for the lines that represent the isobases of the geologically derived displacement curves. Defaults to c("Arendal" = "black", "Porsgrunn" = "darkgreen", "Tvedestrand" = "blue", "Horten" = "darkorange").‘

greyscale
: Logical value indicating whether the plot should include colours or not. Overrides other graphical parameters When set to TRUE. Defaults to FALSE.

Value

A ggplot that displays a background map with the location of the shoreline isobases within the spatial coverage in south-eastern Norway, unless geometries for other regions are provided. If provided, the function also plots the position of target locations represented as centroids.

Examples

```
# Display the background map and default isobases
target_plot()
```

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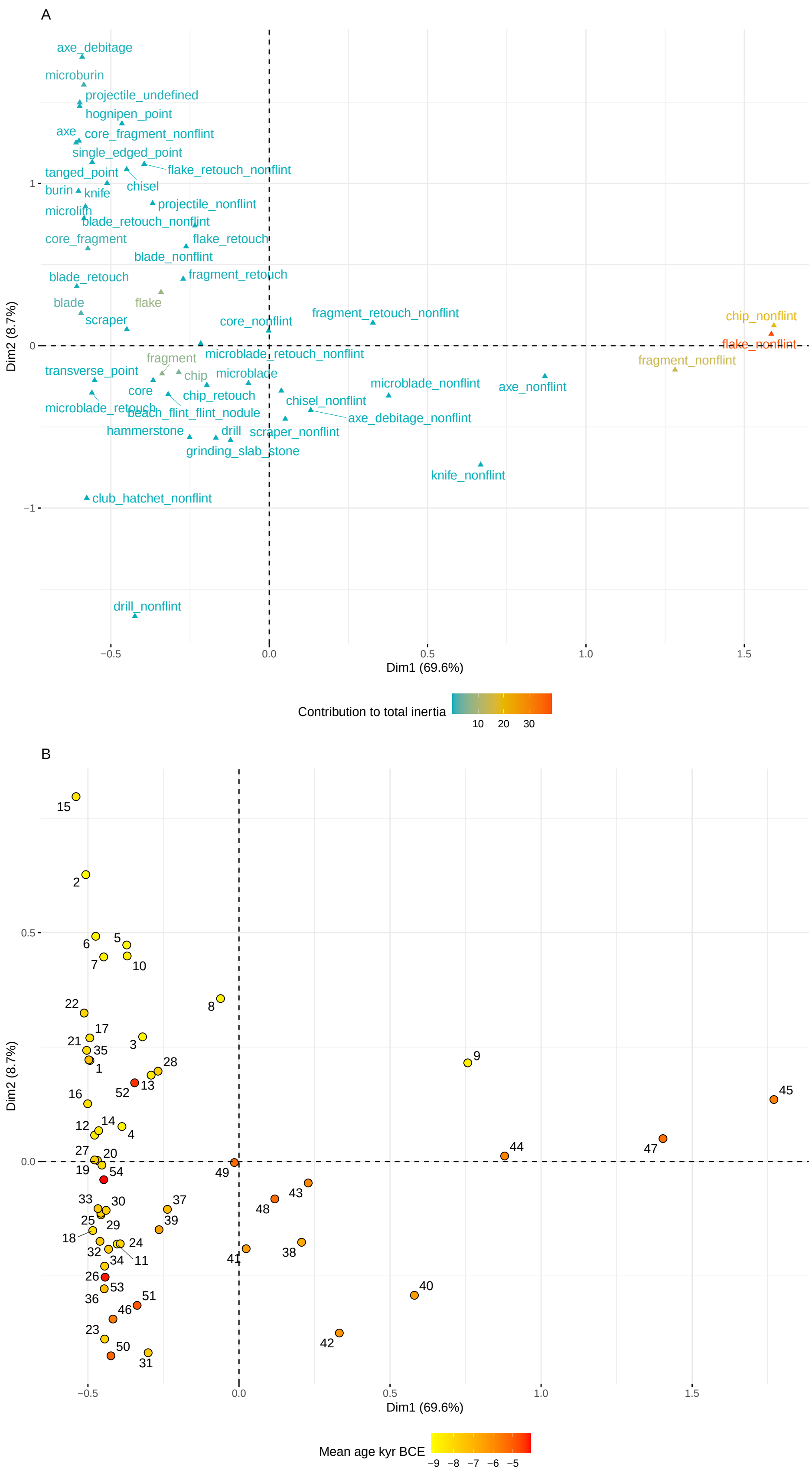

Figure 10: Correspondence analysis using all original artefact categories. A) Column plot, B) Row plot.

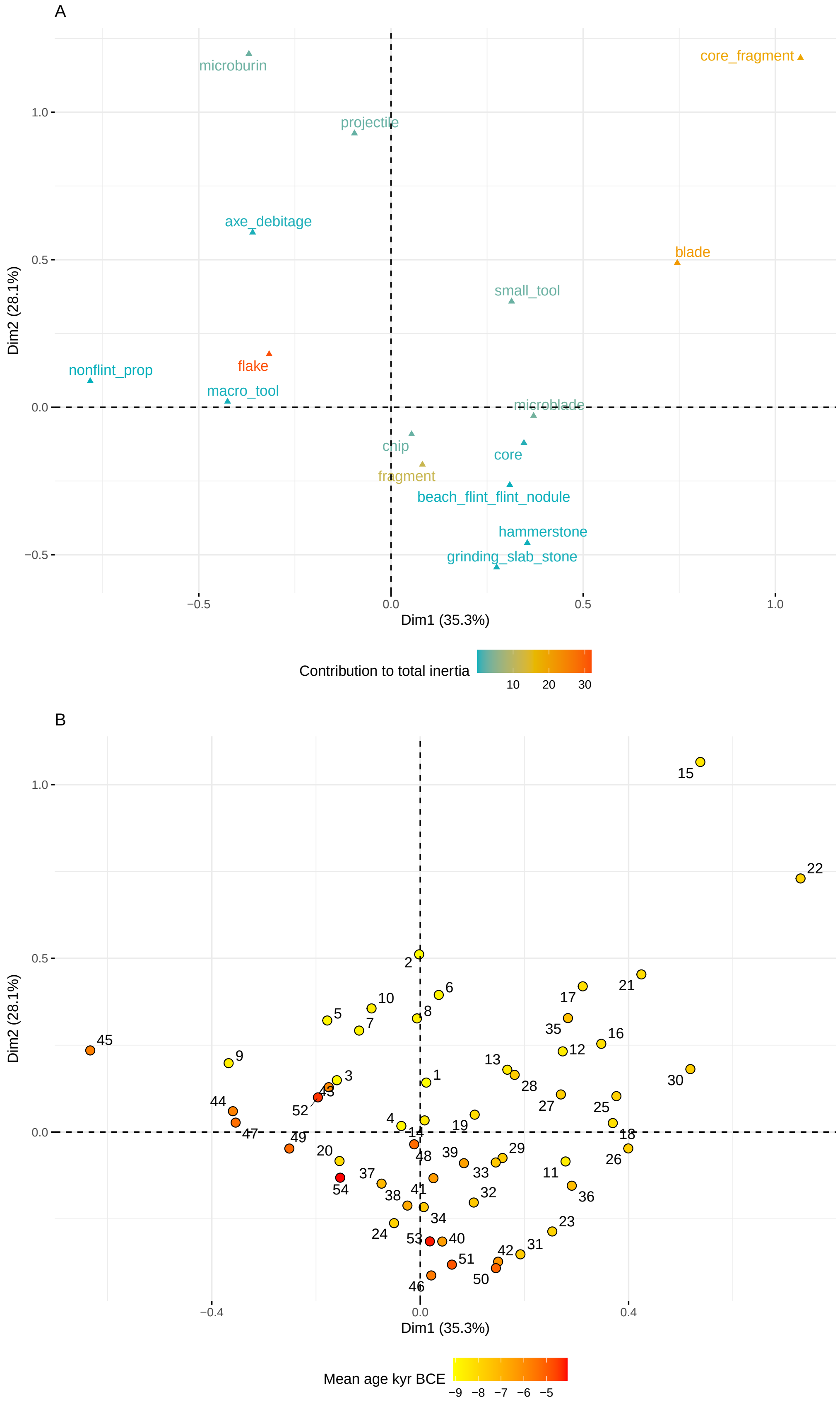

Figure 11: Correspondence analysis collapsing artefact types irrespective of raw-material and including proportion of non-flint as its own variable. A) Column plot, B) Row plot.

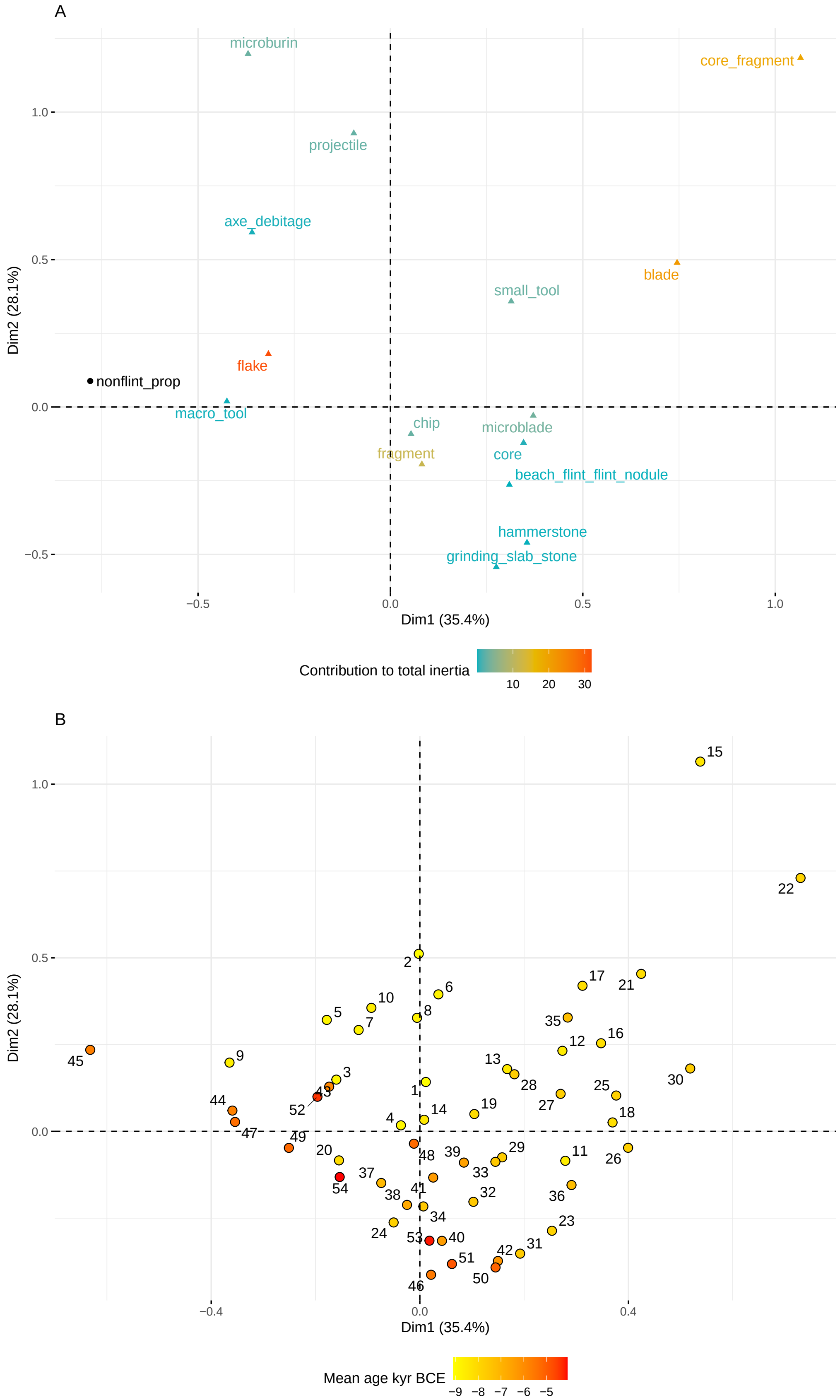

Figure 12: Same as above, only that here the proportion of non-flint is used as a supplementary column. A) Column plot, B) Row plot. The negligble difference between this CA and that above indicates that the flint/non-flint distinction is integrated in the different artefact types, and therefore that the effect of artefact types and raw material cannot be seperated. These plots thus hide important variability that is captured in the ones presented in the main text.