Europe's Lost Frontiers

General Editor
Vincent Gaffney

Volume 1

Context and Methodology

edited by
Vincent Gaffney and Simon Fitch

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Cover: Eleanor Ramsey

Landing by Ava Grauls (Duncan of Jordanstone College of Art & Design).
Oil and watercolour on Japanese shōji (障子) paper. 413 x 244cm

Landing is about location, ownership, shifting land and shifting borders. The painting was conceived after talking to academics about the space between Britain and Europe, and asking the question: 'How do you paint a forgotten landscape?' Landing was made to travel and interact with different environments and can be folded up and packed away into four boxes.
Ava Grauls 11/08/2021

Dedicated to our Families
For putting up with Doggerland for longer than any families since the Mesolithic

 

November 2021

Europe’s Lost Frontiers

Europe’s Lost Frontiers was funded through a European Research Council Advanced Grant (project number 670518). The European Research Council’s mission is to encourage the highest quality research in Europe through competitive funding and to support investigator-driven frontier research across all fields, on the basis of scientific excellence. The European Research Council complements other funding activities in Europe such as those of the national research funding agencies, and is a flagship component of Horizon Europe, the European Union's Research Framework Programme.

European Research Council
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General Editor's Preface

Europe's Lost Frontiers was the largest, directed archaeological research project undertaken in Europe to investigate the inundated landscapes of the early Holocene North Sea – the area frequently referred to as 'Doggerland'. Funded through a European Research Council Advanced Grant (project number 670518), the project ran from 2015 to 2021, and straddled both Brexit and the onset of the Covid pandemic. Despite suffering the curse of interesting times, nearly 50 academics collaborated within the project, representing institutions spread geographically from Ireland to China. A vast area of the seabed was mapped, and multiple ship expeditions were launched to retrieve sediment cores from the valleys of the lost prehistoric landscapes of the North Sea. This data has now been analysed to provide evidence of how the land was transformed in the face of climate change and rising sea levels.

This volume is the first in a series of monographs dedicated to the analysis and interpretation of data generated by the project. Here, as a precursor to publication of the detailed results, we present the historical context of the study and method statements. The following volumes will present the mapping, palaeoenvironment, geomorphology and modelling programmes of Europe's Lost Frontiers. Several supplementary volumes based on the works of postgraduate researchers will also be published prior to a final synthetic publication.

The results of *Europe's Lost Frontiers* confirm that these landscapes, long held to be inaccessible to archaeology, can be studied directly. *Europe's Lost Frontiers* will provide benchmark data for future research on the environmental and cultural heritage of Doggerland. Access to such data will become increasingly important. As this volume goes to press it is clear that contemporary climate change, and the rush for green energy, is pushing development within the North Sea at an unprecedented rate. At the point when archaeologists are finally able to access this unique heritage landscape, the opportunities to do so may be significantly limited in the future. In the face of such change, academics, developers and curators must work together to assist green development, and also continue exploration of Europe's largest and best-preserved prehistoric landscape, Doggerland, before that chance is lost.

University of Bradford
November, 2021

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Chapter 1

Europe's Lost Frontiers: context and development

Vincent Gaffney and Simon Fitch

From bank to bank the waterstrife is spread
Strange birds like snow spots o'er the huzzing sea
Hang where the wild duck hurried past and fled
– On roars the flood – all restless to be free
Like trouble wandering to eternity
John Clare, The Flood (1830)

All large research projects have a history, and *Europe's Lost Frontiers* (ELF) is no exception. Funded through a European Research Council (ERC) Advanced Grant between 2015-2021, the project finds its roots within a long tradition of research related to the extensive, previously habitable, yet initially hypothetical archaeological landscapes preserved beneath the North Sea (Coles 1998; Gaffney *et al.* 2009; Walker *et al.* this volume). Setting aside the arcane historiography of marine palaeolandscapes, the previous two decades have witnessed an exponential rise in awareness of the archaeological potential and significance of these areas; essentially following publication of Professor Bryony Coles' seminal Doggerland paper in 1998. Consequently, the specialist literature associated with the subjects is now substantial. Of specific note are the outputs of another European-funded research initiative – 'SplashCOS', the *Submerged Prehistoric Archaeology and Landscapes* of the Continental Shelf network. Alongside an online database of sites (The SPLASHCOS Viewer (http://splashcos.maris2.nl/ or http://splashcos-viewer.eu/), the network provided invaluable syntheses of recent research across Europe and beyond. SPLASHCOS publications also provided important comparative data on the necessary legal frameworks within which work is undertaken on marine palaeolandscapes (Bailey *et al.* 2017, 2020; Fischer *et al.* 2019; Flemming *et al.* 2017; Harff *et al.* 2016). The emergence of a series of research frameworks related to these studies is also noteworthy, and the 2009 and 2019 iterations of the 'North Sea Prehistory Research and Management Framework' (Peeters *et al.* 2019), the CBA's Maritime Research Agenda (Ransley *et al.* 2013) and Historic England's Maritime and Marine Historic Environment Research Framework: Resource Assessment (2011 and updated in 2013) are worth emphasising in this context. However, whilst this increasing corpus of data will be considered in future *Europe's Lost Frontiers* publications, the topic is tangential to this chapter. Here we are concerned with providing a description of how *Europe's Lost Frontiers* was conceived and planned, as well as the changes in direction that occurred during its operation (Gaffney *et al.* 2017).

Against the general backdrop of research and development activity within the UK, it will be apparent that *Europe's Lost Frontiers* essentially sprang from the results of a series of interrelated research projects and one pilot project. The key, underpinning research projects were the *North Sea Palaeolandscapes Project* (NSPP), the *West Coast Palaeolandscapes Survey* (WCPS), the *the Between the salt water and the sea strand* (BSSS) project – funded by the American National Oceanic and Atmospheric Administration (NOAA), and the *Humber Regional Environmental Characterisation* (Humber REC). Aside from the BSSS, all of these projects were supported by the Marine Aggregates Levy Sustainability Fund (MALSF 2010; English Heritage and Atkins Heritage 2009). Two projects, the NSPP and WCPS, were run through the Visual and Spatial Technology Centre (VISTA, Birmingham Archaeology), prior to the dramatic reduction of archaeological staff at the University of Birmingham, and not long before the funding of *Europe's Lost Frontiers* at the University of Bradford (Fitch *et al.* 2011; Gaffney *et al.* 2007; 2009; WCPP 2011A; WCPP 2013; Young 2012). BSSS was funded through NOAA's Office of Ocean Exploration and Research. The Humber REC was one of a number of regional plans funded through the MALSF and DEFRA, led by the British Geological Survey and including a number of NSPP staff (Tappin *et al.* 2011). A pilot project, directly linked to the successful application for Europe's Lost Frontiers, involved the experimental application of emerging sedaDNA technologies to marine sediments (Allaby *et al.* this volume; Smith *et al.* 2015).

An account of the history of some of these earlier projects has been published previously (Gaffney *et al.* 2009). Here it is only important to note that the NSPP, undertaken with Dr Ken Thomson (1966-2007 Underhill nda), pioneered the use of legacy 3D seismic data, and specifically use of the Petroleum Geo-Services (PGS) 'MegaSurveys' to reconstruct the primary topographic features relating to the southern North Sea (Thomson and Gaffney 2007). Prior to the NSPP, much of the North

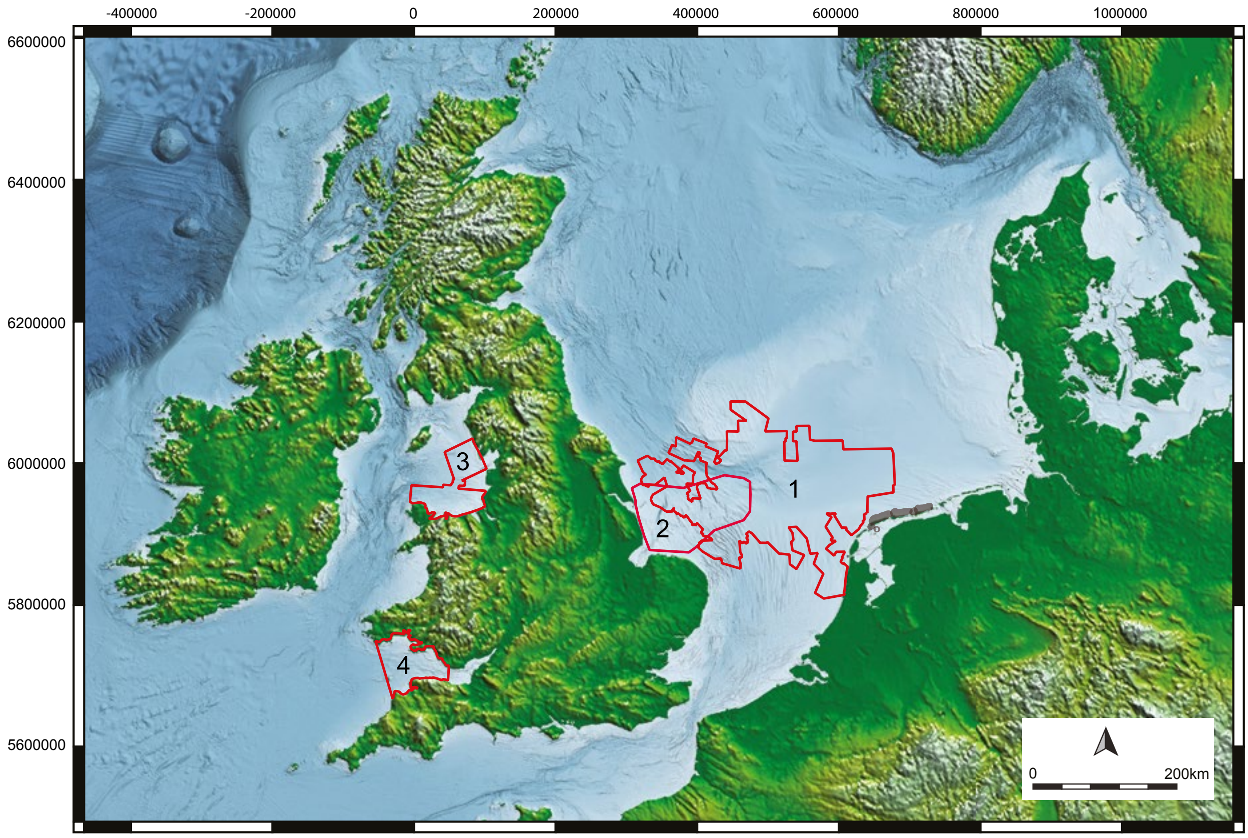


Figure 1.1 Survey areas prior to Europe's Lost Frontiers discussed in this chapter. (1) North Sea Palaeolandscape Project (2) Humber REC (3-4) West Coast Palaeolandscape Project. ASTER DEM is a product of METI and NASA. ETOPO2v2 is the property of the National Geophysical Data Centre, NOAA, US Dept of Commerce.

Sea was effectively a *tabula rasa* in respect of prehistoric archaeology (Amkreutz *et al.* 2018). An original assessment of PGS data, and its use for archaeological purposes, was linked to a doctoral thesis, funded by the Manx Department of Education and undertaken by one of the authors (Fitch 2011).. For this purpose, PGS kindly provided access to the top second of the merged seismic data over an area of *c.* 6000km^2. Exploration of these data suggested that the initial half second of seismic data was likely to include information on surviving, early Holocene landscapes and that this data could be analysed using the technical resources available at the time (Fitch *et al.* 2007). The initial analysis of this data attracted MALSF funding, and the establishment of the NSPP. The final project study area, made possible by further support from PGS, covered approximately 23,000km^2 of the southern North Sea, and stretched from the East Anglian coast to the Dogger Bank and the North Sea median line. At the time, this was the largest contiguous area of geophysical data ever used for archaeological analysis (Gaffney *et al.* 2007). Mapping the upper land-surfaces of these data, combined with supporting seismic sources (Fitch this volume: chapter 4) revealed a wealth of features presumed to relate to the early Holocene of Doggerland, and included estuaries and salt marshes, regions dominated by freshwater river systems and wetlands, through to coastal plains and areas of rolling hills (Figure 1.2).

The value of such an achievement was widely appreciated and attracted several national and international awards (EAA 2013). One aspect of the research which was less valued in some quarters was the historic landscape characterisation mapping and the threat/uncertainty analysis carried out as part of the MALSF contract (Fitch *et al.* 2007a). Essentially a red flag model, this analysis did not simply highlight areas in which important features were located, it also sought to ascertain areas in which the presence or absence of features was uncertain along with the variable level of threat across the mapped area (Figure 1.3).

The response to such imagery was not altogether positive. On March 23rd 2010, Reuters released a news flash entitled 'Stone Age could complicate N. Sea wind farm plans' (https://www.reuters.com/article/energy-wind-idUSLDE62M12020100323). Whilst heritage is frequently a contested area (Flatman 2011; Silverman 2011), the potential of the results of the NSPP to threaten national economic development was never considered

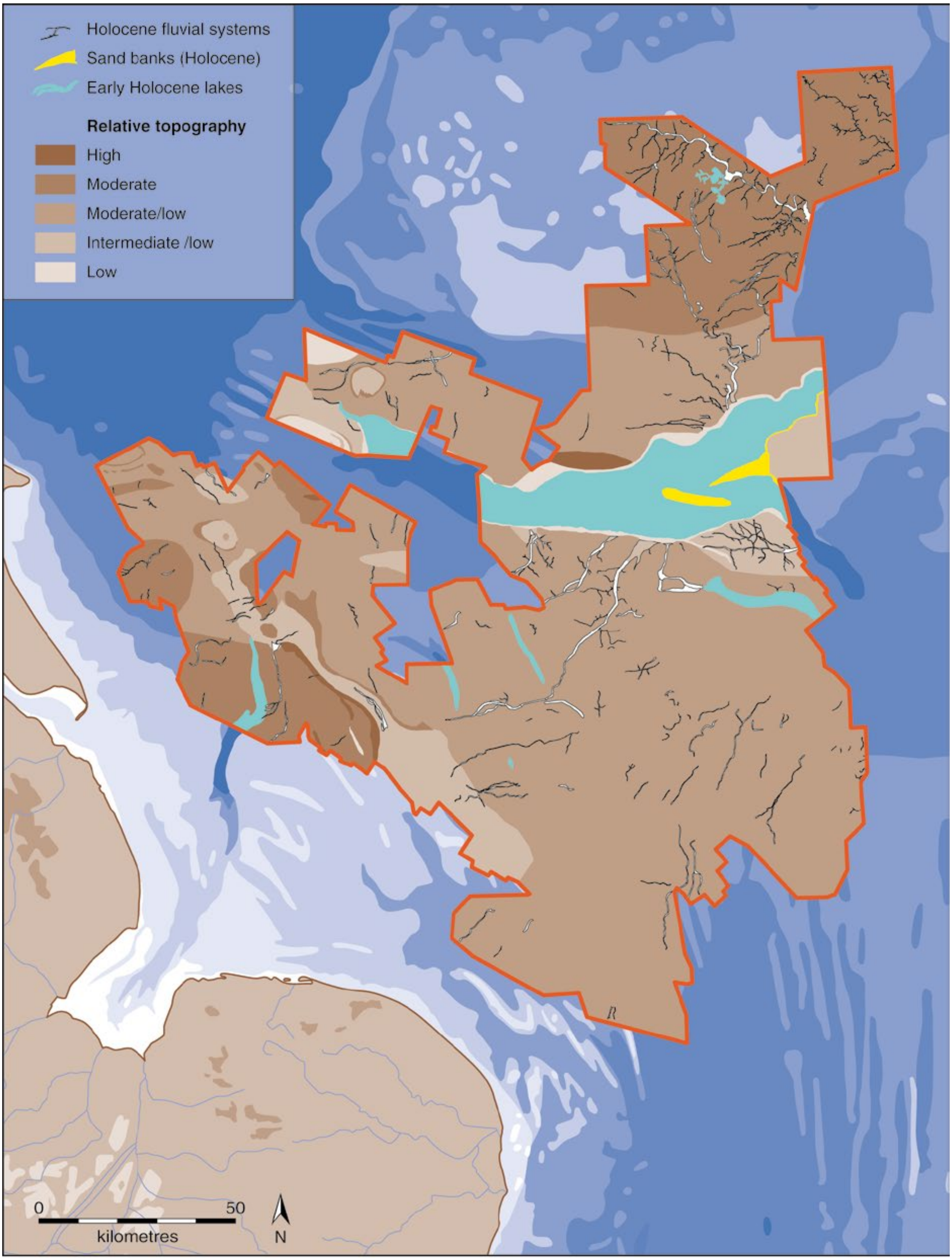


Figure 1.2 Area of Doggerland mapped by the North Sea Palaeolandscape Project (Gaffney *et al.* 2009: Figure 3.23).

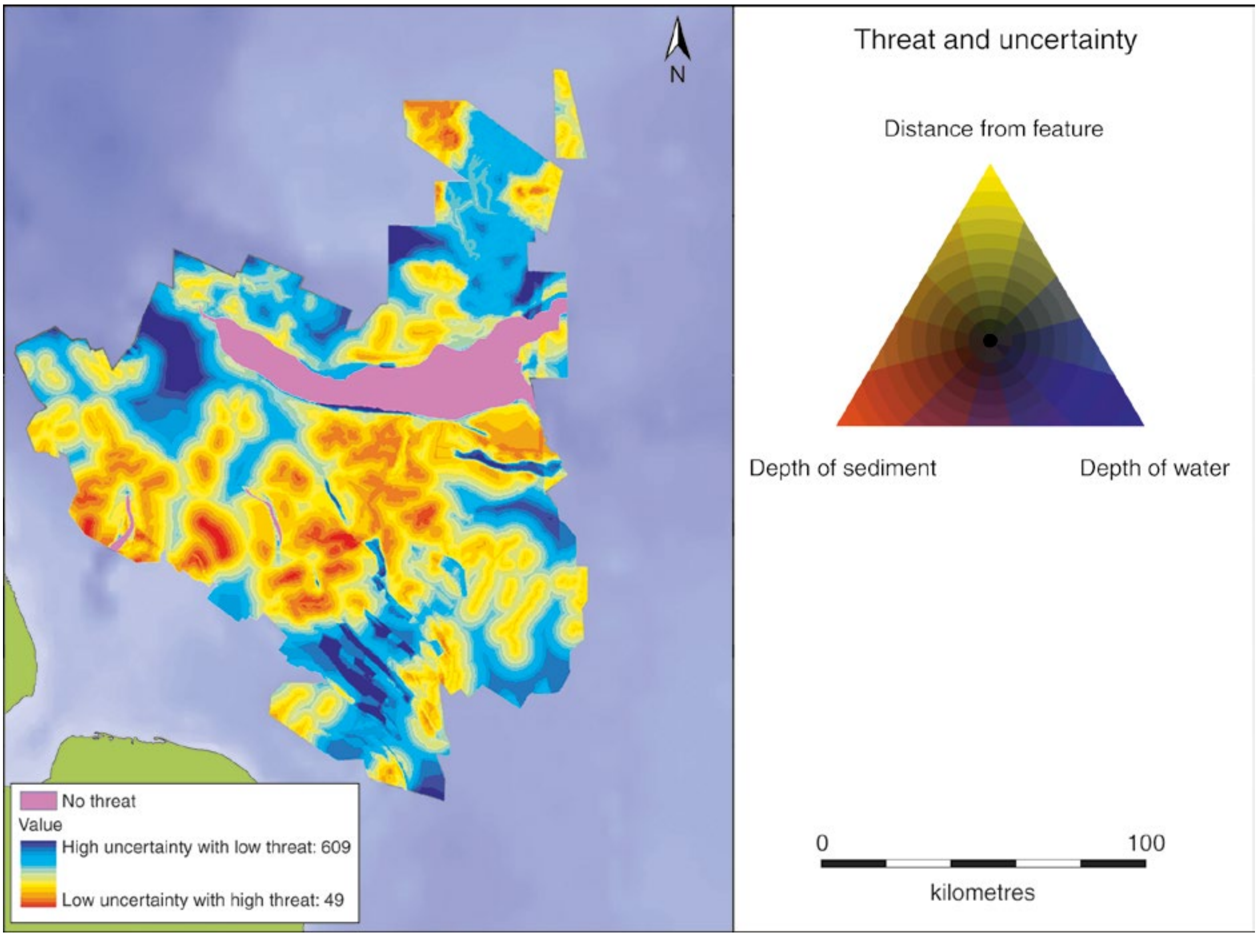


Figure 1.3 Red flag mapping from Gaffney *et al.* (2007: Figure 9.8). This image combines threat and uncertainty data based on distance to feature and depth of overlying sediment. The lack of sediment cover and direct association with identified features with archaeological potential rate as high threats with little uncertainty. Deep overlying deposits lying farther from recorded features rank as low threat areas but with significant levels of uncertainty.

as a likely outcome of the study. This situation changed in 2010 when a national agency contacted the project and asserted that '*the application of your technique is limited to only resolving large scale features which are not obviously related to Mesolithic heritage sensitivity*', and that '*Information in similar adjacent mapped areas suggests that the Birmingham research outcomes may not generally relate to the Holocene and hence not to the Mesolithic or even late Palaeolithic, but potentially earlier events*'. Most telling, perhaps, was the comment that '[we] *believe that there has been a potentially significant mis-interpretation of the late Quaternary geology of the Dogger Bank region by the archaeologists at Birmingham. Ordinarily such differences would not matter unduly, but in this case, there are potentially serious economic consequences for the users of the seabed in the region*' (email to V. Gaffney dated 21/07/2010).

In 2010, a meeting in London was convened with governmental specialists, NSPP researchers and representatives from the British Geological Survey. With the support of English Heritage, as independent chair, the positive role of archaeology in supporting marine development was emphasised strongly, and the validity of the project results asserted. However, it remained true that, whilst there was a technical rationale for the relative dating of the channels mapped by the NSPP, the majority of features remained undated. Moreover, this was a time when the national curator was under considerable stress due to imminent restructuring and, if such assertions had not been successfully challenged, the development of UK marine palaeolandscape research may have been hindered in the short term, at least. If any lesson was to be learned from this fraught exchange, it must have been the importance of working closely with offshore developers and governmental agencies, as well as the dangerous confusion that can emerge if this is not done.

The timing of such a debate was also unfortunate when considered against the attempts by the team to carry out further studies on the UK coastal shelf. The NSPP ran for only 18 months, after which the technical monograph, 'Mapping Doggerland', was published in 2007. A fuller summary of the archaeological implications of the study was provided at a slightly later date through the semi-popular publication 'Europe's Lost World: the rediscovery of Doggerland' (Gaffney *et al.* 2009). By that time the project team were pursuing funding for further strategic research, and the urgent need to ground truth the results of the NSPP was at the forefront. The first opportunity to undertake such work came through the Humber REC (Tappin *et al.* 2011). Here, the results of the NSPP assisted in planning a vibrocoring programme that provided both dating and paleoenvironmental information from palaeochannels. Survey undertaken as part of the Humber REC '*successfully intersected the feature identified previously by the NSPP and ....it was possible to address the aim of the survey by validating the results of the NSPP by sampling*'. (Tappin *et al.* 2011: 156, Figure 2.5.1 and pages 154-166; Fitch this volume: chapter 4).

A related, important technical issue involved the extent of survey. The utility of 3D seismic data for palaeolandscape mapping was largely proven by the NSPP, but large areas of the United Kingdom seabed have no comparable data coverage. This was most notable off the west and north eastern coasts of Wales and England. Aside from some smaller areas of 3D coverage, as in Liverpool Bay, survey sources were primarily limited to legacy 2D data, such as the UK Coal Board datasets off the Northumbrian coast and other data which is held in the UK's onshore geophysical library (UOKOGL – https://ukogl.org.uk). If the area of study was to be extended to larger sections of the coastal shelf, the project team felt there was a need to assess the potential of 2D seismic data to provide comparable detail to that provided by 3D survey. Funding was provided by the MALSF in 2009 to undertake analysis of collocated 2D and 3D datasets in Liverpool Bay and assess their relative value for palaeolandscape mapping locally and wherever similar data existed around the UK shelf (Fitch *et al.* 2011; Fitch and Gaffney 2011). Finally, as MALSF essentially restricted funding to activities within British waters, separate funding was sought from NOAA and the Qatar Museums Authority to undertake a comparative study of the eastern sector of the PGS Southern North Sea MegaSurvey (*c.* 57,000km^2) and the world's then largest high-definition_3D survey (HD3D) acquired over the Al Shaheen Field, Block 5 (2813km^2, Fitch *et al.* 2011)

The rationale for such international investment in the project in Qatar was made clear by reviewer seven for the NOAA application, who observed that little research of this type had taken place internationally and '*success would have ramifications for study of other shelf areas where these kinds of data may be available or soon will be, such as the US Atlantic coast*'. The study of submerged landscapes across the Americas, whilst advancing rapidly, is still a project in development. A recent publication noted that '*within North America, submerged precontact archaeology is one of the last frontiers in First Americans research, and may rewrite what we think we know about the timing and manner of the peopling of the Americas*' (Gussick *et al.* 2021: 106).

In respect of the North Sea, the completion of these projects brought the team to a significant position. The available mapping was extensive and a vast improvement on previous knowledge, but it was not as such authoritative (Figure 1.4). Fundamentally, there were still large areas in which landscape detail was partial or absent. Although there was confidence that the majority of features might be placed within a broad chronological framework (Table 1), this still represented a palimpsest landscape. The lack of chronological or geomorphological information for most features was a significant issue within an area characterised by inundation and subject to major movements, whether from glacial deformation, salt tectonics or other block movements (Gearey *et al.* 2012; Holford *et al.* 2007; Roberts *et al.* 2018). Another, critical issue lay in an appreciation that, whilst the various programmes of mapping were achievements in themselves, with the exception of the palaeoenvironmental work carried out by the Humber REC, the majority of mapped features existed without any associated environmental or cultural context. Despite this, it was certainly true that our knowledge base was continuously improving. The revived research interest in marine palaeolandscapes in Europe, demonstrated by the work of SPLASHCOS, increasingly provided better access to existing knowledge, and new archaeological and environmental data. The onset of major investment in contractual archaeology in the North Sea also provided access to new data within those areas planned for wind farms and other marine developments (Bailey *et al.* 2020a; Brown *et al.* 2018; Hepp *et al.* 2017; Pater 2020; Peeters and Amkreutz 2020; Prins *et al.* 2019; Sturt *et al.* 2017; Tizzard *et al.* 2014; van Hetern *et al.* 2013). However, the lack of any known early Holocene settlement beyond the intertidal zone was apparent. The absence of extensive, directed archaeo-environmental study across the region necessitated a continuing reliance on chance finds, dredged material or cores acquired for other purposes, for information on landscape use or development across the area (Bailey *et al.* 2020c: 207-8; Peeters *et al.* 2020b: 145, the SPLASHCOS viewer http://splashcos-viewer.eu/). At the onset of this project, Professor Bryony Coles' 1998 observation that we knew almost as little about the early Holocene landscape of the North Sea as Grahame Clark during the 1930s, remained substantively correct (see Walker *et al.* this volume, for a fuller discussion of the archaeological context).

Following the end of the NSPP it was apparent that the provision of a topographic map, whilst not an end in itself, would provide the basis for further exploration. The challenges of working in the deeper marine environments of the North Sea Basin would also require a different approach and substantial funding. The initial

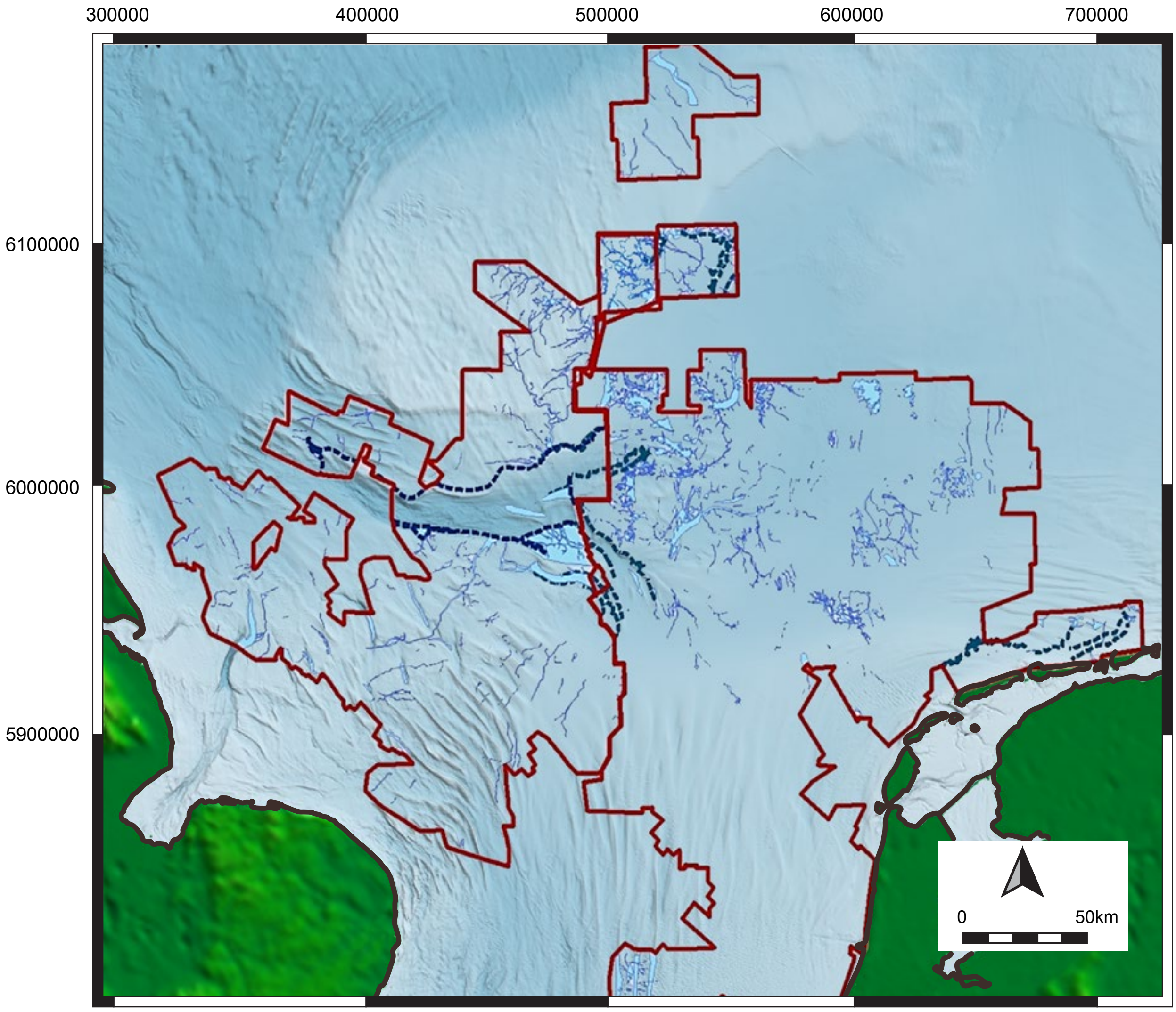


Figure 1.4 Distribution of features located within the southern North Sea during the NSPP and BSSS projects.

development of an ERC Advanced Grant took more than five years and involved three separate applications to the funding agency (in 2010, 2012, 2014). Throughout this period of development, the primary goals of the project were largely consistent. In 2010 these were listed as:

- To produce a near complete topographic map of early Holocene Doggerland using seismic reflection data, fully integrated with other data sources (e.g. sea-level curves, seabed cores)
- To model and simulate, using multi-agent systems inspired by the decentralised, 'bottom up' and emergent phenomenon of nature, possible dynamic scenarios for the geomorphological, ecological and human history of Doggerland
- To use this mapping, modelling and hypothesis generation to inform a programme of seabed coring for palaeoenvironmental and dating evidence which will, along with other proxy data sources, test, or at least constrain, aspects of the models
- To use computer models and simulation-generated data as a basis for real-time, interactive exploration of the virtual landscape, and visualisation of the individual and collective behaviour, and emergent patterns, of the flora, fauna and people affecting the ecosystem
- To provide a robust framework for future research into and management of this extraordinary scientific, heritage and educational resource

Aside from presentational development, between 2010 and 2014 the most significant change within the application was almost certainly the introduction of a major work package related to sedimentary DNA (sedaDNA). This followed an initial meeting with Professor Mark Pallen at the British Association for the Advancement of Science in 2007 which, over time, manifested in a pilot project with Professor Robin

Description	Number	Area in km²
early Holocene basin	1	10
early Holocene channel systems	440	700
early Holocene delta	37	350
early Holocene depression	29	20
early Holocene drier areas within wetlands	20	350
early Holocene high ground	17	200
early Holocene lake	10	150
early Holocene peat beds	8	20
early Holocene sandbank	1	10
EH wetlands	25	550
Last Glacial Maximum channel systems	46	150
Last Glacial Maximum depressions	33	70
Modern sandbanks	26	10
Undated channel systems	36	100
UD depressions	7	30
Undated high ground	3	2
Undated lake	1	20

Table 1.1 Numbers and area of features, excluding coastlines, identified through the NSPP and BSSS projects (2008-2012). After Gaffney *et al.* 2011: Table 5.1

Allaby, analysing sediments from the submarine Mesolithic site at Bouldnor Cliff, off the Isle of Wight in the Western Solent (Momber *et al.* 2011; Momber and Peeters 2017; Smith *et al.* 2015a; 2015b).

The later Mesolithic site at Bouldnor dates between 8030 and 7980 cal BP and is generally considered Britain's best explored, submerged site of Mesolithic date (Momber *et al.* 2021). The results of the sedaDNA pilot study unsurprisingly revealed a wooded landscape that included oak, poplar, apple, and beech, with grasses and a few herbs (Smith *et al.* 2015a). The faunal profile indicated an abundant presence of Canidae and Bovidae (dog or wolf), whilst material interpreted most likely as *Bos* was supported by the find of an auroch bone at the site. The presence of deer, members of the grouse family, and rodents, all compatible with the contents of a Mesolithic diet shared by humans and dogs, was indicative of a later Mesolithic environment. Undoubtedly, the DNA evidence of Triticeae was of considerable surprise and continues to attract discussion (Smith *et al.* 2015b). Neolithic assemblages are not established on the mainland of north west Europe until 7500 BP in the central Rhineland, 7300 BP in the Rhine/Maas delta and adjacent areas, and 7400 BP in western France (Crombé and Vanmontfort 2007; Louwe Koojimans 2007; Marchand 2007; Robb 2013). Consequently, on the presumption that the evidence of DNA is not intrusive, then the source of the *Triticum* signal may come from wheat imported from elsewhere in Europe during the British Mesolithic.

The potential for significant contact between farming and hunter-gatherer communities within the inundated areas of the coastal shelf informed project development. Although the linked issues concerning the final phases of inundation, and the movement of people in relation to the establishment of Neolithic lifestyles, had certainly been of academic interest previously (Coles 1999; Flemming *et al.* 2014; Sturt and Van der Noort 2013), regional investigations of sea-level change had largely been framed in terms of the transition to the current terrestrial context and the impact on the hunter-gatherer environment rather than from hunter-gatherer to farmer societies. This situation existed despite occasional finds of Neolithic artefacts on the seabed, such as the early Neolithic Michelsberg axes from the Brown Banks (Peeters and Amkreutz 2020). These finds had usually been interpreted as votive objects deposited either at sea or at low tide, as gifts to hunter-gatherer ancestors of the inundated plains. However, the position of later prehistoric monuments at the marine interface, such as Seahenge dated at *c.* 2049 BC (Brennand and Taylor 2003), clearly begged the question as to where the earlier Neolithic coastline actually stood and what the implications were in having an enlarged coastal strip during this period (Sturt *et al.* 2017).

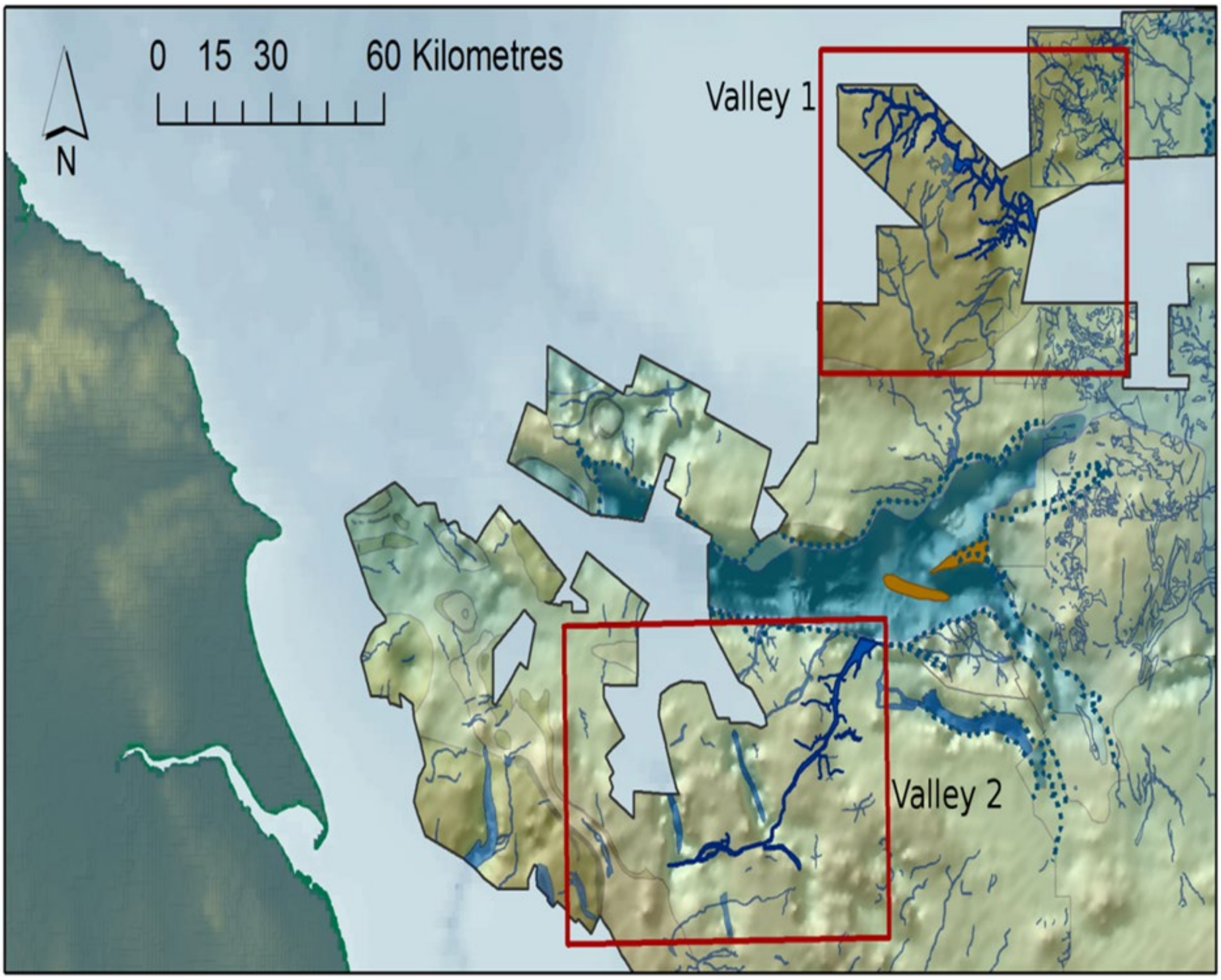


Figure 1.5 Map used in the final ERC application showing course of two submerged river valleys to be targeted for coring by the Lost Frontiers project team, overlaid on NSPP project base map (Gaffney *et al.* 2007).

These results changed aspects of the final, successful ERC Advanced Research Grant that was initiated in December 2015 under the title, *Europe's Lost Frontiers: exploring climate change, settlement and colonisation of the submerged landscapes of the North Sea basin using ancient DNA, seismic mapping and complex systems modelling*. The stated goals of the project were:

- How did the early Holocene Doggerland landscape develop in the face of the ameliorating climate and what was the impact of climate-related land loss on the plant, animal and, ultimately, human communities of the North Sea plain?
- At what time did the Mesolithic people of the north west plains make contact with Neolithic technologies and practices, and what form did this contact take?
- Has our view of the Mesolithic – Neolithic transition been drastically skewed by relying predominantly on land-based sites? If so, what changes need to be made to existing theories as a result of the new data?

Alongside these goals were the following primary objectives:

- To produce a near complete topographic map of early Holocene Doggerland, primarily using seismic reflection data fully integrated with other data sources (e.g. sea-level curves, seabed cores).
- To reconstruct the early Holocene environments of Doggerland through conventional means and by using and developing the emerging methodologies for extracting plant and animal DNA directly from sediments cored from the sea-bed
- To explore these data for evidence of the colonisation of plants and animals associated with climatic amelioration, and also for later markers associated with Neolithisation, including non-indigenous flora and fauna

- To model possible dynamic scenarios for the geomorphological, ecological and, by inference, the human history of Doggerland using complex systems simulations.
- To provide a robust, global framework for future research and management of these extraordinary scientific, heritage and educational resource associated with comparable landscapes around the world.

From the onset of the project, the goal to extend the mapping of Doggerland to achieve the maximum coverage possible, and provide a suitable context for simulation studies of environment and, potentially settlement, was clearly a priority. However, a key output from existing mapping was to identify sediment caches with the potential to be cored for palaeoenvironmental data. Aside from simply retrieving environmental samples, the intention was to use such data in support of complex systems modelling to model ecological development.

It is often said that the first casualty of any battle is the plan, and the same might be said when implementing many large archaeological projects. On the basis of earlier mapping, two valleys with incised channels, and therefore the potential to hold accessible sediments, were chosen to act as sampling transects (Figure 1.5). The first valley ran south west to north east out from the Wash and into the Outer Silver Pit Lake and also from the area associated with the Dogger Island into the Outer Silver Pit (Figure 1.5). If correct, coring downstream should have allowed a dating programme to determine the nature and rate of transgression in a consistent manner. A minimum of 100 cores were planned to recover palaeoenvironmental data (sedaDNA, pollen, plant macrofossils, insect remains, ostracods/foraminifera and diatoms) and radiocarbon and OSL samples for 'rangefinder' dates. These data, along with improved, and more extensive seismic mapping, could then be used to build dynamic models of the changing geomorphology and ecology of Doggerland, from the opening of the Holocene around 12,000 BP until its eventual total inundation around 7500 BP (Murgatroyd this volume).

The selection of individual core locations began early in 2016 and was managed by Professor Richard Bates. From the onset, some variation to the proposed programme was required (Figure 1.6). It was apparent that the central section of the longer west to east transect, running from the British mainland, could not be cored in the central section due to the presence of large sandbanks. The core selection was then modified and included a series of transverse core lines in the lower west-east valley draining into the Outer Silver Pit. To the west, a series of cores followed the river channel and a separate transect to the mainland. Individual selection was also guided by the results of survey by the Humber REC. A final transect, intended to follow the path of inundation independent of river channels, was chosen to run from the central section of the main river, south west and towards the East Anglian coast. Individual cores were sited to investigate specific features identified from seismic mapping including one core in the approximate area associated with the findspot of the Leman and Ower point (Clark 1932: 115; Godwin and Godwin 1933).

On the 23rd of June 2016 the United Kingdom voted to leave the European Union. Aside from bequeathing the project with one of the most ironic titles possible, 'Brexit' did cause significant impacts. It was apparent that permissions for licensing in the aftermath of Brexit would present a problem, and that the initial licence would be for a smaller number of cores than planned. A decision was taken to reduce the numbers of cores in the lower courses of the west to east river valley, and to acquire only two cores (ELF019 and 020) from channels south of the river.

The limitation on the numbers of cores that could be taken initially impacted on the overall unit cost of cores across the two planned expeditions, and this led to further changes (Figures 1.7 and 1.8). Although the details of these locations will be provided in a forthcoming volume in the Europe's Lost Frontiers series, here we can note that the second transect running south and west to the coast was abandoned. Further coring on the lower courses of the valley was limited to the Outer Silver Pit estuary. Following discussion with Louise Tizzard and Wessex Archaeology, coring on the Dogger Bank itself was directed to specific channel features: the northern coast and a lake/pingo on the top of the bank. A series of cores were taken on the northern shore of the Outer Silver Pit and opposite the estuary of the main west-east river. However, analysis of the topographic and seismic data south of the main channel, and specifically the data from ELF019, suggested that further coring should include a major transect along a smaller channel which became known as the Southern River. This decision was taken because this channel was accessible and provided the opportunity to sample sediments, from source to estuary, along the whole course of a large river. Whilst the initial coring plan had presumed the acquisition of up to 100 cores, at the end of the project a total of 78 cores from 60 locations were recovered from areas designated as within the original research study area.

Although there were unforeseen variations associated with the two planned coring expeditions, an invaluable characteristic of the ERC Advance Grant is the flexibility such an award offers. The project team were therefore able to follow several research routes that provided additional value to the project (Figure 1.9). One

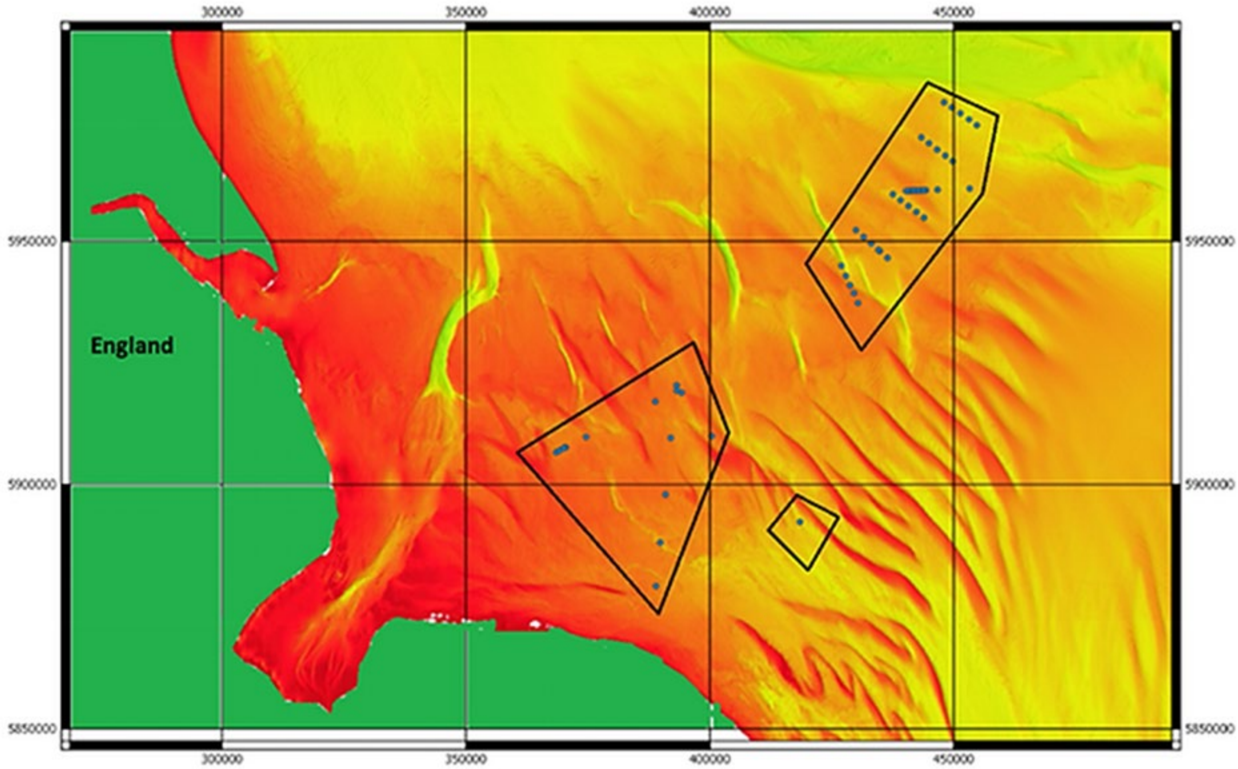


Figure 1.6 Initial modification of the Europe's Lost Frontiers coring programme following funding in 2016.

such opportunity related to the west coast of Wales. Although the North Sea is associated with the largest area of early Holocene, inundated landscape on the European coastal shelf, the archaeological potential of the Irish Sea and the west coast of the United Kingdom is also apparent. Substantive research on intertidal landscapes by Professor Martin Bell (2007) in the Severn Estuary, is of particular note in considering these areas, whilst the evidence for the connectivity of the region both with the adjacent coastlines, the Atlantic shore of Europe and lands beyond has been appreciated for some time (Bradley *et al.* 2016; Brown *et al.* 2018; Cunliffe 2001). However, although the significance of coastlines, in terms of linkage, has been stressed by many (Sheridan 2015: 31; Woodford 2015: 191-205), the literature has tended to concentrate on the evidence for the Neolithic and later periods (Cummings and Fowler 2016). Despite this, the evidence for cross-channel, pre-Neolithic contacts along the southern and western coasts, specifically at the inundated late Mesolithic site at Bouldner Cliff, emphasises the need to provide mapping more broadly along the British coasts (Momber and Peeters 2017; Smith *et al.* 2020).

The initial exploration of the Severn Estuary and Liverpool Bay by the WCPS has been mentioned earlier in this chapter (WCPS 2011; 2013), but further opportunities emerged through a collaborative link with Dr James Bonsall, at the Institute of Technology Sligo, and the Irish Marine Institute. A dedicated survey, using the RV Celtic Voyager, was then planned in Liverpool and Cardigan bays in 2018. Sadly, the appalling weather conditions encountered led to the abandonment of work within Liverpool Bay. Survey of a major river channel in Cardigan Bay was successfully undertaken, although coring proved unsuccessful due to the weather and poor corer penetration. The results of this programme of work will be reported in a forthcoming Europe's Lost Frontiers volume dedicated to remote sensing and landscape reconstruction (Harding *et al.* forthcoming).

2018 also saw the initiation of a collaborative research programme undertaken as part of the 'Deep Sea History' consortium and involving *Europe's Lost Frontiers*, the Flanders Marine Institute (VLIZ), the University of Ghent, the Geological Survey of the Netherlands (TNO), the Deltares Research Institute, Utrecht University and the Royal Netherlands Institute for Sea Research (NIOZ). The initial fieldwork involving *Europe's Lost Frontiers,* was directed at the study of the area known as the Brown Bank. The Brown Bank has long been associated with the recovery of archaeological material; usually found by chance through fishing or dredging and these have included stone, bone and antler artefacts, as well as human remains (Glimmerveen *et al.* 2004; Louwe Kooijmans 1970; Mol *et al.* 2006; Peeters 2011; Peeters and Amkreutz 2020; van der Plicht *et al.* 2016;

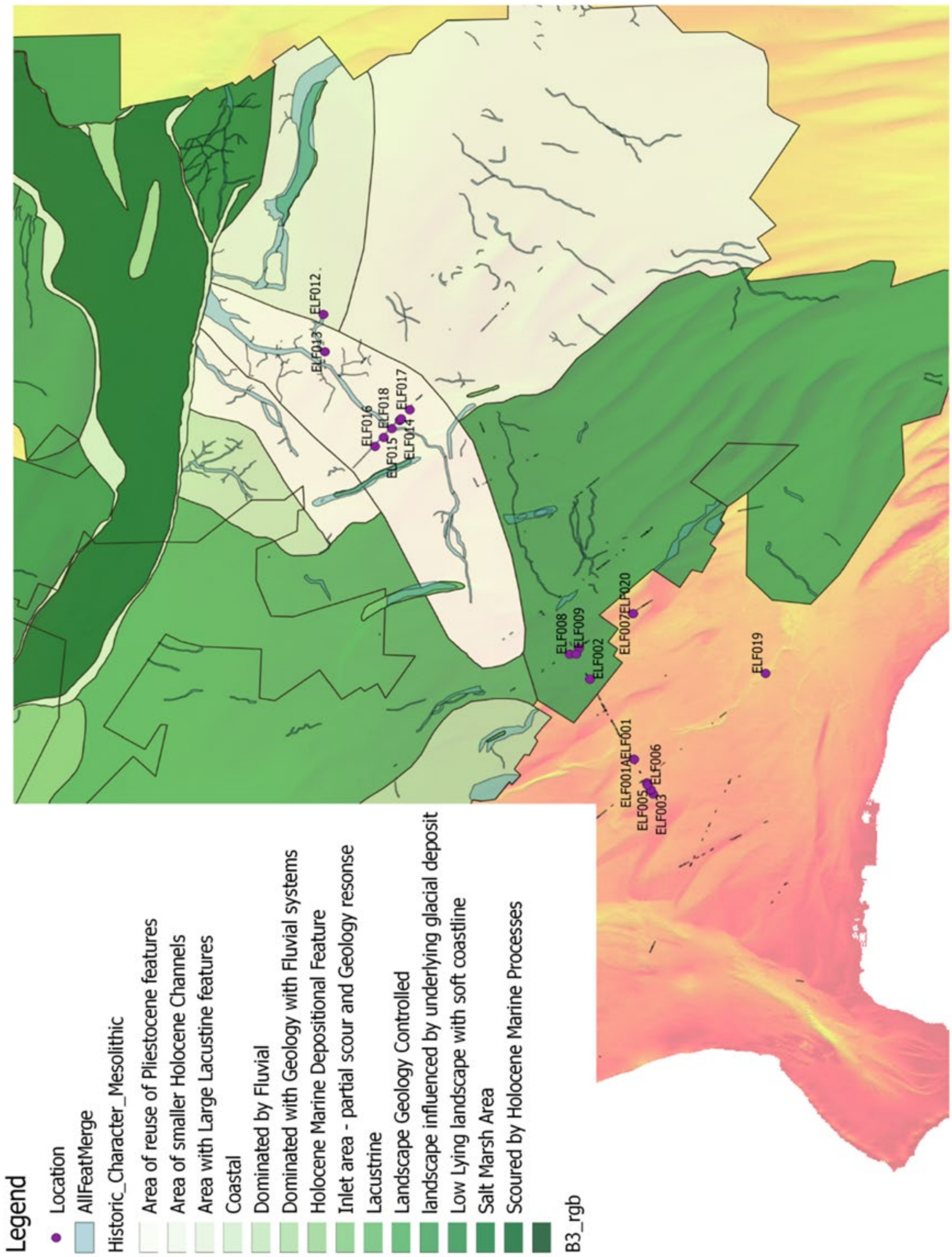


Figure 1.7 Additional modifications to Europe's Lost Frontiers coring programme following BREXIT.

Verhart 2004). Some of the finds are exceptional, such as the find of a cobble mace head, a perforated mattock with remnant of the wooden handle and, unusually, several middle Neolithic polished axes (Peeters and Amkreutz 2020: 160). The concentration, and excellent preservation, of late Pleistocene and early Mesolithic material from several areas across the Bank suggests the material is being eroded from a series of stratified sites or activity zones.

This collaborative programme of work supported three expeditions between 2018 and 2021 and involved research vessels from Belgium (the RV Belgica and RV Simon Stevin) and the Netherlands (the RV Pelagia). The results have provided a significantly enhanced view of the structure of the Banks and indicate areas or eroding peats which may be the source of organic finds (Missiaen *et al.* 2021). The team were also able to mount a short expedition to the Southern River estuary, in support of the mapping undertaken by *Europe's Lost Frontiers*. An area on the estuary was selected for targeted dredging, where it was suspected that erosion might expose archaeological material. Although disrupted by bad weather and poor sea conditions, the few hours of survey available provided the first lithic artefact, a fragment of a hammerstone, found in the deeper areas of the North Sea following directed prospection, rather than as a chance discovery.

As a postscript to this brief description of new surveys undertaken with colleagues in Belgium, Holland and Ireland, it is worth noting that this work was entirely dependent upon the availability of European marine survey vessels and supporting infrastructure. Access to similar resources is simply not available to archaeologists through British research institutions. This situation contrasts strongly with some other North Sea nations. Belgium, for example, provides research vessels to support teams undertaking archaeological exploration, including *Europe's Lost Frontiers*, and will enhance its capacity to undertake such work during 2021 (https://www.eurofleets.eu/vessel/rv-belgica-ii/). If such a situation is maintained this is likely to become problematic for British academics concerned with the cultural heritage of the North Sea. The study of inundated landscapes will become increasingly strategic in respect of our understanding of prehistoric north west Europe, and the requirement to undertake more survey will become urgent if planned marine development across the whole of terrestrial Doggerland takes place (Walker *et al.* this volume).

Aside from new survey programmes it is worth discussing where variation in analytical processes occurred as the project developed. The original ERC application provided for an iterative research methodology with three primary work packages (Figure 1.10). Aside from work package leads, research was supported by specialists contracted through the universities of Bradford and Birmingham, as well as post-doctoral researchers and PhD students based at Bradford and Warwick. The data provided by teams studying seismic mapping, sedimentary DNA and the broader environmental programme was intended to feed into a far-reaching computer simulation exercise. The methodologies associated with specific parts of the analytical programmes are provided in the following chapters, and detailed results of analysis will be reported in forthcoming volumes in the Europe's Lost Frontiers series.

Whilst individual work packages and their components were generally implemented as described in the original ERC application, it is hardly surprising that some variation from the original plan occurred across the five years of research. Most of the individual work packages provide some examples of internal development (Cribdon *et al.* 2020; Missiaen *et al.* 2021; Murgatroyd *et al.* forthcoming). However, it is important to appreciate that disruption and variation to the coring programme impacted upon the project structure and timetable, and the COVID pandemic, significantly delayed analysis and reporting from individual researchers. The extent of these impacts was such that a 12 month 'no-cost' extension was granted to the project by the ERC, extending the project span from its original end date in 2020 through to November 2021.

Undoubtedly, disruption to the project timetable resulted in some negative impacts on the project, and, to a degree, research activity was inevitably more responsive than iterative. However, the addition of Dr Martin Bates to the team, at a relatively early stage, did much to ensure that any variation in the coring plan, and the results of the delayed environmental programme, were supported within an appropriate geomorphological framework, and that the results supported the work of the larger research team (Bates *et al.* this volume). Research methods that were not within the original programme were incorporated as opportunities arose, e.g. palaeomagnetic studies (Harris and Batts this volume). Other techniques, such as the application of geochemistry to the core samples, developed as the project progressed. The addition of Mohammed Bensharada, as a postgraduate student, and Dr Alex Finlay (Chemostrat) to the research team added significantly to the project's analytical capacity (Bensharada *et al.* this volume, Finlay *et al.* this volume). The role of geochemistry as an integrative technology was demonstrated clearly within project's paper on the Storegga tsunami deposit in core ELF01A (Gaffney *et al.* 2020). Alongside the collaborative research links described above, the project attracted external academics to work with Europe's Lost Frontiers researchers. The placement of Dr Merle Muru, through the good offices of Dr Alar Rosenthau (University of

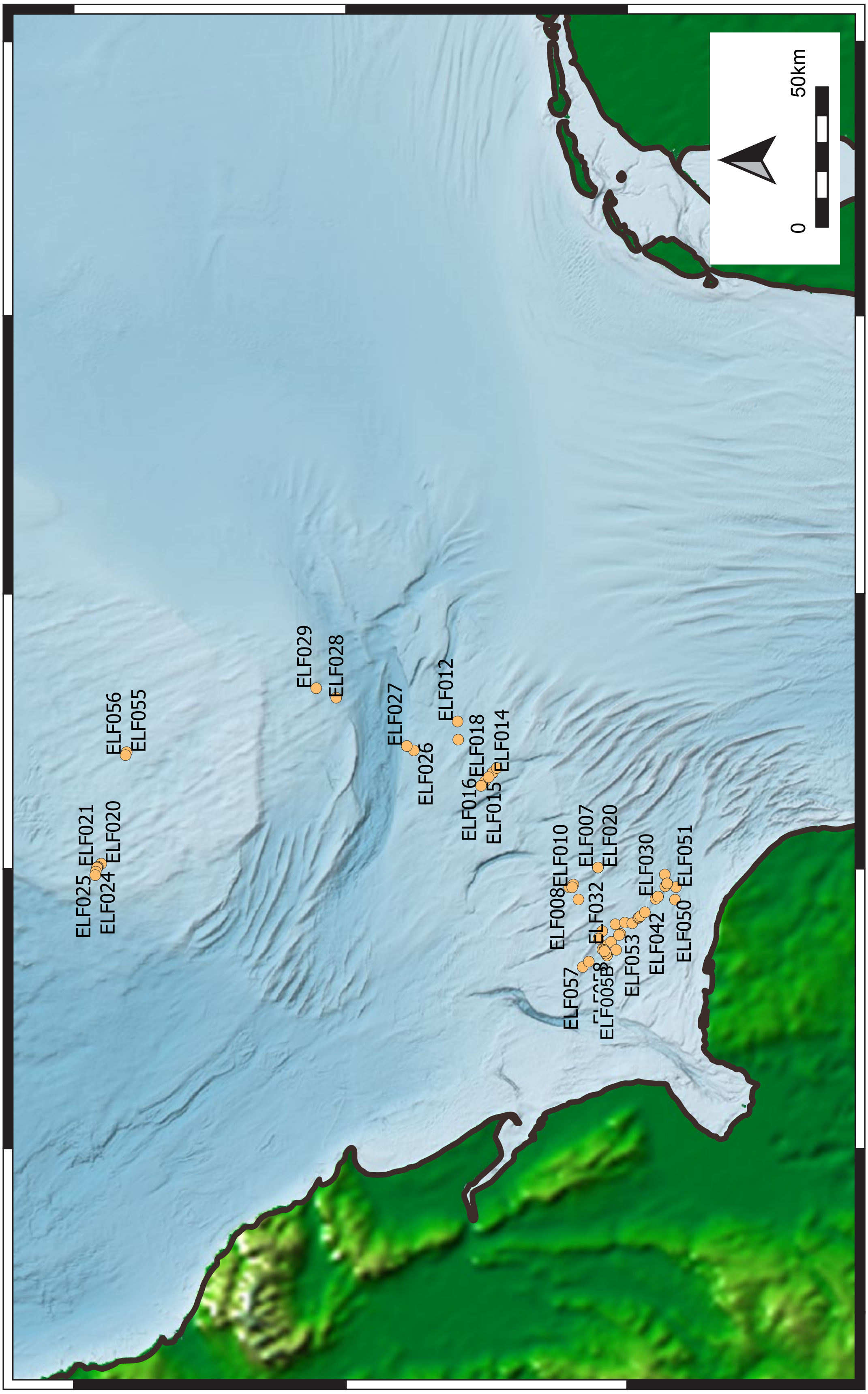


Figure 1.8 Final Europe's Lost Frontiers coring programme.

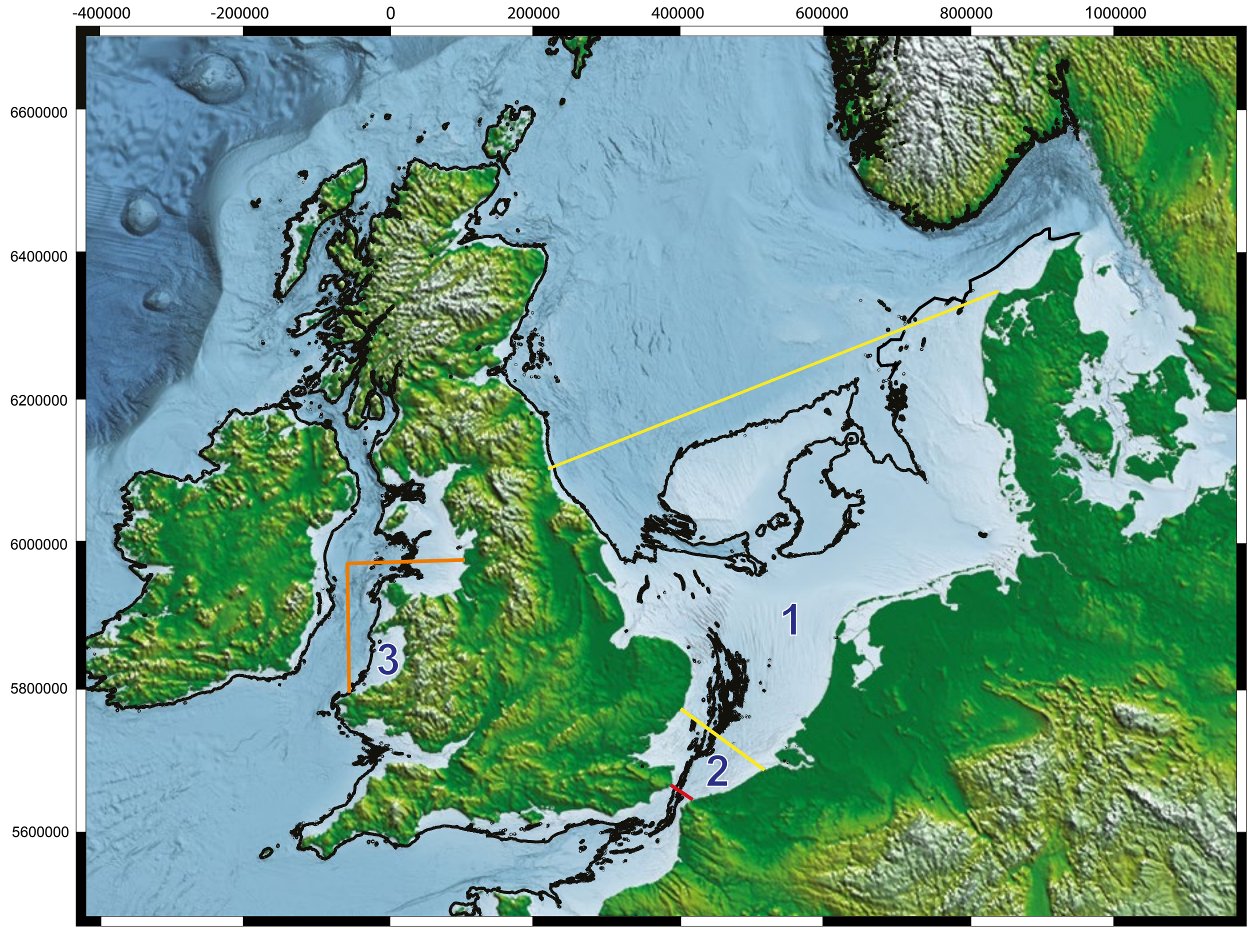


Figure 1.9 Europe's Lost Frontiers core study area (1), Cardigan and Liverpool Bays (3) and area of study added as part of the Brown Bank survey (2).

Tartu), was a significant event. Merle's research on palaeocoastlines, and primary research on the Brown Bank data and the UK Coal Board archive were integral to the project's goals, whilst Dr Muru's considerable expertise in GIS assisted in cartographic development within the project.

The final integrative work package within the project, computer modelling, was managed by Dr Philip Murgatroyd and Professor Eugene Ch'ng. In many respects, this was anticipated to be amongst the most challenging of research themes within the project. The focus of the simulation component as described in the funding application was on agent-based modelling (ABM), a technique ideally suited to examine the actions of individuals within an historic environment. ABM is the most widely used simulation technique within archaeology (Cegielski and Rogers 2016) and it tends to obscure other simulation methods which do not use agents in their design. As the project progressed, it became apparent that there were a series of fundamental questions which were critical to understanding the landscape of Doggerland which were not amenable to ABM. Methods of data downscaling (Contreras *et al.* 2019) became important in providing a basic understanding of how the inundation of the landscape would have looked to the inhabitants of Doggerland (Murgatroyd *et al.* this volume). The taphonomic processes which contributed to the formation of the deposits found within the cores were increasingly understood as vital to our understanding as to how the environmental proxy data within the cores related to the landscape as a whole (Barton *et al.* 2018). These relatively prosaic elements, representing change within the project study area, were examined before widespread, large-scale ABMs were able to be developed. However, ABM development has continued throughout the project and is evidenced by the development of an experimental augmented reality sandbox to simulate response to climate change and sea-level rise (Murgatroyd *et al.* this volume)

This short narrative has outlined the development context of *Europe's Lost Frontiers* and the changes that were imposed upon the project, or occurred through the natural processes of methodological innovation, provision of new data and academic enquiry. Despite such change, researchers within

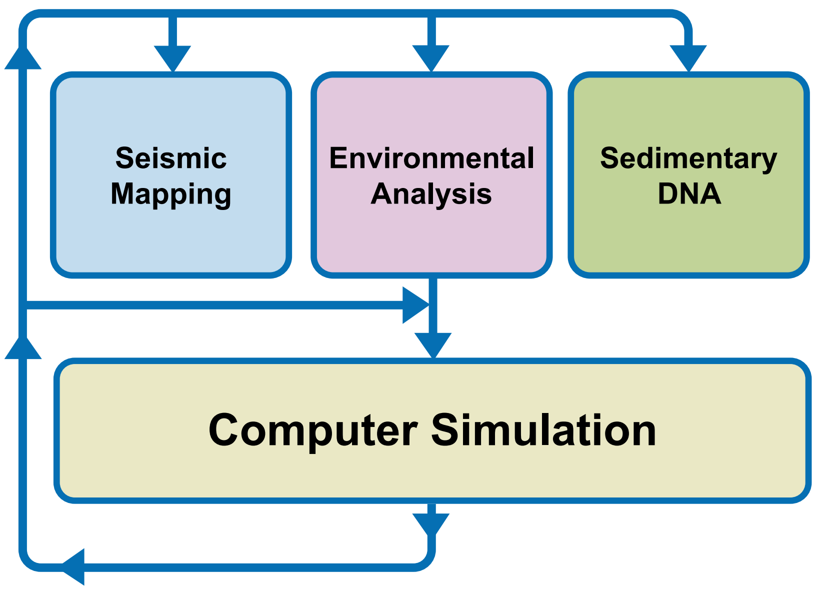


Figure 1.10 Iterative research methodology within Europe's Lost Frontiers.

Europe's Lost Frontiers have pursued key goals relating to the study of the inundated palaeolandscapes of north west Europe, climatic change, sea-level rise and consequent landscape transformation, and these have been achieved on the basis of new geographical and temporal datasets provided through the project and collaborators. The publication of the methodological detail here, and in a series of forthcoming volumes dedicated to the details of mapping, environmental assessment and computer modelling, will support our understanding of how human populations may have reacted to climate change and also the evolving landscape. In the short term, these data will inform our response to current development proposals that will impact much of the area that now constitutes late Pleistocene and early Holocene Doggerland (UK Govt 2020; Fitch *et al.* this volume: chapter 15). Over the longer term, it is hoped that the results of the project will inform the development of research agendas relating to these, increasingly strategic and historic landscapes at a global level.

Chapter 2

Beyond the site: A re-evaluation of the value of extensive commercial datasets for palaeolandscape research

Simon Fitch and Eleanor Ramsey

Introduction

Europe's Lost Frontiers developed from the work of a number of research projects involved in the provision of extensive subsurface landscape mapping of the English sector of the North Sea for archaeological purposes (Fitch *et al.* 2005; Gaffney *et al.* 2007; Gaffney and Fitch this volume). These earlier studies demonstrated that the considerable volumes of legacy marine geophysical data that were available could be used to extend the study of marine palaeolandscapes to a supranational scale within European waters (Bunch *et al.* 2007).

The further development of the *North Sea Palaeolandscape Project* (NSPP) methodology, through a National Oceanic and Atmospheric Administration (NOAA) funded project, provided the opportunity to enhance the interpretation of this data, to integrate extensive 3D seismic surveys with 2D seismic, and to map the archaeological landscapes within the shallower waters of the Dutch sector (Gaffney *et al.* 2011; van Heteren *et al.* 2014). Following these studies, other researchers have utilised similar 3D workflows to that of the NSPP and successfully located early Holocene channel systems in other sectors of the North Sea (Prins and Andresen 2019).

This paper discusses the datasets used within *Europe's Lost Frontiers* and considers the evolution of data use and the developments in method which facilitated the project. It is not, however, an exhaustive discussion of the data available in this area. A vast amount of data has been collected and is currently being produced by offshore activity (Bailey *et al.* 2019). Given the extent of data, as well as the complexities of data types, volume and variable quality of the data generated, it would not be within the scope of the project to provide a detailed overview of all the data that might be used for research. Nevertheless, it is useful to provide an overview of the data utilised within the project, its limitations and the methodology that was developed to facilitate its use.

Evaluation of datasets

Within the *Europe's Lost Frontiers* project, the primary 3D seismic data utilised was derived from the PGS *Southern North Sea (SNS) MegaSurvey* 2017 dataset (see Figure 2.1 and https://www.pgs.com/data-library/europe/nw-europe/southern-north-sea/), extending east from the NSPP study area, and the southern section of the *Central North Sea (CNS) MegaSurvey*. The MegaSurvey data used by NSPP and *Europe's Lost Frontiers* covered approximately 57,000 square kilometres and was created by merging released oil company and non-exclusive 3D seismic datasets. Upon initial examination, the data proved to be of a suitable quality for archaeological interpretation. The seismic dataset has a mean frequency of 21Hz, with 96.5% of the frequencies in the 3–66Hz range (Figure 2.1). A mean frequency of 21Hz provides a near-seabed vertical resolution of approximately 25m when used with a seismic velocity of 1550m/s (typical of seabed sediment, e.g. Shumway 1960; Schock 2004).

However, there is a significant high frequency component within the dataset, which suggests that an improved vertical resolution over the mean value is achievable. Using a frequency value of twice the dominant frequency (42Hz) to include this high frequency content, the frequency value provides a maximum vertical resolution of 10m. The remaining high-frequency content of the signal suggests that the calculated vertical resolution may actually be an underestimate, and a vertical resolution approaching 6m may be achieved (see Figure 2.2). These results suggest that the main limitation of this dataset for archaeological research result from the relatively ephemeral characteristics of features of archaeological interest, and specifically those relating to terrestrial deposits of the early Holocene.

The apparent limitations of the dataset concur with work undertaken by Steffens *et al.* (2004: 35), where it is noted that the near-seafloor section within conventional 3D seismic data often contains a higher frequency content (60 to 70Hz) that will yield resolutions of 6–8m. As a consequence, it is reasonable to conclude that the dataset will support mapping of near-seabed features, and that the resolution is acceptable for archaeological landscape mapping. Unfortunately, the metre-scale resolution suggests that these datasets are not appropriate for locating those smaller features that

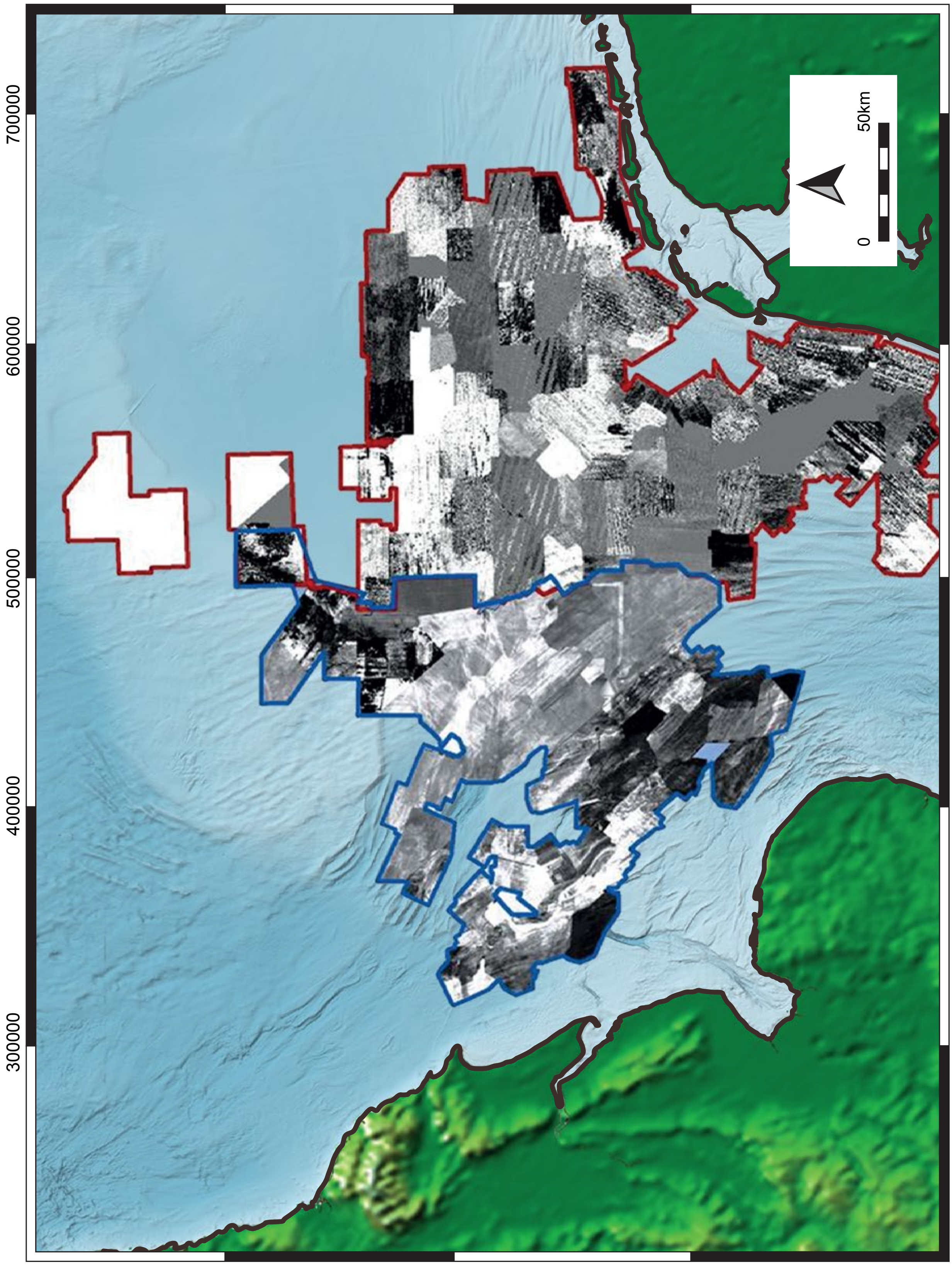


Figure 2.1 Timeslice at 0.076s through the Southern North Sea MegaSurvey 3D seismic dataset. The NSPP study area is outlined in blue and the extended study area discussed within this paper is outlined in red.

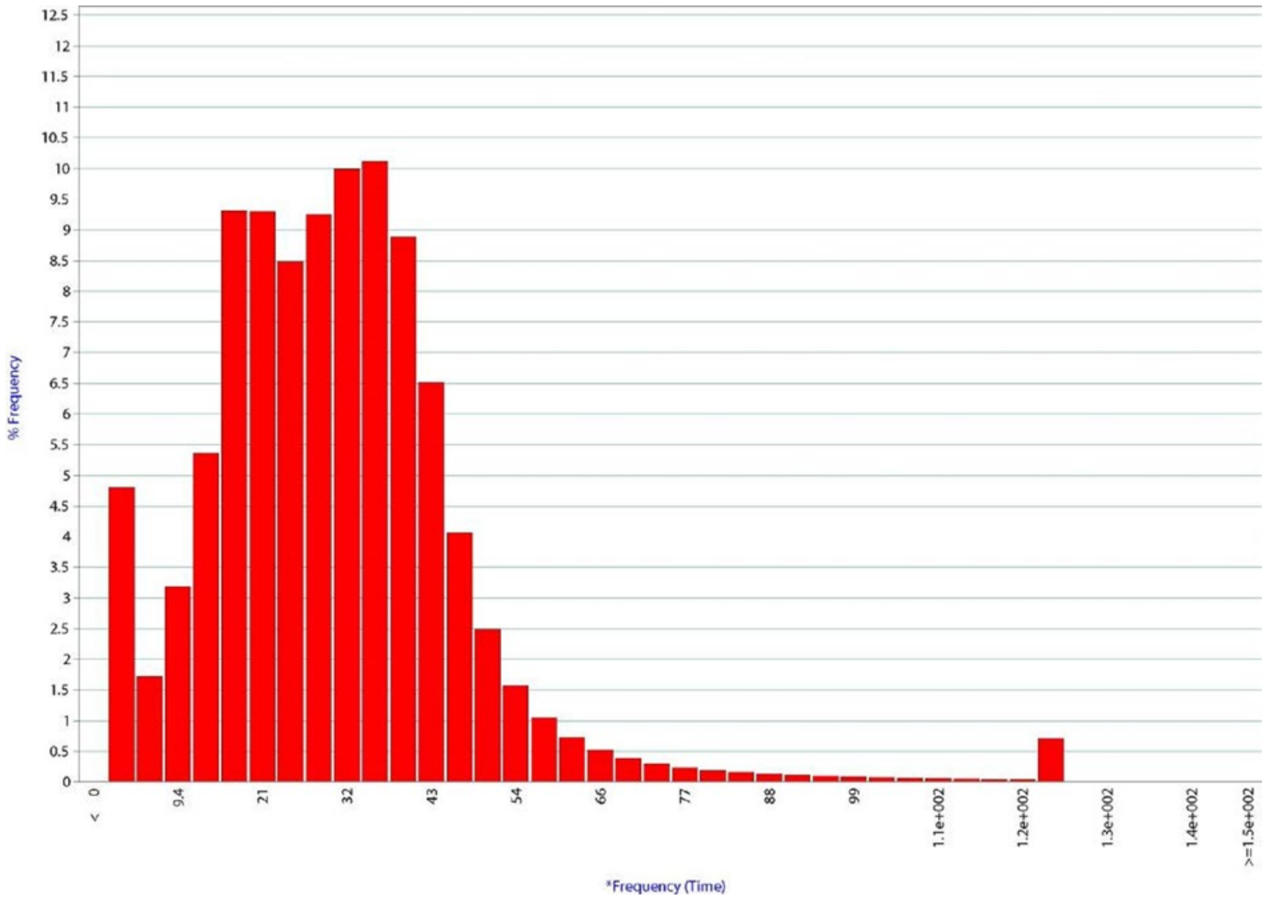


Figure 2.2 Graph of the frequency from the PGS MegaSurvey 3D seismic data.

are associated with individual archaeological sites of the period.

To understand the interpretative trade-offs required when utilising these merged datasets, it is useful to perform a comparison between the MegaSurvey data and the original individual 3D seismic survey data and to assess the ability of the MegaSurvey data to locate and visualise prehistoric landscape features. This analysis identifies potential loss in feature visibility due to data processing and conditioning during the process of creating the MegaSurvey merged dataset. For the purpose of this evaluation the original survey data for several key locations within the *Southern North Sea MegaSurvey* dataset was obtained from the TNO (Dutch Geological Survey, see Table 2.1, Figure 2.3). In addition, datasets from outside the study area were also obtained to extend the survey into key areas identified by the project team beyond the extent of the PGS MegaSurvey.

The selected original 3D surveys were compared to the corresponding 3D MegaSurvey dataset for quality assessment (Figure 2.3). The data were timesliced at 4ms intervals and visualised using identical colour bars for each timeslice between 40 and 80ms. The interpretation of both datasets was undertaken independently. To improve the comparative nature of the analysis, human interpreters were not informed of the origin of the slice data. Once interpreted, the results were exported to GIS to compare the results in both numeric and spatial terms.

From examination of the original datasets, it is apparent that data striping and noise is pronounced in areas of older surveys or shallower water (Figure 2.4). This is not surprising, given the additional pre-processing undertaken by PGS as part of the MegaSurvey data processing (https://www.pgs.com/library-products/megasurvey/). When we compare the original data and the MegaSurvey data (Figure 2.4) we find that most of the larger landscape features can be identified in both datasets. However, some smaller features (sub 50m horizontal resolution) are missing within the MegaSurvey dataset, and it is likely that the post-processing required to merge and join the individual datasets may have masked some of the smaller channels.

When the seismic frequencies of the test areas are examined (Figure 2.5) it is apparent that the MegaSurvey (Figure 2.2) has a similar overall frequency response to that of the original data. However, the more recent test area surveys used (late 1990s) possess

TNO Survey Name	Holocene Visibility	Location within Study Area
Z3NAM1995B	Good	North
Z3NAM1993A	Poor	North
Z3NAM1998B	Good	North
Z3NAM1998C	Good	North
Z3PET1994B	Good	Central
Z3PGS1999B	Good	Central
Z3NAM1988A	Moderate	South
Z3NAM1990F	Poor	South
Z3NAM1992A	Moderate	South
Z3NAM1994A	Moderate	South

Table 2.1 Additional, original 3D datasets used for cross comparison purposes.

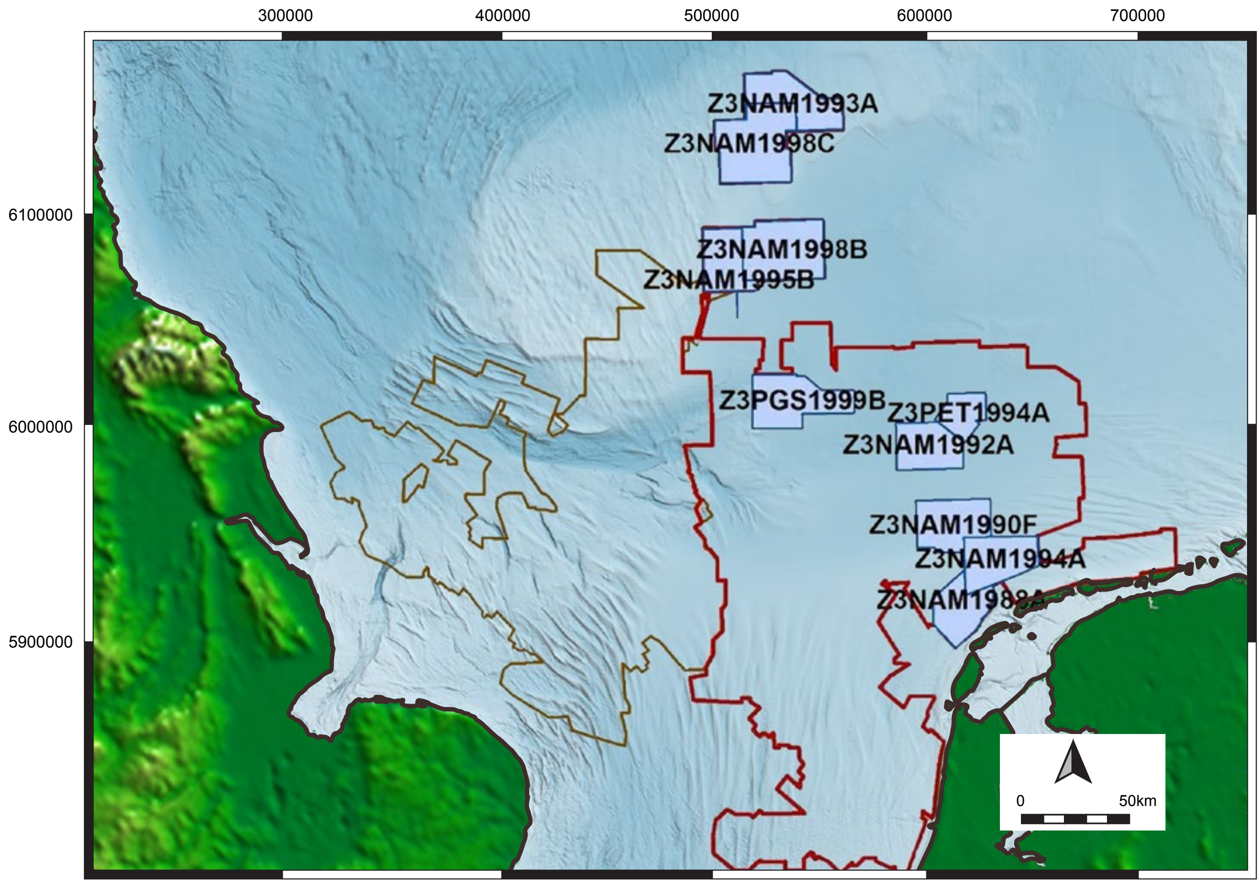


Figure 2.3 Additional, original 3D datasets utilised for comparison with data generated through MegaSurvey processing.

a significant high frequency content, and this is not fully reflected within the MegaSurvey dataset. This unrepresented high frequency content may partly explain the absence of some of some smaller features from the MegaSurvey. Indeed, the survey Z3NAM1998C shows at least 45% of its frequency content in the 40 to 59Hz range. This suggests that the data provides a maximum vertical resolution of at least 10m, whilst the remaining higher frequency content indicates that higher vertical resolutions may be achievable in optimum circumstances. Given the detail of landscape features observed in Z3NAM1998C, the recent survey is preferable for submerged prehistoric landscape survey compared with the MegaSurvey survey or the pre-1998 original surveys. Despite this, it is clear that the results from the MegaSurvey data are comparable, or even better, than those derived from the majority of the original datasets. Use of the MegaSurvey data achieves

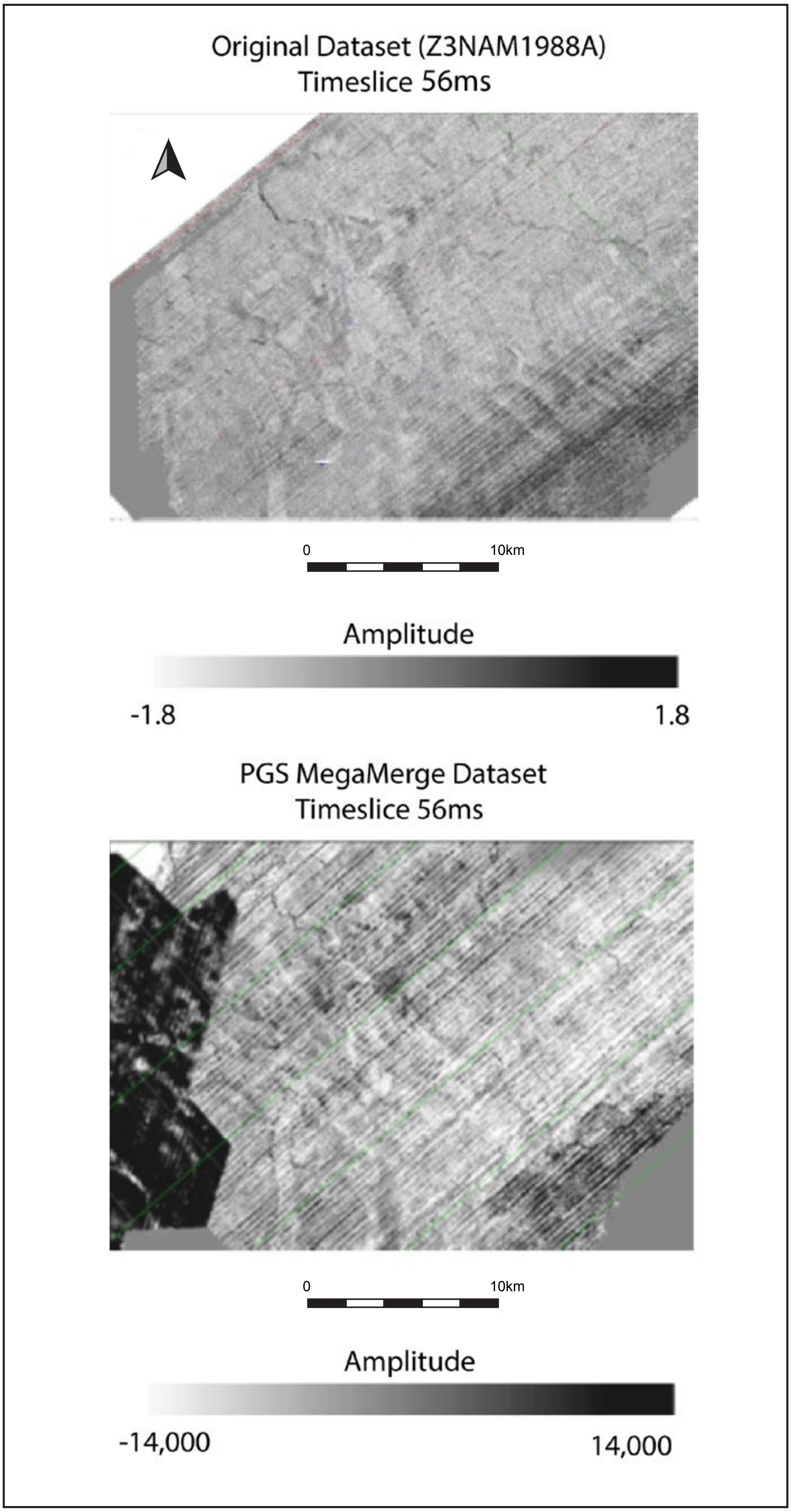


Figure 2.4 Data comparison for survey Z3NAM1988A.

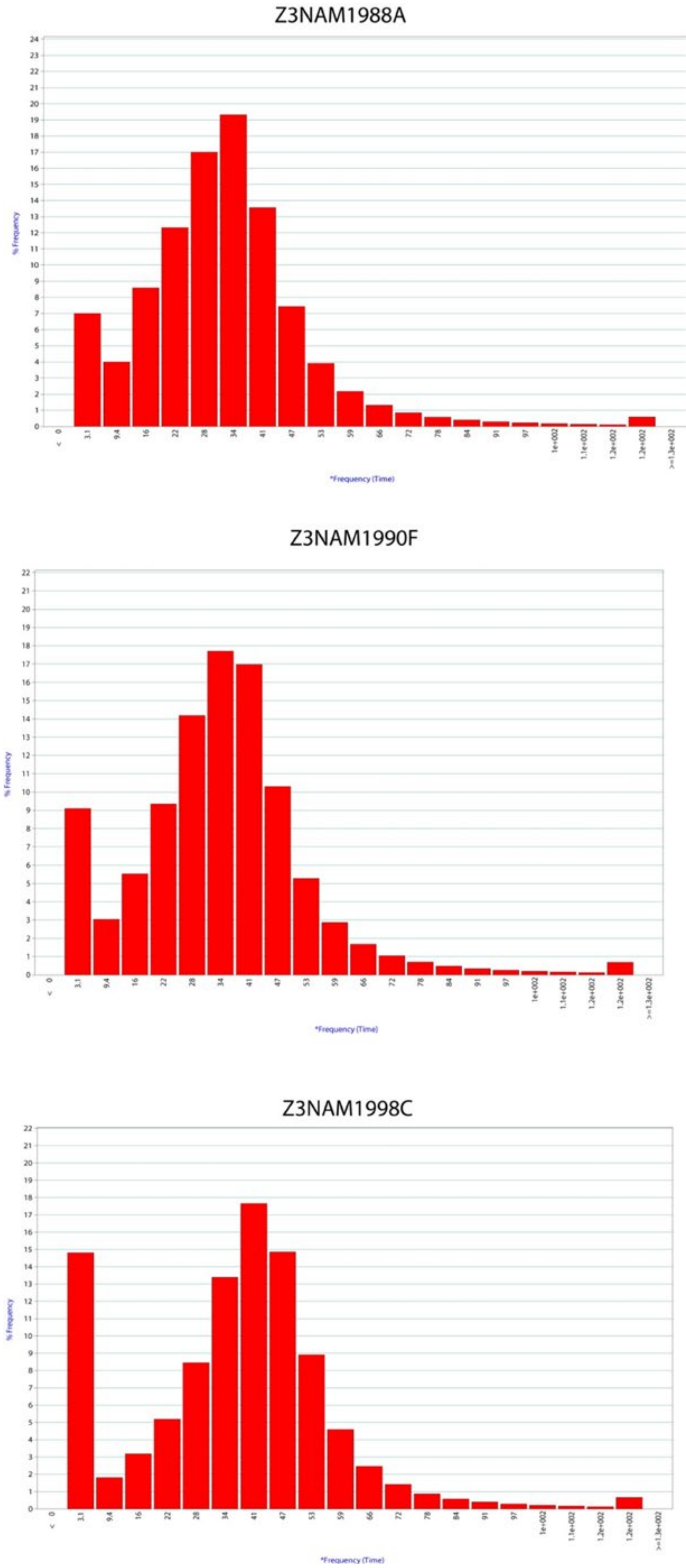


Figure 2.5 Frequency values within the 3D legacy seismic volumes assessed within this study.

the goal of providing a consistent view of features at a landscape scale, and this may not be available through the study of individual surveys.

Future development in the use of oil industry seismic data may be facilitated by the use of recently acquired high-definition 3D (HD3D) surveys. HD3D data represents the 'next generation' of 3D seismic data with a higher density of sampling shots and receivers than traditional 3D seismic data, and thus a greatly increased trace density (PGS 2021). The improved trace density of an individual HD3D survey will, in theory, result in better resolution of smaller features and therefore may enhance the chance of identification of Holocene features. This improved detail will ensure that mapping from the current 3D datasets is likely to be superseded in the future in areas where HD3D datasets become available, and that archaeological mapping derived from earlier datasets will have to be re-evaluated. However, this does not suggest that we should discount the use of older surveys in those situations where sampling density, survey frequency and local conditions (such as water depth) are favourable.

An example of the results achievable through the application of newer technologies and higher frequencies survey can be demonstrated through the data output from a recently acquired Parametric Echo Sounder dataset. This 2018 survey was located over the Brown Bank area of the Southern North Sea using an Innomar SES-2000 *quattro,* which can produce a 3D dataset. Analysis of the Brown Bank dataset indicates a dominant frequency of 6000Hz (6kHz). This source has been studied by Missiaen *et al.* (2018; 2020) and is ideal for archaeological recording of submerged landscapes. The data resulting from this source was analysed with the machine set in its 'low' frequency mode during survey and used a frequency of 6kHz. Even at this 'low' setting the results provide an exceptional vertical resolution of 10cm, and significantly outperforms traditional 3D seismic (Figure 2.6). However, this performance comes at the cost of vertical sediment penetration (*c.* 20 to 30m at 6kHz). As with other high-resolution methods, this covers large areas relatively slowly when compared to oil industry 3D acquisition (Thomson and Gaffney 2007). The Innomar is also capable of higher frequency survey at *c.* 100kHz for even finer detail mapping,

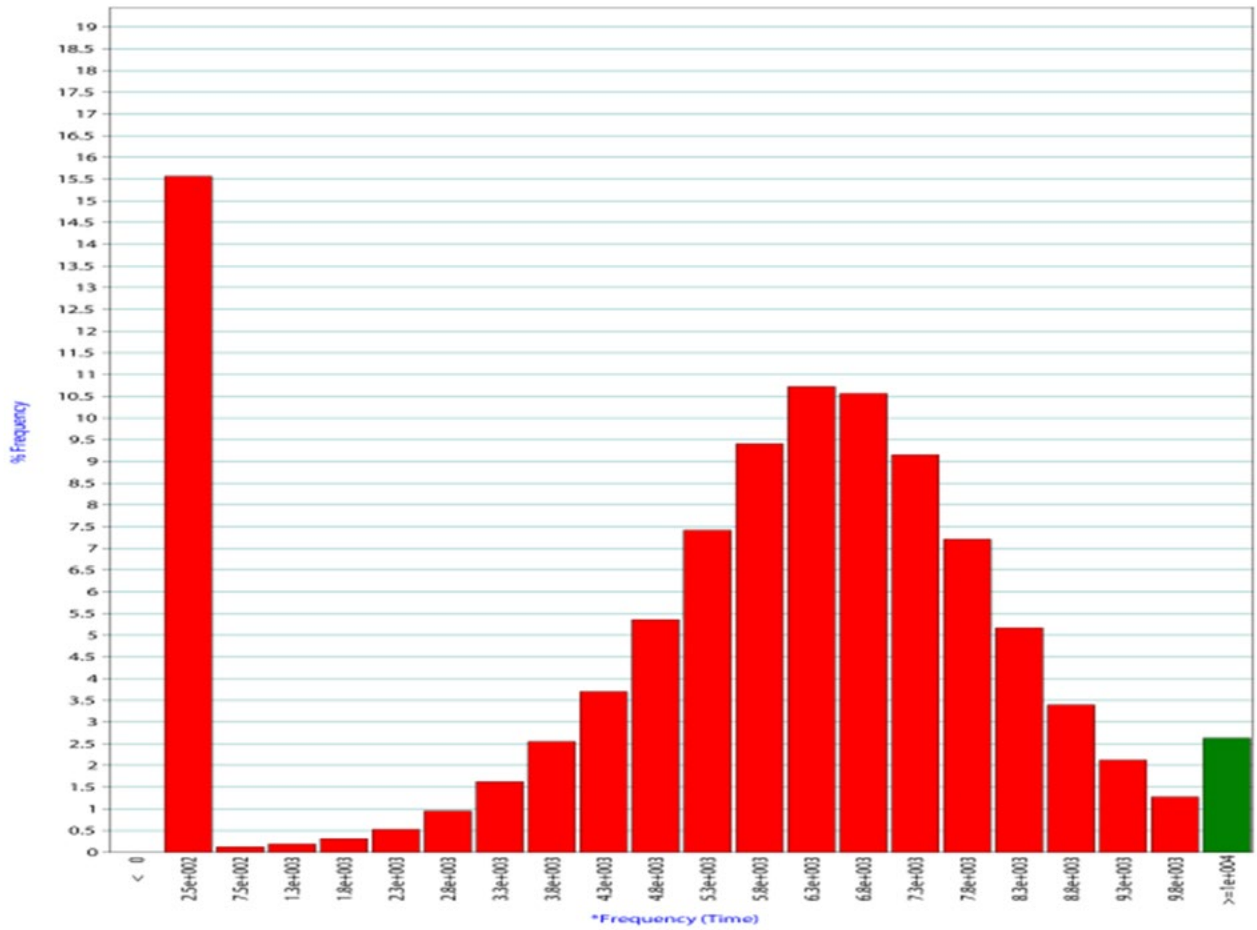


Figure 2.6 Frequency values within the Parametric Echo Sounder dataset.

albeit at similarly reduced penetration capacity. Under these circumstances survey is clearly limited in terms of areal coverage and cost, in comparison to the utility and availability of traditional 3D seismic survey. Consequently, until the costs and coverage of higher-frequency survey improve, traditional 3D seismic data remains well placed to provide a landscape overview. Despite limitations, the ability for high (>1kHz) frequency surveys to record archaeological sites in detail suggests a staged method of working may be a useful solution for current research. This could be achieved by the use of standard 3D or HD3D seismic to record the broader landscape and locate areas of interest, which are then surveyed using very high-resolution sources to allow the location of sites of archaeological interest.

Data analysis methodology and developments

Beginning with the original NSPP project, horizontal timeslicing has always been a key, first step in the interpretation of 3D seismic data. Horizontal slicing is perhaps the most widely used tool in seismic interpretation (Brown 2004) and is achieved by dividing the 3D seismic data volume into a series of horizontal slices of equal time intervals. This approach is suitable for relatively flat successions that are represented by parallel seismic events. Given the lateral continuity within the top sections of the seismic datasets, the relatively gentle topographic nature of the submerged landscapes, and the speed of application, this technique has been applied to the mapping of submerged prehistoric landscapes in preference to other time slicing solutions (e.g. stratal slicing – Zeng 1994; Zeng *et al*. 2010).

Within this project, the MegaSurvey 3D data volume was horizontally sliced at 4ms intervals, starting at 20ms where the first post-seabed multiple was imaged, through to the first clearly resolvable glacial features (120ms). The approach usually provided clear images of some of the larger depositional features. However, the thin Holocene cover in the North Sea results in limited vertical, and hence temporal, separation of features (Cameron 1992). In areas where the seabed was poorly resolved due to noise, multiples were used in time slicing to gain a full understanding of the features at or near the seabed. Low-frequency bandwidth is not necessarily a limiting factor in the analysis of 3D seismic data, as this is compensated by the density of spatial sampling (Praeg 2003). However, features at or near the seabed in shallow water (<25m) tend to be poorly resolved through this process. By using multiples in time slicing, features at or near the seabed may nevertheless be resolved (Fitch *et al*. 2005), and a limited vertical and hence temporal separation of the features can be achieved. The use of higher vertical resolution 2D data alongside existing 3D seismic data, was pioneered to improve feature imaging as part of the West Coast Palaeolandscape Project (Gaffney and Fitch 2019). This technique was applied to the Dutch sector of the North Sea within the shallow waters found in this area. 2D seismic profiling data was acquired from both the British and Dutch Geological Surveys and compared to the existing 3D interpretation to deliver a stronger temporal control (Figure 2.7). Additionally, once a stratigraphic marker was identified, it was possible to pick these surfaces across the 3D seismic volume to generate a horizon with geomorphological or chrono-stratigraphic value. The picking of such features allows the relative dating of features to be derived from the 2D and 3D datasets across the study area. The resulting interpretation from the 3D data can then be digitised (Figure 2.8), exported directly into the project GIS (Figure 2.9), and then cleaned and polygonised to support further analysis (Figure2.10).

Seismic attributes can also be useful to visualise data. Accordingly, attribute data was derived from the seismic source once the amplitude data had been analysed. A seismic attribute is commonly defined as, 'all the information that can be obtained from seismic data, either measured or computed and include the amplitude, frequency, coherency and acoustic impedance of the seismic data, as well as others' (Yilmaz 1987). Attributes are divided into two distinct classes, those of physical attributes and geometric attributes:

- physical attributes are related to the change in responses which is caused by variations in lithology and other such physical properties (impedance etc.)
- geometric attributes are responses to changes in structural and stratigraphic morphology of the sediments and are thus spatial variations of physical attributes

Within the study, attributes were used to calculate a coherency cube, a geometric attribute, for the entire area of 3D data. Coherency cube imaging utilises the 3D seismic volume in conjunction with coherence coefficient equations created by Bahorich and Farmer (1995). This generates an output that clearly images stratigraphic anomalies within timeslices (Chopra 2002). The method provides an estimate of coherence through the use of time cross correlation to provide an estimate of the apparent dips of stratigraphic features within the seismic volume (Bahorich and Farmer 1995). The coherence cube generated from North Sea data was subsequently serially timesliced to improve the definition of the fluvial features. However, whilst no new features were identified beyond those observed within the standard amplitude datasets, the increased definition of features allowed better landscape feature intepretation.

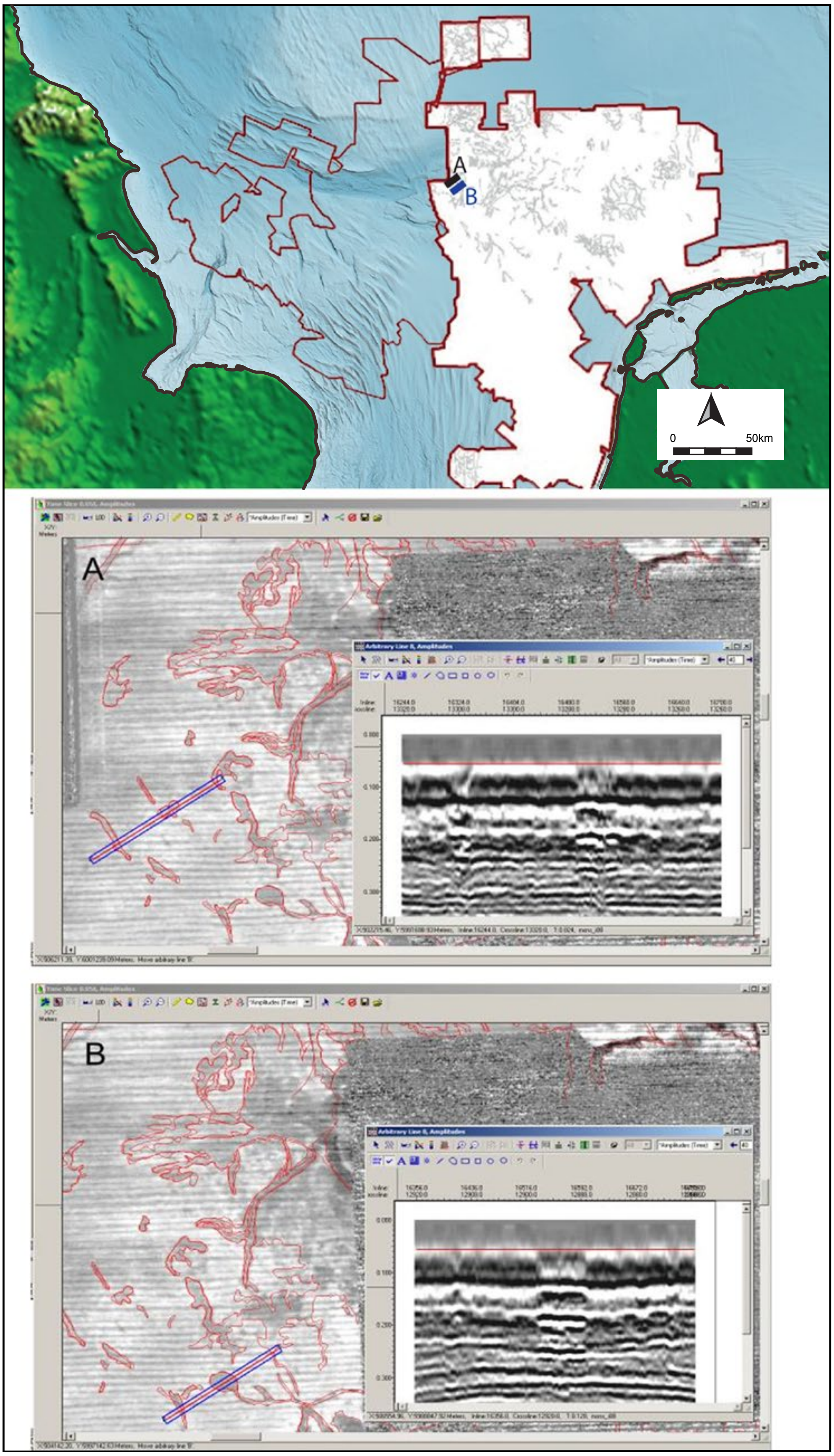


Figure 2.7 Cross-checking between horizontal and vertical slices within the 3D dataset. (A) shows correlation across a wide area with multiple responses along highlighted line, whilst (B) shows the correlation across highlighted line for a single feature.

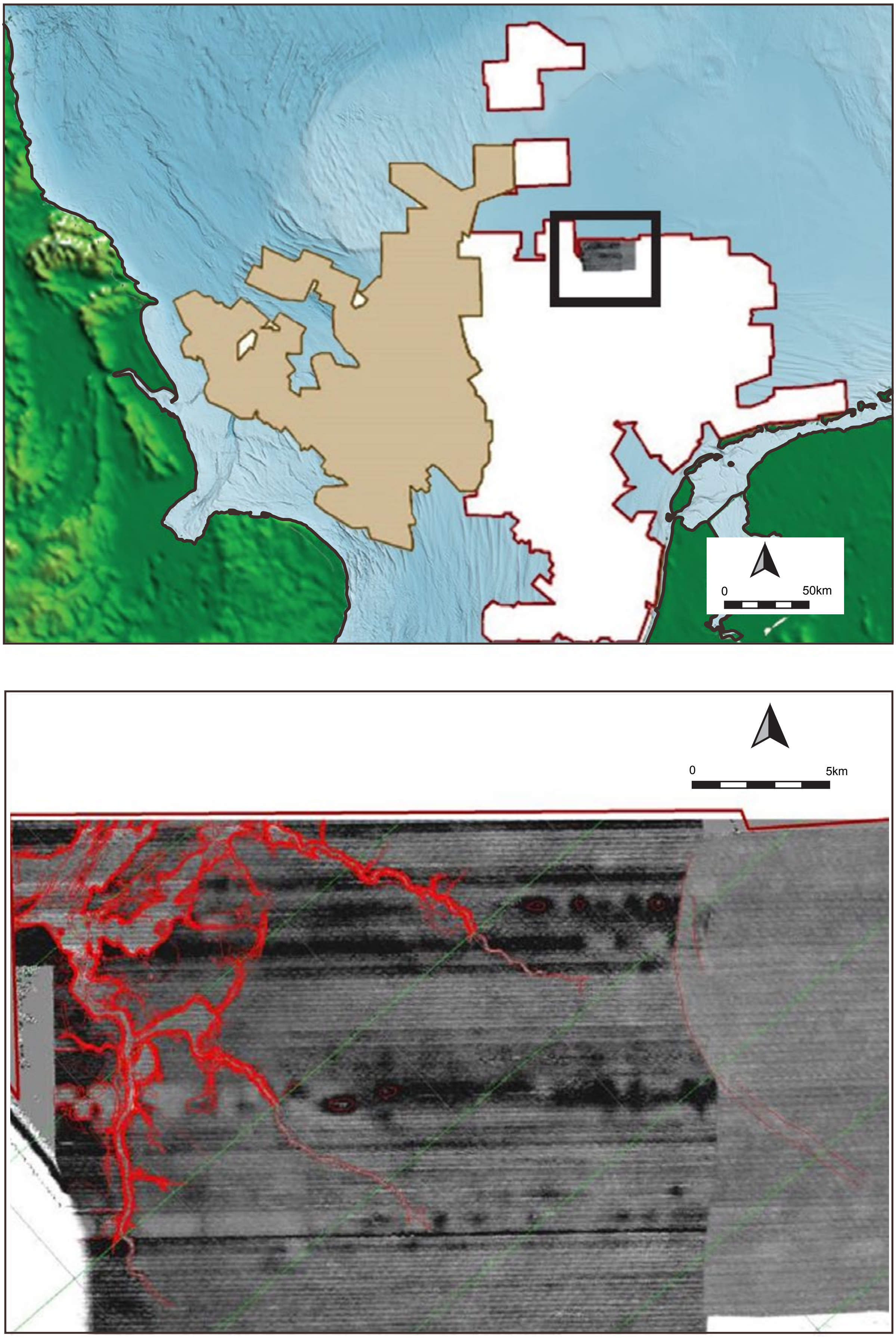


Figure 2.8 Features within sample area, digitised within SMT Kingdom.

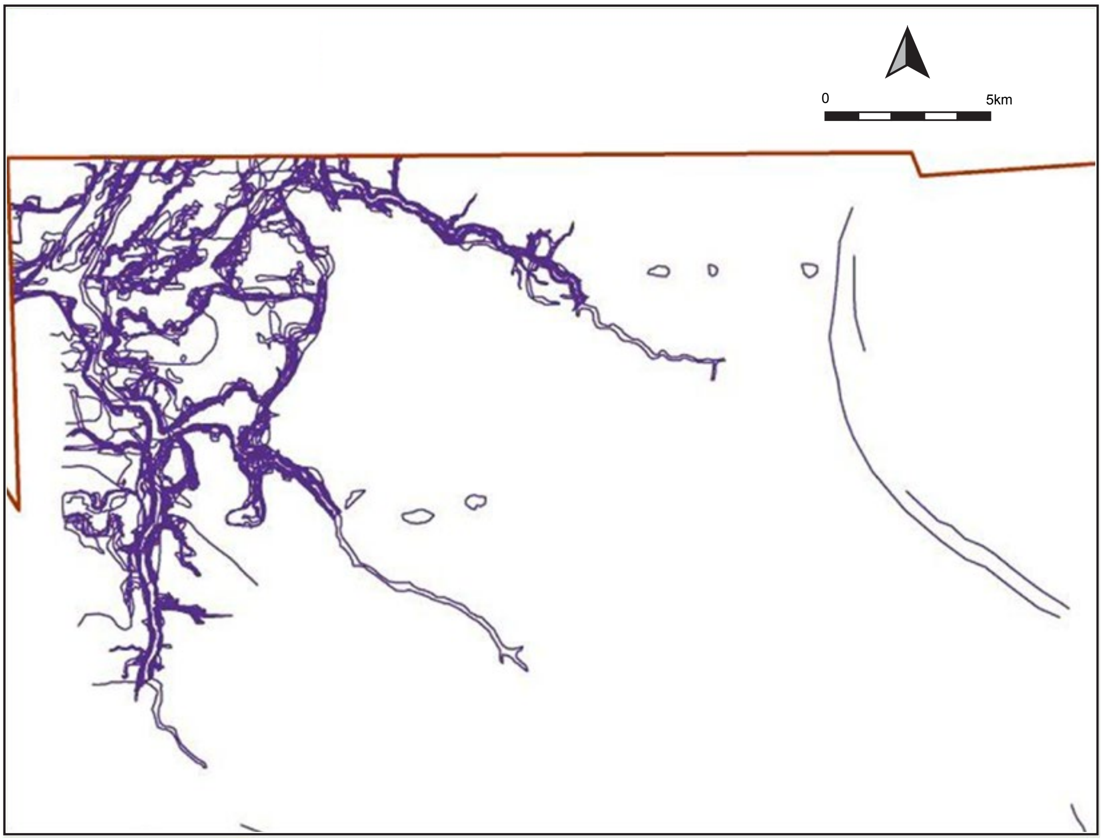


Figure 2.9 Features identified within sample area, imported into an ArcGIS project.

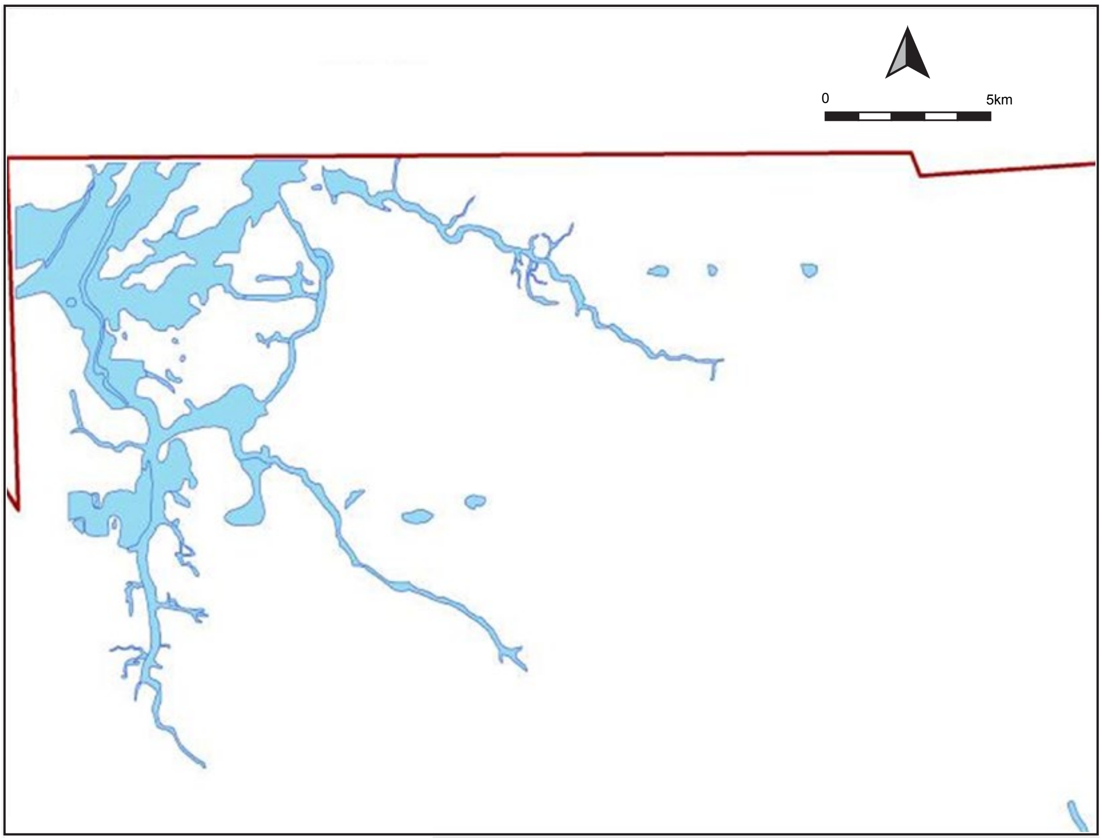


Figure 2.10 Features within the ArcGIS project cleaned and simplified.

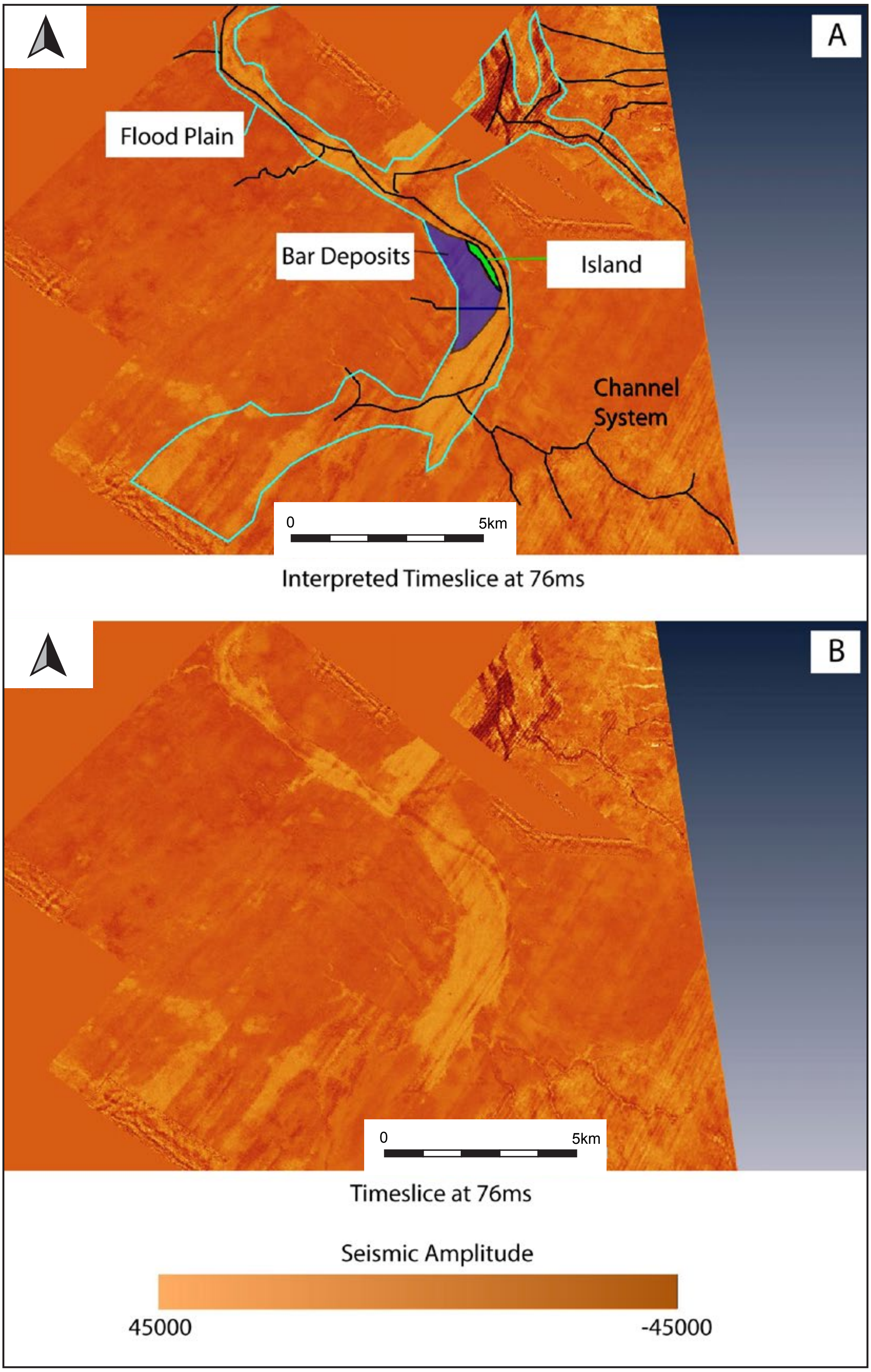


Figure 2.11 A timeslice with opacity filters applied (B), whilst (A) is the resulting interpretation of features derived from image B. It is clear the combination of opacity filters on the timeslice supports fine resolution imaging of small-scale features within this river drainage.

In order to enhance features observed in both the amplitude and attribute timeslices, the project followed the NSPP methodology in applying opacity rendering techniques to the timeslices (Kidd 1999). This technique converts conventional 3D seismic data into a voxel volume. Each voxel contained the information from the original portion of the 3D seismic volume that it occupied, together with an additional (user-defined) variable that controlled its opacity. The opacity of individual voxels can, therefore, be varied as a function of any of their seismic attributes. This allows the user to explore only those voxels that fall within a specific attribute range (usually amplitude). The use of opacity filters to image depositional systems, in conjunction with timeslicing, further resolved fine details of river drainage patterns (Figure 2.11). This is possible as buried fluvial channels have lithologically dependent seismic characteristics that are different from the surrounding materials. It is then possible to make the surrounding material transparent, whilst preserving all but the smallest channels as opaque features. This method enhances visibility of channel systems and improves interpretation of the geometric relationships of channel features both spatially and temporally, and thus allows the relative dating of any observed structures.

Another mode of visualisation implemented within the NSPP methodology, and used within *Europe's Lost Frontiers*, is root mean squared (RMS) timeslicing. This method is similar to the use of timeslicing to produce a map view image from the 3D seismic data volume. However, the method utilises the root mean square of the amplitude within a section of the seismic volume located between two selected time slices (Figure 2.12). The resultant data is illustrated as a slice that emphasises anomalous differences in acoustic impedance (a function of density and seismic velocity) in the selected time interval. RMS slices assist the interpreter to identify changes in lithology and stratigraphic features, aiding geomorphological analysis. In this study, RMS slices were found to be useful in imaging channels in areas of data with poor resolution, as well as aiding the clear imaging of more deeply incised structures.

A problem inherent in all of the visualisation and analysis techniques utilised in this study is data striping, which can mask palaeolandscape features within the shallow sections of the seismic datasets. Striping is an artefact of acquisition resulting from the data being optimised for deeper geological targets, rather than being set to target near surface features. Whilst initial attempts to perform automated destriping were explored during the NSPP, it was apparent that the merged nature of the PGS dataset, and the resulting complexity within the data striping, prevented widespread usage of standard destriping algorithms. Whilst it was confirmed that destriping could be achieved on a survey-by-survey basis, it was deemed too time consuming to perform extensively given the number of slices involved and the difficulty of extracting the original survey data from the MegaSurvey.

Within *Europe's Lost Frontiers,* several key palaeo-landscape zones were identified in which the original survey information was available and considered amenable to destriping. Destriping was undertaken using a base horizon, generated within seismic interpretation software IHS Kingdom, to provide an absolute topographic layer within which the data was of sufficient quality to allow for horizon picking. The value of each shot point within this layer was exported as an 'X, Y, Time' text file, and imported into the GIS project as a point file (Figure 2.13). Discrepancies within the dataset were noted and processed to ensure an even coverage of points across the area. The point dataset was split into six areas (Figure 2.14) and interpolated into six individual 25m resolution raster images, using the Inverse Distance Weighted method within ArcGIS.

Specific technical issues were encountered during destriping. Some areas within the North Sea, such as Area 1, were strongly affected by striping (Figures 2.15 and 2.16). In these areas manual destriping was undertaken to facilitate visualisation (Figures 2.17 and 2.18). In the case of Area 1, the data anomalies were noted to be oriented in an east-west direction. In this case the area was further split up into individual stripes, and the average difference between stripes calculated. The time value was then adjusted accordingly, and a new raster produced for the area based on the amended values (Figure 2.17). It was noted that further detailed destriping would produce better results, but time constraints meant that this was not possible. It was decided that the raster produced from the first pass of manual de-striping would be of sufficient quality for current purposes. Area 2 also contained data striping which was consistently stronger in amplitude than in other datasets (Figures 2.13 and 2.14). The average differential value between Area 2 and the other areas was calculated, and Area 2 adjusted accordingly. Once these issues had been addressed, an overall raster mosaic was produced for interpretation (Figure 2.19).

Volumetric geobody modelling

Many stratigraphic features within the dataset have a volumetric component, and accurate visualisation of these volumes was found to be of value in interpretation. Whilst RMS slice methods do allow for the display of some of the information contained within the volume of seismic data, its generation as a planar slice results in the loss of integrity of complex structures. This is because 3D component of any anomaly is not adequately represented. The potential to lose significant data during processing is therefore

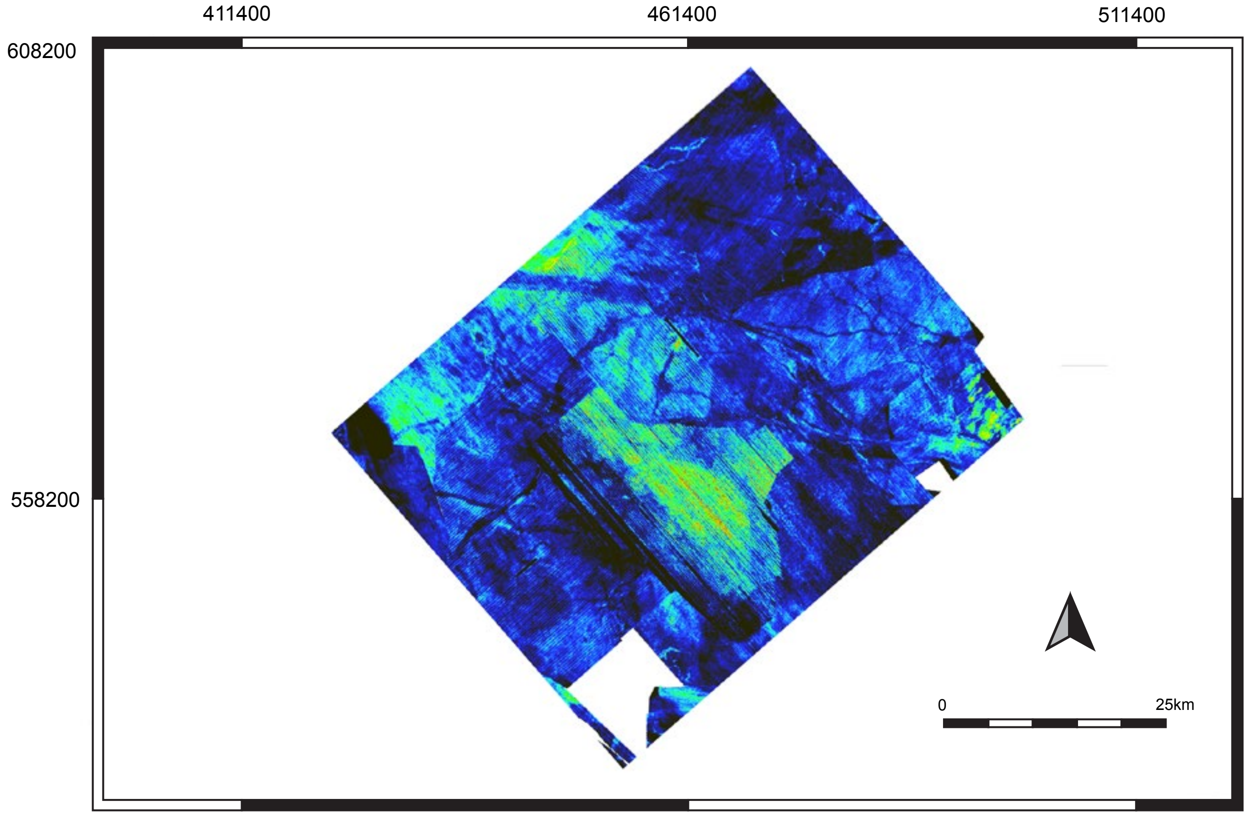


Figure 2.12 An RMS slice from the Outer Silver Pit area. The slice is generated from the volume between 0s and 0.1s.

very real. From the outset of the NSPP, it was decided to follow common practice within petroleum geology, and the relatively, sophisticated display technologies available at The University of Birmingham, and later Bradford, were used to implement analyses permitting geobody modelling and full 3D and stereo visualisation to maximise information extraction.

3D surface modelling has been utilised within archaeological geophysics for some time (e.g., Neubauer and Eder-Hinterleitner 1997). However, the resultant surfaces still represent a single layer or, at best, a 2.5D surface. Surface modelling is not suitable for the representation of volumetric 3D seismic data or for the exploration of internal structure in complex volume features. For this propose, FEI Software's 'Avizo' visualisation package was utilised to explore the volumetric components of geobodies observed within the 3D seismic data. This was supported by an Avizo extension, which supports datasets that may be hundreds of gigabytes in size. Avizo also possesses a suite of tools that make it an effective environment to explore, analyse and display many types of remotely sensed data. The ability to specifically extract information contained within voxels, through a series of solid models using this software, has been demonstrated in a number of related projects (Fitch *et al.* 2007; Watters 2006).

To produce geobody models that inform our understanding of major landscape features, the original seismic data was directly segmented utilising reflection picking techniques commonly employed in the oil and gas sector (Fitch *et al.* 2007). Through segmentation of features of interest, a series of user determined lists were generated, which contained the features of interest. Fully automated selection tools can be utilised to define the data voxels contained within each feature, based upon machine identification of similar seismic properties such as frequency and amplitude. Although this was the most desirable analytical method, the differences between surveys, and the noise within the top sections of the MegaSurvey data, prevented its full implementation.

For these reasons it was necessary to apply a semi-automatic process of isosurfacing, utilising user-set boundaries and thresholds to constrain the process of automatic voxel identification. With the required information, extracted from each seismic dataset, a solid model was built for individual features (Figure 2.20). Once constructed, it is possible to disassemble a feature in order to gain further insights into the 3D structures of specific features (Figure 2.21).

Unfortunately, the results of such an analysis are limited by the inability of most GIS systems to incorporate 3D structural information within spatial

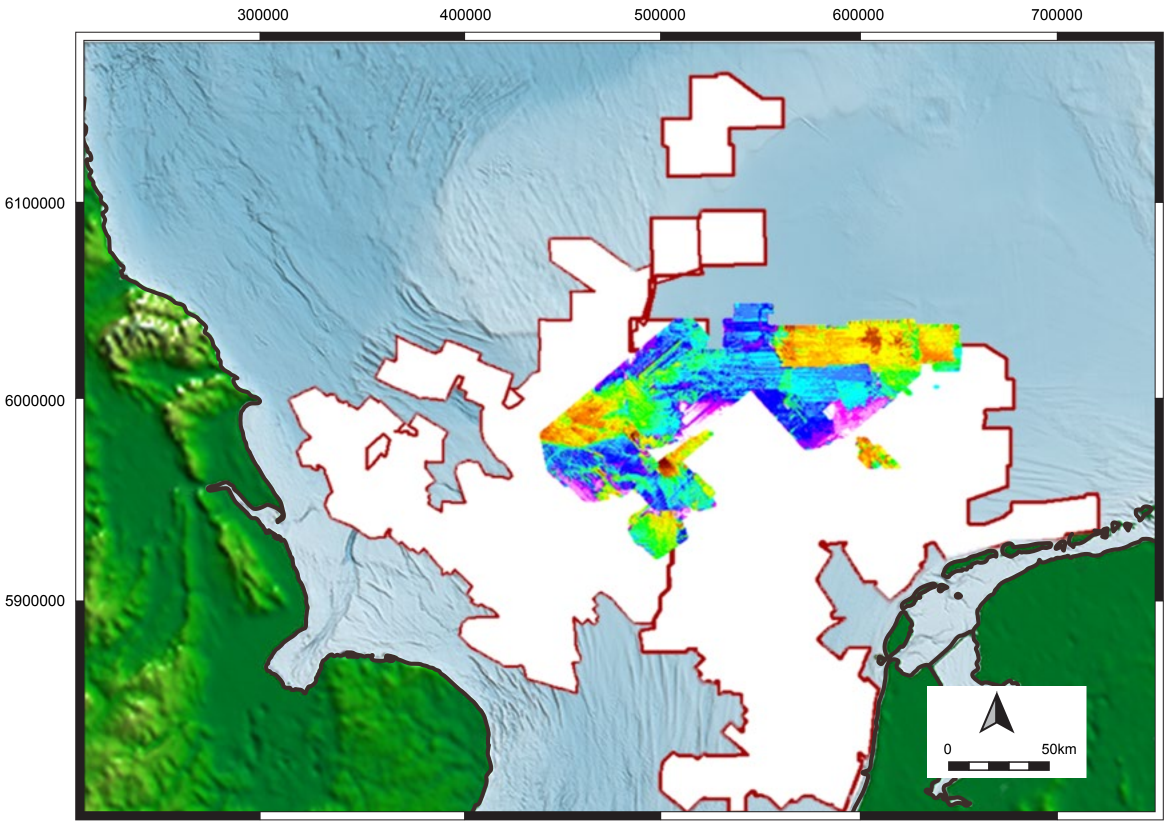


Figure 2.13 Base horizon layer imported from SMT Kingdom into GIS.

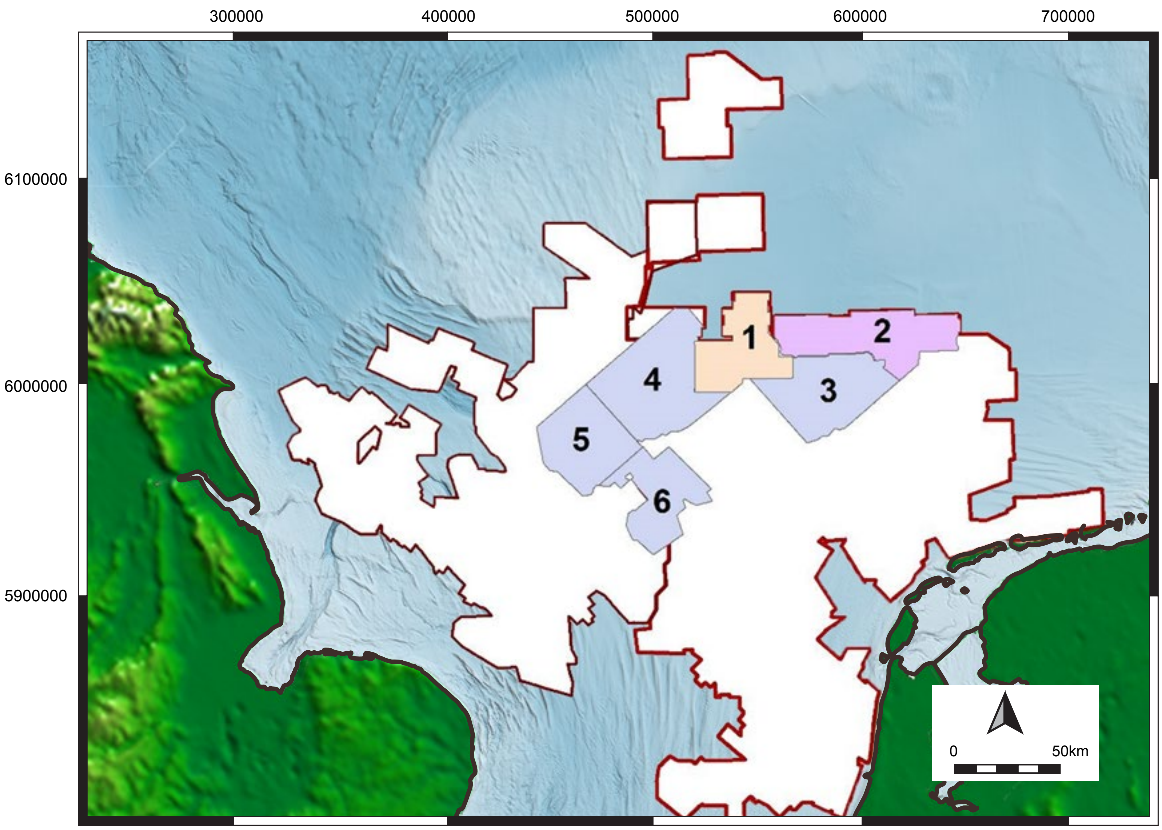


Figure 2.14 Areas used to split the horizon point dataset.

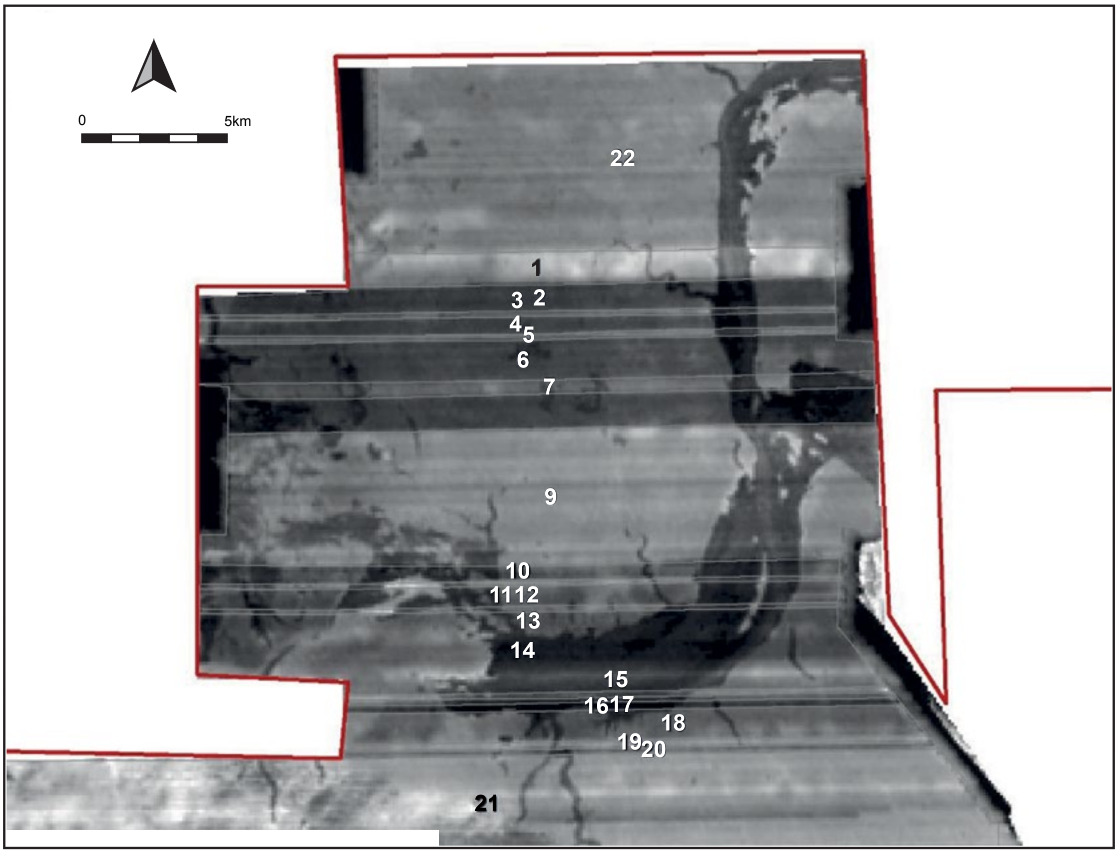


Figure 2.15 Detail within Area 1, showing band divisions used to de-stripe the data.

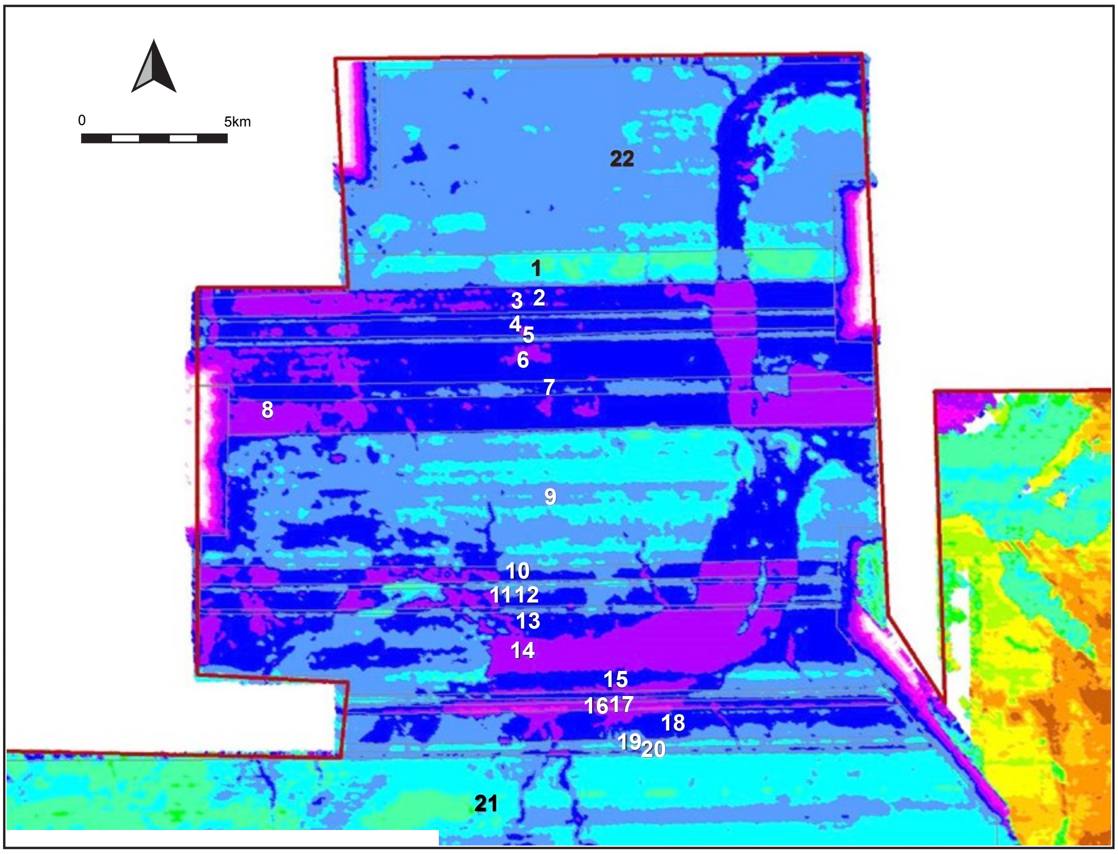


Figure 2.16 Interpolated raster of Area 1 prior to manual de-striping.

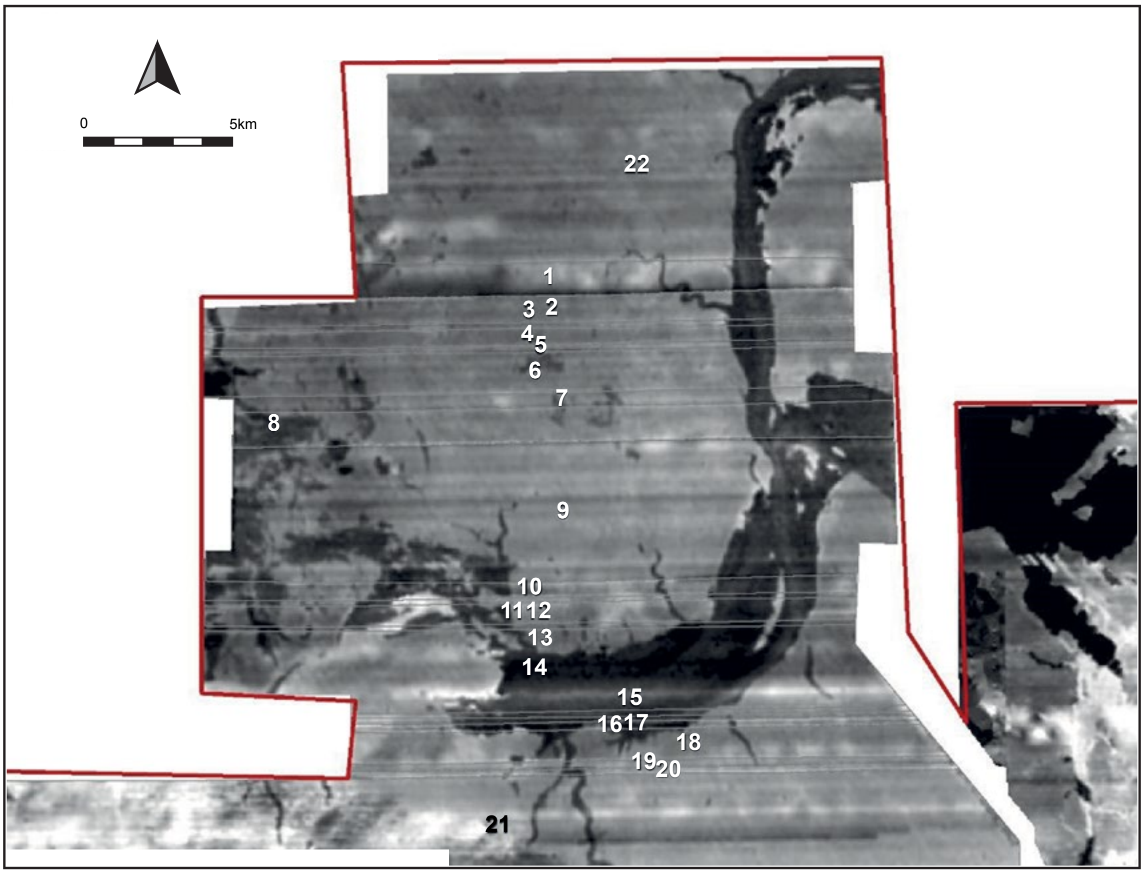


Figure 2.17 Interpolated raster of Area 1 after manual de-striping.

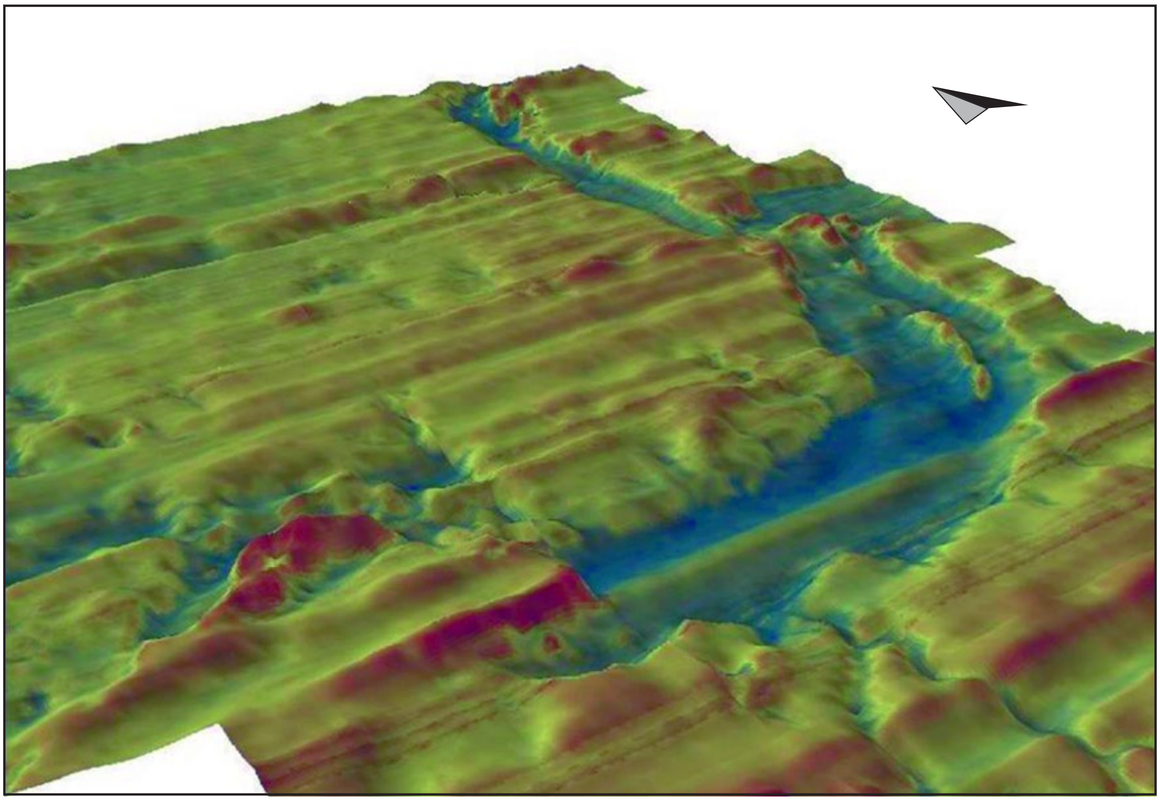


Figure 2.18 3D vertical exaggeration of features within Area 1 using ArcScene.

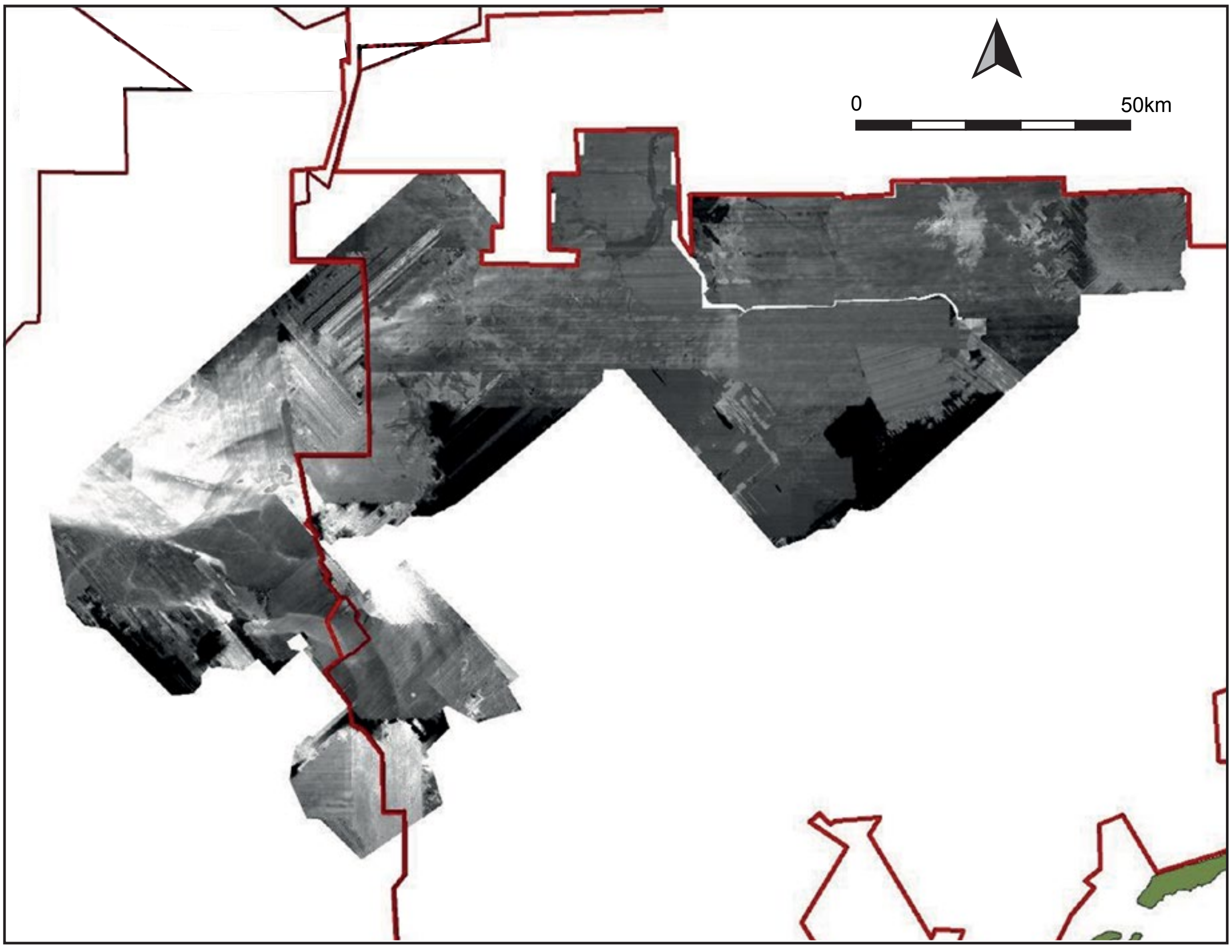


Figure 2.19 Interpolated raster mosaic after values for Area 1 and Area 2 had been re-evaluated.

analysis. Currently, use of solid modelling software is limited to the export of CAD models that can be imported into GIS visualisation tools for display, as well as spatial analysis. These are converted on import into the GIS as layers which are more suited to GIS display. This conversion allows the production of polygonal elements which map the boundary of the acoustic impedance anomaly, and thus allow the user to assess and visualise the size of anomalies. However, this also results in fully 3D models being converted into 2D layers, which represents the shape and size of the anomalies, and thus only approximates the model's volumetric nature. However, because it does not represent the actual volumetric attributes of the model, the limitations associated with displaying volumetric data in most standard GIS softwares are significant. Given the exponential increase in the size of datasets now available, and the lack of software development in these areas, application of such methods was limited to that achieved through the NSPP (Fitch *et al*. 2007). Although significant development of alternative, experimental modes of analysis have been attempted as part of the project (Fraser 2021), the use of planar slices remains the best method of incorporating this information during analysis.

Conclusion

Modifications to the methodology developed by the NSPP have been required to reflect variations in geological conditions (Fraser 2021; Gaffney *et al*. 2007). However, the overall methods of interpretation and mapping have proved remarkably durable and applicable to any area where 3D data is available. Ultimately, the comparative analysis provided here suggests that the greatest limitation to rapid technical development of analytical process is the condition of the data as collected, or as pre-processed. As demonstrated here, such limitations may be independent of the age of the data. Where conditions are conducive, and where acquisition parameters are favourable, even relatively early 3D seismic surveys can potentially be used for archaeological landscape interpretation. These observations are significant for the study of submerged prehistoric landscapes as they suggest that the methodologies described here could be applied virtually anywhere, providing the data conditions are favourable. Certainly, the capacity of the palaeolandscape data provided through the NSPP to guide and optimise offshore survey and coring has been demonstrated through the Humber Regional

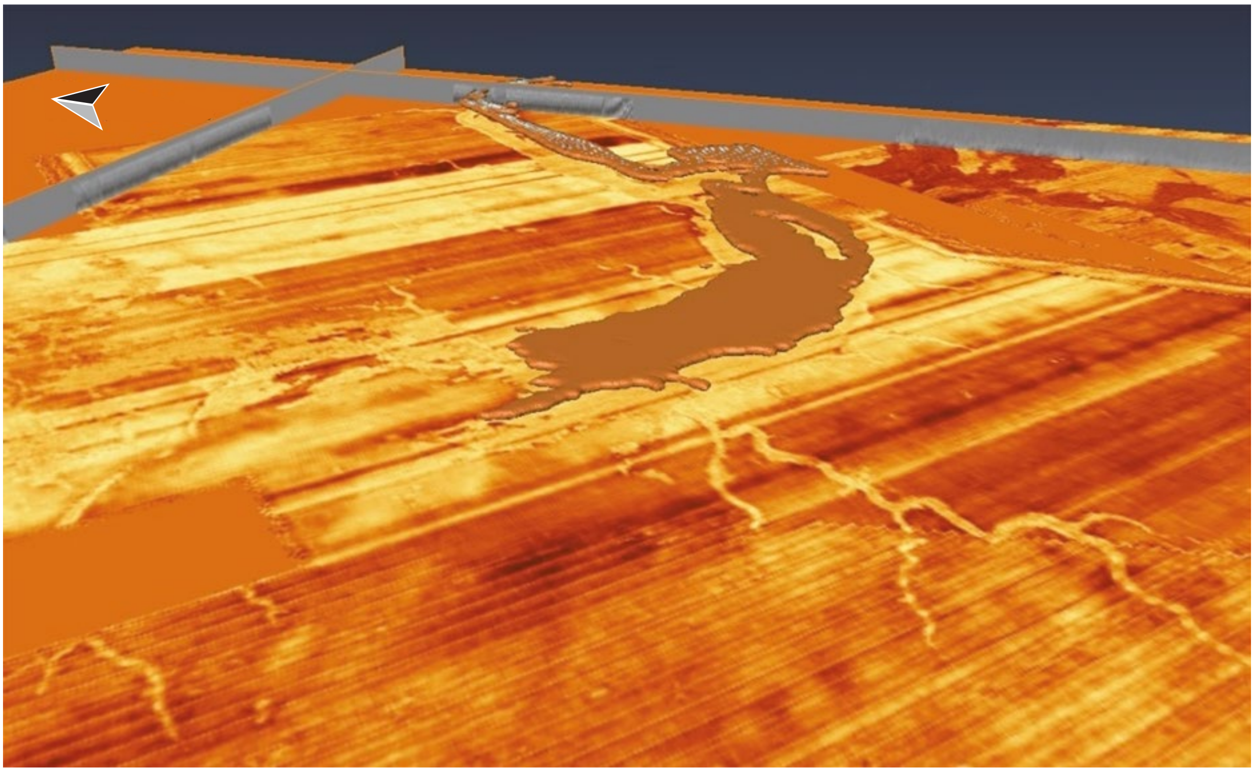


Figure 2.20 A 3D Geobody Model, constructed from the seismic timeslices, and displayed within the seismic volume.

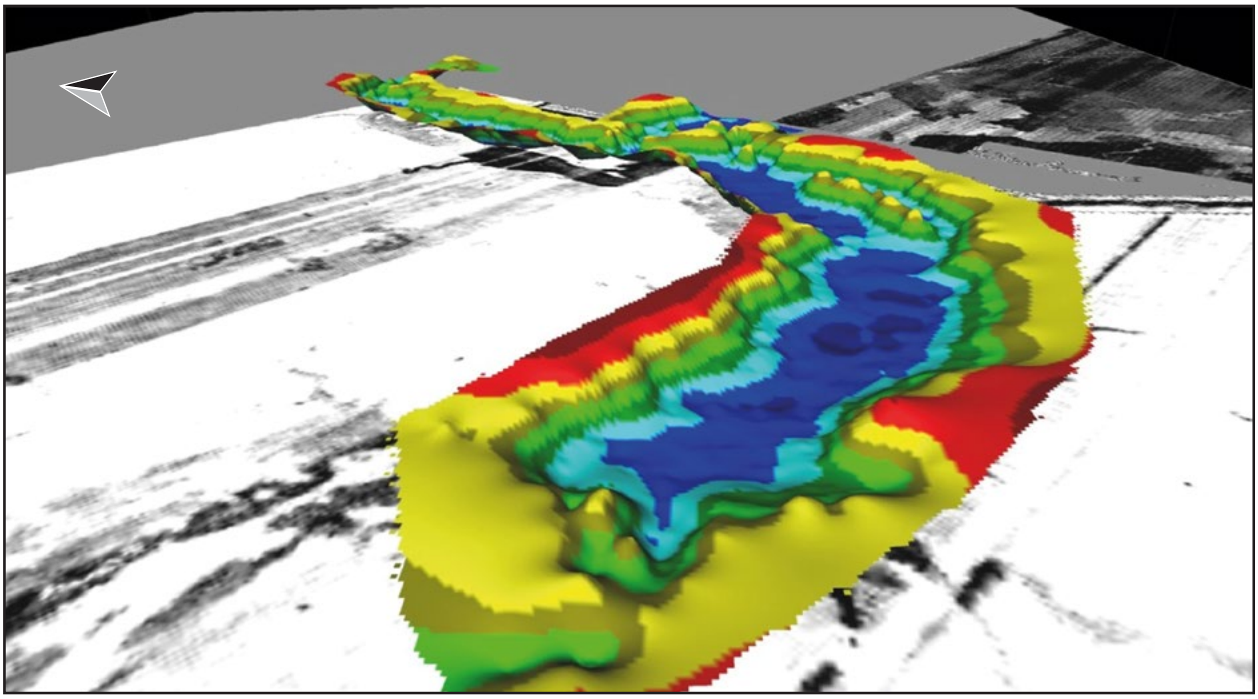


Figure 2.21 A channel visualised by cutting the geobody model to reveal the base of the channel model. By using such methods, it is possible to understand, more fully, the morphology and formation of such structures.

Environmental Characterisation study (Fitch this volume, chapter 4; Tappin *et al.* 2011). Iteratively, the results of that study also provided invaluable dating evidence to confirm the presumed dates of features identified by the NSPP.

Ultimately, these legacy datasets remain the route to provide horizontally extensive mapping of regional scale archaeological palaeolandscapes. These data can be enhanced through the integration of new, higher resolution 2D datasets and high-resolution 3D data, where they are available. Access to high resolution data is, however, the product of commercial marine development and access may be restricted. However, where accessible these datasets have already improved palaeolandscape interpretation (Fitch *et al.* this volume; Murgatroyd *et al.* forthcoming).

The enhanced capacity to resolve features at the level of a landscape does not, of course, resolve the limitations of merged 3D data to identify individual archaeological features or even sites. However, the increased availability of extensive remote sensing data allows a significant expansion of the area available for study, and these enlarged datasets provide the opportunity to study larger, contiguous areas. In doing so, analysis can support definition of locations with greater archaeological potential. The mapping data provided through the NSPP and *Europe's Lost Frontiers* can support a staged approach to prospection, using increasingly higher resolution survey to identify submerged prehistoric sites and place them in their landscape setting (Missiaen *et al.* 2020). Consequently, the landscape information generated here remains significant, and the value of legacy datasets will only be improved as enhanced supporting data becomes available following new survey. Together, these datasets provide a realistic base for a programme of mapping of the submerged prehistoric archaeological landscape, and potentially settlement, from at least the Last Glacial Maximum and at a global scale.

Chapter 3

A description of palaeolandscape features in the southern North Sea

Simon Fitch, Vincent Gaffney, Rachel Harding, James Walker, Richard Bates, Martin Bates and Andrew Fraser

Introduction

The northwest European continental shelf retains, arguably, the most comprehensive record of a late Quaternary and Holocene landscape in Europe. The landscape was extensively populated by prehistoric communities and may have been a core habitat during several periods of prehistory, but was finally and rapidly inundated during the Mesolithic as a consequence of rising sea levels (Mithen 2003: 154-157; Walker *et al.* this volume). In response to the lack of a substantive archaeological context for the period of inundation, the North Sea Palaeolandscape Project (NSPP) undertook extensive mapping of the southern sector of the North Sea in 2007 (Fitch *et al.* 2005; Gaffney *et al.* 2007). This project derived mapping from seismic geophysical data rather than the bathymetric mapping used by earlier studies. As such, the results reflected the presence of buried landscape features which were not necessarily expressed within the current seabed surface (Fitch *et al.* 2005). In 2011 funding was provided by the National Oceanographic and Atmospheric Administration (NOAA) to undertake research on the Dutch sector of the North Sea, using a mega-merge dataset provided by PGS UK Ltd. Combined, these surveys covered *c.* 57,000km^2, located over some of the longest-lived areas of the Mesolithic landscape. Building on this research, the *Europe's Lost Frontiers* Project study area now includes a larger proportion of the southern North Sea, from Northern England across to Denmark in the north and the Dover Strait in the south. This represents an area of over 188,000km^2 (Figure 3.1).

Background

Before considering the results of mapping within the area in detail, it is useful to examine some of the background regarding the nature of the deposits associated with the landscape. Within the *Europe's Lost Frontiers* study area, the Holocene deposits under discussion are on average located between 40 and 80 milliseconds (ms) within the seismic data, with the deepest incised fluvial systems being located *c.* 30m below the seabed. However, it is also important to note that there are more substantial features associated with major fluvial systems and/or reused glacial tunnel valleys within the data. For example, within Figure 3.2 a Holocene channel can clearly be seen to cut into late Pleistocene deposits (Dogger Bank Formation) to a local depth of 75ms. For the purposes of this project, analysis generally did not include features or deposits which were not directly relevant to the project goals. For example, the Outer Silver Pit Formation (Lower Pleistocene) may be up to 80m deep locally, whilst the Markham's Hole Formation achieves 150m (Cameron *et al.* 1992; Lumsden 1986). For this reason, the Lost Frontier's dataset slices are usually derived from between 40ms to 72ms. Additional slices, between 60ms and 72ms, were used specifically to visualise local features with deeper incision but were not generally applied for the purposes of broader landscape interpretation.

Validation of this approach can be demonstrated through the integration of 2D data within the 3D framework and associated core data. For example, in the north of the study area, data from the Gauss survey (e.g. Salomonsen and Jensen 1994) was cross-correlated with the 3D survey data. The palaeochannels visualised in the Salomonsen and Jensen's (1994) survey were cored, dated and determined to be of Holocene date. More recently work by the BRITICE project, working to constrain the extents of the last glaciation, has recovered cores and materials which have also provided evidence for the Holocene landscape (Roberts *et al.* 2018). Dates of 9934 +/- 188 cal BP (SUERC-72886) obtained by BRITICE core 176VC (Roberts *et al.* 2018) evidence the emergence of the landscape during the Holocene and the presence of channel activity within the area of Doggerland. The information derived from recent work is consistent with previous mapping of Holocene formations (e.g. Cameron *et al.* 1992). Consequently, there can be confidence that the derived landscape mapping reflects data relating to the Holocene.

Broad area description of the southern North Sea

Here we will provide broad descriptions for the mapped area of the southern North Sea (Figure 3.3). These supplement the published data for the English sector of the southern North Sea provided in Gaffney *et al.* 2007, and, where overlaps exist, the version here represents a revision beyond that previously published. Further

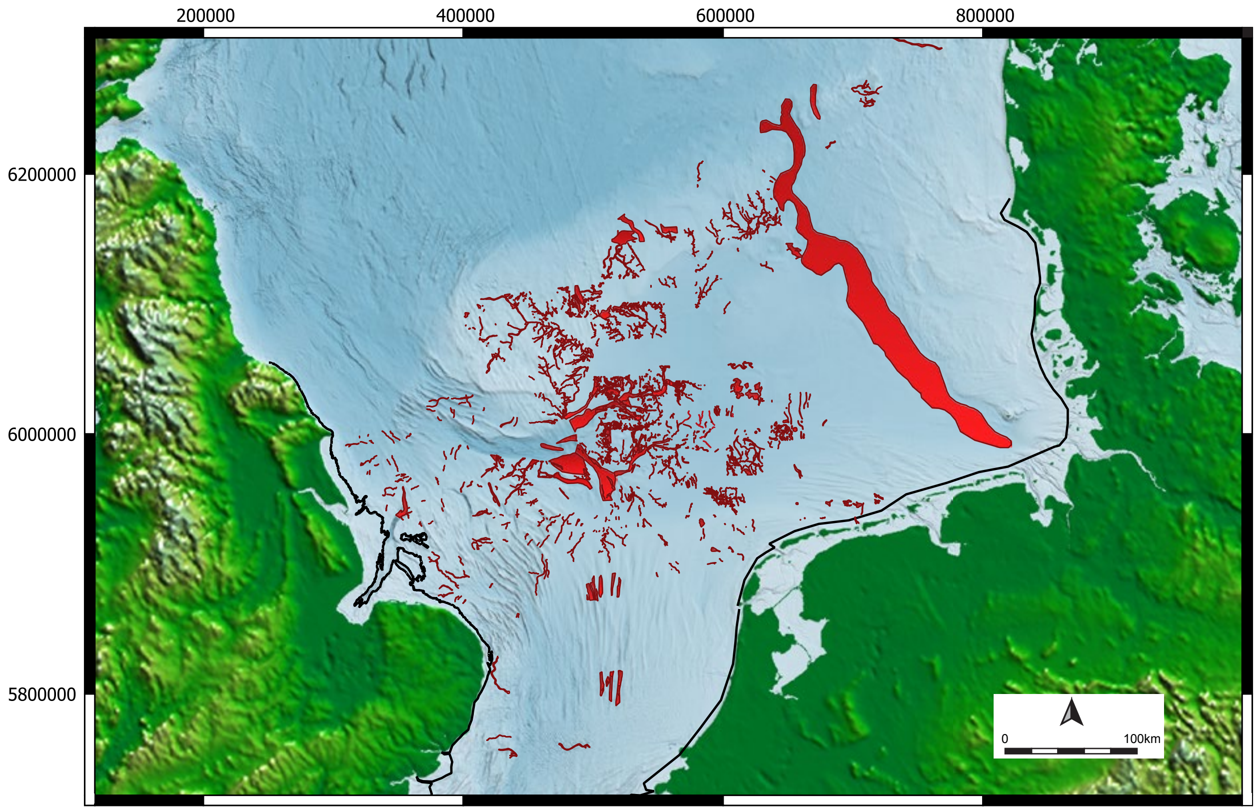


Figure 3.1 GIS Mapping of the features recorded by the Europe's Lost Frontiers project.

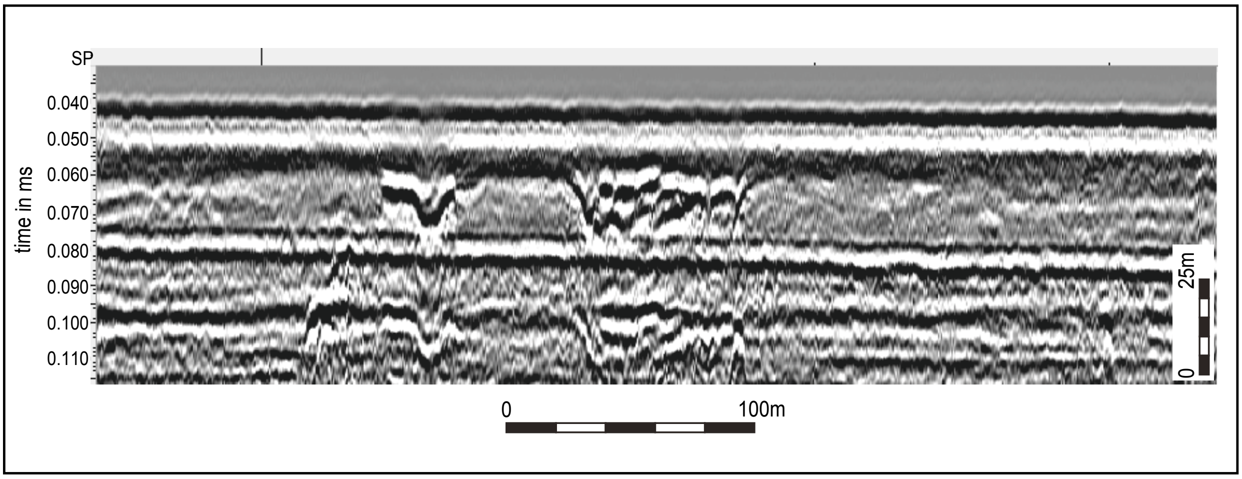


Figure 3.2 Seismic line from 'Gauss 159B' survey acquired in 1990 by the RGD and BGS over the Dogger Bank. A Holocene channel can clearly be seen to be incised into the underlying late Pleistocene deposits (Dogger Bank Formation).

detail on the areas studied by *Europe's Lost Frontiers* will be presented in later project publications.

Area 1 – Northern Sector

The landscape of the Area 1 displays the influence of the underlying late Pleistocene deposits which create an area of higher relief that gently descends into the lower lying areas surrounding the Outer Silver Pit (Figure 3.1).

On the northwest and central area of the Dogger Bank, the predominant trend of the early Holocene fluvial systems is to the south/southeast (Figure 3.8, Shotton River and A), converging on a major channel system running east/west towards the Outer Silver Pit (Figure 3.6 and Figure 3.8, B). The north/south orientation of the channels on the Dogger Bank is thought to be a relic of the late Pleistocene drainage systems of the area (Emery 2020). In the extreme north of the Dogger Bank,

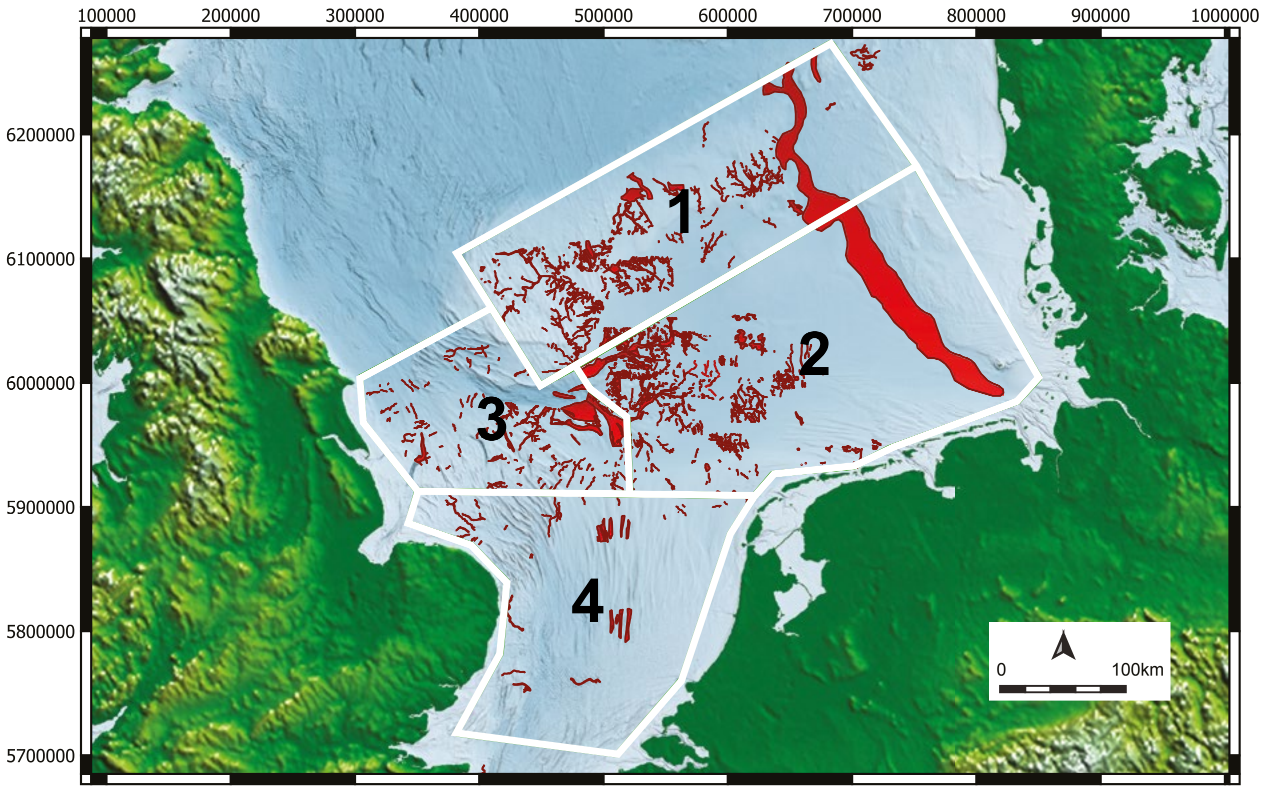


Figure 3.3 Areas divisions of landscape features within the study area.

however, one main channel runs north (Figure 3.8, C), and it is suggested that this may be a later feature with a watershed being located on the top of the Dogger Bank (Figure 3.1).

In the northeast of the Dogger Bank, the drainage directions changes. Here the channels drain from west to east into the Elbe palaeovalley. Running east of the Dogger Bank and west of Denmark, the Elbe channel was clearly a significant feature in this landscape. It has a width of 1.5km and 15m depth and can be seen clearly on seismic lines that cross the region (Hjelstuen *et al.* 2017). Smaller channels in the area were recorded by Andresen *et al.* 2019, and the wider *Europe's Lost Frontiers* data reveals these channels to be lesser tributaries of the Elbe (Figure 3.8, D). Andresen notes that these channels were formed during the Last Glacial Maximum and later morphed into sub-aerial channels. A few small channels can also be seen on the eastern side of the Elbe palaeovalley (Figure 3.18, E). These channel fragments flow to the west and towards the Elbe palaeovalley, although no data currently exists that could allow a visualisation of any junction between these channels and the Elbe itself. The exact age of these features is undetermined but, given the shallow nature of these features, they are thought to be late Pleistocene to early Holocene. As inundation progressed, these small channels would have turned into tidal channels before finally being submerged.

The Holocene fluvial features on the Dogger Bank incise the underlying late Pleistocene deposits (see Figure 3.4) and suggest that the earlier channels were active during the late Pleistocene or early Holocene, and post-date glacial activity in this area. Channel activity during this period can be divided into three main phases of activity. The first stage is seen in the formation of relatively linear channel features and is often associated with the larger features in the area. These features are of late Pleistocene age, associated with deglaciation and represent pro-glacial channels (*c.* 24,000 to 23,000 BP). These indicate the first stage of channel activity and end with the removal of meltwater as a source following glacial retreat. This, coupled with aridity during the period 23,000 to 17,000 BP, low temperatures and tundra conditions, caused the channels to become relict.

The second stage of channel activity in the area occurs, initially, with the reuse of earlier pro-glacial channel structures. These smaller channel systems are incised into the topographic lows associated with pre-existing structures (Figure 3.5). Aside from channel reactivation, the development of new feeders and the formation of new channel systems occurs during this period. These channels (*c.* 17,000 to 10,000 BP) represent an increase in channel activity due to rising precipitation after the end of glaciation (Emery 2020).

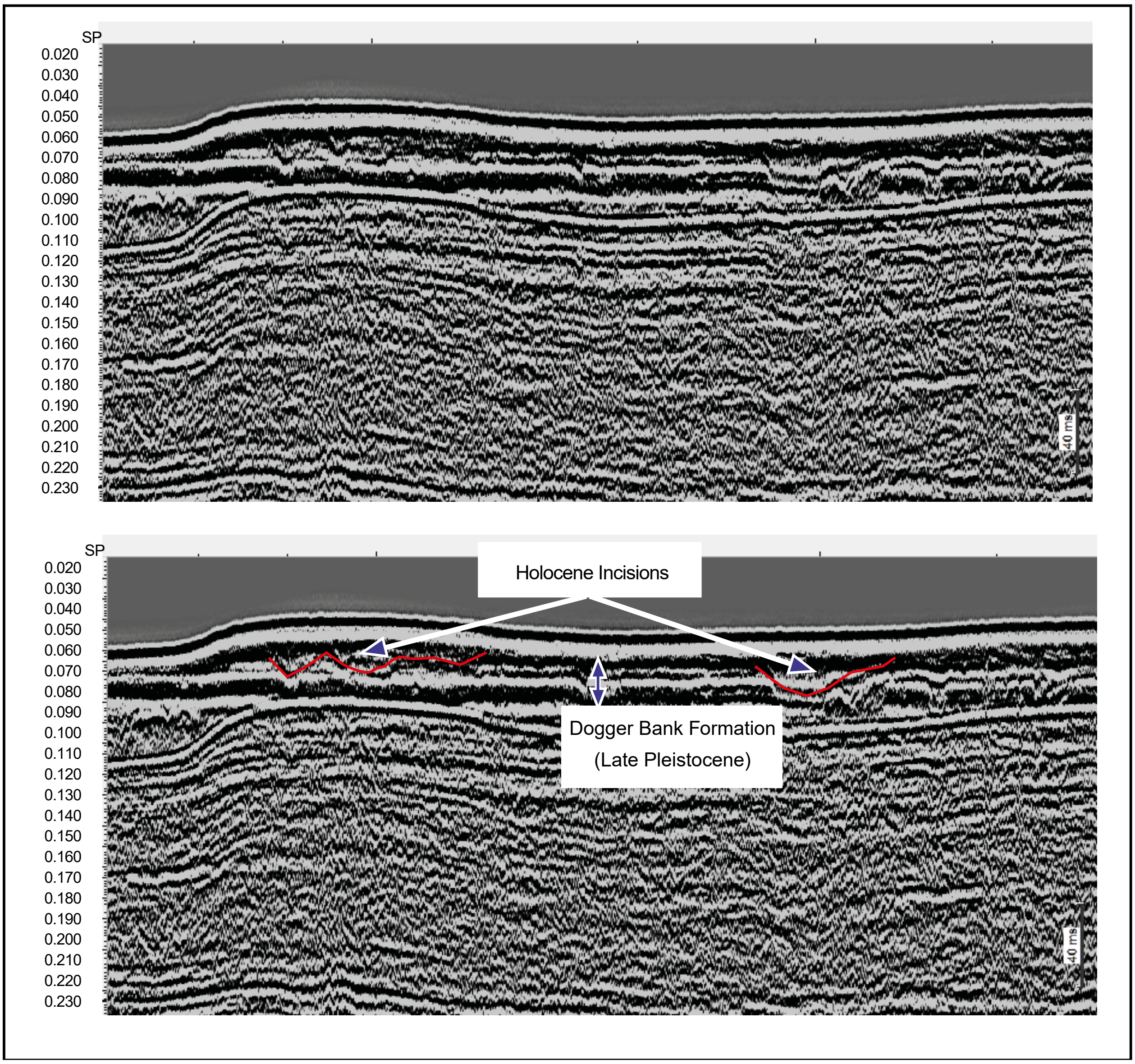


Figure 3.4 Cross section across the southern flank of the Dogger Bank. The Holocene features can be seen to incise into the underlying late Pleistocene deposits.

The geographic location of the fluvial systems on the topographic high of the Dogger Bank suggests they were sub-aerially exposed for a longer period than is evident for most of the survey area, and consequently that the systems are better developed. Roberts *et al.* 2018 suggests that the ice had retreated from this area by 23,000 BP and despite aridity during the period, a period of *c.* 11,000 years was available for channel development before they were inundated *c.* 8000 BP (Emery 2020). Most of the channels are sinuous systems with a high stream order. The channels on the Dogger Bank flow down south into a major east to west flowing channel of considerable size, located within the Oyster ground (see Figure 3.6). A vibrocore, fortuitously taken from one of the feeder tributaries of this system by the BRITICE project, provided a date of (12,629 +/- 90 cal BP SUERC-72883, Roberts *et al.* 2018: 195) which confirms the period of activity for this channel.

A third phase of channel development is evident in the area marked 'A' in Figure 3.6. Although separation of the features is difficult within the seismic data, it is clear that these later channels directly overlie the channels of the previous two stages. In addition, later channels are linked to a coastline which is related to the submergence of the landscape at around 8000 BP (Emery 2020; Shennan and Horton 2002), and therefore likely to have been formed as a response to the break-up of the landscape and a change in river base levels. Given that the channel (Figure 3.6, A) drains the top of the Dogger Bank, later channels are therefore likely to be associated with the final stages of the emergence of the Dogger Bank itself (see Figure 3.8). Zones of 'mottling' in the seismic data are associated with the flooding of the landscape and are thought to relate to peat formation (Emery 2020; Hepp *et al.*2017). These correspond to a different seismic response in the areas

Figure 3.5 Example of the later Holocene reuse of pro-glacial channels. This is evidenced by smaller (black) channels cut within the main valley and the formation of dendritic feeders on the side of the valley.

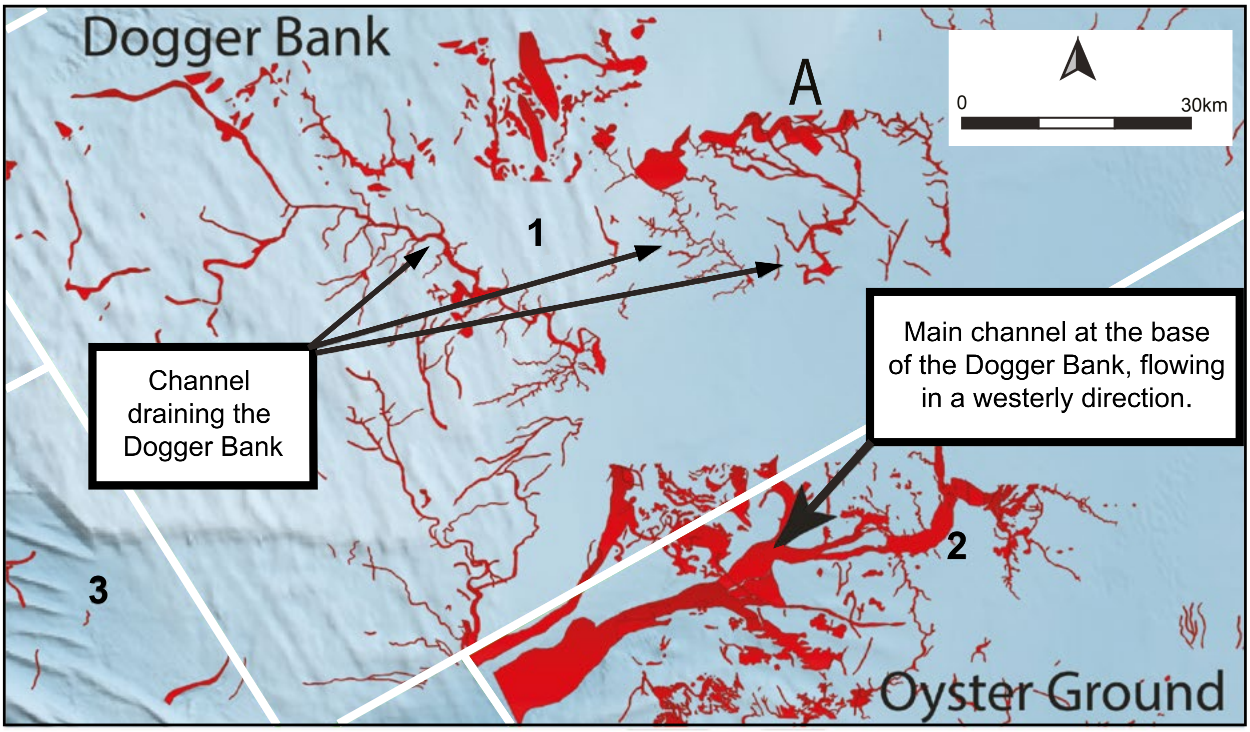


Figure 3.6 The main drainage channels of the Dogger Bank drain south into a major channel located at the foot of the bank and in the area of the Oyster Ground, eventually flowing to the west and into the Outer Silver Pit.

between the channels (Figure 3.7). This is indicative of intertidal/wetland deposits associated with inundation in this area (Hepp *et al.* 2017). The deposits are therefore likely to comprise organic muds and silts similar to deposits in the offshore Humber area (Gearey *et al.* 2017; Tappin *et al.* 2011), and thought to be of a similar Holocene age to those features dated by the Humber REC (Fitch *et al.* 2011). Within the sector, the Elbe flowed through a valley that extended across Doggerland, and is substantial enough to retain a bathymetric expression to the present day, cutting through the high ground formed by the Dogger Bank and Danish shelf. At the extreme northeast of the sector, the mouth of the Elbe palaeovalley valley can be seen clearly (Figure 3.8, F).

Seismic lines acquired across this feature show the channel relating to the Holocene to be incised some 15m below the seabed with a channel width of 3km (Hjelstuen 2017). A study by Özmaral (2017) demonstrates that the Elbe palaeovalley was almost completely devoid of pre-transgressional deposits, with the exception of sediments from a south/north trending channel network within the valley. The seismic profiles from this south/north trending channel is comparable to some of the larger channels studied by *Europe's Lost Frontiers* and suggests a similar sequence. Given the mouth of the Elbe palaeovalley is at a depth of *c.* 56m, which is similar to the late Pleistocene/early Holocene sea level, it is highly likely that parts of this area of the valley were starting to be flooded at that time (Vink *et al.* 2007) and that these channel sediments relate to the brief period following deglaciation and immediately prior to submergence. Özmaral (2017) demonstrates that after inundation was initiated, the valley experienced at least three phases of sedimentary infill due to changes in sea level. This is supported by research in the Palaeo-Ems, which fed into the Elbe Palaeovalley (Hepp *et al.* 2019), which also records these three phases and suggests the onset of fully marine conditions after 9300 cal BP. This, therefore, provides a date at which the majority of the associated Elbe palaeovalley would have also been submerged.

Area 2 – Eastern Sector

There is significant striping evident in the 3D seismic data from the southeast of Area 2. Data quality is, however, reasonable elsewhere, and 2D seismic is available to supplement the 3D data. Analysis reveals the area is largely a gently sloping, emergent plain, cut by the Elbe palaeovalley. This landscape reflects the presence of deep, late Pleistocene sediments which effectively mask any topographic expression from geological movement, such as salt swells (Holford *et al.* 2007). A topographic high is evident near the modern Dutch coastline, descending towards the lower plain of the Oyster Ground, to the south of the Dogger Bank (Figure 3.9, A). However, the dominant feature in the area is the topographic low associated with the Elbe

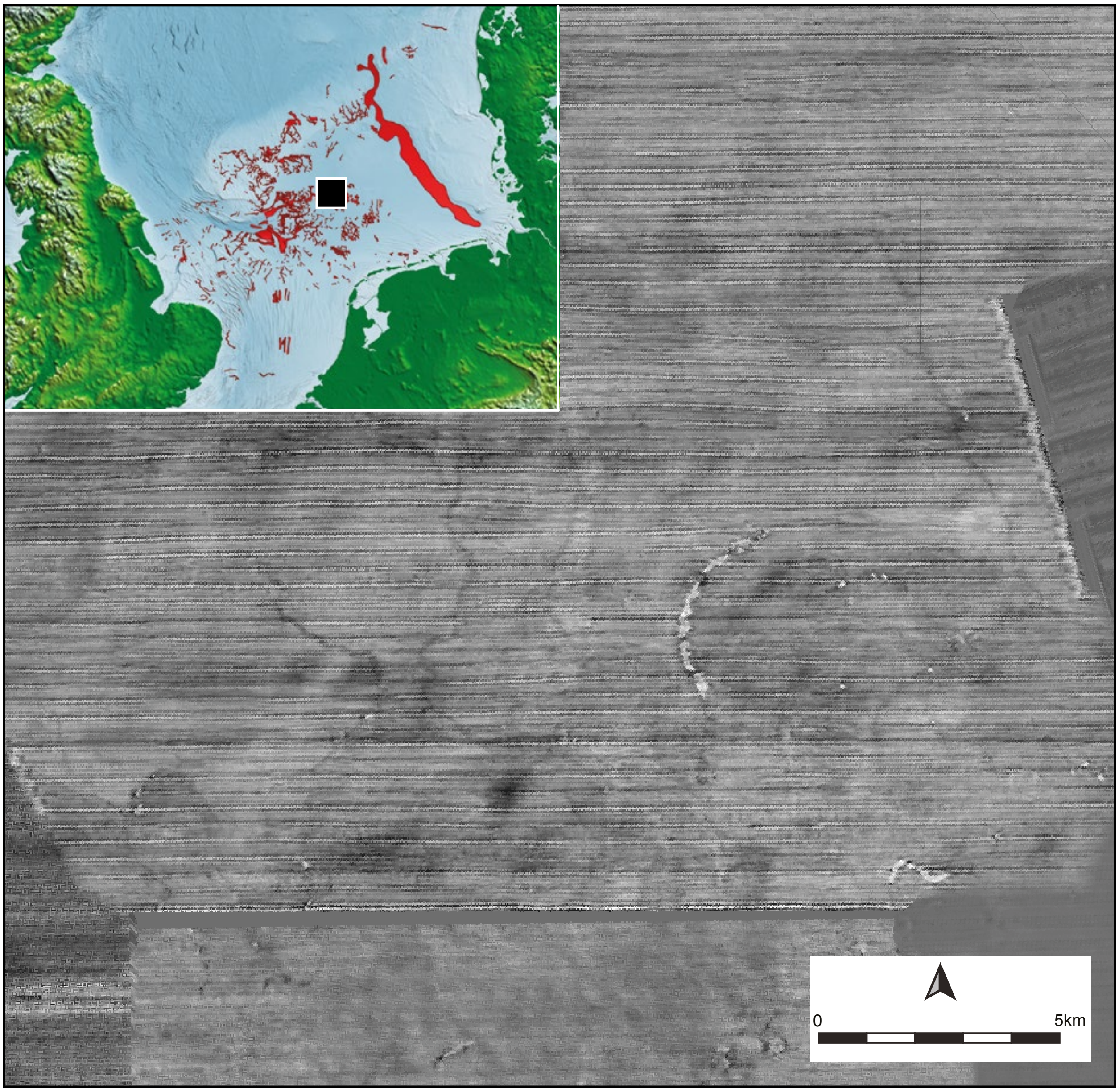


Figure 3.7 Mottling of the seismic data within the Oyster ground can clearly be seen in this image. A number of small palaeochannels can also be seen through the mottling.

palaeovalley, which forms a significant depression in the north-eastern quarter of Area 2 (Figure 3.9, B).

The majority of the fluvial features within the Oyster Ground are oriented to the west, towards the Outer Silver Pit depression and across the large and relatively flat plain (Figure 3.10). The seismic signal generates a 'mottled' appearance (Figure 3.10), the origin of which is uncertain but is thought to relate to peat formation in wetlands prior to inundation (Hepp *et al.* 2017). Several small fluvial channels can be observed within this mottled zone (Figure 3.9, C). Although data striping prevents detailed description of these features, they can be seen to flow into a larger channel system which runs along the base of the Dogger Bank. High resolution 2D seismic survey, undertaken as part of the BRITICE project (Roberts *et al.* 2018; 190), crosses this channel and reveals it to be incised up to 20m below the seabed (Figure 3.11). 3D analysis of this channel was undertaken by the authors and TNO staff (Fitch 2011; Van Heteren *et al.* 2014). These revealed phases of development, which are broadly similar to the sequence outlined by Emery (2020: 113 and 165). Proglacial channels are formed, then abandoned and eventually evolve dendritic tributaries as meltwater is replaced by precipitation. They are then transgressed as sea levels rise during the Holocene.

Analysis further reveals the presence of a large channel valley containing evidence for reuse by a small channel

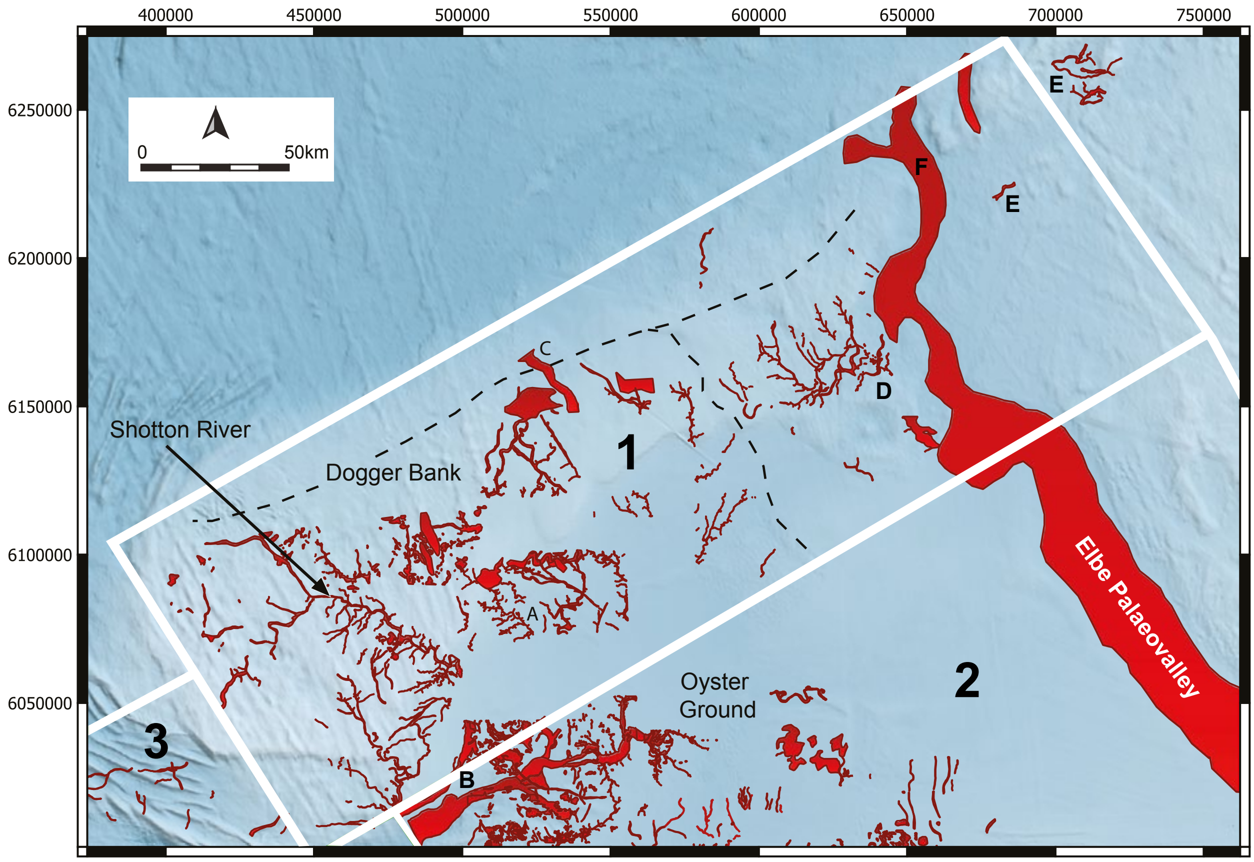


Figure 3.8 Area 1, early Holocene features of the Dogger Bank. The main watersheds are shown as dashed black lines, the features in the southwest of Area 1, including the Shotton River, would have been the longest-lived structures on the Dogger Bank.

(Fitch this volume: Figure 3.5 and 3.9, E). This may suggest such features are the product of proglacial drainage at *c.* 23,000 BP, after the retreat of the ice sheets, and then modified and reused by fluvial channels between *c.* 17,000 to 9000 BP. Later modification is indicated by the formation of tributaries and peat deposits associated with the channels. Dates acquired from nearby cores taken by the BRITICE project (e.g. 175VC Roberts *et al.* 2018) provided early Holocene dates (*c.* 9900 to 9700 BP) but also reveal underlying peat deposits of late Pleistocene age (SUERC-72885, 20,190 +/- 229 cal BP). Fortuitously, one BRITICE core, 147VC, sampled a peat from the Oyster Ground (Figure 3.10), near a likely tributary channel mapped by *Europe's Lost Frontiers*. This provided a C14 date of 12,629 +/-90 cal BP (SUERC-72883) which clearly indicates the period during which this landscape feature was emergent.

Towards the east of the Oyster ground, a slight topographic high forms a watershed (Figure 3.9, D and Figure 3.12). Holocene palaeochannels flowing east of this rise can be seen in the *Europe's Lost Frontiers* data. These have been independently verified by surveys undertaken in the German sector (Hepp *et al.* 2019) and the Danish Sector (Prins *et al.* 2019). As the *Europe's Lost Frontiers* data extends beyond these datasets, these channels can be confirmed as flowing into the Elbe palaeovalley. The Elbe remains a significant feature in Area 2 and is represented by a major depression in the bathymetry extending up to the modern coastline and the modern river Elbe.

Small palaeochannels can be observed flowing into the Elbe on both the eastern and western sides of the valley (Hepp *et al.* 2019) and form a significant drainage system within the Doggerland landscape. A study by Papenmeier and Hass (2020), nearer the modern shore, shows this valley to be partially filled with 16m of sediments. In this section of the channel flooding started around 9600 BP and continued to be tidally dominated until *c.* 5000 BP (Papenmeir and Hass 2020).

The Elbe palaeovalley represents an additional *c.* 400km of river length which, combined with the modern Elbe would give the late Pleistocene/early Holocene river a total length of *c.* 1500km. This is, in comparison, greater than the modern length of the Rhine. The size of the valley also reflects the large volumes of water flowing through the extensive drainage system. The channel would have possessed an extremely large catchment, draining parts of Germany, Poland and the Czech Republic. If the submerged section is included, then

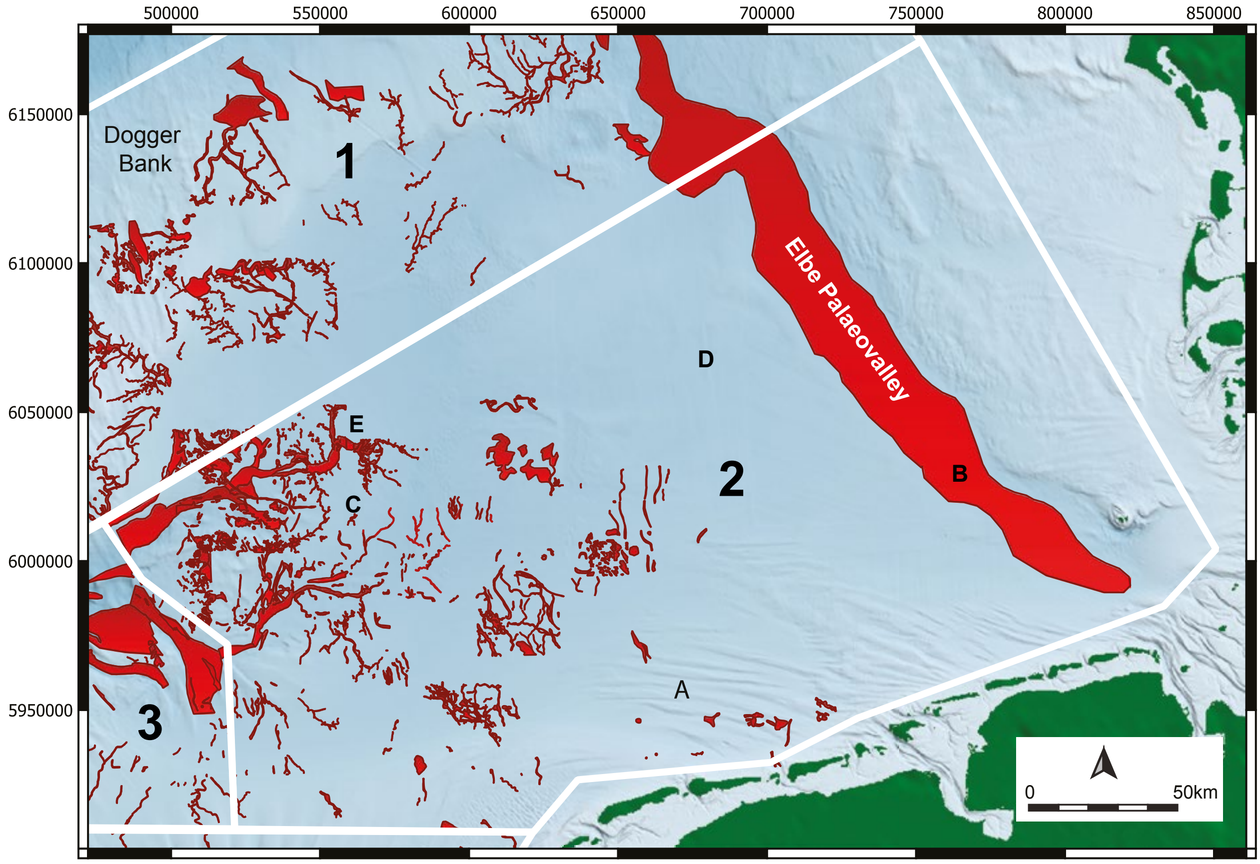


Figure 3.9 Map of the Eastern Sector/Area 2.

this drainage contains parts of Denmark, Netherlands and the Dogger Hills.

Previous researchers have proposed the existence of a palaeolake in the area of the Oyster Ground, formed following glacial melt at approximately 18,700 BP (e.g. Emery 2020; Hijma *et al* 2012; Hjelstuen 2017). This idea originates with Hjelstuen (2017) who suggested that the 12m deep and 3km wide incision at the northeast of the Dogger Bank formed the outflow of such a feature. Hjelstuen's study, however, had no access to seismic data from the area of the hypothesised lake or the Oyster Ground more generally. The suggestion relies on core data from the Ling Bank, which is many kilometres to the north, and well away from the Oyster Ground. Whilst Hjelstuen does acknowledged that there were significant issues in such an interpretation, his work remains the basis for later references to such a feature (e.g., Emery 2020: 119 Fig 4.11).

The 3D and 2D seismic data examined through *Europe's Lost Frontiers*, along with published core data, provides an opportunity to resolve the Oyster ground lake issue. Whilst the data will be discussed in detail in a forthcoming *Europe's Lost Frontiers* volume, no lake deposits were visible within the available seismic data in this area. It is also clear that there are considerable drainage systems present in the Oyster Ground that would have been able to provide drainage, and these trend to the west and into the Outer Silver Pit. The presence and direction of these channels strongly suggest that the hypothesis that a lake formed in this area, at least, is incorrect. Given that the Outer Silver Pit drains in a different direction, west as opposed to northern outflow proposed by Hjelstuen, it is therefore unlikely that the Oyster ground channels, nor the Outer Silver Pit outflow, is likely to be the source of the delta sediments at Ling Bank identified by Hjelstuen (2017). Indeed, given the presence of a ribbon lake between the ice and the northern edge of Dogger Bank at *c.* 23,000 to 21,000 BP (Roberts et at. 2018), it is possible that this may be the source of the Ling Bank delta material, rather than the Oyster ground. Indeed, Hjelstuen (2017: 16) notes that seismic correlation with sediments from the Ling Bank Delta and shallow bore holes (Hjelstuen 2017: 16) suggests that it was related to the Last Glacial Maximum and therefore could be related to the drainage of the lake observed by Roberts *et al.* (2018: 203) at *c.* 21,000 BP. It is important to note however that Hjelstuen provides no absolute dating for the Ling Bank sediments and thus the possibility of any correlation remains tentative.

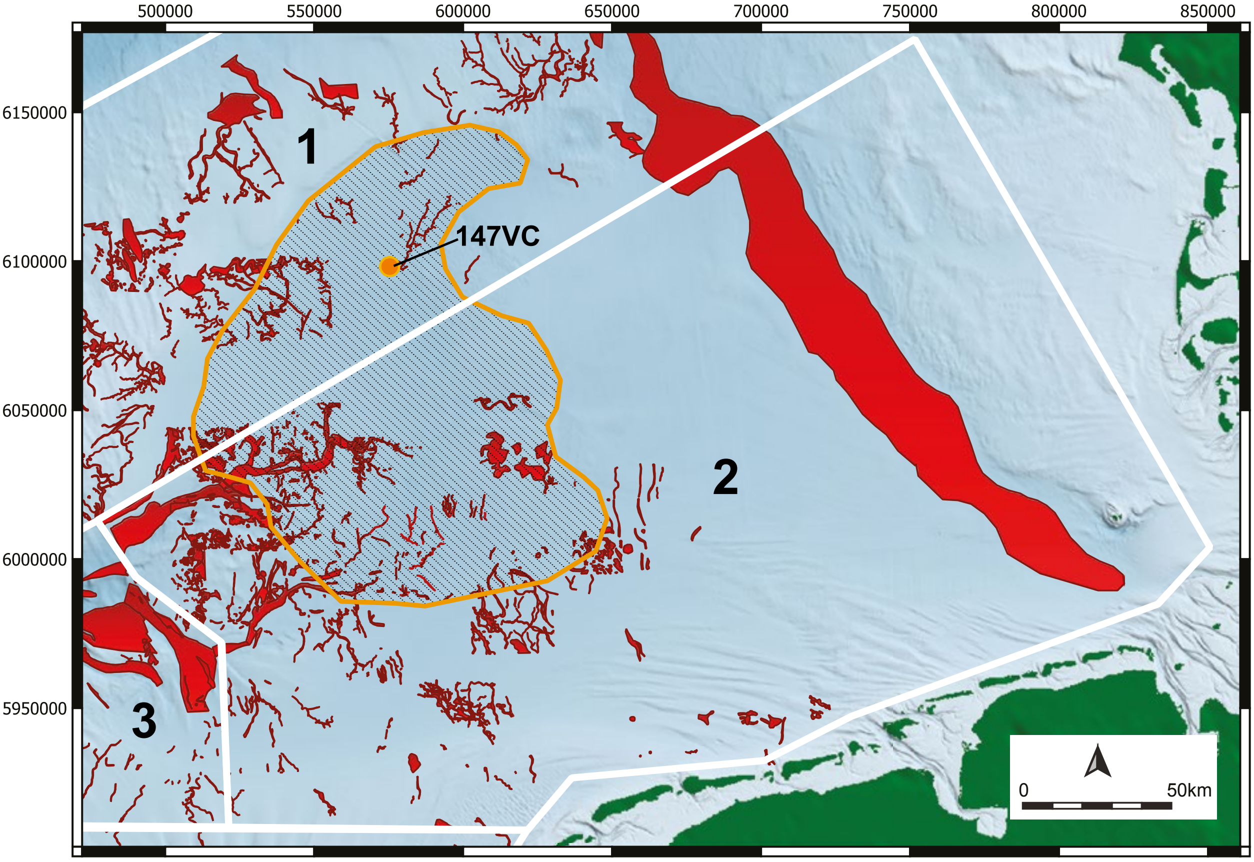


Figure 3.10 The extent of wetland response is outlined within the red hashed area. The location of BRITICE core 147VC is marked in orange.

Other explanations are available for these data. A bathymetric depression (near the area marked 'F' on Figure 3.8) is identified by Hjelstuen as the location of the outflowing of a meltwater burst. However, it must be recognised that this channel cut is the substantial channel associated with the Elbe palaeovalley. There may, therefore, be no need to invoke a lake outburst to explain this depression, indeed, the seismic line presented in the paper (Hjelstuen 2017: Figure 11a) shows the channel to be 15m deep and 3000m wide (Hjelstuen 2017: 14) which is consistent with nearer shore submerged sections of Elbe itself (Papenmeier and Hass 2020), which would not have been affected by a meltwater outburst. It should also be noted that these dimensions are also consistent with other major fluvially derived features within the projects study area that have been recorded by *Europe's Lost Frontiers*.

Finally, it is also important to note that the link to an oxygen isotope anomaly in foraminifera on the Norwegian continental margin, which is dated to *c.* 18,700 cal BP, and was used by Hjelstuen (2017) to infer the presence of a lake, only indicates the possibility of a meltwater plume near the Norwegian continental margin (Lekens *et al.* 2005). This information does not provide evidence of direction and is not sufficient to tie any possible plume to the Oyster ground area. Indeed, this plume has previously been identified as coming from the Norwegian Ice Sheet (Lekens *et al.* 2005). Consequently, there is little need to invoke a glacial meltwater palaeolake in the Oyster ground region.

Although the data on the Ling Bank sediments would benefit from further, detailed consideration and dating, the presence of the channel systems in the Oyster ground observed by *Europe's Lost Frontiers* suggest that any palaeolake in the Oyster Grounds is substantially smaller and shallower than suggested, and thus not visible in the data available, or more probably is absent.

Area 3: Western Sector

This area is largely characterised as a relatively gentle plain sloping to the north and down from the modern British coastline (Figure 3.13). The dominant topographic feature within this area is the Outer Silver Pit, which forms a significant depression in the northwest of the area. The Outer Silver Pit is a distinct east-west trending bathymetric deep and is the largest of a series of depressions in the southern North Sea. This feature is up to 80m deep in places and is thought to result either from quaternary sub glacial processes (Praeg 2003), or a catastrophic drainage event

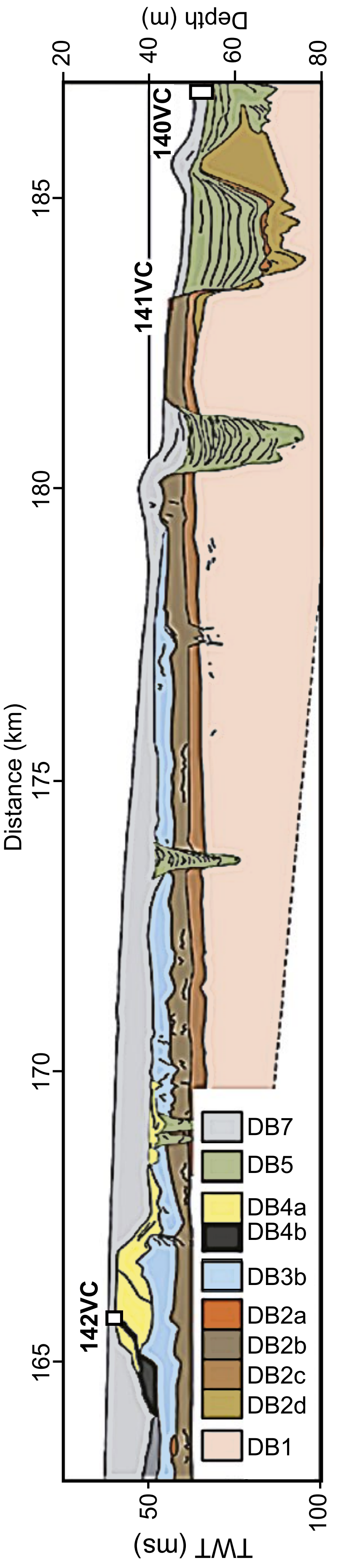


Figure 3.11 Interpretation of a seismic line crossing the base of the Dogger Bank area (near the area marked B in Figure 3.8) clearly shows a large channel running at the base of Dogger Bank (shown here as the DB5 unit between 141VC and 140VC) (Roberts *et al.* 2018: Figure 6).

(Wingfield 1990). This Outer Silver Pit dominates the landscape, with channels from the Oyster Ground (Area 2) flowing into this feature.

The Outer Silver Pit was investigated by the NSPP and thought to have been modified during the Late Palaeolithic/Early Mesolithic by macro tidal processes during marine inundation (Briggs *et al.* 2007: Figure 3.13, A). The Outer Silver Pit was eventually flooded by the sea around 10,000 BP (Shennan *et al.* 2000; Sturt *et al.* 2013). A distinctive zone, characterised by a palimpsest of small channels which cross an area of 5823km^2, can be seen adjacent to the Outer Silver Pit (Figure 3.13, B). In addition, the area contains several small depressions within which the seismic data is 'mottled'. This mottled signal is thought to indicate peatland/wetland and, consequently, the area, along with the small channels, is thought to represent an extensive wetland area close to the edge of the Outer Silver Pit, which formed an estuary during this period (Briggs *et al.* 2007; Gaffney *et al.* 2007). It is assumed that this wetland environment was continuously active from the end of the Pleistocene until the early Holocene. Recent cores from the area, taken by the BRITICE project (Roberts *et al.* 2018), have recovered peat which dates to 9801 +/- 171 cal BP (SUERC-72162) supporting this hypothesis.

In the centre of Area 3 (Figure 3.13, C), are a series of large anastomosing channels flowing from the southeast and into the Outer Silver Pit. Several of the larger channel features have been associated with the Botney Cut formation and dated to the late Pleistocene to early Holocene (Cameron *et al.* 1992). Detailed survey during the Humber REC over one of the smaller features has revealed that these were active during the Holocene (Fitch this volume; Tappin *et al.* 2011) although coring failed to reach the base of the feature.

A significant outflow channel is partially visible in the southeast corner of the Outer Silver Pit (Figure 3.13, D). This appears to drain the Outer Silver Pit to the south and is of a sufficient size for the channel to have a contemporary bathymetric expression. Imaging this feature using 3D seismic data suggests that the channel must have been formed following a considerable outflow, and that it extends much further south than is visible on the bathymetry. Although no dating evidence from this feature is currently available, the presence of a small number of re-use channels suggests that the feature is of pre-Holocene age. The current models for the last glaciation suggest two possible points of origin for this feature (Roberts *et al.* 2018). The first requires an outflow from the lake in the Outer Silverpit (referred to as 'Dogger Lake' by Roberts *et al.* 2018: Fig 17), and which may have occurred a short time prior to 30,000 BP. Roberts *et al.* (2018) note that sometime between 30,000 to 25,000 BP, following an ice advance, a separate glacial lake was moved eastwards by the ice from the

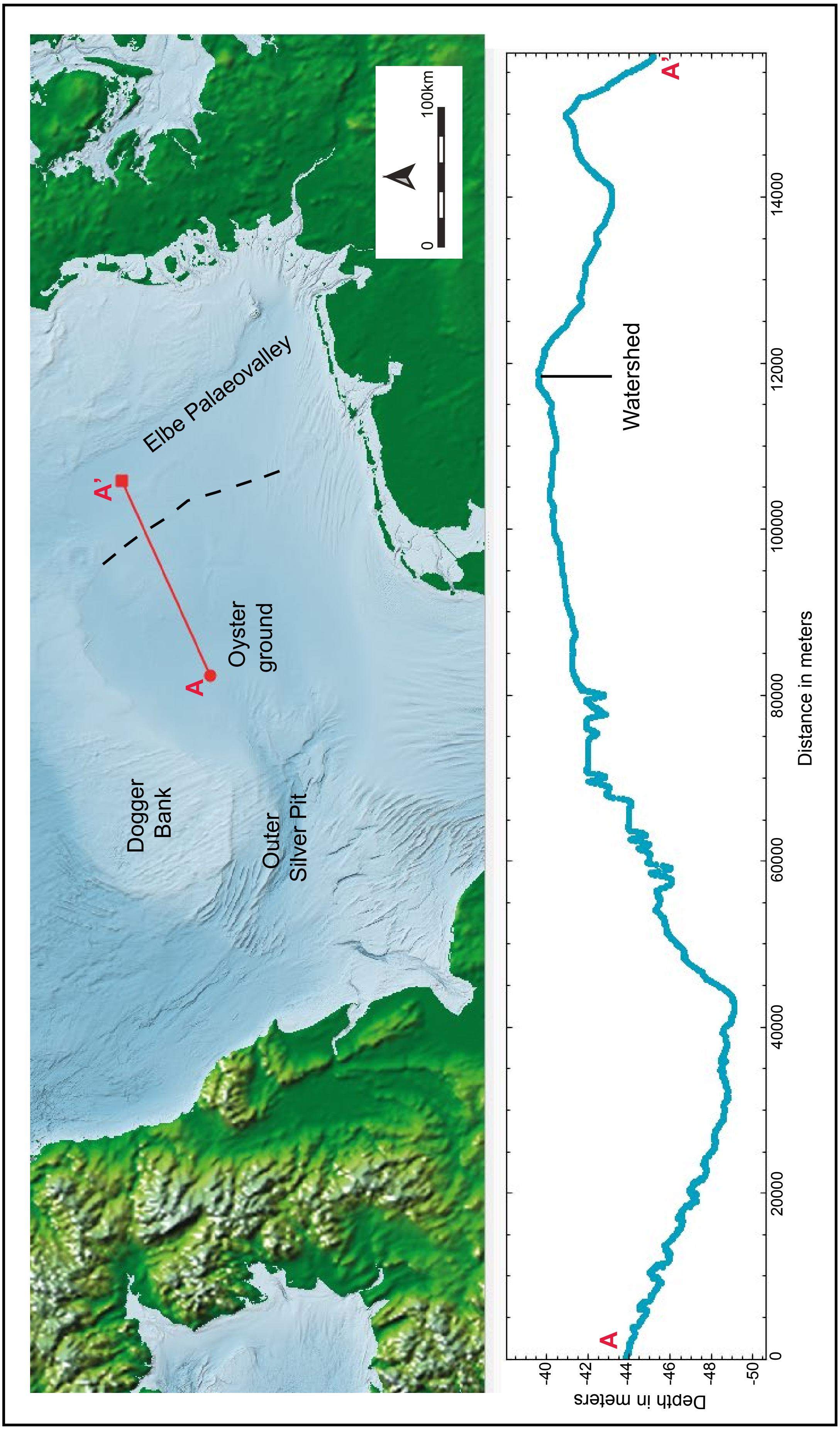


Figure 3.12 Cross section across the east of the Oyster ground. The topographic rise which forms the watershed is apparent.

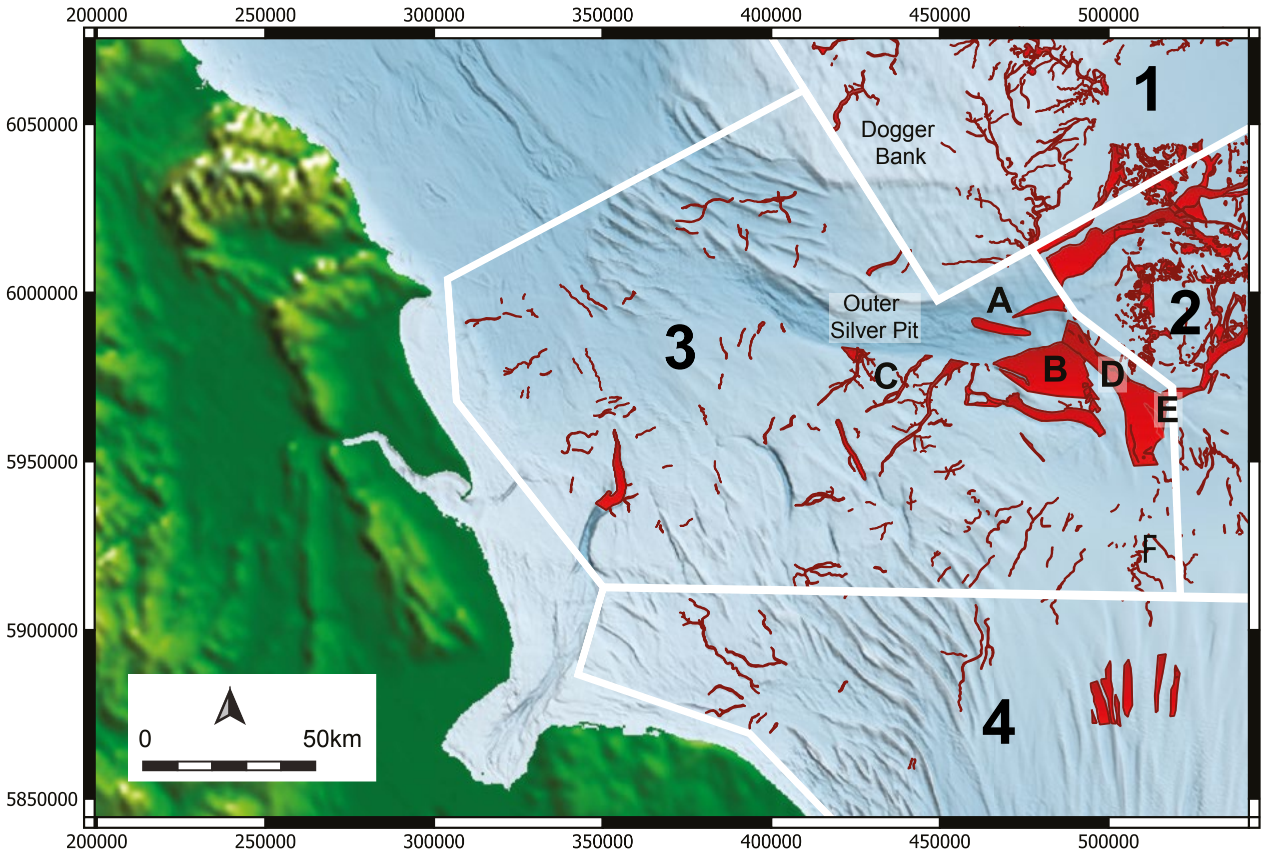


Figure 3.13 Location of mapped features within Area 3.

area around the Outer Silver Pit to the northeast of the Dogger Bank. This water movement may have provided the opportunity to breach the Outer Silver Pit banks to the south and produce a meltwater outburst that could have, feasibly, created this feature. The second point arises during the 22,000 to 21,000 BP ice advance. Around 23,000 BP, a ribbon lake had formed to the north of the Dogger Bank (Roberts *et al.* 2018), and it is possible that this feature may have extended around the Dogger Bank into the Outer Silver Pit. Ice re-advance beginning at *c.* 22,000 BP may then have pushed into the area of the ribbon lake and induced an outburst from the lake creating this feature. Whilst it is impossible currently to provide an accurate date for origin of the channel, its size, position, and the evidence for later re-use suggest that it was a significant feature within the Holocene landscape, and that it was a route for flooding from the south during final inundation.

Slightly to the east of the outburst channel, close to the boarder with Area 2, is another large, deeply incised channel system (Figure 3.13, E). This is *c.* 1400m wide and appears to drain part of the Oyster Ground (Area 2). It can be seen to flow southwest in the seismic data, before eventually meeting the large outflow channel south from the Outer Silver Pit. At this point the channel changes direction, re-uses the outflow channel, and flows south. This relationship suggests that the channel (Figure 3.13, E) is later than the outwash feature (Figure 3.13, D), and dates from a period either post *c.* 30,000 BP or *c.* 21,000 BP.

The presence of this channel is also indicated in a map of the area by Emery (2020: 119 Figure 4.11), and the feature may drain some of the European rivers prior to the formation of the Elbe palaeovalley). However, Emery emphasises the speculative nature of this interpretation, and the seismic data is unable to provide sufficient evidence of any extension to the Elbe Palaeovalley channel to support this suggestion. As the channel links with dendritic feeders where it extends into Area 2, this suggests that the feature was sub-aerially exposed during the Holocene and thus remained a feature in the landscape throughout the late Pleistocene/Holocene period.

The southwards trend of this large feature is paralleled by several smaller channels (Figure 3.13, F), one of which was recorded by Preag who suggested a Holocene date for the feature (1997). The *Europe's Lost Frontiers* 3D seismic interpretation suggests that this channel, and those nearby, have a well-developed, high sinuosity. The *Europe's Lost Frontiers* data also reveals additional features related to these features, including floodplains, bars and oxbow

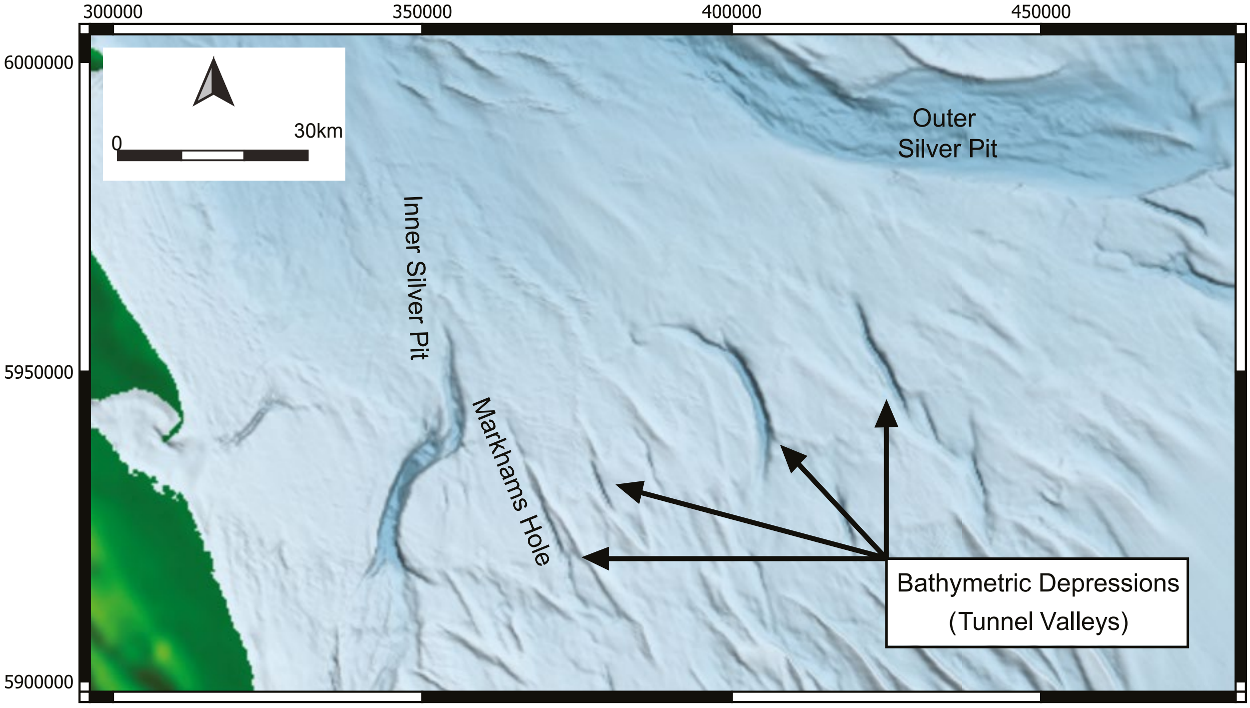


Figure 3.14 Topographic depressions southeast of the Outer Silver Pit (Area 3)

lakes, which illustrate the development of this plain. Many of the channel features recorded are comparable to those seen in the Danish sector (Prins and Andersen 2019), and presumably form at a similar time and environment. It is apparent that several of the features are well preserved and within reach of future high resolution geophysical survey and environmental sampling.

The western part of this landscape includes a number of large depressions, including Markham's Hole (Figure 3.14), which are tunnel valleys and may have contained lacustrine features during the Mesolithic. The seismic data reveal that these features are much deeper than the bathymetry suggests and contain deposits that can be directly related to the late Pleistocene, Botney Cut Formation. The late Pleistocene sediments are then directly overlain by sediments of recent origin. The sedimentary relationships therefore suggest that the valleys date from the late Pleistocene. As these features would have formed topographic features in the Holocene landscape, it is likely that these depressions may have contained lakes during the Early Holocene. This interpretation is supported by the work of the British Geological Survey (Brown 1986), who records the presence of late Weichselian to Holocene glacio-lacustrine deposits in similar features in the British sector.

Area 4: Southern Sector

Although it is suspected that Area 4 (Figure 3.16) has significant information relating to the early Mesolithic landscape, data striping and noise in the 3D seismic data hindered interpretation. Fortunately, new 2D seismic data acquired during windfarm development, and research surveys undertaken as a collaboration between *Europe's Lost Frontiers* and the Deep History Project, provides valuable supplementary information for the area (e.g., Messiaen *et al* 2020). The expansion of windfarms within this area will also offer future opportunities to significantly refine and improve the mapping for this area (Peeters *et al.* 2019).

A brief description of the area and the results of survey are provided here, more detail will be provided in a later volume (Fitch *et al.* forthcoming). Whilst the details of the majority of the channels observed are yet to be fully resolved, they do tend to be smaller in scale than those discussed in the other mapping areas of the study area.

The lack of palaeochannels within this area is striking (Figure 3.15). The central zone within Area 4 is totally devoid of these features (Figure 3.15, A). Those that do exist (e.g. the Southern River, Figure 3.15, B) are scattered toward the periphery of the area, but appear to flow towards the central axial area between East Anglia and the Netherlands (Figure 3.16) and seem to terminate at or near the 40m meter bathymetric contour. This dearth of landscape features in the central zone is probably explained by the presence of a large marine embayment infilling during the Mesolithic. Isostatic models (e.g. Sturt *et al.* 2013), and more recent models utilising improved core data from the region (Ch'ng *et al.* forthcoming), suggest that flooding of this area was initiated by 10,500 BP. This is supported

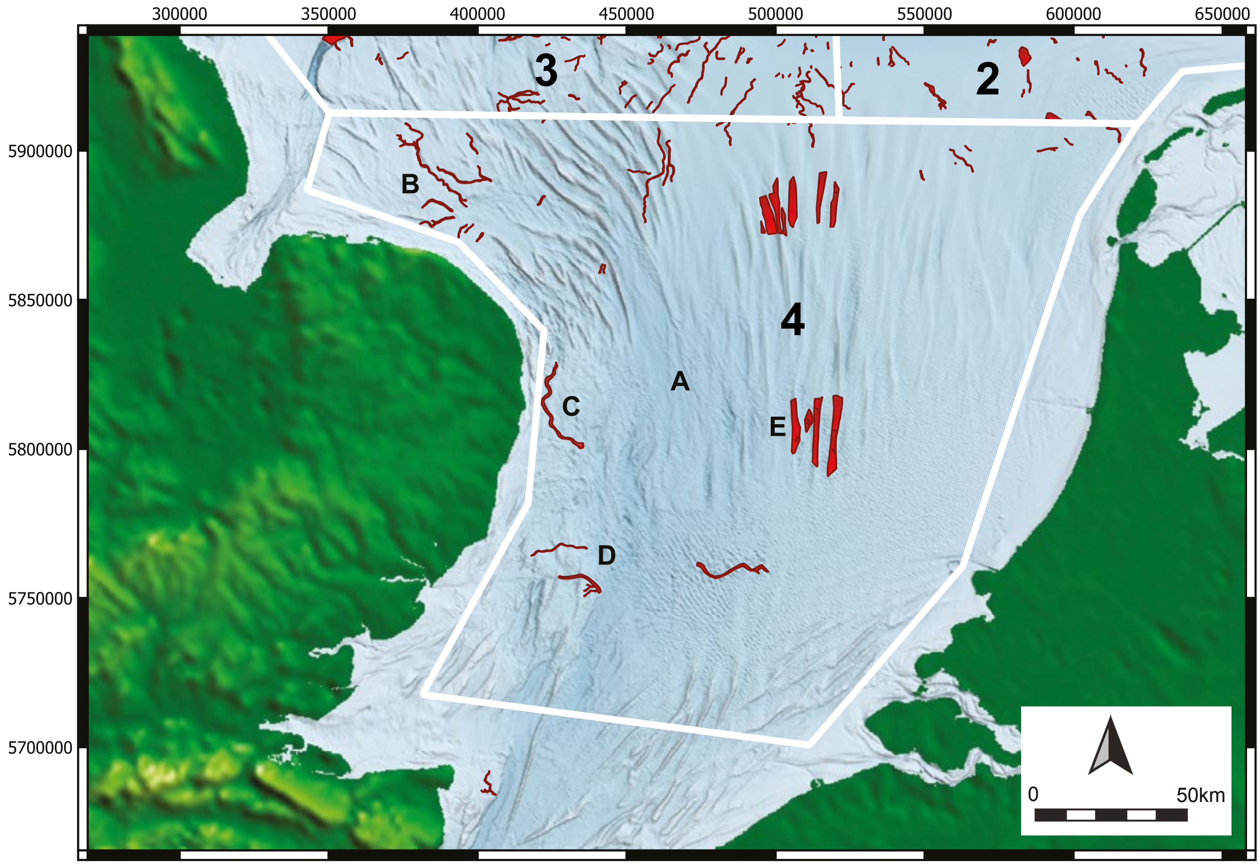


Figure 3.15 Early Holocene landscape features in Area 4.

by core data from the Belgian continental shelf which indicates marine influence in the area at 10,000 BP and possibly earlier (De Clercq 2018). A core (VC39), taken by the TNO in 2019 near the Brown Bank, also provides a sea-level index point at 10,280 +/- 77.5 cal BP (Busschers pers. comm.). This information, combined with radiocarbon dates from the estuary of Southern River (VC51: 8827 +/- 30 cal BP, SUERC-85716), strongly support the existence of a marine inlet in this area during the Mesolithic.

Of the palaeochannels that are visible, the majority are situated on the western flank on the East Anglian shelf (Figure 3.15, C and D). These channels are characterised by broad, but shallow, meanders, suggestive of a gentle water flow. The channels can be seen to widen as they progress towards the marine inlet, indicating the direction of flow. Mapping of these features suggest that the heads of the channels are filled with fine grained sediment and organic material (possibly peats) as the channels approach the contemporary coastline, the seismic signal suggests this material then progresses into silts and clays. This sequence of sediments is similar to those seen in other channels in the southern North Sea (e.g., Missiaen *et al.* 2020, Fitch *et al.* this volume) and a description is provided by the East Coast Regional Environmental Characterisation (ECREC, Limpenny *et al.* 2011). A single vibrocore acquired from one channel (Figure 3.15, C) recovered peats dated at 10,670-10,250 cal BC (SUERC 11978) at 30.80m deep and 7530-7350 cal BC (SUERC 11975) at 30.05m deep (Limpenny *et al.* 2011: 131). These dates are broadly comparable to those from near the Brown Bank on the eastern bank of the embayment (8,716-8,566 cal BC (SUERC 89491)), and Southern River (ELF051 (2.84m): 7844-7606 cal BC (SUERC 85724), ELF051 (3.78m): 11,080-10,854 cal BC (SUERC 85725)). The termination of these palaeochannels at or near the *c*. 40m meter bathymetric contour, suggests a period of coastal stability. However, it may also be true that subsequent flooding did not result in erosive conditions comparable to those during the initial formation of the central marine inlet, possibly because the widening channel may have induced lower current speeds.

Fewer channels are observed within the available 3D seismic data on the eastern flank of the marine inlet. However, high resolution survey, undertaken as part of the Deep Sea History collective, combined with data from recent windfarm projects, has demonstrated that there are Holocene deposits in the region, and those channels which have been cored are sand filled, and often have organic rich and occasionally peat layers (Harding *et al.* forthcoming, Missiaen *et al.* 2020, Plets *et*

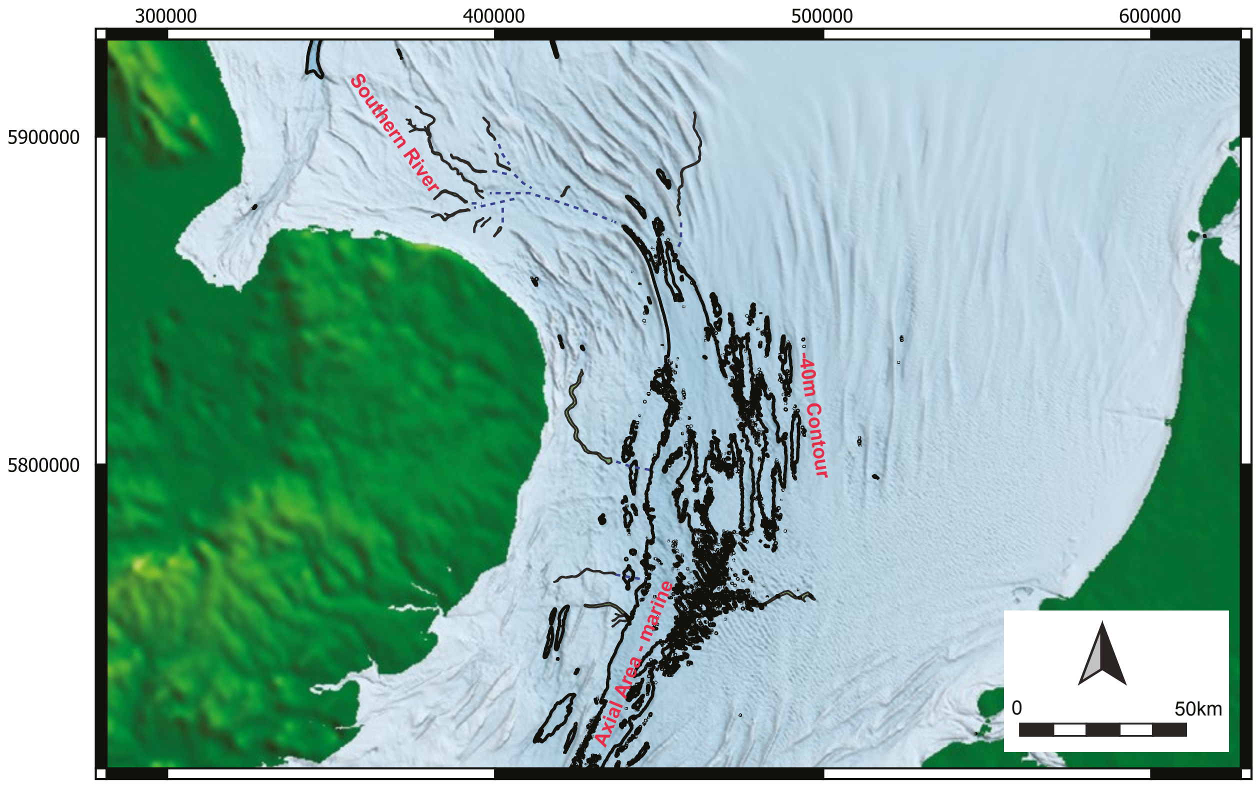


Figure 3.16 Mapped palaeochannels in Area 2 flow towards the -40m bathymetric contour, below this line virtually no features are mapped. This supports the hypothesis that the axial area was a marine inlet during the Holocene/Mesolithic.

al. forthcoming, Thal 2019). Aside from palaeochannels, land surfaces are occasionally visible (Harding *et al.* forthcoming: Figure 3.15, E), which are overlain by organic layers, intertidal deposits and frequently buried under sandbanks. These surveys have also provided a clear, acoustically strong high amplitude signal in the seismic data which has been identified as the top of the Naaldwijk Formation and associated with the marine inundation of the area. Landsurfaces associated with the Naaldwijk Formation may provide responses characterised by a coherent negative, flat parallel reflection. These are often regarded as indicative of peat layers (e.g. Plets *et al.* 2007). These peats are thought to have formed as the post-glacial soils were impacted by higher levels of salinity, sedimentary accretion and flooding (Andrews *et al.* 2000). The base of the Naaldwijk Formation is poorly resolved further east, possibly due to a lack of signal penetration resulting from the increasing thickness of the overlying sand banks.

Any palaeochannels that may have existed in the central zone in the Late Palaeolithic (pre-10,000 BP) were presumably impacted by marine erosion following formation of a marine inlet. As the area of the inlet was inundated and exposed to marine erosion at a relatively early date, the chances of such features surviving is presumably significantly lower.

Area 2 also possesses significant surface topography and modern (less than 4000 BP) seafloor features including sand waves. These structures are imaged in the bathymetry as north-south-trending peaks and troughs. The modern sediments have an erosional contact with the Holocene. Several modern sandbanks also directly overly and preserve areas of Holocene landscape (e.g. the Brown Bank Missiaen *et al* 2020: Figure 3.15, E). Consequently, the modern bathymetry does not necessarily reflect the Holocene landscape morphology in this area. Additionally, the size of many of these sandbanks can render the underlying Holocene landscape relatively inaccessible to archaeological sampling. However, where topographic or erosional conditions allow, it is possible to recover sediment samples, as has been successfully demonstrated near Brown Bank (Missiaen *et al* 2020).

An archaeological narrative of landscape development from the Late Palaeolithic to the Mesolithic

Having provided a general description of landscape features identified during recent study, it is useful to support this with a summary chronological and archaeological overview.

At the end of the Late Palaeolithic, the northern edge of the current Dogger Bank essentially represented the coastline of Doggerland (Figure 3.17). Although the Outer Silver Pit and the embayment to the south, near Brown Bank, had already started to flood, research by BRITICE suggests that the coastline north of Dogger Bank had existed from *c.* 21,000 BP Roberts *et al.* 2018). This coastline remained a relatively stable component of the landscape for approximately 11,000 years prior to the start of the Mesolithic. The implications of a relatively stable northern coastline are significant. The coastline, with its rich and varied resources must have been extremely important in economic and cultural terms to the human communities in the region.

As sea levels rose there would have been impacts affecting large areas away from this coastline. The Outer Silver Pit would been become a significant marine inlet, and an outlet for major drainage systems from the Dogger Bank and East Anglia (Figure 3.17). The other main drainage basin, associated with the Elbe palaeovalley, would have experienced flooding with a significant inlet forming on the north-eastern coastline of Doggerland. Whilst these areas flooded, the Elbe palaeovalley channel would have continued to drain areas in the east of Doggerland, as well as Denmark and Germany (Figure 3.17). Inundation would also have continued in the south of Doggerland. Here, flooding would have preceded from the area of the English Channel (Figure 3.17) and created a relatively shallow marine inlet between Britain and the Netherlands (Figure 3.18). Although low lying, most of the study area remained emergent during this time and the landscape could have provided a diversity of environments that would have made the area attractive for a range of subsistence activities. The extensive river systems would have provided excellent transport corridors for both human and animals, as well as providing wetland resources. Given the connectedness of the landscape, it is reasonable to surmise that groups from what are now the Netherlands and Britain were connected through Doggerland (Reyneir 2000 citing Verhart pers. comm.). Aside from connections across the land, the boat technology of the day must have supported travel (Pedersen *et al.* 1997), supporting trade and contact between communities who lived in or visited the region (Gaffney *et al.* 2009). A number of cultural indicators are suggestive of such links. These include the rare antler head dresses, found at Bedburg-Konigshoven in Germany (Street 1989), through the Low Countries (Verhart 2008) and as far north as Star Carr (Clark 1972; Conneller 2004). Such linkages may suggest a 'northern technocomplex' centred on the great plains of the North Sea (David 2006: 139).

Between 10,000 BP and 8500 BP sea-level rise continued and large tracts of the landscape of central Doggerland must have been inundated, initially through the three main inlets in the landscape (Figure 3.18). The area around the Outer Silver Pit was submerged, allowing the inundation of large parts of the centre of Doggerland including the relatively low-lying area of the Oyster Ground.

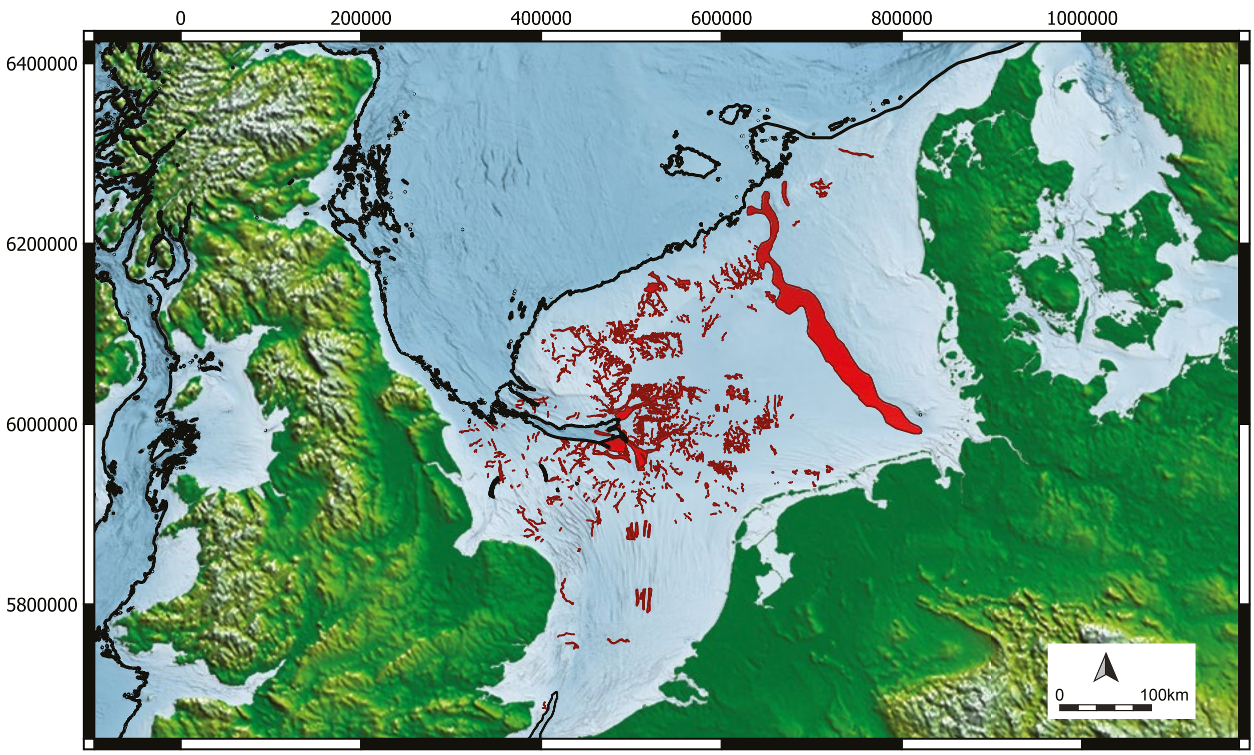


Figure 3.17 Major features, Late Palaeolithic c. 11,500 BP.

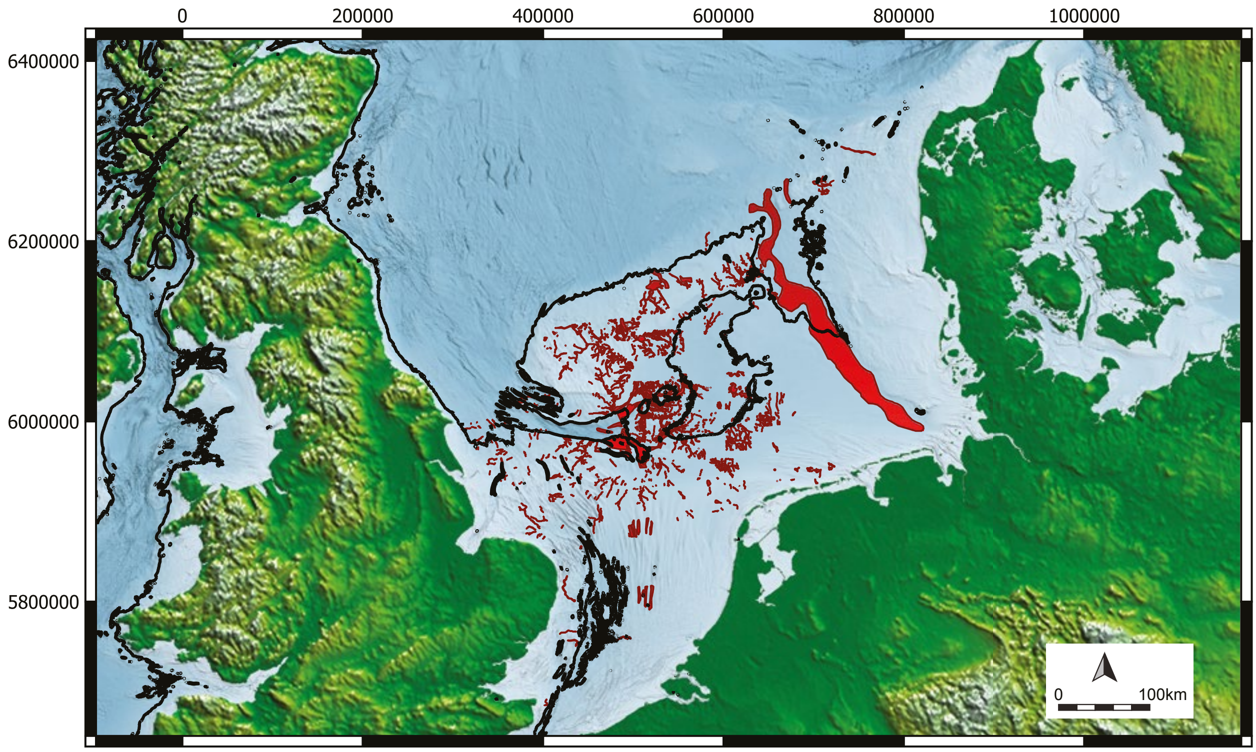


Figure 3.18 Coastlines of early Mesolithic Doggerland c. 10,000 BP.

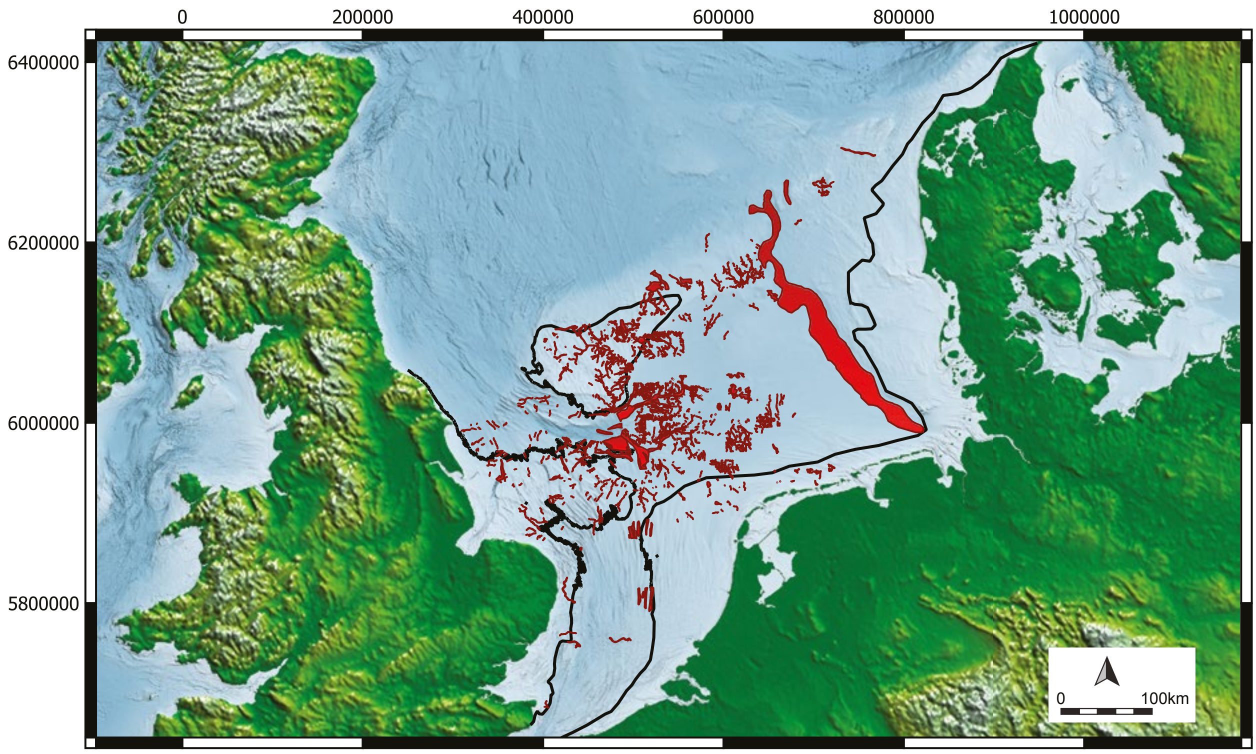


Figure 3.19 Coastlines of Mesolithic Doggerland c. 8500 BP.

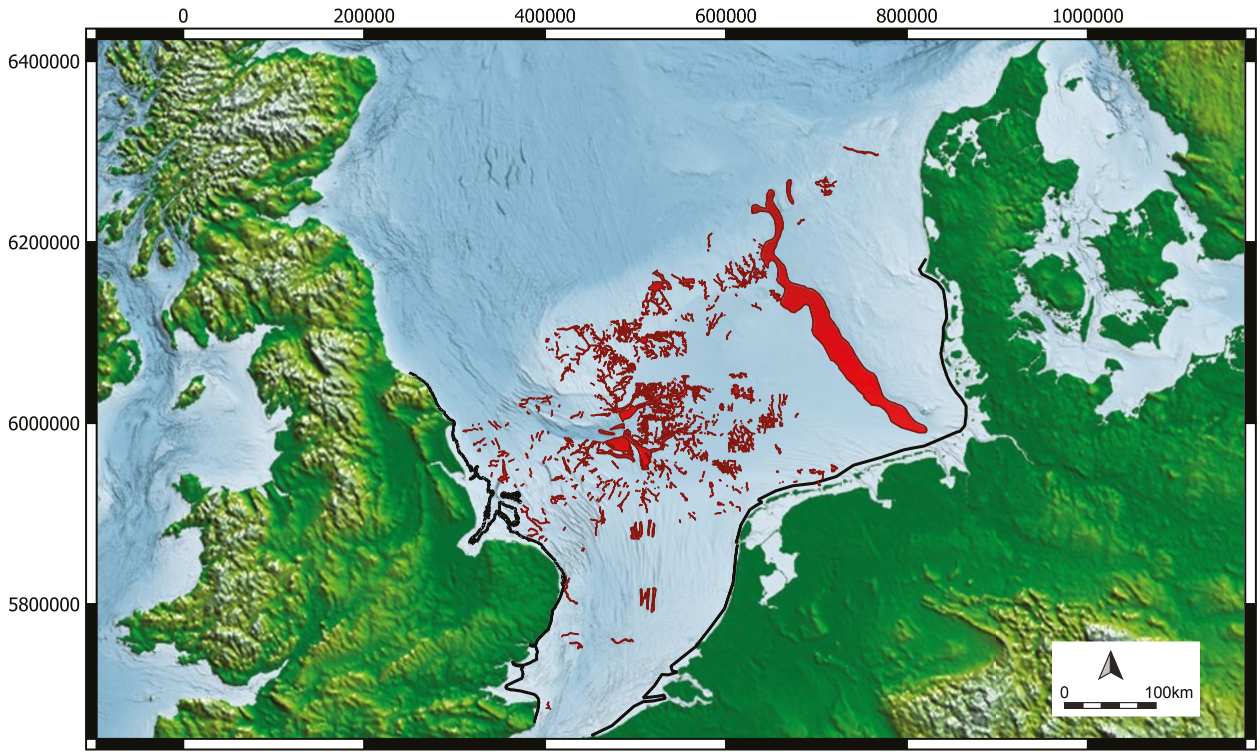


Figure 3.20 Coastlines of the earliest Neolithic c. 7000 BP.

It is during this period that the Dogger Bank became an island (Figure 3.19). Its links to the east was cut as waters flooded the Elbe palaeovalley. Additionally, with the coastline retreating from the south and into the central part of Doggerland, the terrestrial linkage between Britain and Europe would have rapidly reduced to a strip and was eventually breached. These relatively rapid changes presumably had an impact on the Mesolithic communities inhabiting the new coastlines. Not all change was bad. New coastlines may would have provided access to marine resources and enhanced the subsistence base for coastal communities, who may have also taken advantage of the new marine inlets for travel.

As the landscape fragmented and terrestrial interconnectivity reduced (Figures 3.18 and 3.19), it is possible that the groups living in this area may have found maintaining traditional links increasingly difficult. It is possible that connections were severed even before the inundation of the final land linkages.

By about 7000 BP, the emergent landscape of Doggerland was largely lost to the sea (Figure 3.20). During this period, Britain and Europe were separated by a considerable body of water and the Dogger Island would have been flooded. However, areas of landscape would still have existed as extensions of East Anglian and the European coastlines at the end of the Mesolithic and into the Neolithic (Figure 3.20). Continuing sea-level rise and loss of landscape would have remained noticeable to contemporary communities and was likely to have influenced the cultural development of these regions.

Conclusions

Europe's Lost Frontiers and its preceding projects have enabled a significant advance in our understanding of the emergent landscape of the southern North Sea and provided first pass mapping of an area of prehistoric landscape of *c.* 188,000km^2. The full archaeological implications of this work will be explored in later project volumes but will also act as a springboard for future researchers studying climate, sea-level history, palaeogeography, geology as well as archaeology.

Chapter 4

From extensive to intensive: Moving into the Mesolithic landscape of Doggerland

Simon Fitch

Introduction

The potential for the continental shelf of the United Kingdom to contain a unique record of the late Pleistocene and Holocene archaeology and environments has long been recognised (e.g. Bailey *et al.* 2017; Cameron *et al.* 1992; Clark 1936; Coles 1998; Gaffney *et al.* 2007; 2017; Jacobi 1976;). The dredging of archaeological material from areas such as the Dogger Bank suggests probable *in-situ* survival of deposits in previously waterlogged areas (Peeters and Amkreutz 2019; van der Plicht *et al.* 2016). It was, however, the work of Coles that sparked renewed interest in the southern North Sea as a key archaeological resource (1998; 2000). These publications contained a series of inspirational maps of the early Holocene, pre-inundation landscape. However, largely based on bathymetric data, the topography of the landscape as presented was mostly speculative; whilst the methodological problems of investigating this submerged landscape, or recovering material for study, had long prevented any concerted attempts to investigate the area in detail.

Previous attempts to reconstruct the morphology of the landscape at a broad scale have generally utilised 'isostatic rebound' models. These utilise the current seabed bathymetry, and are usually derived from satellite altimetry, in conjunction with models of the earth's crustal movement in response to glacial unloading. Whilst such models may provide outline representations of the former landscape (e.g., Lambeck 1995; Shennan 2012), the coarse scales at which these maps were generated make them unsuitable for the purposes of detailed archaeological inference or interpretation. The cell size of higher resolution models (1.2 × 1.2km, Shennan and Horton 2002: 513) is restrictive and can be further complicated by other oceanographic and geological factors (Bell *et al.* 2006: Box 1, 14).

The first, tentative steps towards reconstructing the 'landscape archaeology' for Doggerland were undertaken using seismic data originally collected by the petroleum industry as part of the *North Sea Palaeolandscape Project* (NSPP, Gaffney *et al.* 2007; 2009). This chapter focuses on the *Humber Regional Environmental Characterisation* project (Humber REC), funded by the *Marine Aggregates Levy Sustainability Fund* (MALSF). It considers how the Humber REC built on the results of earlier research and utilised integrated intensive survey and associated sampling to test hypotheses regarding submerged features of Doggerland. The primary aim of the work described here was to test the validity of the landscape interpretation provided by the NSPP (Gaffney *et al.* 2007; 2009). The availability of high-resolution geophysical data, acquired as part of the Humber REC, was also an opportunity to enhance our understanding of the existing geophysical and stratigraphic datasets available regionally. This approach was undertaken with the ultimate goal of providing a methodology for locating deposits of archaeological and archaeo-environmental significance beneath the North Sea (Gearey *et al.* 2017; Tappin *et al.* 2011). The project was unique in that it represented the first concerted attempt to utilise the extensive landscape data generated by the NSPP to target the early Holocene, pre-inundation landscape, and then allow any newly generated information to be considered iteratively, alongside the broader results of the NSPP, to understand their broader landscape context.

Methods – study area and marine geophysical survey

In this chapter, we focus on 'Arch-Area_1' within the Humber REC study. This is, located 115km offshore from the Humber Estuary (Figure 4.1). The study area covers approximately 3.5km^2, with a mean water depth of 30m. This area was selected to test the hypothesis derived from NSPP interpretation, that a palaeochannel with *in-situ* sediments, and probably of early Holocene age, was preserved at this location (Gaffney *et al.* 2007: 89). Initial interpretation of the feature was that the channel was part of a north-east oriented, anastomosing channel system (Figure 4.2).

As with the majority of features identified through the work of the NSPP, this channel was presumed to be of early Holocene date on the basis of its location and depth. The lack of a chronology for such features was a significant issue during the NSPP study, and there was concern that they may not have been Holocene but much earlier in date. The aim of the Humber REC

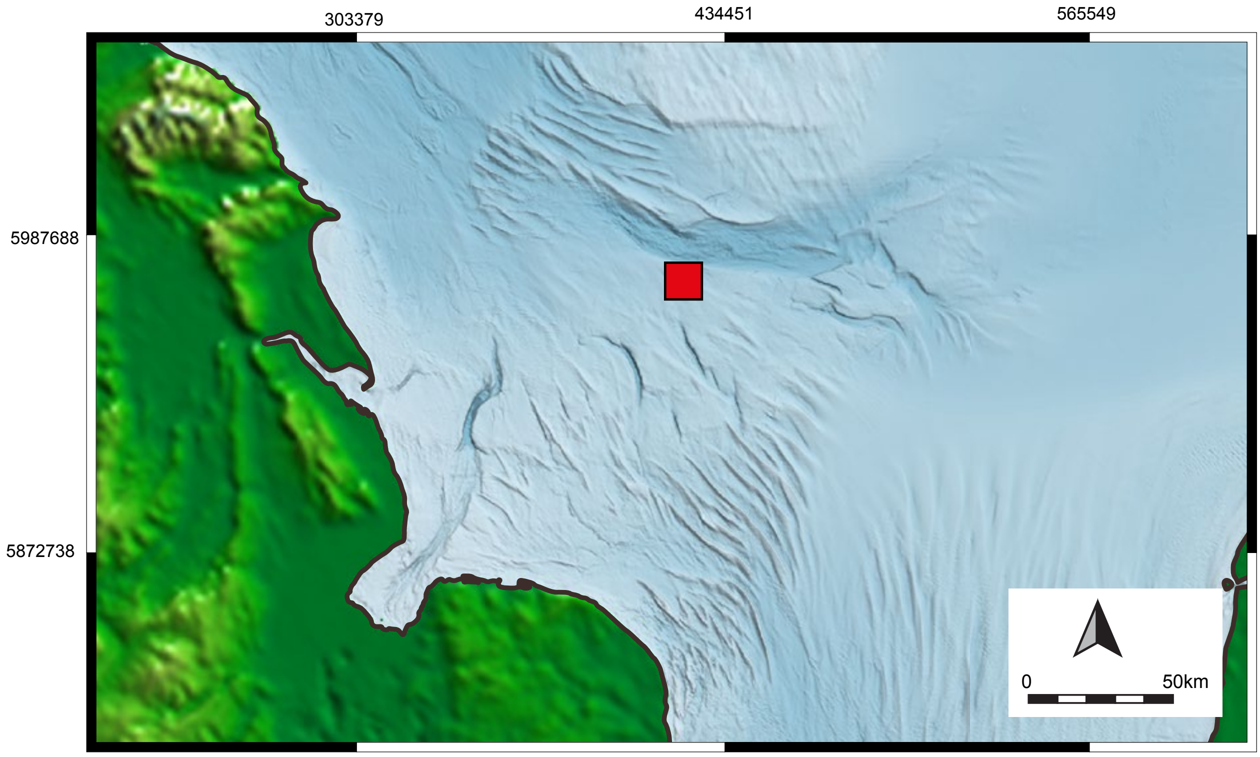


Figure 4.1 Location of the Arch-Area_1 study area is shown by a red box. Bathymetric data courtesy of EMODNET Bathymetry Portal, ETOPO1 topographic data courtesy of the NCEI and NOAA.

study was therefore to provide a methodology capable of better characterisation of such channels, and to support recovery of dating and environmental material with some confidence.

The feature under study was present in the bathymetric data (Figure 4.2), and separately identified in the NSPP 3D geophysical dataset (Figure 4.6). Due to the vertical resolution of the available 3D dataset, no internal structures or details were detectable within the palaeochannel.

Issues relating to channel identification within the NSPP are generally associated with use of oil industry, 3D reflection seismic data, and which are acquired by the towing of multiple streamers. The process produces a 3D dataset with a 25m resolution that can, due to its continuous acquisition, clearly map a structure in the horizontal plane. However, traditional 3D data has a lower resolution in the vertical plane and is generally more limited in the near surface and/or when attempting to locate smaller stratigraphic units. The recording method utilised within the Humber REC consisted of a traditional archaeological 2D approach to sub bottom data acquisition and was acquired along a single line (Hepp *et al.* 2017; Tappin *et al.* 2011; Velgrakis *et al.* 1999). Whilst possessing a very restricted horizontal resolution, these data are characterised by a much higher vertical resolution (10cm) in comparison to the 3D data (5m).

The process of 2D data acquisition involves towing a single energy source and a cable (streamer) containing several pressure sensitive receivers to record reflections from the underlying strata. These reflections, caused by changes in lithology, are acquired as a series of discrete vertical profiles. With appropriate processing this supports the production of 'pseudo-depth' sections of the subsurface structure, with the vertical axis being two-way travel time to the reflection. The identification and characterisation of sedimentary structures can then assist in understanding the local context for any associated submerged features that may have archaeological significance.

For the Humber REC survey, the seismic survey was performed by the Gardline Vessel *Vigilant*, equipped with a surface-towed seismic source and a multi-element streamer to permit digital recording of the response. The data was acquired in a series of lines spaced 100m apart (Tappin *et al.* 2011). A boomer system was used as a seismic source (single piezoelectric), which generated an acoustic pulse at approximately 3.5kHz. The resultant Humber REC 2D seismic data (Tappin *et al.* 2011) was integrated with the NSPP 3D seismic data (Thomson and Gaffney 2007) allowing an enhanced visualisation of the high resolution 2D seismic profiles and 3D timeslices.

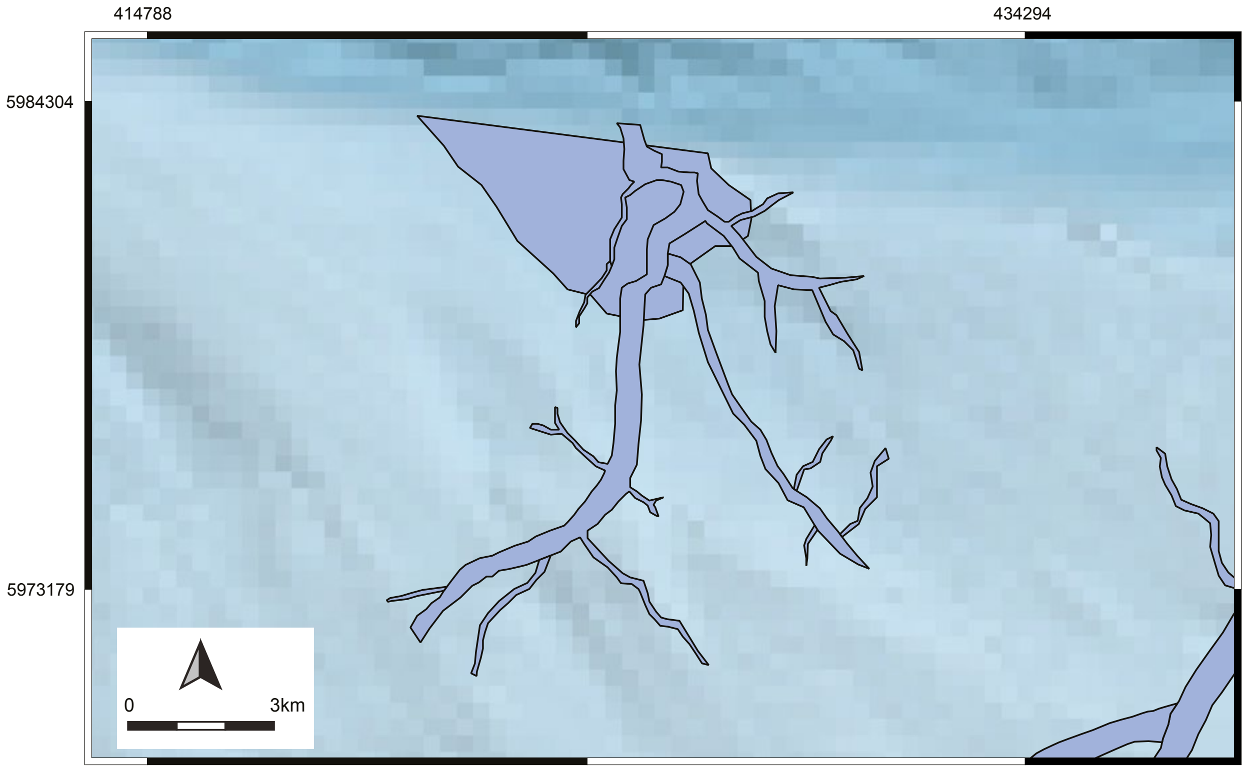


Figure 4.2 The NSPP 2007 interpretation of the channel system overlain on EMODNET bathymetry.

This acquisition pattern resulted in the collection of multiple profiles, although the spacing between the profiles is often in orders of magnitude greater than the 'trace' spacing (i.e. the horizontal sampling interval along the profile). This approach has two main disadvantages: firstly, the reflected seismic energy is assumed to have originated from a point directly beneath the profile, even though it could have originated from a point laterally offset from the profile (Thomson and Gaffney 2007). Secondly, the spacing between lines is sufficiently wide that it can be difficult to accurately map the position of a given morphological feature. Thus, a significant line density is required to compensate for these issues (Fitch *et al.* 2011). The 100m line spacing used in this project was thought to be appropriate for palaeolandscape survey.

Whilst this approach is often employed for petroleum exploration, it had not previously been applied to archaeological landscape survey prior to the NSPP, and applications remain relatively rare. Significant benefits, however, can be derived through the utilisation of both 3D and 2D seismic datasets (Thomson and Gaffney 2007). The advantages of data fusion are improved vertical resolution of the 2D seismic when combined with the aerially extensive and continuous, but relatively coarse resolution, 3D survey. However, such data can be used to resolve the stratigraphy and morphology of any feature to a level of detail that can facilitate guided core sample recovery. Recovered cores can then be sub-sampled for dating assays (e.g. radiocarbon and Optically Stimulated Luminescence (OSL) dating), and for associated palaeoenvironmental assessments to determine the character of the deposits (Tappin *et al.* 2011).

To confirm that the channel feature identified by the NSPP, and any related archaeological features, had surface expression, multibeam sonar was utilised to provide object detection and seabed character information. Multibeam uses a combination of hardware and software control of multiple transducers to produce a number of sonar signals that propagate from the sonar head in a fan and return a bathymetric and amplitude measure of the seafloor along the swath covered by the boat track (Blondel and Murton 1997). The method produces a bathymetric map of the seafloor, which can be mosaiced into a full 3D chart, if there is sufficient overlap between each swath. Most multibeam systems are hull mounted and high-resolution systems, using frequencies of up to 450kHz, and can discriminate objects of 20cm. Because the multibeam is hull mounted the beam angles result in amplitude maps that lack the dynamic range of true sidescan images. However, these maps have the advantage that the amplitudes are co-located with the bathymetry in true geographic space. For archaeological investigations, very detailed models can be produced using the multibeam sonar, and upstanding palaeolandscape features on the seafloor can be identified where they are coincident with the modern seabed.

However, this requires dedicated time to survey at pre-determined locations and is not conducive to routine line surveying. In addition to producing high resolution models of archaeological features with a bathymetric expression, the method has also successfully been applied to mapping palaeolandscapes where they are coincident with the current (modern) seafloor. (Gupta *et al*. 2004)

Results – multibeam sonar

An initial assessment of this area using legacy bathymetric data in the form of BGS Digbath250 data and EMODnet bathymetry, suggested that the channel did not have any surface expression. This was confirmed during 2008 when no bathymetric correlation was recorded between the palaeolandscape feature observed within the subsurface 3D seismic data and the bathymetric data acquired with the multibeam sonar. The multibeam image revealed a relatively flat surface with bathymetric depths ranging from -30m to -32m (Figure 4.3). Several recent sand and scour features are observable within the dataset (Figure 4.3). The northwest-southeast trending scour features do not correlate with the palaeolandscape feature which

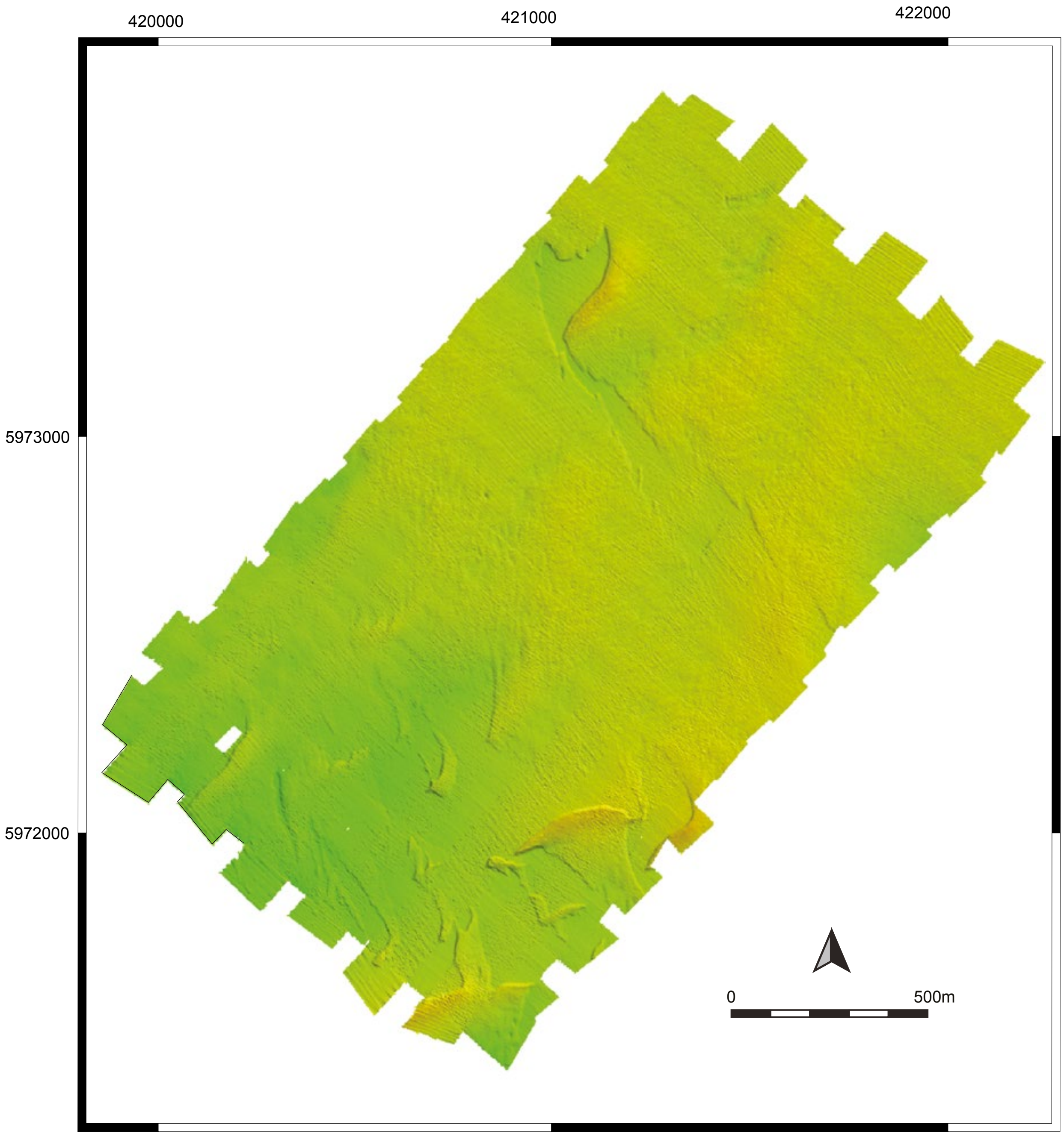


Figure 4.3 Multibeam Bathymetric image of the survey area generated through the Humber REC.

trend northeast-southwest. Nevertheless, the main scour feature directly crosscuts the palaeolandscape feature and provided an opportunity to core the structure, whilst minimising the recovery of more modern sediments. Although a positive correlation with bathymetric datasets was not expected, nor achieved, during this survey, the information on surface conditions fed into a subsequent coring campaign and validated its use.

Results – 2D seismic survey

The 2D survey was of sufficient resolution to allow the gross channel morphology to be modelled. The main channel recorded in the 2D dataset is 110m wide, with two smaller channels located parallel to the main channel. The entire system is up to 1.4km wide. The main channel is cut into the Boulders Bank Formation, a late Pleistocene glacial deposit (Cameron *et al.* 1992). The base of the channel has a fill which produced a chaotic seismic response, which suggests a gravel lithology (Figures 4.4 and 4.5). The remaining fill of this unit (SU1) comprises a relatively structureless seismic response which is thought to represent a fairly homogeneous, sand rich material. Above SU1, lies a second deposit (SU2), which can be seen along with a number of internal structures relating to channel development. Indications of migration are apparent, indicating the mobility of the channel within the landscape over time. Several strong reflections are present *c.* 7m below seabed which may indicate clay rich or peaty deposits (Figure 4.5). At the top of the channel, a strong reflector can be seen separating more recent deposits (SU3) from those within the channel (SU2). Away from the main channel is a smaller feature that was also recorded within the original 3D dataset. This feature has a similar structure to the main channel; although it lacks the evidence for migration associated with the main channel (Figure 4.4).

The high-resolution geophysical survey reveals numerous internal features, although channel migration structures are particularly common. The presence of such structures indicates that the channel itself had enough time to develop and respond to change in base level before submergence. Crucially, the characterisation of these features confirmed the initial NSPP interpretation that initial results represented the channel and floodplain, rather than the channel alone. Although Holocene channel courses can be detected using oil industry data (Figure 4.6), this tends to be restricted to seismic datasets acquired post 1990. Older 3D datasets have a lower resolution and different recording techniques limit their use. Analysis of the merged PGS dataset available for interpretation within this area suggested that the original, underlying dataset utilised in the merge was much older and unlikely to provide improved data.

The correlation of the fluvial feature in the Humber REC data (Figure 4.7, A), with the NSPP interpretation (Figure 4.7, B) supports the original hypothesis that the sub-sea floor features at this location represent a north-east trending, anastomosing channel system (Gaffney *et al.* 2007). These features extend beyond the NSPP survey area suggesting that this feature continues into areas that have not yet been assessed for palaeolandscape potential.

A minor anomaly in the data relates to the position of the tributary channel of the river (Figure 4.7). This was located by the Humber REC some 100m away from that recorded by the NSPP 3D data. It is likely that this is a locational issue resulting from the higher resolution of the Humber REC data and GPS positioning errors located within the earlier 3D data. Despite this, the location for the thalweg of the main channel is consistent between both datasets.

The general correlation of the geophysical response between seismic surveys is important. These results confirmed the nature of the channel but also the integrity of the earlier data and the potential to use legacy data to identify deposits of archaeo-environmental significance in future studies including *Europe's Lost Frontiers*. The application of these methods to geophysical data from the broader study area indicates that significant sediment sequences are preserved beneath the seabed within the Humber REC region and must extend beyond it. The depth information derived from the seismic data indicates that the early Holocene deposits can reach a thickness of up to 18m locally in the Humber REC area, and greater depths (+20m) are achieved in nearby areas of the North Sea (Cameron *et al.* 1992).

To ground truth these results, three cores (VC39, 39A and 40, Figure 4.6) were acquired by the Humber REC over the channel feature. Seismic responses were correlated with the stratigraphy located within the vibracores and found to be consistent. The seismic response from the boulder clay/Holocene transition was observed to be coincident with that recorded by those vibracores. Seismic units SU3 and the upper sections of SU2 were sampled. The minerogenic nature of the sediments recovered from SU2 meant that only OSL dating and foram/ostracod analyses were carried out on the sediments, as the material was not favourable for other palaeoenvironmental analyses or dating methods. The material producing strong reflections within SU2 was not sampled as this lay beyond the reach of the 5m vibracorer. Modelled OSL dates indicate that sandy clays at the base of the core began accumulating in the earlier Holocene, at an estimated date of 8230-6580 cal. BC (GL-09070 2.16-2.26m). Other dates within the core suggested that accumulation may have been rapid (Tappin *et al.* 2011 Table 5.6.21). A transition from laminated sands/silts to shell rich sands (SU3) at 1.36m

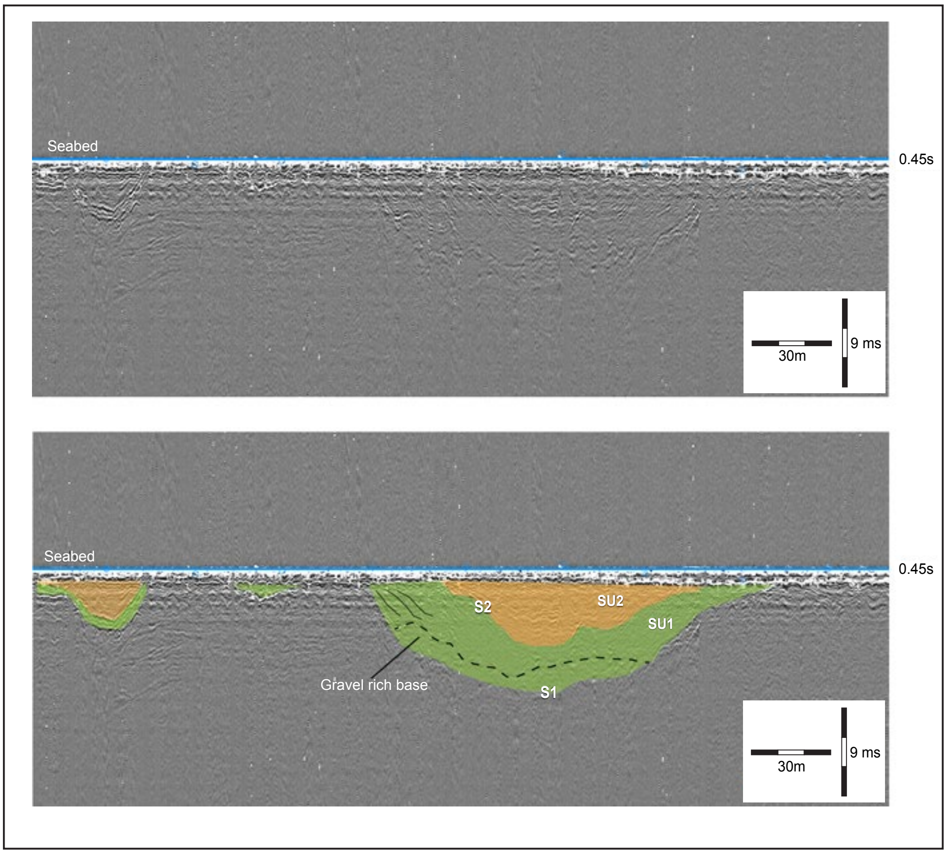


Figure 4.4 Humber REC 2D seismic line over main channel and tributary channel

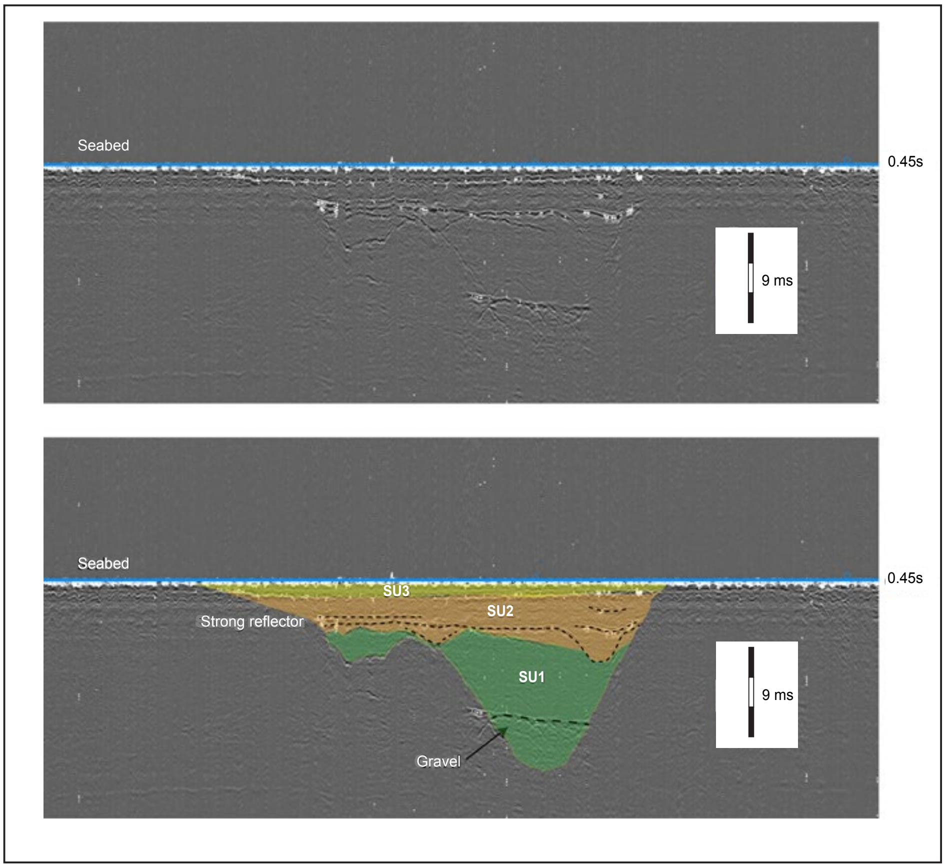


Figure 4.5 Humber REC 2D seismic line showing several strong reflectors in the main channel.

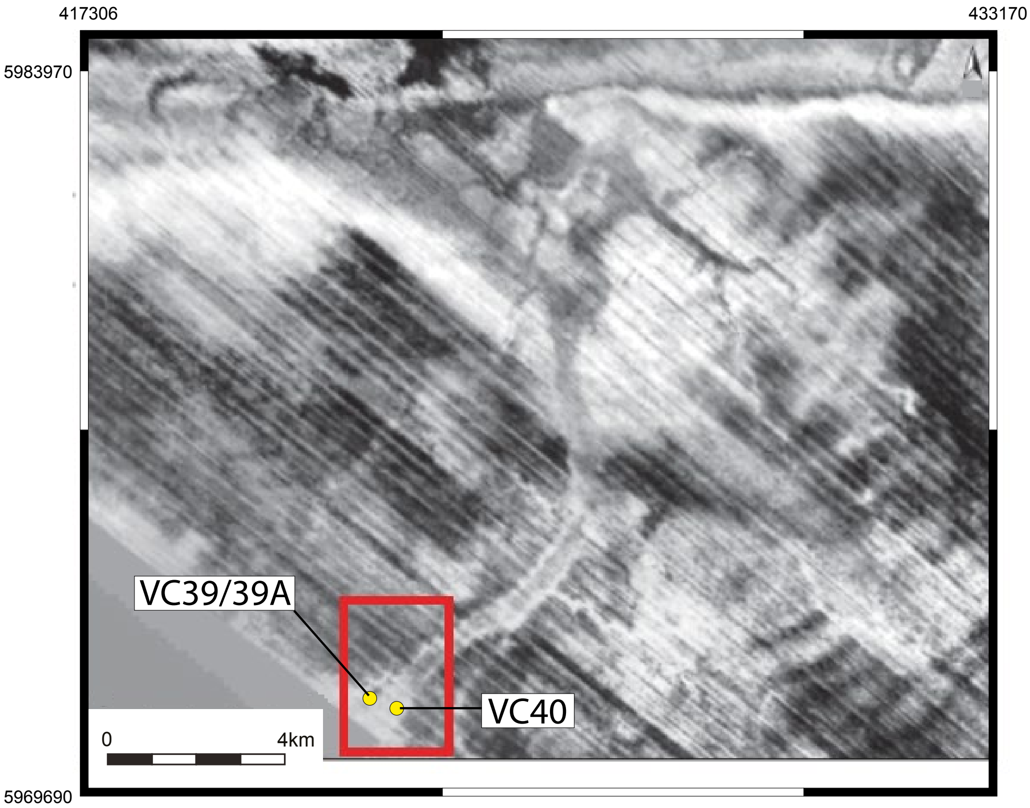


Figure 4.6 A timeslice from the 3D seismic data at 0.076s derived from the PGS Megamerge dataset. The red box is the position of the Humber REC 2D survey, and the position of vibracores VC39/39A and VC40 are shown as yellow circles.

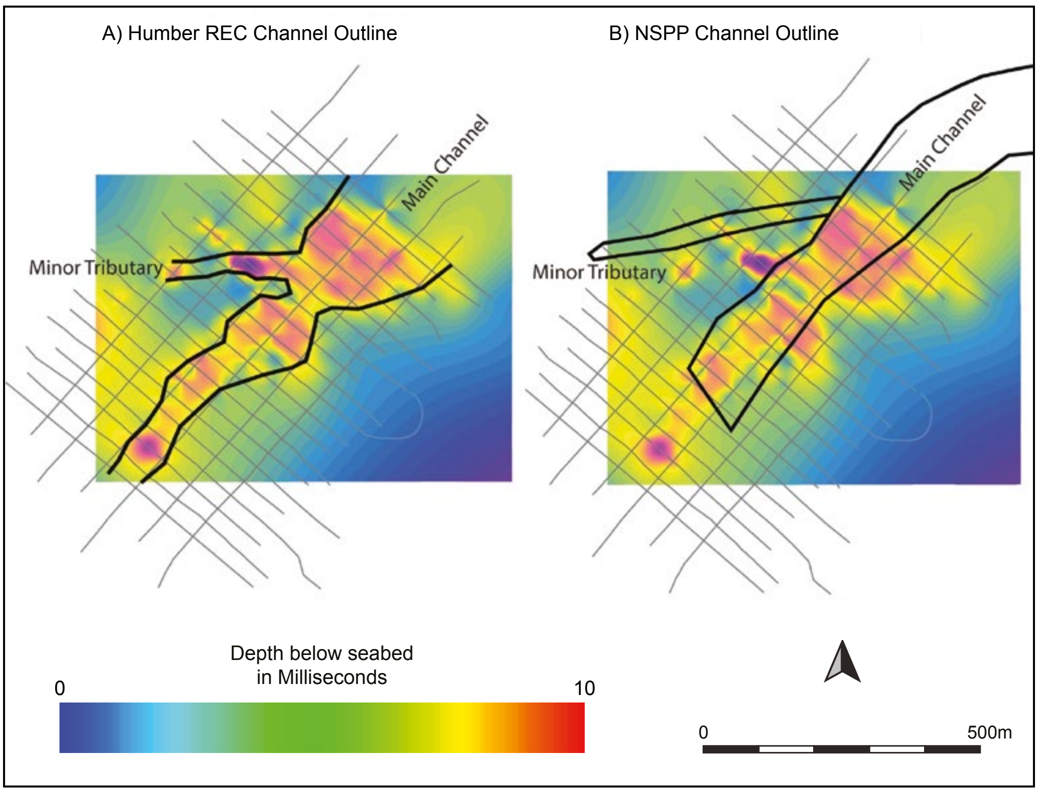


Figure 4.7 Comparison between the GIS channel outlines as derived from A) the Humber REC 2D survey interpretation and B) the NSPP survey GIS interpretation. Both are overlain on a depth surface derived from the Humber REC 2D dataset.

indicates the onset of full marine conditions at the site with a *terminus ante quem* estimated at 7920-6280 cal. BC (GL-09068, 1.02-1.10m).

Whilst the vibracores were unable to reach the base of the deepest parts of the feature (SU1), the OSL dating indicates that the feature was active during the Early Mesolithic at least. Thus, the channel features could be associated with the Mesolithic landscape of Doggerland. Whilst these results were encouraging in terms of the *in-situ* preservation of sediments associated with the early Holocene history of the North Sea, the survey also demonstrated the need for coring equipment capable of recovering deposits associated with the earliest Holocene stratigraphy.

Discussion

The results of the Humber REC project were critical to the development of future research planning and, ultimately, the funding applications underpinning *Europe's Lost Frontiers*. The confirmation and clarification of the nature of features derived from NSPP mapping finally demonstrated that the interpretation and sampling of fragments of the surviving landscape of Doggerland was possible for locations at a significant distance from the current coastline. Whilst there were some minor differences between the NSPP and Humber REC surveys, these are a result of the coarser resolution of the 3D data and were not unexpected. Indeed, the correlation between the surveys was excellent and the results validate the use of legacy 3D geophysical data to explore the extensive landscape archaeology of Doggerland. Additionally, the project confirmed that archaeologists could attempt the detailed exploration of the numerous channels identified within the submerged landscapes of the North Sea, and that fusing 2D and 3D geophysical datasets has significant advantages in terms of accuracy and resolution.

At a time when industrial development within the region is generating even larger datasets, these are significant results that will support future archaeological prospection (Firth 2015; Sturt *et al*. 2017). The planned expansion of wind farm across the North Sea is now providing researchers with very high resolution 2D datasets offering significant improvements in vertical resolution (e.g. Thal *et al*. 2019). When merged with existing 3D datasets these will improve our knowledge of the development of the pre-inundation landscape and assist in our efforts to understand the effects of sea-level change upon the Mesolithic communities of this region.

The resources required to recover archaeological or environmental data from the marine environment are significant, and the need to accurately target locations for investigation is crucial. The results presented here represent a relatively small area of the data being studied or potentially available for research, but they illustrate a methodology that moves from larger scale to smaller, possibly site-specific areas. This landscape data can provide a context and chronology within which any archaeological material recovered from the region can be placed. Accurate information on the nature and history of river channels may also assist archaeologists in exploring possible routeways for prehistoric human communities to move through Doggerland and identify optimal areas for recovering archaeological material, that are also accessible to prospection (cf. Bradley 2007). Ultimately, the Humber REC project demonstrates our capacity to identify, target and sample *in-situ* deposits of early Mesolithic/Holocene age and has implications for the future study of submerged prehistoric landscapes in the southern North Sea and elsewhere.

Chapter 5

The archaeological context of Doggerland during the final Palaeolithic and Mesolithic

James Walker, Vincent Gaffney, Simon Fitch, Rachel Harding, Andrew Fraser, Merle Muru and Martin Tingle

Introduction

For much of the second half of the 20th century, archaeological accounts of Doggerland either relegated the landscape of the southern North Sea to having simply been a land-bridge, important for what it connected rather than what it was, or worse, overlooked it altogether (Coles 1998). At best, those whose work hinted at the importance of this lost landscape were hamstrung by the lack of available data from which to expound their ideas (Murphy 2007). For a long time, archaeologists have presumed, based upon similarities in material culture between the British Isles and continental mainland, that from at least the Final Palaeolithic, Doggerland may have once been among the most densely populated areas of Europe (e.g. Smith 1992: 4; Mithen 2003: 150), without much direct evidence from its inhabitants. In many respects, Doggerland remains an area of which we know frustratingly little when it comes to the prehistoric peoples who once lived there. However, if nothing else, the growing weight of finds recovered over recent decades (e.g. Louwe Kooijmans 1970; Amkreutz *et al.* 2018) gives reason to anticipate archaeological potential from at least some areas of this submerged landscape.

Doggerland, therefore, has remained a landscape of latent prehistoric promise, as it has for over a century. Following the work of Clement Reid (1913) and, in 1931, the discovery of the Leman and Ower banks (or Colinda) 'harpoon' (Burkitt 1932; Godwin and Godwin 1933; Figure 5.1), this area was recognised as a place of central importance from an early stage in Mesolithic research (Childe 1931; Clark 1936a; Godwin 1945). Despite this early recognition, with a few notable exceptions (e.g. Louwe Kooijmans 1970; Verhart 1987; 1989), Doggerland faded from archaeological attention for much of the second half of the 20th century (Murphy 2007). This situation changed in the mid-1990s when Bryony Coles (1998; 1999; 2000) and others (Verhart 1995; Bjerck 1995) returned the area to our collective archaeological conscience.

Since the mid-2000s, there has been a profusion of work in and around the southern North Sea basin which has transformed our understanding of this submerged prehistory (Murphy 2007; Firth 2013; Amkreutz and van der Vaart-Verschoof 2021). A significant contribution has been the efforts of researchers working with the *Europe's Lost Frontiers* (ELF) project and those involved in its predecessor, the *North Sea Palaeolandscapes Project* (NSPP) (Gaffney *et al.* 2007; Gaffney *et al.* 2009; Fitch *et al.* 2007). However, whilst this research transformed our knowledge of the evolution of Doggerland's physical geography (or at least aspects of it), our knowledge of the human geography continues to lag.

Even now, over two decades on from Bryony Coles' work, what little we know about the archaeology of Doggerland is heavily skewed towards the coastal margins of the North Sea basin rather than the offshore zone. Thanks, however, to significant advancements in our knowledge of the Holocene landscape's palaeogeography and prehistoric environments (Fitch 2011; Fitch *et al.* 2005; 2007; Gaffney *et al* 2007; 2017; van Heteren *et al.* 2014; Vos *et al.* 2015; Ward and Larcombe 2008), prospection for submerged Postglacial landscapes far from the current shore is at last becoming an attainable reality (Missiaen *et al.* 2021).

The core focus of this chapter is the recent work and context of the European Research Council (ERC) funded *Europe's Lost Frontiers* project – successor to the NSPP (Gaffney *et al.* 2007; 2009) and the Humber Regional Environmental Characterisation (Humber REC) project (Gearey *et al.* 2012; 2017; Tappin *et al.* 2011). The *Europe's Lost Frontiers* project has adopted a perspective focused on Doggerland itself rather than a national or regional portion of the nearshore zone. Nevertheless, the invaluable contributions of other researchers must also be acknowledged. These include reviews of collected materials from ongoing fishing activities and industrial developments (Amkreutz and Spithoven 2019; Groningen 2020; Peeters and Momber 2014; Peeters *et al.* 2020a; 2020b; 2019; 2009), attempts at the dating of organic finds (Ward and Larcombe 2006), and even dietary analyses of the few Mesolithic human remains that have been recovered through fishing, aggregate extraction or other intrusive activities (van der Plicht *et al.* 2016). Various other studies have also contributed significantly to our understanding of palaeolandscapes (van Heteren *et al.* 2014; Ward *et al.* 2014), including areas such as the Elbe palaeochannel, German Bight (Hepp *et al.* 2017) and the Danish sector (Prins and Andresen 2019). These, along with preliminary efforts at palaeoenvironmental reconstruction (Krüger *et al.* 2017; Brown *et al.* 2018) perhaps share the most in common with overarching goals of the *Europe's Lost Frontiers* and NSPP projects (e.g. Fitch *et al.* 2005; 2007; Gaffney *et al.* 2007; 2009; 2017; Gearey *et al.* 2012; 2017; Missiaen *et al.* 2021).

Following such research, here we can present an overview of the current state of our knowledge about the late Glacial and Postglacial archaeology of Doggerland, with some broader contextualisation of emerging details regarding the late Glacial landscape, and implications for the survival of a littoral fringe landscape into the Early Neolithic. The chapter is effectively divided into two sections. The first section covers the reasons why the NSPP and *Europe's Lost Frontiers* projects have been directed primarily at the palaeogeography of the Postglacial, a brief note regarding the recent historical context of research, discussion of the extent of the landscape and its evolution since the Final Pleistocene, and a review of finds, findspots and sites from different areas of the southern North Sea. The second part of the chapter details the need for a uniquely landscape-based approach to future archaeological work, before providing a more general discussion of Mesolithic Doggerland, including a broader archaeological context from the surrounding areas of northwest Europe, and exploration of some impactful environmental events.

Why the Postglacial?

Doggerland, the submerged palaeolandscape of the southern North Sea, has been a habitable place at various times over the last 700,000 years, if not earlier (Bynoe 2018; Sturt 2015; Firth 2013; Flemming *et al.* 2014: 78; Parfitt *et al.* 2005). The archaeological potential of this landscape for Pleistocene prehistory is well attested through the recovery of Palaeolithic fauna, artefacts and even hominin remains (Bynoe *et al.* 2016; Hijma *et al.* 2012; Hublin *et al.* 2009; Mol *et al.* 2004; Stapert *et al.* 2013). The recovery of an extensive middle Palaeolithic assemblage through underwater excavation at Area 240, off the East Anglian coast, clearly demonstrates the potential for the preservation, investigation and recovery of *in situ* archaeological remains from ancient prehistory (Tizzard *et al.* 2015). The main focus of the *Europe's Lost Frontiers* project (Gaffney *et al.* 2017), however, as well as that of precursor projects such as the NSPP, has been the Postglacial palaeogeography and archaeology, and primarily the Mesolithic (*c.* 11,500–5500 BP).

There are various important benefits to focusing on this period of Doggerland's history. Most if not all discoveries of marine prehistory from the North Sea, such as Area 240, have been made by chance through interventions in industrial work, rather than by targeted archaeological prospection (although see Vos *et al.* 2015 and Weerts *et al.* 2012). Both the NSPP and *Europe's Lost Frontiers* projects have sought to develop our understanding of Doggerland's palaeogeography with a view to being able to both hypothesise more reliably about possible patterns of human activity, and to prospect for archaeological remains with a greater degree of confidence. Meeting both these aims would constitute a significant advance on the speculative state of knowledge presented in earlier accounts (Fitch *et al.* 2007).

The Postglacial landscape is particularly attractive in this regard, as a much higher resolution of data across time and space is currently attainable for this timeframe than for earlier periods, particularly regarding changes in sea level (Cohen *et al.* 2017: 22; Flemming *et al.* 2014: 79; Firth 2013). This in turn allows a greater degree of confidence both in reconstructing prehistoric palaeogeography, and for understanding histories of erosion and variable potential for archaeological preservation (Peeters *et al.* 2019: 19).

Radiocarbon dating generally becomes unreliable for ages beyond 50,000 years (Guilderson *et al.* 2005). Optically stimulated luminescence (OSL) dating does not face this tail-off in efficacy, but for landscapes younger than this period, palaeosols datable through radiocarbon – i.e. those with relatively high organic components, and most notably peat deposits – can supplement OSL dates to help generate more tightly constrained chronologies, including for fluctuations in sea level. This is particularly useful because variability in sea-level change can be highly localised, and benefits from increased sea-level index point (SLIP) data as well as an appropriate glacio-isostatic adjustment (GIA) model. Readily datable soil horizons offer a greater likelihood of higher density SLIP data being achievable.

In addition to this, reconstructions of landscapes from the late Glacial or earlier have to contend with the formidable landscape alteration processes associated with glaciation and deglaciation cycles - the southern North Sea was on the periphery of the maximal glacial extent during the peak of marine isotope stage 2 (MIS2) (Clark *et al.* 2021). Still earlier phases of Doggerland underwent repeated marine transgressions (Cohen *et al.* 2017; Flemming *et al.* 2014: 79; Sturt 2015; Van Andel and Tzedakis 1996). The Mesolithic, in contrast, represents the most recent period at which most of Doggerland was inhabited prior to its current inundation. Relative to older periods of prehistory, this period of Doggerland's occupation has the best potential for high-resolution palaeogeographic reconstruction, and for preservation of archaeological materials, whilst

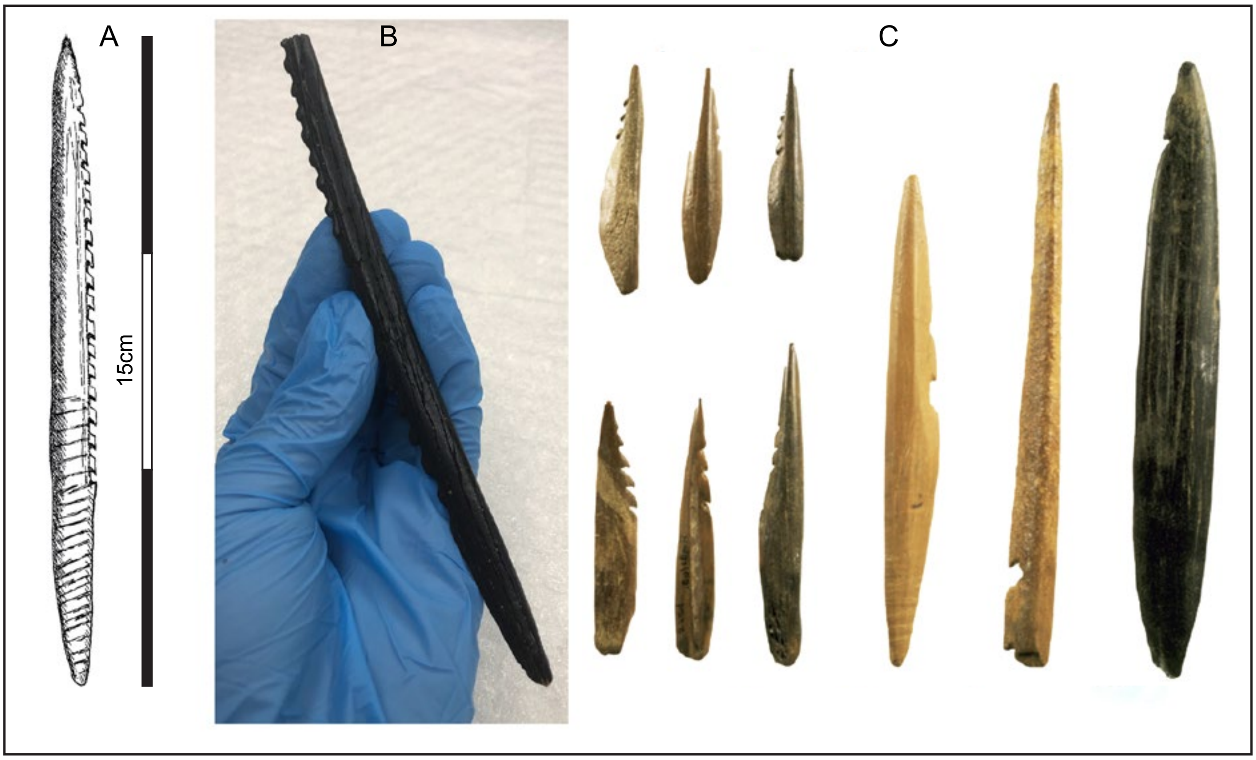


Figure 5.1 A) The Colinda 'harpoon', found within a chunk of 'moorlog' peat dredged from the Leman / Ower banks off the Norfolk coast in 1931 (after Flemming 2002); B) A bone point recovered from beach walking at Massvlakte 2 in the Netherlands (courtesy of Luc Amkreutz); C) An array of barbed bone points from Maasvlakte 1 off the Dutch coast (courtesy of the Rijksmuseum van Oudheden). Many other examples of organic artefacts from Dutch waters may be found in Peeters and Amkreutz (2020), Amkreutz and Spithoven (2019) and Louwe Kooijmans (1970).

also providing sediments that are accessible for direct prospection. This is also partly reflected by the relative preponderance of Mesolithic age finds compared to those from other periods recovered from the southern North Sea (Riede 2015: 560).

Following the late Glacial, the relative climatic stabilisation of the early Holocene (see Figure 5.2) coincided with the onset of the most dramatic stages of sea-level rise in the last twenty thousand years of Doggerland's history. An aerial view of the North Sea basin 5000 years ago would appear recognisably similar to how it looks today. The same view, seen from 11,000 years ago, however, would have looked remarkably different. At the beginning of the Holocene, Doggerland would have, save for major bodies of water such as the Outer Silver Pit, and river outlets such as the Elbe, spanned the breadth of the southern North Sea, from the east coast of Yorkshire in the UK, to the west coast of Jutland in Denmark. Over the course of the Mesolithic, it dwindled in area substantially (Gaffney *et al.* 2009; 2020; Sturt *et al.* 2013; Walker *et al.* 2020). Yet this was not simply a period of loss for this landscape. Doggerland was also, almost certainly, one of the most attractive and important areas for human settlement in northwest Europe in the Late Pleistocene/Early Holocene, and at least some Mesolithic communities occupied positions within this landscape throughout the ongoing changes that witnessed sites and landscapes transition from inland to seaward locales (Peeters *et al.* 2019: 22). Consequently, although the postglacial occupation history of Doggerland spanned a dynamic period of landscape transition and inundation, it is nevertheless among the most archaeologically viable periods for investigation.

Recent developments in the submerged prehistory of northwest Europe

Much has already been written on the history of archaeological research into Doggerland (Coles 1998; Gaffney *et al.* 2009; 2017; van de Noort 2011). These accounts have all tended to focus on the more recent history of research, rightfully emphasising the impact of Clement Reid's work and the discovery of the Colinda harpoon, as described above. Recognition of the presence of an ancient submerged landscape in the North Sea is, however, a much older concept (Sturt *et al.* 2018: 657), with a far more extensive research history than has yet been covered in detail, and this is the subject of forthcoming volumes in the *Europe's Lost Frontiers* series which will provide a much more

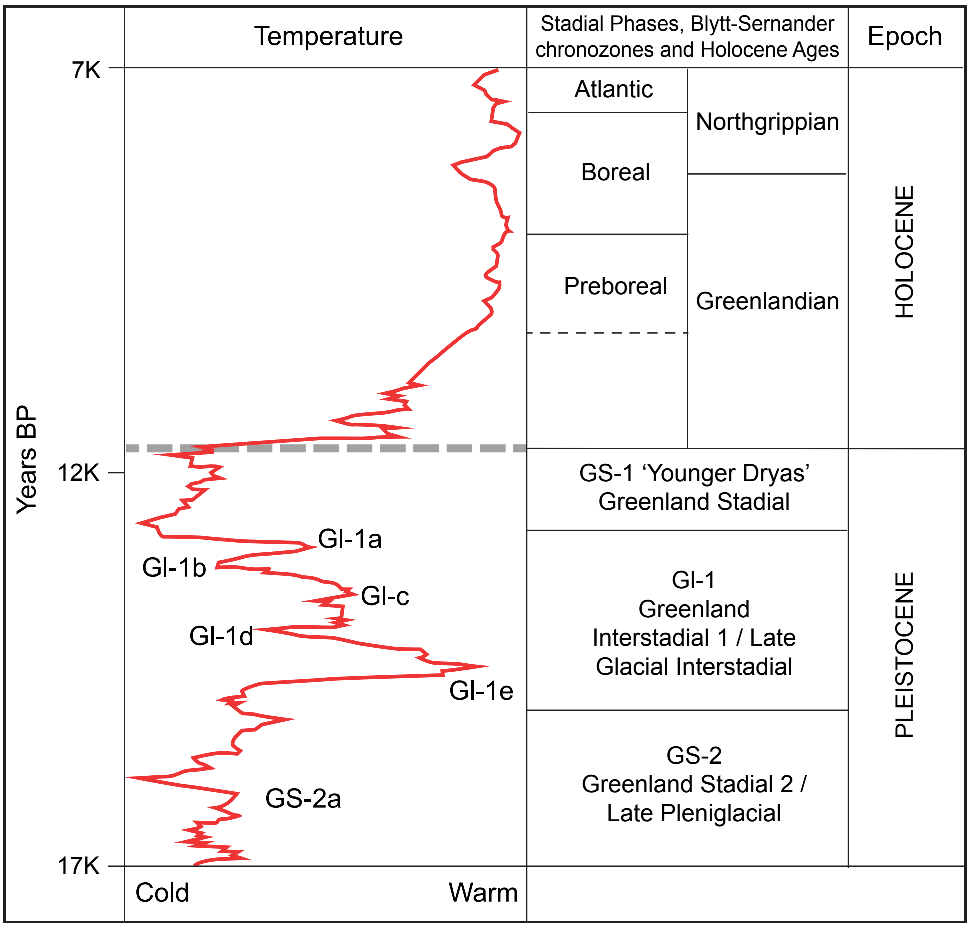


Figure 5.2 Temperature curve for the Final Pleistocene and Early Holocene (Late Glacial and Postglacial between 17 and 7 thousand years ago) as derived from Greenland Ice Core data, and redrawn from Price (2015). Note the climatic variability of the Final Pleistocene relative to that of the Holocene.

extensive consideration of the history of submerged palaeolandscape research than scope permits here.

Nevertheless, it is pertinent to provide a brief historical context for how recent developments have shaped current knowledge, especially as it is within recent decades that some of the most significant advances have been made. Bryony Coles' work (1998) reintroduced the name Doggerland into common parlance and popularised it among archaeologists. Alternative designations (e.g. Childe 1957; 1958; Leary 2015; Porr 2009) and regional subdivisions (Hammer *et al.* 2016) have been suggested, but as the oldest and most widely used placename (see Gaffney *et al.* 2017), 'Doggerland' has become the enduring *nom de guerre*. Coles' work reignited archaeological interest in a topic that had largely lain dormant for much of the second half of the 20th century. This lull is all the more remarkable considering the long and close association between Mesolithic research and coastal landscapes – particularly shell midden sites – and the recognition early on that fluctuating sea levels in the wake of the LGM must have altered the landscape significantly at different times throughout the Late Pleistocene and Early Holocene (Clark 1936).

The last thirty years have seen various major developments take submerged prehistory research forward in Europe. The 1990s was, in Denmark at least, a formative time for the development of diver-based survey, which has yielded a plethora of submerged Mesolithic sites from the shallow waters in and around Denmark (Fischer 1993; Pedersen *et al.* 1997). This followed investigations at the submerged settlement complex of Tybrind Vig throughout the late 1970s and 1980s, which demonstrated the potential for Mesolithic archaeology with astonishing qualities of preservation to exist within submerged landscapes (see Andersen 2013). More broadly, it was a time when recognition of the importance of prehistoric coastlines and submerged landscapes was beginning to grow throughout Mesolithic archaeology, as heralded by the 'Man and Sea in the Mesolithic' volume among others (Fischer 1995; see Verhart 1995 and Bjerck 1995 for explicit consideration of the southern central North Sea).

In the 2000s, various researchers expanded upon these ideas (Bailey and Flemming 2008; Flemming 2004a), challenging long-held and ill-founded negative preconceptions regarding the relevance and potential of underwater prehistory (see Bailey 2004 for critical discussion). It was also during this time that the NSPP, the first project of its type or scope anywhere in the world, came into being, establishing the first extensive insights into the palaeotopography of Doggerland (see Gaffney and Fitch this volume). Towards the end of the decade, in 2009, the SplashCOS (Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf) initiative was established, a European-wide network connecting marine prehistorians and those working in related disciplines across the continent. In addition, numerous site-based projects in and around the southern North Sea – for example at Bouldnor Cliff (Momber *et al.* 2011), Area 240 (Tizzard *et al.* 2015), and Yangtze harbour (Moree and Sier 2015) were undertaken, which all demonstrated the potential for the archaeological investigation of submerged prehistoric sites in uniquely challenging conditions.

The late Glacial and Postglacial extent of Doggerland

Investigating the palaeogeography of submerged prehistoric landscapes is neither simple nor straightforward. Reconstructing prehistoric coastlines, and how they changed over time, is a particularly difficult challenge. However, our understanding of Doggerland as a landscape of human significance has improved immensely, and follows the increasing resolution at which we can reliably reconstruct the evolution of the southern North Sea landscape over time and space (Flemming *et al.* 2014).

For decades now, the common archaeological perception of Doggerland as a landmass has been based around maps presented by Bryony Coles in the late 1990s, which were themselves updated hypothetical alternatives to older maps generated by Saskia Jelgersma (1979) in the late 1970s. New research in the geosciences, however, suggests that traditional notions of geographical extent may need significant revision. Specifically, research undertaken by the BRITICE Project (Roberts *et al.* 2018) has demonstrated that the landscape north of the Dogger Bank was flooded during deglaciation, possibly as early as 21,000 BP (Figure 5.3). This means that the habitable landscape available for human populations in Doggerland extended considerably less far North than envisaged by many (e.g. Ballin 2017; Coles 1998; Lambeck 1995). The northernmost region of the North Sea was, consequently, not available for occupation, beyond the possibility of temporary visitations upon remnant sea ice (Bjerck 2019) or the use of boats along the northern coast.

The northern flank of the Dogger Bank, therefore, must have been a relatively stable marine coastline from *c.* 21,000 to at least 15,000 BP. Most of what is now the southern central North Sea was never glaciated, even during the most severe times of MIS2 (Clark *et al.* 2021), and this, combined with the stability of its northern coastline, means that Doggerland may have been a viable if not attractive place for the early re-colonisers of northerly latitudes in Europe. Although this means that Doggerland was not well suited for supporting the recolonisation of northern Scandinavia (see Glørstad *et al.* 2017), it does suggest that it may have remained a place of importance throughout the Final Palaeolithic. The portion of this landscape surrounding Denmark, east of the Elbe, may nevertheless have been significant for peoples moving into Norway via western Sweden, even though central and northern Doggerland itself would probably not have been a bridgehead for colonisation (Glørstad 2016).

It is not only the northernmost extent of Doggerland that has been significantly revised through recent research. By at least 10,000 BP, it is estimated that the English Channel had encroached inland much further north than has traditionally been posited, joining with the outflow of the Thames estuary somewhere between East Anglia and the Netherlands (Sturt *et al*. 2013; Figure 5.3). This would mean, in addition to the Silver Pit to the North, and banks of the Elbe to the east, that another major estuary/inlet existed in the southwest of Doggerland. The existence of this inlet would have also restricted the land connection between the UK and the rest of Europe to a relatively narrow landscape just south of the Dogger Bank for much of the Holocene. It seems increasingly likely that the southern outflows of the Outer Silver Pit may, at some point relatively early in the Holocene, have joined with the Channel inlet to the south, precipitating the severance of the UK from the mainland by around 9000 BP, broadly coeval with Grahame Clark's initial estimate (Clark 1936b: 239).

The separation of the British Isles from mainland Europe

As Doggerland diminished in area and fragmented into an archipelagic area and, eventually, a littoral fringe of the contemporary North Sea basin coastline, the landmass of the current day British Isles would have become separated from mainland Europe. The encroachment of a substantial marine inlet into the Southern Bight by 10,500 BP, several millennia earlier than has traditionally been posited (see Funnel 1995), suggests that the English Channel may have been a more substantial obstacle in the final Palaeolithic recolonisation of northerly latitudes. Combined with the rapid diminishment of Doggerland's northernmost coast from around 12,000 years ago, it seems that the British Isles may have separated from the rest of Doggerland by around 9500 BP (Walker *et al.* 2020), and almost certainly no later than 8500 BP (Sturt *et al.* 2013).

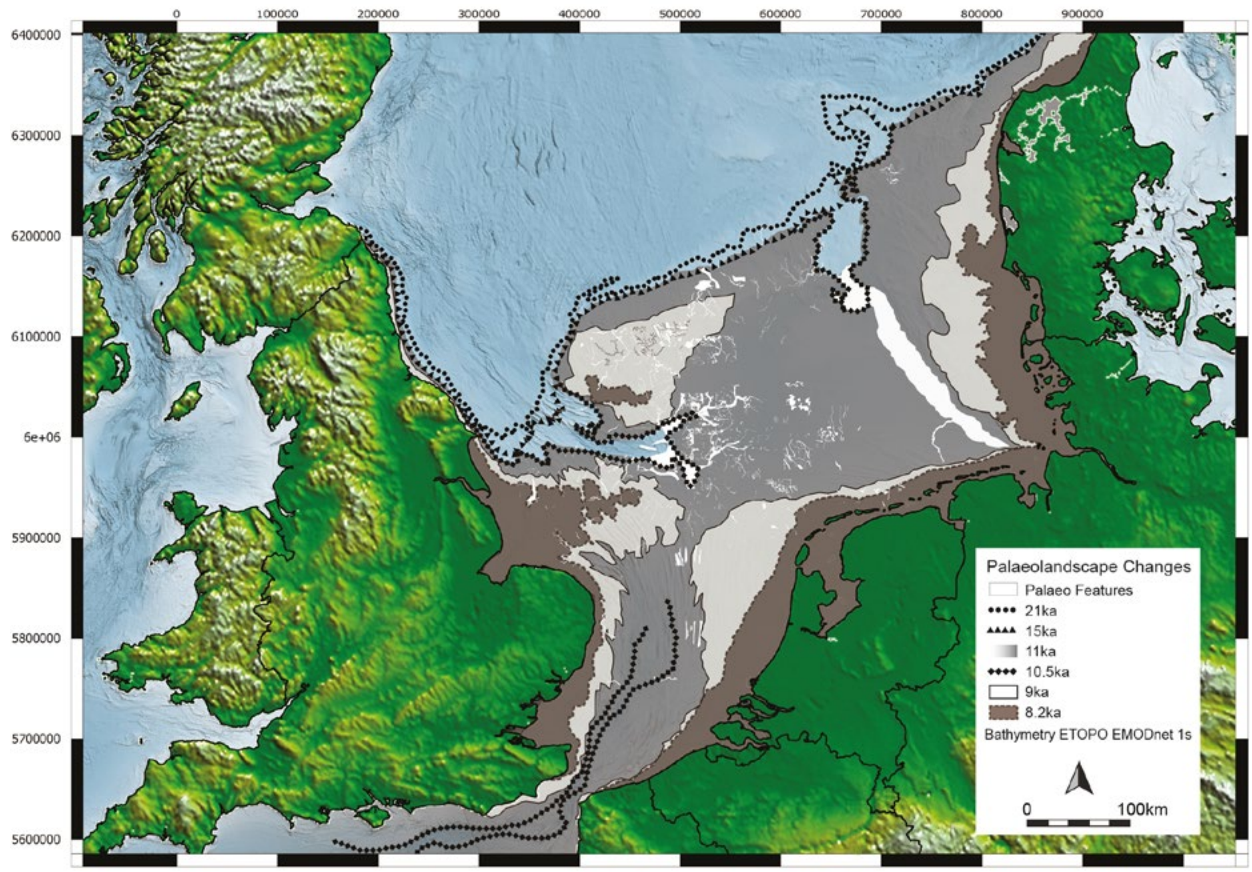


Figure 5.3 Map showing the projected coastlines of Doggerland and the southern North Sea since the final millennia of the Last Glacial Maximum, with key dates for the transgression highlighted.

The separation of the British Isles from the mainland has been a recurring theme of importance for British Mesolithic research (Clark 1936b; Wymer 1991), and many recent accounts have typically given a later date for this (e.g. Barton and Roberts 2004; Waddington 2015). It has been assumed that this process might have caused or catalysed realignments of social networks and cultural identities that might be reflected as changes in the archaeological record. It is difficult to causally relate such changes with confidence however, particularly in light of the earlier date now proposed for this event. First the landward connection, centred in the Early Holocene around the east of England (northern East Anglia, Lincolnshire and Yorkshire), would have narrowed. Once this connection broke, the gulf of waters separating the landmasses would have grown. Although the physical separation of the British Isles appears to have happened relatively quickly, perhaps over a matter of centuries, the actual degree of social and cultural separation from groups on the European mainland may have been a much slower process. For a while, at least, the waters that divided the two would have been eminently traversable (Garrow and Sturt 2011; Momber *et al.* 2021), and although the frequency and nature of contacts across the water would have presumably changed as the distance grew, any associated evidence for change in the archaeological record may be more modest and gradual in nature, or lag sometime after the actual physical separation. Equally, such changes may actually pre-empt the separation, as social connections may have begun to strain as the landward connection dwindled, bringing about social tensions and reconfiguration prior to the actual physical separation (Waddington 2015).

Although, under this new revision, the English Channel appears to have become a significant obstacle even earlier than traditionally thought, the presence of both water-faring transport and cultural contacts with the European mainland from the submerged site of Bouldnor Cliff, in the Solent waters around the Isle of Wight, suggests that Mesolithic peoples were not necessarily hindered by this (Momber *et al.* 2021). Nevertheless, palaeogeographic reconstructions of prehistoric coastlines currently indicate that by the Final Palaeolithic, and certainly in the Early Holocene, the focal point for landward connections between inhabitants of the British Isles and Doggerland, would have been the east of England, rather than the south, or even south-east. How the nature of this connection and the timing of its eventual diminution affected the cultural and ecological development of both Doggerland, and the British Isles as they became separated, is an area for future research.

Sites and findspots from Mesolithic Doggerland

Tables 5.1 and 5.2 present submerged Mesolithic findspots and sites from Doggerland collated as part of the recently concluded SplashCOS network (www.SplashCOS-viewer.eu; Bailey *et al.* 2017; 2020; Flemming *et al.* 2014; Fischer and Pedersen 2018). These sites and findspots are divided according to whether they were found in the nearshore (<12 nautical miles within Territorial Seas, Table 5.1) or offshore zone (>12 nautical miles, Table 5.2). This distinction is used to illustrate the close proximity of the considerable majority of submerged prehistoric sites to the contemporary shore. It also reflects the distinction of Territorial Seas, within which such archaeology falls under the curatorial responsibility of respective coastal nations. Prehistoric archaeology located more than 24 nautical miles away from the contemporary shore (an area beyond Territorial Seas, referred to as the 'Contiguous Zone'), is afforded less protection (Dromgoole 2020).

Excluding sites located inland and up rivers e.g. Rettendon, Mayland Creek and South Woodham Ferrers in Essex (Wilkinson and Murphy 1995) or inlets such as the Limfjord in Denmark (Bailey *et al.* 2020d), only two stratified Mesolithic sites/findspots are known from the North Sea: Seaton Carew off the Yorkshire Coast (Trechmann and Kennard 1936), and the Yangtze harbour in the Netherlands (Moree and Sier 2015). Figure 5.4 and Tables 5.1 and 5.2 show that the considerable majority are unstratified findspots rather than archaeological sites. This reflects the circumstances of their discovery–generally industrial aggregate dredging, shipping-lane development, or fish trawling.

Other finds, both Mesolithic and much older (Niekus *et al.* 2019), turn up in beach sediments dredged from the seabed following efforts to artificially reinforce the vulnerable coastlines of the Low Countries through programmes of beach nourishment and replenishment. Secondary locations, such as Scheveningen/Monster, and Westkappelle-Domburg (Amkreutz *et al.* 2017; Verhart 1995; Peeters and Amkreutz 2020) may provide invaluable information but are excluded from this itinerary as it is often particularly difficult to relate these finds to their original depositional context, despite the depth of their recovery – Palaeolithic and early Mesolithic material from the Monster location, for example, comes from 5-7km from the coast and a depth of somewhere between 25.9 and 26.1m (Verhart 1995: 298).

In Belgian waters, there are currently no known submerged Mesolithic sites or findspots (Pieters *et al.* 2020). A number of Palaeolithic and Neolithic finds are held within museum and private collections, and these were recovered from beach-walking, examining sediment dredges or finds brought ashore by fishing boats (Niekus *et al.* 2019; Pieters *et al.* 2018, 2020). Similar work has yielded a wealth of Mesolithic materials from the neighbouring Netherlands (Peeters and Amkreutz 2020). Such finds provide tantalizing insight both into the former inhabitants of this landscape, and the sorts of discoveries that may await future archaeological investigations (Amkreutz and Spithoven 2019; Dekker *et al.* 2020; Spithoven 2019). For the most part, however, the lack of any secure archaeological context makes it very difficult to derive meaningful inferences of behaviour rooted in time and space.

The site / findspot dichotomy

While the difference between stratified and unstratified archaeology is fairly plain, distinguishing between what constitutes a site, and what constitutes a findspot, is much less clear-cut, and may often be reduced to a matter of semantics. An isolated find would almost never be regarded as anything other than a findspot, but at what point does a collection of finds, stratified or not, become an archaeological site, or further still, a settlement site? This question may be posed ethnographically and taphonomically, theoretically and practically. More often than not in Mesolithic archaeology, a site fits a type (e.g. a shell midden, or flint scatter, etc.). Although the nature of the site may be unclear, it typically involves either a concentration of finds, or some other evidence of presence within the landscape, that if not stratified, must at least give some indication of its position in time and space. For a settlement, a particular breadth of artefacts may be expected, along with some evidence of prolonged stay at a particular location, rather than repeat visitation. These are archaeological expectations formed without even delving into the question of what the people themselves might have regarded as a settlement, or home. These problems of definition, conceptualisation and categorisation are by no means exclusive to submerged prehistory, but they are compounded by the challenges of working underwater. Working at depth is particularly challenging, as it renders *in situ* excavation more problematic than in shallower waters. This complicates any endeavour to evaluate structuration of space, or even to reasonably delimit the area of archaeological interest.

Although it has been stated in this chapter that there are two confirmed Mesolithic sites in the waters of the North Sea, the best argument in favour of either of these being interpreted as such is the stratified nature of their associated finds. With regards to the Yangtze Harbour, we may regard this as much a site (or perhaps a complex of sites) as any equivalent

Table 1	Site name/Location	Grid Ref	Type	Period	Age est.	Dating	Depth	Sources
Norway	Hummervikholmen	58.064000 , 7.742410	Grave (S)	Meso	7580-5445	C14	0-2	Nymoen & Skar (2011b)
	Paradis	58.108800 , 7.167640	CF (U)	Mid Meso	8000-5000	SLC	0-1	Nymoen & Skar (2011a)
	Kirkehavn	58.229600 , 6.530980	SF (U)	Meso	7725-7535	C14	1-2	Nymoen & Skar (2011a)
	Sandvika	58.077900 , 6.868100	CF (U)	Meso/Neo	9000-5000	T-C	0-1	n/a
Denmark	Skallingen	55.513300 , 8.219930	SF (U)	L. Meso	5400-3951	T-C	0-n/a	kulturarv.dk/fundogfortidsminder/Lokalitet/152931
	Blåvands Huk	55.557900 , 8.075260	SF (U)	E. Meso	9000-6401	T-C	0-1	kulturarv.dk/fundogfortidsminder/Lokalitet/198125
	Blåvands Huk	55.559300 , 8.073748	SF (U)	L. Meso/E. Neo	8000-4000	T-C	0.1-1	kulturarv.dk/fundogfortidsminder/Lokalitet/197850
	Blåvands Huk	55.562800 , 8.070240	SF (U)	E. Meso	9000-6401	T-C	0.1-1	kulturarv.dk/fundogfortidsminder/Lokalitet/78923
	Vejers Strand	55.612700 , 8.106940	SF (U)	E. Meso	9000-6401	T-C	0-n/a	kulturarv.dk/fundogfortidsminder/Lokalitet/117501
	Klegod	56.083600 , 8.100930	SF (U)	L. Meso	5400-3951	T-C	0-0.5	kulturarv.dk/fundogfortidsminder/Lokalitet/65043
	Vigsø	57.101400 , 8.766420	SF (U)	Meso	9000-3951	T-C	0-n/a	kulturarv.dk/fundogfortidsminder/Lokalitet/152169
Germany	Juist	53.676600 , 6.935440	CF (U)	Pal-Meso	50000-4100	T-C	0-n/a	Niedersächsische Institut für historische Kustenforschung (*in press*) no. 103
	Langeoog	53.745900 , 7.528450	SF (U)	Meso	10000-4100	T-C	0-n/a	Niedersächsische Institut für historische Kustenforschung (*in press*) no. 25
Netherlands	Eurogeul	51.990600 , 3.950030	CF (U)	Meso	8000-6000	C14	0-n/a	Mol *et al*. (2006)Van de Noort (2011)
	Maasvlakte	51.972800 , 4.002210	CF (U)	Meso	9000-6500	T-C	0-n/a	Vos *et al*. (2015)
	Yangtze harbour	51.970800 , 4.032860	Sttmt (S)	Meso	9000-6500	C14	17-22	Weerts *et al*. (2012); Vos *et al*. (2015) Moree & Sier (2015)
	Europoort	51.944900 , 4.142730	CF (U)	Meso	10000-6000	C14	0-n/a	Verhart (1987; 1989); Van de Noort (2011)
UK	unnamed	52.560200 , 2.012680	SF (U)	L. Pal/E. Meso	50000-4000	T-C	25-30	BMAPA
	Low Hauxley	55.308900 , -1.555660	Other	Meso	5330-4990	C14	0	Eadie & Waddington (2013)
	Whitburn	54.946400 , -1.353650	SF (U)	Meso	10000-4000	T-C	0	Mellars (1970)
	Seaton Carew	54.681300 , -1.196570	CF (U)	Meso	5000-4000	Strat	0-1	Trechmann & Kennard (1936); Buglass (1994)
	Seaton Carew	54.674100 , -1.193600	CF (S)	Meso	10000-4000	T-C	0-3	Trechmann & Kennard (1936); Buglass (1994)
	Trimingham	52.933700 , 1.406520	SF (U)	Meso	10000-4000	T-C	10-20	Bailey *et al.* (2020)
	unnamed	52.550000 , 2.038890	SF (U)	Meso	10000-4000	T-C	25-30	BMAPA
	Queenborough-in-Sheppey	51.444400 , 0.826235	SF (U)	Meso	10000-4000	T-C	0	Wymer & Bonsall (1977)
	Herne Bay	51.377600 , 1.152670	CF (U)	Meso	10000-4000	T-C	0	Wymer & Bonsall (1977)
	Minnis Bay	51.378900 , 1.267750	CF (U)	Meso	10000-4000	T-C	0-1	Wymer & Bonsall (1977)
	Hartlepool Bay	54.680400 , -1.198130	CF (U)	L. Meso/E. Neo	5000-3000	T-C	0-n/a	Trechmann & Kennard (1936)

Table 2	Location	Grid Ref	Type	Period	Age est.	Dating	Depth	Sources
Denmark	20 nautical miles NW of Thyborøn	56.948200 , 7.818830	SF (U)	Meso	7137-7062	C14	18-22	n/a
UK	Southern River	53.086713 , 1.421608	SF(U)	Meso	9000-8500	C14	28-31	Missiaen *et al*. (2020)
	Dogger Bank	54.568100 , 1.997240	SF (U)	Neo	4500-4000	T-C	15-30	Van de Noort (2011)
	Leman and Ower Bank	53.153400 , 1.894850	SF (U)	Pal	11900-11500	C14	n/a	Godwin & Godwin (1933)
	Viking-Bergen	60.423000 , 1.403000	SF (S)	Pal	11000-9000	Strat	140-145	Long *et al*. (1986); Bailey *et al*. (2020)
Netherlands	Dogger Bank	54.956900 , 3.389640	SF (U)	Neo	4300-3700	T-C	n/a	Van de Noort (2011)
	Brown Bank	52.517800 , 3.210420	CF (U)	Neo	4300-3700	T-C	n/a	Van de Noort (2011)
	Dogger Bank	56.105200 , 3.875390	SF (U)	Meso	7000-6400	C14	30-40	Andersen (2005)
	Dogger Bank	54.537300 , 2.939180	CF (U)	Meso	7000-6000	T-C	n/a	Van de Noort (2011)
	Brown Bank	52.575100 , 3.295190	CF (U)	Meso	9000-7000	T-C	n/a	Louwe Kooijmans (1970/1)
	Brown Bank	52.300000 , 2.500000	CF (U)	Meso	10000-6000	C14 + T-C	n/a	Louwe Kooijmans (1970/1)
	Brown Bank	52.100000 , 2.510000	CF (U)	Meso	10000-6000	C14 + T-C	n/a	Louwe Kooijmans (1970/1)
	Brown Bank	52.400000 , 3.000000	CF (U)	Meso	10000-6000	C14 + T-C	n/a	Louwe Kooijmans (1970/1)
	Brown Bank	52.300000 , 3.000000	CF (U)	Meso	10000-6000	C14 + T-C	25-40	Louwe Kooijmans (1970/1)
	Brown Bank	52.300000 , 3.030000	CF (U)	Meso	10000-6000	C14 + T-C	n/a	Louwe Kooijmans (1970/1)
	Brown Bank	52.250000 , 3.300000	CF (U)	Meso	10000-6000	C14 + T-C	n/a	Louwe Kooijmans (1970/1)
	50 miles WSW of Lijmuiden	52.189700 , 3.561370	SF (U)	Meso	10000-6000	T-C	n/a	Louwe Kooijmans (1970/1)
	Eurogeul	52.010000 , 3.510000	SF (U)	Meso	10000-6000	T-C	n/a	Mol *et al*. (2006); Amkreutz *et al*. (2018); RMO
	Eurogeul	52.000000 , 3.550000	SF (U)	Meso	10000-6000	T-C	n/a	Mol *et al*. (2006); Amkreutz *et al*. (2018); RMO

Table 5.1 Mesolithic sites and findspots from territorial waters, the nearshore zone (<12 nautical miles of the shoreline) of the North Sea basin. This table excludes submerged sites and findspots located from inland waters (rivers, inlets and estuaries) in Essex (UK) and the Limfjord (Denmark). For category Type: CF = Collection of Finds; SF = Single Find; (U) = Unstratified; (S) = Stratified. For category Dating: C14 = Radiocarbon Dating; T-C = Typo-chronology; Strat = Stratigraphically; SLC = Sea Level Curve. For Sources, BMAPA stands for British Marine Aggregate Producers Association. Age estimates are given in approximate years BC, and depth is given in metres. Some locales comprise multiple findspots, and grid references are approximate. Data primarily compiled using SplashCOS Viewer available at www.SplashCOS.maris2.nl

Table 5.2 Palaeolithic, Mesolithic and Neolithic findspots from the offshore zone beyond territorial waters (>12 nautical miles of the shoreline) of the North Sea basin. For category Type: CF = Collection of Finds; SF = Single Find; (U) = Unstratified; (S) = Stratified. For category Dating: C14 = Radiocarbon Dating; T-C = Typo-chronology; Strat = Stratigraphically. For category Sources: RMO stands for Rijksmuseum van Oudheden. Age estimates are given in approximate years BC, and depth is given in metres. Some locales comprise multiple findspots, and grid references are approximate. Data primarily compiled (excluding the Southern River find) using SplashCOS Viewer available at www.SplashCOS.maris2.nl

that may be encountered in a terrestrial context. A wealth of different finds have been recovered, with accompanying ecological data, from multiple stratified deposits in a single locale that all point to repeated stays within this part of the landscape over a long period of time. It is clear that people frequented this area at different points in time throughout part of the Mesolithic, and seemingly for the pursuit of a variety of activities (Peeters *et al.* 2015). With regards to Seaton Carew however, the Mesolithic finds from this location refer to a flint assemblage that was found stratified within a submerged forest, and which is, arguably, as much intertidal as it is submarine. The investigations at Seaton Carew were conducted in the early 20th century to the standards of the time (Trechmann and Kennard 1936), and save for the contention that they comprise

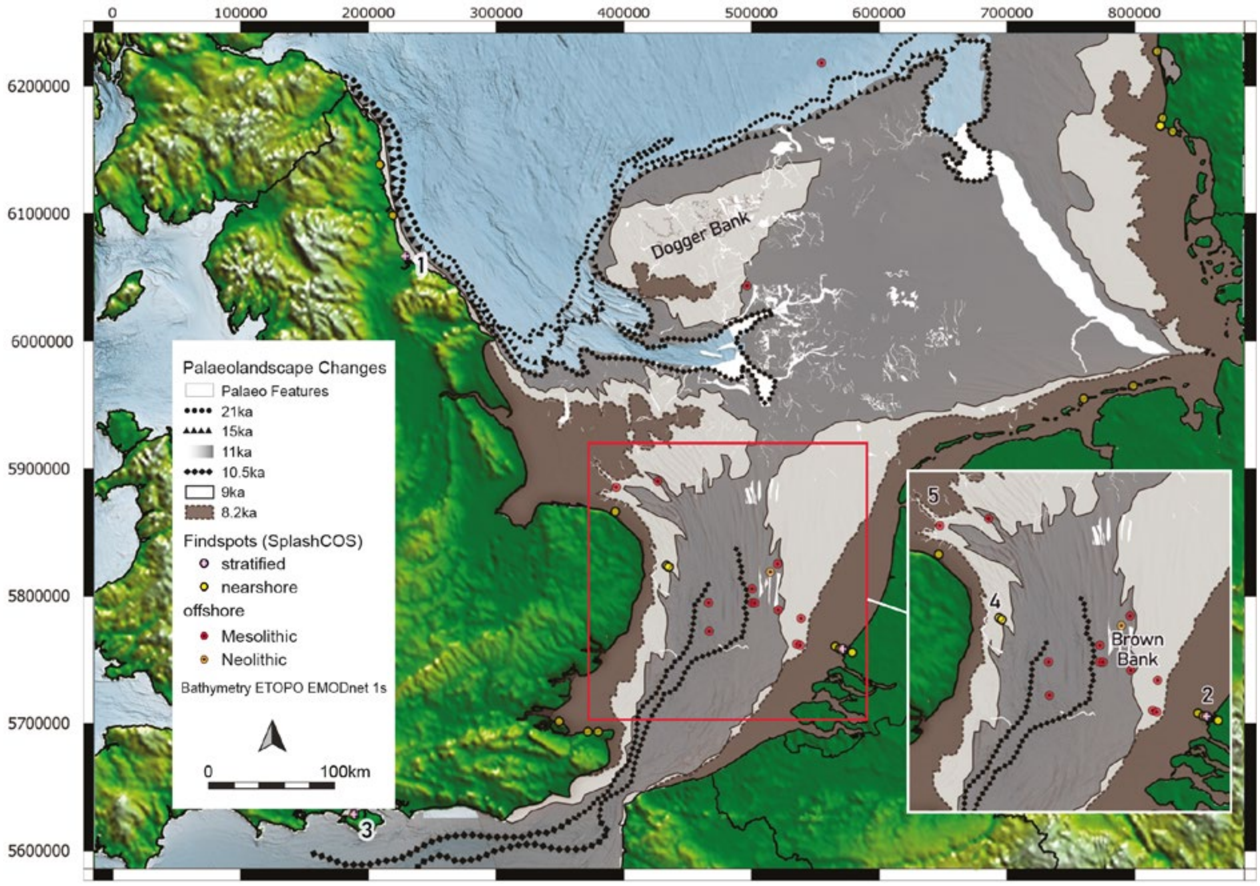


Figure 5.4 The sites and findspots located on the map are a combination of the SplashCOS viewer database, and data points presented in Tables (5.1 and 5.2), with the exception of findspots from Norwegian waters beyond the extent of the map. See this volume, chapter 16 for further information.

a stratified assemblage, are not much different from various other finds from the North Sea.

While the question of how to satisfactorily designate an archaeological site remains, it nevertheless further emphasises the paucity of finds from stratified contexts, and the nature by which most of these sites are discovered. The Yangtze Harbour site(s) were discovered through targeted exploration (Weerts *et al.* 2012), and the Seaton Carew finds were found from survey of the submerged-forest beds. Most other finds from the North Sea, which are unstratified, and therefore lacking in archaeological context, were found by chance. The circumstances of discovery may have a significant impact on the types of find that are documented (Louwe Kooijmans 1970: 35). Furthermore, this lack of archaeological context means that while they are evidence of human presence within the landscape, it is of limited interpretive value to think of these finds in terms of archaeological sites *per se* without further information regarding their original depositional context.

Southern Norwegian nearshore finds

With the exception of a pilot survey undertaken by Gaffney *et al.* (2007) and a preliminary synthesis of data conducted by Hammer *et al.* (2016), the offshore waters of Norway remain relatively understudied (Wickham-Jones 2019: 151). They are, however, likely to be of limited (if any) archaeological interest for this period, as little to none of this area would have been habitable since the end of the last Glacial (Glørstad *et al.* 2017; Roberts *et al.* 2018), in contrast to some parts of the Norwegian nearshore zone (Glørstad *et al.* 2020: Figure 6.4). Any Postglacial hunter-gatherers much further north of the Dogger Bank must have been exploiting temporarily available ice sheets (Bjerck 2019), or on the landward side of the Norwegian trench (Glørstad *et al.* 2017).

Parts of southern Norway (see Skar *et al.* 2016. Figure 14.1), like parts of Scotland, differ from other North Sea basin countries discussed here, in that glacio-isostatic readjustment has rendered the prehistoric coastline above current sea level. The relationship between up-rise of water and land is neither simple nor straightforward though, and transgressive episodes (known locally as the Tapes) have resulted in locally variable patterns of preservation (Bang-Andersen 1995; Flemming 2002). Nevertheless, the potential for underwater Mesolithic archaeology has been confirmed in areas of southern Norway where the Mesolithic coast has become submerged, with some exceptional quality discoveries among the southern islands of West Agder, including human remains from graves found at the site of Hummervikholmen (Glørstad *et al.* 2020; Nymoen and Skar 2011; Skar *et al.* 2016).

Danish nearshore finds

Denmark, arguably, boasts the most developed programme of submerged prehistoric archaeology in the world. However, with over 160 purported submerged Mesolithic settlement sites and a great many more unstratified finds (Bailey *et al.* 2020d: Table 3.2), many sites are yet to be subject to detailed archaeological investigation (or indeed confirmation) comparable to that undertaken at Tybrind Vig or Hjarnø (Andersen 2013; Astrup *et al.* 2019). The majority of these sites come from the interior waters or the Storebælt (Pedersen *et al.* 1997), with only five unstratified findspots from Denmark's Atlantic coast (Bailey *et al.* 2020d). While this area will doubtless have been exposed to different and perhaps greater destructive marine taphonomic processes than the more sheltered Limfjord or Storebælt embayments (Flemming 2004), it should nevertheless hold significant potential for future research (Jonsson *et al.* 2019).

A significant recent development has been Peter Moe Astrup's reappraisal of the evolution of the Danish coastline throughout the Mesolithic. The majority of submerged Mesolithic sites in Danish waters appear to be Ertebølle (Late Mesolithic) in date. This has left Mesolithic archaeologists in Denmark faced with the question of whether the Late Mesolithic represented a shift towards intensified exploitation of coastal resources, in contrast to earlier period sites that appear more focused towards inland landscapes, or whether this is a product of site visibility, and the coastal facet of the earlier Maglemose sites simply being missing. Astrup's results are preliminary, but suggest that there is potential to redress the imbalance of early Mesolithic sites in future survey (Astrup 2018). Certainly it is true that many areas of what would have been the North Sea basin coastline of the Early Mesolithic are now submerged, and not always close to the contemporary shore, so it is easy to imagine that this might be a biasing factor.

German nearshore finds

The only notable German North Sea Mesolithic site currently listed under the SplashCOS database is located on the southern coast of the island of Langeoog in the Wadden Sea. As with Denmark, there is a significant number of Mesolithic sites from an area that might be considered adjacent to Doggerland. These include the Bay of Wismar and the Mecklenburg waters of the Baltic (Jöns *et al.* 2020), in addition to the potential for palaeolandscape preservation in the German Bight (Hepp *et al.* 2017).

Dutch nearshore finds

The importance of the submerged Mesolithic archaeology in the Netherlands was highlighted by the work of Louwe Kooijmans (1970) in the 1960s with his analysis of various bone and antler implements recovered by fishermen from the offshore vicinity of the Brown Bank. This area, we now know, would have been in close proximity to a significant marine inlet from at least 10,500 BP (Figure 5.3) (Missiaen *et al.* 2021). Subsequent programmes of land-drainage and the dredging of marine sediments in preparation for the construction of the Rotterdam harbour have since resulted in the identification of key areas off the coast of the Netherlands. These sites, in addition to the dredged sediments redeposited to bolster the contemporary shoreline, have yielded significant quantities of Mesolithic material, including bone and antler points and harpoons (see Amkreutz and Spithoven 2019 for the most recent survey of these artefacts). Locations include the Eurogeul, from where Mesolithic human remains have been recovered, and the Maasvlakte-Europoort complex (Peeters and Amkreutz 2020). Taken in conjunction with finds recovered through pedestrian survey of replenished beaches, sites located in reclaimed landscapes or areas near to the contemporary coastline (e.g. Peeters 2006), the Mesolithic of the Dutch coast and nearshore zone presents a relative wealth of materials (see Amkreutz *et al.* 2017; Peeters and Amkreutz 2020 for synthesis). Although many of the nearshore finds were not necessarily recovered through archaeological survey, various analytical techniques have successfully been applied to these finds, including use wear (Spithoven 2019), and genetic identification, which revealed that some of the points were made from human bone (Dekker *et al.* 2020).

In his comparison of assemblages from the Brown Bank and Europoort (along with other findspot sites), Leo Verhart noticed that the assemblage diversity from Europoort appeared more reminiscent of lost hunting (and perhaps also fishing) gear than a settlement site (1995: 298). Although the sheer size of the assemblage seems surprising under this interpretation (>500 as of 1995), the lack of flint artefacts or other types of find is curious. A recent use-wear analysis of 28 small barbed bone points has been undertaken, from a cumulative assemblage of approximately 800 recovered from the sand-extraction area used to reinforce the Dutch coastline. This, potentially, supports the idea that these particular implements served as curated hunting weapon tips (Spithoven 2019). Conversely, the various finds from the Brown Bank are noteworthy for their diversity, but lack bone and antler points (Verhart 1995: 295). This is perhaps because smaller points may have slipped through the fishing nets which recovered many of these finds (Louwe Kooijmans 1970: 35). Although no settlement has yet been located, it is assumed that the variety of materials including various faunal remains (associated with evidence of dog gnawing), bone production waste, as well as some flint artefacts, may indicate the presence of one or more such sites in this area (Verhart 1995: 295).

Perhaps the most exciting development in the study of the Dutch nearshore Mesolithic, is the implementation of grab-sample excavations at the site of the Rotterdam-Yangtze harbour, which revealed a Mesolithic settlement at a depth of 20m that has yielded thousands of fragments of bone, flint artefacts and charred plant remains (Moree and Sier 2015; Peeters and Amkreutz 2020). While other Dutch nearshore Mesolithic finds may lack a comparably secure archaeological context, the work at the Yangtze Harbour, confirms the potential for the discovery of archaeologically rich Mesolithic sites within the nearshore zone (Peeters and Amkreutz 2020).

The Yangtze Harbour site

Industrial development, shore defences and land reclamation along the Dutch coast and particularly in the vicinity of the Rhine-Meuse delta has produced some of the most exciting discoveries in Dutch Stone-Age archaeology from recent decades (Louwe Kooijmans 1970; 1980; Verhart 1995; Peeters 2007; 2011). The transformation of coastal waters to facilitate the development of port infrastructure has led to the discovery of what is currently the only stratified Mesolithic site known from a submerged context in the waters of the southern North Sea. The Yangtze Harbour site was located through multi-faceted survey and prospection, drawing upon earlier research results, modern survey techniques and landscape modelling undertaken during the expansion of the Massvlakte 2 harbour expansion of the Rotterdam Port (Weerts *et al.* 2012). A 'geogenetic' approach, combining geophysics and high-density coring, was adapted to refine landscape models at a highly localised level in order to shed light on areas deemed likely to be most valuable for archaeological materials and palaeoenvironmental data (Vos *et al.* 2015). The latter allowed an understanding of the transition of the landscape as it became first coastal, and then deltaic in nature, before final inundation, providing context for the duration of archaeological occupation (Moree and Sier 2015). Following these results of this geogenetic approach, a strategy of excavation through targeted grab-sample was devised and implemented (Vos *et al.* 2015).

Over the course of the investigations at Yangtze Harbour, a wide variety of floral and faunal taxa were recorded, along with a lithic assemblage of 2976 pieces of flint, of which 114 were identified as formal tools (Niekus *et al.* 2015). The occupation history of the site is interpreted as having spanned a millennium or more, albeit discontinuously, between 10,400 and 8400 BP (Peeters *et al.* 2015: Table 7.3). Over this time, the changing relationship between the site's location and the encroaching sea level, may have impacted the nature of occupation and activity at the site, but suggest that the place within the landscape provided opportunity, if not significance, for local Mesolithic groups as the situation of the site transitioned from being relatively inland to an estuarine locale (Peeters *et al.* 2015). Although there are limitations imposed when undertaking excavation at considerable depth (17-25m), and using a grab sampler (e.g. Niekus *et al.* 2015: 151), the investigations at Yangtze Harbour, along with the excavations of middle Palaeolithic material at Area 240 (Tizzard *et al.* 2015), further confirm the potential for this kind of exploration. Despite the incredibly challenging tasks of correctly predicting the location of the site, and excavating at such a depth with archaeological control, a huge amount of information was extracted. This sets an exciting prospect for what may be possible in other submerged environments, including those further away from the contemporary coast.

United Kingdom nearshore finds

Aside from chance finds, such as the Whitburn point (Mellars 1970), and a number of sites from inland estuarine contexts in East Anglia, the number of submerged Mesolithic finds and sites from the UK is disproportionately small. The most notable sites of this period which have attracted substantial research activity in Britain include Goldcliff in the Severn Estuary (Bell 2007) and Bouldnor Cliff in the Solent (Momber *et al.* 2011), neither of which are located in the North Sea. Currently, the site at Seaton Carew, in Yorkshire, is the only stratified Mesolithic findspot known from the British nearshore of the North Sea. Other sites, like Low Hauxley, have yielded noteworthy organic finds, but originate from an eroded inter-tidal peat deposit (Waddington and Bonsall 2016).

Offshore finds

Whilst no offshore finds have been documented *in situ* (although see the Southern River find reported in Missiaen *et al.* 2021 and the final chapter of this volume), the same is true of most finds from the nearshore zone. Various stratified submerged sites do exist (e.g. Tybrind Vig, Hjarnø, Møllegabet II, Bouldnor Cliff, Goldcliff), but these are, with the exception of Yangtze harbour and Seaton Carew, located in waters adjacent to the southern North Sea, and potentially in more sheltered locales than might be afforded from much of the more exposed sea front. Despite this lack of stratified sites, studies of unstratified finds from both the offshore and nearshore have significantly aided our understanding of Doggerland, ranging in nature from isotopic studies (Groningen 2020: van der Plicht *et al.* 2016), morphological analysis (Amkreutz and Spithoven 2019) and C14 dating (Smith and Bonsall 1989).

Additionally, many of the recovered materials, including bone and antler remains and artefacts, and human remains, whether Mesolithic or older, are often made of materials that are rarely found in comparably good condition at terrestrial sites (Glimmerveen *et al.* 2004; Louwe Kooijmans 1970; Mol *et al.* 2006; Peeters 2011; Peeters and Amkreutz 2020; van der Plicht *et al.* 2016; Verhart 2004). Indeed, conditions for preservation are often so good at sea that finds of Mesolithic human bone from the Dutch sector exceeds that currently reported from the contemporary terrestrial record (Peeters *et al.* 2019; Verhart 2008).

Of particular note is the distribution of offshore findspots. Part of the fascination with Doggerland, historically, is the idea that the former prehistoric landscape centred on a relative upland area associated with the area of the current Dogger Bank. Various accounts attest to the retrieval of faunal and archaeological finds (including some of great antiquity) from, and around, the Dogger Bank. The Dogger Bank was also a primary focus for early palaeoecological investigations seeking to analyse and date moorlog (peat) deposits (Erdtmann 1925; Godwin 1943; Reid 1913; Whitehead and Goodchild 1909). However, of the currently known findspots from the offshore zone of the southern North Sea, relatively few come from the Dogger Bank vicinity, and details of many that do, remain vague and circumspect. Furthermore, it has been suggested that parts of the early Holocene Dogger Bank land surface may now be heavily overlain with sediment (Fitch *et al.* 2005), or damaged from centuries of fish trawling.

The majority of offshore finds from the southern North Sea come from the waters of the Southern Bight, around the recently posited southern marine inlet that had opened within this landscape by at least 10,500 BP. Many of these are found in Dutch waters, including the rich assemblages associated with the Brown Bank (Louwe Kooijmans 1970), with a smaller number from British waters, mostly around East Anglia (Bailey *et al.* 2020c). Although these finds are also unstratified, there is at least greater detail available for many regarding their provenance and the circumstances of their recovery.

While finds from Dutch offshore waters have taken prominence in discussions of archaeological potential in recent decades (see Missiaen *et al.* 2021) it is from the British offshore waters that two of the most historically noteworthy finds have been made, the Colinda harpoon and the Viking Bergen flint. The Colinda harpoon is a barbed antler point (and probably not a harpoon at all) that has been described varyingly as Kunda or Maglemose in its typological affinity. It dates, somewhat arbitrarily, to the Final Palaeolithic rather than Mesolithic (Bonsall and Smith 1989: Table 1; Ward *et al.* 2006). It was found somewhere between the Leman and Ower banks, some 40km off the Norfolk coast, but the exact provenance of the find is unknown. Both the retrieval of the moorlog deposit from which it was found, and the extraction itself were done without any precise note of location or stratification (Gaffney *et al.* 2009). Consequently, the Colinda harpoon find is perhaps more significant for the interest it inspired in submerged prehistoric landscapes than anything else.

The location of the discovery of the Viking-Bergen flint, retrieved from a BGS core taken in the Viking Bergen area in the 1980s, has been partly responsible for the enduring popularity of a northern territorial extent for Doggerland, and the persistence of an island far to the North (e.g. Coles 1998; Flemming 2004; Hammer *et al.* 2016: 59). This has proven a puzzling find – it has been tentatively dated, via relative sea-level curve, to between 11,000 and 9000 BP (Long *et al.* 1986), but there is little indication that there were any islands or landmasses capable of sustaining populations there at this time (Sjerup *et al.* 2016; Peacock 1995), and glacial coverage of northern waters would have melted by then, precluding the possibility of it resulting from a foray on to a temporarily available ice-sheet (Bicket and Tizzard 2015: 658). Consequently, it seems that this find must be removed from its original depositional context, and potentially, by quite some geographical if not also chronological distance.

Summary of extant Mesolithic archaeology from Doggerland

The majority of submerged Mesolithic sites known in Germany and Denmark are either inland (in the waters of the Limfjord region) or on the coastlines of the Storebælt and Wadden Sea. In Belgian waters, Mesolithic finds have yet to be found, perhaps because a faster than conventionally imagined rate of inundation may have rendered the Mesolithic shoreline closer to the contemporary coast in this area (De Clercq 2018). The most notable submerged/intertidal Mesolithic sites in the UK (Bouldnor Cliff and Goldcliff), are not on the North Sea coast, and are located within a kilometre of the modern shoreline of the Channel and Severn Estuary. Several important Mesolithic sites exist on the east coast of the UK, particularly in the northeast of

England, but are at best, like Low Hauxley, intertidal, or as at Howick, coastal rather than submerged (Waddington 2007). While there has been a wealth of material recovered from sites in Dutch waters, this relates only to a handful of locations and has been recovered largely as a result of industrial activity. Of the offshore finds, there are even fewer, with no stratified Mesolithic sites currently confirmed, but significant indicators of activity and preservation in the areas of the Brown Bank and, to a lesser extent, the Dogger Bank. While the Mesolithic archaeology of Europe's drowned landscapes has, and continues, to develop at a rapid rate, our knowledge of the Doggerland palaeolandscape as a 'living environment' remains poor (Peeters *et al.* 2020: 146). The work of the *Europe's Lost Frontiers* project is in large part directed towards overcoming the problems that have given rise to this predicament.

The need for a landscape based approach

The lack of stratified sites from Doggerland is partly due to the difficulties of prospecting for prehistoric archaeology in submerged environments. This is especially true of the offshore zone, where sites may be overlain by many metres of water and sediment overburden. Without *a priori* knowledge of the submerged landscape, looking for Mesolithic archaeology would be akin to 'finding a needle in a haystack' (Engen and Spikins 2007; Verhart 1995: 302; Weerts *et al.* 2012; see also Faught and Flemming 2008). Thus far, the majority of offshore finds have been discovered by chance (see Peeters *et al.* 2020: Table 1), and a substantial number of nearshore discoveries have been made only following intervention linked to industrial development. By reconstructing the landscape, and how it changed over time, we might begin to think more meaningfully about likely patterns of behaviour and mobility, and also consider which areas might provide conditions conducive to preservation (e.g. Fitch 2013; Ward and Larcombe 2008). Such knowledge informs future archaeological investigation, but also identifies areas we may wish to protect from development, or otherwise look to mitigate loss (Firth 2013).

In order to look for a coastal site from 9000 BP, one must first have some confidence as to where the Mesolithic coastline *was* at 9000 BP, rather than at 10,000 or 8000 BP. Furthermore, while mapping the evolution of the coastline is certainly a major issue, it is far from the only one. Any attempt at palaeolandscape or environment reconstruction, is further compounded by the dynamic nature of this landscape during and after the Mesolithic. Palaeobathymetry may provide detail regarding the current seabed, but within such a dynamic environment, deposits can be mobile and may form and vanish in relatively short time scales, particularly in front of river outlets and estuaries or large sandbanks. Large scale geophysics and seismic data offers a solution to this otherwise superficial reading of the seabed, but to date, only data collected by the energy sector are so extensive that they can feasibly cover significant areas of the historic landscape. It is through studying and supplementing these datasets, that the *Europe's Lost Frontiers* project has undertaken large scale mapping and paleoenvironmental reconstruction of the submerged Holocene landscape.

The Europe's Lost Frontiers Project

The *Europe's Lost Frontiers* project has sought to upscale the integrated seismic (3D and high-density 2D), palaeobathymetry, and marine vibrocoring surveys used to great success in the completion of the NSPP (Fitch *et al.* 2007; Gaffney *et al.* 2007). Thus far, an expanse of over 180,000 square kilometres has been included within the project survey area, making it the largest study of its kind, with over 82 core samples collected to ground truth the results and provide supporting environmental information from the sediments. Also, thanks to current resolution of sea-level change over time through improved SLIP data and contemporary models of GIA (Bradley *et al.* 2011; Shennan *et al.* 2018), it is possible, through dating sequences within these cores, to tie topographic features identified in the seismic data to particular points in time, allowing for estimates of coastline whereabouts and the general evolution of the landscape at periodic intervals.

In addition to the available seismic and bathymetric surveys, a group of specialist analytical teams have collaborated in the analysis of the core data in an effort to better our understanding of how the environment changed. While these analyses are ongoing, preliminary results suggest an unprecedented level of insight regarding the landscape and environmental history, as shown in recent discussion of the Storegga tsunami (Gaffney *et al.* 2020).

One of the early outcomes of the project is the realisation of a more nuanced model for the significant evolutionary stages of the coastline, by providing approximations at 10,000 BP, 9000 BP and 7000 BP (Figure 5.5). Over this three-thousand year period, Doggerland would have become an archipelago, as the landscape fragmented, before being reduced to a littoral fringe (Walker *et al.* 2020). Indeed, this remnant landscape of Doggerland probably survived beyond the end of the Mesolithic before finally becoming submerged. As a result of this, the *Europe's Lost Frontiers* survey has presented a starkly contrasting difference between final Pleistocene and Holocene Doggerland. The former appears to have had a relatively stable northern coastline during the late Glacial, with the most notable change being the opening up of the deep marine inlet to the southwest, extending far north of the Dover/Calais straits by 10,500 BP. By 11,000 BP,

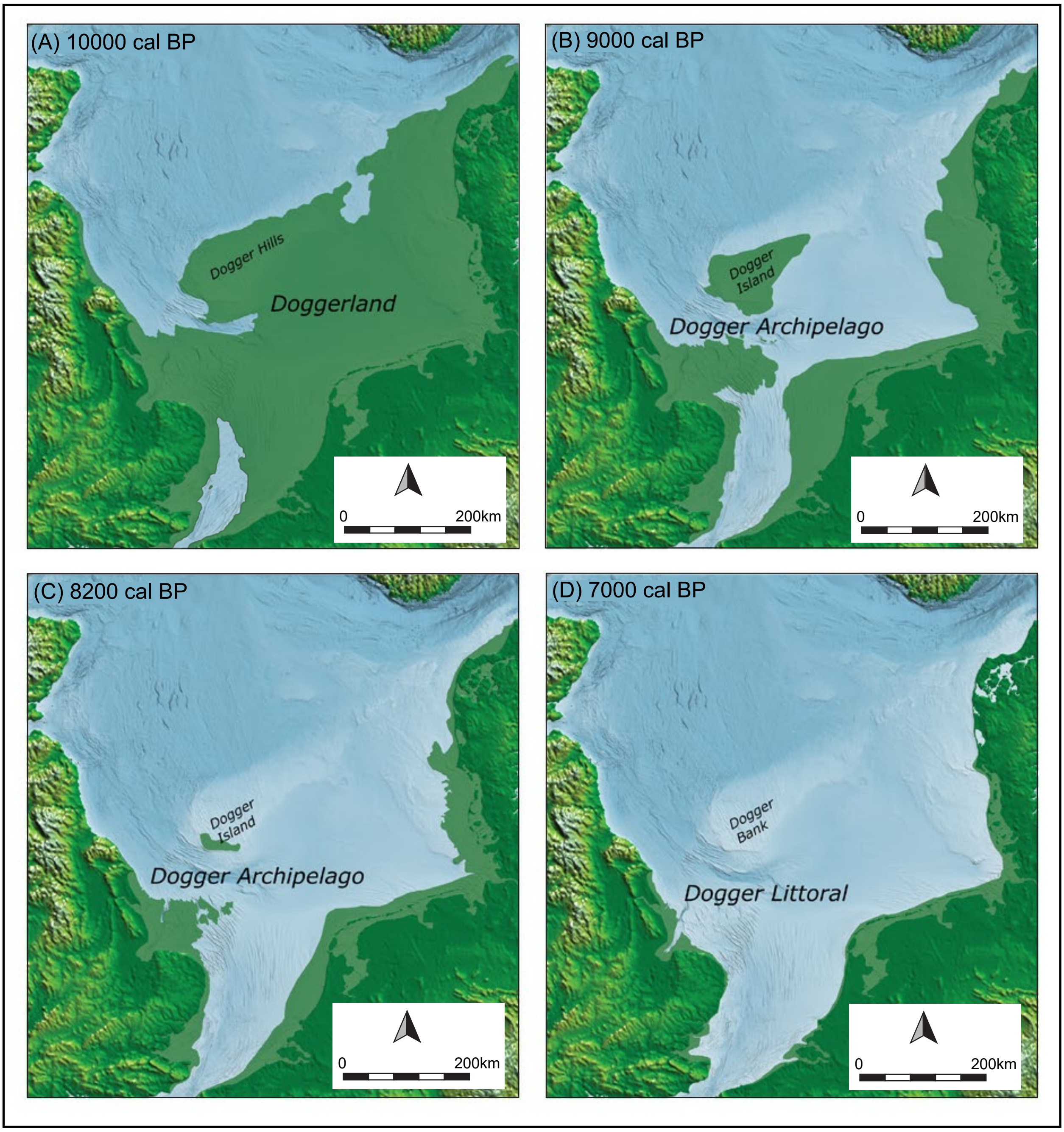


Figure 5.5 Four snapshots of landscape evolution across the period of 10,000–7000 cal BP. The period in question spans both the 8.2 ka cold event, and the Storegga tsunami, and shows different stages of Doggerland as it transitioned into an archipelago and, eventually, a littoral fringe landscape.

however, and throughout much of the Mesolithic, Doggerland underwent rapid and dynamic evolution, as the northernmost coastline began to change rapidly until around 7000 BP. The focus of *Europe's Lost Frontiers* on the reconstruction of early Holocene landforms has revealed a very different pattern of landscape evolution to that which preceded it in the Late Pleistocene.

Archaeological potential and logistical issues of working in the offshore zone

As already stated, Doggerland has not, at least since before the late Glacial, extended much into the northern North Sea. The northernmost coastline would have been relatively stable throughout much of the late Glacial (Roberts *et al.* 2018), which suggests that coastal sites from this area and time period are likely to have been highly eroded. Even prior to this new information regarding Doggerland's landward extent over the course of the late Glacial, it had been suggested that the northern North Sea would be relatively unconducive to archaeological preservation, due to effects of exposure and wave turbidity (Bailey and Flemming 2008: 8; although see Flemming 2002 for discussion of positive potential). Equally, however, it has long been suspected that the situation is rather different for the southern North Sea, where storm-wave exposure would generally have been less prolonged or extreme, and changing patterns of sedimentation might create the conditions for more favourable, albeit variable, depositional environments. It appears that what was left of Doggerland by the start of the Holocene became submerged relatively quickly. Rapid inundation during this period would help minimize extended exposure to wave action, and therefore favours archaeological preservation (Cohen *et al.* 2017). This is significant as it is the Early Mesolithic which has traditionally fared less well in considerations of coastal and submerged prehistory (Astrup 2018; Bailey 2004; 2007; Crombé and Robinson 2019). As the early Mesolithic coastlines of northwest Europe were further out at sea, future development of current research methodologies capable of implementation in these challenging environments are vital, if we are to be able to investigate these shorelines adequately. Furthermore, the prospect of undisturbed deposits with a high potential for organic preservation from the final Upper Palaeolithic would be of international significance for understanding the Postglacial recolonisation of northern latitudes, and the transition to the Mesolithic (Wenban-Smith 2002).

There are further reasons to be optimistic about the potential for the offshore zone as a resource to study the early Mesolithic and terminal Palaeolithic landscape. The attainable resolution (both spatially and temporally) typically becomes much coarser the further back in time one goes (Cohen *et al.* 2014: 22). Consequently, reconstructions of the evolution of the North Sea basin may be presented at 500-year intervals for the Holocene (e.g. Shennan *et al.* 2000; Sturt *et al.* 2013) in a way that is not feasible for such a large-scale area much further back in time. This makes the Postglacial landscapes of Doggerland a better prospect for mapping and reconstruction, rather than the Glacial or pre-Glacial landscape. The Mesolithic landscape may also be better suited to investigation than some of the inundated Neolithic landscape. The Neolithic coastline of the North Sea basin probably falls largely within the nearshore zone, where underwater excavation can be more readily conducted. However, nearshore depths of between 15 and 25m have been described by Kim Cohen and colleagues as a 'white zone' for gathering direct data on submerged landscapes, due to various difficulties associated with both coring and conducting effective seismic surveys within this depth range (Cohen *et al.* 2017: 164).

Coincidentally, the upper-limit of this depth range broadly aligns with many currently recommended safety limitations for diving work. Diving beyond these depths requires specialist equipment (Flemming 2004: 23) and predictive models that have proved effective in shallow waters around Denmark (Figure 5.6) may not necessarily provide comparable results when tested at greater depths or in the more extreme conditions faced in the North Sea (Sparvath 2012: 69-72). This has two consequences. The first is that the last ten metres of this diving range (between 15 and 25m), cannot be expected to be as effective as work conducted at other depths. This is due to the reduced extent of information available that may be brought to bear through sediment coring data or seismic based landscape reconstructions. Secondly, accessing archaeology at depths of greater than 25m, including many areas of the offshore zone, will necessarily be more expensive as specialist diving equipment, or alternative sampling and survey methods, such as use of remotely operated vehicles, dredges, or targeted grab sampling, will be required. While these areas may prove immensely valuable in terms of their archaeological potential, they nevertheless remain a challenging prospect for investigation. The various difficulties of conducting archaeological research at depth have been explored (Bailey and Flemming 2004; Flemming 2004), but as new research indicates, a detailed knowledge of where to prospect, is our best strategy for mitigating expense and logistical difficulties (Missiaen *et al.* 2021; see also Gaffney *et al.* 2007).

Working towards a landscape driven approach to Mesolithic Doggerland

Ethnographers have long pointed to the importance of landscapes in hunter-gatherer archaeology (Binford 1980; 2001; Kelly 1995; Oswalt 1973; Thomson 1939). The conscious move away from older models of economically-oriented, strictly behavioural-ecology based approaches for understanding the Mesolithic, towards arguably more experientially based approaches, has only reaffirmed the need for a landscape-based perspective (see Chapman and Lillie 2004; Conneller and Warren 2006; Dewing 2012; Gaffney *et al.* 2009; Leary 2009; 2011; 2015; Taylor 2018; Zvelebil and Moore 2006). Outside of areas that boast an unusually high density of sites, such as southern Scandinavia (Price 2015), north and west Flanders in Belgium (Crombé *et al.* 2011), or the Western Isles of Scotland (Mithen 2000), considerations of Mesolithic landscape use are sometimes troubled by the 'tyranny of the site' (Gaffney and Tingle 1984) in shaping their perceptions of landscape use (e.g. Grøn and Kuznetsov 2003; Zvelebil and Moore 2006). In Doggerland, we are currently faced with the inverse

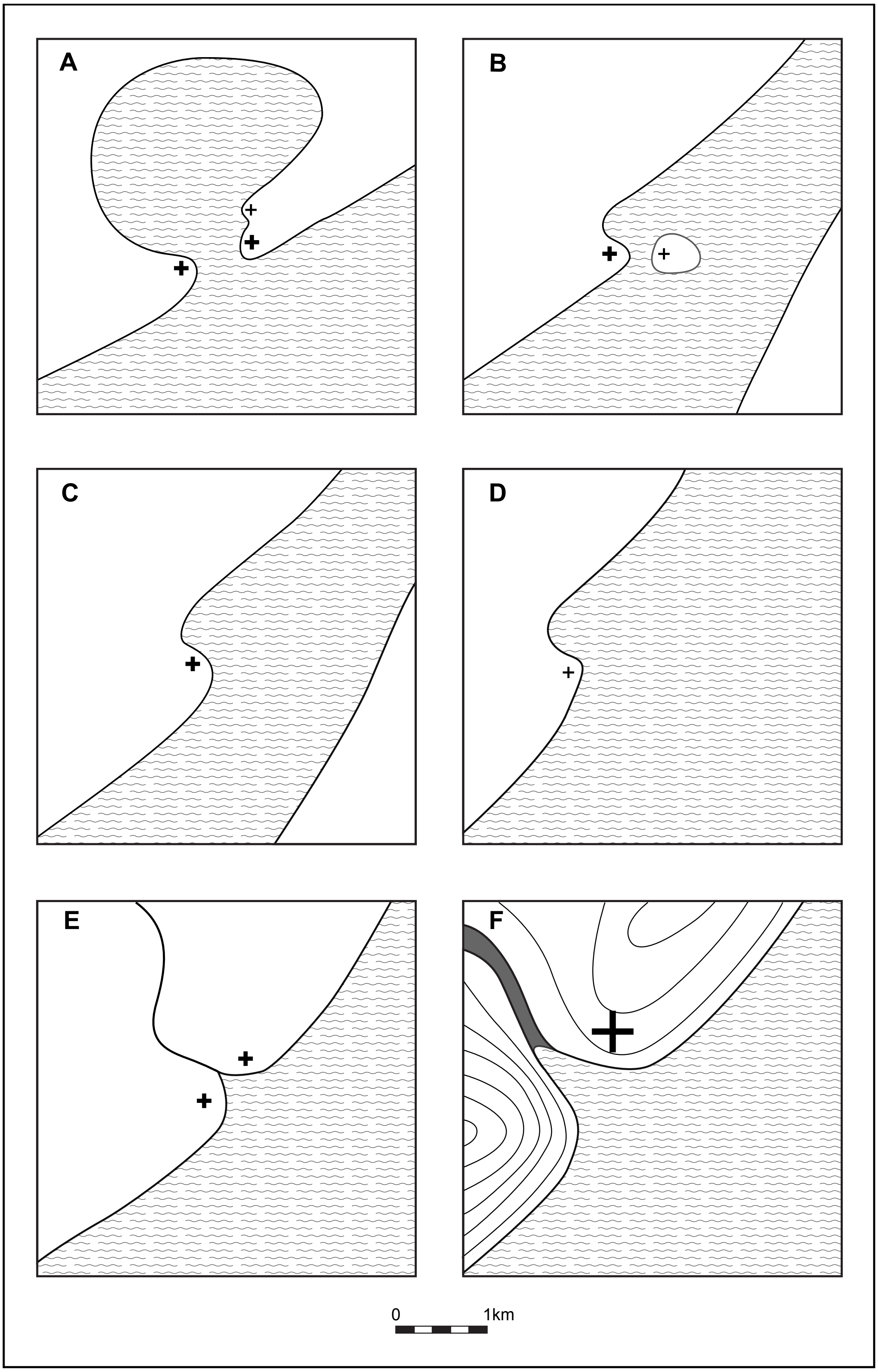


Figure 5.6 Anders Fischer's model for the predictive location of submerged Mesolithic sites has been used to great effect in the nearshore waters in and around Denmark. Image from Fischer (2007). The model shows potentially favourable site locations in different coastal landscapes: A) near an estuary mouth or inlet with access to a hinterland; B) in close proximity to islands, but with preference for landward situation; C) on headlands, with particular preference for (D) those offering access to sheltered waters; and E) at river mouths, with preference for (F) flat and even ground.

scenario. Despite the potential for stratified deposits that are characterised by good conditions for organic preservation and unimpinged by the impacts of industrialised agriculture or urbanization, such sites, with the exception of the Yangtze Harbour (and much earlier Area 240 complex), have yet to be found. Decades of extensive surveying and sampling, undertaken by numerous research and contract archaeological teams, and occasionally at an unprecedented scale thanks to private stakeholders sharing datasets, means that we have an increasingly detailed and nuanced understanding of various aspects of Doggerland's landscape, topography and environment over time. In contrast, however, our knowledge of the Mesolithic archaeology remains extremely limited in these same areas. Hopefully, the integration and comparison of terrestrial site-based data, with the increasingly rich landscape data available from the southern North Sea, will result in a more even understanding of patterns of land-use over time.

Areas of the nearshore zone in Danish waters hint at the profitability of developing such an approach for the offshore zone. The landscape-oriented 'fishing-site' model developed by Anders Fischer (Figure 5.6), resulted in the discovery of anywhere between 13 and 21 (out of a predicted 26) 'Stone-Age habitation sites' when applied to Småland Bight (Smålandsfarvandet, the water between Zealand, Lolland and Falster) (Fischer 1993; 2007; 2004: 31). Such models have yet to be implemented to any significant extent outside of Denmark (e.g. Benjamin 2010; Engen and Spikins 2007; Fitch 2013; Hall 2014), and due to differences in bathymetric development, the offshore zone cannot be interpreted in the way that the sheltered waters of the immediate nearshore around the Storebælt can. However, with the results of the *Europe's Lost Frontiers* project, we may be able to adapt such a model for the prospection of the offshore zone.

Relict tunnel valleys, in addition to fenlands, flood plains and glaciolacustrine environments, were potentially both attractive settings for hunter-gatherers, and areas we may anticipate as being conducive to good archaeological preservation (Flemming 2002; Fitch *et al.* 2007; Ward and Larcombe 2008: Table 1). Such may be the case around the Outer Silver Pit, which was a large lake to the south and southwest of the Dogger Bank (Fitch 2011) prior to its transition into an estuary. These areas hold great potential because they represent places within the landscape that endured for some considerable time – landscape stability in these specific areas may indicate reduced exposure to high-velocity erosive processes, and allow incipient peat formation, which in turn helps protect deposits from the effects of superficial marine reworking. These low-velocity depositional environments, that were ultimately transgressed at a relatively rapid rate, may also coincide with areas which also contain high-quality archaeological deposits (Cohen *et al.* 2017: 173). By contrast, an exposed coastline, even if relatively stable, may be repeatedly exposed to storm surges to the extent that preservation conditions remain relatively poor.

While a landscape approach is a logistical necessity for investigating the Mesolithic of Doggerland, the potential of the landscape itself for large-scale preservation, at least in some areas, is unique. This resource will become increasingly important as the exceptional preservation at key terrestrial sites that have traditionally dominated our understanding of the Mesolithic begin to face diminishing returns. While we cannot expect an even spread of preservation quality across the landscape (Fitch *et al.* 2007; Ward and Larcombe 2008), areas that have so far escaped dredging and development may yield large area land-surfaces that present unique opportunities for study as technologies change and archaeological methodologies are refined, and may constitute an important future opportunity for the development of Mesolithic archaeology (Grøn 2006).

Life in Mesolithic Doggerland

Of particular interest in recent years has been the growing interest in how Mesolithic people perceived and experienced environmental change within the landscape (Moore 2003), including sea-level rise and loss of land (Chapman and Lillie 2004; Leary 2009; 2011; 2015). While it is difficult to second-guess what the actual views and feelings of the inhabitants of Doggerland may have been, there are indications that in some areas, there may have been periods where the sea level rose by as much as 2m in a few centuries (Hijma and Cohen 2019), presumably having a profound effect on local populations in low-lying areas. Events such as pronounced storm surges, or indeed the Storegga tsunami, must doubtless have been the source of stories for generations. Yet, it has been inferred that, while sea-level rise around the coasts of Mesolithic Denmark would have been noticeable and transformative, there is little evidence to suggest that it prompted any sort of explicit adaptive response among the native population (Astrup 2018) – although a different scenario has been proposed for the British Isles (Waddington 2015). Currently, such responses are difficult to evince given the small number of high-quality sites available.

While it is too premature to attempt an artefact or site-based characterisation of Mesolithic Doggerland, we can at least theorise as to life within the landscape through analogy with the extant terrestrial archaeological record (e.g. Bell *et al.* 2013: 43; Chapman and Lillie 2004) and more generally about the significance of Doggerland in Postglacial Europe. Waterways have long been recognised as influential features of hunter-gatherer settlement patterns, and Doggerland likely had a profusion of dendritic streams, rivers, channels, estuarine and marsh tributaries that evolved in size and direction over time as the landscape transformed (Figure 5.7). These may have acted as major routeways, connecting inland areas and peripheral hinterlands to more resource-rich ecosystems, focused around lakes, estuaries and coasts. In this sense, river-valleys may have facilitated the means to connect places within the landscape, offering paths of least resistance and navigational reference through wooded environs (Tolan-Smith 2003). Evidence for Mesolithic boats and fishing is variable across northwest Europe. Interestingly, whilst there is a wealth of compelling evidence for the latter of these activities in Denmark (Andersen 2013; Enghoff 1995, Pedersen 1995; Smart 2003), there has been, artefactually, curiously little evidence for such activities from the United Kingdom. However, recent discoveries at the submerged site of Bouldnor Cliff (Momber *et al.* 2021), and at Star Carr (Taylor *et al.* 2018), hint at evidence of Mesolithic boats, and equally, evidence of fishing structures may be present, but simply yet to be found (see Hall 2014 for discussion).

Increasingly, it seems unreasonable to maintain that waterways were inherently barriers to Mesolithic peoples. Over time, as Doggerland became a series of archipelagic islands and tidal flats, these may have

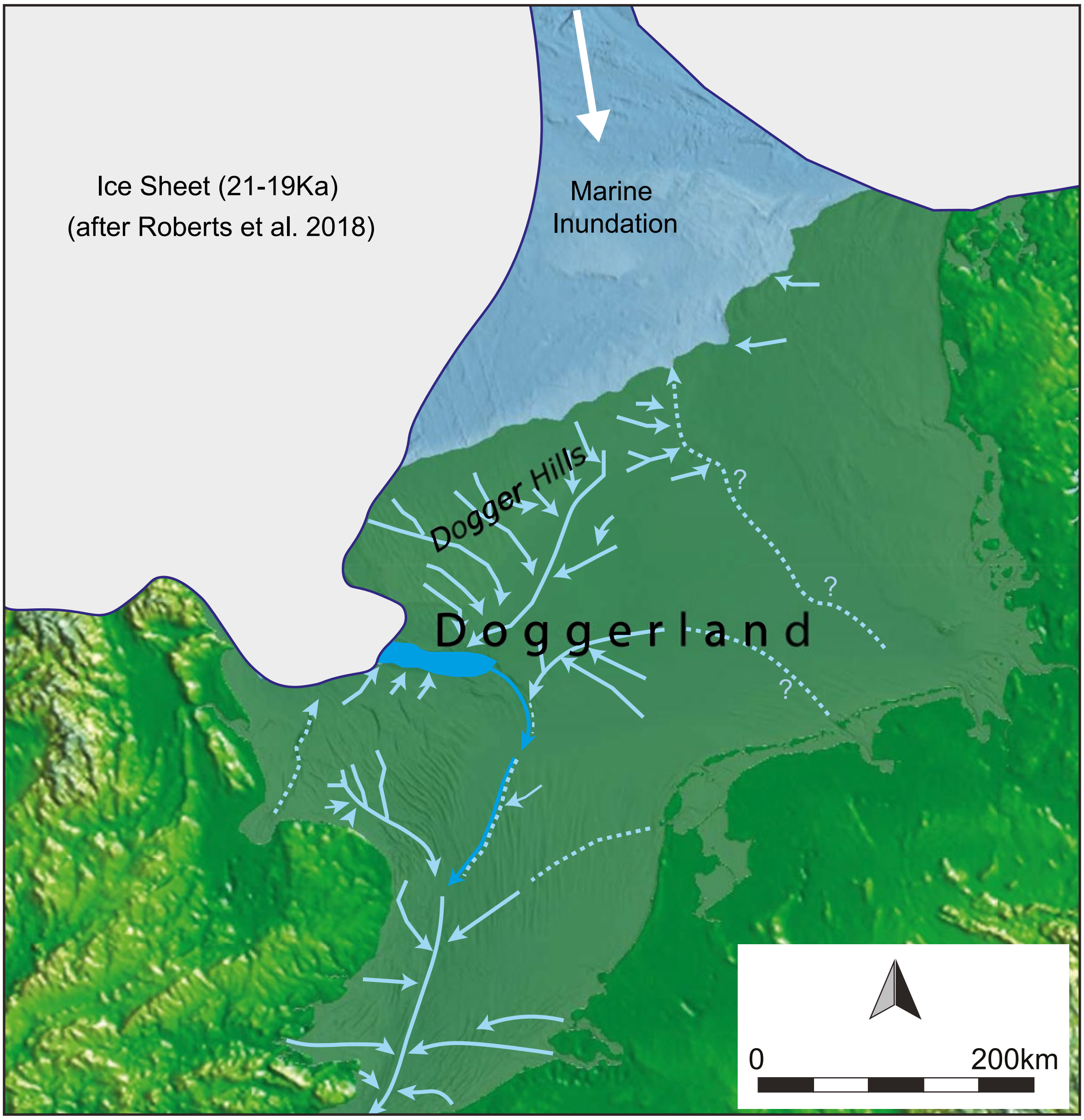


Figure 5.7 River Valleys active in the Mesolithic, identified through seismic survey and palaeobathymetry, and marked by blue arrows.

provided a landscape/seascape that was just as accessible for Mesolithic as Neolithic peoples. Waterways may have been more than just arterial transport routes. They may also have served as physical referents of cultural territories. Such divisions have been inferred in studies of stylistic spatial variability among Mesolithic lithic and osseous toolkits from lowland Europe (see Gendel 1987; and Perdaen *et al.* 2008), although Bell *et al.* (2013) caution against assuming territorial divisions between the Irish mainland and the UK despite divergent material typologies. With the prospect of stratified assemblages including lithic and organic materials, it may be possible to infer changes in territoriality over time as Phillipe Crombé has done in the Rhine-Meuse-Scheldt basin (2019).

The rapidly changing coastlines of Doggerland throughout the Holocene mean that the relative context of sites occupied (or repeatedly visited) over extended periods, and by multiple generations, would have changed. This may conceivably have impacted how people considered these places within their broader landscape, and affected the kinds of activities undertaken at sites. The changing proximity of the coastline has been noted for coastal (e.g. Bicket *et al*. 2017; Waddington and Bonsall 2016), and nearshore sites (Peeters *et al*. 2015). This has also been suggested in interpretation of changing trends in isotopic based dietary reconstructions, which presently indicate a predominantly freshwater (and terrestrial) resource focus giving way to increased marine exploitation over time, however this interpretation is limited by the context of the finds available for analysis (van der Plicht *et al*. 2016: 116-117).

With regards to the loss, or rather, diminishment and fragmentation of Doggerland, Clive Waddington has suggested that the appearance of long, or narrow-blade microliths and small scalene triangles in the northeast of England, contrasts with the contemporary European Late Mesolithic, and may reflect disruption of cultural connections (Waddington 2007; 2015; Waddington *et al.* 2017), although this interpretation has been contested (Conneller *et al.* 2016). Similarly, Torben Ballin, has remarked that the removal of raw material provisions as a result of the submergence of Doggerland may have had a knock-on effect within community networks, particularly in the west (2017). Ultimately, further work is needed to clarify the timing, nature and extent of the impact that the loss of Doggerland had on Mesolithic communities. This is particularly important given that Britain now appears to have become separated from mainland Europe earlier (*c*. 9500 BP) than has traditionally been posited in recent years. Nevertheless, these remain intriguing propositions, and the impact (or lack thereof) of the fragmentation of Doggerland on extended cultural and social networks is an issue that can only be truly addressed with a better approximation of the submerged prehistoric record.

Perhaps Doggerland provides the opportunity to locate further evidence of artefacts and sites that attest to unique or rarely represented lifestyles, including the otherwise lacking, coastal/marine element of early Mesolithic societies in much of northwest Europe (Bailey 2004). Nearshore investigations have predominantly returned evidence of later Mesolithic sites (Crombé and Robinson 2019). However, recent research by Peter Moe Astrup suggests that the Maglemosian in Denmark may have been less interior-centric than is often presumed (2018). Nevertheless, he cautions against assuming that all early Mesolithic societies would have exploited the coast in the same way (Astrup 2020: 26), and his research area was not focused on the Atlantic coast of Denmark. On the basis of current evidence, while Doggerland may indeed have been an extension of the broad continuum of Mesolithic hunter-gatherers across northwest Europe, the nature of the archaeology may differ significantly from that which we are accustomed to finding in terrestrial contexts. At the moment, such differences are based on extremely limited evidence and likely biased by the lack of dedicated and targeted archaeological investigation. Doggerland has yielded a significant number of organic artefacts relative to the number of stone tools that have been recovered, something which noticeably contrasts with the situation in terrestrial Mesolithic archaeology, but probably reflects the circumstances under which most finds have been recovered.

A connected and connective place

While we have sought to stress the importance of considering Doggerland within a broader continental context, this chapter has largely retained a narrowly focused discussion with regards to archaeological finds and sites. Nevertheless, it would be remiss to discuss the significance of Doggerland without reflecting on what its transformation and reduction might have meant for the rest of Mesolithic Europe.

Doggerland has long been regarded as a land-bridge, important for what it connected rather than as an area of settlement, significant in its own right (Murphy 2007). Although this perspective has changed since the 1990s, the practical necessity for regional if not national frameworks (Peeters *et al.* 2020), and concentration of known and accessible archaeological evidence in the nearshore zone relative to the offshore area (Figure 5.4), has, inevitably, influenced traditional narratives. To date, there has been a paucity of evidence from the Final Palaeolithic recovered from the North Sea (Peeters and Momber 2014), although this situation is beginning to change (Amkreutz *et al.* 2018; Momber and Peeters 2017). As a resource-rich and dynamic landscape, Doggerland may have been a driving attraction in the recolonisation of northern latitudes in the late Glacial Interstadial. Indeed, it may have been the preeminent landscape within northwest Europe (Clark 1936: 22-23; Fagan 2013; Gaffney *et al.* 2017: 306). However, others have expressed scepticism regarding the attractiveness of this environment, at least initially, for late Pleistocene hunter-gatherers (Mithen *et al.* 2015: 397; Riede 2015: 560). Certainly, the late Glacial encompassed a higher degree of climatic fluctuation, and changes in population dynamics are reflected in the terrestrial archaeology of this time (Pettitt and White 2012; Riede 2015). Doggerland would probably have been a landscape in flux too, and not necessarily viable for year-round habitation. The now-submerged coastal plains may, at some points, have played an important role in plugging the autumnal gap within the terrestrial record of late Palaeolithic reindeer hunters (Price 2015: 39).

The revelation that Doggerland never extended much further north than the northernmost extent of the Dogger Bank (Roberts *et al.* 2018), further rules out theories of its direct implication in the colonization of the deglaciated Norwegian coastline after 14,000 years ago (see Glørstad *et al.* 2017 for discussion). With the additional evidence that the Channel estuary may have reached much further north (by 10,500 BP), the land connection between the UK and mainland Europe, may have been narrower than previously thought. Consequently, we must now consider Doggerland both as a central place in its own right, but also important for the connection between east Yorkshire, Lincolnshire, and north Norfolk in the UK with Denmark, the Netherlands, and the rest of Europe.

The recent discovery of Mesolithic boating technology from British sites, including at Star Carr and Bouldnor Cliff (Momber *et al.* 2021, Taylor *et al.* 2018), demonstrates that various hunter-fisher-gatherer groups across this part of Europe must have been competent water-farers. There is little reason to believe that this would have been a uniquely Mesolithic phenomenon. Certainly, the reindeer hunters of central northern Europe, are also believed to have commonly taken their quarry while on water (Fletcher 2015). Part of the significance of the discovery of such technology in British contexts, is that it removes beyond doubt the idea that the loss of Doggerland, and eventual separation of Britain from Europe, was an exclusively isolating experience. The presence of potentially early exotics and Neolithic woodworking 'techniques' at Bouldnor during the Mesolithic (Momber *et al.* 2021), further suggests an element of connectivity with mainland Europe at a time when separating waterways were becoming increasingly significant. Despite this, it is important to consider that Doggerland was only connected to Europe via a relatively narrow land-bridge by the start of the Mesolithic, and even this had disappeared by 9500 BP. The implications of an early breach with Europe for native late Pleistocene populations (floral and faunal as well as human), and of a landward focus of connection and interaction for species, artefacts, ideas and ultimately people, is the subject of consideration in forthcoming project publications.

Broader archaeological context

Northwest Europe and southern Scandinavia were first recolonised during the late Glacial period by late Palaeolithic reindeer hunters. The cultural chronology of this period is the subject of considerable debate, specifically the significance of the groupings (e.g. Hamburgian, Ahrensburgian, Federmesser, Bromme) which are based primarily on differences in flint projectile points (Pettitt and White 2012; Price 2015). It has been suggested that these different groupings might reflect different colonisation, and repopulation pulses in response to fluctuating climate, ecological disequilibrium (Riede 2014; Riede and Pedersen 2018), and potential environmental disaster events such as the Laacher See eruption at *c.* 13,000 BP (Riede 2008). Apparent hiatuses in occupation have also been posited from the discontinuous record of late Glacial archaeology in the British Isles (Pettitt and White 2012). The discovery of a final Palaeolithic materials from Scotland demonstrates that people reached northerly latitudes, in some areas at least, much earlier than was previously thought (Ballin *et al.* 2018; Mithen *et al.* 2015). Consequently, it has been reasoned that the southern North Sea may have been an important landscape during the periods of the late Glacial when these latitudes were inhabited. Certainly, whilst the evidence of final Palaeolithic archaeology from Doggerland remains limited, it has grown in recent years (Amkreutz *et al.* 2018; Momber and Peeters 2017; Peeters and Momber 2014). It is possible that the submerged coastlines of the southern North Sea may have played an important role in the seasonal round of late Palaeolithic reindeer hunters (Price 2015).

The beginning of the Mesolithic is effectively synchronous with the beginning of the Holocene, following the end of the Younger Dryas. In terms of human populations, it is not clear to what extent the early Mesolithic archaeological record of different regions of northwest Europe represents continuity or repopulation (e.g. Conneller and Higham 2015; Conneller *et al.* 2016). Perhaps the most notable shift in this period is the decline of subarctic fauna (and notably Rangifer) and emerging temperate ecologies along with their respective vegetation and faunal communities. The Holocene also contrasts with the Final Pleistocene as a period of *relative* (although non-unilinear) climatic stability and warmth (see Figure 5.2). The classic Mesolithic prey species of northwest Europe are often characterised as Red Deer (*Cervus elaphus*), Roe Deer (*Capreolus capreolus*) and wild boar (*Sus scrofa),* with aurochs *(Bos primigenius)* and elk (*Alces alces*) featuring less commonly over time (Aaris-Sorensen 2009). While these species are often discussed as the primary indicators of environment and economy (if not also taphonomic survival), the exceptional preservation of organic remains at some key Mesolithic sites (including shell middens) has shown that a much broader variety of fauna were exploited for food and other purposes (e.g. Blankholm 2008: 117).

Broadly speaking, the Mesolithic of the southern North Sea basin has been characterised by a transition from immediate return to delayed return societies (*sensu* Woodburn) from upwardly mobile hunter-gatherers towards reduced mobility and sedentism. These are associated with accompanying increases in territoriality, specialised food exploitation (including of marine and coastal resources), and changes in kin-structure (Rowley-Conwy 1998; Price 1985; Smith 2008; Tolan-Smith 1992), and perhaps best exemplified by the Ertebølle in southern Scandinavia. This generalised development was neither universal, (see, for example, the case described in the southern Netherlands by Verhart (2008)) nor something that happened without stimulus or the invocation of driving mechanisms or catalysts. To assume otherwise would be to entertain a problematically progressivist epistemology (Rowley-Conwy 2002; Rowley-Conwy and Layton 2013). Finds such as the Antrea fish net from Lake Karelia in Finland, for example, hint at a greater propensity for both complex food-getting technology and delayed return subsistence practices than is typically accredited to early Mesolithic cultures (Bērziņš 2020: 106; Carpelan 2008). Doggerland holds significant potential for learning more about the Early Mesolithic prior to submergence, and is potentially a route towards better understanding the patterns of change associated with Mesolithic technocomplexes around the margins of the southern North Sea basin.

Recent research endeavours have framed some of these regional level changes in hunter-gatherer cultures as responses to sea-level rise and short-term climate events. However, it is possible that some of these apparent trends are regionally variable, or products of differential data visibility. It is perhaps no surprise that the diminution of Doggerland, and severance of the British Isles from mainland Europe early in the Holocene, may have been a major factor (albeit one of many) in the emergent social changes within the terrestrial record of hunter-gatherers around the southern North Sea basin across the Mesolithic (see for example Waddington 2015). However, it is not yet apparent that the relationship between sea-level rise, and archaeologically unclear environmental changes, can be related to these developments either simplistically or unilaterally. It is easy to imagine that the reduced area of land and relative increase of coastline, and presumably, accompanying resources, might have played an important role in the cultural evolution of Mesolithic groups in Denmark, the British Isles and the coasts of northwest Europe, along with the arrival of the first Neolithic farmers on the loess plains of northwest Europe (Coles 1999; Walker *et al.* 2020). Doggerland remains such a gap in our knowledge of prehistory in northwest Europe, that the potential for filling the geographical hole to a greater extent than has yet been possible, remains a hugely enticing prospect (Coles 2000; Fitch 2011).

As our knowledge of the European Mesolithic has grown in recent decades, regional bodies of knowledge have developed extensively, and offer the potential for multiple views and contentions regarding the cultural history of hunter-gatherers in northwest Europe between approximately 15,000 and 5000 years ago. This is evident through a number of collected papers (Bailey and Spikins 2008; Crombé *et al.* 2009; McCartan *et al.* 2009; Schülke 2020; Waddington and Pedersen 2007). These include volumes dedicated to submerged prehistory (Bailey *et al.* 2020; 2017; Benjamin *et al.* 2012). The offshore reaches of Doggerland remain, however, *terra incognita.*

Environmental change, tsunamis and submergence

As our understanding of landscape change throughout the Early Holocene has improved, it has become increasingly clear that the submergence of Doggerland was neither gradual, uniform, nor linear. At times, the disappearance of land may have occurred at an alarming pace, while at others it may have been relatively imperceptible, or even temporarily halted. The loss of land was not the only issue – with encroaching sea levels, comes potentially significant environmental change. The opening of a large lacustrine area such as the Outer Silver Pit could have had a significant impact on the surrounding communities for whom the lake would most likely have been a resource-rich and attractive hub. The salination of these waters and their surrounding soils, along with the reconfiguration of their tributaries, could have brought about drastic impacts on the local ecology.

The Younger Dryas and late Pleistocene

The archaeological evidence for the occupation of Doggerland during the Final Pleistocene has so far been even less forthcoming than that for the Mesolithic (Amkreutz *et al.* 2018; Peeters and Momber 2014). It has, however, been clear for some time that at various points following the late Glacial Maximum and throughout the Final Palaeolithic, it must have been at least visited, traversed and inhabited. It is possible that the relative lack of archaeological finds from the Final Palaeolithic is because, like the coasts of the Early Mesolithic, the late Glacial shorelines are, in many areas, now located out at sea. This has been apparent for some time from the presence of various lithic pieces that bear affinity to types commonly associated with the various final Palaeolithic cultural groups of central northern Europe (Pettitt and White 2012; Smith 1992). It seems untenable to maintain that Doggerland might have been uninhabited prior to the Holocene, and as evidence continues to mount, it seems as though it may also have been an attractive place at times throughout the late Glacial (Price 2015; Momber and Peeters 2017).

The end of the Pleistocene (between 12,900 and 11,700 BP) was punctuated by a particularly cold period, known as the Younger Dryas (Figure 5.2). This was the last major climatic downturn of the late Glacial, and saw temperatures become bitterly cold prior to the prevailing trend of climatic amelioration experienced throughout the climatic optimum of the Holocene. The Younger Dryas may have provided a short, sharp shock in terms of the temperatures, but it was, at least by glacial standards, relatively short-lived, spanning just over a thousand years. Gauging the impact of this event has proven difficult – for example, although much of the Norwegian coastline had deglaciated prior to the Younger Dryas (Bang-Andersen 1995), it was not until well into the Preboreal that the earliest Mesolithic sites are found (Glørstadt *et al.* 2017: 297). It is not clear that this lag in colonisation was a direct result of the Younger Dryas, but it is reasonable to imagine that it may have had some impact. By contrast, however, although conditions may have returned to being more tundra-like during this period, the earliest Hamburgian settlers of Scotland appear to have weathered the inclement conditions (Ballin 2018).

It has been suggested that Doggerland might have facilitated the movement of Ahrensburgian groups into Scotland (Mithen *et al.* 2015), but as the central southern North Sea landmass did not extend that far north, this can only have been possible for part of the journey. If such a migration did occur, and did not make use of the rest of the British Isles, then it must have relied on areas now lost through deglaciation, or perhaps the now submerged coastal strip that spanned from the northeast of England up to the east coast of Scotland.

Although environmental analyses from the *Europe's Lost Frontiers* project are, at the time of writing, concluding, preliminary results from investigations into multiple environmental proxy data from sediment cores in the Southern River valley, north of the Norfolk coast, have yielded surprising findings. Pollen and icthyological remains from sediments dating to the Younger Dryas in Core ELF33 indicate relatively thermophilic taxa for this period. At present, the results are preliminary, the source data limited, and the potential implication of taphonomic factors cannot yet be ruled out. It would be premature to conclude that these findings indicate some sort of a refugium, even at a highly localised resolution, but it nevertheless presents an interesting possibility. Future research may establish just how severely the Younger Dryas was felt, and whether it is possible that some areas of Doggerland remained relatively clement at a time when much of the rest of northern Europe was, for around more than a thousand years, returning to tundra-like conditions. It is at the very least worth noting that the location of the core sample in question is not far from where the uniserial Colinda Harpoon was found. Implements of this type are sometimes associated with lakeside fishing and wooded environments. Dated to 11,740±150 BP (Bonsall and Smith 1989), this is at the very end of the Younger Dryas. The possibility of the North Sea offering some relative respite during this climatic downturn is an interesting prospect for future research, and might suggest that similar conditions occurred during earlier, late Glacial, cold periods (Price 2015).

The Baltic Sea

Both Childe (1931) and Clark (1936a) recognised the importance of the Baltic in their consideration of submerged landscapes of Postglacial Europe, regarding it as a continuum of a broader Boreal population of northwest Europe. In addition to the terrestrial Mesolithic of the Baltic region (see Zvelebil 2008 for summary), the shorelines of this area offer immense potential for submerged prehistory due to fluctuations in sea level and salinity since the retreat of the ice sheet around 13,000 years ago and following the end of MIS2 (e.g. Hansson *et al.* 2018; Homlund *et al.* 2017; Jöns 2011; Jöns *et al.* 2020; Muru *et al.* 2017; Nilsson *et al.* 2018). Between 16,000 and 7500 BP, the Baltic Sea evolved through five marine phases (Rosentau *et al.* 2021). The change in sea level and salinity associated with these changes, must have had an impact on the coastal communities of the Baltic during this time, but also may have had a knock-on effect for the submergence and, perhaps population dynamics, of Doggerland. The magnitude of these fluctuations, as well as the means and locations where water drained and re-entered into the Baltic, remain issues of ongoing debate, but it is probable that the Kattegat was a main route of waterflow (among others) into the North Sea (Rosentau *et al.* 2021). Expulsions of water associated with the formation of the Yoldia (*c.* 11,600 BP) and Littorina Sea (7500 BP) stages may have had ramifications for changing eco- and hydrodynamics of the coastlines and nearshore waters of the southern North Sea coastline, although relating the sea-history of these areas remains difficult (Behre 2007: 96), and connections are only apparent from after 8500 BP (Rosentau *et al.* 2021: 8).

The 8.2 ka BP event: cold, and rising waters

The southern North Sea appears to have transgressed relatively late, at least from its northern shore, allowing boreal-to-temperate forest cover to develop in many places before a rapid and high rise in sea level, 'Drowns last, sinks fast' as Kim Cohen and colleagues describe it (Cohen *et al.* 2017: 161). In terms of inundation, this means that the Early Holocene saw the most dramatic changes in sea-level rise and loss of land. Perhaps the two single biggest environmental events in Doggerland's Holocene history, however, are the 8.2 ka 'cold snap' event and the Storegga tsunami. The effects of the 8.2 ka event were seemingly felt across many northern latitudes, but its human impact remains the subject of much debate. The 8.2 ka event appears to have been the most significant of a series of periodic cooling phases, such as the 9300 BP event (Yu *et al.* 2010). It struck during the climatic optimum and was, seemingly, not nearly as severe or as long as the Younger Dryas cold snap that marked the end of the Pleistocene. Such relative statements should not, however, be relied upon for gauging human impact.

Attempts to correlate adaptive responses through changes in technology, settlement pattern or some other aspect of behavioural ecology, have generally been met with mixed success. Perhaps it is overly simplistic to expect such a dramatic response to what might have been a relatively small drop in temperature (e.g. Breivik *et al.* 2018; Manninen 2014). Alternative means of gauging the effect of the event upon Mesolithic populations have sought to invoke palaeodemography (e.g. Mithen and Wicks 2021; Waddington and Wicks 2017; Wicks and Mithen 2014). However, consensus is lacking, with larger-scale regional overviews suggesting a relatively muted impact (Griffiths and Robinson 2018), and there is considerable divergence of opinion as to the associated causes of such change. Different authors cite societal instability in the wake of pronounced climatic changes and natural hazards, broader responses to rising sea levels, or something else altogether (Astrup 2018; Crombé 2019; 2017; Crombé *et al.* 2011; Maldegem *et al.* 2021; Mithen *et al.* 2020). At present, it is not entirely clear just how cold the 8.2 ka cold snap really was, or indeed how its severity might have varied regionally, including across the North Sea. Consequently, it is difficult to guess what the adaptive response (assuming there was one) of the Mesolithic people who lived through it might have been. At present, our best line of enquiry, perhaps, is to focus on regionally localised investigations (e.g. Astrup 2018; Fossum 2020; Maldegem *et al.* 2021) and avoid presupposing a one-size-fits all interpretation. One corollary of the 8.2 ka event that we can be more certain of, however, is the rise in sea level with which it is associated must have had an impact on the remnant Doggerland landscape that remained extant at this time.

The cooling episode at this time was the result of a significant meltwater-pulse: the release of waters contained in Lake Agassiz and Lake Ojibway, linked to the final collapse of the Laurentide ice sheet (Lewis *et al.* 2012). A spike in the rise of sea levels by potentially as much as 4m has been recorded in association with this event from the Meuse-Scheldt basin (Hijma and Cohen 2019). Even if this did not happen instantaneously, it must have happened within a timeframe of around 200 years, meaning it was nevertheless a significant rise in sea level, and one that seemingly must have had a visible impact for the coastal communities of Doggerland. A rise of 4m over several centuries could, in low-lying areas with minimal gradient, have extended inundation across tens of kilometres. Indeed, it may have been sufficient to have inflicted the final inundation of much of the Dogger Bank, which would have been an island of diminishing size at the time (Emery *et al.* 2019). A marine core from the Dogger Bank indicates marine inundation (at least from the locality of the core) not long after 8140±55 BP (AA22662) (Shennan *et al.* 2000). Doggerland was already submerging at a relatively rapid rate between 11,000 and 8000 years ago, but the 8.2 ka event may well have been a significant final step in transforming the landscape from a fragmented archipelago to a littoral fringe around the current North Sea basin coastline. To make matters worse, at around 8150 BP, and apparently during the coldest spell of the 8.2 event (Bondevik *et al.* 2012), Doggerland would have been hit by the Storegga tsunami – the largest known Holocene tsunami event to hit the North Sea basin.

The Storegga tsunami: a wave, but not goodbye

For years, the narrative surrounding the Storegga tsunami has been one of wipe-out for Doggerland and the coastal Mesolithic communities of the North Sea basin (Hill *et al.* 2014 although see Hill *et al.* 2017 for a revision of this view; Weninger *et al.* 2008). New evidence of the tsunami however, the first from the southern North Sea (Core ELF001A, Gaffney *et al.* 2020), has helped us to develop a significantly different picture (Walker *et al.* 2020) (Figure 5.8). Certainly, the tsunami would have been devastating for any who were unfortunate enough to be caught in its path, and more generally, could have destroyed structures, settlements, habitats and resources along the coast. However, it seems much of Doggerland may have already been inundated by the time of the tsunami, and the impact of the wave upon extant coastlines may have varied according to bathymetry and topography. While the rapid inundation associated with the 8.2 ka event might have created favourable conditions for preservation in some parts of Doggerland, reconstructing the sea level from this time is particularly difficult (Cohen *et al.* 2017). The punctuation of this phase, near its end, by the Storegga tsunami, could have had a destructive affect upon recently deposited archaeology (see

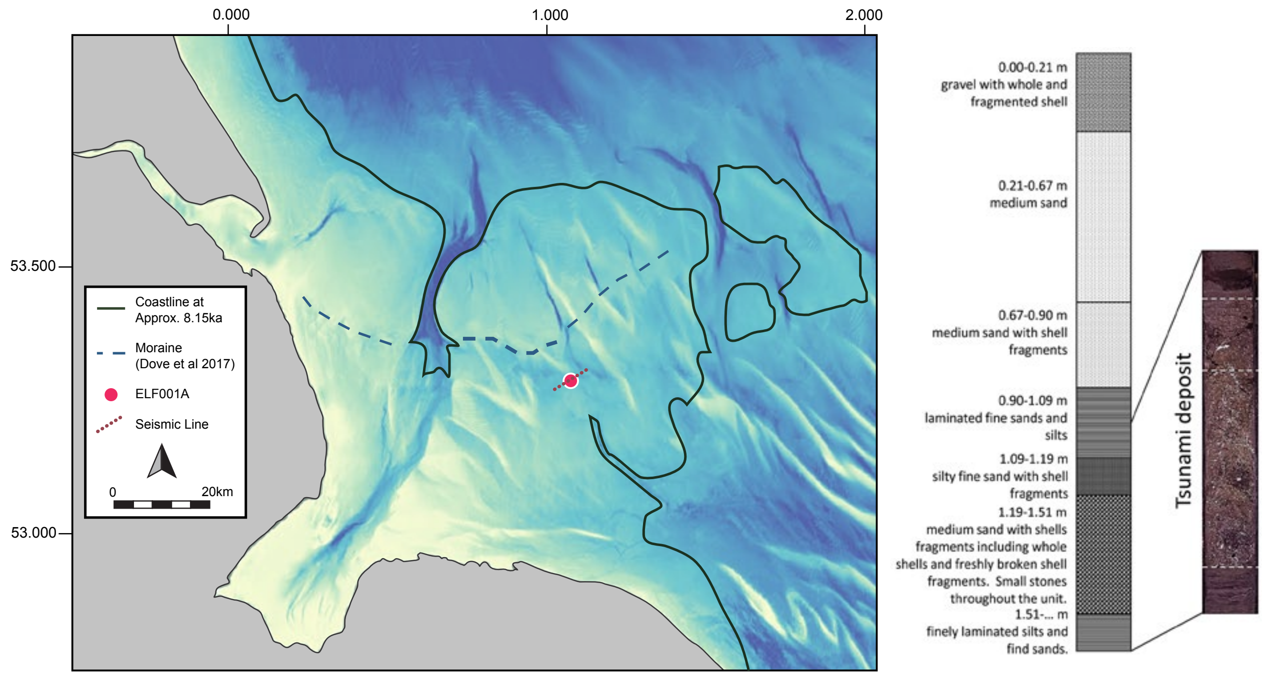


Figure 5.8 The location of Core ELF001A where evidence of Storegga tsunami run-up deposits in highly localised areas prompted reconsideration of the event's impact.

Waddington and Wicks 2017). A destructively variable, but ultimately high-velocity wave event, may well have destroyed any extant archaeology from this period or the preceding centuries. This has been posited for a relative drop in the number of Mesolithic sites in the northeast of the UK from immediately prior to 8000 BP (Waddington and Wicks 2017). Consequently, discovery of submerged sites from this period may be biased against coastal or nearby valleys and inlets in favour of inland sites that may have benefited from shelter.

There is, of course, much more to the environmental history of the Mesolithic than the 8.2 ka event and Storegga tsunami, although it is hard to envisage any that were more impactful. Environmental reconstruction of Doggerland remains at a very early-stage relative to topographic reconstructions, but initial investigations are highly promising in revealing detailed histories of paludification and ecological transformation (see Brown *et al.* 2018; Gearey *et al.* 2017; Krüger *et al.* 2016). Such studies will provide a data resolution that will be essential for understanding the broader impact of these and other environmental events and trends. In revising the long-held view that Doggerland was subject to a short, sharp, and absolute end in the form of the Storegga tsunami (Hill *et al.* 2017; Gaffney *et al.* 2020; Walker *et al.* 2020), we are faced with the prospect that the Dogger Littoral may have continued into the Early Neolithic, as Bryony Coles originally suggested (2000). The implications for this require significant consideration in discussion of the emergence or arrival of the Neolithic into northwest Europe.

Neolithic implements, including Michelsberg axes, have been recovered from the Brown and Dogger Banks (Gaffney *et al.* 2009; van de Noort 2011) – although the location for the latter is not clear (Bailey *et al.* 2020). At Bouldnor Cliff, in the English Channel, possible evidence of exotic foodstuffs have been found (Smith *et al.* 2015), along with other indicators of connections between the UK and mainland Europe including practices typically associated with Neolithic peoples (Momber *et al.* 2021: 9). However, it seems unlikely that Doggerland at this time would have been much more than a littoral fringe, whilst the area of the Brown Bank would have been inundated. Whilst these finds have typically been ascribed to artefacts lost at sea, increasingly, we should countenance the possibility that Neolithic goods, if not people, did move further into the seascape than previously imagined. If places such as the Brown Bank were submerged, which seems likely given the current evidence, finds from these locations may suggest a continued focus of activity in the North Sea even as coastlines retreated inland (Garrow and Sturt 2011). Neolithic artefacts recovered from the area may indicate a brief visitation, or a return to a liminal place within the landscape where a remembered locale was visible, but no longer habitable (van de Noort 2011: 144).

Final hunter-gatherer groups known from around the North Sea basin at the onset of the Neolithic include the Ertebølle in Denmark, a group long-known for their predilection for coastal resources (Rowley-Conwy 1983), the Swifterbant in the Lowlands (Devriendt

2008; Niekus 2005/2006), and some very late Mesolithic sites in the Western Isles of Scotland, such as Oronsay (Mellars 1987). The persistence of a littoral fringe into the Neolithic and beyond, means that areas including (but not restricted to) the current nearshore zone may well be imperative for understanding the Final Mesolithic and indeed the relationship of early Neolithic frontier farmers with the coast. Might the compression of hunter-gatherers between the coastline and farming groups have resulted in fundamental changes in settlement patterns, territoriality, and intergroup relations? Alternatively, perhaps the success of coastal adaptations among some terminal Mesolithic groups allowed for an extended persistence (Elliot *et al*. 2020). While the loss of land may certainly have had a significant effect, a frequently overlooked function, population demographics aside, is the increase in relative available coastline (and accompanying resources). A decrease in territorial availability would nevertheless have been partially offset by a relative increase in coastal perimeter. Certainly, these are priority issues for future investigation.

Summary

Thanks to several decade's worth of extensive research into marine geology and the palaeogeography of the North Sea, conducted by multiple different teams, our understanding of the history of Doggerland throughout the course of the Late Pleistocene and Early Holocene has improved significantly since Bryony Coles' speculative survey, some twenty-five years ago. We now know that:

- Doggerland was never fully glaciated even during the coldest period of the last Glacial Maximum and would have been a habitable if not important landscape in the recolonisation of northerly latitudes in Europe during the Bølling-Allerød interstadial (Amkreutz *et al*. 2018; Momber and Peeters 2017).
- However, the northernmost extent of Doggerland never extended much beyond the north of the current Dogger Bank. This suggests that Doggerland was probably not a 'jumping-off' point in the late Palaeolithic colonisation of northern Scandinavia or Scotland.
- Throughout the Late Pleistocene, the northern coastline of Doggerland remained largely stable, but a deep marine inlet formed to the south between southeast England and lowland Europe.
- This marine inlet had probably connected to the North Sea around 9500 BP, meaning that Britain was separated from the continental mainland earlier in the Holocene than many have previously posited, and connected only via a relatively narrow area to the east of northern East Anglia and Lincolnshire. This may have been an important route in the spread of new species of flora and fauna, as well as ideas, artefacts, and ultimately people during the Pleistocene/Holocene transition.
- While the northern coastline of Doggerland was relatively stable throughout the Late Pleistocene (between at least 21,000 and 15,000 BP), the Early Holocene (11,000-7000 BP) marked the beginning of rapid and variable inundation that saw Doggerland transition from a broad coastal landscape to an increasingly fragmented archipelagic landmass, with the Dogger island to the north and, finally, a littoral fringe of variable extent around the current day circumference of the North Sea basin.
- Perhaps the most significant period of sea-level inundation during this period was the 8.2 ka BP event. This may have been associated with sea-level rise by as much as 2-4m in just a few centuries and with it, potentially, the final submergence of what is now the Dogger Bank.
- During this period, the coasts of Doggerland were struck by the Storegga tsunami, the largest tsunami event to have struck the North Sea basin since the beginning of the Holocene. Although this wave event has typically been assumed to have had catastrophic consequences for Mesolithic peoples, including the final inundation of Doggerland, it is likely that the impact would have been highly variable. Far from resulting in permanent inundation, most if not all associated inundation would have been temporary.
- Contrary to previous claims regarding the inundation caused by the Storegga tsunami, a littoral fringe around the North Sea basin persisted beyond 8000 years ago, into the Neolithic and beyond, as had been suggested by Bryony Coles (2000). This opens the possibility that parts of Doggerland that survived within the nearshore zone may retain key evidence regarding the final hunter-gatherers of northwest Europe, as well as their interactions with the first farmers to settle in coastal landscapes.

The efforts of *Europe's Lost Frontiers*, the NSPP and many colleagues and collaborators, have helped reach a point where it is now possible to reconstruct localised landscape histories at thousand-year intervals or less. Such work may be of vital importance for the development of targeted archaeological prospection. Although our understanding of Doggerland's palaeogeographic history has improved considerably, knowledge regarding the archaeology of this landscape remains scant, for the following reasons:

- Waters adjacent to the southern North Sea have provided a rich assortment of Mesolithic sites and findspots in recent decades, but relatively

few have been found from the waters we might consider as having once been part of Doggerland.
- The majority of findspots come from waters quite close to the contemporary shoreline, meaning that we know comparatively little about the archaeology from the area that constituted the main portion of Doggerland for the Final Pleistocene and the Early Holocene. This is because the difficulties to locate significant prehistoric finds increase with depth and distance from the shore. Methods used to great success in the nearshore zone may be poorly suited for direct adaptation towards the offshore area.
- In the southern North Sea itself, only unstratified findspots have been identified, with two exceptions, only one of which, the Yangtze Harbour site in the Netherlands, has been excavated. While these discoveries demonstrate an abundance of archaeological material from parts of the Doggerland landscape, including areas with the potential for exceptional levels of preservation, the lack of stratified finds makes it difficult to infer chronologically or spatially constrained patterns of behaviour.

Concluding remarks

In *Oceans of Archaeology*, Anders Fischer wrote that '*When it comes to underwater archaeology's potential to fill geographical gaps in the archaeological record for early prehistory, the North Sea provides examples that are unsurpassed in a global context*' (2018: 182). Fischer and others, have, over recent decades, demonstrated the rewards to be gained in the exploration of the submerged Mesolithic archaeology around the Danish Coast (Andersen 2013; Bailey *et al.* 2020). Similarly, research conducted in parts of the Baltic (e.g. Hansson *et al.* 2018), provide an exemplar that other North Sea basin countries could look to follow (see Benjamin 2010). Depositional differences around the perimeter of the North Sea basin necessitate a flexible and multi-stranded approach to archaeological investigation, and the offshore zone presents an altogether more challenging prospect, both logistically and legislatively. Nevertheless, the prospect of the existence of well-preserved, stratified Mesolithic sites, and indeed landscapes, along with the increasing risks of development that this unique and shared submerged landscape faces, are compelling incentives for further work (see Fitch *et al*. this volume: Chapter 15).

Doggerland was clearly a central arena of human activity in the Mesolithic period, and its gradual disappearance must have had a profound effect on shaping the physical and human geography of the entirety of northwest Europe. Despite captivating our imaginations (Blackburn 2019; Fagan 2013; Smith 2019), the archaeological potential of this area has so-far eluded us. We are, however, now on the cusp of beginning to explore this previously inaccessible landscape in a comprehensive manner, and to finally understand the role and significance of Doggerland within the larger puzzle of Mesolithic Europe.

Chapter 6

The Southern River: methods for the investigation of submerged palaeochannel systems

Simon Fitch, Richard Bates and Rachel Harding

Introduction

The *Humber Regional Environmental Characterisation* (Humber REC) project (Tappin *et al.* 2011) identified an area in the southern North Sea that potentially preserved a late Mesolithic/early Neolithic landscape. The landscape contains river systems that were finally submerged at *c.* 6500 (±500) BP (Tappin *et al.* 2011: 215). This result appeared to contradict dates provided by previous GIA modelling for the area (e.g. Shennan 2000), which suggested the area had been inundated by this date. The Humber REC therefore revealed the possibility of the existence of a tract of land extending from the north shore of East Anglia that was exposed during the Late Mesolithic to Early Neolithic. The existence of a Neolithic Doggerland is rarely considered although, Bryony Coles (1999) did discuss the possibility. Following analysis of seismic data acquired by industry and the Humber REC, the area, now known as the Southern River, was subject to a detailed coring program. Cores were located along the length of the palaeoriver channel on the basis that the temporal sequence of the transect might provide detailed information on the timing, progress and eventual submergence of the river. The Southern River Valley is not only a key area within the *Europe's Lost Frontiers* research programme, it provides an exemplar of the analysis of individual large channels within the project, and this chapter provides a preliminary description of methods and results of the seismic analysis in this valley.

Background geology of the Southern River Valley

The basement for this region consists of upper Palaeozoic through Mesozoic sediments including chalk, sandstone and siltstones. Regional structural patterns have been published in a number of oil and gas basin atlases, see for example Campbell (2013) and Cameron *et al.* (1992). These features provide the backbone of the landscape on which the overlying, more recent sediments are located. However, it is with the overlying, largely unconsolidated or partially consolidated geology that this study is mostly concerned.

During the Pleistocene, subsidence in the southern North Sea followed regional, underlying faulting patterns with an approximately northerly trend. The subsidence occurred at a rate of approximately 0.5m per thousand year (Stoker *et al.* 1985). During the Early Pleistocene (2.5 Ma to 774,000 BP), deposits in the area are derived from a series of deltaic deposits which Long *et al.* (1988) observed to be both thick and laterally extensive. The provision of sediment from the British Isles into this depositional system is related to restricted deposits in the region, but the overall deposition reflects the dominant European input of sediment which extended the Netherlands delta plain (Zagwijin 1989). This massive input of material caused rapid sedimentation in the Southern Bight, which conversely starved the northern sector of the North Sea of sediment (Cameron *et al.* 1992).

The Middle Pleistocene (774,000 to 125,000 BP) begins with the record of glacial ice extending into the southern North Sea. Large 'scaphiform' tunnel valleys were created at the base of the ice sheet (Ehlers *et al.* 1984), and were subsequently infilled with glacial clay and later by lacustine and marine clays. The glacial material in this region likely was deposited predominantly during the Anglian glaciation (Gibbard *et al.* 1991), which also caused the eventual blocking of the Southern Bight, thus diverting fluvial activity, including glacial melt water, south through the English Channel (Gibbard *et al.* 1988; Hamblin *et al.* 1992).

The late Pleistocene (125,000 to 11,650 BP) within the southern North Sea basin contains several glacial and interglacial periods (Laraminie 1989b) characterized by transitions between glacial, terrestrial and marine environments. The end of the period is marked by glaciolacustrine and glaciomarine infill. These geographical changes ultimately created the landscape to the extent that it can be traced today (Eisma, 1979). Whilst these terminal glacial deposits form the backbone of the recent geology within this region, later Holocene erosion and deposition has also been significant.

Holocene sediments dating from between 11,650 to 6500 BP, attain a thickness of 1 to 5m within the region, and locally, deposits can reach thicknesses of between 16 to 30m (Laraminie 1989a, Fitch *et al.* 2005). These

Geological Period	Archaeological Period	Date	Deposits
Mid to Late Holocene	Submerged	7,000BP to Present Day	Nieuw Zealand Gronden Formation, Well Hole Formation, Modern Sediments
Early Holocene	Late Upper Palaeolithic/Mesolithic	11,500BP to 7,000BP	Nieuwkoop Formation, Naaldwijk Formation (previously Elbow Formation)
Earliest Holocene/ Late Pleistocene	Late Upper Palaeolithic	20,000BP to 11,000BP	Botney Cut Formation
Late Pleistocene	Upper Palaeolithic/ Late Middle Palaeolithic	50,000BP to 16,000BP	Well Ground Formation, Bolders Bank Formation
Middle Pleistocene	Lower Palaeolithic	420,000BP to 375,000BP	Egmond Ground Formation
Middle Pleistocene	Lower Palaeolithic	420,000BP to ?	Sand Hole Formation
Middle Pleistocene	Lower Palaeolithic	475,000 to 420,000BP	Swarte Bank Formation
Early Middle Pleistocene	Lower Palaeolithic	700,000 to 475,000BP	Yarmouth Roads Formation
Mesozoic	N/A	+60,000,000BP	Upper Cretaceous Chalk

Table 6.1 Geological deposits within the study area

Holocene deposits record the history of the emergent landscape and its subsequent marine transgression and are of central interest to archaeologists and the *Europe's Lost Frontiers* project. The Holocene sequence is divided into two formations, namely the Nieuwkoop, which consists of a freshwater peat and the Naaldwijk, which records tidal flats and salt marsh environments (Rijsdijk *et al.* 2005). These have previously been described as the Elbow Formation (e.g. Cameron *et al.* 1992) but are now recognised as separate entities. Overlying these deposits are modern marine sediments including extensive sand banks of the Nieuw Zeeland Gronden member (Table 1 & Cameron *et al.* 1992).

Sturt *et al.* (2013) provide models of marine inundation across the southern North Sea which show that the inundation had started in this area at *c.* 10,000 BP. The models demonstrate that marine inundation continued across the area until fully flooded at *c.* 7000 BP.

The study area

The 'Southern River' is located approximately 22km offshore from the coast of East Anglia (Figure 6.1). The river channel runs for almost 260km^2, with a mean water depth of 21m and localised deeps to -39m. The river feature has a bathymetric expression on the seafloor and thus has not been completely infilled. The origin of the channel follows a glacial meltwater outwash system, with the first part cut into the underlying deposits during the earlier Late Devensian (Dove *et al.* 2017). The Holocene aspect of this channel is extant through its re-use of this pre-existing channel, which is made visible via the later networks of sub-aerial feeder channels which must have formed between the late Pleistocene to early Holocene. The floodplain of the river is approximately 1.1km wide with an average channel width of *c.* 250m. The Holocene channel shows a typical river profile with two tributaries in the upper reaches and some additional minor dendric tributaries joining these. The river channel would have experienced several periods of infilling, including fluvial sedimentation, estuarine deposition during inundation and eventually marine sedimentation following inundation. Given the regional history of infilling, it was speculated that evidence of the marine transgression might be preserved and that a coring programme along the length of the channel might capture the sequential history of infilling.

The presence of Holocene deposits in this area were first indicated following recovery of peat within a gravity core taken by the BGS (then known as the Institute of Geological Sciences) in the 1970s. This core recovered a peat which was covered by a series of Holocene laminated silts and clays of intertidal origin (Cook 1991). This core was re-evaluated by the Humber REC project (Gearey *et al.* 2017) which showed the presence of fluvial material of a Holocene date. Further cores, acquired nearby in 2008 by the Humber REC project, revealed that the area contains a variety of terrestrial, estuarine and fluvial deposits as well as associated peat material. The cores, dated between 9000 to 8000 BP (Tappin *et al.* 2011: 197), suggested that conditions might be good for preservation of environmental deposits, although the Humber REC remit did not allow for an evaluation of the wider landscape and environment in this area. However, this material was sufficient to suggested that features in this area may contain *in-situ* sediments of early Holocene age (Tappin *et al.* 2011: 225) that would support the academic aims of *Europe's Lost Frontiers*. Recently, nearby commercial development has revealed a similar Holocene environment on the Dungeon Wind Farm, *c.* 10km away from the study area (Brown *et al.* 2018). Here freshwater deposits have been dated at 9755 ±52 BP (UBA-33301) with a thin upper peat covered by a shelly sand potentially representing final submergence dated at 8411-8331 cal BP (GU-34111).

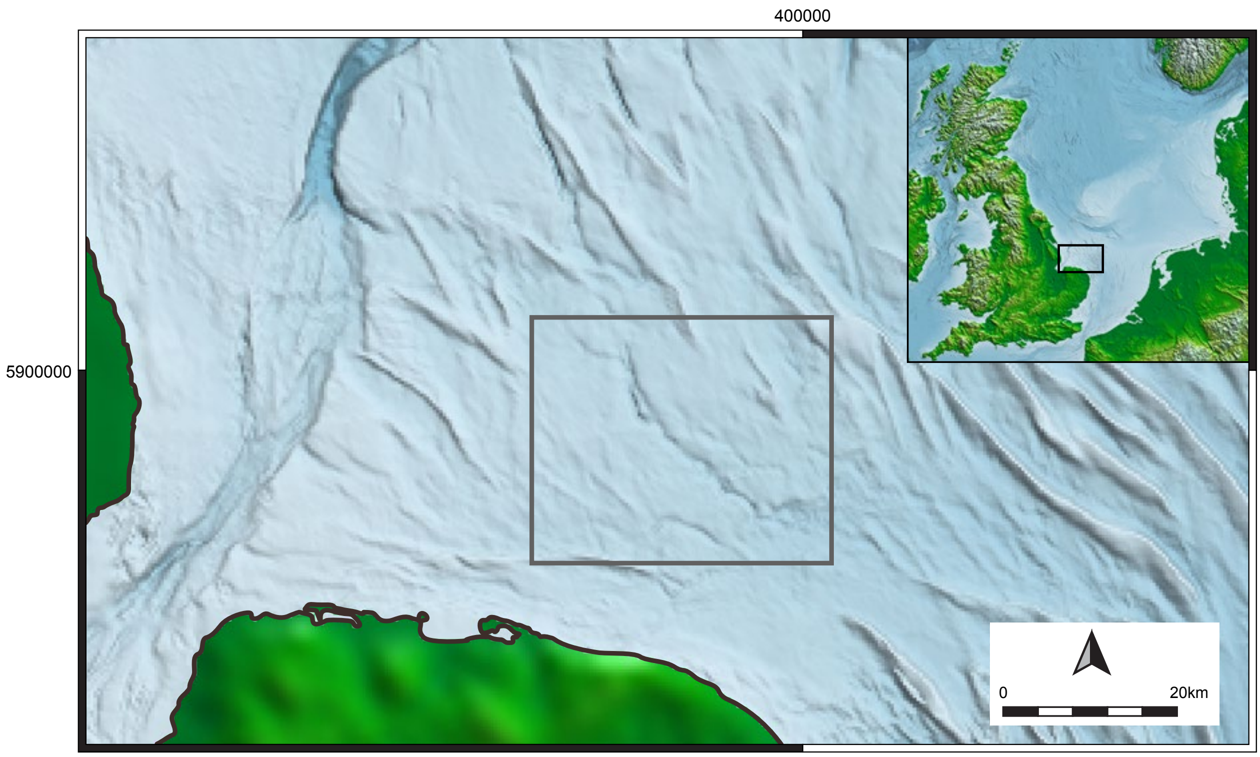


Figure 6.1 The location of the Southern River is within the box on the main map.

Methodology

An initial examination of the river channel was undertaken using bathymetric data from EMODNET. (https://www.emodnet-bathymetry.eu/). This data layer has a resolution of 115m and is suitable for displaying larger features which have a seabed expression. The bathymetric data indicates that the channel has a northwest-southeast orientation draining to the south and into a Holocene marine embayment (Figure 6.5).

Seismic interpretation of the data

The legacy seismic data available for this analysis was acquired by Gardline Surveys Ltd, using the vessel *Vigilant* equipped with a surface-towed boomer system (see Tappin *et al.* 2011: 73 for more details). This boomer system consisted of an Applied Acoustics 300 Plate powered by an Applied Acoustics CSP 1500 Pulse Generator and 12-element single channel hydrophone stream. The system was operated at a power level of 300 joules with a 350-millisecond fire rate. Initial data inspection and preliminary processing was accomplished using Chesapeake SonarWiz and Coda GeoSurvey (Figure 6.2). Processing included swell filtering, where necessary, and application of a band pass filter between 1kHz and 8.4kHz (Figure 6.3). All data was reduced to the Lowest Astronomical Tide Datum using predicted tidal ranges from the nearest standard ports of Immingham and Cromer. Further processing utilising IHS Kingdom 2019 software was undertaken and included using a built-in running-sum amplitude gain correction filter (Figure 6.4).

Initial examination of the data showed a number of different seismic characters that were divided into seven distinct seismic facies. The seismic facies, prefixed 'SRF' (Southern River Facies), were determined using the seismic attributes of amplitude, frequency and continuity. Additional features of interest that were mapped included major reflection terminations (e.g. erosional truncations).

Targeted vibracoring

The *Europe's Lost Frontiers* vibrocores were acquired by Gardline, based on the project's interpretation of legacy seismic data. A total of 35 cores were acquired in this paper's study area, with a maximum penetration of 6m. Whilst it was noted that the 6m length of the available corer would not allow penetration of the deepest/oldest parts of the channel feature, the use of a longer corer would have been cost prohibitive and reduced the number of cores that could be acquired. In most cases the cores that were recovered were sufficient to support the project's goal of studying the early Holocene sequence. Core treatment followed the method outlined in Bates *et al.* (this volume).

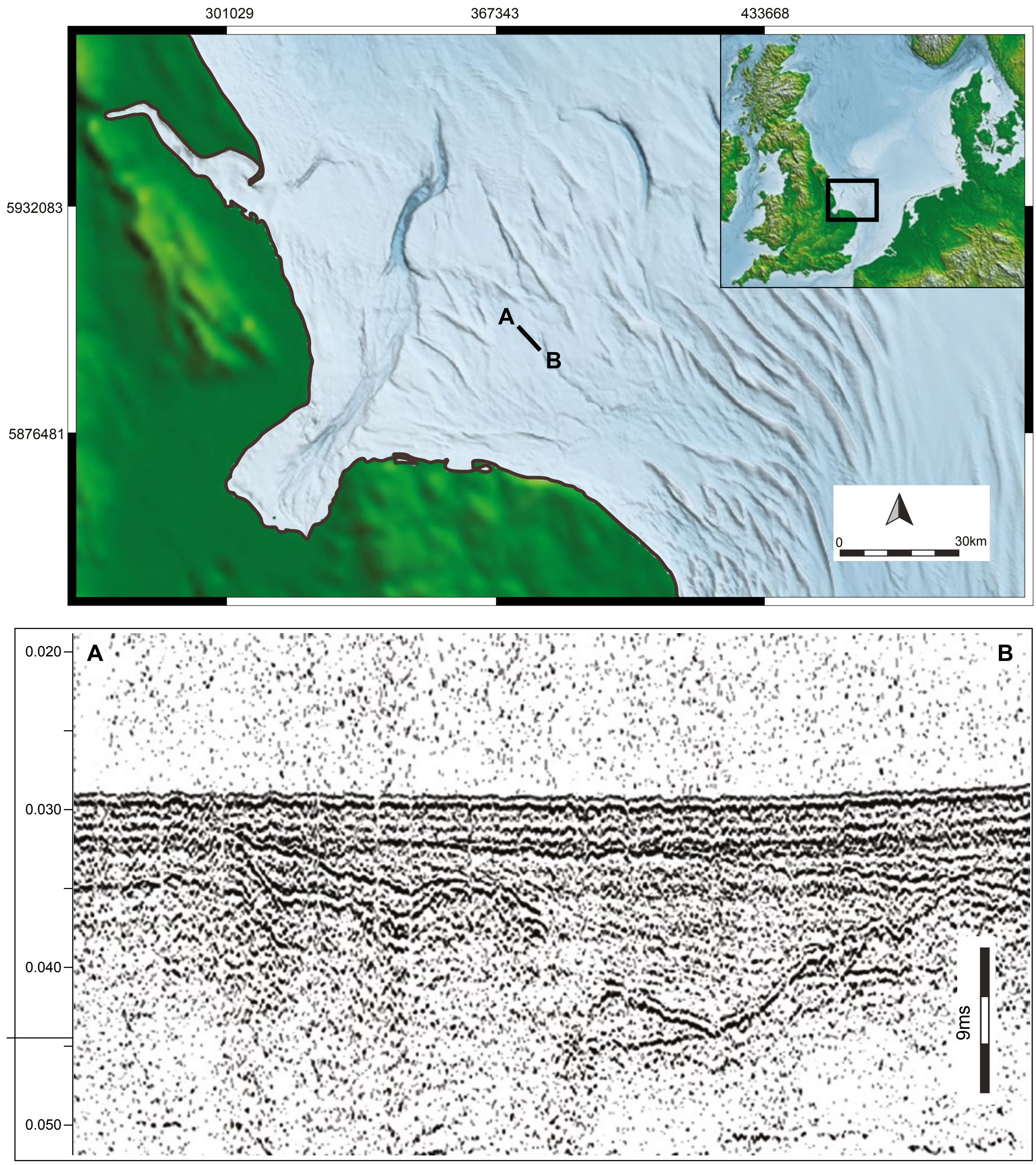


Figure 6.2 The location of the 2D seismic data shown in Figures 6.3 and 6.4 is indicated by the black line (top). The lower image is an example of the original 2D Boomer dataset used for targeting the cores within the Southern River.

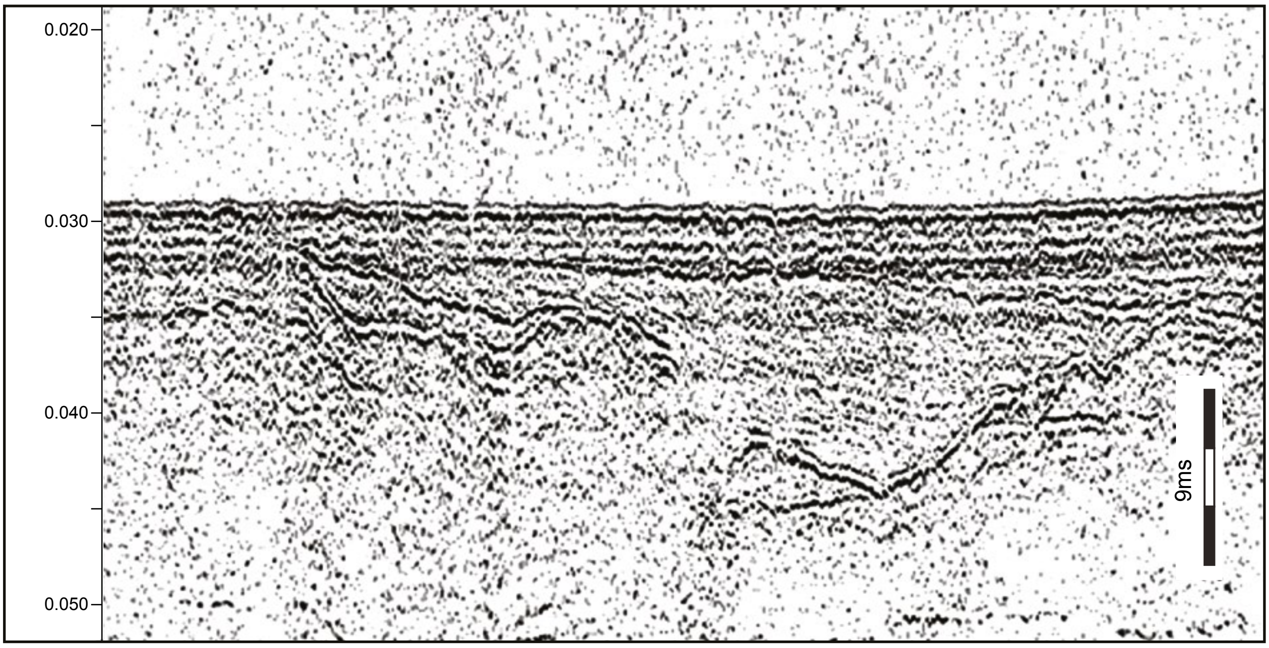


Figure 6.3 2D Boomer data after bandpass filtering applied.

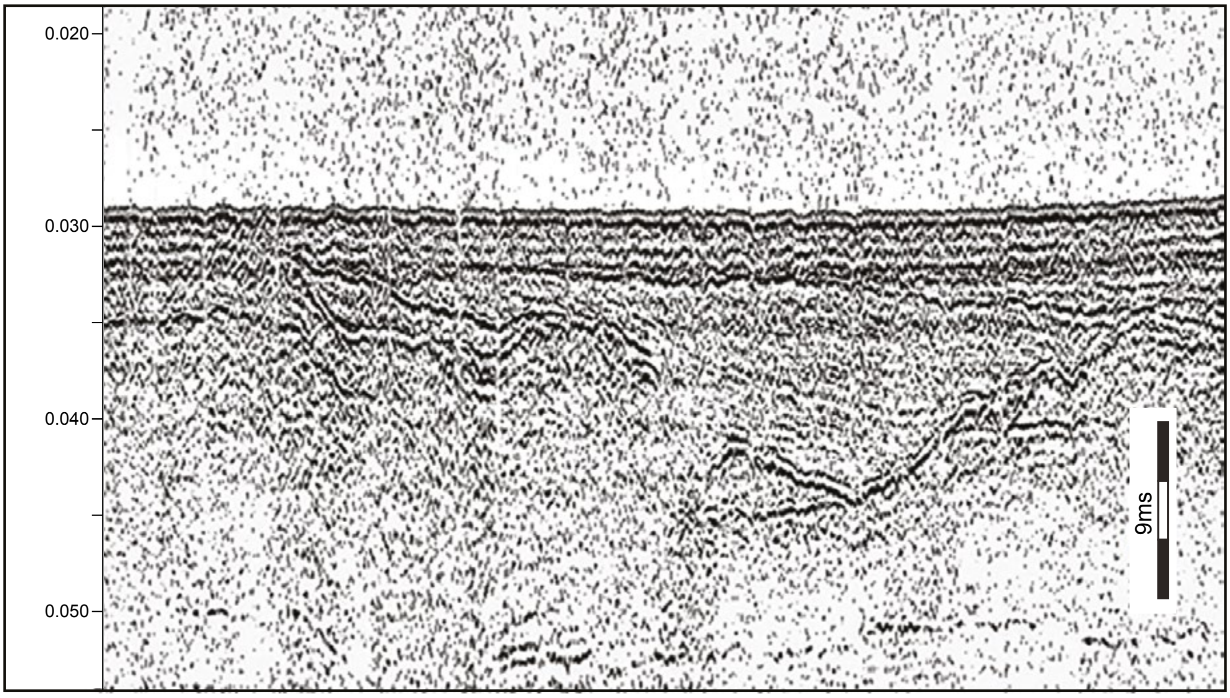


Figure 6.4 2D Boomer data after amplitude and gain correction applied.

Results: seismic facies

The seismic sequences of interest in Table 6.2 are described from the base of the sequence to the surface as seen in both the legacy industry 2D seismic and Humber REC seismic data. Data quality in the seismic dataset is highly variable due to differences in age (legacy data) and the inclement weather conditions during acquisition and the strength of seabed reflection (Humber REC). Boomer data was seen to have the best results in this area, and whilst maximum penetration depth of 50m was seen, the features were best resolved in the top 15m of the data.

SRF1

This is the deepest observable seismic facies in the boomer data and thus represents the seismic 'basement' for this study. The facies is characterised by having few internal reflections that are of high amplitude and low frequency. The internal reflections rarely extend laterally with opaque intervals of hundreds of metres. The unit is bound on its upper surface by a strong, regionally laterally continuous positive reflector.

SRF2

This is a geographically limited facies, being constrained to a small tunnel valley in the middle of the study area (Dove *et al*. 2017). The unit is moderately chaotic but has some internal discontinuous reflections that are of high amplitude and frequency. The unit fills the valley with an erosional truncation at its base that cuts into the SRF1 unit (Boundary SRB1). The unit is discordantly overlain by SRF6.

SRF3

This unit is geographically limited to both sides of the channel area. The facies is characterised by parallel internal reflection structures which are continuous within the unit. These parallel reflections are largely horizontal to sub-horizontal with a dip not exceeding 5 degrees and are of alternating high/low amplitude. The base of the unit is defined by an erosional truncation and can be seen to overlie SRF1. The unit is also overlain unconformably by SRF7

SRF4

This facies shows a massively chaotic internal reflection character with discontinuous internal reflections of high amplitude. The facies is bound by clearly definable high amplitude, high frequency boundaries. The deposits are cleanly cut into facies SRF1 and are separated by the erosional boundary SRB2. The SRF4 facies is overlain concordantly by SRF6 (Holocene age).

SRF5

This facies is shows little structure with few, moderate amplitude internal reflectors. The facies is bound by clear channel cut reflectors at the base of a high amplitude, low frequency character. The base of SRF5 cuts down into the SRF1 deposits and is separated by the erosional boundary SRB3. Similar to other units in this area, the top of the facies is unconformably overlain by SRF6. Some opacity is seen in places, and this may relate to gas charging of the material.

SRF6

This unit is characterised by continuous, high amplitude internal parallel reflectors that are laterally continuous over tens of meters within the channel. The parallel reflectors are largely horizontal within the main body of the channel, but dip upwards to 30 degree with onlap at the channel margins. The base of the facies can be seen to unconformably overly SRF2, SRF4 and SRF5 and is separated at the base by an erosional unconformity (SRB4) with high seismic amplitude.

SRF7

The top surface of this facies is represented by a high frequency parallel reflector which can be seen overlying all deposits in this region. The internal reflections are chaotic in nature and the facies has some localised variations in thickness. This material is separated at the base from the other facies by an erosional boundary SRB4 which is of a high amplitude nature.

Erosional boundaries

SRB1

This erosional boundary is demonstrated by the erosional truncation made into SRF1 deposits. The truncation is U shaped in form, and the boundary is of very high amplitude, moderate frequency and located at 0.066s in the seismic section.

SRB2

These boundaries are channel shaped with an irregular base, represented in the seismic data with a boundary of high frequency and a moderate amplitude. It is most closely associated with an irregular surface which is present between 0.062s and 0.050s in the seismic data.

SRB3

This is erosional boundary is located between 0.053s to 0.037s. It is an irregular feature located above the SRB2 boundary and can be seen to separate SRF1 and

SRF5. The boundary is moderate frequency and high amplitude in nature.

SRB4

This is the latest erosional boundary in the seismic section. The boundary is located at 0.035s and 0.027s in the section. The boundary features high amplitudes and is of a moderately high frequency.

Discussion

New seismic reflection data has been divided into distinct units based on internal facies character and bounding contacts. Four major erosional boundaries (SRB1 to SRB4) have been identified that are consistently mapped across the survey area. The facies character and truncations can be interpreted to provide a sedimentological history consistent with the known regional patterns of geomorphological change during the Holocene.

The first phase of evolution mapped by seismics in this area, and the deepest recorded, starts with the formation of a glacial tunnel valley. Dove *et al.* (2017) suggest that the tunnel valleys likely correlate to the final position of ice in this area. This hypothesis finds support in recent investigations by Roberts *et al.* (2018). The base facies in this study (SRF1) shows identical acoustic characteristics to facies DB4 from Roberts *et al.* (2018: 193). Roberts correlates this material on the basis of cores taken by the BRITICE project to the Bolders Bank Formation, which is a sub glacial till located in complex sheet structures (Davies *et al.* 2011). The Bolders Bank formation was formed during the final major advance of the ice sheets and relates to ice front movements between 30,000 BP and 22,000 BP (Roberts *et al.* 2018). The SRF1 facies is cut into by the erosional boundary SRB1, whose character and overall shape match that for a typical glacial tunnel valley in the southern North Sea, and relates to glacial outwash.

Facies unit SRF2 partially fills the tunnel valley with onlap to the sides and an internal character that shows laterally discontinuous, bifurcating reflections. This character is consistent with an infilling of a channel by a fluvial system that is meandering across the accommodation space as a braided river system. An acoustic facies, DB5 was observed by the BRITICE project (Roberts *et al.* 2018), which possesses similar characteristics. The material was ascribed to the Botney Cut Formation, and Cotterill *et al.* (2017) suggests that the material may be related to pro-glacial drainage. The source of water for this fluvial activity was the outflow from glaciers to the north of region. The cold climate of the pro-glacial tundra provided ideal conditions for the formation of braided channels (Cotterill *et al.* 2017). The material SRF2 is thought to date to before the onset of aridity due to the periglacial climate in the area (from *c.* 23,000 BP, Emery 2021: 118), and therefore of late Devensian age.

Following this arid stage there is a further period of late Pleistocene fluvial activity. The phase of activity is closely associated with an irregular surface present between 0.072s and 0.050s in the seismic data, which represents the channel cuts. The material contained within these channels (SRF4) appears to be associated with channel migration features, and gravel bottoms which show as a strong chaotic signal at the base of the features within the seismic data. These channels overlie or crosscut previous material and thus are later than 23,000 BP. Unfortunately, it is not possible to correlate these channels to previous studies, but it is possible that comparable features were observed by the BRITICE survey (Roberts *et al.* 2018) near the Southern River. These (DB5 and SRF2) were ascribed to the late Pleistocene/early Holocene Botney Cut Formation. It is known that a period of channel incision occurred elsewhere in the North Sea during the period 17,000 to 12,000 BP (Emery 2020). Given the channel stratigraphy seen in the seismic data, it is thought that the SRF4 deposits are related to this latest Devensian age (17,000 to 12,000 BP). OSL dates from ELF cores into these features have confirmed this association (see Kinnaird *et al* this volume and forthcoming *Europe's Lost Frontiers* volumes for more details).

The third phase of fluvial activity relates to a reuse of earlier features and the full development of Holocene fluvial landscape through erosion and reuse of late Devensian structures (SRF3 & SRF5). The erosional boundary formed by this activity, SRB3, is located between 0.053s to 0.037s within the seismic data. These channels are smaller in size and form part of a sinuous dendritic river network that is visible within both the seismic data and bathymetry (Figure 6.5). The increase in sinuosity is thought to reflect the increased precipitation in the area and a warming climate. The smaller grain size of the material suggested in the seismic response of SRF5, reflects low sediment supply and source material from within the region. Similar channels were observed during the Humber REC and these were ascribed as Holocene fluvial systems (Tappin *et al.* 2011: 214). *Europe's Lost Frontiers* project cores which penetrated these deposits returned a similar Holocene age and thus the facies seen are thought to be identical to those observed by Tappin *et al.* 2011 (Figure 6.6). As these cores penetrate features that are broadly of similar morphology and age, and that are in close proximity (within 5km) to each other, it is reasonable to assume the sediments they contain are from the same unit.

The final phase relates to the development of estuarine deposits in the channels formed in response to sea-level rise in the early Holocene. These highly distinctive

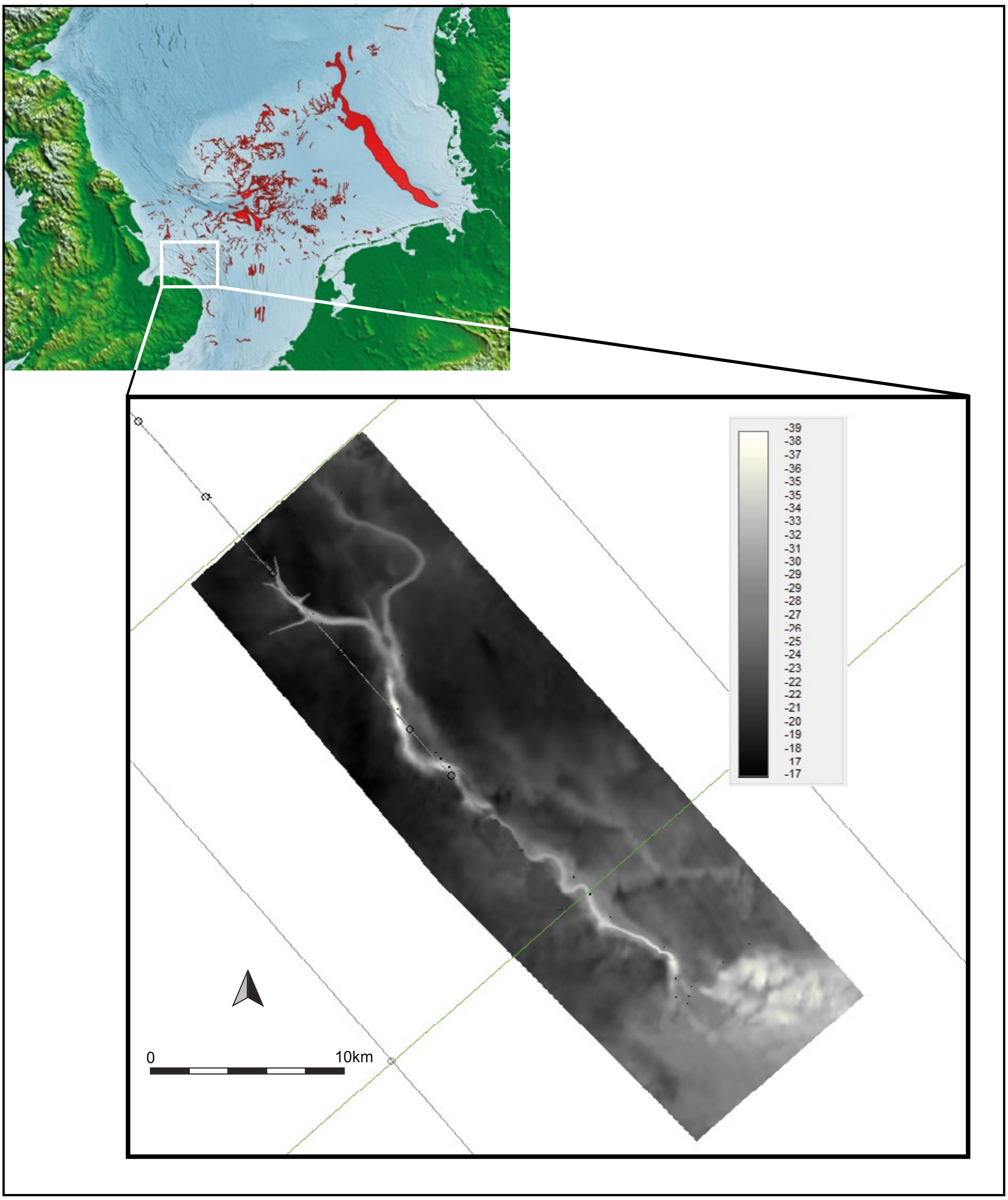


Figure 6.5 A combined Bathymetric and seismic data surface of the Southern River. The dendritic network is visible at the head of the river, whilst sinuousity increases as the river proceeds south towards the location of the Holocene coastline.

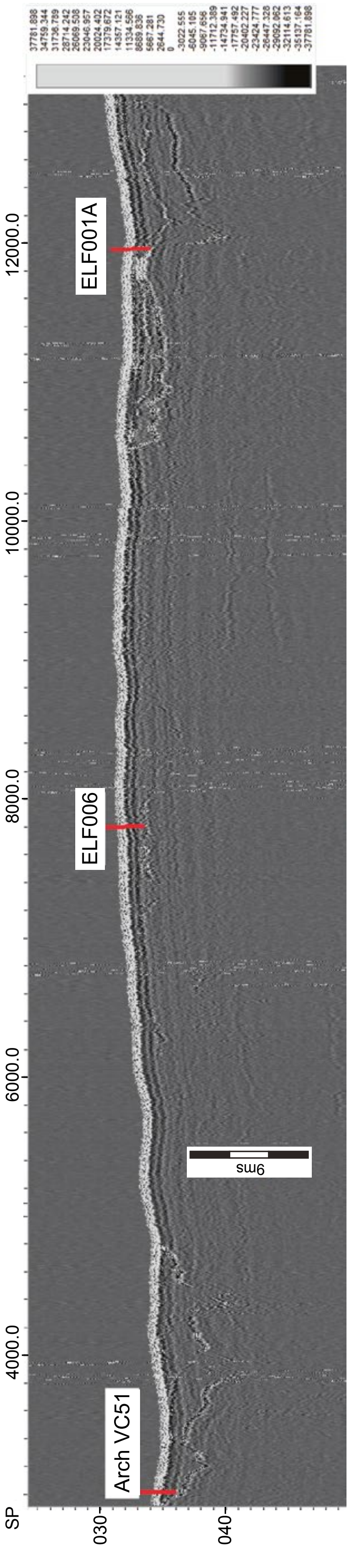


Figure 6.6 A seismic cross section showing the position of the Humber REC core Arch VC51 and Europe's Lost Frontier's cores ELF006 and ELF001A.

laminated features (SRF6) are clearly visible in both the seismic data and core material recovered by *Europe's Lost Frontiers* (e.g. ELF054 and ELF033, Figure 6.7). Located between 0.035s and 0.027s, these reflect the tidal erosion surface (SRB4), and the later infilling of this and earlier landscape features, with intertidal silts and muds by SRF6. This sequence can be seen, repeatedly, in many *Europe's Lost Frontiers* cores along the southern river (see Bates *et al*. this volume and forthcoming *Europe's Lost Frontiers* volumes), and similar deposits were recovered during the Humber REC (Tappin *et al*. 2011: 194). The Humber REC also recovered cores from the SRF6 facies which comprised intertidal laminated silts and clays which dated to the period 9000 to 8000 BP (Tappin *et al*. 2011: 198). This material is therefore related to the final submergence of the Holocene landscape during the period 8500 to 8000 BP suggested by sea-level models (Shennan *et al*. 2000). It is, however, important to note that the Holocene channel cuts are in some parts of the study area not totally filled by this tidal silt and clay. This partial infilling, coupled with some modern erosion, has meant that some Holocene channel features have a reduced, but observable bathymetric expression on the current seabed.

The final facies within the dataset relates to modern sands (SRF7) which can be seen to overlay the entire study area and have been formed by more modern marine processes post 7000 BP.

Conclusions

The analysis presented here provides an example of the interpretative process carried out by *Europe's Lost Frontiers* researchers with respect of one, important feature. The data indicates that the channel system under study clearly has its origin in the advance and retreat of the ice sheet (Dove *et al*. 2017; Emery *et al*. 2019; Roberts *et al*. 2018). The channels cut the Bolders Bank formation till which, as observed by Roberts *et al*. (2018), is 'a series of overlapping sheets' relating to numerous ice front movements between 30,000 BP and 22,000 BP. Despite this, by *c*. 23,000 BP the ice sheets had advanced and retreated for the final time and the boulder clay and tunnel valley were subaerially exposed. The meltwater from the retreating ice then flowed, initiating the formation of the valley which constrained the later Southern River channel.

The interpretation of the seismic data therefore suggests that there are three distinct phases of channel development present:

1. an initial phase of incision by fluvio-glacial channels (Late Devensian – prior to 23,000 BP)
2. a later reuse and new channel formation stage (Late Devensian – 17,000 to 12,000 BP)

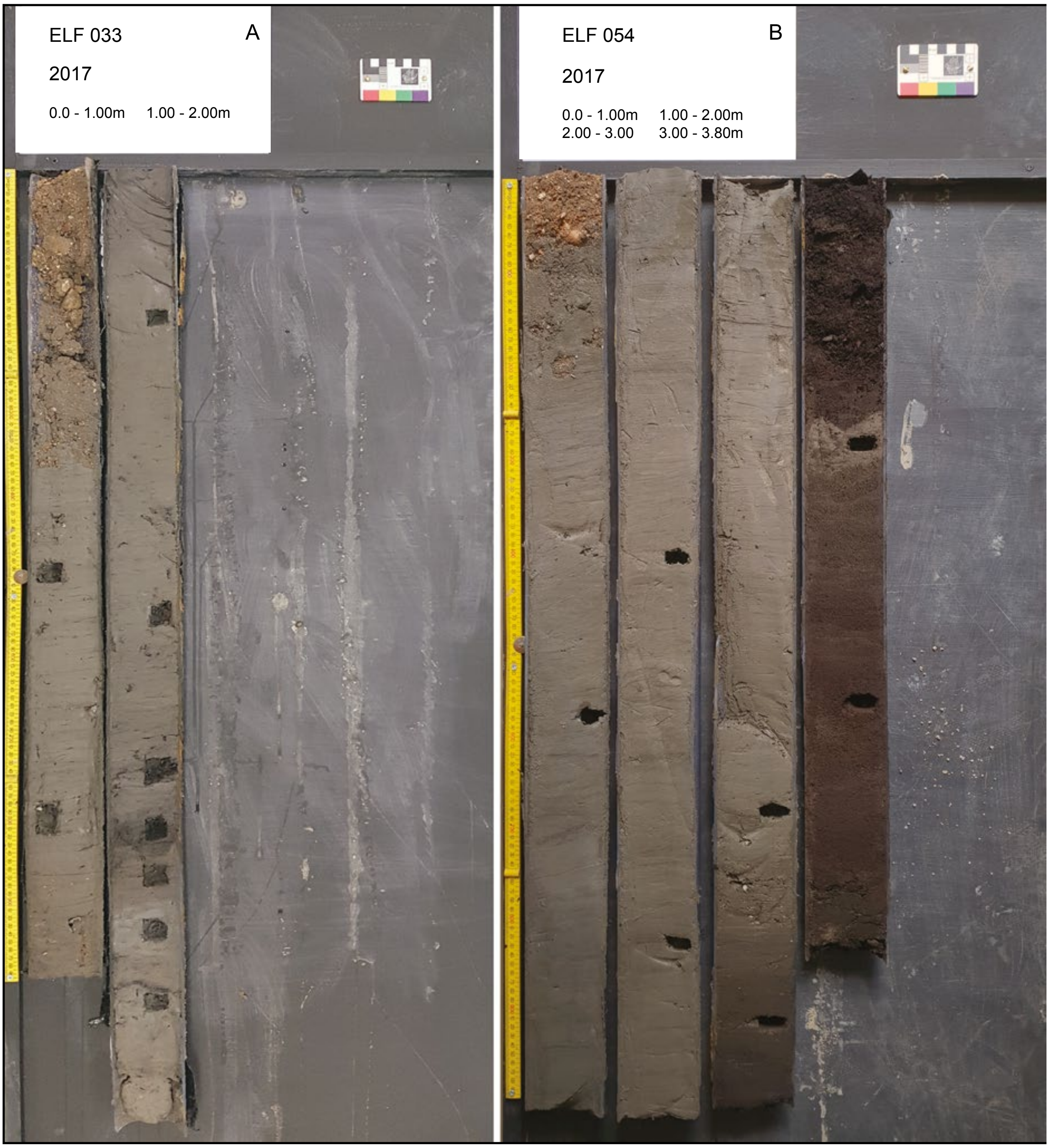


Figure 6.7 The distinctive laminated sediments (SRF6) that produce a clear signal in the seismic data are visible in these images of cores ELF033 and ELF054.

3. the final channel development (latest Pleistocene to early Holocene – 12,000 to 8000 BP)

The seismic data for this channel therefore records a history of landscape development after the ice. The data demonstrates not only the early phases of fluvial development, but also the responses of fluvial systems and the landscape to sea-level rise and eventual submergence over an entire catchment. A full history of this channel, including a detailed geomorphological and environmental assessment, based on the new surveys, the core transect, as well as the archaeological context will be presented in later *Europe's Lost Frontiers* volumes.

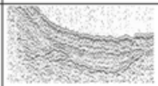
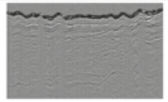
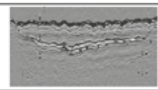
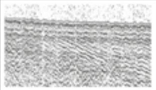
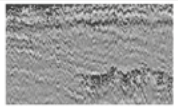
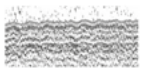
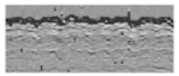
ELF Seismic Facies	ELF Example	ELF Character	ELF Reflector Configuration	ELF Interpretation	Tappin et al. 2011 (Humber REC)	Tappin 2011 Interpretation	Roberts et al. 2018	Roberts 2018 Units
SRF1 Chaotic Background		Variable frequency, low continutity	Chaotic bound by trunction above.	Boulder Clay from the Last Glacial Maximum		Boulders Bank Formation		DB4 Boulders Bank Formation Boulder Clay
SRF2 Tunnel Valley Infill		High Amplitude, High Frequency, Moderate internal continuity	Moderately chaotic with some interal parallel reflectors. Cut into SRF1 deposts.	Late Devensian Tunnel Valley infilled with contemporanious Fluvio-glacial deposits.		Late Glacial valley infill		DB5 Botney Cut Formation
SRF3 Holocene Floodplain		High Amplitude, medium frequency, high continuity	Aggrading, Parallel. Largely conformable, with a very strong amplitude reflector at base found near to SRF8 and SRF7	Floodplain deposits - most likely silts and clays, moving into tidal flat deposits. Roberts et. al. 2018 sampled the associated terrestrial peats with C14 dates ranging from 9.9 to 9.7 Ka BP		Holocene Sediments	UNRESOLVED	Unassigned - although peat units from this area ascribed to DB6 (Holocene)
SRF4 Chaotic Channel Infill		Variable frequency low internal continuity	Highly Chaotic mass, bound by base channel reflector. Cut into SRF1 deposits	Latest Glacial/Earliest Holocene Fluvial Deposits - most likely sands and gravels	UNRESOLVED	Unassigned	UNRESOLVED	Unassigned - although may relate in part to DB5
SRF5 Holocene Channel Infill		High Amplitude, low frequency, low internal continuty	Small rumer of reflectors, bound by base channel refector. Cut into SRF1 deposits. Opacity seen in some channels	Early Holocene Fluvial deposits. Opacity most likely caused by channel sands filled with gas		Holocene Sediments	UNRESOLVED	Unassigned
SRF6 Laminated Channel Infill		High Amplitude, medium frequency, high continuity	Aggrading to Parallel with base usually cut into SRF1 deposits. Often overlies SRF6 and/or SRF7 deposits.	Laminated Silts and clays associated with muddy tidal flats and esturine activity		Holocene Sediments	UNRESOLVED	Unassigned - although note in some cores laminated units below peat beds assigned to DB6 (Holocene)
SRF7 Modern Drape		Low Amplitude, high frequency, continuous across dataset	Aggrading, Parallel.	Seafloor, with shallow modern sands		Modern Seabed Sands		DB7 Holocene Seabed sediments

Table 6.2 Seismic facies within the Southern River system

Chapter 7

Establishing a lithostratigraphic and palaeoenvironmental framework for the investigation of vibracores from the southern North Sea

Martin Bates, Ben Gearey, Tom Hill, David Smith,
John Whittaker and Erin Kavanagh

Introduction

Pivotal to the aims and associated objectives of the Lost Frontiers project, two phases of fieldwork in the southern North Sea resulted in the recovery of 78 cores varying in length from less than 1m to greater than 5m. These cores span a wide geographic space and many topographic locations from the top of the Doggerbank to a submerged palaeovalley system off the Norfolk coast (Figure 7.1). Additionally, some cores targeted geomorphological saddles between drowned valleys and the interfluves between palaeovalley systems, while others were taken on the margins of assumed submerged lakes or estuaries. This paper sets out our methodology and rationale for the development of a lithostratigraphic and subsequent multiproxy palaeoenvironmental analytical workflow, for the assessment and analysis of cores deemed to be of greatest potential to reconstruct the landscape evolution of Doggerland. Such investigations assisted in the initial provision of first order geological and geomorphological settings for the recovered cores,

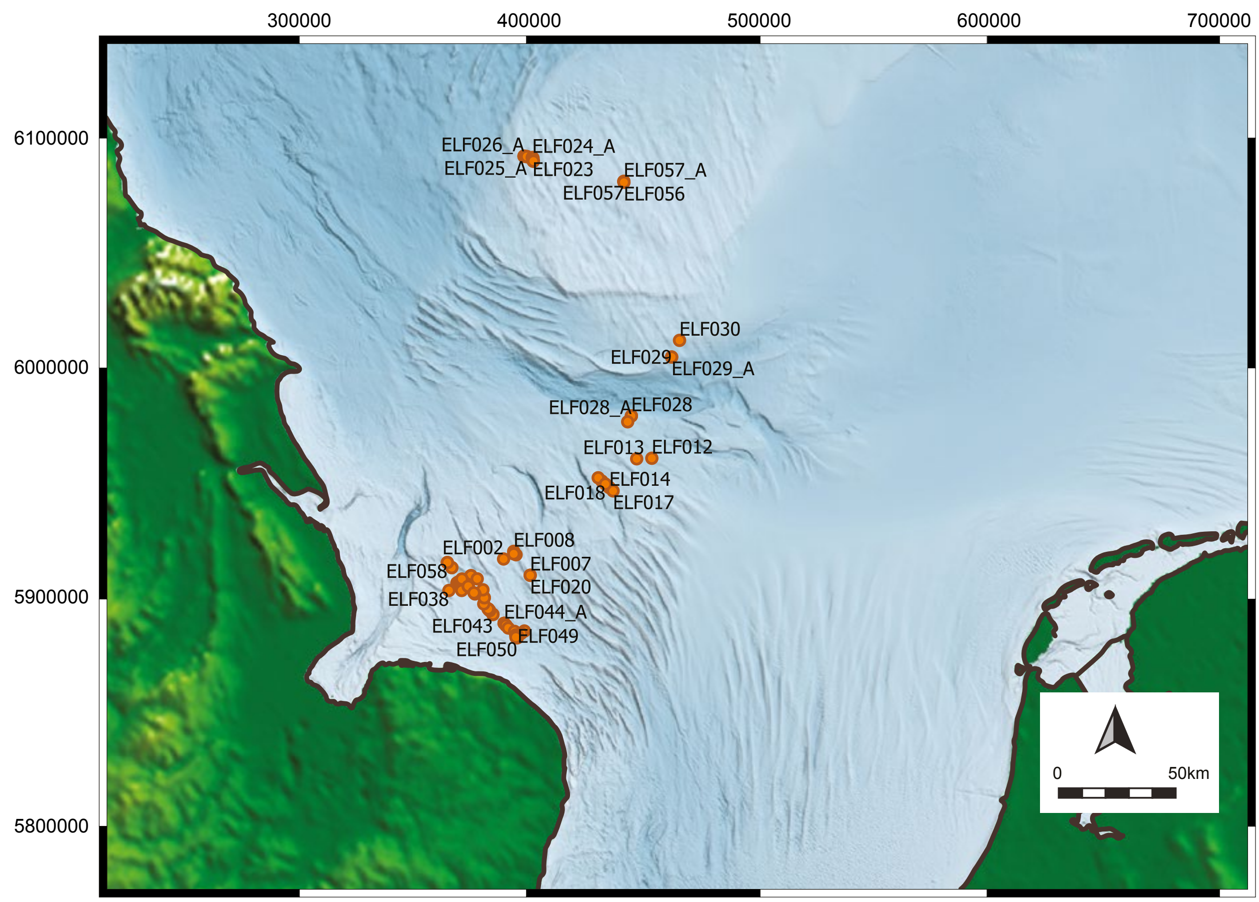


Figure 7.1 Distribution of cores taken during Europe's Lost Frontiers

to guide the subsequent identification of the most appropriate proxy assessments to be applied.

Core recording and sampling

Core processing was undertaken in order to deliver material to a range of specialists working on diverse materials in the project (Figure 7.2). In order to satisfy the needs of individual specialists the following workflow was adopted from the outset of the project:

1. Core cutting was carried out under controlled conditions at the University of Warwick laboratories. Cutting of cores and initial sampling for preserved sedimentary DNA (Allaby *et al.* this volume) was undertaken within environmentally controlled laboratories in order to minimise chances of sample contamination by modern DNA. In addition, cutting was undertaken under red light so as to minimise likely light contamination of sediments designated for Optically Stimulated Luminescence (OSL) profiling and dating (Kinnaird *et al.* this volume). After cutting, one half of the core was immediately sealed in black plastic for OSL dating. The other half of the core was rapidly scanned and locations for the recovery of sedaDNA samples identified and samples taken (Figure 7.2). The sampled cores were sealed in plastic and both halves of the core were returned to cold storage at the University of Wales Trinity Saint David (UWTSD) laboratories in Lampeter, Ceredigion.
2. Core recording was undertaken at UWTSD laboratories in Lampeter where cores were photographed (Figure 7.3 and 7.4), recorded and sub-sampled for rapid calcareous microfossil (foraminifera and ostracoda) assessments and initial 'rangefinder' radiocarbon dating. Samples were taken from key lithological units (Figure 7.3B).
3. Profiling and sub-sampling of cores for OSL dating was also undertaken in the laboratories at UWTSD.
4. Upon completion of the preliminary rapid assessments, sampling for palaeoenvironmental assessments (pollen, diatoms, mollusca) could be initiated (Figure 7.3), and was also undertaken at UWTSD. Phase 1 was a low resolution, preliminary assessment, focussing on stratigraphy deemed to be of the greatest interpretative value for each analytical technique (such as organic horizons, fine grained minerogenic horizons, or where mollusca were visible).
5. Upon completion of Phase 1, further high-resolution sampling was undertaken (Phase 2) within the stratigraphic units where proxies were found to be present in sufficient abundance and diversity for full analyses to be achieved. This included the high-resolution radiocarbon dating sampling to improve the chronological control provided from preliminary range-finder dates.
6. Once all dating and proxy sampling was completed to achieve full analysis investigations, the remaining organic units (predominantly peats or organic-rich silts and clays) were subdivided into bulk samples (Phase 3). These were for macrofossil palaeoenvironmental investigations (beetles and waterlogged plant remains) requiring large sample volumes to return suitable counts.

Stratigraphic and associated environmental methodologies of core sampling

As outlined in the workflow above, due to the large number of cores and associated samples, combined with the need to produce a basic lithological model of the recovered material, it was decided that during lithostratigraphic logging, key units would be sampled and subject to a rapid assessment for the preservation of foraminifera and ostracods. This would provide a basic characterisation of the key environments of deposition. In conjunction with this, sampling for range-finder 14C dates were also undertaken, to provide a crude chronological framework for the data being developed. Upon completion of the initial rapid assessments and preliminary dating, Phases 1-3 of the palaeoenvironmental workflow was undertaken. A summary of the relevant methodologies is now provided

Lithostratigraphic assessments of core profiles

Core recording procedures follow the guidelines of Jones *et al.* (1999) (Table 7.1). Full details of all cores and recording are presented in Table 7.2. The basic lithostratigraphic profiles produced from the core logging have been drawn into sections to facilitate interpretation (Figure 7.5). The lithology recorded exhibits the range of commonly occurring facies types typically associated with tide dominated estuaries (*sensu* Dalrymple *et al.* 1992).

Foraminifera and ostracod rapid assessments

Of the samples selected for rapid palaeoenvironmental assessments, each was broken into smaller pieces by hand, placed in ceramic bowls and dried in an oven. After drying, a small quantity of sodium carbonate was added (to facilitate the removal of the clay fraction). The sediment mix was immersed in hot water and because of the high organic content of many of the samples, was left to soak overnight; for some this process had to be

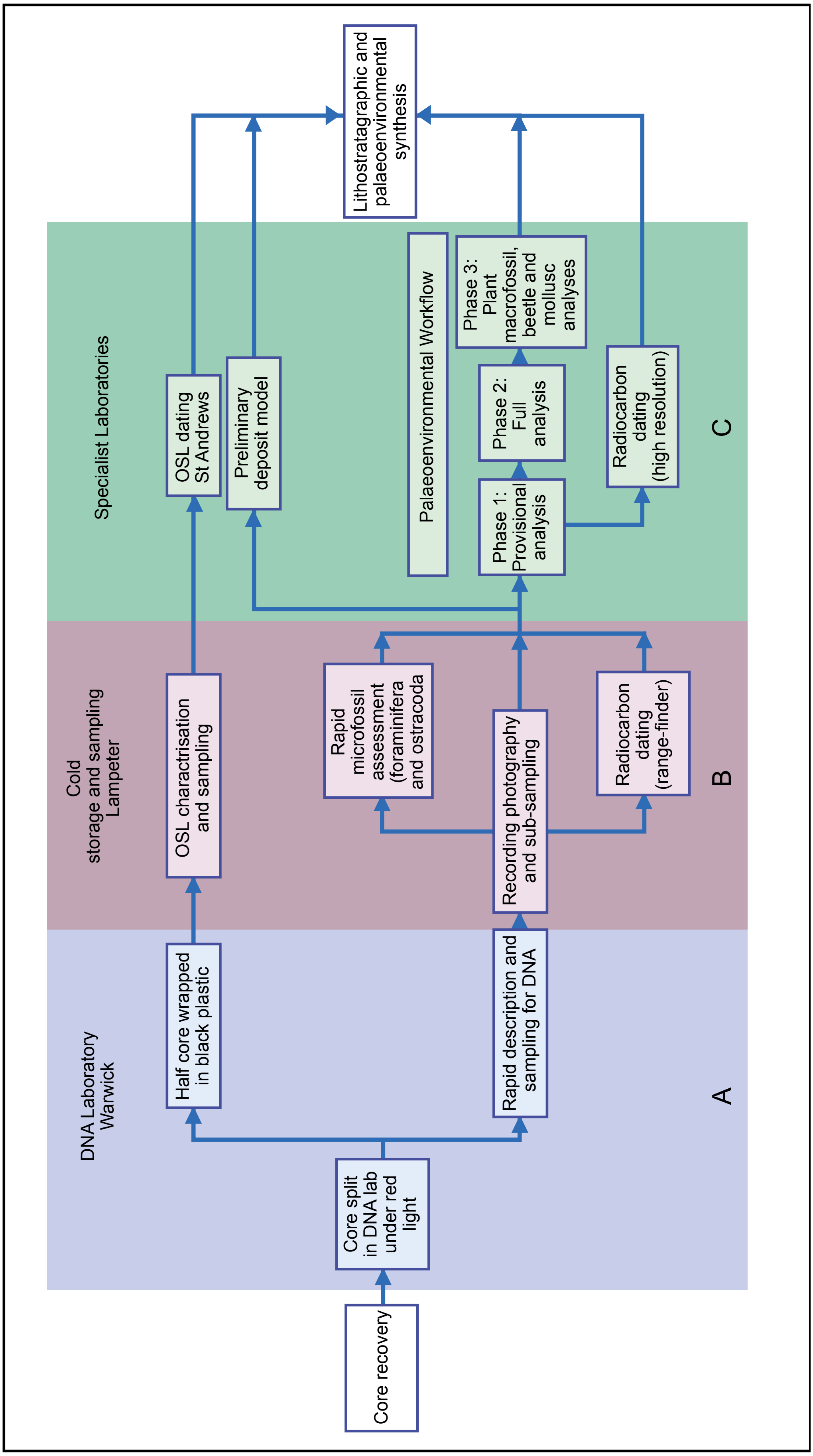


Figure 7.2 Flow diagram illustrating pathways of samples in the laboratory.

Figure 7.3 Cold storage facility for the Lost Frontiers Project at Lampeter (Left). Core recording (Right).

repeated to achieve a full breakdown. Sediment was then washed through a 75-micron sieve with hand-hot water, the resulting residue being returned to the bowl for drying. Once thoroughly dry, the residue was transferred to plastic labelled bags for storage and picking. For examination, the residue was first sieved through a nest of >500µ, >250µ and >150µ sieves. Sediment from each grade was then picked by sprinkling a small amount of residue onto a tray and examining it under a binocular microscope. A representative selection of material from each sample (foraminifera, ostracods and other sub-fossil material) of potential environmental value was picked out into 3x1 inch plastic faunal slides and recorded on a presence/absence basis (see Tables 7.3 and 7.4). Only foraminifera and ostracods were identified to species level.

The ecological preferences of the microfaunas are based on one of the authors own observations (JEW), and on the work of Murray (2006) for the foraminifera, and Athersuch *et al.* (1989) and Meisch (2000) for the brackish/marine and freshwater ostracods, respectively. All foraminiferal and ostracods are grouped and colour-coding in order to document the main ecological groups

Dating

There were two stages to the radiocarbon dating programme: an initial selection of samples for 'rangefinder' dating, followed by a more focussed programme of sample selection, based on the results of these 'rangefinder' dates and the various proxy assessments (see below). A full description of the radiocarbon dating programme including Bayesian modelling of the chronologies is presented in Hamilton and Kinnaird (this volume). Optically Stimulated Luminescence dating was also undertaken on selected cores (see Kinnaird *et al.* this volume).

Pollen assessment and analyses

Sub-samples for assessment (Table 7.5) were selected from vibrocores on the basis of sediments most likely to preserve pollen; hence predominantly organic units such as peats and silts. On the basis of the assessment stage and the rangefinder radiocarbon dating (see above), seven sequences were selected for full analyses.

Sub-samples were taken at regular intervals, dependent on the thickness of the stratigraphic unit under question. Pollen preparation for all samples followed standard techniques including KOH digestion, HF treatment and acetylation (Moore *et al.* 1991). Pollen concentrations were established by adding a known concentration of *Lycopodium clavatum* spore (batch number 161018201) to the samples before treatment (Stockmarr 1971). Pollen counts were made using a Leica DM 1000 LED microscope at x400, x800 and x1000 magnification under oil immersion for critical examination of pollen sculpture and measurement of pollen grains. A minimum terrestrial pollen sum

Project	Europe's Lost Frontiers	**Borehole**	ELF 045
Easting	393559.6	**Northing**	5885524
Elevation	-27m O.D.	**Date drilled**	
Date to laboratory		**Date recorded**	4/4/18
Date sampled	4/4/18	**Location of samples**	Lampeter Cold Store
Depth below ground surface (m)	**Depth O.D.**	**Lithological description**	
0.00-0.20	-27.00 - -27.20	Greyish brown, medium, sand with common shell fragments, some articulated. Structureless.	
		--- Diffuse Contact---	
0.20-0.41	-27.20 - -27.41	Greyish brown, becoming grey with depth, slightly silty medium sand with shell fragments <1cm. Structureless. Moderately compact.	
		--- Sharp Undulating Contact---	
0.41-0.75	-27.41 - -27.75	Grey silt with grey, medium, silty sand patches. Finely laminated in places. Extensive burrowing filled with sand as above.	
		--- Sharp Contact ---	
0.75-1.40	-27.75 - -28.40	Dark grey, laminated, slightly sandy silt with thin laminations of fine sand, typically 0.5cm-1cm in thickness. Occasional dark brown organic laminations, Occasional shell fragments. Burrowing continues to about 1.10.	
		--- Abrupt Contact ---	
1.40-2.94	-28.40 - -29.94	Mid grey clay silt with occasional darker grey, slightly organic, horizon, Occasional thin sand beds 1cm in thickness. Occasional thin dark brown organic laminations, quite soft.	
		--- Abrupt Contact ---	
2.94-3.02	-29.94 - -30.02	Dark greyish brown silty fine sand with common organic fragments.	
		--- Diffuse Contact ---	
3.02-5.21	-20.02 - -32.21	Grey to dark grey laminated sandy silt with thin fine sand laminations. Occasional dark brown silty fine sand.	
		--- Sharp Dipping Contact ---	
5.21-5.46	-32.21 - -32.46	Dark grey shelly silty sand, becoming coarser sand with depth. Small stones towards base. Possibly bedded.	
		--- Base 5.46 ---	

Table 7.1. ELF 045, lithology table.

of 500 pollen grains, excluding spores and aquatics, was employed. Indeterminate grains include broken, degraded and obscured grains. Pollen grains were identified mainly using the key of Moore *et al*. (1991), Beug (2004) and the pollen reference collection at the University College Cork, with reference to Fægri *et al*. (1989). The nomenclature employed followed Stace (1997) with suggestions from Bennett *et al*. (1994).

The designation '*cf* ' indicates that this was the closest identification possible but not an exact match, or that type material was not available to confirm the identification. *Cerealia*-type pollen (cereal) was distinguished from other Poaceae (grass) pollen based on size of grain pore and annulus and were presented in a separate curve (cf. Beug 2004). Monoporate pollen grains of less than 39µm were placed in the Poaceae (non-cultivated grass) curve. The difficulty in the separation of *Myrica gale* (sweet-gale) and *Corylus avellana* (hazel) pollen resulted in these grains being classified as *Corylus avellana*-type (Edwards 1981). For the saccate grains of *Pinus* (pine) the individual air sacs were counted and subsequently divided by two, in order to estimate the number of grains. The programmes TILIA and TILIA-GRAPH (Grimm 2013) were used to construct spreadsheets and pollen diagrams. The pollen sum consists of total land pollen grains (TLP), excluding aquatics and spores.

Diatom assessments

Sub-samples for assessment were selected from vibrocores on the basis of sediments most likely to preserve diatoms; hence predominantly minerogenic units and organic-rich silts (Table 7.5). On the basis of the assessment stage and the rangefinder radiocarbon dating (see above), seven sequences were selected for full analyses.

0.5g of sediment was required for diatom assessment preparation. All samples were first tested with dilute HCl to assess for carbonate content prior to the

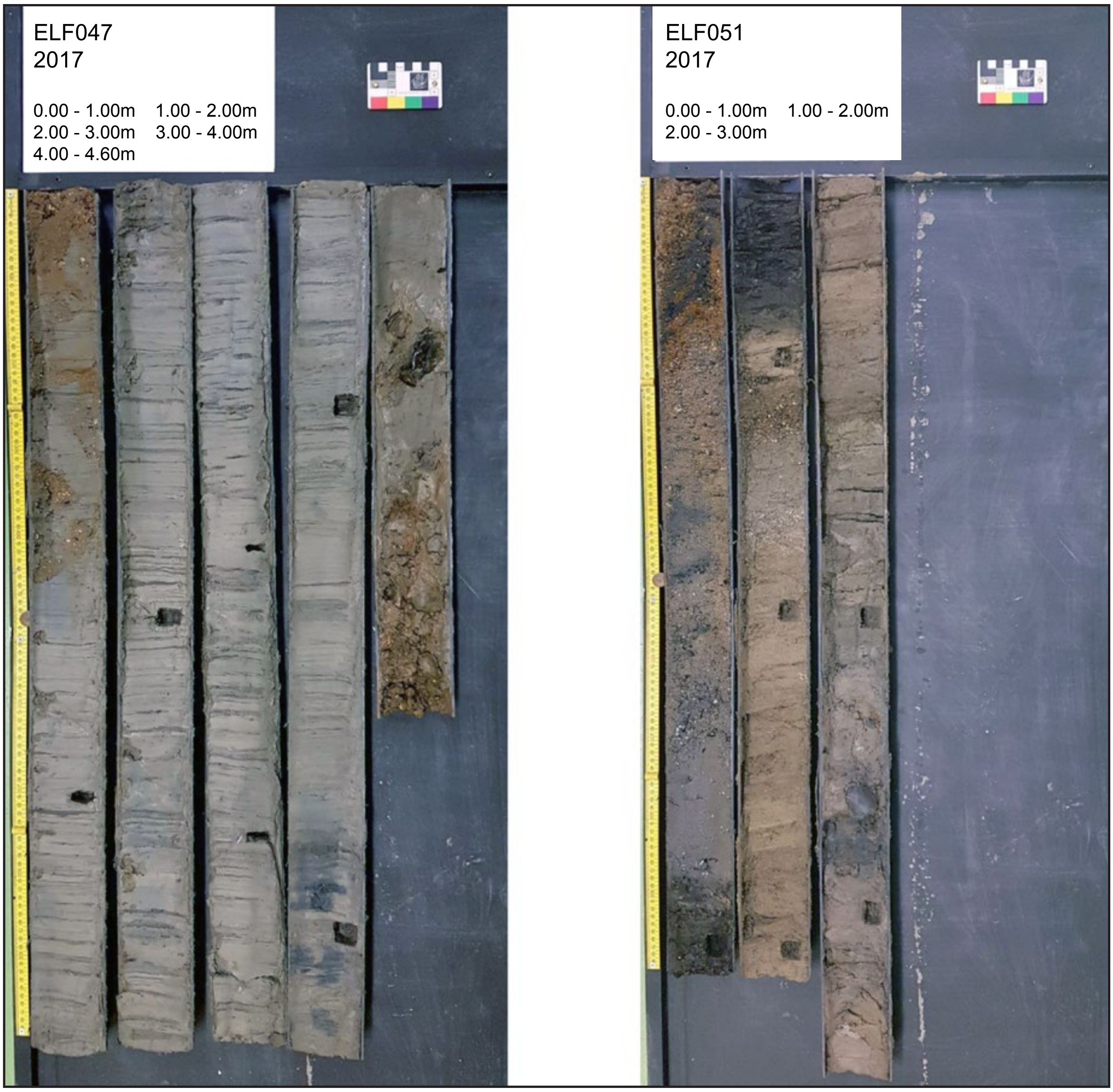


Figure 7.4 Cores ELF 47 and ELF 51.

initiation of sample preparation. In the majority of cases, HCl reactions were minimal and hence the need for subsequent carbonate removal pre-treatments was unnecessary. Due to the high silt and clay content of most samples, samples were then treated with sodium hexametaphosphate and left overnight, to assist in minerogenic deflocculation. Samples were then treated with hydrogen peroxide (30% solution) depending on organic carbonate content. Samples were finally sieved using a 10μm mesh to remove fine minerogenic sediments. The residue was transferred to a plastic vial, from which a slide was prepared for subsequent assessment.

For samples undergoing an initial assessment of potential, if present, a minimum of 100 diatom valves were identified. If preservation was found to be poor, ten slide traverses were undertaken in an attempt to extract the diatom data available from the sample under assessment. For samples proceeding to full analysis, a minimum of 300 diatoms were identified for each sample depth. Diatom species were identified with reference to van der Werff and Huls (1958-74), Hendy (1964) and Krammer & Lange-Bertalot (1986-1991). Ecological classifications for the observed taxa were then achieved with reference to Vos and de Wolf (1988; 1993), Van Dam *et al.*, (1994), Denys (1991-92; 1994) and Round *et al.* (2007).

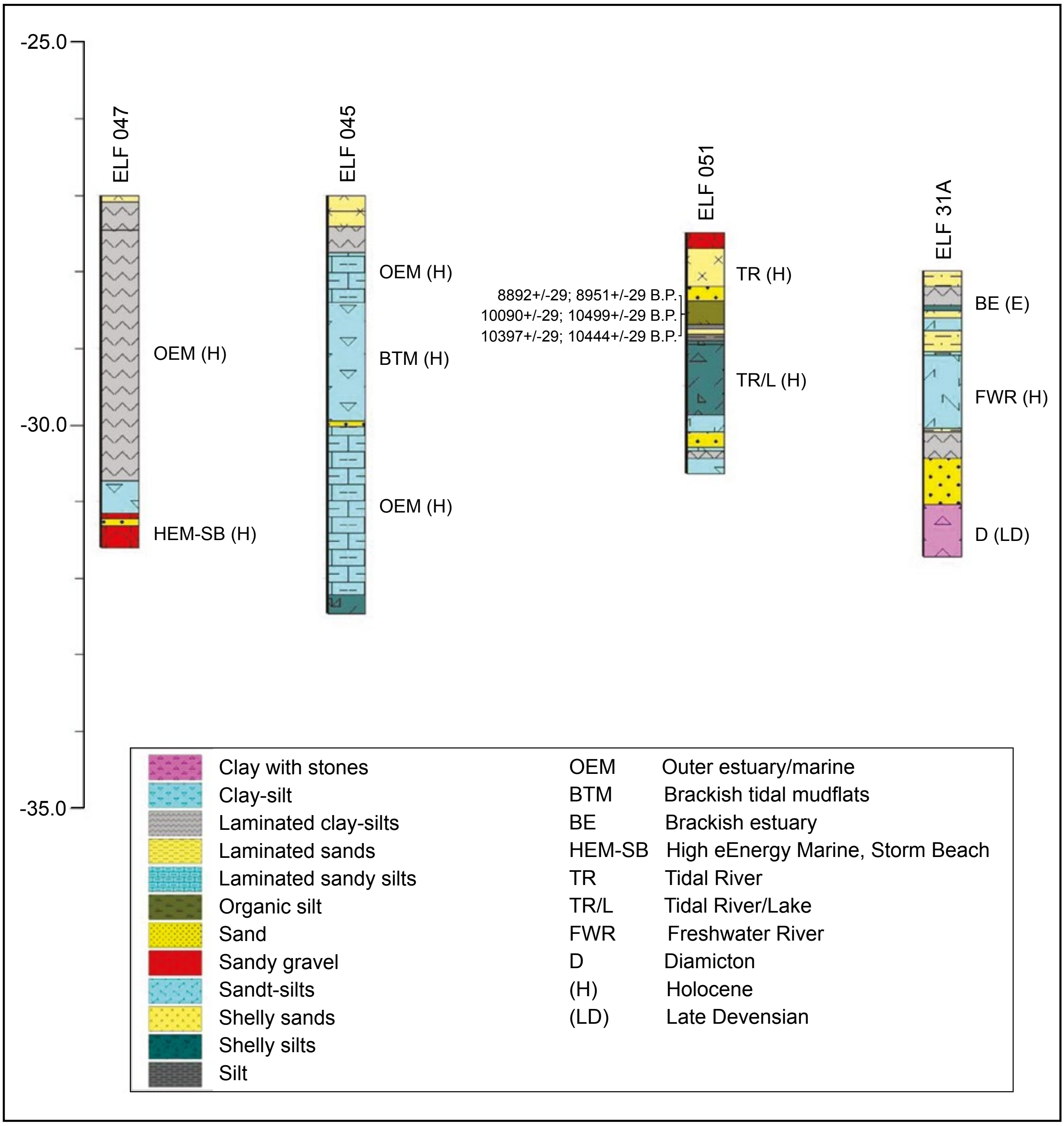


Figure 7.5 Basic lithological profiles drawn up in the Southern Valley.

Assessment and sampling of macrofossils from the cores

During the assessment for Foramifera and Ostracods the presence and quality of a number of other macrofossils was also recorded. This included molluscs, plant and insect remains. Based on this assessment, and the description and lithography of the cores themselves, a number of locations in the cores were selected for further sampling for macrofossils.

The sampling for macrofossils (Table 7.6) followed late in the project since there was a need to ensure that all other samples that need to be taken for dating and other forms of analysis had occurred first. This is down to the relatively large volume of material needed for such work (normally >1l). This resulted in the 'emptying' of selected cores, or parts of cores, for which plant macrofossil/insect/mollusc works was to be undertaken on.

Core	Description	Photograph	Samples	Core scan	Fossil material	14C	OSL (P1, P2, D)
ELF 001A	Y	Y	17	Y	Y	Y	Y (P1, P2, D)
ELF 002	Y	Y	9	N	Y	Y	Y (P1)
ELF 003	Y	Y	12	N	Y	Y	Y (P1)
ELF 004	Y	Y	9	N	Y	N	N
ELF 005	Y	Y	12	N	Y	Y	N
ELF 005A	Y	Y	10	N	Y	Y	N
ELF 005B	Y	Y	8	N	Y	Y	Y (P1, P2)
ELF 006	Y	Y	6	N	Y	N	Y (P1, P2)
ELF 007	Y	Y	10	N	Y	Y	N
ELF 008	Y	Y	4	N	Y	N	N
ELF 009	Y	Y	11	N	Y	Y	N
ELF 010	Y	Y	7	N	Y	N	N
ELF 011	Y	Y	4	N	Y	N	N
ELF 011A	Y	Y	7	N	Y	N	N
ELF 012	Y	Y	4	N	Y	N	Y (P1, P2)
ELF 013	Y	Y	6	N	Y	N	N
ELF 014	Y	Y	3	N	Y	N	N
ELF 015	Y	Y	1	N	N	N	N
ELF 016	Y	Y	2	N	N	N	N
ELF 017	Y	Y	1	N	N	N	N
ELF 018	Y	Y	5	N	Y	Y	N
ELF 019	Y	Y	14	Y	Y	N	Y (P1, P2, D)
ELF 020	Y	Y	9	N	Y	Y	N
ELF 021	Y	Y	-	N	-	N	N
ELF 021A	Y	Y	2	N	Y	N	N
ELF 022	Y	Y	16	N	Y	N	Y (P1)
ELF 023	Y	Y	3	N	N	N	N
ELF 023A	Y	Y	3	N	Y	N	N
ELF 024A	Y	Y	3	N	N	N	N
ELF 025A	Y	Y	-	N	-	N	N
ELF 025B	Y	Y	3	N	Y	N	N
ELF 026	Y	Y	2	N	Y	N	N
ELF 026A	Y	Y	3	N	Y	N	N
ELF 027	Y	Y	10	N	Y	N	Y (P1)
ELF 028	Y	Y	1	N	Y	N	N
ELF 028A	Y	Y	-	N	-	N	N
ELF 029	Y	Y	4	N	Y	N	N
ELF 029A	Y	Y	6	N	Y	N	N
ELF 030	Y	Y	14	N	Y	N	N
ELF 031	Y	Y	7	N	Y	N	N
ELF 031A	Y	Y	14	N	Y	N	Y (P1)
ELF 032A	Y	Y	6	N	Y	N	N
ELF 033	Y	Y	12	N	Y	N	N
ELF 033A	Y	Y	6	N	Y	Y	N
ELF 034	Y	Y	11	N	Y	Y	Y (P1)
ELF 034A	Y	Y	4	N	Y	Y	N
ELF 035	Y	Y	2	N	Y	N	N

Core	Description	Photograph	Samples	Core scan	Fossil material	14C	OSL (P1, P2, D)
ELF 036	Y	Y	2	N	Y	N	N
ELF 037A	Y	Y	5	N	Y	N	N
ELF 038	Y	Y	2	N	Y	N	N
ELF 039	Y	Y	14	N	Y	N	Y (P1)
ELF 040A	Y	Y	13	N	Y	N	Y (P1)
ELF 041	Y	Y	4	N	Y	N	N
ELF 042	Y	Y	11	N	Y	N	Y (P1)
ELF 043	Y	Y	-	N	-	N	N
ELF 044	Y	Y	7	N	Y	N	N
ELF 044A	Y	Y	8	N	Y	N	N
ELF 045	Y	Y	11	N	Y	N	Y (P1)
ELF 046A	Y	Y	11	N	Y	N	N
ELF 047	Y	Y	12	N	Y	N	Y (P1)
ELF 047A	Y	Y	5	N	Y	N	N
ELF 048	Y	Y	2	N	Y	N	N
ELF 049	Y	Y	15	N	Y	N	Y (P1)
ELF 050	Y	Y	2	N	Y	N	N
ELF 051	Y	Y	14	N	Y	N	Y (P1)
ELF 052	Y	Y	3	N	Y	Y	N
ELF 053	Y	Y	12	N	Y	N	Y (P1)
ELF 054	Y	Y	11	N	Y	Y	Y (P1)
ELF 055	Y	Y	2	N	N	N	N
ELF 056	Y	Y	-	N	-	N	N
ELF 056A	Y	Y	-	N	-	N	N
ELF 057	Y	Y	1	N	Y	N	N
ELF 057A	Y	Y	3	N	Y	N	N
ELF 058	Y	Y	-	N	-	N	N
ELF 058A	Y	Y	-	N	-	N	N
ELF 059	Y	Y	11	N	Y	N	N
ELF 059A	Y	Y	8	N	Y	N	N
ELF 060	Y	Y	10	N	Y	N	Y (P1)
Total	**78 cores**		**502 samples**				

Table 7.2. Cores sampled in project. Abbreviations as follows: P1, profile 1, uncalibrated OSL; P2, profile 2, calibrated OSL; D, OSL sediment ages.

The areas of the cores identified as being of interest were normally sampled in 10cm lengths (which has the potential to produce enough material for a suitable sample from this size of core) unless there are any obvious stratigraphic divisions that had to be taken into account.

Sample processing for macrofossils from the cores

The samples obtained from the cores for macrofossil analysis were prepared as a 'chained' sample. Normally 'general biological samples' such as these weigh around 10 kg and can be subdivided for each specialism. Due to the small volume of material per sample available from the cores it was decided that the same sample would be processed for each type of macrofossil in a distinct sequence or 'chain'.

The sample was sieved over a 300-micro mesh sieve following the process for plant macrofossils outlined in Kenward *et al* (1980). Plant remains were then extracted from the material. The remaining material is then available for mollusc/vertebrate material extraction. Finally, the same material was paraffin floated (see Kenward *et al*. 1980) to recover any insect remains present. A X7-40 stereo-microscope was used throughout this process.

DEPTH IN CORE	0.60-0.62m	0.98-1.00m	1.20-1.22m	1.60-1.62m	2.20-2.22m	2.60-2.62m	3.20-3.22m	3.60-3.62m	3.98-4.00m	4.10-4.12m	4.24-4.26m	4.50-4.52m
DEPTH (LAT)	27.60-27.62m	27.98-28.00m	28.20-28.22m	28.60-28.62m	29.20-29.22m	29.60-29.62m	30.20-30.22m	30.70-30.62m	30.98-31.00m	31.10-31.12m	31.24-31.26m	31.50-31.52m
CONTAINED MATERIAL												
plant debris	x	x	x	x	x	x	x	x	x	x	x	
molluscs	f + j	j	f + j	f + j		j	j	f + j	f + j	x	x	
diatoms (>75μ)	x	x	x	x	x	x	x					
brackish foraminifera	x	x	x	x	x	x	x	x	x	x	x	x
outer estuarine/marine foraminifera	x	x	x	x	x	x	x	x	x	x	x	x
outer estuarine/marine ostracods	x	x	x	x	x	x	x	x	x	x	x	x
brackish ostracods	x	x			x	x	x	x	x	x	x	
freshwater ostracods									x	x	x	
stones											x	x

Contained material is recorded on a presence (x) / absence basis; f – fragments; j – juveniles only

Table 7.3. Example of data from rapid assessment of cores samples.

DEPTH IN CORE	0.60-0.62m	0.98-1.00m	1.20-1.22m	1.60-1.62m	2.20-2.22m	2.60-2.62m	3.20-3.22m	3.60-3.62m	3.98-4.00m	4.10-4.12m	4.24-4.26m	4.50-4.52m
DEPTH (LAT)	27.60-27.62m	27.98-28.00m	28.20-28.22m	28.60-28.62m	29.20-29.22m	29.60-29.62m	30.20-30.22m	30.70-30.62m	30.98-31.00m	31.10-31.12m	31.24-31.26m	31.50-31.52m
Ecology	*Outer estuary, initially forming in Early Holocene at seaward end of valley feature (on till landscape). Latterly with less marine influence, perhaps due to changing position of estuary mouth.*											
BRACKISH FORAMINIFERA												
Ammoniasp. (brackish)	x	xx	x	xx	xx	xxx	xxx	xxx	xxx	xx	xxx	x
Haynesina germanica	x	x		x	x	x	x	x	xx	x	x	
Elphidium williamsoni	x	x	xx	x	xx	xx	xx	xx	xx	x	x	
Trochammina inflata									o			
OUTER ESTUARINE/MARINE FORAMINIFERA												
Nonion depressulus	x	x	x	x	o	x	x	x				
miliolids	x	x	x	x	x	x	x	x	xx	xx	xxx	x
lagenids		o										
Elphidium macellum			x						x			
Ammonia batavus					xx			x		xx	x	
Elphidium margaritaceum						x	o	x	x	x	x	
Elphidium excavatum						x	x	x	x	x	x	
Nonion orbicularis											o	
OUTER ESTUARINE/MARINE OSTRACODS												
Palmoconcha guttata	x	xx	x	x		x	x	x	x	x	x	o
Hirschmannia viridis	x	x	x	x	x	x	x	x	x	x	x	o
Bonnyannella robertsoni		o					x					
Hemicythere villosa			o		o	x	o	x	x	x	x	
Heterocythereis albomaculata					x	x	x	o	x	o	x	
Hemicyherura clathrata					o							
Semicytherura nigrescens						x	x	o			o	
Leptocythere pellucida								o	o			
Pontocythere elongata								o		o		
Robertsonites tuberculatus									o		o	
Palmoconcha laevata											x	
BRACKISH OSTRACODS												
Leptocythere castanea	o									o	o	
Leptocythere lacertosa	o	x				o	x					
Xestoleberis nitida					o	o	x	x		x	o	
Cyprideis torosa							x		x	x	o	
Cytherois fischeri								x				
Loxoconcha elliptica									o		o	
FRESHWATER OSTRACODS												
Cytherissa lacustris									o	o	o	

Foraminifera and ostracods are recorded: o – one specimen; x – several specimens; xx – common; xxx – abundant

cold/cool indicator, extinct in Britain since Early Holocene

cold/cool indicator

cold/cool freshwater indicator

Table 7.4 Detailed assessment of microfossils from ELF 047.

Cores selected for assessment	Cores selected for analysis
001A, 002, 003, 005, 007, 009, 019, 020, 031A, 034, 039, 045, 051, 054	001A, 002, 007, 020, 034, 051, 054

Table 7.5. Cores selected for pollen and diatom investigation.

Core number	Number of samples
ELF 002	3
ELF 007	3
ELF 020	6
ELF 034	19
ELF 39	2
ELF 51	22
ELF 54	12

Table 7.6. Cores samples for macrofossil analysis.

Any plant remains recovered were identified under a low power binocular microscope. Species identification were made through plant reference collections and the Digital seed Atlas of economic plants (Cappers *et al.* 2010). Material that could not be identified using these sources were compared to the more extensive collection housed at Historic England, Fort Cumberland. Ecological interpretation used a number of plant flora.

Molluscs were identified to species level where possible under a low-power binocular microscope in consultation with a reference collection. Ecological interpretation was carried out with reference to standard sources for marine and non-marine Mollusca (Graham 1971; Evans 1972; Macan 1977; Kerney and Cameron 1979; Kerney 1999; Killeen *et al.* 2004; Davies 2008; Allcock *et al.* 2017). Nomenclature followed WoRMS Editorial Team (2020) for marine fauna, and Anderson and Rowson (2020) for non-marine Mollusca. The assemblage is discussed in relation to its ecological, biogeographical and climatological implications, and consideration made of the taphonomy of the assemblage. Where appropriate, standard statistical analyses will be undertaken, as outlined in Claassen (1998) and Law (2017).

Insect identification occured using a 7-40x binocular microscope and by direct comparison to the Girling and Gorham collections of British Coleoptera housed at the University of Birmingham. Ecological interpretation are drawn mainly from Buckland and Buckland (2006). Where appropriate basic statistical analysis will be based on Kenward (1978) and Kenward and Hall (1995).

Chapter 8

Sedimentary ancient DNA palaeoenvironmental reconstruction in the North Sea landscape

Robin Allaby, Rebecca Cribdon, Rosie Everett and Roselyn Ware

Introduction – the rise of sedimentary DNA as a tool

Background

A key objective of *Europe's Lost Frontiers* was to recover floral and faunal information from the Early to Mid-Holocene period from ancient DNA that persists in the sediments of the North Sea, offering the potential of unprecedented insight into the ecology of Doggerland. Ancient DNA (aDNA) has been the subject of investigations for over three decades from various biological remains, however the neoteric retrieval of ancient DNA from permafrost and cave sediments was both a major, surprise discovery and opened up a new vista of possibilities in palaeoenvironmental reconstruction (Willerslev *et al.* 2003). Sedimentary ancient DNA (sedaDNA) is diffuse environmental DNA which can be taken from a variety of sources, including permafrost, ice, soils, lake and marine sediments, cave deposits, and middens (Rawlence *et al.* 2014). In recent years these sources of aDNA have been used in the development of palaeoenvionmental reconstructions (Parducci *et al.* 2012; Pederson *et al.* 2013; Rawlence *et al* 2014), the study of human-environment interactions (Pansu *et al.* 2015), studying past catastrophic events (Szczuciński *et al.* 2016), the study of mass floral or faunal extinction events (Graham *et al.* 2016; Haile *et al.* 2009; Seersholm *et al.* 2020), studies of historical climate variation (Alsos *et al.* 2016a; Crump *et al* 2019; Sønstebø *et al.* 2010; Wood *et al.* 2018), hominin reconstructions from cave sediments (Slon *et al.* 2017; Zhang *et al.* 2020), and to assess water quality changes (Dixit *et al.* 1999). It is also possible to identify functional genes within the sediment to assess functioning of an ecosystem (Corinaldesi *et al.* 2008), and to identify novel antibiotic metabolisms from unculturable bacteria (D'Costa *et al.* 2011; Séveno *et al.* 2002).

Ancient sedaDNA is in many ways comparable in scope to the study of modern environmental DNA (eDNA), itself a disciplinary child of sedaDNA research that examines not only modern sediments as sources of DNA, but also other environmental sources such as ice (Alsos *et al.* 2016b; Bayless *et al.* 2015), water from lakes, rivers and marine sources (Pederson *et al.* 2015), and even air (Folloni *et al.* 2012).

The ubiquity of sources of sediment has led to an increasing interest in sedaDNA sequencing. Typical sources of aDNA, such as plant and animal remains, are often very limited in the archaeological record, and are variably preserved depending on environmental contexts. The destructive sampling typical of aDNA studies leads to a reluctance to release valuable archaeological remains to this type of analysis (Thompson *et al.* 2009). However, with sedaDNA this is far less of an issue as large volumes of sediment can often be retrieved as required.

However, the utilization of sedaDNA is replete with pitfalls and challenges. Early studies demonstrated dangers of simplistic interpretation of DNA signals, particularly in terrestrial environments where leaching may occur through faunal urination, for instance in Haile *et al.* (2007), leading to the presence of mixed age assemblages. A second type of challenge is in the identification of DNA sources, especially where DNA is similar between species, uncharacterised species are present, or species of interest are themselves model organisms and so difficult to distinguish from false positives. Furthermore, very little research has been directed towards a complete taphonomy of environmental DNA. These challenges led to the development of a number of innovations within *Europe's Lost Frontiers*, discussed in sections below and in detail in a later volume, which substantially increase the level and robustness of sedaDNA interpretation.

Best practice approaches to sedaDNA sampling and contamination sources

General approaches specific to ancient DNA are primarily occupied with avoiding contaminating the samples or enabling the identification of contamination where it occurs. There are many and varied sources of contaminant DNA, originating from the sampler, from the environment that the sample is taken from, from cross-contamination within the aDNA lab, or from the reagents that are used in sample preparation: the 'Kit-ome' (Salter *et al.* 2014). General approaches are widely discussed elsewhere (Poinar *et al.* 2000; Willerslev *et al.* 2005), but briefly, these include the appropriate avoidance of contamination during sampling, the recording of all applicable metadata, use of appropriate aDNA facilities, reagents and equipment whilst extracting and preparing DNA, the use of extraction and library preparation controls, independent replicability of results, amongst others.

When working with sedaDNA, many studies target the metagenome (the total DNA within the sample, rather than from just one target organism). As a result, sedaDNA analysis is particularly vulnerable to contamination, and contamination can be harder to identify. In addition to the traditional approaches, there are sedaDNA-specific considerations that should be observed. Before sampling is undertaken, it is important to attempt to ensure that the sediment has not been physically disturbed, which could dissociate sediment and DNA from their stratigraphic context: This may occur as a result of geological events such as landslides or earthquakes; human driven events such as excavation, agriculture or other activities, modern root growth penetrating through ancient sediments; or movement of fauna (Prosser *et al.* 2018; Willerslev *et al.* 2003).

Another source of modern contamination that can occur before sampling is attempted is the vertical migration of DNA through strata, resulting in modern DNA leaching through into the ancient sediments (Haile *et al.* 2007). This is generally considered to be less likely in dry conditions (Hebsgaard *et al.* 2009). However, only one inundation event in a dry sediment (e.g. a flooding event or use as latrine by animals) could potentially cause leaching (unless sediment is highly compacted). Where permafrost samples have been studied, DNA leaching has not been observed (Hebsgaard *et al.* 2009; Willerslev *et al.* 2004), however historical freeze thaw events in the sample resulting in leaching would be difficult to detect. Some studies select samples from high altitude locations, or places where there are no higher lands that DNA can percolate downwards from (Boessenkool *et al.* 2014). This approach makes the assumption that DNA migration only occurs in a downward direction. For this to be the case, sampling must be from above the water table, especially in low altitude or high rainfall areas. Leaching is thought to be limited in permanently water-saturated sediments (Giguet-Covex *et al.* 2004; Pansu *et al.* 2015). Other factors can impact the extent and rate of DNA leaching through sediment, including the density and compaction of the sediment or the sediment type. In order to assess the extent of DNA leaching, it is necessary to attempt to authenticate the DNA sequenced. If DNA leaching occurs, and modern DNA is present along with ancient DNA, this does not necessarily mean that the data is useless, however, extreme caution must be taken with authentication in order to distinguish between ancient and modern DNA (Skogland *et al.* 2014).

When extracting the samples from the site, and when subsampling from cores, it is crucial that modern DNA is not introduced. Once taken, cores should remain sealed and transported to a clean facility where the core may be opened and subsampled at the core centre (i.e. where they cannot have come into contact with the coring equipment used).

Sampling of sedaDNA from cores has a distinct advantage above many other aDNA sample types in that it is often possible to take samples that represent a distinct time series by sampling along the length of the core. When combined with accurate dating of sediment layers and analysis of appropriate blanks, the extent of both contamination and leaching can be assessed. Comparisons between strata enable differences within the taxa present to be identified. Where taxa can be identified in upper (or younger) strata but not in older strata, confidence is increased that leaching has not occurred (Lejzerowicz *et al.* 2013; Smith *et al.* 2015).

In sediment, there may be metabolically active bacteria, even in permafrost samples (Tuorto *et al.* 2014). This presents two issues. First, this may result in high levels of DNA degradation in these samples by bacterial exonucleases, although DNA adsorption may help prevent this (Ogram *et al.* 1988). Second, the DNA from these bacteria may swamp the signal of the ancient DNA.

Once appropriate levels of precautions have been taken during the sampling procedure, contamination is monitored through controls. It is generally best practice to repeat DNA sequencing runs in duplicate to identify stability of signal, but also to sequence all reagents (blanks). Blanks would be expected to contain common contaminant taxa, allowing these to be filtered out of samples. A level of several percent human DNA contamination is usual in all studies, for instance. *Bona fide* taxa identified in the environment should not occur in the blank controls, taxa unique to samples should be authentic. However, the most robust confirmation of authenticity of sedaDNA is through the identification of patterns of damage through DNA diagenesis.

Ancient DNA in the marine environment

DNA diagenesis and the environment

Once deposited post-mortem, DNA accumulates chemical damage in characteristic patterns which restrict its retrieval and utilization, but also provides a basis of authentication to identify false positive results. These patterns include fragmentation of DNA strands; and deamination of cytosine to uracil (Dabney *et al.* 2013). DNA fragmentation is caused by hydrolytic depurination. In this process, the *N*-glycosyl bond is cleaved, leaving an abasic site that is subject to β-elimination resulting in a double strand break that causes the fragmentation of the strand. As a result, aDNA typically comprises a distribution of low molecular weight (short) fragments. Hydrolytic damage can also lead to miscoding lesions, the most common of which is the spontaneous deamination of cytosine to uracil (Hofreiter *et al.* 2001; Lindahl 1993; Willerslev and Cooper 2005). In double stranded aDNA, there is an elevated level of observed deamination at overhangs (Briggs *et al.* 2007). In contrast to the fragmentation of DNA, the rate of cytosine deamination of these overhangs appears to be a time dependent process, where older samples tend to show a greater number of deamination events (Kistler *et al.* 2017).

Different sediment types are expected to have different DNA preservation profiles. This may be driven by a number of factors: the temperature and thermostability of the sediments, the DNA diffusion rates, the proportion of organic content in the sample, the metabolic activity of bacteria and fungi, and the chemistry of the sample such as pH, salinity and redox potential (Corinaldesi *et al.* 2008). Of these, the temperature and thermostability of the sediments are likely to be the most influential for DNA preservation (Kistler *et al.* 2017). This is reflected in the success of studies using cores taken from ice (Willerslev *et al.* 2007) and permafrost (Haile *et al.* 2009; Sønstebø *et al* 2010; D'Costa *et al.* 2011; Boessenkool *et al.* 2012; Hansen *et al.* 2006; Johnson *et al.* 2007; Bellemain *et al.* 2013; Epp *et al.* 2012; Jørgensen *et al* 2012a; Lydolph *et al.* 2005; Porter *et al.* 2013; Willerslev *et al.* 2003; 2004; 2014). These are at low temperatures, and the ideal samples for aDNA preservation will not have undergone great fluctuations in temperatures or freeze-thaw cycles. These samples have yielded the oldest DNA yet sequenced from macrofossil remains (Orlando *et al.* 2013) and many of the oldest authenticated sedaDNA studies were on permafrost (Hansen *et al.* 2006; Lydolph *et al.* 2005; Willerslev *et al.* 2003; 2007). Another major advantage of using frozen samples, is that DNA leaching is thought to be limited (D'Costa *et al.* 2011; Andersen *et al.* 2012; Hebsgaard *et al.* 2009). However, it is important to consider that not all biochemical processes are halted in frozen samples; indeed, there are metabolically active permafrost bacteria below the freezing point (Rivkina *et al.* 2000).

Frozen samples can typically only be obtained at very high latitudes or altitudes. Conversely, non-frozen sediments, including marine, freshwater, and terrestrial sediments are widely available and can represent a wide range of different environmental types. Some sources of sediment confer additional advantages for DNA preservation, such as the thermostability seen in some types of sediment, as fluctuations in temperature can cause the DNA breakdown rate to increase (Kistler *et al.* 2017).

Marine sediments, in addition to their ubiquity and high DNA concentrations (Dell'Anno *et al.* 2005), are commonly at a stable 4°C due to the supply of cold water conveyed from the polar regions. Water is densest at 4°C, and thus sinks to form stratification of the marine environment by temperature. Additionally, increased salinity increases the density of marine water, causing further stratification (the halocline), with freshwater often settling on top of saline water in poorly mixed water bodies such as fjords. Freezing rarely occurs in deep marine sediments due to high pressures and high salinity, but the stability and cool temperatures means that they have the potential to be excellent sources of sedaDNA (Boere *et al.* 2011; Braker *et al.* 2000; Coolen *et al.* 2006; Coolen *et al.* 2007; Corinaldesi *et al.* 2008; Kim *et al.* 2011; Lejzerowicz *et al.* 2013; Raniello *et al.* 2002; Schipperw *et al.* 2006; Smith *et al.* 2015). It is further likely that the ionic potential of sea water improves DNA preservation by reducing the impact of the polar nature of water molecules. Positive and negative ions from the salt occupy the polar ends, leaving fewer free to damage DNA through hydrolysis (Corinaldesi *et al.* 2008; Lindahl and Nyberg 1972). Additionally, the stratification of water can lead to anoxic conditions which may be beneficial in the preservation of DNA (Corinaldesi *et al.* 2011; Parducci *et al.* 2017). In comparison, in surface waters, such as inshore waters (Härnström *et al.* 2011), or estuarine environments (Coolen *et al.* 2004), temperatures can fluctuate greatly with changes in local climactic conditions, which can impact sedaDNA preservation negatively.

Freshwater sediments, such as those taken from rivers, lakes and ponds are an additional source of sedaDNA (Ahmed *et al.* 2018; Alsos *et al.* 2016a; Alsos *et al.* 2018; Anderson-Carpenter *et al.* 2011; Bissett *et al.* 2005; Boessenkool *et al.* 2014; Giguet-Covex *et al.* 2014; Graham *et al.* 2016; Last *et al.* 2006; Limburg *et al.* 2002; Pedersen *et al.* 2013; Pedersen *et al.* 2015; Pedersen *et al.* 2016). Although lakes often thermally stratify, particularly over summer months, they generally do not have the same temperature stratification as marine waters, with the temperature only dropping to 4°C at the deepest points if there is a source of cold water or ambient temperatures are low. Where thermal stratification occurs, sediments taken from the deepest points will be in contact with the coldest water, and can be a good source of sedaDNA (Parducci *et al* 2017). Lakes will tend towards ambient temperature unless very large, due to a lack of source of cold water. The mixing of lakes is caused by wind, inflows, and high ambient temperatures, whilst lakes may also demonstrate seasonal fluctuation. Where sediments are taken from rivers, small lakes or floodplains, the sediments are likely to reflect ambient temperatures (Haile *et al*, 2009). The best predictors of lake sediment temperature (and thus DNA preservation) are latitude and altitude (Fang *et al.* 1998).

SedaDNA can be taken from terrestrial sources, such as from caves (Haile *et al.* 2007; Haouchar *et al.* 2014;

Hebsgaard *et al.* 2009; Hofreiter *et al.* 2003; Slon *et al.* 2017; Wilmshurst *et al.* 2014; Willerslev *et al* 2014; Zhang *et al.* 2020). When these sediment types are in dry conditions, it is often thought that leaching of DNA is less likely than in wet conditions (Hebsgaard *et al.* 2009), although this may not be the case where sediments are not dry for the full time span of the sediment (Haile *et al.* 2007). Additionally, the location and type of cave system from which the sample is taken can have a profound impact on DNA preservation; deep cave systems have stable temperatures, which can help with DNA preservation, but high humidity, which can be disadvantageous for DNA preservation. At cave entrances, fluctuations in both temperature and humidity can be high (Smith *et al.* 2003). 'Dirt' samples taken from dry and cold areas such as nunataks, can also be good for DNA preservation and have been used as a proxy for studying glacial refugia (Jørgensen *et al.* 2012b; Willerslev 2003).

The preservational environment of the North Sea

The sedaDNA retrieved during Europe's Lost Frontiers originated from the early to mid-Holocene land surfaces of Doggerland and represents a complex composite of the environments discussed above. The samples represent lacustrine, riparian and terrestrial environments to our best knowledge of the landscape reconstructions, which then became inundated by a marine transgression. Consequently, the conditions of preservation would be expected to reflect those initial environments, and different levels of sedaDNA damage would be expected in different environments. This is indeed borne out when comparing the extent of DNA fragmentation and terminal 5' end cytosine deamination to environment (based on floral composition), Figure 8.1.

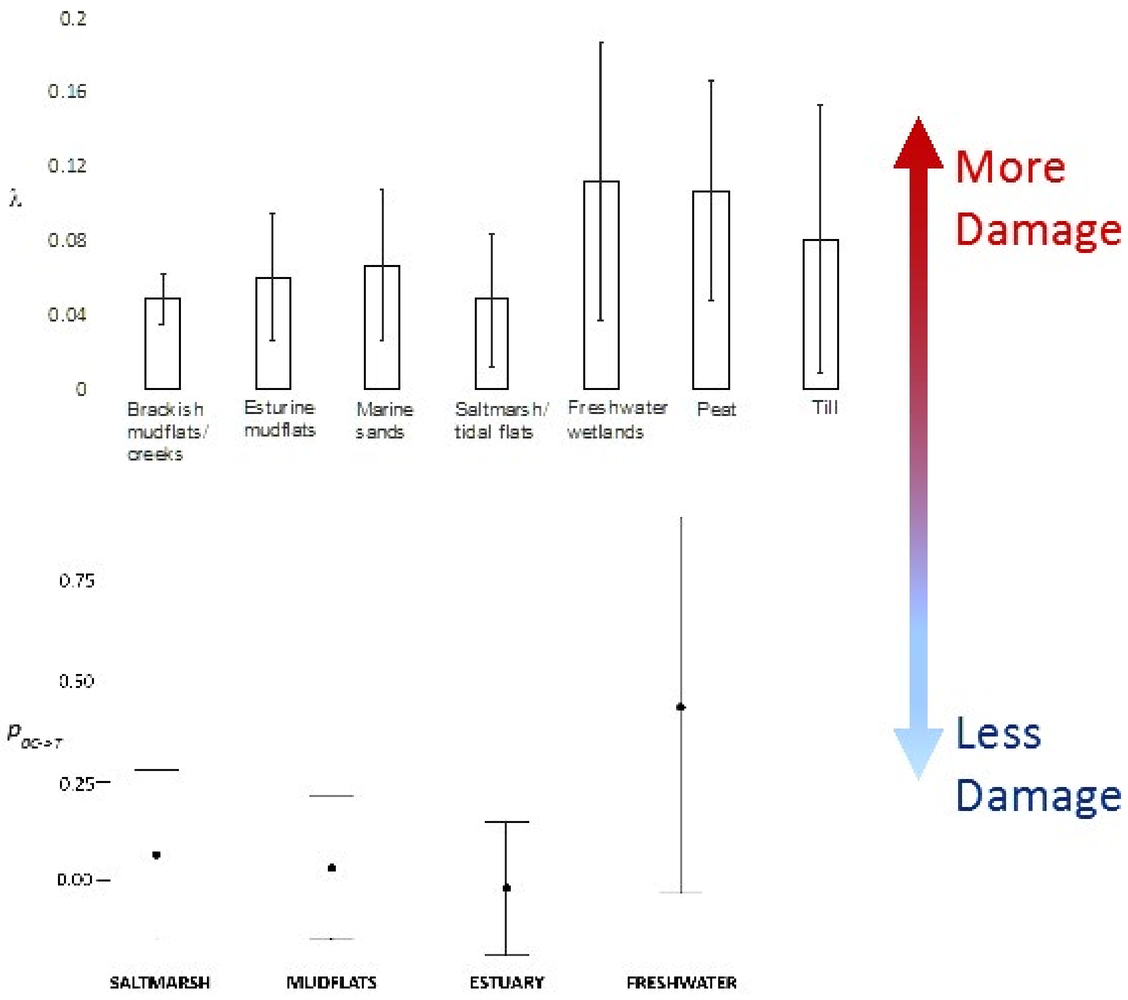


Figure 8.1 Differential sedaDNA fragmentation (top) and deamination (bottom) damage patterns in Doggerland palaeoenvironments. Fragmentation expressed as the lambda parameter of the exponential distribution of sedaDNA fragment sizes. Deamination expressed as the probability of observing a C to T change at the terminal position (position 0) of the 5' end of DNA fragments, caused by cytosine deamination.

High ionic environments, where salt water occurs show a clear reduction in fragmentation levels relative to freshwater or terrestrial environments, demonstrate the strong environmental influence on preservation before sedaDNA became sealed within the sediment and inundated by the encroaching North Sea.

An outstanding question is to what extent the marine environment itself contributes to biomolecular preservation. The proxy evidence is strongly suggestive that once sealed in sediment, there was little or no penetration of the sediment by marine waters. When first opened up in the ancient DNA laboratory the cores were generally dry to the touch rather than waterlogged, a fact verified by dry weight estimates of sediment during OSL analysis. The retention of datable OSL signal from soluble radionuclides in the uranium decay series chain (see Kinnaird *et al.* this volume) indicates that there was no percolation of marine waters. Similar evidence is seen from elemental core scans in which the Br/Ti ratio can be taken as a salinity indicator: estuarine and river systems are discernible in cores, further showing a lack of marine penetration into the core (see Finlay *et al.* this volume). A major concern of sedaDNA studies is the potential leaching of DNA through the system due to water movement, for which we developed a statistical framework data analysis (see below). That also indicated a stratified signal of sedaDNA, in agreement with the geochemistry. This lack of leaching is in general agreement with previous sedaDNA studies (Bálint *et al.* 2018; Domaizon *et al.* 2017), and suggests that the drivers of DNA preservation are down to a combination of the depositional environment and the long-term temperature, which would have been close to a steady 4°C. The relatively good preservation of sedaDNA of even early Holocene/late Pleistocene age in the project is highly suggestive that preservation can be expected over tens of thousands, possibly hundreds of thousands of years. In part this will depend on how closed system sediments are, so preventing the bulk diffusion of DNA, a key parameter in the loss of DNA signal over time (Kistler *et al.* 2017). The evidence so far suggests that the sediments of the North Sea tested during *Europe's Lost Frontiers* are relatively closed systems.

Methodological challenges and advances

The sedaDNA project within *Europe's Lost Frontiers* faced a number of methodological challenges, which in part reflected the start of the art at the outset of the project. This resulted in a number of innovations, which are discussed below. Some of the innovations were only possible because of the type of data that was generated, so called shotgun metagenomic data. The popular alternative for sedaDNA to date has been metabarcoding. The latter is one of the few areas of ancient DNA research that still directly amplifies DNA extracts by polymerase chain reaction (PCR), the method of choice before the Next Generation Sequencing (NGS) era, which began for ancient DNA in 2006 (Poinar *et al.* 2006). In metabarcoding the amplicons produced by PCR are then sequenced on an NGS platform. The PCR systems amplify a wide range of taxa, typically targeting the *trnL* loop of the chloroplast genome in plants (Taberlet *et al.* 2007), and mitochondrial targets of *16S* or *12S* rDNA, *CO1* or *cytb* (Hofreiter *et al.* 2003; Willerslev *et al.* 2003; 2007). These targets are mostly highly variable between species and so each species is expected to be defined by a particular haplotype DNA sequence, and are complemented by highly comprehensive databases against which sedaDNA can be compared. The metabarcoding approach has been popular in part because of its cost efficiency and perceived sensitivity, but comes with a number of severe limitations. The most important of these is the lack of a robust approach for authentication of ancient DNA amplification. Since the terminal regions of molecules are generally not amplified, the characteristic 5' cytosine deamination patterns cannot be tracked, which is the standard approach of authentication in the field. Rather, authentication approaches rely on reproducibility and negative blanks, as carried out during the 90s and which substantially lacks in rigor (Taberlet *et al.* 2007). A second issue is in the clonal biases that can occur during PCR which can lead to allelic dropout – the stochastic lack of amplification of some templates in low copy number – and deviant frequency profiles as a result (Ficetola *et al.* 2015). The third major problem with this approach is the ascertainment bias inherent in the target primer design which requires *a priori* assumptions about what taxa are present in the sample. When reconstructing an unknown Pleistocene environment, such assumptions are difficult to justify, and the possibility of finding as yet genetically uncharacterized organisms is real.

The alternative approach is to sequence all the DNA present in a sediment sample. Such unfocussed techniques are referred to as shotgun approaches in molecular biology. The advantages are that the sedaDNA can, theoretically, be robustly authenticated through damage profiling, could potentially be more sensitive at organism detection than metabarcoding, and the profiles obtained more likely to be informative of the level of an organism's presence. Shotgun approaches exploit any part of the genetic material left behind by an organism, rather than the tiny fraction exploited in metabarcoding, leading to the potential of the latter approach being more sensitive at detecting the presence of organisms. Shotgun profiles generated from Bouldnor Cliff suggested that this was likely the case, with over tenfold more of the profile coming from nuclear DNA rather than organellar DNA (Smith *et al.* 2015). Increasingly, the value of shotgun approaches is being recognized as more studies have employed this approach (Parducci *et al.* 2019; Pedersen *et al.* 2016; Smith *et al.* 2015). However, despite the potential advantages, the use of shotgun data provided a series of methodological challenges. Firstly, the use of genetic material outside of taxonomically very well characterized organellar regions is difficult to interpret when databases are relatively incomplete. This leads to a danger of false positive identifications. Secondly, damage-based methodologies of authentication at the time of the project initiation were designed for single, well represented genomes rather than a large number of poorly represented taxa. A final challenge, common to all sedaDNA studies, is to provide a framework of analysis which addresses and tests against the possibility that DNA has leached through the sediment and is, therefore, not representative of the depositional environment (Haile *et al.* 2007).

Solving the identification of taxa in the face of incomplete databases

Investigating unknown environments carries the inevitable risk that, when attempting to identify taxa, the organisms of that environment are not represented in comparative databases. Under such circumstances, often the 'nearest' species can be mistakenly assigned as the identity of the unknown species. The literature of palaeometagenomics is replete with such inferences, such as the unlikely use of a New World species of poplar by Neandertals to cure headaches (Weyrich *et al* 2017). This problem is accentuated in the case of shotgun metagenomics, where the potential of the increased amount of genetic material for analysis is tempered by the increased probability of poor database coverage leading to false positives. Often, such false positive organisms are model organisms, ones that are studied to a very great depth as exemplars in biology. A common practice to deal with such signals has been to assume they represent contamination, for instance from the 'kit-ome'. This however requires a subjective judgement about what was present *a priori* in the unknown environment. This problem is particularly acute when considering the Mesolithic/Neolithic transition, because the influx of exotic organisms that define the Neolithic are also typically model organisms because of their continued agronomic importance (Smith *et al.* 2015).

The aim of the DNA team within *Europe's Lost Frontiers* was to develop a solution algorithm which objectively removes false positives without *a priori* assumptions about the organisms present in the environment (see the forthcoming *Europe's Lost Frontier* environmental volume for more detail). The approach we used made a fundamental assumption that the organism present in the unknown environment may not be present in the comparative database, and consequently identifies phylogenetic ranges through a phylogenetic intersection analysis (PIA) (Cribdon *et al.* 2020). The algorithm is the most stringent available for taxonomic assignation at present, and has been calculated to have up to a 96% accuracy even when the true organism is absent from the comparative database. The most popular alternative approach has an 80% accuracy under the same conditions (Cribdon *et al.* 2020). Combined with removal of taxa that also appear in blank controls, the taxonomic assignment of sedaDNA in *Europe's Lost Frontiers* is highly robust. Despite this, a few exotic assignments still persist. Interestingly, these have been shown to carry a damage signature which suggests misidentification rather than contamination. Taxa which are phylogenetically remote, such as members of the Eulipotyphla, will tend to be removed in these analyses because a sufficient phylogenetic range cannot be established. Consequently, algorithm improvement is an ongoing process.

Authenticating sedaDNA through damage

Ancient DNA is typically characterised by its *post-mortem* DNA damage patterns. These characteristic patterns are a crucial tool for the authentication of ancient DNA, and include DNA fragmentation as a result of hydrolytic depurination, and cytosine deamination (Dabney *et al.* 2013). Both genomic and metagenomic data typically demonstrate characteristic fragmentation patterns which can allow some level of discrimination from modern DNA, which is typically of large molecular weight.

Tools such as mapDamage (Ginolhac *et al.* 2011; Jónsson *et al.* 2013), are used to identify damage such as cytosine deamination in genomic data by mapping reads to a reference genome and identifying mismatches. However, with metagenomic DNA such as that typically studied from sediment, it is rare to achieve enough coverage of a genome to be able to map sufficient DNA reads to the reference genome to be able to use such tools with any confidence. One '*grand challenge*' for working with metagenomic data is the development of equivalent tools that can handle these kinds of data. To address this within *Europe's Lost Frontiers*, the team developed a tool called *MetaDamage* which specifically targets damage caused by cytosine deamination (Everett *et al.* 2020). This tool calculates the mismatch frequency of all possible base changes along the entire length of sedaDNA molecules by taking the closest matching sequence from a database identified through local alignment searches, and retrieving the coordinates of the database entry that match the entire length of the sedaDNA molecule. These are then realigned, and the mismatches recorded. In this way we have been able to establish the level of damage that has occurred in the palaeoenvironments of Doggerland, which brings a level of authentication to palaeoenvironmental metagenomic reconstruction not previously seen. The damage we observe is surprisingly little for the age of the sedaDNA retrieved, typically in the 10% range, which is about a quarter of the theoretical maximum measurable, suggesting that sedaDNA may persist in these sorts of environments for many tens of thousands of years, and even hundreds of thousands of years.

A statistical framework to test for stratification of sedaDNA signal

Another '*grand challenge*' for sedaDNA studies is to establish methodology that can identify whether the ancient molecules that are retrieved were deposited *in situ*, or whether there has been subsequent leaching over time, and sedaDNA from various time intervals may be present in one sediment sample. This often cited problem (Haile *et al* 2007) has rarely, if ever, been addressed. Movement of DNA would be expected to lead to a homogenization of signal, which could be driven by upward, downward or bidirectional migration. To test this, we took an approach in which we used the identified taxonomic composition of one stratum to test for significant difference to the composition of an adjacent stratum. The shotgun approach allows a more secure link between taxonomic count and abundance (but see biogenomic mass discussion below) than metabarcoding. This can therefore be exploited for a given total number of observations, so accounting for differences due to library preparation between samples. Environments may in some respects not vary between strata, simply because there has been no significant change over time. However, specific taxa may be present in one stratum, but not another. For each taxon, therefore, one can ask the question for the number of observations of a taxon out of the total number of observations in stratum *a*, what is the probability of the observed number of observations of the same taxon in stratum *b* given the total number of observations in that stratum. In this way probabilities can be assigned to each taxon profile of change over strata. Where we see a taxon in one stratum and a significant reduction or absence the same taxon in the stratum below, we have evidence of a lack of downward DNA movement, and similarly if there is a significant reduction or absence in the stratum above evidence of a lack of upward movement. The whole core can then be metricized for the extent of stratified signal obtained. No signal is not necessarily an indicator of no stratification, it may indicate an unchanging environment, but the presence of signal provides positive evidence of stratification. In line with the evidence from chemical proxies discussed above, evidence for stratification was widespread across the cores, suggesting that sedaDNA moved little after deposition in these sediments once sealed. The framework here should be equally applicable to other count based environmental proxies such as pollen and diatoms, and was applied in this way to studying the project core with evidence for the Storegga tsunami - ELF001A (Gaffney *et al*. 2020). An interesting finding in this case was a contrast between the evidence of stratification for sedaDNA and pollen, suggesting a more consistent regional signal for the latter and a more localized signal for the former. This suggests sedaDNA is deposited locally in the case of plants from the main body of the organism rather than pollen, in agreement with previous studies (Willerslev *et al*. 2007).

Biogenomic mass – a biomass estimator from sedaDNA

A desirable inference from sedaDNA is an insight into species abundance. Shotgun metagenomics offers a route to this in that it reflects the relative abundance of the genetic material left behind by taxa. The amount of genetic material left behind by an organism is largely dependent on two parameters: the number of cells in the organism, in other words the organism's biomass, and the size of the organism's genome. There are also differences between the various tissue types of the organisms in terms of preservational qualities, but the free environmental DNA quantity will largely be determined by just the two factors. The read count will therefore be a function of biomass, genome size, and the proportion of the genome that is identifiable. An approximation of biomass represented can therefore be interpreted from the read count by accounting for genome size, giving a measure of biogenomic mass, which was usefully applied to the tsunami core to show a highly significant increase in woodland biomass associated with the wave itself (Gaffney *et al*. 2020). However, to directly compare such measures between samples requires an underlying assumption that library efficiency is comparable. Stochastic differences can be addressed through dual sequencing of samples, which should be considered as standard good practice. It may be the case that systemic differences between samples, such as the disproportional presence of inhibitive qualities between samples, could theoretically give an erroneous impression of overall differences in biomass. However, there has been little to suggest such inhibitors are in play in the *Europe's Lost Frontiers* project samples, as exemplified by the tsunami signal itself.

Taphonomy of sedaDNA

The innovations of this project have revealed a great deal about the taphonomy of sedaDNA in terms of its localized signal, the influence of the deposition environment and relatively low level of damage and movement once sealed in sediments. More generally, persistence of ancient DNA signal has been related to long term bulk diffusion processes (Kistler *et al*. 2017), which is expected to be a function of permeability in the case of sediments. The differences found between adjacent samples suggests permeability is very low indeed, in agreement with chemical proxies, suggesting fairly closed systems. However, much remains to be discovered about the taphonomy in terms of how the sedaDNA reached the depositional environment. To this end we considered several intertidal environments as well as the marine core sediments to better understand the fate of sedaDNA *post-mortem*, which is explored in more detail in a later volume.

It is not necessary for sediment to contain identifiable physical remains for viable DNA to be extracted; DNA may exist where remains may have disintegrated beyond the point that macrofossils can be identified. DNA in sediment comes in two forms: intracellular DNA (iDNA) in un-lysed cells, and extracellular, environmental DNA (eDNA) which has been released during cell lysis or through extrusion mechanisms (Pietramellara *et al.* 2009). Much DNA within sediment is in the form of eDNA, some of which is 'free' DNA and some of which appears to be bound to inorganic minerals within the sediment (Torti *et al.* 2015). The most commonly studied eDNA in sediments is of bacterial, mammalian, and plant origin. In ancient sediments, bacterial DNA may originate from truly ancient bacterial DNA (aDNA), or from metabolically active ancient populations (Johnson *et al.* 2007; Rivkina *et al.* 2000). The potential sources of DNA from larger organisms are still highly speculative. From animals, sources of aDNA are thought likely to include skin, faeces, saliva, bone, nail, hair, feathers, scales, moulted insect exoskeletons, and shells (Pedersen *et al.* 2015). From plants, a large proportion of the aDNA is thought to originate from root cells, or from detritus such as leaf litter and woody remains (Pedersen *et al.* 2015). Pollen may also be present, although these are not thought to contribute a great deal to sedaDNA, and thus aDNA from pollen is often extracted separately (Parducci *et al.* 2015; Pedersen *et al.* 2016; Sjögren *et al.* 2017). A potential source of plant aDNA in sediments is phytoliths, the presence of which in sediments is well documented (Fearn *et al.* 1998). At present, there have been no successful attempts to isolate DNA from phytoliths, although other biomolecules have been retrieved (Elbaum *et al.* 2009; Kistler 2012), however, if DNA could be retrieved, it may demonstrate low levels of degradation due to the silicification process generating a 'closed' system.

An emerging picture of the Doggerland landscape

A three-phase approach

Coring in *Europe's Lost Frontiers* was carried out in two principal phases over two seasons (Figure 8.2). Cores 1-20 gave a transect across the Doggerland archipelago, while cores 21-60 gave an in depth transect of the Southern River system, as well as the Dogger Island area. The first glimpse of the landscape came from the analysis from core ELF001A in which the biological record of the events of the Storegga tsunami were recovered (Gaffney *et al.* 2020). The sedaDNA revealed a wooded estuarine environment, with many of the taxa expected for such a landscape, with oak and birch forest, willows growing along the riverine system and a mixture of meadow and marsh. The tsunami itself was associated with a leap in biogenomic mass as trees were torn up from the landscape and dumped in the locality of the core, a lakeside area near the head of the Southern River valley through which the tsunami had funnelled (Gaffney *et al.* 2020). After the tsunami receded, a more open meadow and marsh environment returned indicating that the complete marine transgression had not occurred by this time. Generally, the cores do show a marine transgression over time, and this will be detailed in a forthcoming volume in the *Europe's Lost Frontiers* series.

The recovery of sedaDNA from 60 of the 78 cores collected by the project has enabled a taxonomic overview of the Doggerland Archipelago landscape. On the basis of these results, combined with information from pollen and diatom environmental proxies, a series of ten cores were selected for deep sequencing to retrieve a greater depth of information, and the facility to examine to authenticity through damage patterns of specific taxonomic groups, Figure 8.2D. This set of data focussed on the Southern River system specifically in order to capture a detailed account of the marine transgression.

An anthropological and ecological landscape

The Southern River system is of high anthropological potential. The estimated coastline of 8200 BP shows the river opening in a southern direction through a headland which makes an ideal situation for potential human settlement from a period of history that touches the Mesolithic/Neolithic transition, Figure 8.2. A key question for *Europe's Lost Frontiers* is whether such human influence could be detectable in perturbations of the floral and faunal composition. The floral profiles of the cores, described in the forthcoming environmental volume, suggest the presence of a number of species currently associated with Northern Europe, some of which appear to have been established rather early relative to the UK mainland, such as *Tilia* over 8200 BP. This may suggest a relatively mild environment in the Doggerland landscape, although such an interpretation is not clear from other environmental proxies such as diatoms. The presence of such mesophilic taxa may have several possible causes. Either the environment was mild enough for such taxa to reach these latitudes under their own post glacial expansion, or alternatively, the apparently pristine environment may have already been subject to modification through the facilitated transport of flora. Similarly, apparent pristine environments in the Amazonian forest have subsequently been found to be largely anthropogenically driven by early peoples of the

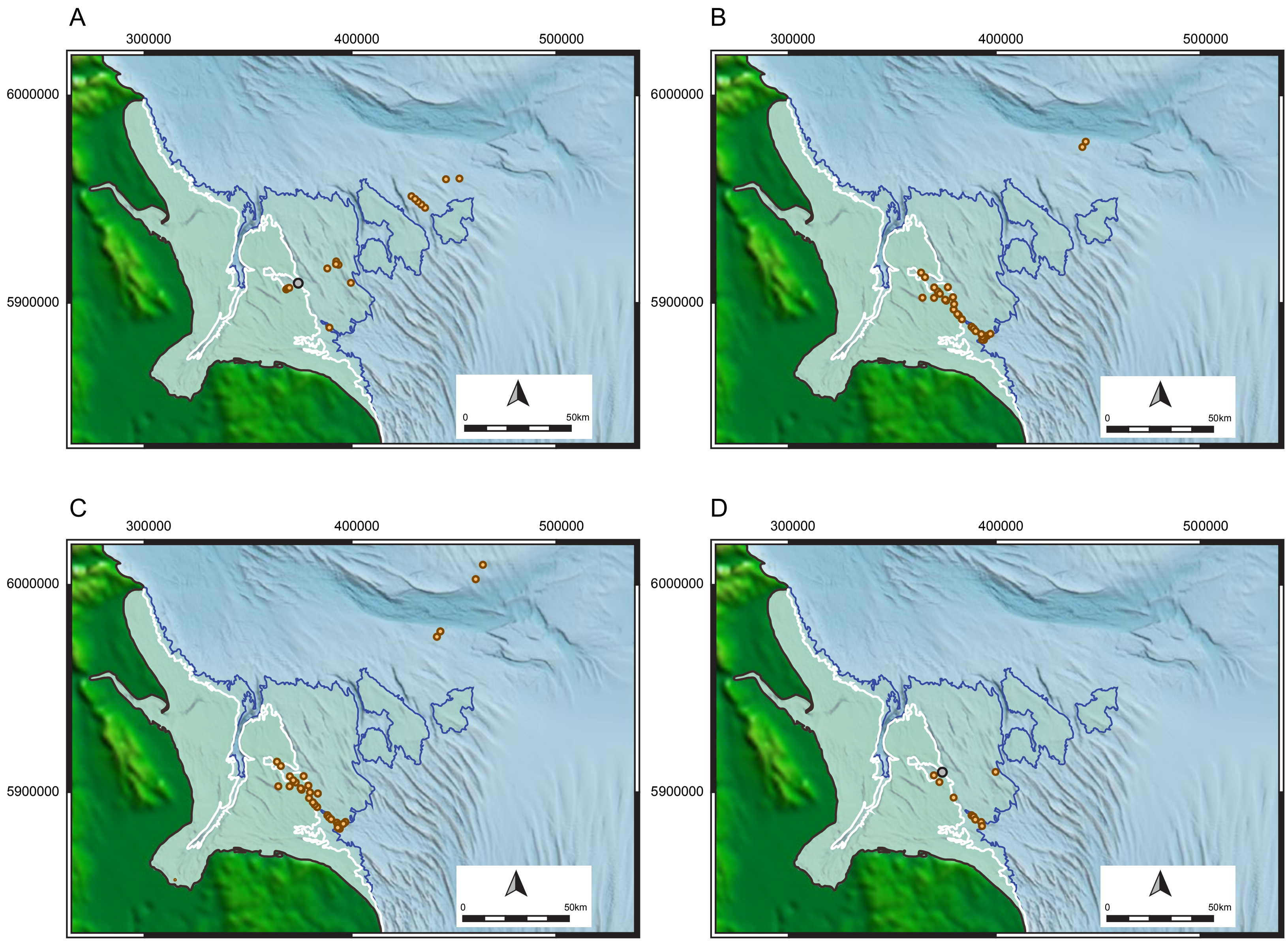


Figure 8.2 Coring sites used for sedaDNA analysis. A) Cores 1-20. B) Cores in range 21-60 over the Southern River area. C) Cores 20-60. D) Core sites selected for deep sequencing. Estimated 8200 BP coastline shown in black and estimated Storegga tsunami run up extent shown in white. The Storegga tsunami core (ELF001A) shown in grey.

region (Heckenberger *et al.* 2003; Levis *et al.* 2017). These possibilities are investigated in detail in a forthcoming volume in the *Europe's Lost Frontiers* series.

The future of sedaDNA studies in the North Sea

The field of sedaDNA has challenged generally accepted wisdoms, most seminally with the discovery of a forested Greenland over half a million years ago (Willerslev *et al.* 2007). Leading up to this study, in 2015, evidence was discovered that wheat was present at a site off the Isle of Wight in the United Kingdom, 2000 years earlier than previous estimates for mainland Britain (Smith *et al.* 2015), and 400 years before estimates had placed it in nearby European sites (Collard *et al.* 2010, Meylemans *et al.* 2018). These findings stirred lively debate within the community (Bennett 2015; Smith *et al.* 2015b; Weiß *et al.* 2015) and led to the development of better tools for determining DNA degradation patterns within ancient DNA samples, which supported the results of the original sedaDNA study (Kistler *et al.* 2015; 2017). Ongoing archaeological study also continues to support the suggestion of an underlying connection to European technologies (Momber *et al.* 2020). The innovations of sedaDNA methodology of *Europe's Lost Frontiers* have built substantially on this foundation (Cribdon *et al.* 2020; Everett *et al.* 2020; Gaffney *et al.* 2020). The detailed view provided through sedaDNA goes far beyond that available from microfossils alone. The levels of damage we have observed, and the evidence of the extent to which the sediment system is closed to bulk DNA diffusion, suggests that sedaDNA is also likely to be retrievable deep into the Pleistocene and at a scale of tens to hundreds of thousands of years. This promises the potential of deep glacial and preglacial profiles. Furthermore, the technology is in place to reconstruct human settlements and their economies if and when they are discovered.

Chapter 9

Palaeomagnetic analysis of cores from Europe's Lost Frontiers

Samuel E. Harris, Catherine M. Batt and Elizabeth Topping

Introduction

Palaeomagnetic studies were carried out at the University of Bradford's Archaeomagnetic Dating Laboratory in conjunction with the facilities at Lancaster University's Centre for Environmental Magnetism and Palaeomagnetism. A total of 510 palaeomagnetic samples were obtained from cores: ELF001A (25), ELF002 (26), ELF019 (132), ELF031 (25), ELF031A (119), ELF044 (42), and ELF045 (145) for the purposes of a preliminary palaeomagnetic study. This section brings together the different strands of work which have been carried out on cores: ELF001A, ELF002, ELF003 (not sampled), and ELF0019 (Figure 9.1).

Rationale for analysis

The aim of this study was to assess the potential of extracting past geomagnetic field behaviour in the Early Holocene from sediment cores recovered from the southern North Sea, and to investigate the feasibility of using that information to establish a chronology and cross correlation between cores. In addition, the analysis aimed to use rock magnetic measurements to determine palaeoenvironmental conditions at the time of deposition and integrate magnetic measurements with the independent dating (OSL and Radiocarbon).

Background to palaeomagnetic studies

The geomagnetic field behavioural changes through time are known as secular variation (SV). Studies of past SV (or palaeosecular variation - PSV) over a range of timescales (archaeological and geological) have been crucial in aiding understanding of the Earth's evolution and geodynamo behaviour (Pavón-Carrasco *et al.* 2014; Torsvik *et al.* 2012). Archaeomagnetic dating has been utilised for 60 years and the importance of defining PSV for geographical areas and archaeological time periods has been well documented as a necessity for its use in

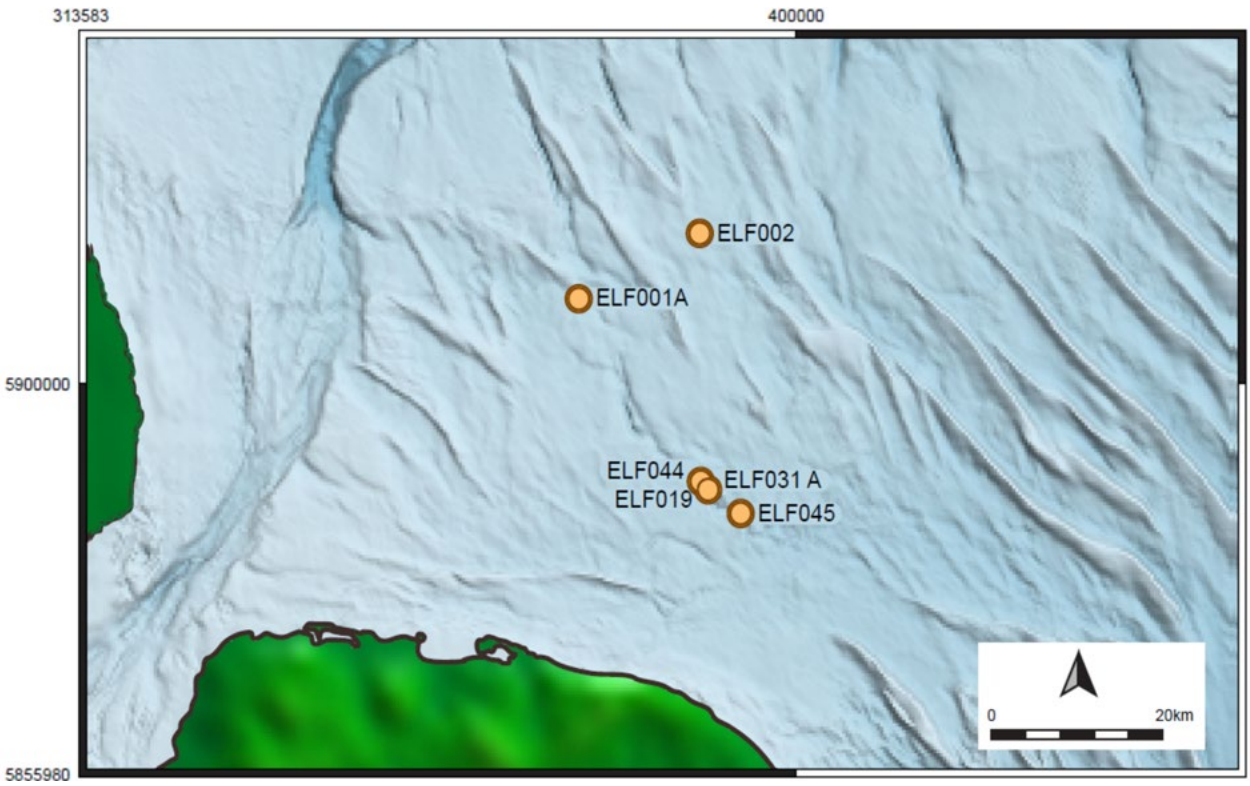


Figure 9.1 Locations of cores used in this study.

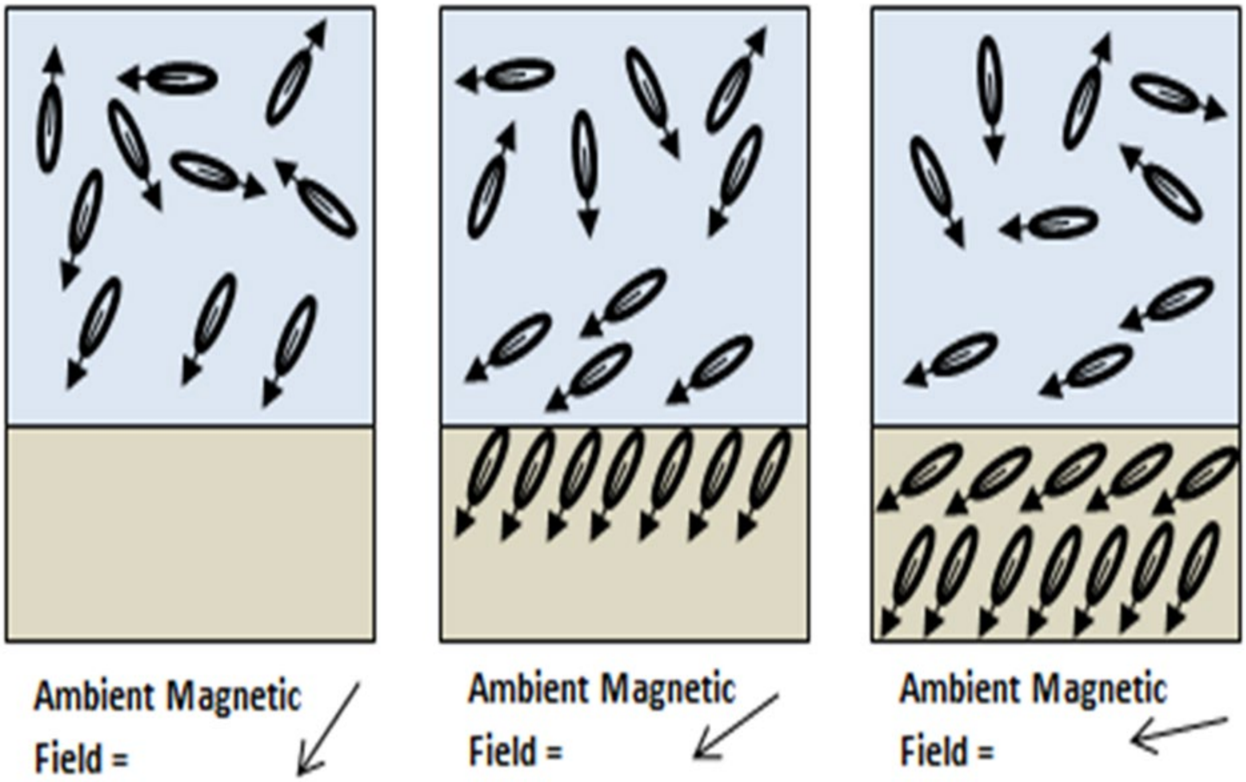


Figure 9.2 Schematic representation of the detrital remanent magnetisation mechanism from left to right - how the acquisition of the geomagnetic field occurs in sediments.

dating fired archaeological remains (Aitken 1958; Batt *et al.* 2017). These commonly represent single 'snapshots' of the geomagnetic field, retrieved from fired *in-situ* archaeological remains (Kovacheva *et al.* 2014). However, through the analysis of lacustrine or marine sediments it is possible to retrieve near continuous PSV records (Avery *et al.* 2017; Clelland and Batt 2012). When fine-grained magnetic particles within a water column are exposed to the ambient geomagnetic field (GMF), they orientate in the direction of the field at the time and settle in the sediment to form a continuous record of change (Figure 9.2) (Tauxe *et al.* 2006). This means that the sediment present in the *Europe's Lost Frontiers*' cores has the potential to represent a record of the geomagnetic field during or shortly after deposition.

Palaeomagnetic dating usually seeks to date sediments or lithologies of geological date through magnetostratigraphic correlation of cores utilising polarity reversal frequency rates in sections of known date. *Europe's Lost Frontiers* offers a unique opportunity in that the cores drilled from the southern North Sea could preserve records dating from the late Pleistocene/ early Holocene – a period which has seen increased research interest in recent years (Avery *et al.* 2017; Korte *et al.* 2011; Nilsson *et al.* 2014). Palaeomagnetic dating will improve the chronological understanding of these cores, particularly when used in combination with radiocarbon dating.

Palaeomagnetic studies applied to late Pleistocene/ early Holocene sediments around the NW European continent

Palaeomagnetic studies have been carried out on Holocene sediments across the globe, however the area around the North Sea has seen limited investigations. The closest studies which could be used for comparison from the surrounding region of the North Sea Basin are located in Figure 9.3.

There have been several palaeomagnetic studies in the North Sea area. However none of these have studied the Holocene deposits in any detail, with the majority investigating the most recent polarity reversals (Ali *et al.* 1993) i.e. Brunhes-Matuyama. Onshore palaeomagnetic studies around the basin were carried out on Pleistocene samples from sites in East Anglia (UK), Belgium, Netherlands, and Germany (van Montfrans 1971: and references therein). The study of the East Anglian sediments were advanced by the work of Maher and Hallam (2005) and were important for the refinement of the regional stratigraphy's chronology. Palaeomagnetic studies on material from boreholes taken in the early 1980s from the North Sea were reported on, however they also were limited to the Pleistocene period (Stoker *et al.* 1983). This complemented onshore research (van Montfrans 1971) and the polarity reversal rates for the Pleistocene (2.588mya to 11.7kya) are well established

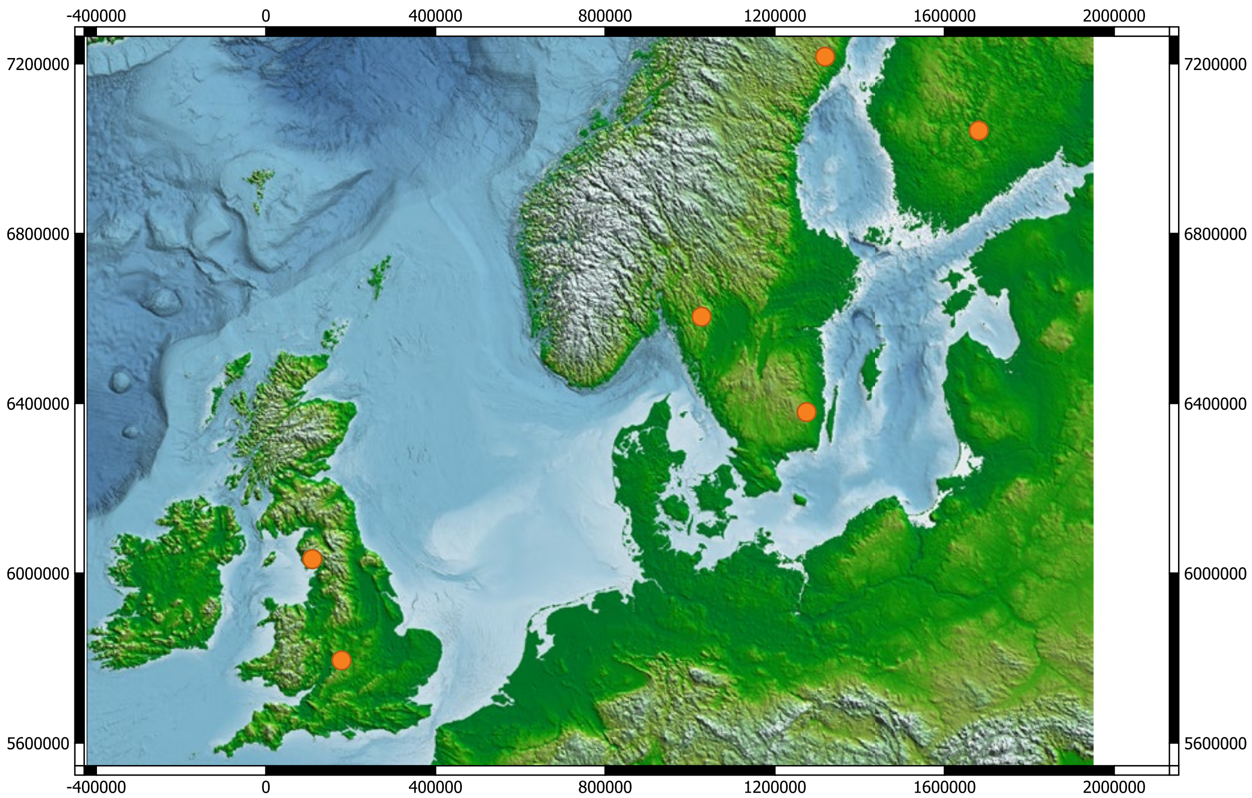


Figure 9.3 Location of the UK archaeomagnetic PSVC (Meriden: 52.43°N, -1.62°E), UK Lake Windemere sequence WINPSV_12k (Avery *et al.* 2017), and FENNOSTACK comprised of seven lake sediment sequences from four lakes (Snowball *et al.* 2007).

(Thompson *et al.* 1992). However, geomagnetic reversals and excursions are generally before the period of interest for archaeologists, with the most recent reversal taking place during the Brunhes-Matuyama transition approximately 780,000 year BP (Hillhouse and Cox 1976). Geomagnetic excursions are recognised as short-lived deviations from the contemporary geomagnetic field of more than 40°– 45° (Roberts 2008). The most recent geomagnetic excursion is widely regarded as the Laschamp event which has been securely dated to *c.* 40,000 years ago at multiple locations around the globe (Collins *et al.* 2012; Ingham *et al.* 2017; Lund *et al.* 2005).

The global research effort to understand detailed secular variation for the Holocene from marine sediments has been underway for a number of years (Haltia-Hovi *et al.* 2010; Lund *et al.* 2017; Rolph *et al.* 2004) and has led to the development of robust regional PSV reference curves derived from sediments. These studies have been successful at defining the geomagnetic field behaviour for specific regions and locations, and the opportunity to investigate marine sediments securely dated to the Holocene is a powerful addition to understanding the geodynamo.

Palaeomagnetic analysis of lake sediments in Britain was instigated by Mackereth (1971), then developed by Turner and Thompson during the late 1970s and 1980s to create the first sediment derived UK PSV master curve (Turner and Thompson 1979; Turner and Thompson 1981; Turner and Thompson 1982). This has formed the basis of dating other studies from both lacustrine and marine sediments (Saarinen 1999; Vigliotti 2006). However, due to the limitations at the time of research the chronology of these original cores was obtained by conventional radiocarbon dating material from 20cm bulk sections, resulting in wide errors on the date margins. To take advantage of recent advances, recent work has reconstructed a high-resolution record of the Holocene by re-coring Lake Windermere and applying AMS radiocarbon dating (Avery *et al.* 2017). Analyses of the Windermere cores have produced a complete PSVC for the Holocene (WINPSV-12K). This is the most relevant curve for comparison and could be used to correlate geomagnetic features isolated in the southern North Sea cores. Avery *et al.* (2017) extracted contiguous secular variation behaviour from the analysis of four sediment cores and compiled the results into a single PSV stack (WINPSV-12K) following similar approaches by Xuan *et al.* (2016). The PSVC is defined at 50 year intervals between 50 and 11,750 cal BC.

In addition to the study of palaeosecular variation records, magnetic properties of sediments can be beneficial to environmental studies. They can relate to the origin, transportation, deposition and post-depositional processes of the sediment. Through the characterisation of the magnetic minerals present and their concentrations and magnetic grain-sizes these can act as proxies for the varying paleoenvironment (Thompson *et al.* 1980; Maher 2007).

Materials and methods

The sampling of the *Europe's Lost Frontiers* cores was undertaken at the University of Wales Trinity St David Lampeter Campus, where the cores are held in cold storage. The sampling programme to date has occurred over three separate trips: November 2017, August 2018 and January 2019. The first trip aimed to sample several cores with varying lithologies from geographically different locations, and to assess the potential of these cores for palaeomagnetic study. Cores ELF001A, ELF002 and ELF019 were all sampled at 10cm intervals. *In-situ* magnetic susceptibility measurements were obtained with a Bartington MS3 susceptibility meter attached to the ultra-stable MS2K sensor. Each core was measured three times and the average taken with measurements taking place at 0.05m intervals (which is the same as the sensor range). A total of 906 measurements were taken from the four cores.

The second sampling trip in the summer 2018 was primarily to gain continuous sampling of core ELF019 which had been identified as having the highest potential for preserving a record of the past geomagnetic field. In addition, cores ELF031, ELF031A and ELF044 were sampled for future study. The third sampling trip aimed to sample one of the longest identified successions of fine-grained sediments obtained as part of *Europe's Lost Frontier's* coring programme. Core ELF045 was sampled continuously in an attempt to obtain a long profile of the past geomagnetic field.

The sampling methodology applied was an adapted method, as utilised by Trapanese *et al.* (2008), where a polycarbonate plastic sample holder (2cm diameter) is placed in the central axis of the core, starting at the top and working down the length of the core section. The core sections are affixed to the laboratory bench before a non-magnetic plastic block is used to push the sample tube into the sediment with a spirit level on top to ensure the sample holder enters the core in the horizontal plane (Figure 9.4). Once the sample holder has penetrated the sediment, the sample is marked with a fiducial arrow going up core and a sample code identifier. This process was repeated for all the core lengths. Apart from the cores sampled as part of the initial sampling trip, all sampling was continuous representing an approximate resolution of 0.03m. The depth was recorded for each sample down the core length with each measurement taken from the centre of the sample. The samples were all removed and stored in plastic boxes with damp paper towels to stop them from drying out before transport to the University of Bradford where they remained in cold storage until analysis. Table 9.1 summarises all cores sampled to date with the precise geographical locations of the cores.

The analysis protocol is schematically represented below (Figure 9.5), and the analytical procedure which has been applied to each core is recorded in Table 9.2.

Figure 9.4 Sampling of core ELF019 during the first sampling trip (© Erin Kavanagh).

Core	No. Samples	Core Length (m)	Sample Int. (m)	Sampling Res. (m)	Latitude (°N)	Longitude (°E)
ELF001A	25	3.68	2.67	0.10	53.32186	1.11754
ELF002	23	3.64	2.40	0.10	53.39013	1.32762
ELF019	132	4.43	4.21	0.03	53.13127	1.35017
ELF031	25	0.85	0.69	0.03	53.13944	1.35278
ELF031A	119	3.75	3.12	0.03	53.13944	1.35278
ELF044	42	2.05	1.2	0.03	53.13917	1.34056
ELF045	145	5.46	4.4	0.03	53.10861	1.41000

Table 9.1. Summary of palaeomagnetic sampling details with core locations.

The preliminary measurements were all carried out at the University of Bradford's Archaeomagnetic Dating Laboratory. The natural remanent magnetisation (NRM) of each sample was measured on a Molspin small sample spinner magnetometer. The low and high frequency magnetic susceptibility values were obtained using a Bartington MS2 meter

In order to assess the magnetic stability of the remanence bearing minerals in the sediments, progressive demagnetisation on pilot samples was carried out from each core. This subset of samples were all demagnetised by the alternating field method. Each chosen sample had the NRM progressively stepwise demagnetised at: 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 40, 50, 60, 80, 100mT.

All samples from core ELF001A were measured on the 2G cryogenic magnetometer with the Rapid sample system at Lancaster University's Centre for Environmental Magnetism and Palaeomagnetism. These samples were AF demagnetised at: 2, 4, 6, 8, 10, 15, 20, 30, 40, 50, 60, 70, 80mT. The 2G RAPID system can generate gyroremanent magnetisation (GRM) by static AF demagnetisation of ferromagnetic materials in fields above ~30mT. In order to remove this effect, measurement procedures set out by Stephenson (1993) were followed, and all results were corrected using the GRM correction tool in the software GM4Edit (Hounslow 2018). The characteristic remanent magnetisation (ChRM) for all samples was determined by principal component analysis (PCA) using one of two tools. These were the Demagnetisation Analyses in Excel (DAIE) software (Sagnotti 2013), which also allowed visualisation of the demagnetisation behaviour, or the LINEFIND program (Hounslow 2004). This statistical approach allows maximum angular deviation (MAD) to be utilised as a representation of the errors associated with each ChRM at the 95% confidence interval.

Rock magnetic analyses were carried out once the ChRM had been isolated for each sample after completion of the demagnetisation cycle. An anhysteretic remanent magnetisation (ARM) was imparted on each sample using either the 2G cryogenic magnetometer system or the attachment for the Molspin AF demagnetiser. The ARM was imparted using an in-line single axis direct current (DC) coil set at 0.6, 0.8, 1.0, and 1.2mT bias in conjunction with a symmetric AF peak of 80mT along the z-axis. The imparted ARM was consequently removed in seven demagnetisation fields up to 80mT. The Molspin AF demagnetiser attachment allows a DC field of 0.1mT in-line with an AF peak field of 80mT. The ARM of susceptibility reflects the concentration of fine, single-domain (SD) ferrimagnetic grains (primarily magnetite) present in the sediment and can be combined with χ_{lf} as a ratio (ARMχ/ χ_{lf}) to define trends in grain sizes to distinguish between SD and multi-domain (MD) grains (King *et al.* 1982; Maher *et al* 1999; Peters and Dekkers 2003). Those samples that were too magnetically strong for analysis on the 2G cryogenic magnetometer were measured on an AGICO JR6 magnetometer (except for IRM measurements as defined below).

After complete removal of the imparted ARM several samples underwent isothermal remanent magnetisation (IRM) procedures to identify IRM acquisition and total saturation (SIRM). Samples received pulse magnetisations along the x-axis in fields of +1000mT, -20mT, -50mT, -100mT, -300mT, and -1000mT with subsequent measurement on the Molspin spinner magnetometer. Due to time constraints, and the application of slightly different methodological approaches, not all cores sampled have received a full analysis. The reporting of the analyses presented here represents the pilot palaeomagnetic study of the Holocene marine deposits and will form the fundamental point from which to launch any future investigation. The NRM results presented for all the cores, while useful for discerning the total magnetic remanence of a sample, should not be treated as the characteristic remanence due to the prevalence of multi-component behaviour in marine sediments. Until the magnetic history of the sample can be characterised through the demagnetisation procedures outlined above, the NRM could be affected by remanences acquired since the deposition of the detrital deposits known as viscous overprints. The acquisition of a viscous remanent magnetisation (VRM) can occur over any time period and is best detailed in Tarling (1983: 29-31).

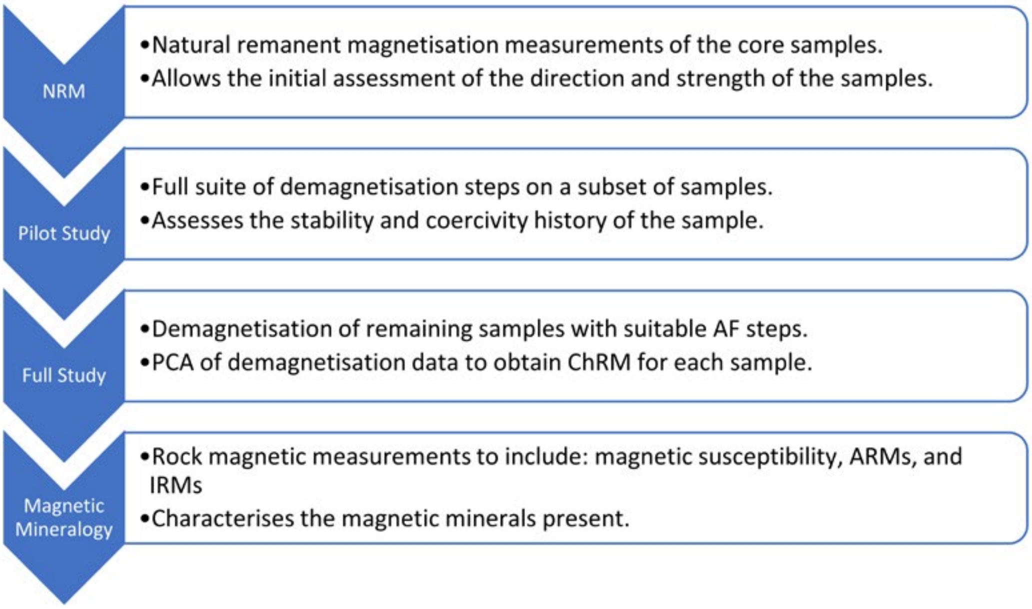


Figure 9.5 Palaeomagnetic analysis procedure followed when full analysis takes place.

Core Sampled	NRM	Pilot	AF	Magnetic Susceptibility	ARM	IRM
ELF001A	X	X	X	X[1+2]	X	X
ELF002	X	X		X[1+2]		
ELF019	X	X	P	X[1+2]	P	P
ELF031	X			X[1]		
ELF031A	X			X[1]		
ELF044	X			X[1]		
ELF045	X			X[1]		

Table 9.2 The stage of palaeomagnetic analysis carried out on each core to date: X denotes completion, P denotes partial analysis. Magnetic susceptibility carried out on obtained samples at the University of Bradford (1) and carried out using the handheld MS2K directly on the core sections (2).

Results

ELF001A

Core ELF001A represents a series of laminated mudflats interrupted by a 40cm layer of clastic sediment consisting of stones and broken shells, overlain by sands (loose and compact). Crucially, this turbidite deposit is consistent with a powerful marine event, the Storegga Tsunami (Gaffney *et al.* 2020), and the palaeomagnetic analysis of this core was expanded to include the magnetic mineralogy of the material to understand the depositional environment prior to and during this event.

The 25 samples show a relatively unchanging magnetic strength throughout the material ranging from 0.603 $x10^{-8}$ Am^2 to 1.816 $x10^{-8}$ Am^2, showing gradual increase towards the top of the core. The NRM values show a large variation in inclination for the sampled interval 0.93m – 1.60m as would be expected from such a highly disruptive event. After complete principal component analysis (PCA) of all the samples from ELF001A the characteristic remanent magnetisation (ChRM) was successfully extracted. Most of the ChRM directions isolated had MAD angles of ≤5° and are well within the recommended tolerance limits as defined by Hervé *et al.* (2013). Four samples showed MAD angles above this limit, however they are still presented here due to the low sampling resolution of this core.

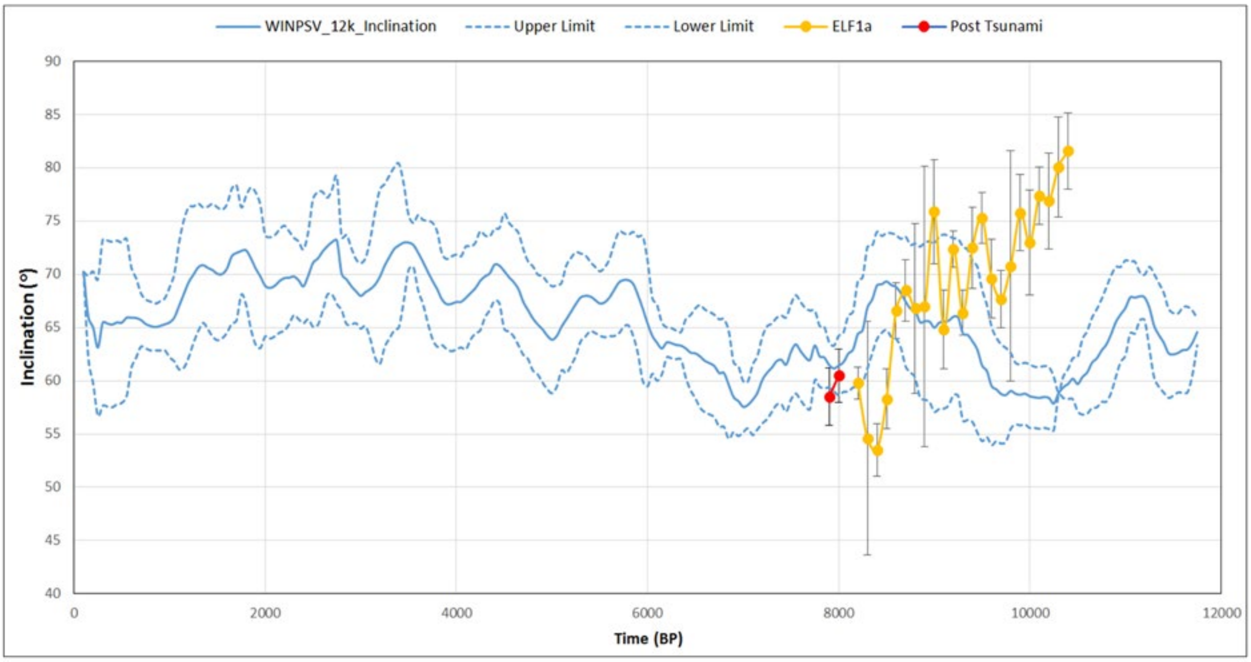


Figure 9.6 Comparison of the Inclination data isolated through PCA with associated errors against the WINPSV-12k (Avery *et al.* 2017) calibration curve.

Current understanding of the independent dating of core ELF001A is that the clastic sediment between 1.10 – 1.50m dates to the 8200 BP tsunami linked to the Storegga slide (Dawson *et al.* 2011; Gaffney *et al.* 2020; Walker *et al.* 2020). The sedimentation rate of the other cores can be inferred from the radiocarbon dating which shows an approximate rate of 0.10m/100 years. By using that sedimentation rate to anchor the inclination data of ELF001A, tentative comparison can be made with the known WINPSV-12k (Avery *et al.* 2017). Although there are assumptions in this approach it does indicate that the data obtained is consistent with current knowledge of the geomagnetic field (Figure 9.6).

This interpretation must be treated with caution. Firstly, the current dating of this core does not extend throughout and to assume that the deeper sediment could date to almost 20,000 BP could be fallacious. Secondly, the assumption that the sedimentation rate throughout the core is linear would require the support of independent dating. Additional radiocarbon dating throughout this core would be needed to justify the palaeomagnetic interpretation of the core.

The magnetic mineralogical analysis carried out on the core was able to identify key variations in the magnetic properties valuable for interpreting the depositional environment. ELF001A shows the strongest magnetic susceptibility signal (Figure 9.7a) where the loose ocean sand hits the pale greyish yellow medium sand and probably relates to iron oxide bearing mineral grains settling through the loose sand by flocculation. The variation seen in susceptibility between points a and b in Figure 9.7 shows the concentration of magnetic minerals increasing downcore and could also be a result of compaction. The sudden decrease in susceptibility values at point b coincides with the lithological change to the mudflats and remains low until point c apart from the location of the turbidite between 1.1 – 1.5m (tsunami deposit), which most likely reflects the changing grain sizes. At point c the low susceptibility value is most likely due to the organic material located at 3.20m. Crucially the susceptibility values are not diamagnetic which shows that the material could retain a magnetic remanence.

The magnetic proxy information calculated from the full suite of analyses shows four distinct magnetic stages indicative of the changing depositional palaeoenvironment (Figure 9.8). The definitions for the magnetic proxies calculated and discussed in the text are defined in Table 9.3.

Stage 1 (0.90 – 1.10m)

Corresponding to stratigraphic unit 4 this interval lies above the identified tsunami event. From all the proxy parameters calculated this interval stands out. There appears to be a much greater abundance of magnetic minerals at this horizon. The lower percentage of IRM between 0 – 20mT signifies a lower concentration of coarse magnetite. This is reflected by the ARMχ values showing a higher abundance of ultra-fine magnetite at the Superparamagnetic/Single Domain (SP/SD) boundary. The S-ratio and coercivity of remanence values show a higher concentration of harder magnetic

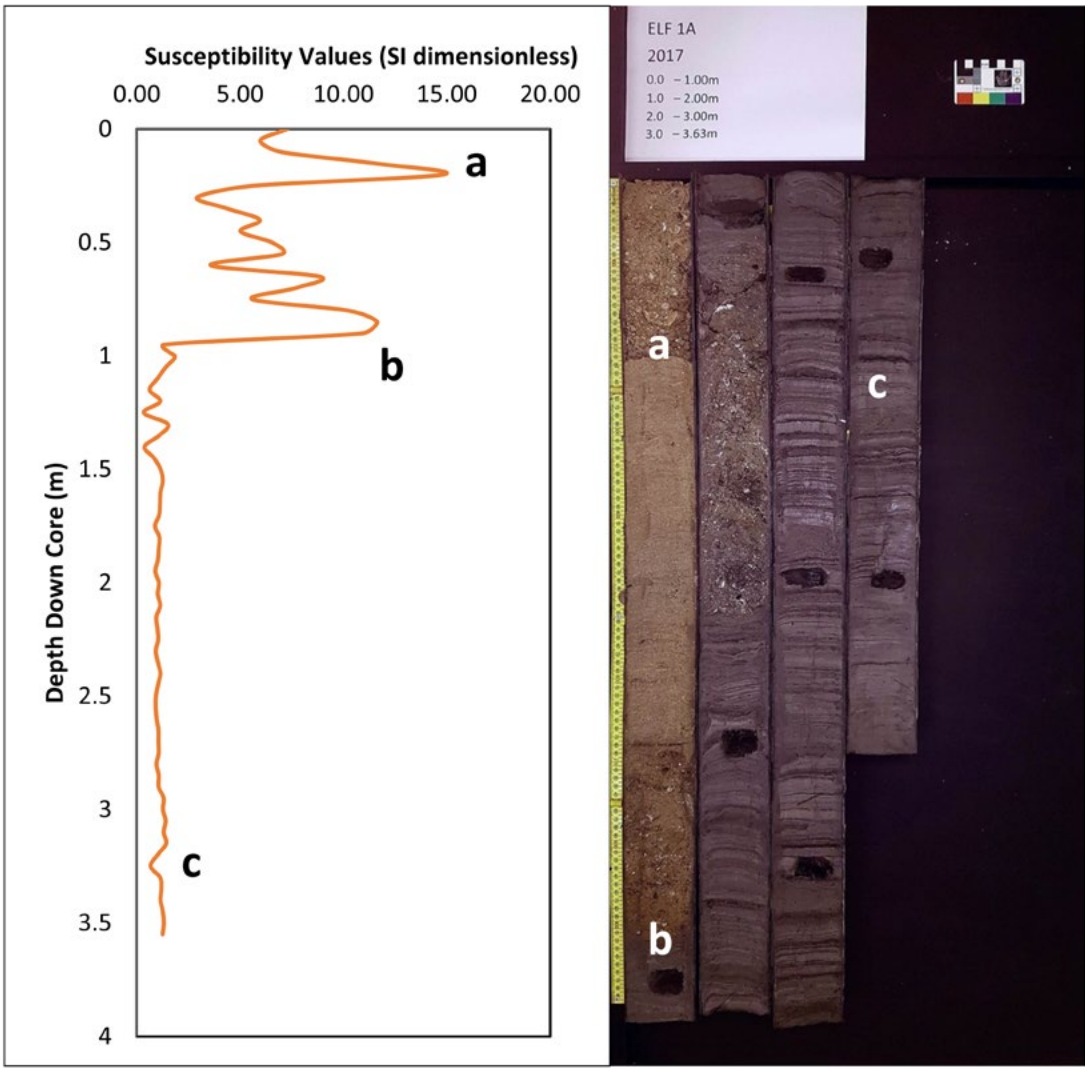


Figure 9.7 Left: Magnetic susceptibility values for core ELF001A averaged from three separate runs and corrected for drift of sensor. Features on the plot are noted in the text. Right: Image of the core for comparisons.

minerals such as haematite and goethite. This clearly represents a significant change in detrital input from the surrounding catchment compared to before the tsunami. The low %FD values (not shown) do not point to a high Fe-bearing clay input as would be seen from clay rich soils. Instead what this suggests is that the input could be from glacial till which at this time would have been deposited on the East Anglian coast after the glacial retreat. The deposition of glacial till on the surrounding landscape could have weathered to produce haematite as seen in similar studies of glacial retreat (Gurney and White 2005). There is clearly an increase in the transport of glacial till into this system resulting in increasing trends for the magnetic concentration proxies (ARMχ, χlf, and SIRM). Could the surrounding landscape have been dramatically altered from the Tsunami to allow for this?

Stage 2 (1.10m – 1.50m)

This section relates to stratigraphic unit 6 and is the deposit associated with the tsunamic event. Characterised by a much lower χlf value then the surrounding units in parallel to a drop in fine-grained magnetite (ARMχ), this suggests the material brought in by the Tsunami is from a different origin to the local supply containing a lower abundance of SP particles. The S-ratio for this phase suggests a higher concentration of haematite and goethite, however this is not mirrored by the hard IRM proxy or the coercivity of remanence suggesting that this is actually the result of multi-domain (MD) (coarser grained) magnetite co-existing with fine grained greigite. The presence of greigite particles in this deposit are indicative of intense changes in the palaeoenvironment (Su *et al.* 2013).

Magnetic Proxy	Definition
ARMχ	Susceptibility of anhysteretic remanent magnetisation is the magnetic remanence produced by the decaying AF field in a small DC field. Proxy for concentration of ultrafine Single Domain (SD) magnetite or maghemite
χlf	Mass specific low-frequency magnetic susceptibility. Total abundance of magnetic minerals.
S-ratio	The S-ratio is the "soft" IRM / "hard" IRM ratio which is a proxy for the relative abundance variations of magnetite and/or maghemite /hematite and/or goethite in terms of magnetic remanence. Less negative values indicate higher concentration of hematite/goethite.
SIRM	Saturation IRM usually created through pulse magnetisation fields of 1000mT<. Indicative of the abundance of magnetic minerals capable of carrying a magnetic remanence.
ARMχ/SIRM	This ratio provides a proxy for tracing relative changes in the grain size of magnetic particles above the SP/SD boundary. The higher the value of this proxy the higher percentage of finer grains present.
%bIRM0-20mT	The ultra "soft" IRM proxy for the abundance of coarse grained magnetite and maghemite.
Hcr	The coercivity of remanence equates to the field strength required to reduce the SIRM to "0". This is a proxy for the relative concentration of "hard" magnetic minerals.
HIRM	The mass specific "hard" IRM proxy for the relative abundance of harder magnetic minerals such as hematite and/or goethite.

Table 9.3 Definitions of magnetic proxies referred to in text and used to characterise the magnetic minerals present.

Stage 3 (1.50m – 1.90m)

This magnetic phase is only significantly evident in the %bIRM$_{0\text{-}20mT}$ and the coercivity of remanence which shows a larger abundance of coarse-grained magnetite up to and including the tsunami interval. At the start of this interval (~1.90m) the change in these proxies could represent the start of the glacial retreat from the southern North Sea and sea-level rise. The increase in ARMχ reflects the gradual increase in ultra-fine magnetite which would occur as the water column rises in conjunction with fresh glacial till deposition (Gurney and White 2005; Su *et al.* 2013).

Stage 4 (1.90m – 3.60m)

This phase represents little or no change in detrital input consistent with a low energy estuarine system. The S-ratio gradually decreases suggesting a higher ratio of magnetite being deposited through this phase. The abundance of magnetic minerals does not appear to change which could mean that the increase in magnetite is due to a change in salinity (Katari and Tauxe 2000; Larrasoaña *et al.* 2014).

ELF002

The first 0.20m of core ELF002 was a void due to the compaction of material when the core was lifted. The highest value of magnetic susceptibility in this core is at point a in Figure 9.9 however measurements above 0.60m should be treated with caution due to the loose compaction of the material and the high likelihood of movement. Between point a and point b, the MS values fluctuate with the grain concentrations before peaking at 1.80m representing an in increase in the abundance of magnetic minerals suggesting a large influx of sediment due to high rainfall or a flood event. At point c, the MS values show the material as diamagnetic which is consistent with the observation that this is peat, and the peak at point d reflects a higher portion of magnetic minerals due to the pedogenic processes of peat or could be a palaeosol.

ELF003

The highest MS value in this core is at point a (Figure 9.10), and could represent the first compacted layer within this section with the loose sand matrix sitting

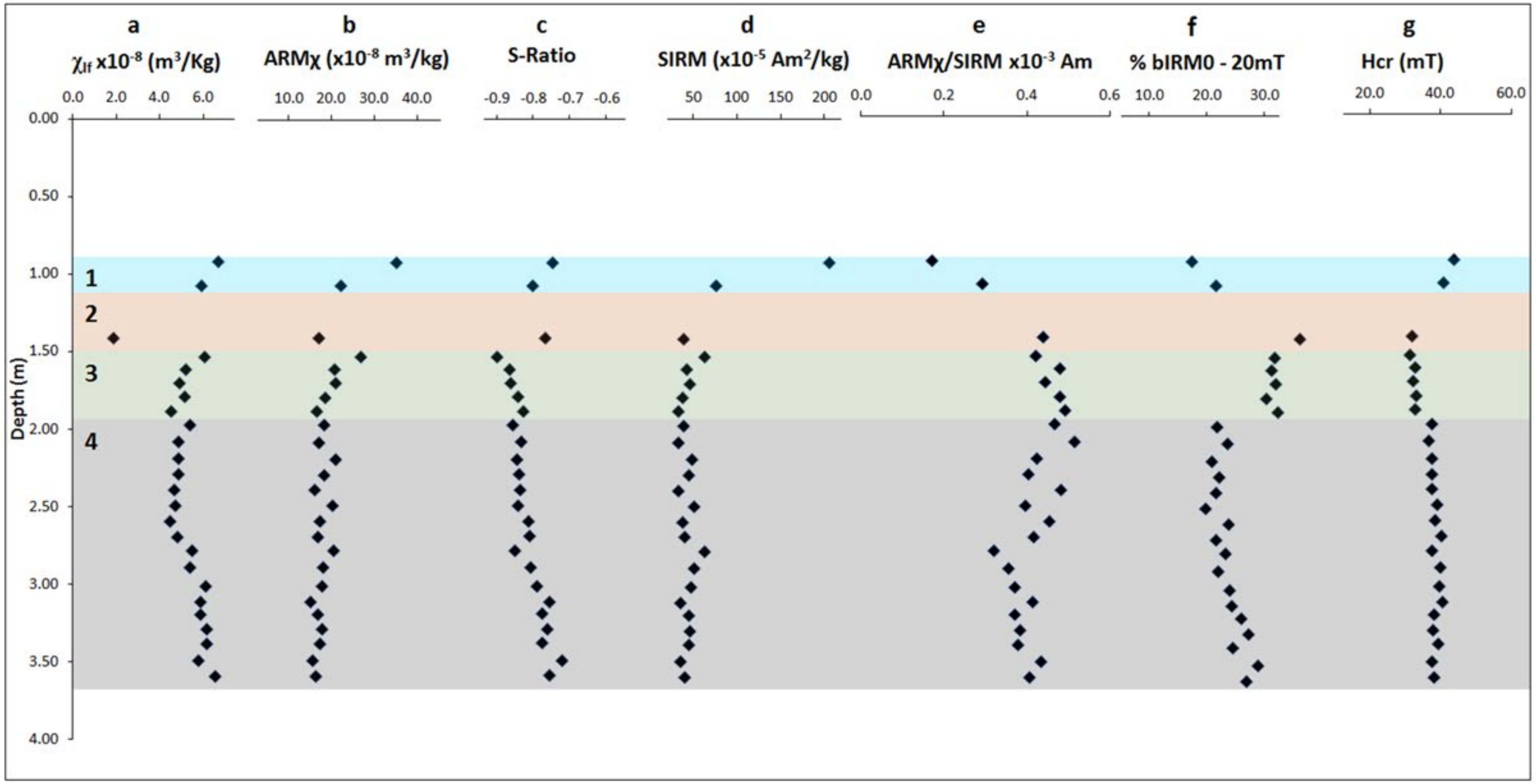


Figure 9.8 Stratigraphic trends of the rock magnetic parameters for ELF001A. The plots show the variations in a) magnetic susceptibility, b) susceptibility of ARM, c) S-ratio, d) Saturation Isothermal Remanent Magnetisation (SIRM), e) ARMχ/SIRM ratio, f) percentage of bIRM acquired between 0-20mT, and g) the Coercivity of Remanence.

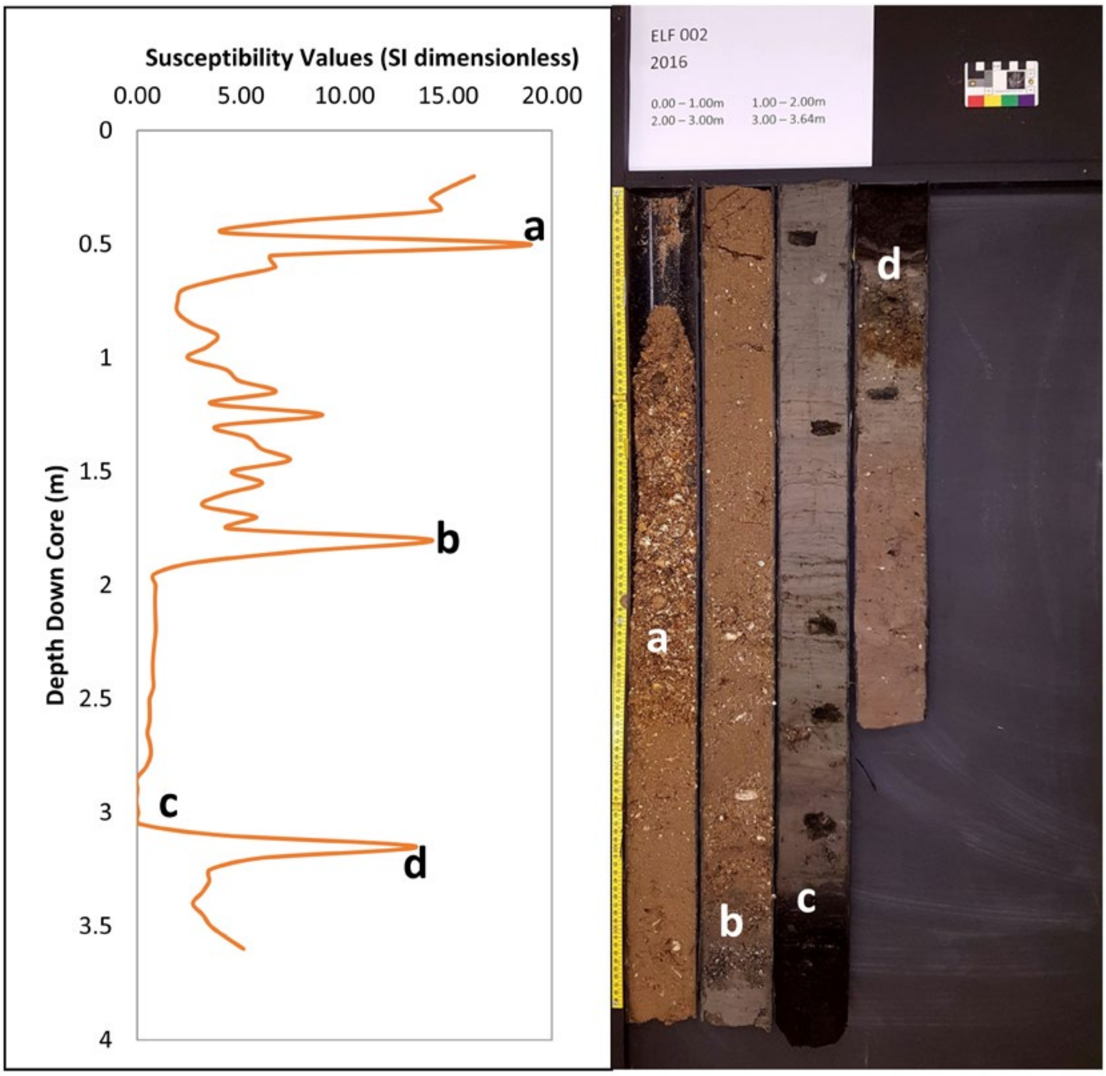


Figure 9.9 Left: Magnetic susceptibility values for core ELF002 averaged from three separate runs and corrected for drift sensor. Features on the plot are noted in the text. Right: Image of the core for comparisons.

above. The MS values drop significantly at b, down core through the dark grey medium sand which could be due to the increase in organic content. At c, the MS values show slight peaks and, although not significantly high, these could represent the introduction of new sediment from rainfall in the environment (see Maher 2007). The slightly higher value at d reflects the lithological change to iron bearing clay.

ELF019

ELF019 was the longest core analysed as part of this preliminary study. Figure 9.11 shows the base of the loose sand matrix at a; however, the mudflat sediments are shallower in this core with the MS decreasing through to the peat formation at b. The low MS values followed by the rise in values again (c) relate to the pedogenic formation and the exchange of magnetic minerals (ferrite, goethite and/or haematite) through the peat. The high MS peak at d clearly defines a palaeosol. The values between d and e are consistent, suggesting a low energy environment. The sediments contain the magnetic minerals necessary to record the ancient geomagnetic field.

The work carried out to characterise the geomagnetic field through ELF019 as part of an MSc project (Topping 2018) unfortunately did not have use of the 2G SQUID magnetometer, so it was not possible to utilise the full suite of AF demagnetisation steps due to time constraints.

The pilot samples suggested that there was a likelihood of surviving magnetic remanence characteristic of the geomagnetic field during the Holocene. The demagnetisation procedures applied to 21 of the samples from ELF019 ascertained that there is secular variation through the core sediments (Figure 9.12). However, due to the single step demagnetisation procedure, it is unwise to

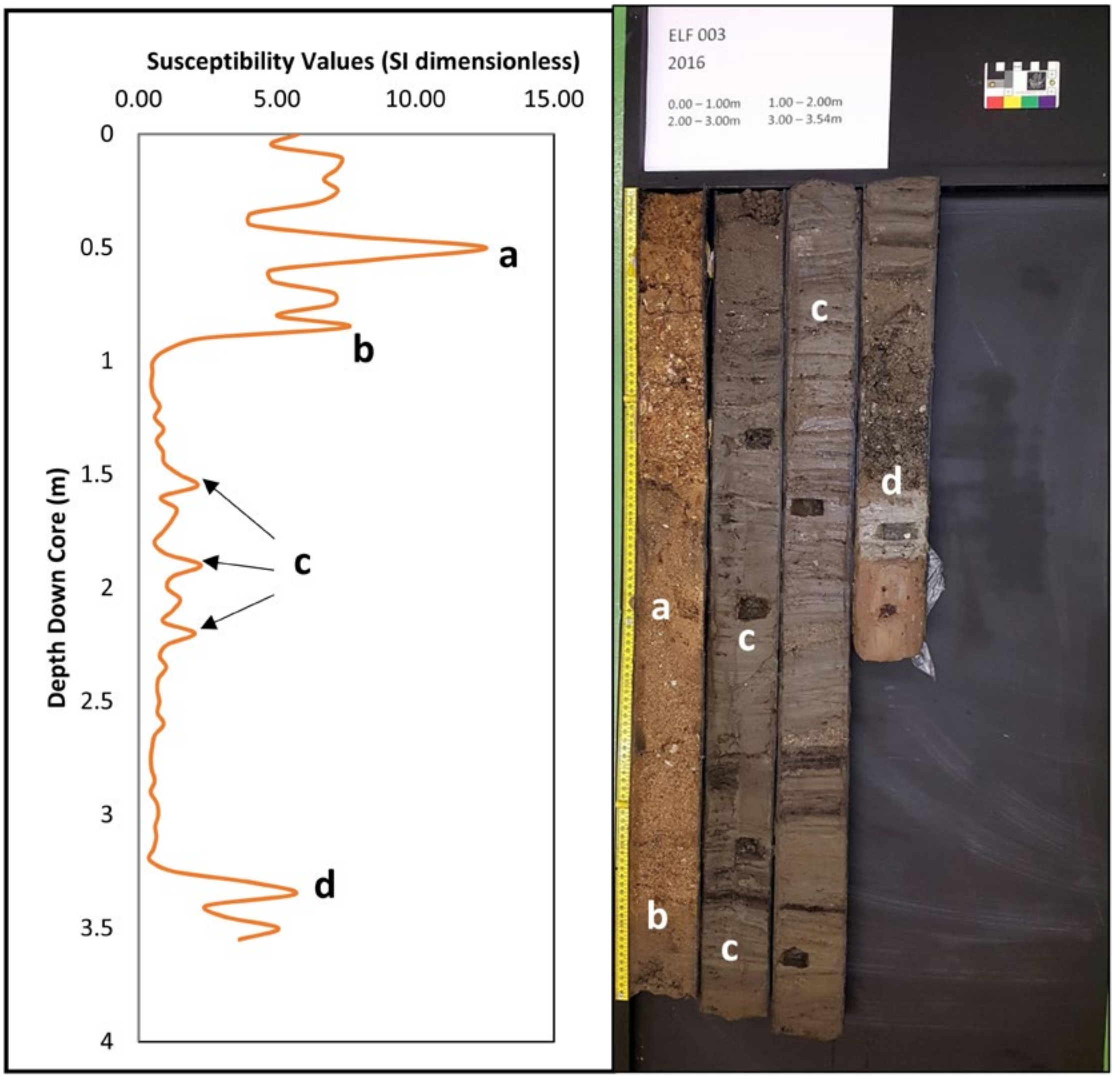


Figure 9.10 Left: Magnetic susceptibility values for core ELF003 averaged from three separate runs and corrected for drift sensor. Features on the plot are noted in the text. Right: Image of the core for comparisons.

infer overall behaviour. Analysis of core ELF001A showed the complexity of the demagnetisation behaviour and the need for the complete AF demagnetisation analysis to carry out PCA, hence the reservations placed on using purely the NRM data.

The declination values for the 21 samples (Figure 9.12) show significant variation with changes of over 100° which is most likely due to inability to completely re-orientate the separate core sections. There is the possibility that the core could be re-orientated utilising the VRM characterised in the first couple of demagnetisation steps. The extracted inclination values are all positive after removal of the unstable overprints and show that it is possible to successfully define this component of the geomagnetic field.

In addition to the demagnetisation study, partial rock magnetic procedures were applied to characterise the magnetic bearing minerals present in the sediments. A total of 21 samples were imparted with an ARM before being AF demagnetised at 40mT and 14 samples were progressively imparted with IRM fields as set out in the methods section. The time constraints did not allow for completion of the magnetic mineralogical study, however the samples analysed here show the variety of minerals present (see Table 9.2). Figure 9.13 shows the magnetic proxies which best characterise the magnetic minerals present. The resolution of this analysis does not allow distinct magnetic phases to be seen through the core, but there are samples which show large deviations. At approximately 2.0m depth the SIRM value shows a very large abundance of magnetic minerals in conjunction with a large decrease in the %bIRM$_{0-20mT}$. In addition to the large susceptibility of ARM, this horizon shows a large inundation of ultra-fine-grained magnetite with a higher concentration of harder magnetic minerals such as hematite/goethite

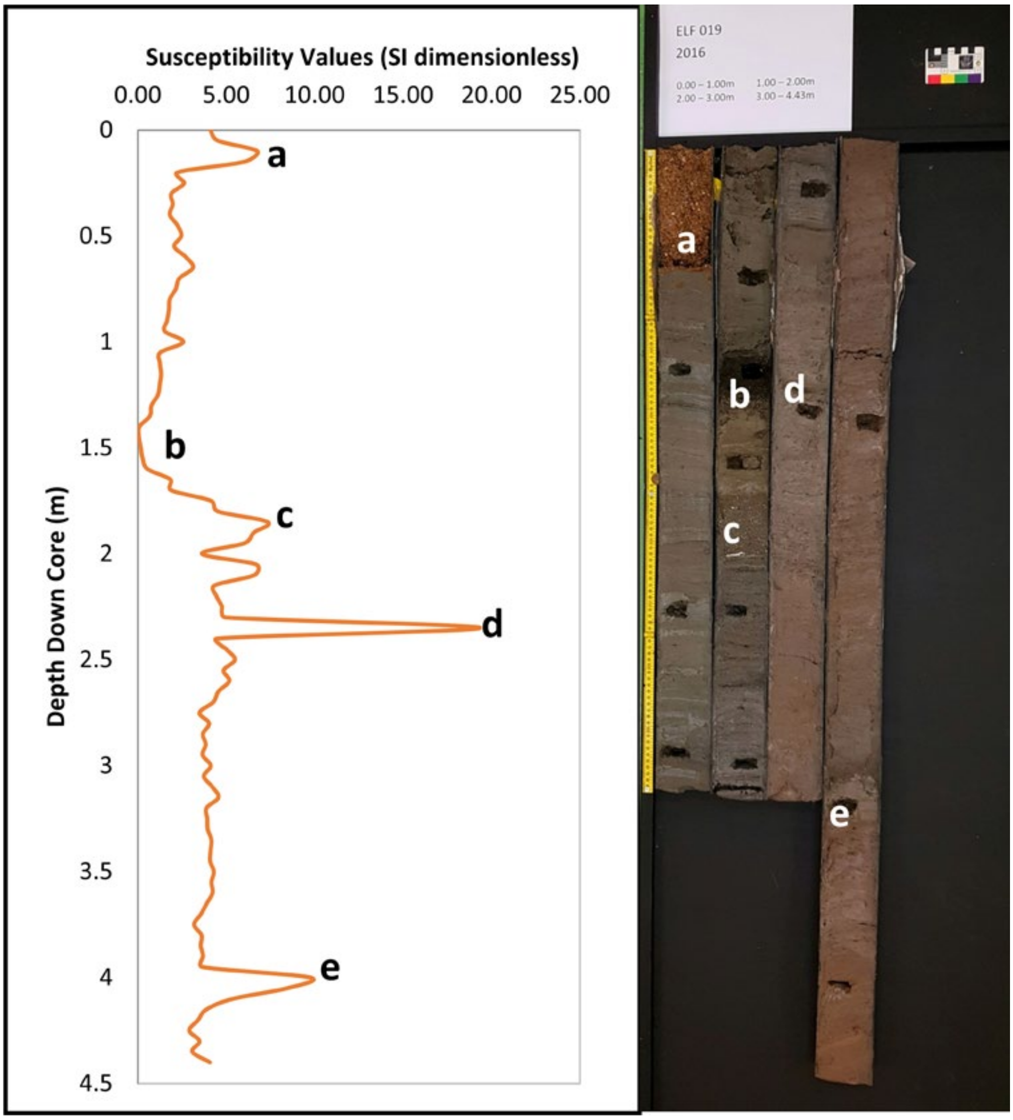


Figure 9.11 Left: Magnetic susceptibility values for core ELF019 averaged from three separate runs and corrected for drift sensor. Features on the plot are noted in the text. Right: Image of the core for comparisons.

which could be indicative of a large rainfall event or mass flooding.

Conclusions

There are two main conclusions which can be drawn from this study. Each provides the basis for moving forward with further study.

The first is that the record of the past geomagnetic field is evident in these cores and the results show that it is possible to extract that information. However, there are several factors which can affect the quality and reliability of this information. The palaeomagnetic sampling resolution must be contiguous (either through utilisation of equipment which can analyse the whole core or u-channel sampling) and longer cores provide more useful data. Ideally, analysis of overlapping core lengths would provide robusticity (comparison of overlapping data) and allow stacking of the data to cover longer timescales. This study shows that the ultra-fine clay bearing sediments are much more reliable then the sandier sediments at preserving a post-depositional remanence. While the extracted inclination values are consistent with those expected in the Holocene, inclination shallowing (Tauxe *et al.* 2008) and the possibility that coring might have deviated from the vertical should be explored.

The second conclusion is that the magnetic mineralogical analysis can be used to inform on the depositional environments and show nuanced changes in the lithology. Further work through the analysis of multiple cores could be utilised to show sediment transport systems and provide further robusticity of the geomagnetic record by characterising the magnetic

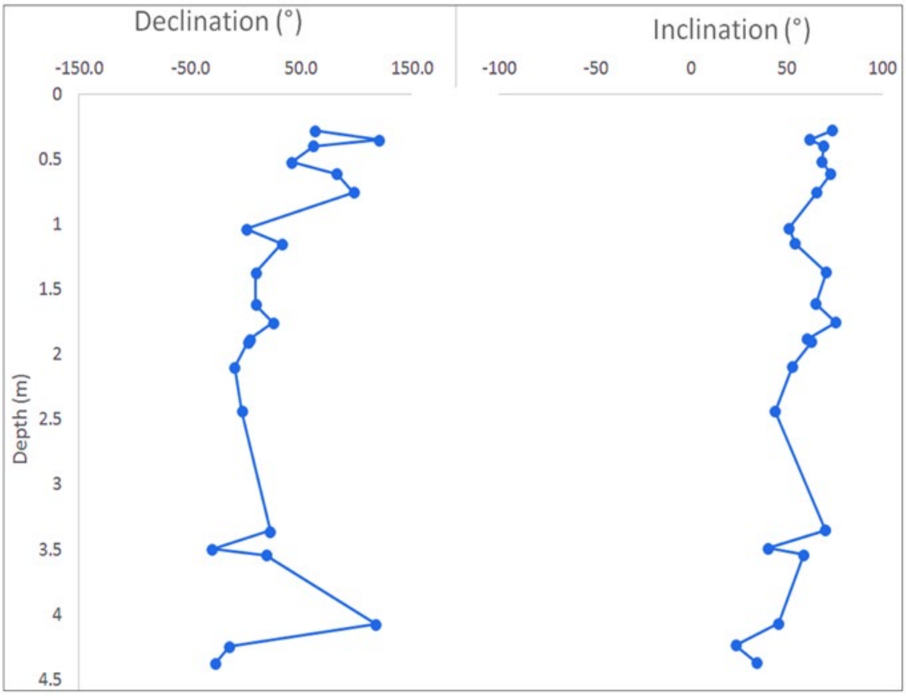


Figure 9.12 The declination and inclination values plotted down core for ELF019 from the analysis of 21 samples.

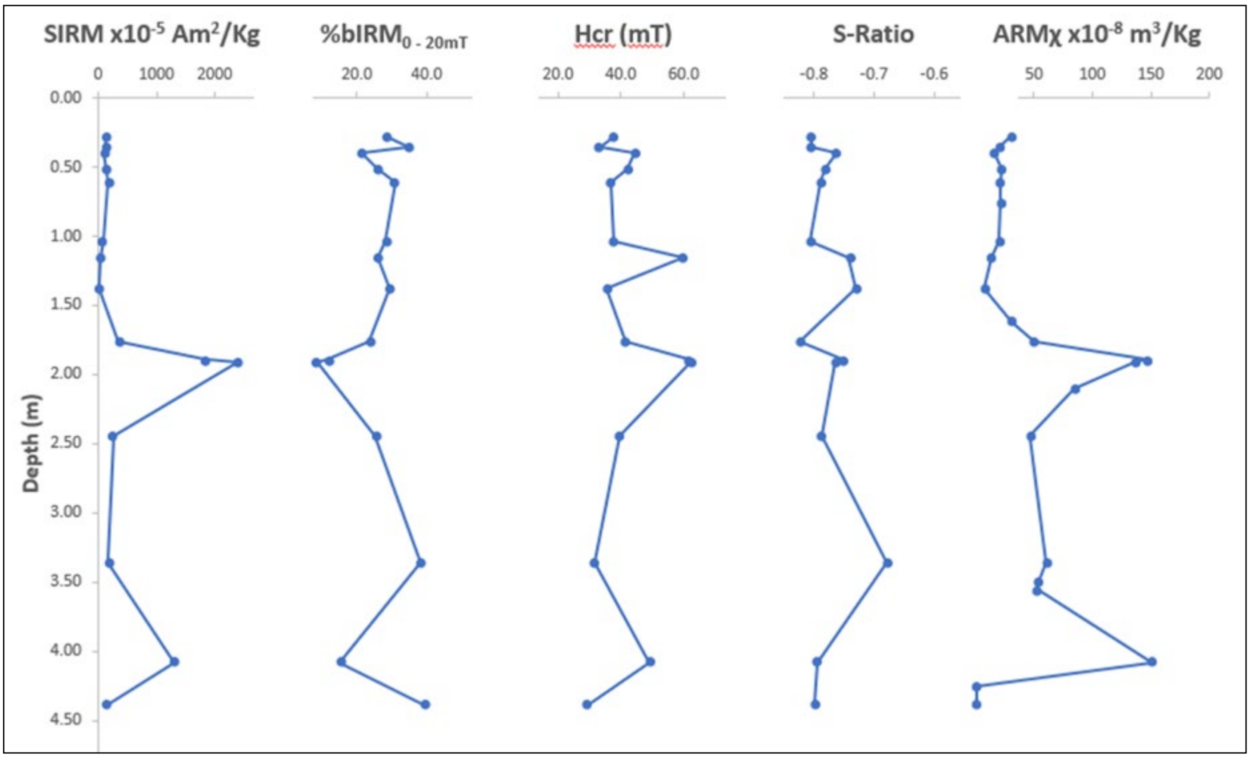


Figure 9.13 Down core plot of magnetic proxies calculated for core ELF019.

minerals and ensuring they formed/aligned at the point of chronological interest. Through a corpus of data from a larger quantity of material it would be possible to correlate cores using magnetic proxies.

This study has demonstrated that palaeomagnetic investigations can provide valuable information. In order to unlock the full potential of these cores further palaeomagnetic analysis is advised, starting with the other sampled cores. The understanding of the past geomagnetic field is paramount if the method is to advance and allow correlation of cores in the future. Combining the high number of radiocarbon determinations now available with further palaeomagnetic studies would represent an important step in elucidating geomagnetic field change for this period and region.

Chapter 10

Applying chemostratigraphic techniques to shallow bore holes: Lessons and case studies from Europe's lost Frontiers

Alexander Finlay, Richard Bates, Mohammed Bensharada and Sarah Davies

Introduction

The range of applications of analytical geochemistry in the geosciences extends from hydrocarbon studies to forensic investigations with samples from billion year old material formed deep within the earth to material from contemporary environments (Poulton *et al.* 2010). Within archaeological and palaeoenvironmental research, elementary geochemistry can also provide an excellent analytical tool for the investigator. There are numerous examples of these techniques being applied, from the provenance and identification of manufacture of anthropogenic material (e.g. Finlay *et al.* 2012) through to palaeoenvironmental studies e.g. Croudacre and Rothwell (2015). This chapter will demonstrate how geochemical and chemostratigraphic techniques have been applied within the *Europe's Lost Frontiers* project. A review of commonly utilised analytical techniques in archaeological and paleoenvironmental studies is first presented, followed by details on the methods of data collection, quality control and interpretation. Key cores are used as case studies to demonstrate particular aspects of the method.

Case study 1 demonstrates how geochemical analysis can be utilised to characterise a core into a series of chemostratigraphic zones (chemo zones), assign these to geochemical facies (chemo facies) reflecting their depositional environment and then validate these chemo facies by integrating them with other ecological datasets.

Case study 2 demonstrates how a comparison of chemo zones and facies from multiple cores within a study area can be used to produce a regional chemostratigraphic correlation, and so aid palaeolandscape reconstruction.

Case study 3 demonstrates the integration of chemostratigraphy with other methods such as seismic interpretation through the production of chemical modelled density profiles to link to the seismic data. This in turn is utilised for a greater understanding of the spatial coverage of the chemo zones and interpreted facies.

The chapter concludes with an overview of other applications of geochemical analysis that may be applied to future studies using unconsolidated sediment cores and palaeoenvironmental reconstruction.

Elemental analysis

Quantitative methods

The range of geochemical analysis techniques available for sediment quantitative elemental data include inductively coupled plasma-optical emission spectrometer (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence (XRF Figure 10.1 e.g. Jarvis and Jarvis 1992; Ratcliffe *et al* 2012). ICP-MS and ICP-OES are laboratory based elemental tools requiring significant sample preparation including microwave, flux fusion or acid digest processes in order to place the sample into a solution prior to analysis (Olesik 1991). The ICP-MS detects the mass of the ions hitting its detector and provides a mass spectrum for the sample, with the intensity of each mass peak in the spectrum being directly proportional to the concentration of an element of the same mass within the sample. The mass is quantified by comparing the intensities of the mass spectrum to known calibration standards (Tyler and Jobin Yvon 1995). The ICP-OES differs in that it measures the effect of the ions on the sample on the plasma itself. When the sample solution is introduced to the plasma the elements contained within loose electrons and give off radiation with wavelengths characteristic to the element itself. The optical spectrometer detects this radiated energy, and through comparison with the intensities of known calibration standards the elemental abundance can be quantified within the sample (Jarvis and Jarvis 1992; Olesik 1991; Tyler and Jobin Yvon 1995). The combined use of both ICP-MS and ICP-OES enable the quantification of major elements (greater than one weight percent of the sample) and trace elements (typically down to parts per billion level; Jarvis and Jarvis 1992).

X-ray fluorescence (XRF) is the emission of characteristic 'secondary' (or fluorescent) X-rays from a material that has been excited by being bombarded with high-energy X-rays. Analytical tools vary from laboratory-based techniques that can produce analysis similar to ICP instruments to highly portable handheld tools that can be used in the field. Dependant on lithology it provides data for ten major and approximately twenty trace elements, importantly including both chlorine

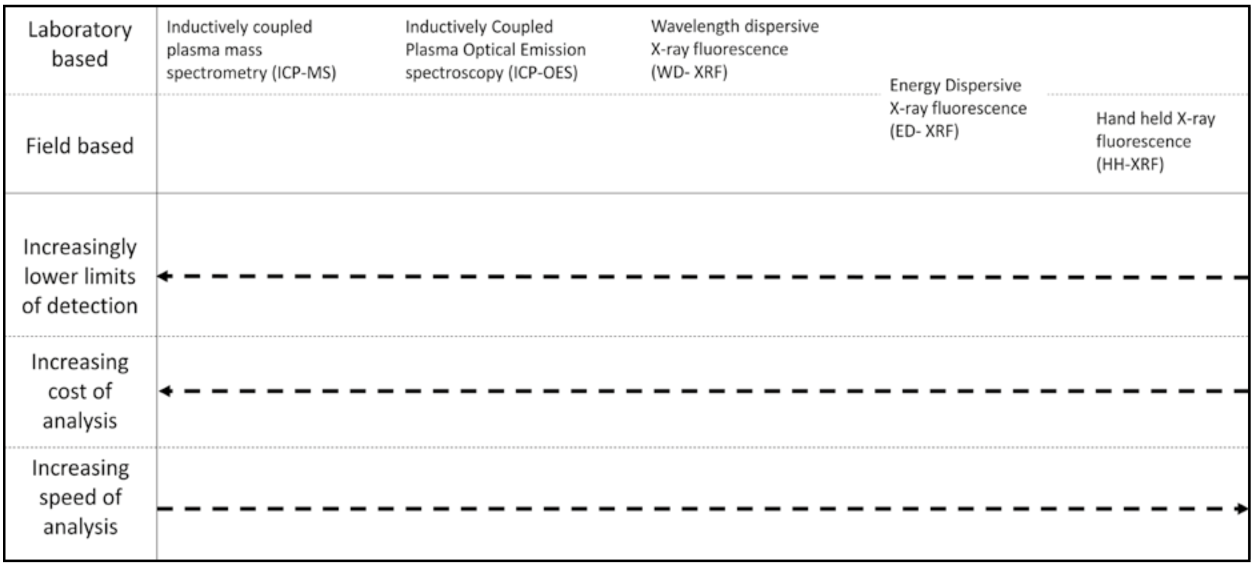


Figure 10.1 A summary of the benefits of typical analytical tools utilised in chemostratigraphic studies and their acronyms.

and sulphur making it the ideal tool for analysing saline samples. Handheld X-Ray Fluorescence is capable of providing rapid elemental data (Hennekam and de Lange 2012; Schmidt *et al.* 2018). The tool is non-destructive and capable of high spatial resolution analysis thus making it ideal for use in core scanning (Schmidt *et al.* 2018). However, it does not have the same limits of detection that more powerful x-ray tools possess.

Qualitative methods – Scanning/Micro XRF

An ITrax X-Ray Fluorescence core scanner (Cox Analytical Systems), based at Aberystwyth University, was used in *Europe's Lost Frontiers* project. The ITrax is a laboratory XRF scanner capable of very high resolution, continuous environmental core scanning at a relatively rapid automated rate (Croudacre and Rothewell 2015). While the data it collects is quantitative there are currently no standard reference materials for the technique and thus results are more appropriate to analysis of relative changes in elemental abundance rather than absolute elemental values reported by techniques such as ICP-MS. In *Europe's Lost Frontiers*, the ITRAX provided data at a resolution of 0.5mm thus allowing for chemical fingerprints of very short-lived climatic, depositional, and environmental changes. An additional benefit of the ITrax is its ability to record the incoherent (Compton) and coherent (Rayleigh) scattering caused by the XRF interaction with the core, enabling key information such as core density to be calculated (e.g. Fortin *et al.* 2013; Gaffney *et al.* 2020). Calculation of core density enables a comparison to be made of the geochemistry with other regional remote sensing techniques such as seismic analysis.

Data acquisition, quality control, data processing

A single data quality control and interpretation method was developed and utilised for all cores in the *Europe's Lost Frontiers* project in order to ensure that, as much as possible, data from different cores collected at different times was comparable.

The cores were initially split lengthwise, and the exposed surface scraped to ensure a smooth and flat surface. The scanner was typically set for a resolution of 0.5mm along core-interval and a dwell time of 15 seconds with the x-ray tube at 30kV and 50mA. For the individual core sections, the scanning line was adjusted to avoid sampling holes. All reported data was smoothed using a ± 4mm moving average filter applied to the data in order to remove any 'nugget' effect caused by clasts of a specific elemental composition leading to an overestimate of those elements compared to that of the core (e.g. Croudace and Rothwell 2015; Gaffney *et al.* 2020).

To test the validity of the recorded data, distance to sample surface, total counts and Argon (as the Ar signal is derived from the excitation of argon in air between the sample and X-ray source, rather than the sample) was plotted by core depth (below surface) and compared to the ITrax chemical data. A fall in total counts that coincides with a peak in Ar, suggest that any changes in chemical data at these depths may be caused by physical damage or irregularities in the core surface rather than elemental variations in the core (Croudace and Rothwell 2015). If these conditions were met, then the elemental data from these depths was not utilized in this study. Furthermore, any data that were outside two standard deviations of the mean depth to sample

Element	Symbol	Common mineralogical control	Common interpretations
Aluminium	Al	Clays	Depositional energy/Grain size
Bromine	Br	Organic material	Productivity/Salinity/marine influence
Calcium	Ca	Calcite	Evaporite or marine signal
Iron	Fe	Heavy and/or clay minerals	Detrital input
Potassium	K	Clay minerals	Detrital input and depositional energy
Magnesium	Mg	Dolomite	Dolomitisation
Sodium	Na	Halite	Salinity
Phosphorus	P	Apatite and phosphates	Heavy minerals or Nutrient enrichment
Sulphur	S	Organic material/Gypsum	Productivity/Salinity/marine influence/palaeosoils
Silica	Si	Quartz	Depositional energy/Grain size
Strontium	Sr	Aragonite	Shell material/marine signal
Thorium	Th	Heavy minerals	Depositional energy/Grain size. Link with gamma ray logs
Titanium	Ti	Heavy and/or clay minerals	Detrital input
Uranium	U	Heavy minerals or anoxia	Depositional energy/Grain size. Organic content. Link with gamma ray logs
Zirconium	Zr	Heavy minerals	Depositional energy/Grain size

Table 10.1 Elements commonly utilised for archaeological and paleoenvironmental research (summarised from Davies *et al.* 2015 and Chemostrat multiclient report NE118).

surface, thus indicating an irregular surface, were also treated with caution.

Three methods are proposed to ensure confidence in using ITrax derived identification of mineralogical or deposition drivers for variations in elemental chemistry. Where possible, additional quantitative mineralogical analysis (e.g. X-ray Diffractions/Raman minerology or SEM-EDS techniques) on a subset of samples can be made for comparison of the sediment chemistry with the minerology. If additional data is not available, a comparison with observed changes in the core from more traditional methods such as colour, shell fragments and grain size can be made. Finally, the data can be analysed using statistical methods such as principal component analysis (PCA).

Principal Component Analysis (PCA) is a mature statistical technique that is widely used for identifying patterns in data of multiple dimensions. PCA finds a set of orthogonal dimensions, which account for the variance in a specific dataset, by reducing the dimensionality of a complex system of correlations into a smaller number of dimensions. The first principal component accounts for as much data variance as possible and each subsequent principal component accounts for remaining data variance (Michoux 2020). For example, in a hypothetical interbedded sand/mud section that transitions from marine to fluvial control, PCA1 would likely be controlled by a variation in elements associated with the sand (e.g. Si and Zr) and clay fractions (e.g. Al, Rb and K), whereas PC2 may be marked by the variation between these detrital minerals and elements associated with marine settings (Ca and Sr).

An in-depth review of possible controls in elemental data are reported by Rothwell and Croudace (2015) for marine sediments and Davies *et al.* (2015) for fluvial sediments. Table 10.1 lists the common drivers of elemental variation within sedimentary units. However, it is stressed that sediments are complex mixtures of natural materials and so this may not always be true.

Case study 1 – Chemostratigraphic zonation, chemostratigraphic facies and integration with sedimentological and ecological data to establish the depositional environment of Core ELF19

Introduction

Case study 1 comprises a comparison of elemental data to microfossil analysis and observed variations in minerology within core ELF19. This was collected off the East Anglian coast in the *Europe's Lost Frontiers* study area (Figure 10.2) and measures ~4.3 meters long. Microfossil analysis shows that it contains three depositional settings:

- 0.18-1.34m depth – estuarine mudflats latterly with some algae; initially an eroded peat, with onset of tidal access
- 1.46-4.01m depth – river or lake with some cool/deep water, latterly with hint of low salinity as tidal access approaches with sea-level rise
- 4.27-4.29m depth – till

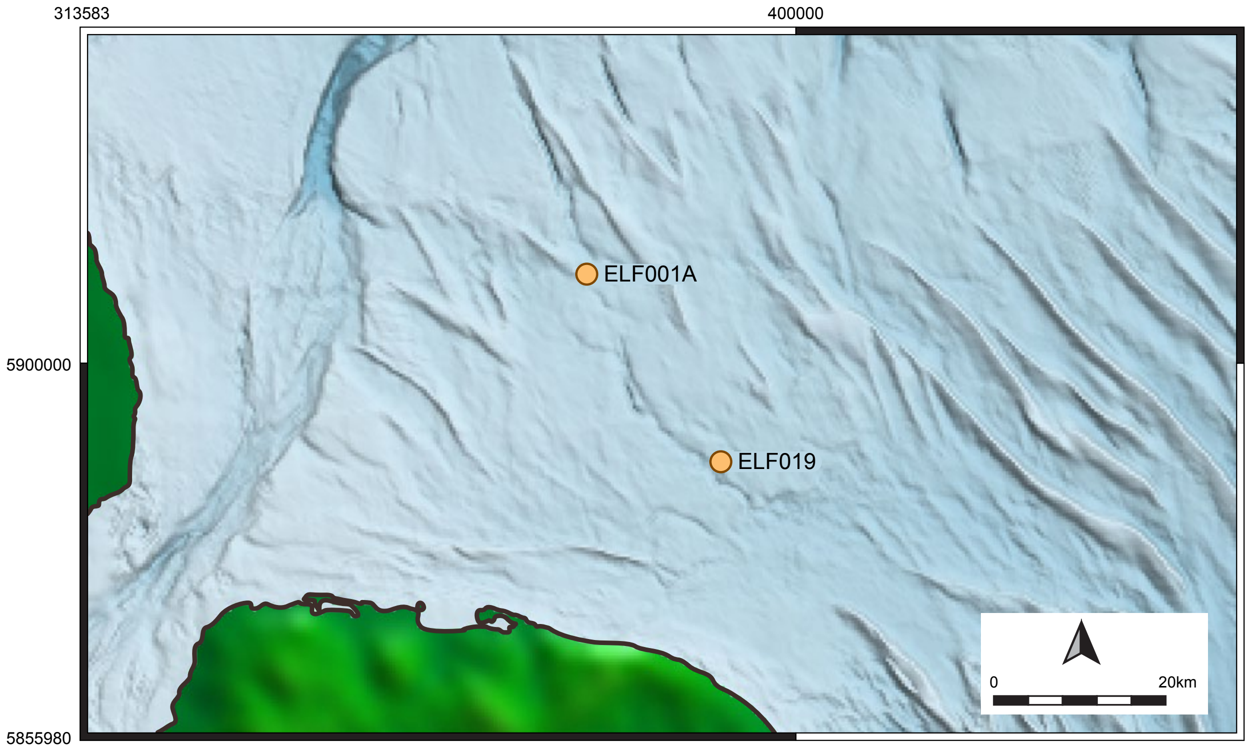


Figure 10.2 Location map of cores referred to in this paper. Bathymetric data is derived from the EMODnet Bathymetry portal - http://www.emodnet-bathymetry.eu. Topographic data derived from the NOAA ETOPO1 dataset, courtesy of the NCEI - https://www.ngdc.noaa.gov/mgg/global/

The top ~3m of core underwent elemental analysis and the data produced was used for chemostratigraphic interpretation. Chemostratigraphy (chemical stratigraphy) is the application of whole rock or sediment geochemistry to understand the depositional history, correlation and palaeoenvironment of a core. It involves building a chemostratigraphic zonation (chemo zone) of the analysed material, assigning each zone facies information based on its chemistry (chemo facies) and where there is the need, correlating similar chemo zones between different cores and/or outcrops and so producing a chemostratigraphic correlation (Ellwood *et al.* 2008).

The chemo zones produced in ELF19 were driven by variations in detrital grain size, carbonate, clay, organic material and salinity. These variations enabled the core to be subdivided into six chemo zones, each ascribed a chemo facies description. These chemo facies were then compared to available sedimentological and biostratigraphic information to produce a set of integrated core facies.

Elemental data and controls

Core ELF19 was scanned from a depth of ~18.5cm to ~296cm at a 0.05cm resolution. Reported data underwent the quality control methods outlined above, and eleven elements passed the test (Table 10.1). These elements were subject to PCA analysis (Figures 10.3a and 10.3b) to establish the dominant mineralogical controls on elemental variation (Table 10.2).

Chemostratigraphic zones

To establish a chemostratigraphic zonation, the dominant element from each principal component cluster in Table 10.2 were ratioed and plotted for each reported depth down the length of the core. Using ratios to compare elemental data is preferred as this removes any dilution effect caused by variations in other elements analysed at that depth (Weltje *et al.* 2015 and references inter alia). These elemental ratios likely reflect down core variations in:

- Si/Rb: quartz/clay – changes in detrital grain size
- Ca/Rb: carbonate/quartz – marine/fine terrestrial sediment
- S/Rb: organic material/clay
- Br/Ti: salinity (De Boer *et al.* 2014)

Visual comparison of the results of the analysis enabled the core to be split into five chemo zones (numbered top down; Figure 10.4; Table 10.3).

Chemo facies

It is possible to assign likely chemo facies to the above chemo zones based on their observed chemistry and

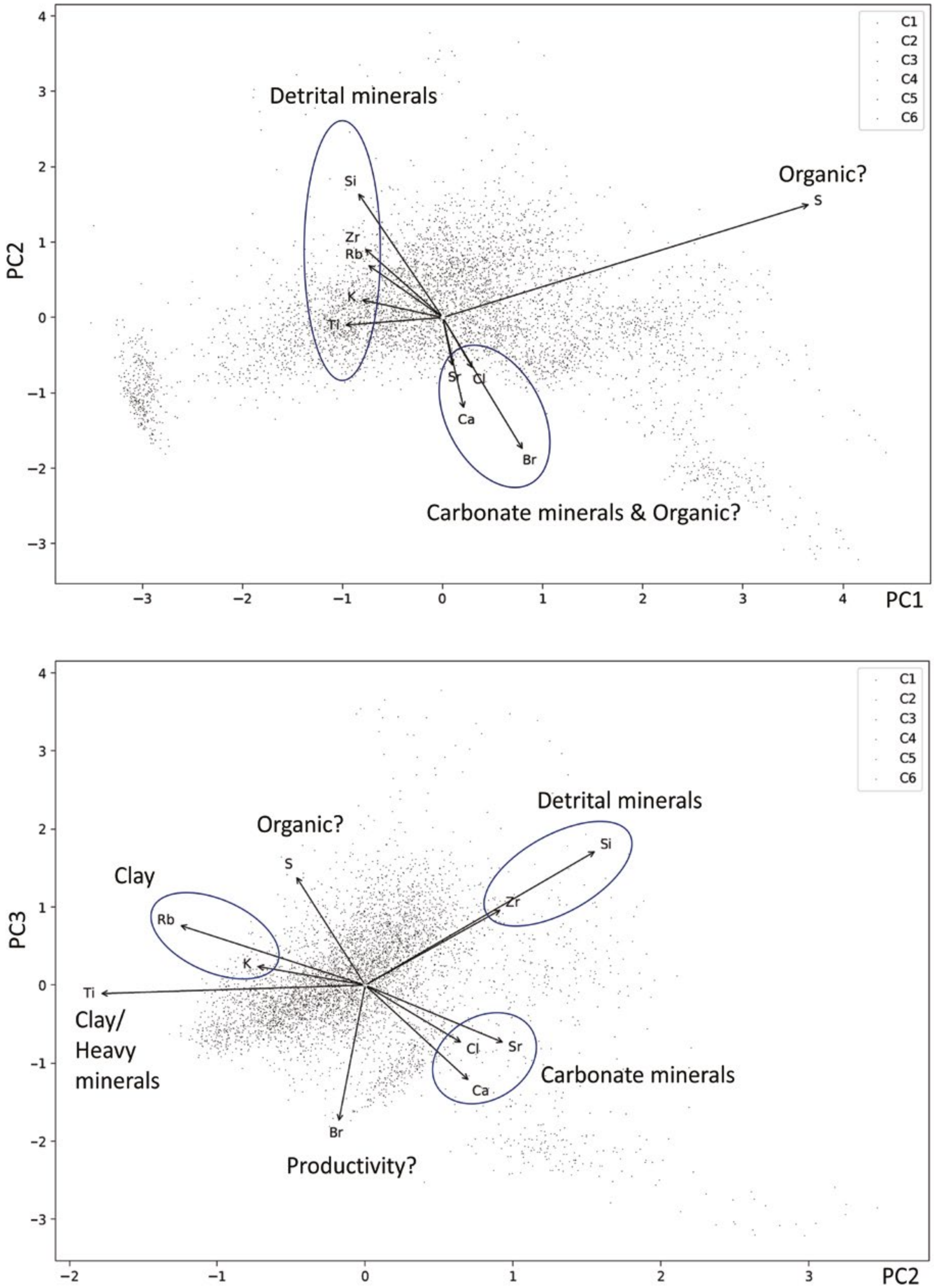


Figure 10.3 PCA of elemental data for core ELF19 showing the likely mineralogical and material drivers for variation in elemental compositions. a - component 1 and 2, b - component 2 and 3.

Element	Symbol	PC1 and 2 control cluster	PC2 and 3 control cluster	Likely mineralogical control
Silicon	Si	Detrital minerals	Detrital minerals	Quartz
Zirconium	Zr			Detrital Zircon
Rubidium	Rb		Clay minerals	
Potassium	K			
Titanium	Ti		Heavy Minerals/Clay minerals/Oxides?	
Sulphur	S	Organic material		
Bromine	Br	Carbonate minerals and salinity	Salinity?	Organic material/Salinity?
Calcium	Ca		Carbonate minerals	Carbonate minerals (Calcite)
Strontium	Sr			Carbonate (Aragonite)
Chlorine	Cl			Uncertain - Sea water chemistry?

Table 10.2 Likely elemental affinities for core ELF19.

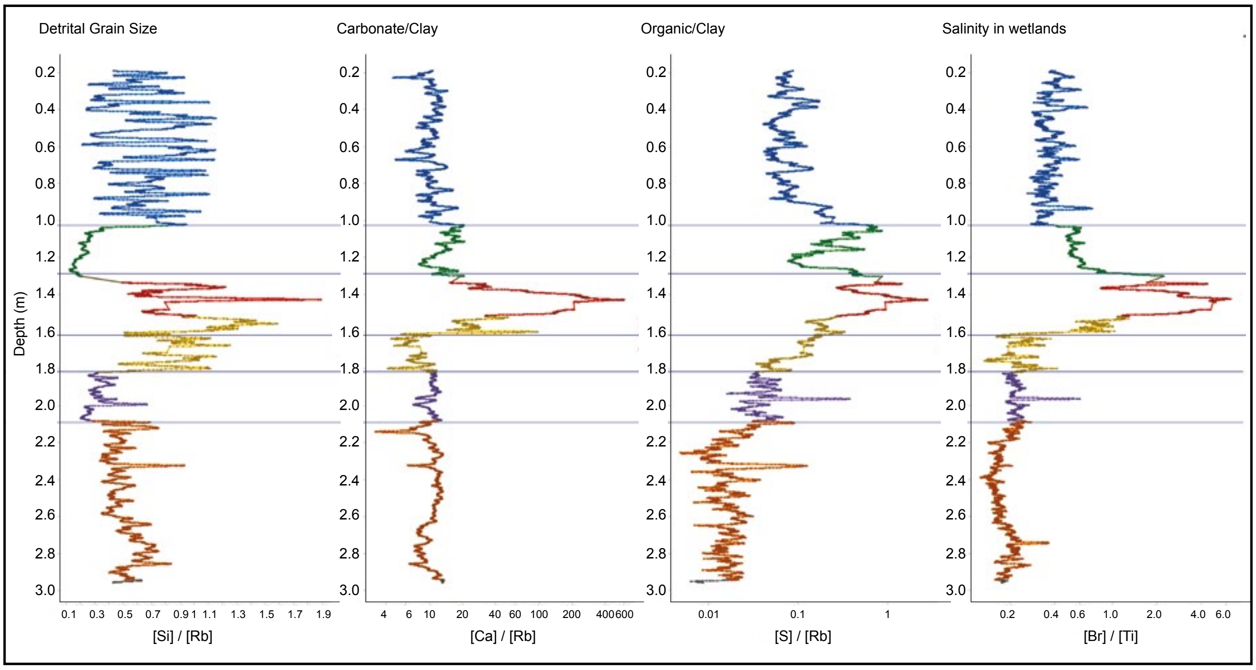


Figure 10.4 Chemostratigraphic zonation of core ELF19. Si/Rb likely reflects variations in grain size with higher values being more Sand (Quartz) rich and higher Rb being more Clay rich. Ca/Rb likely reflects variations in carbonate (Ca) compared to clay material. S/Rb likely reflects variations in organic material (S) to clay. Br/Ti is a proxy for salinity in wetlands (see text for references).

the hypothesised mineralogical controls on chemical data (Table 10.2):

- Chemo zone C1: interbedded sandy/silt and silty/clay horizons (Si/Rb variations) likely of a more saline depositional setting (moderate Br/Ti values) and some shell/carbonate material (Ca/Br); the finer horizons are more organic rich (Si/Rb troughs correlate with S/Rb peaks) and more saline (Si/Rb troughs correlate with Br/Ti peaks)
- Chemo zone C2: massive clay rich unit (very low Si/Rb values) with decreasing downhole organic (S/Rb) content; a higher level of salinity (Br/

Chemo Zone	Depth	Si/Rb (~Quartz/Clay)	Ca/Rb (~Carbonate/Clay)	S/Rb (~Organic material/ Clay)	Br/Ti (~Salinity; (De Boer *et al.* 2014)
C1		Highly variable, ranging from vales of ~1.1 to ~ 0.01 over ~10cm of stratigraphy	Variable, ranging from ~10 to ~5. Variations occur over a similar scale to Si/ Rb and troughs in Ca/ Rb correlate with Si/ Rb peaks	Moderate (~0.06) with three peaks at ~0.36, 0.6 and 0.7m depth.	Moderate to low
Boundary		Sharp fall	Sharp rise	Sharp rise	Sharp rise
C2		Constantly very low (~0.025)	Moderate to low (~17 at top dropping to ~8 at base of zone)	High at top of unit (0.8) dropping to moderate in centre (~0.08), rising to high again at base (0.5)	Moderate
Boundary		Sharp increase	Sharp increase	Sharp increase	-
C3		Rising to a very high peak in the centre of zone (~1.9)	Rising to a very high peak in the centre of zone (up to ~575)	Rising to a very high peak in the centre of zone (~2.8)	Rising to a very high peak in the centre of zone (~6.4)
Boundary		Trough	Decrease	Decrease	Decrease
C4*		Variable but decreasing from high (~1.6) at top of the zone to moderate at base (~0.8)	Moderate at top of zone (~23) dropping to low at base of zone (~1.7)	Moderate at top of zone (~0.19) dropping to low at base of zone (~0.08)	Moderate at top of zone (~0.8) dropping to low at base of zone (~0.25)
Boundary		Drop	-	Plateauing	Plateauing
C5		Very low/low (0.3)	Low (10.5)	Low (0.04)	Low (0.2)
Boundary		Increase	-	Decrease	Decrease
C6		Moderate (0.5) with a gradual down hole rise.	Low (10.5)	Low (~0.01)	Low (0.2) to very low (0.2) down hole
* Based on the variations in data over the unit it may be possible to split zone C4 into two sub zones.					

Table 10.3 Chemical definition of Chemo Zones and boundaries for core ELF19.

Ti) than zone C1 some shell/carbonate material (Ca/Br)

- Chemo zone C3: the coarsest unit in the core (Si/Rb) that also contains a large carbonate content (Ca/Rb), organic material (S/Rb) and salinities (Br/Ti)
- Chemo zone C4: a coarse unit (Si/Rb) with low carbonate content (Ca/Rb), decreasing organic material (S/Rb) and low salinity (Ti/Rb)
- Chemo zone C5: a clay rich unit (Si/Rb) with low carbonate content (Ca/Rb), moderate to low organic content (S/Rb) and low salinity (Br/Ti)
- Chemo zone C6: a silty unit (Ca/Rb) with low carbonate content (Ca/Rb), low to very low organic content (S/Rb) and low to very low salinity (Br/Ti)

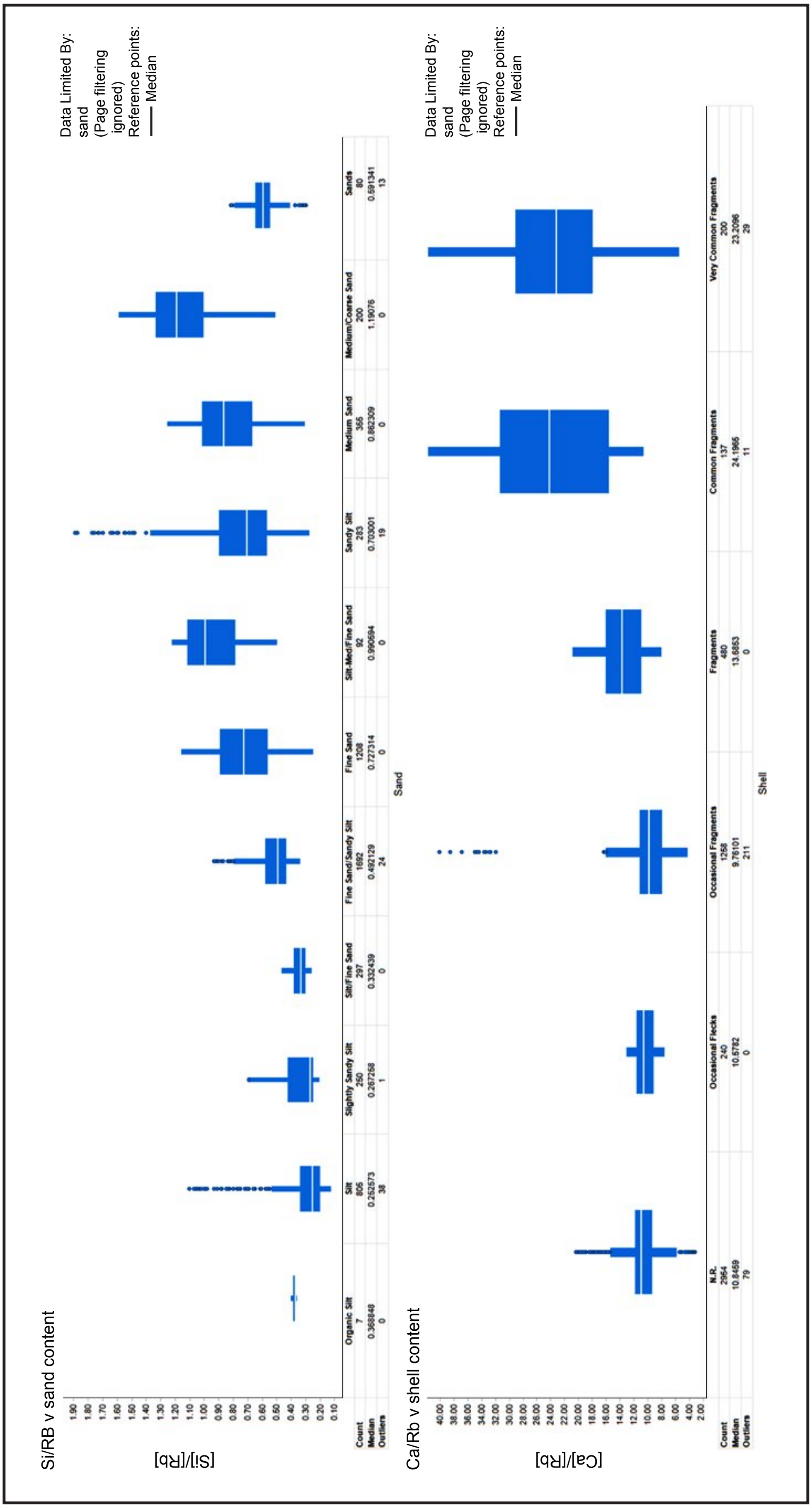


Figure 10.5 Boxplots showing the correlation of observed mineralogy and chemistry within core ELF19.

Integration of chemo zones with sedimentological and ecological data

Without any other data the chemo zones presented in section 3.3 are only hypothesised. However, the results can be compared to other geotechnical information such as grain size, shell content and biostratigraphy. A reasonable comparison is achieved between the Si/Rb values and observed sand content as is the comparison of Ca/Rb values with shell contents (Figure 10.5).

When ecological facies, derived from the biostratigraphic data, are compared to chemistry (Figure 10.6) there is also a good coincidence between the ecological boundaries and the chemo zone boundaries. Chemo zones C1 and C2 have Br/Ti values of ~0.4 and S/Rb values of ~0.1 whereas chemo zones C4, C5 and C6 have lower Br/Ti values of ~0.2 and S/Rb values of ~0.05 demonstrating a drop in salinity and organic content down core. Consequently, C1 and C2 are both interpreted as representing estuarine mudflats, whereas, C4-C6 are interpreted as river or lake sediments. Unit C3, shows greater complexity. Based on initial chemistry it is expected this would be a coarse marine bed. The ecological facies data also suggests that this is a course unit, however the lack of marine fossils suggest it is deposited in a freshwater setting.

Conclusions

The chemostratigraphic zonation of ELF19 based on an interpretation of the chemical, grain size and ecological analysis is summarised in Table 10.4 below.

Case study 2 – Chemostratigraphic correlation of chemo zones within Holeocene shallow cores.

Introduction

Case study 2 seeks to demonstrate how chemostratigraphic zonations can be used to produce a chemostratigraphic correlation for multiple cores across a palaeolandscape for further understanding of palaeotopography, geography and depositional setting.

Chemostratigraphic correlation is a stratigraphic technique that is commonly used in both the petroleum and minerals industries to correlate core and drill cuttings. This can be undertaken at a variety of different scales from regional scale (Ratcliffe *et al.* 2012), quarry or oil field scale (e.g. Pearce *et al.* 2010) through to field outcrop scale (Ellwood *et al.* 2008). Generally, the more localised the study area the more detailed a correlation is possible.

Chemostratigraphic correlation involves the characterisation, correlation or differentiation of sedimentary rock successions based on stratigraphic variations in the elemental geochemical data. This geochemical data is influenced by changes in the mineralogical and organic content of the rock, and in particular by changes in clay mineralogy and the heavy mineral content. Mineral and organic changes are often a manifestation of changes in palaeoclimate, palaeoenvironment, sediment provenance and both weathering or diagenesis. The dependence of chemostratigraphy techniques on minerals means that it can be used on any lithology, including those that are barren of biostratigraphy. For example, mapping the concentrations of elements such as Zr, Nb and Ti can display changes in heavy mineral abundance, which can provide insight into sediment dispersal patterns and changes in provenance. Mapping elements such as U and Mo reflect the presence and abundance of organic matter that, together with biostratigraphic information, enable the reconstruction of depositional environments.

Chemostratigraphic correlation

At the time of writing, work within *Europe's Lost Frontiers* had not progressed to the point that project data could demonstrate the use of chemostratigraphy to correlate unconsolidated cores, therefore a case study has been produced from data collected from cores sourced from Orkney (Figure 10.7). Three approximately 2 to 3m cores (Core A, B and C), spaced over approximately 300m, were collected from the same sub-basin and underwent geochemical analysis and data interpretation to identify three key elemental ratios:

- Sr/Br – shell material (aragonite)/organic content

Chemo Zone	Top depth (m)	Ecological facies	Integrated interpretation
C1	0.19	Estuarine mudflats	Interbedded estuarine sandy silts and silty clays
C2	1.03	Estuarine mudflats	Estuarine clay
C3	1.33	Freshwater channel in a fluvial system	Coarse sediment of an uncertain marine/fluvial system
C4	1.52	River or lake	Freshwater sands
C5	1.82	River or lake	Freshwater clays with some organic content
C6	2.08	River or lake	Freshwater silts

Table 10.4 Integrated chemical and ecological results for core ELF19.

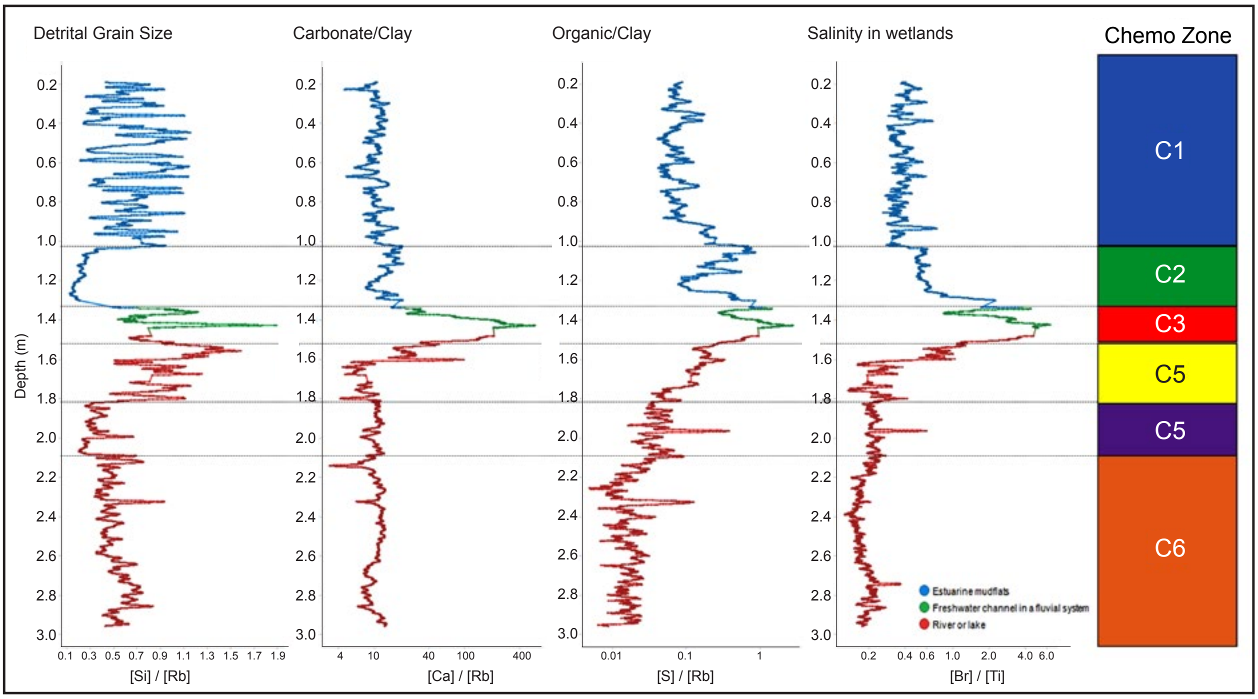


Figure 10.6 This figure demonstrates an excellent match in the chemostratigraphic zonation of core ELF19 and ecological biostratigraphic data.

- Sr/Rb – shell material (aragonite)/clay
- Si/Br – sand (quartz)/organic content

These key ratios were used to establish a chemostratigraphic zonation comprising four chemo zones (C1-C4), furthermore, chemo zone C2 was split into four sub zones (C2-1 to C2-4) in core B and C. Not all zones were present in all cores and so a composite core has been produced to illustrate the full chemostratigraphic zonation (Figure 10.8).

As in case study 1, chemo facies information was produced for each chemo zone. Core B had undergone biostratigraphic analysis and cores A and B had undergone sedimentological analysis and therefore it was possible to 'ground truth' the chemo zonation with other data to produce confident facies descriptions for each chemo zone (Table 10.5).

Chemostratigraphic zonation, correlation and palaeolandscape interpretation

The presence and absence of the chemo zones in each core enables the chemo zones and subzones to be correlated across the cores (Figure 10.9 and 10.10).

To the authors knowledge, this represents the first attempt to correlate shallow Holocene cores using chemostratigraphy. Based on this chemostratigraphy, the following depositional history is hypothesised for the study area (further work is currently ongoing to confirm this):

- Chemo zone C1 is found across all three cores, suggesting the carbonate sands blanket the study area
- Chemo zone C2 is only found in cores B and C and thickens from core B to core C; this suggests that this silty unit with differing levels of organic material was either infilling existing topography that deepens towards core C or it has been differentially eroded from the surface – the fact that all subzones within unit C2 thicken towards core C suggest the former is the more likely
- Chemo zone C3 is not found in core B and is underlain by peat in zone C4 – this suggests that core C may have been a sub-aerial peat when the possibly lacustrine C4 sediment was being deposited around it; the lacustrine C3 sediment is also much thicker in core C than A suggesting greater accommodation space formed by palaeotopography
- The peat zone C4 has not been penetrated in core C; in core A it is found below the thin lacustrine C2 unit and so may be present at depth

Due to the high resolution of the scanning XRF, the chemostratigraphic zonation is able to record the exact point at which major palaeoenvironmental changes occurred and the chemostratigraphic correlation map these boundaries spatially (Figure 10.9 and 10.10). Furthermore, the highly precise placement of these palaeoenvironmental changes means that future point sampling (e.g. geochronology, SedaDNA and biostratigraphy) can be carried out at the exact

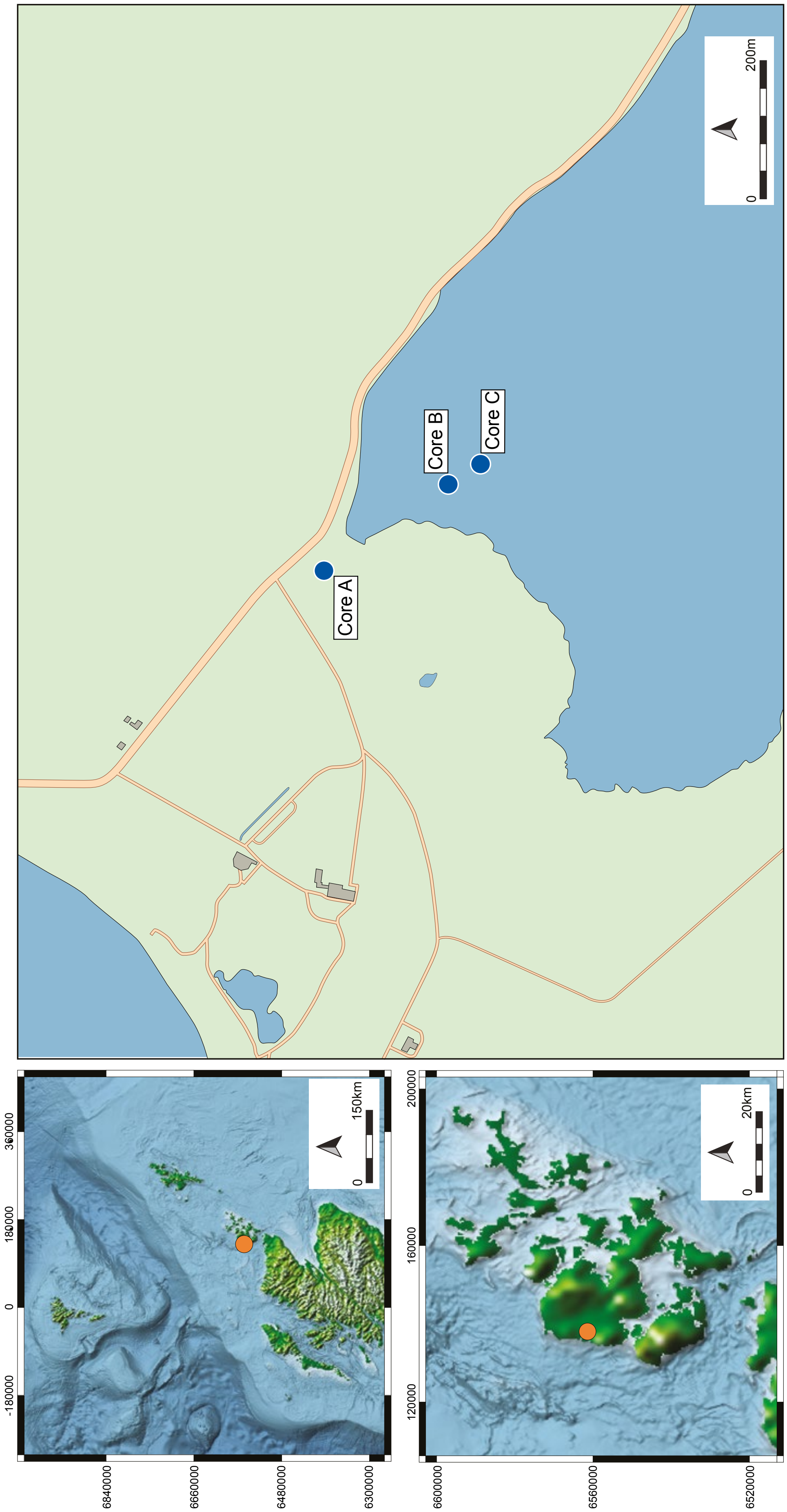


Figure 10.7 Orkney core locations

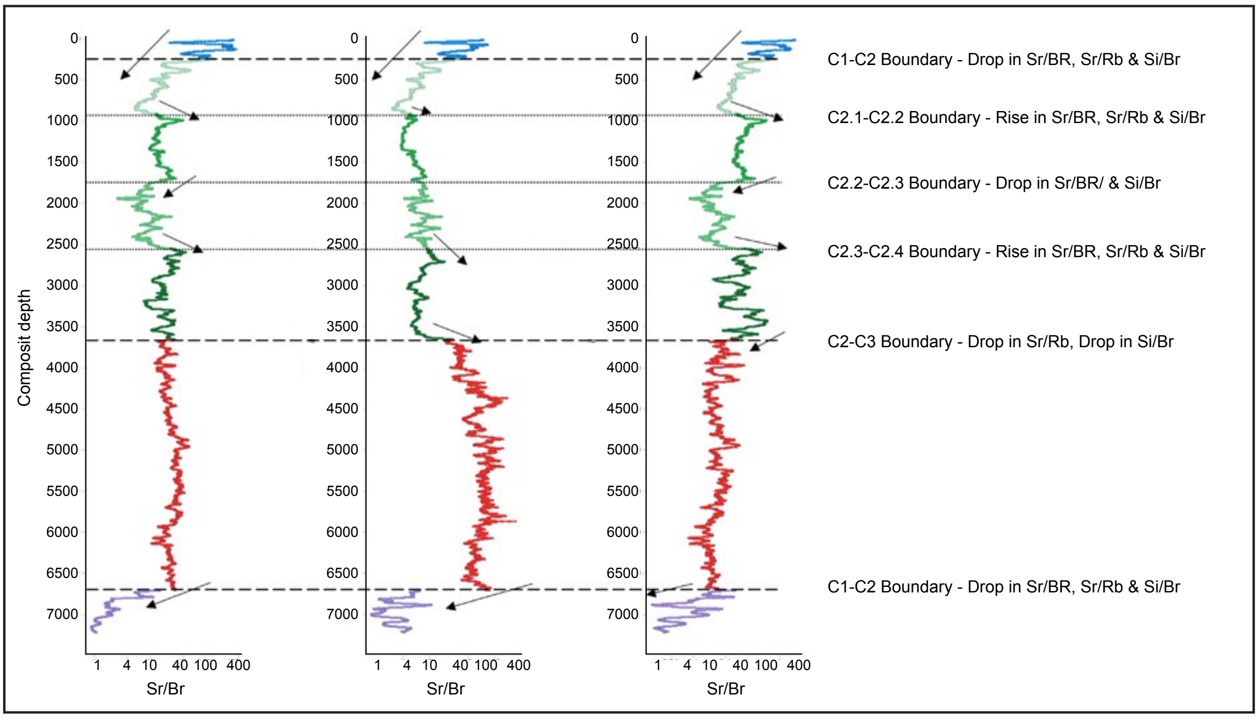


Figure 10.8 The elemental variations utilised to define the chemostratigraphic zonation in the study area. Sr/Br likely reflects variations in shell material (Sr - aragonite) and organic material (Br). Sr/Rb likely reflects variations in shell material (Sr - aragonite) and Clay (Rb). Si/Br likely reflects variations in sand (Si - Quartz) and organic material (Br).

Chemo Zone	Chemical interpretation	Sedimentology	Environmental interpretation	Integrated facies
C1	Shelly sand	Sand, Sand and Mud, Sand and Weed	Freshwater	Shell rich sand
C2	Silt with some shell material. Sub zones C2.1 and C2.3 marked by more organic rich material, where as subzone C2.2 and 2.4 are more shelly and sandy.	Mud	Brackish/ Freshwater	Fresh to brackish silt with some organic rich beds
C3	Carbonate rich	-	Freshwater	Freshwater carbonate rich sediment – Lacustrine?
C4	Low levels of all elements - organic rich sediment?	Peat	-	Peat

Table 10.5 Chemical, sedimentological and environmental interpretation of chemo zones and integrated facies identification.

point these changes take place, removing the need to interpolate between data.

Case study 3 integrating chemostratigraphy with seismic studies

Introduction

This case study seeks to demonstrate how, in addition to producing chemostratigraphic zonations and correlations from elemental data, incoherent (Compton) and coherent (Rayleigh) scattering caused by the XRF interaction with the core and recorded by the ITrax scanning XRF can be used to calculate a relative density profile for the analysed core. The variations in density can be utilized to link geochemistry to seismic geophysical data and by so doing enable interpretation of palaeo-depositional/environmental scenarios. This can both aid seismic interpretation and be used to extrapolate the chemical analysis away from the core

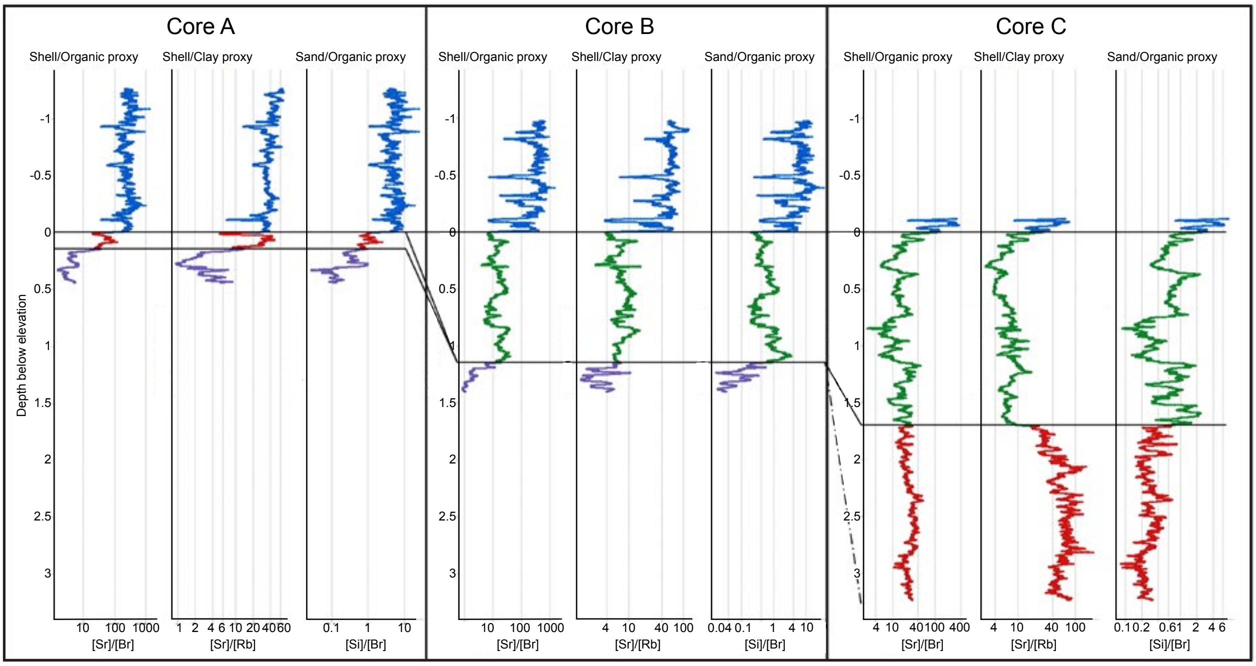


Figure 10.9 Chemostratigraphic correlation of chemo zones in wells A, B and C

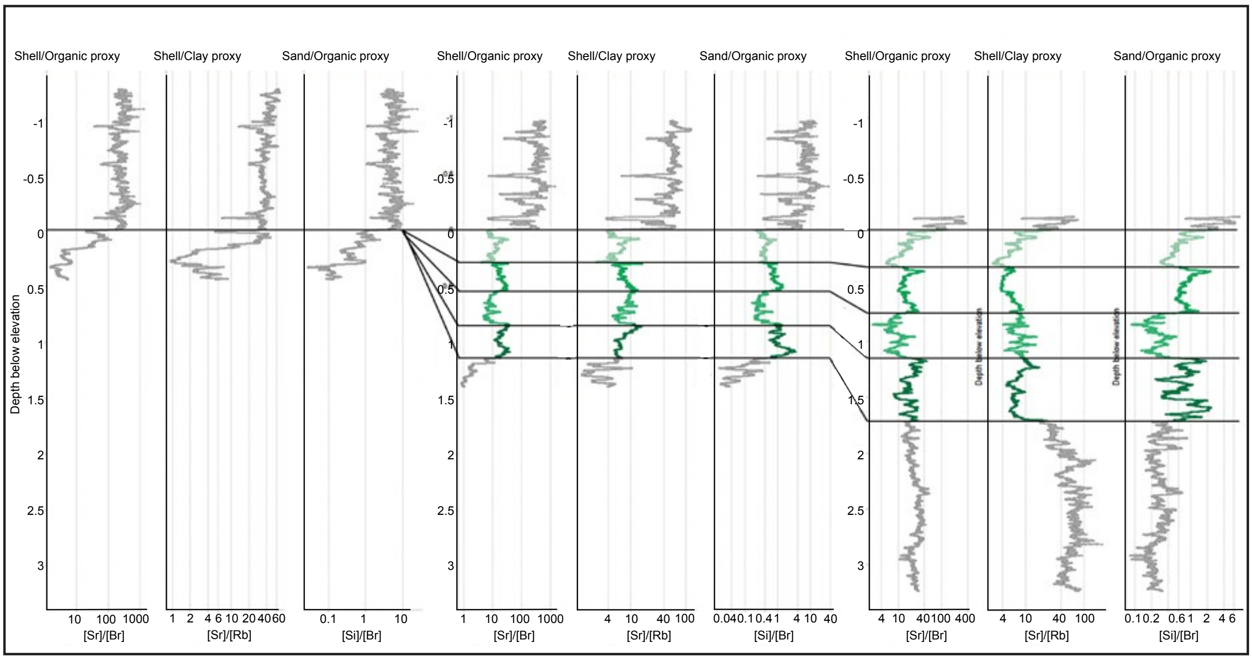


Figure 10.10 Chemostratigraphic correlation of chemo sub zones in wells A, B and C.

locations. This case study utilizes elemental and seismic data published in Gaffney *et al.* (2020) from core ELF1A, which was collected approximately 20 miles north east of core ELF19 (Figure 10.2).

Chemo zones and facies

Project core ELF1A has undergone chemostratigraphic zonation with the goal of identifying key geochemical signatures that could result from a tsunami event. Details of the investigation have been previously presented in Gaffney *et al.* (2020). Using the same method as that outlined in Case study 1, the chemical analysis was used to divide the core into six chemo zones (Figure 10.11) based on variations in:

- Sr – a proxy for shell material
- Rb – a proxy for clay
- Si – a proxy for quartz
- Zr – a proxy for detrital zircon

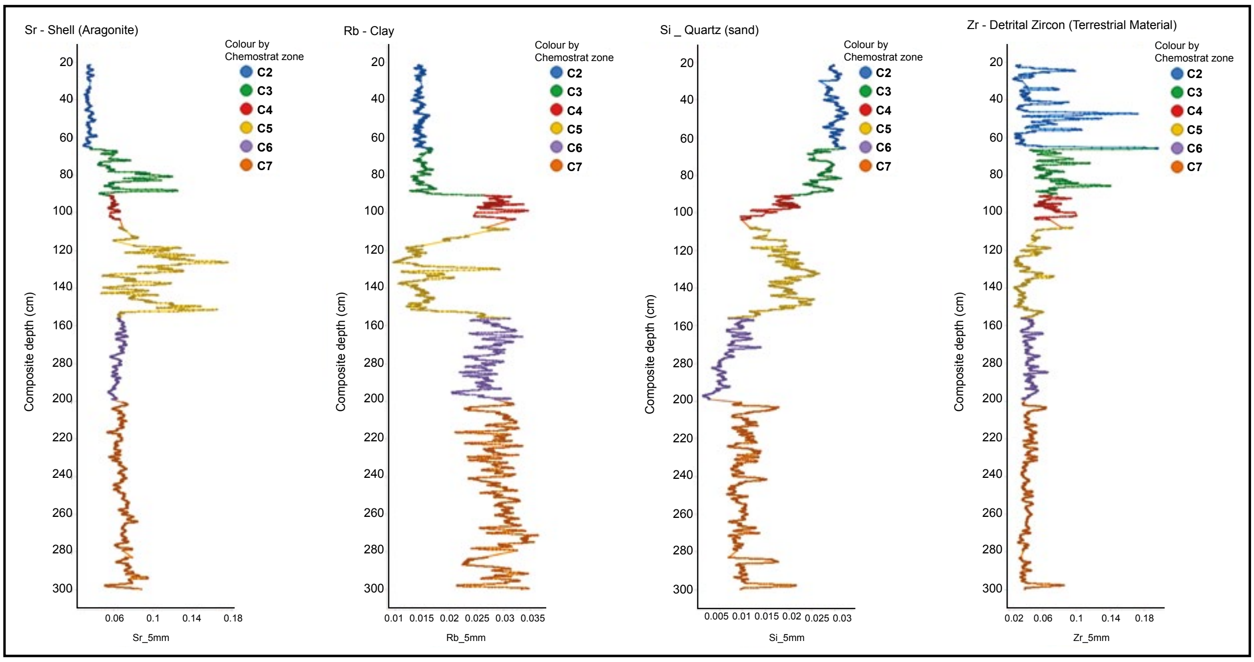


Figure 10.11 Chemostratigraphic zonation of core ELF1A (from Gaffney *et al.* 2020). Sr likely reflects the amount of shell material (aragonite) Rb likely reflects the amount of clay, Si likely reflects the amount of sand (Quartz) and Zr the amount of detrital zircon in the core.

These chemo zones have been interpreted to represent a series of chemostratigraphic facies (Chemo facies) which can be used to understand the depositional environments shown in Table 10.6 (see Gaffney *et al.* 2020 supplementary information).

Chemo zone C5 had been hypothesized to contain a Storegga tsunami deposit, and so a more detailed investigation of this zone was undertaken (Gaffney *et al.* 2020). This enabled the zone to be divided into eight separate sub zones based on changes in:

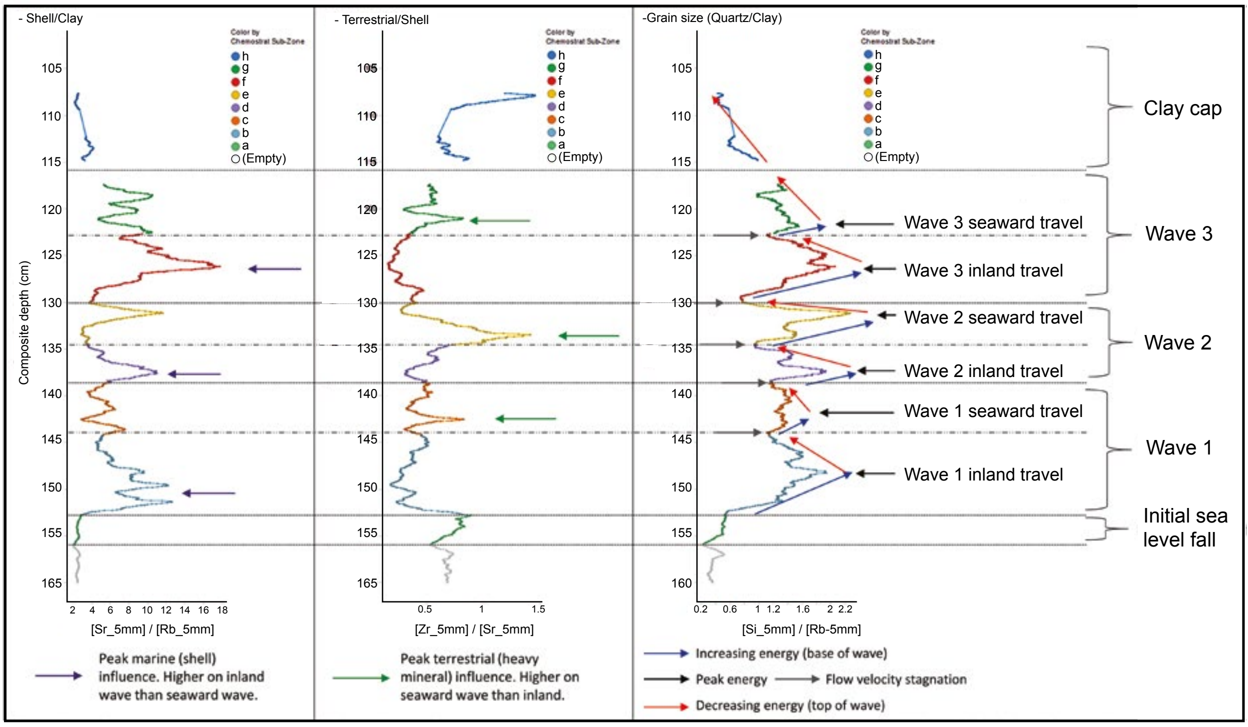


Figure 10.12 Chemostratigraphic zonation of the Stroregga tsunami deposit preserved in core ELF1A (from Gaffney *et al.* 2020).

Chemo zone	Chemo facies
C2	A clean high energy sand with little to no shell/marine material or marine influence. Several beds display high Zr/Sr values suggesting increased terrestrial derived heavy mineral sand beds.
C3	A high energy interbedded terrestrial sand and marine/shell dominated deposit.
C4	A clay/silt environment similar to that seen in units C5 and 6 with no shell material, however the moderate Zr/Sr values suggest a more terrestrial input compared to units C5 and 6.
C5	High energy/coarse material including shell/marine material. The large variation in data within C5 does suggest there is an internal stratigraphy (see Gaffney *et al.* 2020). The top of this unit shows a grading change back to values similar to those in units C6 and 7. These observations suggest this may either be a tsunami or surge deposit; an erosive base, high energy deposit bringing distal marine sediment into a previously terrestrially dominated low energy environment topped by a gradational decrease of energy.
C6	The lowest energy unit in ELF001A is dominated by clay material, little shell material and a constant balanced marine/terrestrial influence.
C7	A clay/silty unit with interbedded siltier horizons (marked by increases in Si/Rb). Little shell material and a constant balanced marine/terrestrial influence.

Table 10.6 Chemo facies identified in core ELF1A (see Gaffney *et al.* 2020 supplementary information for full discussion).

- Sr/Rb – marine signature reflecting the chemical proxy for aragonite as shell content vs clay content
- Zr/Sr – a terrestrial vs marine sediment chemical proxy based on the input of terrestrial detrital zircons compared to a marine shell signal.
- Si/Rb – grain size proxy reflecting the chemical proxy for quartz (coarser sand grain) vs clay content; the coarser-grained sediment indicates a higher depositional energy than the finer clay-sized grains

The eight chemo subzones were interpreted to represent an initial fall in sea level, overlain by deposits associated with three pulses each comprising an initial inland wave identified by its marine depositional signal, topped by a seaward wave characterized by its terrestrial signal (Gaffney *et al.* 2020). The final chemo subzone represented a clay cap, likely reflecting the post tsunami deposition of suspended fine material (Figure 10.12; reproduced from Gaffney *et al.* 2020).

This use of elemental geochemistry enabled the identification of the tsunami deposit which was dated using both C14 and OSL methods. It was postulate that the deposits were associated with the Storegga slide event (Gaffney *et al.* 2020) and represented the furthest south in the North Sea such deposits have thus far been recognised.

Linking geochemistry to seismic

Several studies have demonstrated that the ratio of the Compton and Rayleigh scattered intensity, recorded by scanning XRF tools, are affected by the average atomic number of the sample, mineralogical composition, water, organic carbon content and therefore density (Fortin *et al.* 2012, Croudace *et al.* 2006). Seismic reflection strength is also a function of the impedance contrast in velocity, in turn based on elastic moduli, and density, based on lithology/mineralogy, porosity, saturation and organic content of a material. Thus, as the acoustic impedance that produce seismic reflectors are the product of density and velocity so the Compton scattering too is a function of density and there should be a correlation between both.

Core ELF1A has both the interpreted seismic and geochemical data necessary to test this method (see Gaffney *et al.* 2020). There is a large downhole increase in density from approximately 2.6 to 3.2 chemical density units at *c.* 1.55m depth that corresponds to the base of chemo zone C5 and the tsunami deposit (Gaffney *et al.* 2020). When this is compared to the published seismic (Gaffney *et al.* 2020, Figure 10.12) this Is the same depth as the tsunami seismic reflector, suggesting that this method is valid.

Within the XRF data, there are two density changes visible at ~0.8, ~1.15 and ~2m depth. The 0.8 and 1.15m density changes occur at a similar depth to two large amplitude shallow sea floor reflectors in the seismic data (I [green] and II [purple] in Figure 10.13). The ~2m depth density change also coincides with a lower amplitude reflector (IV [black dashed], Figure 10.13). Therefore, we can use the seismic to understand the spatial extend of the chemo zones (Table 10.7). Importantly, this show how spatially limited the Storegga tsunami deposit is within the study area.

Future geochemical applications to Europe's Lost Frontiers type studies

This chapter has demonstrated how elemental chemistry can be used to recreate palaeoenvironments within the *Europe's Lost Frontiers* project. It has been shown how geochemistry can be utilised to identify variations in sediment cores (often not visible to the

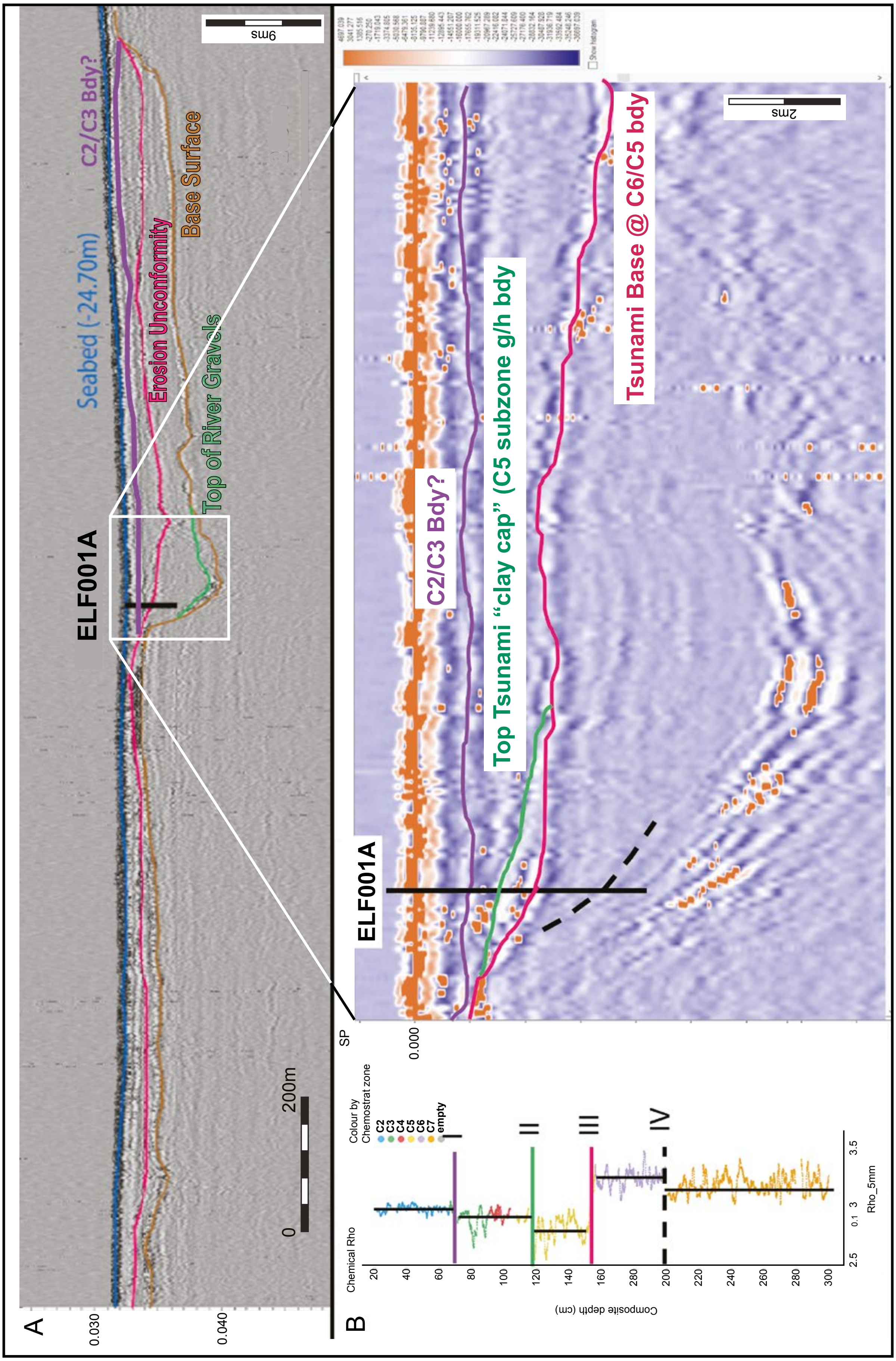


Figure 10.13 Comparison of the relative density of core ELF1A calculated from XRF data to the interpreted seismic data (from Gaffney *et al.* 2020).

Density change	Chemo zone	Chemo facies variation	Spatial extent on seismic line
I	C2-C3 Bdy	a down hole change from (C2) to sand and shell (C3) material -	laterally continuous
II	Upper C5	The transition between high energy tsunami sediments and the low energy clay cap.	Only found locally to ELF19 - suggests only a small preservation of Tsunami deposit
III	C5-C6 Bdy	Base of Storegga Tsunami deposit	laterally continuous
IV	C6-C7 Bdy	A down hole transition to a clay rich (C7) unit	hard to tell, maybe only local preservation?

Table 10.7 A summary interpretation of geochemical and seismic datasets.

eye) and to chemostratigraphically divide the core into separate chemo zones. It has been shown how the causes of these variations can be understood through statistical methods enabling chemo zones and facies to be assigned and thus in turn aid understanding of the depositional environments. The differentiation and chemostratigraphic correlation of multiple cores has then been undertaken, demonstrating how palaeosurfaces can be identified and palaeolandscapes recreated. There are of additional benefits for conducting geochemical analysis to further the understanding of palaeoenvironments that include:

- with the use of chemical signatures together with stable isotope data to link changes in paleoenvironment with changes in palaeoclimate
- identification of detrital zircon, heavy mineral and chemical provenance signatures in the cores; such studies are commonly utilised in the Carboniferous-Permian hard rock basement, below the Doggerland sediment, identifying if a sediment is sourced from the south (Variscan orogeny/bohemian massif) or north (Norway; e,g, Cram *et al.* 2014) – it is highly probable that this method could be of utility to provenance sand filled channels around Doggerland
- quantitative elemental chemistry is commonly utilised to identify the provenance of clay (e.g. Finlay *et al.* 2012) and geological materials (e.g. Bevins *et al.* 2020) in archaeological studies – could these methods be applied to lithic materials dredged from Doggerland and so both establish chemical families of lithics and potentially even correlate them to known (Present day) onshore sites?
- the chemo zones presented in this study are all linked to natural changes in the sediment record – however, could some of them be signals of human activities such as habitation? For example:
  - within North Sea oil and gas studies, the Si/Zr ratio is commonly utilised to identify flints in chalks – could this ratio be used to identify micro-debitage from knapping sites?
  - phosphorus is commonly associated with coprolite and hardgrounds – could it be used to identify phosphates caused by animal and human waste, vivianite or bone beds?
  - can Sr data be utilised to identify shell middens?

Elemental geochemistry is a powerful tool for archaeological and palaeoenvironmental studies. It can be used to identify depositional changes in any fluvial, lacustrine, marine or terrestrial setting, and correlate them across study areas, revealing palaeo- surfaces and landscapes. The wide range of modern analytical tools, from portable closed source tools that can be deployed in the field, through to lab-based scanning XRF tools that are capable of recording high vertical resolution data mean that geochemistry is a highly flexible tool suitable for application to a wide variety of settings. Furthermore, the ability to use geochemical tools to generate density data means that the results are easily linked to other investigative techniques, such as geophysics, and so aid the integration of disparate analytical datasets. Therefore, it is hoped that elemental geochemistry will become an increasingly utilised tool for studies across archaeology, palaeoenvironmental sciences and the humanities.

Chapter 11

Introduction to geochemical studies within Europe’s Lost Frontiers

Mohammed Bensharada, Ben Stern and Richard Telford

Introduction

Geochemistry

In broad terms, geochemistry is the combination of geology and chemistry, or the application of analytical chemistry to geological materials. Organic geochemistry is the study of organic residuals, which specify the source and distribution of organic compounds in the geosphere (Gale *et al.* 1999; Chester 2009). Moreover, the sources of sediments can be identified using the mineral composition, where various minerals composition can be characterised (Karikalan *et al.* 2020; Maity and Maiti 2016).

In the present study, three analytical techniques were applied to three samples taken from the base of separate cores acquired by the *Europe’s Lost Frontiers* Project from the area known as Doggerland (Figure 10.1). Each core possessed different characteristics and might be expected to be representative of the larger sample set in the project. The three analytical techniques are:

- Weight Loss-on-Ignition (LOI) provides the percentage organic matter and carbonate composition (Heiri *et al.* 2001); it can be used to characterise each layer in the core and is especially useful for identifying and understanding the transactions from one environment to another, while the results may also be used to assist the project’s computer simulations (Murgatroyd *et al.* this volume)
- Gas Chromatography-Mass Spectrometry (GC-MS) uses separation, identification and quantification for lipid analysis; it identifies specific biomarker organic compounds such as *n*-alkanes and fatty acids, which then can be utilised as an indicator of the original depositional environment and for provenance of organic matter (Battram *et al.* 2015; Carreira *et al.* 2016; Chen *et al.* 2019)
- X-ray Powder Diffraction (XRD) is a non-destructive, highly sensitive and reliable technique, providing a qualitative means to study the inorganic mineralogical composition of samples (Brendryen *et al.* 2010; Karikalan *et al.* 2020; Ramasamy *et al.* 2009)

The primary aim of this chapter is to explore the use of these analytical techniques on the Doggerland sediment samples. Based on the results obtained, this study can go forward and be applied to a larger number of *Europe’s Lost Frontiers* samples. Studying organic and inorganic content of core samples will assist in distinguishing between different layers and horizons within the cores, as types of soil; fresh water, terrestrial vegetation, aquatic vegetation and lacustrine environments can also be identified using these techniques (Sikes *et al.* 2009; Vaezzadeh *et al.* 2015).

Sample descriptions and locations

The three samples used to test the project’s geochemical methods were taken from the base of cores ELF002, ELF007 and ELF009 (Figure 11.1). They were collected on 14th September 2016; and have since been kept at the University of Bradford in a dry and cold environment. The core ELF002 sample contained reddish brown silty fine sand and was expected to contain little organic matter. The sample from core ELF007 was very dark brown/black peat with stem and root fragments and occasional sand grains. The sample from core ELF009 was a very dark brown amorphous and dense peat and was expected to contain a high percentage of organic matter compared to the other samples. The core names, locations, and the observed seafloor depth are provided in Table 11.1 below:

Methodology

Loss-on-Ignition (LOI) methodology

Prior to analysis, each sample was ground to fine powder, and subsamples were taken for detailed study. The LOI procedure used here follows the standard method provided in Konare *et al.* (2010). Each sample was weighed to 5.00 ± 0.01g and placed into clean and dry high-form crucibles. These were then set in a furnace at 150°C for about two hours to remove all moisture. The samples were removed from the furnace to cool down to room temperature in a desiccator and were then weighed accurately. After which the samples were returned to the furnace at a temperature of 550°C for two hours. The samples were removed, cooled and

Core name	Location X WGS84	Location Y WGS84	Observed seafloor depth
ELF002	1.1175304	53.321959	18.29m
ELF007	1.4084871	53.407806	26.19m
ELF009	1.5035641	53.329026	26.19m

Table 11.1 Core identifiers, location and depth.

reweighed. The lost mass was used to measure the percentage of organic matter using equation 1. The process above was repeated at 950°C, and by using equation 2 the percentage of carbonate was calculated.

$$LOI_{550} = \frac{(\text{Wt. at } 150°\text{C} - \text{Wt. at } 550°\text{C})}{(\text{Wt. at } 150°\text{C})} x\,100$$

$$LOI_{950} = \frac{(\text{Wt. at } 550°\text{C} - \text{Wt. at } 950°\text{C})}{(\text{Wt. at } 550°\text{C})} x\,100$$

Gas Chromatography-Mass Spectrometry (GC-MS) methodology

Sample preparations

For GC-MS analysis an extraction of lipids is required, as the samples must be in a liquid phase. For this purpose, the samples were dried at room temperature for 48 hours to remove excess moisture, which may otherwise affect the solvent extraction process. The solvent used in extraction was a mix of dichloromethane: methanol (2:1 v/v).

Dichloromethane (CH_2Cl_2) is a high selective polar solvent, which can extract wide ranges of organic compounds. In addition, methanol (CH_3OH) can extract more polar compounds. Approximately 3g from each sample was used in this extraction. An ultrasonic bath was used for the sonication process, which assists extraction, and a centrifuge running at 2000rpm separated the undissolved solid from the solvent. The extracted solvent was dried under a nitrogen stream at 40°C before derivatizing, using BSTFA (N,O-Bis(trimethylsilyl)trifluoroacetamide) with 1% TMCS (trimethylchlorosilane), at 70°C for one hour. This process ensures the analytes are chemically changed to become more amenable to analysis. Subsequently, the excess BSTFA was removed under a nitrogen stream. Finally, 1ml of dichloromethane was added to each vial, and the extracted solvents were transferred into GC-MS vials for analysis.

Instrumentation and conditions

An Agilent 7890A gas chromatograph coupled with a 5975C Inert XL mass selective detector was used for the lipid analysis. The splitless injector and interface were maintained at 300 and 340 respectively. Helium, the carrier gas, was kept at a constant flow of 0.8cm^3/min. The temperature of the oven was programed from 50 (2min) to 350°C (10min) at 10°C/min. The GC was fitted with a 30m x 0.25mm, 0.25µm film thickness 5% Phenyl Methyl Siloxane phase fused silica column. The column was directly inserted into the ion source, where

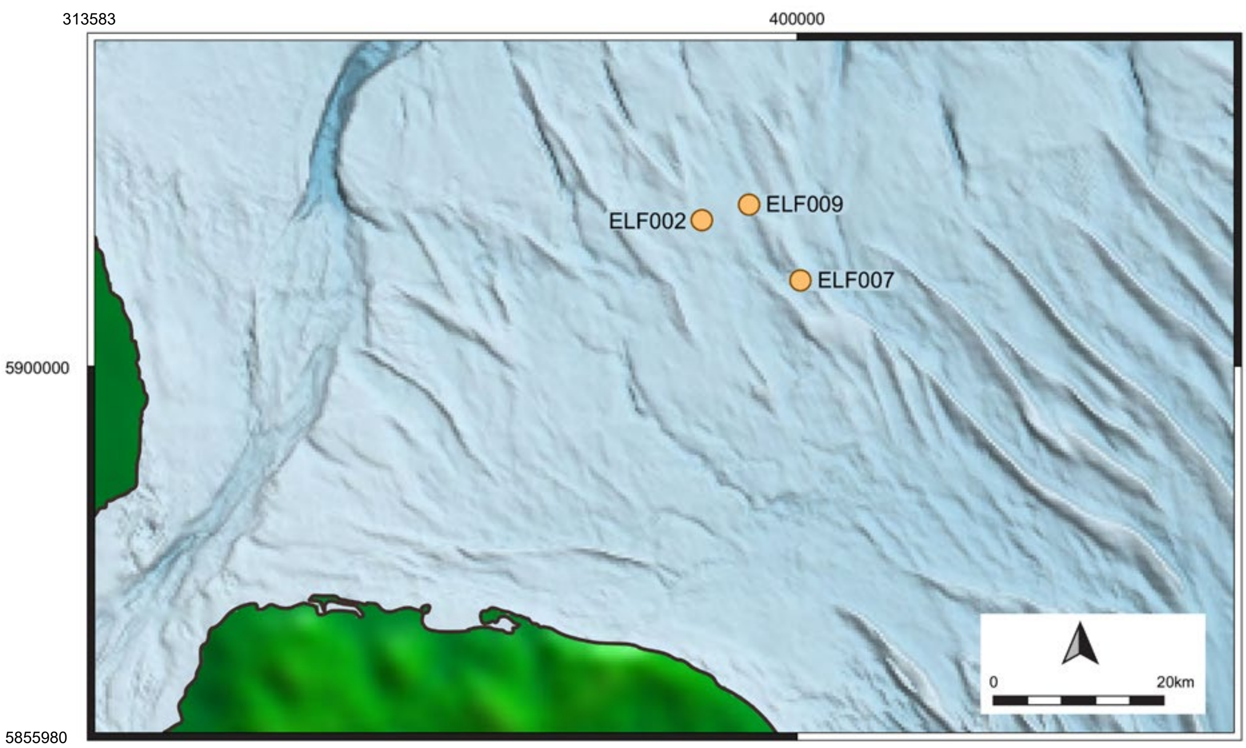


Figure 11.1 Locations of the three cores mentioned in the text.

electron impact (EI) spectra were obtained at 70eV. Samples were analysed using a full scan method from *m/z* 50 to 800.

X-ray Powder Diffraction (XRD) methodology

Sample preparations

The procedure described by Marathe (2012) was used here. The samples were transferred into standard samples holders, using a glass slide to pack the sample powders, and the excess removed to obtain a smooth surface (important to avoid sources of random error and effects on the resultant peak intensities (Lu *et al.* 2001)).

Instrumentation and XRD parameters

The instrument used was a Bruker AXS D8 Advance X-ray diffractometer, run in Bragg-Brentano geometry, with a copper Kα X-ray source operating at a wavelength of 0.15406nm, a voltage of 40kV and a filament emission of 30mA. The samples were analyzed following the method used by Linsen *et al.* (2014), scanning over range of 5° to 65° (2θ). The collection of the scattered X-ray intensities was five seconds at each step, and the step size was 0.03° with sample spinning applied.

Results and discussion

LOI results

The methods described were applied to the three samples, which were chosen to be indicative of various layers from the submerged landscape of Doggerland. The results are presented in Table 11.2.

Sample number	Organic matter	Carbonate contain	Residual
EFL002	0.08%	0.01%	99.91%
ELF007	10.47%	0.19%	89.34%
ELF009	17.95%	14.08%	67.97%

Table 11.2 The percentage of organics and carbonates.

Characteristic information regarding the overall quality of sediment samples can be gained from measurements of weight loss-on-ignition. Most sediment samples contain various materials; carbonate, organic materials, water and minerogenic residue, and they can be quantitatively analyzed at a selected temperature (Luoto and Ojala 2017). However, the stability and the percentage of organic matter in sediment samples is affected by the percentage of clay minerals present in that sample, where they have an inverse relationship. Hence, if a sample has a high percentage of organic matter, it is highly likely to have a low percentage of clay minerals (Konare *et al.* 2010).

Sample ELF009 produced the highest percentage of carbonate (14.08%) and organic matter (17.95%), which indicates the complexity and environmental diversity in this sample. In addition, the enrichment in organic matter reflects the fact that it has more faunal and floral residues at different decomposition stages, and/or cells of microorganisms, than the other two samples. Thus, it likely reflects a fertile horizon. The sample ELF007 contains 10.47% of organic matter, 0.19% of carbonate and 89.34% residual material. This may indicate the movement of organic matter, by water, into a sandy horizon (Heiri *et al.* 2001). The sample with the lowest proportions of both organic matter (0.08%) and carbonate (0.0074%) is ELF002. The primary constituents of any inorganic soil are the small particles of sand, which were reduced from rock over time. This sample perhaps presents a sandy layer with an extremely low percentage of living organisms.

Lipid results (GCMS)

Normal alkanes (n-alkanes)

n-alkanes are natural compounds which occur widely in terrestrial plants, bacteria, aquatic organisms including algae, zooplankton and phytoplankton. They are long-lived and stable organic compounds, which can survive for millions of years in the fossil record (Bush and McInerney 2013; He *et al.* 2016). These compounds are widely used as a tool to identify the biological source of archaeological samples (Kirkels *et al.* 2013; Pancost and Boot 2004; Xia *et al.* 2008). The data obtained were analyzed using two methods: first, the *n*-alkane distribution patterns, where terrestrial plants, marine materials and bacteria present differently. Secondly, using the calculated *n*-alkanes indexes, these were calculated using the area of the peaks of detected compounds.

Distribution of n-alkane patterns

The *n*-alkanes distribution patterns and the abundance of peaks are indicators of sources and hence their past environments (Kirkels *et al.* 2013). Terrestrial plant waxes produce high molecular weight *n*-alkanes from C_{27} to C_{35}, with an odd-over-even carbon number predominance and maximum abundance at C_{27} and C_{29} (Vaezzadeh *et al.* 2015). The odd mid-chain *n*-alkanes C_{21}, C_{23} and C_{25} are abundant in aquatic organic materials including submerged and emergent plants (emergent plants are rooted with stiff or firm stems and stand above the water surface) (Vaezzadeh *et al.* 2015). In contrast, the low molecular weight *n*-alkanes from C_{15} to C_{19} are abundant in cyanobacteria, microorganisms and algae (Battram *et al.* 2015).

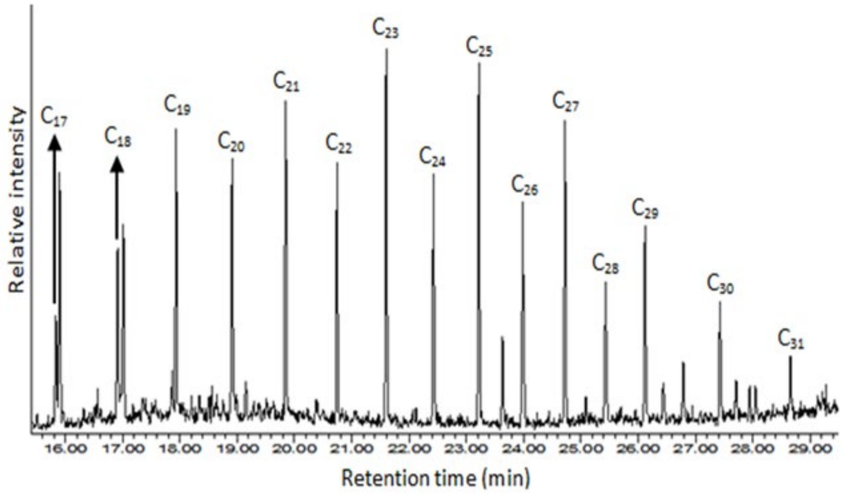


Figure 11.2 Extracted ion chromatogram (EIC), for 71m/z showing n-alkanes in the sample ELF002.

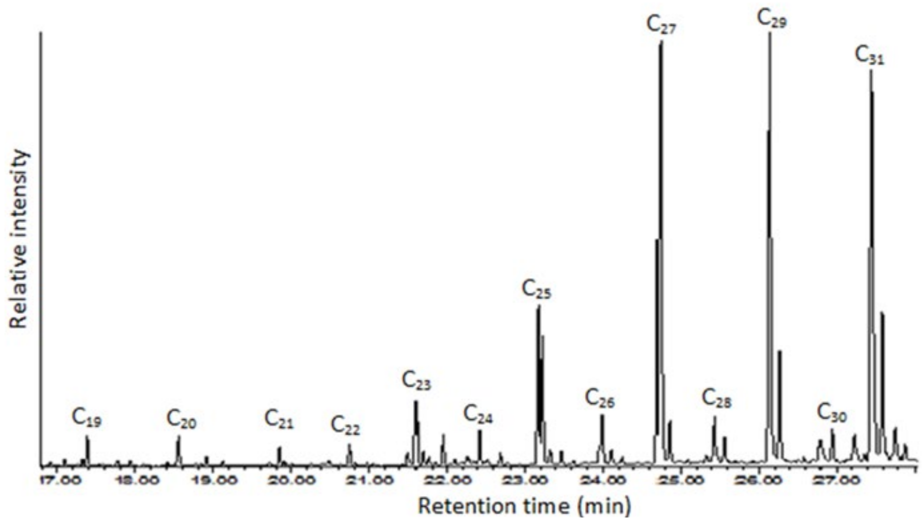


Figure 11.3 Extracted ion chromatogram (EIC)' for 71m/z, showing n-alkanes in the sample ELF007

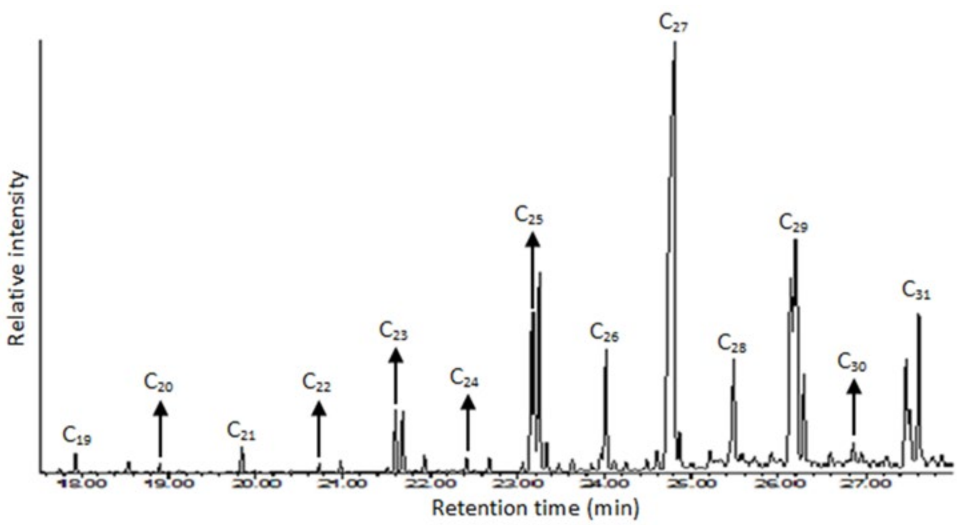


Figure 11.4 Extracted ion chromatogram (EIC)' for 71m/z, showing n-alkanes in the sample ELF009.

The distribution of *n*-alkanes in sample ELF002 is characterized by the presence of *n*-alkanes from C_{17} to C_{31} and the most abundant *n*-alkane C_{23} (Figure 11.2). This is considered to be a characteristic pattern of marine inputs (Rielley *et al.* 1991). The appearance of the *n*-alkanes from C_{27} to C_{31}, with predominant odd numbers may suggest that, in addition to the marine inputs, there are secondary *n*-alkane sources.

In samples ELF007 and ELF009 the *n*-alkanes ranged from C_{19} to C_{31}, with the most abundant *n*-alkane at C_{29} and C_{27} respectively (Figures 11.3 and 11.4); the odd carbon numbers dominate the even numbers. This is indicative of terrestrial plants (He *et al.* 2016; Kirkels *et al.* 2013; Rielley *et al.* 1991). In addition, the abundant appearance of C_{31} in both samples (Figures 11.3 and 11.4), suggests that both samples are characterized by the presence of herbaceous plants, as the C_{31} *n*-alkane is a biomarker for these species (He *et al.* 2016).

Characterizing n-alkane indexes

In some circumstances, there is an overlap between different sources of *n*-alkanes in a single sample making the process of interpretation more complicated. Therefore, applying descriptive methods such as the Carbon Preference Index (CPI) and the *n*-alkanes proxy ratio (Paq) can be useful for distinguishing between different *n*-alkane sources (Sikes *et al.* 2009). These parameters are applied using the peak areas of the detected *n*-alkanes, which are representative of the abundance of the compounds within the sample. (Battram *et al.* 2015).

The n-alkanes proxy ratio (Paq)

The Paq ratio is designed to distinguish between the various types of aquatic vegetation. Emergent aquatic vegetation produces values from 0.10 to 0.40, whereas submerged aquatic vegetation produce the highest values of Paq, generally from 0.40 to 1.0 (Ficken *et al.* 2000). The Paq ratio is calculated using equation bellow:

$$\text{Paq} = \frac{(C23 + C25)}{(C23 + C25 + C29 + C31)}$$

Sample ELF007 produced a Paq that corresponds to emergent vegetation (0.15), while samples ELF002 and ELF009 gave Paq of 0.66 and 0.50 respectively, which are within the range for submerged aquatic vegetation.

Carbon Preference Index (CPI)

The Carbon Preference Index has been widely used in order to measure the marine versus terrestrial *n*-alkanes inputs: a CPI value over four indicates terrestrial plants, while a value less than four indicates marine inputs (Sikes *et al.* 2009). The CPI is calculated by the equation below:

$$\text{CPI} = \frac{\sum odd\ n-alkanes\ C15\ to\ C33}{\sum even\ n-alkanes\ C14\ to\ C34}$$

The CPI value of the sample ELF002 is 0.27 indicating the primary source of *n*-alkanes in this sample is a marine input. The CPI values of samples ELF007 and ELF009 are very different at 5.37 and 4.60 respectively, which suggest the major sources of the *n*-alkanes in both samples are terrestrial plants.

Fatty acids

A number of investigations that examined sediments ranging from the Precambrian to recent, revealed fatty acids as the most common compounds present in samples (Meziane and Tsuchiya 2000). Geochemists, especially those who are interested in petroleum and archaeological studies, have studied and used saturated fatty acids as a source biomarker (Yamamoto *et al.* 2014). In contrast, unsaturated fatty acids have attracted less interest, as the concentration of unsaturated fatty acids declines rapidly with depth. Additionally, they have not been found in any ancient sediment (DeMott *et al.* 2004). In most sediments, the abundance of the even numbered chain length saturated fatty acids is greater than those that have odd carbon numbers. This difference in abundance is seen in ancient and modern sediments, marine lipids, and ocean water (Meziane and Tsuchiya 2000).

In the current work, the profile of abundances of normal fatty acids present in the three samples differs. The most common fatty acids have even carbon numbers; palmitic ($C_{16:0}$) being the most abundant in all three samples (Figures 11.5, 11.6 and 11.7). The other even numbered normal fatty acid found in all three samples is $C_{14:00}$. $C_{12:00}$ was detected in samples ELF007 and ELF009 but not in ELF002. Additionally, samples ELF002 and ELF009 contain an odd fatty acid ($C_{15,}$ pentadecanoic acid), which is present at low levels compared to those with even carbon numbers (Figures 11.5, 11.6 and 11.7). The even numbered fatty acids $C_{14:00}$, $C_{16:00}$ and $C_{18:00}$ are ubiquitous in nature with various concentrations (Meziane and Tsuchiya 2000) and are, therefore, observed in all samples.

The odd carbon numbered fatty acids are believed to be synthesised by activities of bacterial communities, and where bacteria derive their food from organic detritus in the sediment (Leo and Parker 1966; Meziane and Tsuchiya 2000). This indicates bacterial degradation in samples ELF002 and ELF009.

XRD results

The three Doggerland samples ELF002, ELF007 and ELF009 were analyzed by XRD, and the patterns obtained from the bulk samples are shown below in Figures 11.8 to 11.10.

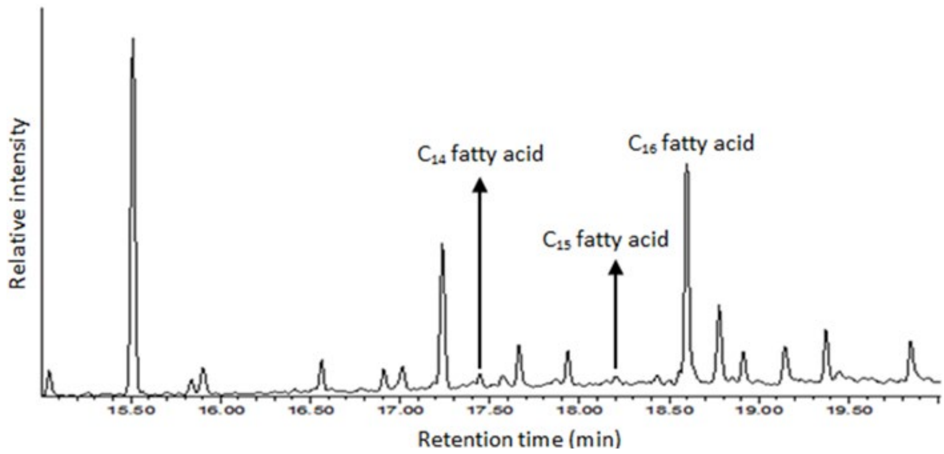


Figure 11.5 Fatty acids found in sample ELF002.

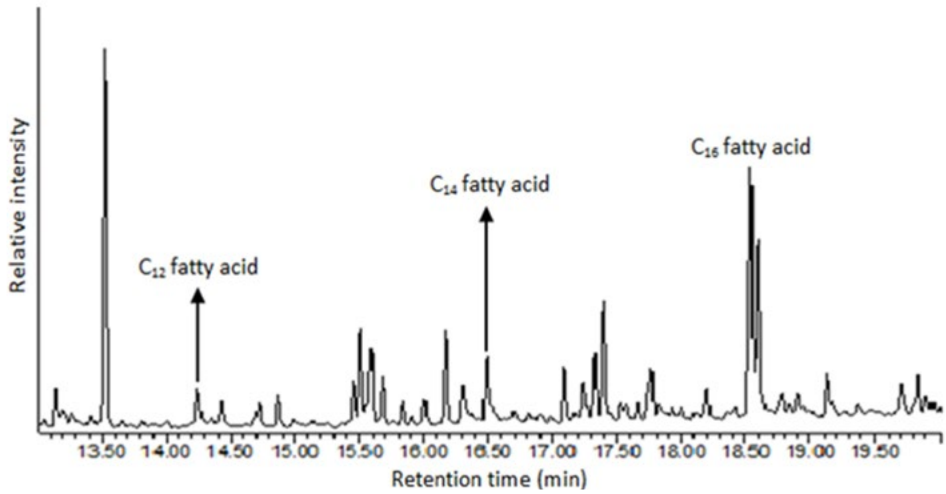


Figure 11.6 Fatty acids found in sample ELF007.

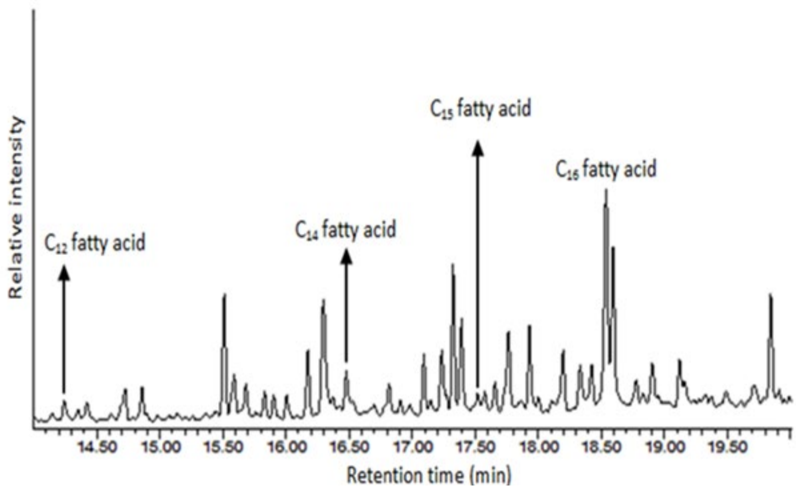


Figure 11.7 Fatty acids found in sample ELF009.

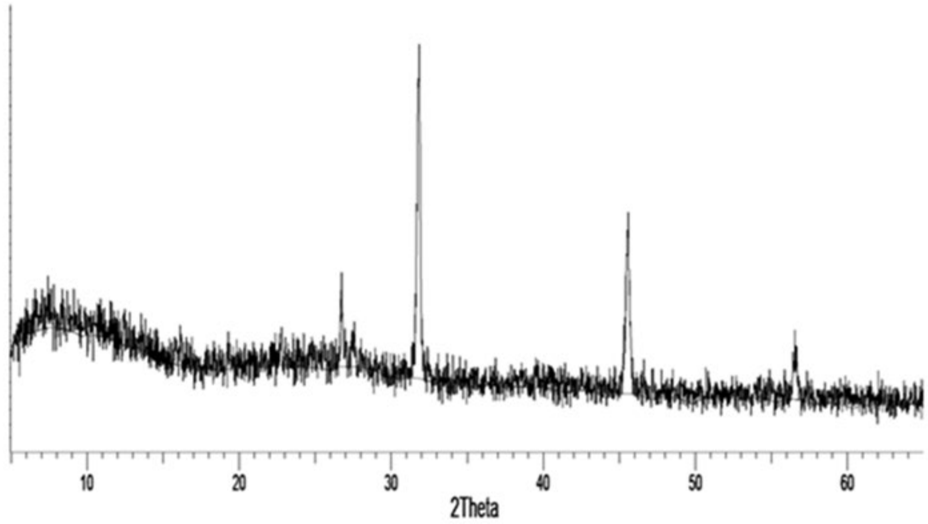


Figure 11.8 XRD pattern of sample ELF002.

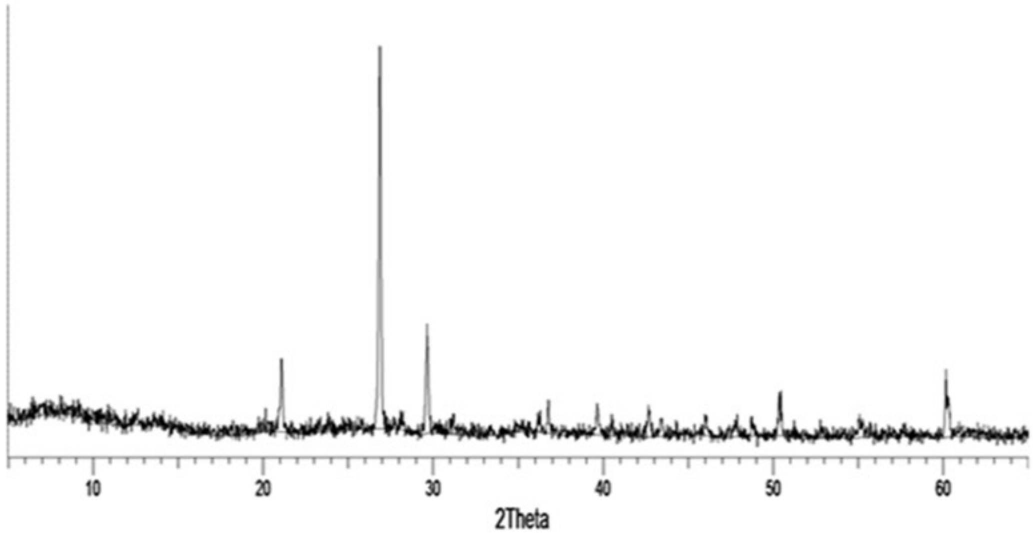


Figure 11.9 XRD pattern of sample ELF007.

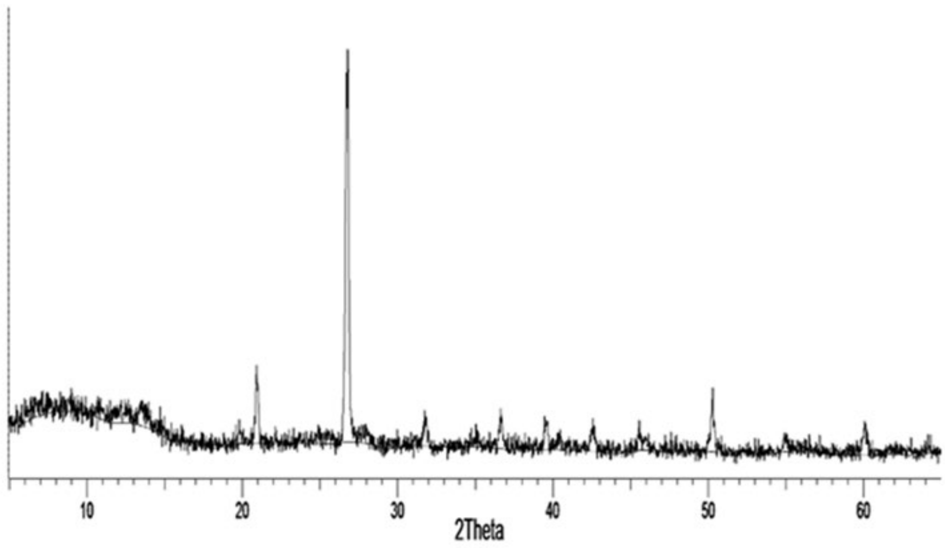


Figure 11.10 XRD pattern of sample ELF009.

Several inorganic compounds would be expected in sediment samples, such as quartz, halite, calcite, hematite, mica and kaolinite, each being distinguished by its characteristic (2θ) and the relative d-spaces (Linsen *et al.* 2014). The characteristic (2θ) values and the d-spaces of the obtained samples pattern are shown in Table 11.3.

The XRD pattern of sample ELF002 shows several peaks. The peaks at 26.87° (2θ) with d-space of 3.31A° and at 21.08° (2θ) with d-space of 4.24A° (Table 11.3 and Figure 11.8) indicate the presence of quartz (SiO_2) (Cook *et al.* 1975; Linsen *et al.* 2014; Srinivasan and Bandyopadhyay 2016). The peaks observed at 29.65° (2θ) with d-space of 3.01A° and at 36.77° (2θ) with d-space of 2.47A° (Table 11.3 and Figure 11.8) suggests the presence of calcite ($CaCO_3$) (Cook *et al.* 1975; Linsen *et al.* 2014). The determination of quartz and calcite indicate sandy horizon, as they are widely known as primary sand compounds (Nguyen *et al.* 1991). The peaks observed at 50.36° (2θ) with d-space of 1.81A° and at 60.20° (2θ) with d-space of 1.53A° indicate the presence of berlinite ($AlPO_4$) (Marincea and DumitraȘ 2005). Berlinite is an aluminum phosphate compound and is common in sedimentary systems (Dill 2001: 192-203). The pattern acquired for sample ELF002 is presented, and overlain with reference patterns for quartz, berlinite and calcite, in Figure 11.11.

The XRD pattern of sample ELF007 shows several peaks with those at 26.74° (2θ) with d-space of 3.32A° and the peak at 20.94° (2θ) with d-space of 4.25A° (Table 11.3

Standard	ELF002	ELF007	ELF009
Quartz	Quartz	Quartz	Quartz
26.45°-26.95° (2θ) d-space of 3.37-3.31A°	26.87° (2θ) d-space of 3.31A°	26.74° (2θ) d-space of 3.32A°	26.73° (2θ) d-space of 3.33A°
20.70° (2θ) d-space of 4.28A°	21.08° (2θ) d-space of 4.24A°	20.94° (2θ) d-space of 4.25A°	did not identify
Calcite	Calcite	Calcite	Calcite
26.25°-29.60° (2θ) d-space of 3.01°-3.04A°	29.65° (2θ) d-space of 3.01A°	Not detected	Not detected
36.29° (2θ) d-space of 2.47A°	36.77° (2θ) d-space of 2.47A°		
Halite	Halite	Halite	Halite
45.30°-45.65° (2θ) d-space of 1.99-2.00A°	Not detected	45.59° (2θ) d-space of 1.98A°	45.55° (2θ) d-space of 1.98A°
31.83° (2θ) d-space of 2.80A°		31.79° (2θ) d-space of 2.81A°	31.80° (2θ) d-space of 2.80A°
Berlinite	Berlinite	Berlinite	Berlinite
49.69° (2θ) d-space of 1.83A°	50.36° (2θ) d-space of 1.81A°	50.25° (2θ) d-space of 1.81A°	Not detected
59.65° (2θ) d-space of 1.55A°	60.20° (2θ) d-space of 1.53A°	60.08° (2θ) d-space of 1.54A°	

Table 11.3 Characteristic (2θ) values, and the d-spaces of standards and the obtained samples pattern.

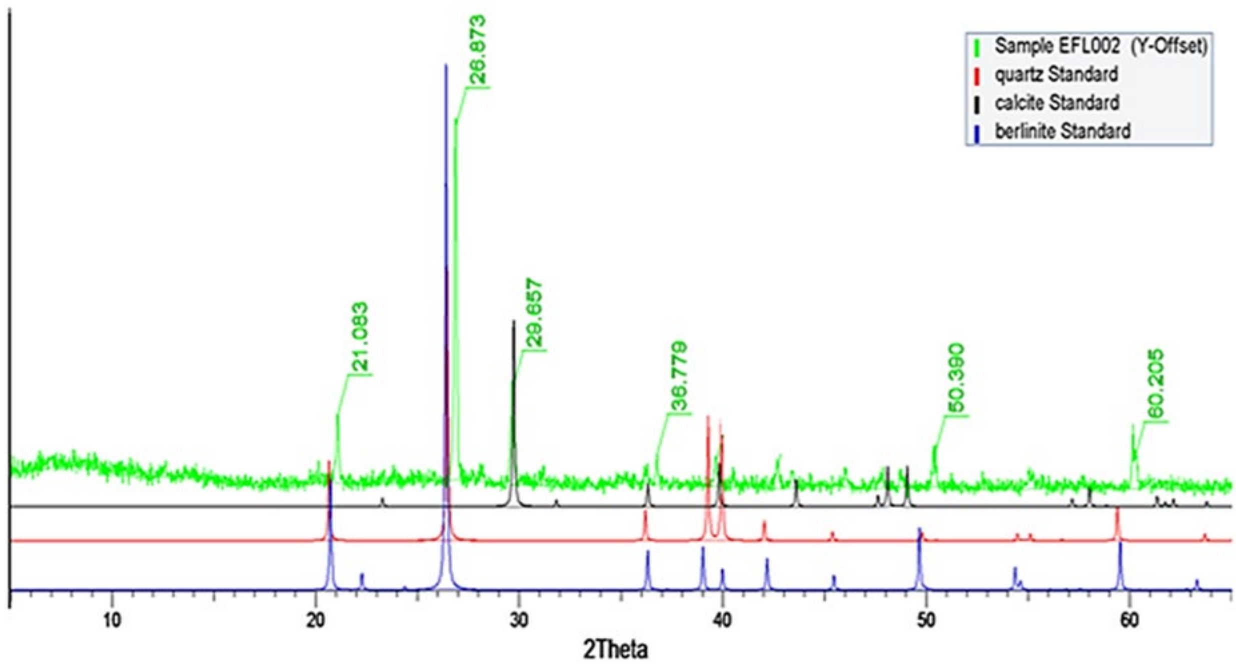


Figure 11.11 Comparison between the ELF002 pattern and the standard of quartz, berlinite and calcite.

and Figure 11.8) indicating the presence of quartz (Cook *et al.* 1975; Linsen *et al.* 2014). The peaks at 45.59° (2θ) with d-space of 1.98A° and at 31.79° (2θ) with d-space of 2.81A° indicate the presence of halite (NaCl) (Cook *et al.* 1975; Linsen *et al.* 2014). Halite is naturally present in groundwater samples (Christiansen *et al.* 2009). The peaks at 50.25° (2θ) with d-space of 1.81A° and at 60.08° (2θ) with d-space of 1.54A°, suggest the presence of berlinite (Marincea and DumitraȘ 2005; Narayan *et al.* 2012). The XRD pattern of ELF007 sample is presented overlaid with reference patterns of quartz, berlinite and halite in Figure 11.12.

In the case of sample ELF009, the XRD pattern shows the main quartz peak at 26.73° (2θ) with d-space of 3.33A° (Table 11.3 and Figure 11.9, Linsen *et al.* 2014). In addition, the peaks at 45.55° (2θ) with d-space of 1.98A° and at 31.80° (2θ) with d-space of 2.80A° indicate the presence of halite in sample ELF009. The ELF009 pattern is presented in Figure 11.13 and overlain with reference patterns of quartz and halite. All these results demonstrate that XRD is a useful technique to distinguish between environmental conditions based on the inorganic compounds detected in each sample.

Conclusion

The sediment samples from cores extracted from the prehistoric, inundated palaeolandscape known as Doggerland provided an opportunity to assess the value of three analytical techniques; (i) the percentage of organic materials in each sample as determined using the Weight Loss-on-Ignition (LOI); (ii) Gas Chromatography-Mass Spectrometry (GC-MS), used to identify the sources of various lipid biomarkers and (iii) X-ray Powder Diffraction (XRD) utilised for the identification of inorganic components.

From the results of analysis, sample ELF002 can be seen to possess a very low percentage of organics and carbonates 0.08% and 0.0074%. These are the lowest percentages among the three samples studied and indicate the high percentage of inorganic minerals within this sample. XRD has shown the presence of the two main soil components, quartz (SiO_2) and calcite ($CaCO_3$). The two groups of organic biomarkers, *n*-alkanes and fatty acids were identified and allowed calculation of CPI and Paq ratios. These indicate that the primary source of *n*-alkanes in sample ELF002 is marine vegetation. The presence of odd fatty acid indicates bacterial activity. Together, these data suggest that the area from which this samples was taken contains typical soil components, a bacterial community and marine vegetation inputs.

Sample ELF007 provided a medium organic percentage (10.47%), which suggests a high percentage of inorganic materials within the sample. XRD identified three inorganic components: quartz (SiO2), halite (NaCl) and berlinite (AlPO4). Halite is naturally present in groundwater and seawater samples. The analysis of *n*-alkanes, fatty acids and the PCI ratio (5.37) indicates the presence of terrestrial plant residues. The Paq ratio (0.15) suggests the presence of emergent aquatic vegetation, which have a strong correlation with lakes and/or rivers.

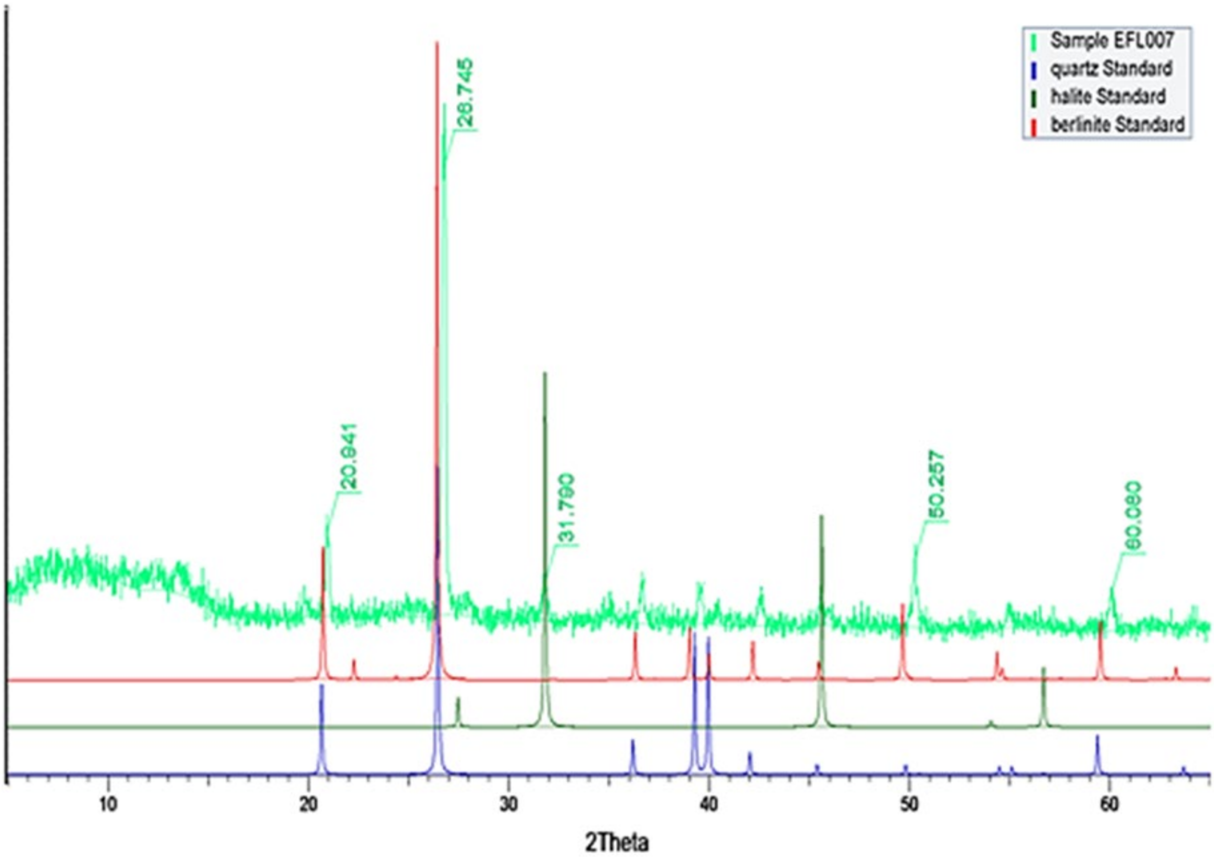


Figure 11.12 PXRD of ELF007 overlain with reference patters of quartz, berlinite and halite.

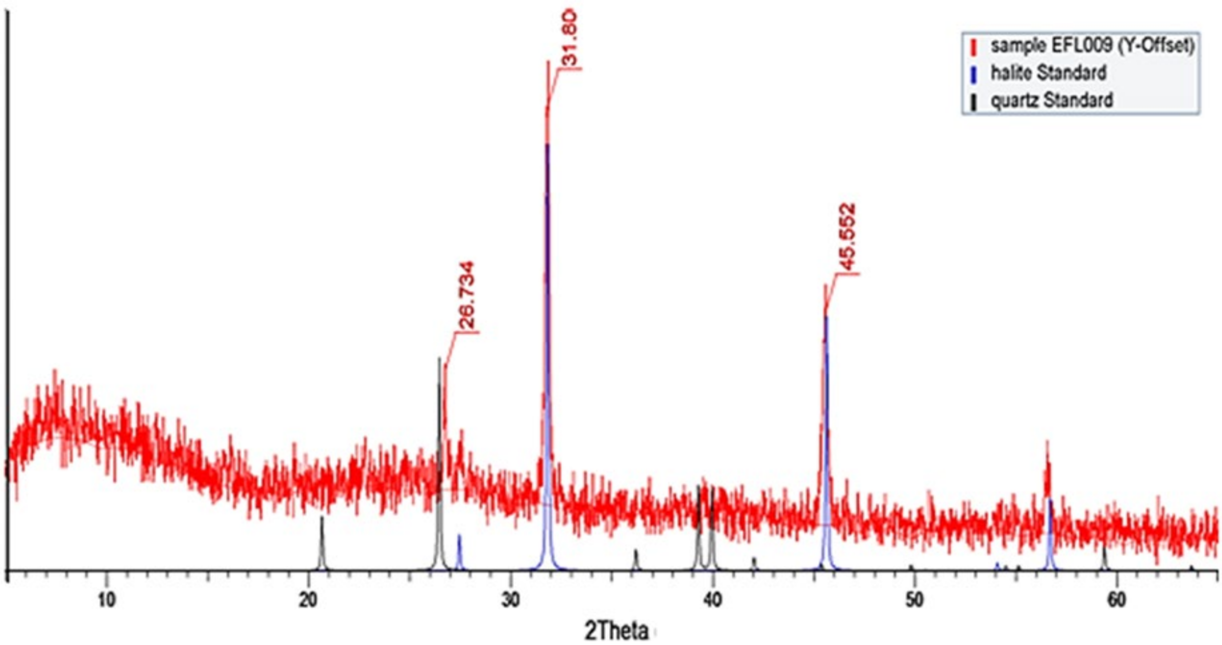


Figure 11.13 PXRD of ELF009 overlain with reference patters of quartz and halite.

Sample ELF009 has the highest percentage of organic materials (17.95%), which suggests it has the highest percentage of living organisms present among the three samples studied. In addition, it contains the highest percentage of carbonate (14.08%), which may indicate a mixture of sandy and rich organic material, possibly due to movement within this horizon. Two inorganic components were found, quartz (SiO_2) and halite (NaCl). Quartz is one of the most abundant compounds in nature, which explains its presence in all three samples. Halite is naturally present in groundwater and sea water samples. Two organic biomarkers, *n*-alkanes and fatty acids were detected in this sample. Suggesting that terrestrial plants were the main source of the extracted lipids.

The pilot application described here set out to provide a methodology to use sediment from marine cores for archaeological and geochemical studies. The results clearly demonstrate the potential of geochemical methods to distinguish between different depositional environments and to track the sources of organic compounds using core samples. As such, geochemistry provides a suite of tools to assist in studying inundated palaeolandscapes in Doggerland or elsewhere in the world.

Chapter 12

Constructing sediment chronologies for Doggerland

Tim Kinnaird, Martin Bates, Rebecca Bateman and Aayush Srivastava

Introduction

Luminescence dating is an important tool for constraining sediment ages and depositional processes in many Quaternary environments. This chapter provides examples of how optically stimulated luminescence, or OSL, has been applied to late Pleistocene to Holocene deposits recovered from core in the southern North Sea, to establish a chronology and define sedimentation histories. These sediment chronologies contribute to the palaeo-environmental reconstructions of Doggerland discussed elsewhere in this volume. Doggerland exhibits a complex palaeo-geography, with sediments deposited in diverse terrestrial, littoral and marine settings (see Bates *et al.* this volume), which presents some challenges to dating these sediments. The chapter begins with a brief consideration of the principles of luminescence dating, followed by a discussion of its application in the context of the North Sea. Then, the 'challenges' associated with OSL are discussed with reference to Doggerland, prior to outlining some potential solutions. Finally, the methods and protocols used in dating Doggerland sediments are discussed, illustrated with the example of establishing a sediment chronology for core ELF001A.

The luminescence dating technique exploits the energy retained in certain minerals, typically quartz and feldspar, which accumulate as a consequence of naturally occurring ionising radiation in both the sample and its environment. These signals are depleted, or reset, when the minerals are exposed to either heat or daylight. 'Zeroing' can be achieved during daylight exposure in phases of erosion or transport. After burial, or deposition, luminescence will grow *in situ* in response to the radioactivity of the surrounding sediment and cosmic rays. This is quantified as the equivalent dose (abbreviated to De), which is determined by calibrating the intensity of the OSL signal against the response to known laboratory-administered radiation doses (in Gray, abbreviated to Gy). To calculate an age, it is also necessary to measure the rate of radioactivity delivered to the sample from the surrounding sediment matrix, and this is called the environmental dose rate. A luminescence age is derived using the equation below:

$$\text{Age (ka)} = \text{Burial dose (Gy)}/\text{Total environmental dose rate (Gy ka}^{-1}\text{)}$$

OSL is routinely used to date sediments in terrestrial environments, as recently reviewed by Smedley (2018) and Rittenour (2018). Marine sediments were first dated by thermoluminescence in 1979 (Wintle and Huntley 1979), and using OSL techniques in 2003 (Stokes *et al.* 2003). Wintle and Huntley (1979; 1980) developed TL dating procedures to date marine sediments, extracted from deep cores in the Antarctic and North Pacific oceans. The ages were stratigraphically coherent, but issues including time-dependent dose rate calculations, anomalous fading in feldspars and large uncertainties, discouraged further applications of TL dating to marine sediments. After a long hiatus, Stokes *et al.* (2003) revisited luminescence dating of marine sediments and applied a single aliquot, regenerative dose (SAR) OSL technique to silt-sized quartz from cores extracted from the Arabian Sea. The authors reported ages that had low standard errors and showed agreements with independent chronometric control. They used thin source alpha spectrometry to examine the uranium (U) and thorium (Th) decay series for time-dependent changes in dose rate.

Since 2003, studies have applied various luminescence dating techniques to a range of different types of coastal and marine deposits, involving a variety of depositional processes and environments (e.g. Armitage 2015; Jacobs 2008; Jakobsson *et al.* 2003; Sanderson and Kinnaird 2019; Tappin *et al.* 2011): establishing OSL dating as a suitable method to determine timing of depositional events in nearshore and offshore marine environments. Bateman (2015) provides a comprehensive review of luminescence dating applied in coastal and marine contexts.

In the North Sea region, there are relatively few comparative studies: Alappet *et al.* (2010) constructed chronologies for shallow terrestrial and marine deposits in the southern North Sea, south east of Dogger Bank. They obtained late Weichselian and early Holocene ages for glacio-fluvial and lacustrine sediments 2.0 to 0.5m beneath the terrestrial-to-marine transition that attested to sedimentation in a predominantly periglacial, fluvial environment. The authors noted significant scatter in the equivalent dose distributions of quartz due to heterogeneous bleaching. Further north and west, offshore the Humber Estuary, Tappin *et al.* (2011) applied a combination of OSL and radiocarbon dating to re-interpret the geological evolution of the area over the last 21,000 years, from when the region was glaciated and the Brown Bank Formation was laid down to marine transgression. Madsen *et al.* (2005) showed that it is possible to date young, fine-grained estuarine deposits by OSL: they obtained OSL sediment ages for a length of core through tidal mudflats in Ho Bugt, ranging from 7.0 ± 1.5 (near surface) to 305 ± 16 years (at 68cm depth), concordant with ^{210}Pb ages back to *c.* 1975. Moreover, an average OSL age of 9 ± 3 years for the surface mixing zone showed that in this setting the OSL signal of the quartz grains was well-zeroed at deposition.

22 of the 78 sedimentary cores recovered from the Outer Dowsing Deep region of the southern North Sea were investigated in the context of OSL dating and four are referenced within this chapter (Figure 12.1). The objectives of this chapter are, therefore, threefold:

1. to evaluate the potential of OSL for establishing a chronology and sedimentation history of late Pleistocene to Holocene deposits at Dogger Bank
2. to discuss the challenges associated with OSL, with reference to the submerged Doggerland palaeo-environments: partial bleaching, mineralogical variations with varied luminescence response, stable dose rate conditions and disequilibrium in the uranium decay series
3. to review these challenges and design a methodology to date the submerged Doggerland marine, nearshore and terrestrial deposits

This will be the reference to all OSL depositional ages reported in this, and subsequent volumes, in the *Europe's Lost Frontiers* (ELF) monograph series.

'Challenges' to dating the sediments of Doggerland

Challenge 1: Partial bleaching of sediments

It is a clear requirement of the technique that the sedimentary grains used as the luminescence dosimeter are exposed to adequate light at deposition to bleach, or zero, the luminescence signals. Where the mineral grains are not exposed to sufficient daylight, we observe a phenomenon known as partial bleaching, which can contribute to significant scatter in determined De values and hence determined ages (Duller 2008; Olley *et al.* 1998). Poor 'zeroing' at deposition leading to large overestimations in age.

The resetting of the luminescence signals during transportation and deposition is a function of environmental conditions and luminescence behaviour (Figure 12.2).

In the littoral zone, the optimum depositional environment is commonly considered to be coastal dunes, because aeolian transport (particularly, saltation) provides a very high probability of daylight exposure prior to burial. Whereas, in intertidal, marsh and lagoonal settings, exposure to daylight prior to burial is less certain, with diminished light penetration

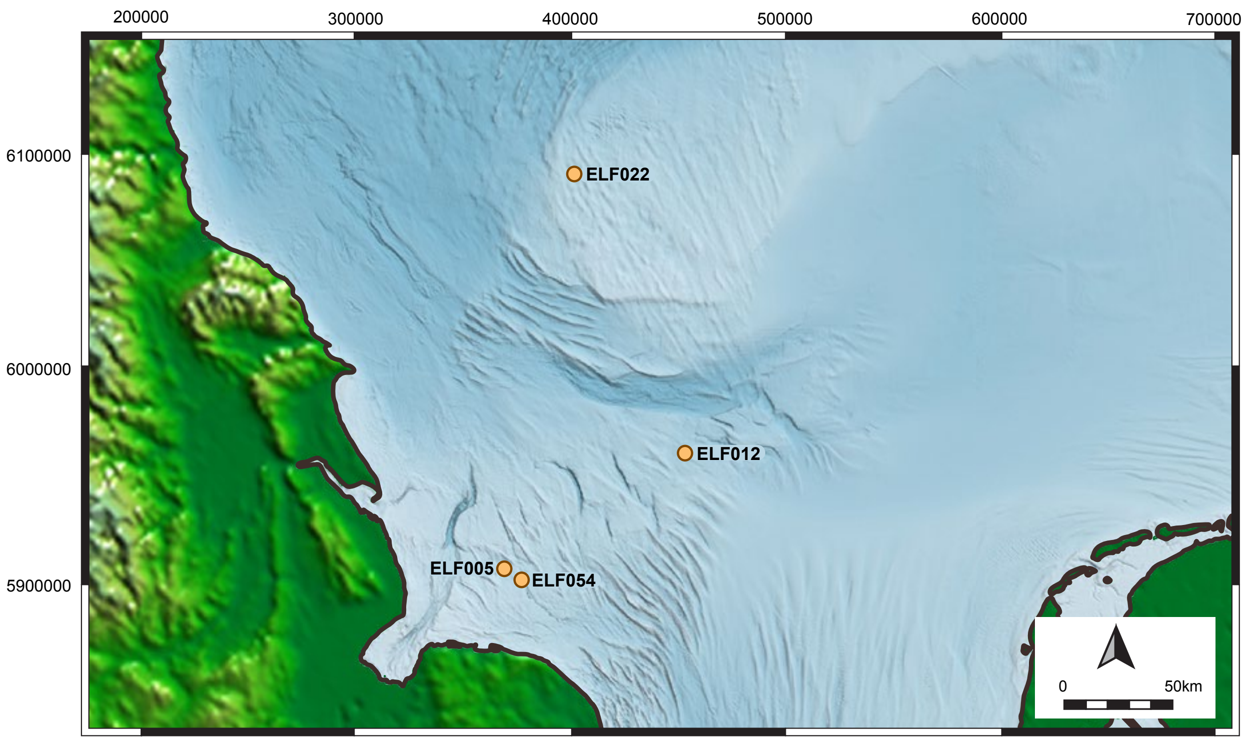


Figure 12.1 Locations of cores mentioned in text.

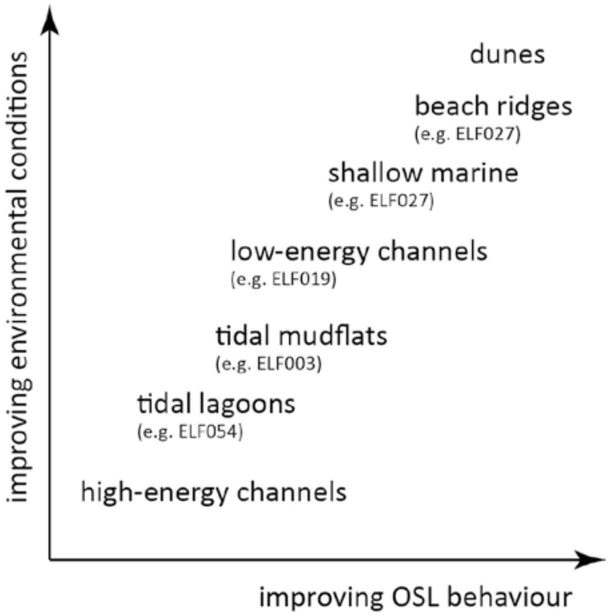


Figure 12.2 For successful OSL dating, both environmental and mineral characteristics are important: zeroing during transport and deposition is a function of environmental conditions and luminescence behaviour.

through the water column, and mixing of suspended sediment with sediments deposited from singular or episodic events (Bateman 2015).

Challenge 2: Post-depositional sediment mixing

Post-depositional mixing can be due to bioturbation or geomorphic processes (e.g. sediment slumping). Either phenomena could contribute to further scatter in determined De values and determined ages. Bioturbated sample may exhibit multi-modal De distributions, but unlike poorly bleached sediments, these distributions may contain De that tend to both higher and lower apparent doses, obscuring the true burial age (Bateman *et al.* 2007). In the context of Doggerland, this issue is important as bioturbation is a ubiquitous process in shallow marine and estuarine environments (Madsen *et al.* 2010; Reed *et al.* 2006).

Challenge 3: Mineralogical variations

Luminescence response is variable between mineral systems, and between minerals of the same system: quartzes and feldspars are characterised by variable brightness and stability of signals. This is quantified as luminescence sensitivity – a measurement of luminescence per unit dose. In the context of Doggerland, this issue is important as mineral response will vary within, and between cores, varying with (and not restricted to) mineral provenance, erosional and depositional histories, and post-depositional diagenesis.

Challenge 4: Stable dose rate conditions and disequilibrium in uranium decay series

In routine luminescence applications, secular equilibrium in the decay chains of U and Th through time are assumed, as is 'closed system' behaviour. In 'closed systems', each decay chain tends towards radioactive equilibrium; whereas in 'open systems' exchange of radionuclides, by a variety of physical and chemical processes such as dissolution, sorption and precipitation, can lead to disequilibrium in the decay series, more so for the decay series of uranium (see discussion in Degering and Degering 2020). In many terrestrial settings, it is valid to assume secular equilibrium, and closed system behaviour; but, in marine and near-shore settings this should be not assumed. Surficial deep-sea sediments are known to contain an excess of ^{230}Th over the series parent ^{238}U (Armitage and Pinder 2017; Jakobsson *et al.* 2003; Sanderson and Kinnaird 2019), this can decay with depth, and introduce a time dependent component into the dose rate.

Therefore, in the context of Doggerland, in evaluating dose rates to the full range of terrestrial, littoral and marine deposits, anomalies in the concentrations of uranium and/or thorium need to be identified, such that excess activity is quantified and incorporated into dose rate calculations. Moreover, temporal variations in burial conditions need consideration, as the thickness of overburden has implications for the cosmic dose, and fluctuating moisture contents in the sediments will attenuate the external dose.

In addition to the challenges discussed above, there are important, practical considerations when sampling from core materials: a.) there is potential for some light exposure during core retrieval and storage; b.) there is potential for barrel smearing, which could cause additional mixing of sediments (and contributing to further scatter in determined De values) and c.) smaller sample quantities that are obtained from core, compared to sampling from terrestrial sections, necessitate more careful sample preparation and increased counting times. Nelson *et al.* (2019) and Sanderson and Kinnaird (2019) discuss these issues in detail and provide recommendations for secure sampling of subsurface deposits from core in terrestrial and marine settings, respectively.

Our methodological approach

'Solutions' to challenges 1-3

A number of OSL screening methods have been developed to provide insights into the luminescence properties of sediment and to interpret the depositional mechanisms and zeroing processes. These range from methodological developments such as standardised growth curves (Roberts and Duller 2004), range-finder ages (Durcan *et al.* 2010; Roberts *et al.* 2009) and laboratory profiling (Burbidge *et al.* 2007; Kinnaird *et al.* 2017a; Kinnaird *et al.* 2017b) to instrumentation developments, such as the portable OSL equipment developed at SUERC (Munyikwa *et al.* 2020; Sanderson and Murphy 2010).

In this research, a combination of these approaches was employed: at the time of sampling, luminescence stratigraphies were generated from proxy luminescence data generated with portable OSL equipment (Sanderson and Kinnaird 2019: stage 1). These stratigraphies were 'calibrated', by subjecting sub-samples to laboratory luminescence screening and characterisation measurements, and constructing apparent dose-depth and sensitivity-depth profiles for each core (stage 2). Finally, targeted samples were taken forward to full quantitative quartz SAR OSL dating (stage 3). This approach has several advantages: first, by characterising the 'depositional' sequences for the full length of the core, sampling is better informed and more effective. Second, by generating relative sediment 'chronologies' for the entirety of each core, direct comparisons of sedimentary units down, and between, cores is possible. This provides a means to relate discrete events (e.g. peat inception, inundation) across cores. Moreover, the 'chronology' is not reliant on a small number of dates from arbitrary selected points.

Figure 12.3 illustrates this approach. The examples shown are:

- ELF05B, a length of core 2m long, penetrating *c.* 50cm of grey, laminated silts representing saltmarsh, then brackish mudflats, then *c.* 50cm of grey, fine sands, occasionally speckled with black organic material, attributed to wetland deposition, culminating in peat formation, then tidal access; at 115cm depth in core, till is encountered
- ELF012, a 4m long core of structureless, mid-brown to greyish brown medium- to fine- sands, with common shell fragments and occasional black mottling; there was some debate ahead of sampling as to whether these sediments should be attributed to the Botney Cut Formation (Stoker *et al.* 2011) or if they were a modern sand bank
- ELF022, 6m of alternating medium- and fine-sands, frequently with clay silt laminations, and occasional shell fragments
- ELF054, a length of core 3.8m long, penetrating 2.6m of grey clay silt, with phytal ostracod and clinging foraminiferal fauna suggesting marine-algae and/or seagrass, in a brackish lagoon, then 1.1m of silts (10cm thick) interbedded with dark brown fibrous peats (*c.* 50cm thick)

Figure 12.3a shows how breaks, or step changes, in IRSL and OSL net signal intensities might indicate where discontinuities, or unconformities, are present in the core stratigraphies. This was observed when sampling ELF005B: net signal intensities drop off through units 5B-3, -4 and -5, approaching the transition from brackish lagoon to wetland deposition. (The inverted signal-depth progression through 50 to 64cm tracks a reduction in grain size through the same interval, and an increased prevalence of wavy, sub-parallel clay-silt laminations). Across the 5B-5/-6 transition, there is a substantial step-change in intensities, across an order of magnitude, which attests to this boundary representing a considerable amount of time. The subsequent calibrated laboratory analyses provide some quantification to this: the break corresponds to 20Gy.

Figures 12.3b and 12.3c show how signal-depth progressions can provide insights on rates of sedimentation: consistent signal intensities with depth might indicate high rates of sedimentation (Figure 12.3b), whereas, slow, steady signal-depth progression likely represents a slow rate of sedimentation (Figure 12.3c). The range in intensities across these progressions provides the relative rate of sedimentation. With ELF012, we concluded during sampling that the range in signal intensities observed across the 6m length of core suggested that these sands had accumulated rapidly. Moreover, as there was no distinction between the signal intensities at the very top of the core (i.e. modern sands) and those at 6m depth, that these sands are modern and represent a sand bank on the seabed. In contrast, in ELF022, between 50 and 80cm depth in core, there is a steady increase in signal intensities with depth, implying a slower and more steady sedimentation across this interval.

Finally, Figure 12.3d, illustrates how the amalgamation of all proxy luminescence data (together with sedimentological observations, and when available other environmental proxies (e.g. Allaby *et al.* this volume; Bates *et al.* this volume) provides temporal (and spatial) frameworks to aid interpretation of the depositional sequences and histories. It demonstrates that: a.) the marine sands encountered through 0.00 and 0.88m depth in core are stratified, with some chronology, which led to re-appraisal of this unit, and the recognition that this was more than a recent sand wave; b.) through 0.88 to 1.25m, and then 1.25 to 1.45m, IRSL and OSL signal intensities track a reduction in silicate content, with implications for reconstructing dosimetry; c.) through 1.45 to 2.60m, intensities increase with depth, which notwithstanding b.) implies a considerable chronology across this interval on the order of ×2-5; and d.) that the till encountered at 2.85m was reworked to a depth of 15-20cm, during deposition of the overlying unit.

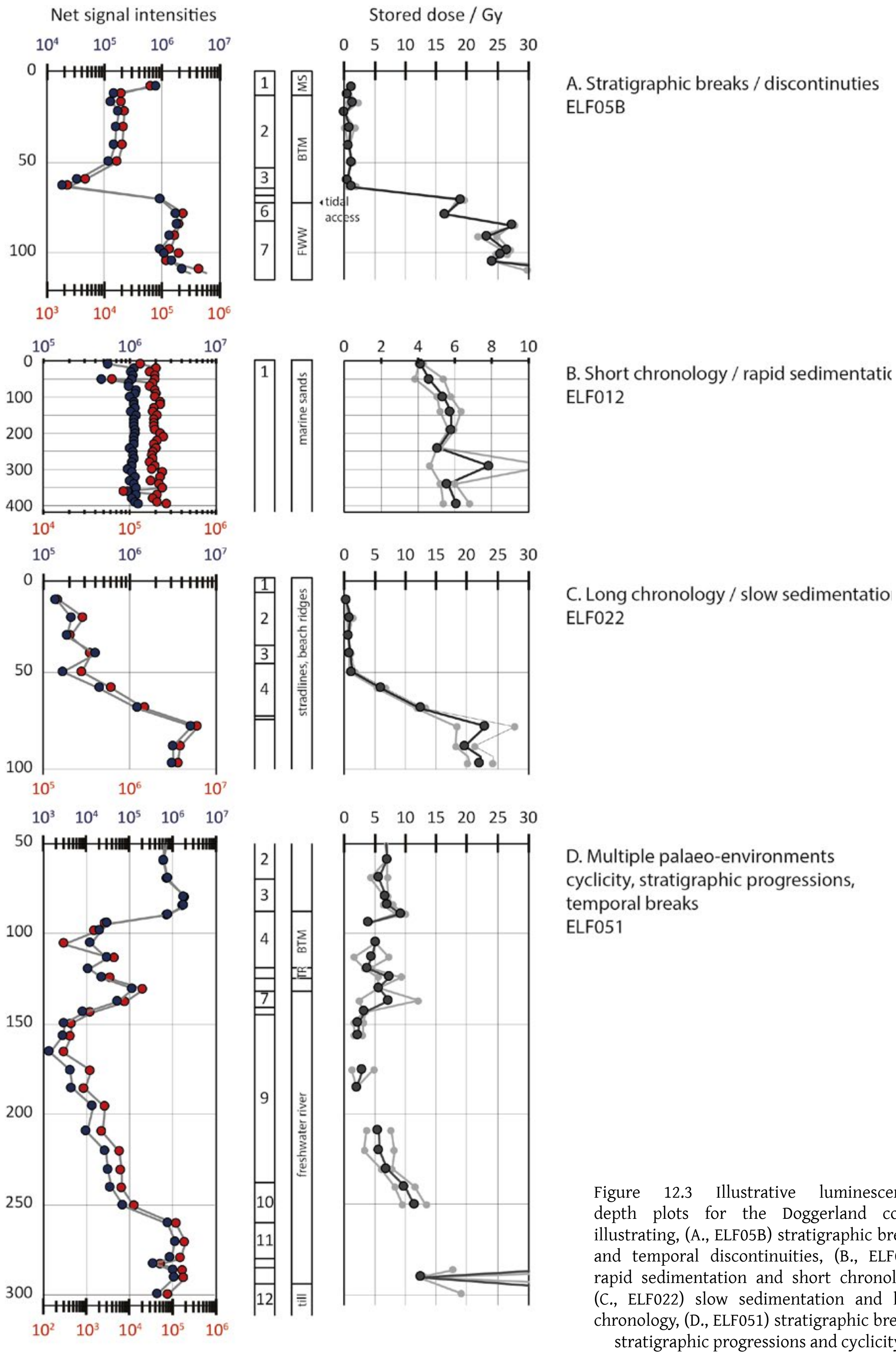


Figure 12.3 Illustrative luminescence-depth plots for the Doggerland cores: illustrating, (A., ELF05B) stratigraphic breaks and temporal discontinuities, (B., ELF012) rapid sedimentation and short chronology, (C., ELF022) slow sedimentation and long chronology, (D., ELF051) stratigraphic breaks, stratigraphic progressions and cyclicity.

Therefore, only samples with promise are selected for luminescence dating, maximising the chances of success for dating. When more challenging samples were sampled, and partial bleaching or post-depositional sediment mixing were identified as issues, statistical techniques examining the degree of over-dispersion in De and the measure of skewness and kurtosis in De distribution were examined (Galbraith *et al.* 1999; Olley *et al.* 1998).

Application to the *Europe's Lost Frontiers* Project

Europe's Lost Frontiers is investigating the submerged landscape of Doggerland, reconstructing it's palaeoenvironments through extensive marine survey and sediment coring (Gaffney and Fitch this volume); with the sediment cores subjected to detailed sedimentological, palaeoenvironmental (Bates *et al.* this volume), geochemical (Bensharada *et al.* this volume; Finlay *et al.* this volume) and sedimentary ancient DNA (Allaby *et al.* this volume) analysis.

OSL and radiocarbon dating (Hamilton *et al.* this volume) provide the chronologies to underpin these studies.

78 cores from 60 locations have been collected, of which 40 have material of interest; 22 of these have been sampled for OSL profiling and dating. The recovered materials in these cores are from a range of palaeo-environments, including marine sands, intertidal muds, brackish lagoons, peats (from a few centimetres thick to 1.8m), lakes, rivers and palaeosols (Figure 12.2).

The methods and protocols employed in luminescence dating, as applied in the *Europe's Lost Frontiers* project, are illustrated with reference to core ELF001A. Core ELF001A is significant to palaeo-environmental reconstructions of Doggerland, as its sedimentary sequences preserve a proxy record of final submergence of Doggerland, and potentially encloses materials related to the Storegga Tsunami (Gaffney *et al.* 2020).

Borehole ELF001A is located at the head of a palaeo-river system near the Outer Dowsing Deep (the Southern River, Fitch *et al.* this volume: Chapter 6). Prior to final submergence, with the majority of the landscape already lost to sea-level rise, the surviving land would have been low lying and close to sea level. This landscape would have been vulnerable to catastrophic flooding events. A key regional event during this period was the Storegga Tsunami, which occurred in response to a series of underwater landslides off of the Norwegian coasts 8.15 thousand years before present. This tsunami hit the eastern Scottish and English coastlines, and likely reached the southern North Sea. Some workers (Bondevik *et al.* 2012; Fruergaard *et al.* 2015; Weninger *et al.* 2008) have suggested the Storegga Tsunami led to the final abandonment of the island by Mesolithic communities.

Seven lithological units were identified within this core: units 1A-1 to 1A-3, consist of sands or sandy gravels with marine shells; units 1A-4, well-laminated fine-grained sandy silts; unit 1A-5, a thin sequence of silty sands with broken shell fragments; unit 1A-6, well-laminated sands and silts, overlain by poorly sorted sands and shell detritus; unit 1A-7, well-laminated fine-grained sandy silts. Modern or recent mobile bottom sands are represented by units 1A-1 to 1A-3 and have not been sampled or considered in any detail.

Estuarine mudflat conditions are represented in the core in units 1A-4 and 1A-7, which are interrupted by coarse poorly sorted shelly gravel (1A-5/1A-6). The mixture of marine and brackish material alongside broken and fragmentary shell remains, and common small clasts, suggests these sediment units represent a high-energy event intruding into otherwise sheltered mudflat environments Further multi-proxy data from ELF001A, as reported in Gaffney *et al.* (2020), provided evidence to suggest that these units were the deposits of the Storegga Tsunami.

Methodological details

Stage 1 – Preliminary OSL screening of cores

For the subset of sedimentary cores selected for OSL investigation, the sedimentological and geophysical evidence were reviewed, and the key stratigraphic intervals and depths of interest noted. Cores were split under subdued light conditions at the University at Warwick, with one half retained there for sedaDNA analyses, and the other transferred to the University of Wales Trinity Saint David, Lampeter campus, for sedimentological and luminescence investigation. At Lampeter, the cores were subsampled for luminescence screening using portable OSL equipment (Munyikwa *et al.* 2020).

The protocol adopted throughout the study was as follows:

1. through each core, sediment was extracted at regular 10cm intervals, with tighter resolution sampling at stratigraphic and lithological boundaries (and if available, prominent breaks in the geochemical data; Figure 12.4)
2. these sub-samples were immediately measured using a SUERC portable OSL reader, using an interleaved sequence of system dark-count, IRSL and OSL (cf. Sanderson and Kinnaird, 2019)
3. from this, IRSL and OSL net signal intensities and IRSL and OSL depletion indices were calculated

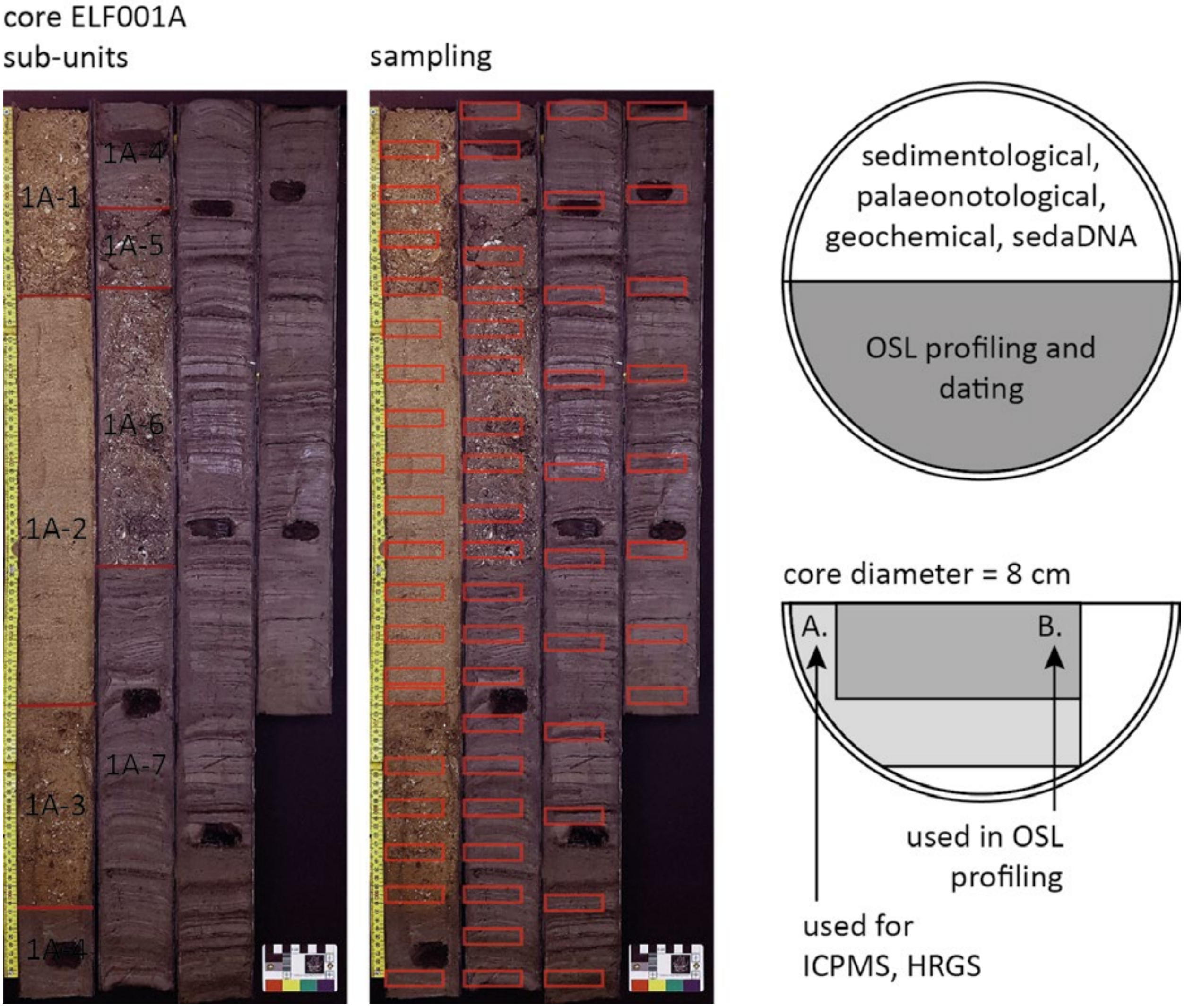


Figure 12.4 Sampling strategy for ELF cores – illustrated with core ELF001A: (a) core, with sub-units identified; (b) core, with sampling positions indicated; (c) removal of sediment for OSL profiling, OSL dating and dosimetry.

for all samples, and luminescence-depth profiles generated for each core (Figures 12.3 and 12.5)

4. this, in combination with sedimentological observations and the expectations of dating, were used to position samples for quantitative quartz OSL dating
5. for the positions in the core selected for dating, larger samples were taken from between the profiling samples, and associated samples collected for dosimetry

Using this approach, the 22 investigated cores were appraised through more than a thousand samples, which permitted the construction of high-resolution luminescence 'stratigraphies'. IRSL and OSL signals were readily detectable in all cores, confirming that phases suitable for luminescence dating were present. IRSL signal intensities range from 120 to 1.83×10^7 counts; and excluding the more organic rich horizons in ELF002, 005B, 034, 051, 054, from 5160 counts. Peats and very-organic rich silts were not sampled for OSL. OSL signal intensities range from 1440 to 1.57×10^8 counts; and excluding the more organic rich horizons, from 2.29×10^4 counts. IRSL and OSL depletion indices range between 1.09 and 3.03, and 1.09 and 3.17, respectively. The dynamic range in IRSL signal intensities observed down individual cores is at least one order of magnitude (41% of investigated cores), and commonly more (2 orders, 36%; 3 orders, 18%; 4+ orders, 5%); similar dynamic ranges were observed in OSL net signal intensities (1 × 10, 32%; 2, 45%; 3, 18%; 4+, 5%).

Luminescence responses, therefore, vary down core, and clearly record mineralogical, luminescence age, sensitivity and dosimetry variations.

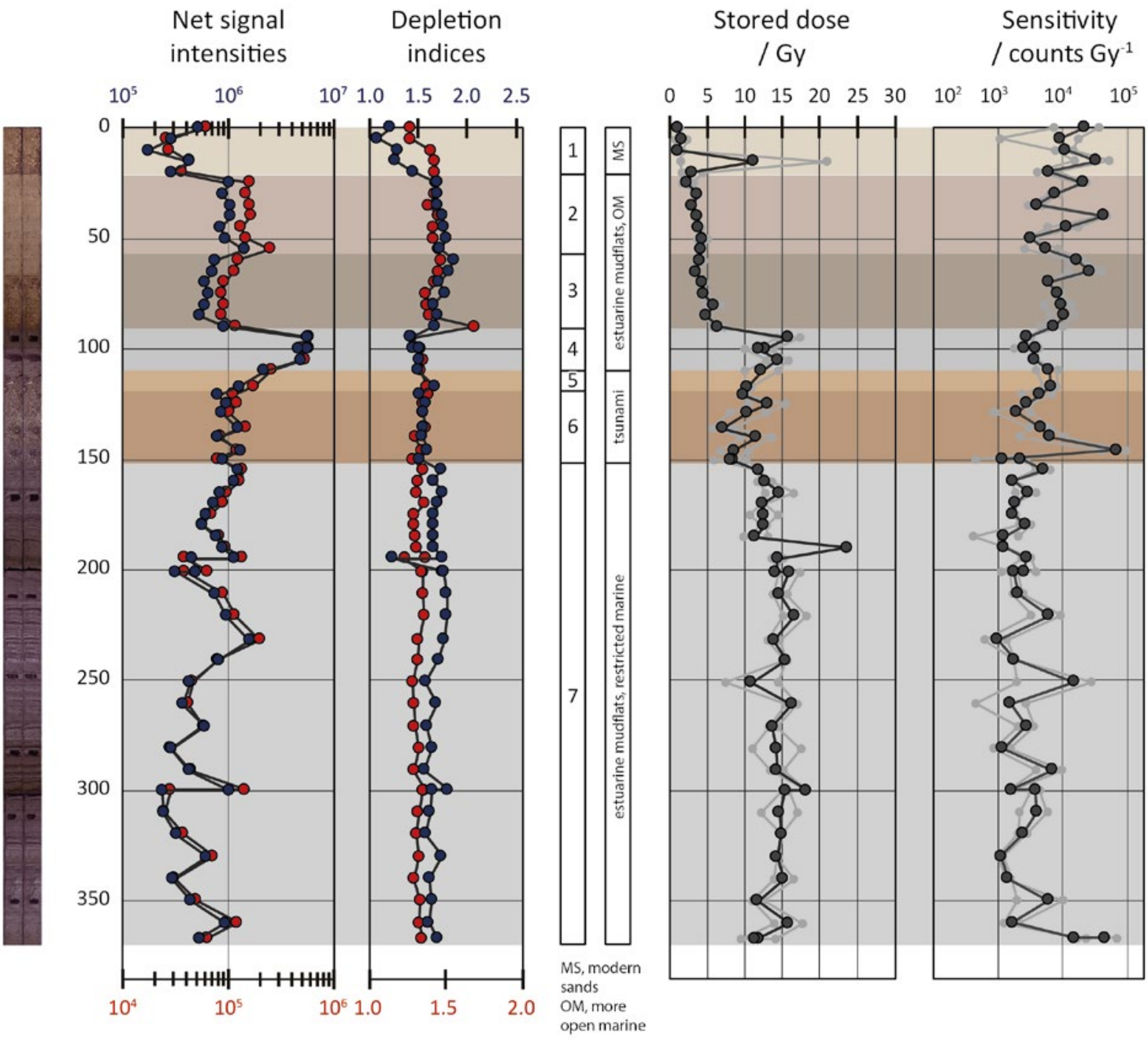


Figure 12.5 Illustrative luminescence-depth plots for ELF001A: on the left, IRSL and OSL net signal intensities and depletion indices; on the right, apparent dose and sensitivity distributions.

To illustrate this, we use the example of ELF001A. Figure 12.5a shows the proxy luminescence stratigraphies relative to the lithostratigraphy of the core, through units 1A-1 to 1A-7. Observations, and inferences from these, are tabulated in supplementary data. From 0 to 21cm depth, the sands are characterised by fluctuating OSL signal intensities in the range 1.75 to 5.30 × 10^5 counts, with no stratigraphic coherence, and low depletion indices, <1.3. Together, this data suggests that these sands are modern and mobile. The trend in fluctuating OSL signal intensities with depth continues through 21 to 67cm, although across a greater range, 7.08 × 10^5 to 1.44 × 10^6 counts. From 67 to 90cm depth, there is a slight signal-depth progression from 6.01 × 10^5 to 9.26 × 10^6 counts, and depletion indices are higher than observed in unit 1A-1. The step change in OSL intensities across the unit 1A-1 / 1A-2 boundary, then the signal-depth progression in unit 1A-3, all suggest that units 1A-2 and 1A-3 record some chronology and stratigraphy is preserved.

From 90 to 109cm, unit 1A-4, there is an inverted signal-depth progression from 5.71 to 4.96 × 10^6 counts, and the lowest depletion indices observed in the core aside from unit 1A-1. The step-change in OSL intensities across the unit 1A-3 / 1A-4 boundary implies that the sediment has a difference provenance. The low depletion indices suggest that this material is poorly bleached, and that the composite OSL signals include residuals.

Between 109 and 151cm depth, units 1A-5 and 1A-6, the luminescence profiles are more complex: with 'couplets' on the scale of 4 to 5cm, characterised by both normal and inverted signal-depth progressions. Interestingly, in each 'couplet' the lower signal intensities correlate with higher depletion indices. The 'cyclicity' in OSL intensities and depletion indices is interpreted here as reflecting deposition from multiple waves: the first influx of sediment is characterised by low OSL intensity and high depletion index; then, higher intensities and lower depletion indices. The first wave is well-bleached and characterised by low intensities and high depletion indices, then the subsequent waves, are only partially bleached and characterised by high intensities and low depletion indices. It is notable that across the 'couplets', signal intensities vary over a similar magnitude and range, suggesting a common provenance.

From 155 to 180cm, signal intensities drop from 1.24×10^6 to 5.78×10^5 counts, before increasing with depth through the interval 180 to 200cm, from 5.78×10^5 to 1.16×10^6 counts, from 200cm to depth, signal intensities remain relatively consistent at approximately 1.59×10^6 counts. This implies that unit 1A-7 should be further sub-divided into two sub-units 1A-7a and 1A-7b and illustrates for this interval that screening at sampling can identify crypto-stratigraphic boundaries.

Having shown that there are readily measureable IRSL and OSL signals, and that these signals vary with stratigraphy down core, the investigations progressed to laboratory analysis, first to calibrated luminescence screening and characterisation (stage 2), then to full quartz SAR OSL dating. The 'calibrated' profiles as obtained in stage 2 (below), remove some of the ambiguity in interpreting the relative 'luminescence stratigraphies', relating to bulk mineral properties (mineralogy, grain size, sensitivity, colour etc).

Stage 2 – OSL calibration and characterisation of cores

Sample preparation and laboratory analyses were undertaken in the luminescence laboratories of the School of Earth and Environmental Sciences (SEES), University of St Andrews. This stage in the methodology is to characterise a sub-set of the profiling samples in the laboratory, to provide a first approximation of the magnitude and range in luminescence sensitivities and apparent (or burial) doses. OSL measurements were carried out using Risø TL/OSL DA-15 and DA-20 automated dating systems. Full technical details of the SEES instruments are provided in García *et al.* (2019).

The protocol adopted here, was as follows:

1. sub-samples from the initial luminescence profiling were subjected to simplified mineral separation procedures (cf. Sanderson and Kinnaird 2019: supplementary data)
2. paired aliquots of HF-etched from each sub-sample were subjected to a simplified SAR OSL protocol for a preliminary assessment of apparent dose (cf. Sanderson and Kinnaird 2019); The readout cycle consisted of: a.) a preheat at 220°C, held for 10s; b.) OSL at 125°C for 60s, c.) a test-dose of 1Gy, d.) a preheat of 220°C, e.) OSL at 125°C for 60s, f.) then, repeats of steps a.) to e.) following regenerative doses of nominal doses of 10, 30, 60Gy (extended to 120Gy, when necessary) and 0Gy. The zero dose was omitted from the readout cycles of ELF003, 005B and ELF031A. A recycling dose of 10Gy was added to the readout cycles of at least one length of core from ELF001A, 007, 019, 022, 027, 034, 039, 054 and 059
3. from this, the distributions in sensitivities and apparent dose were calculated, and plotted vs depth in core
4. these plots were used to test the assumptions made during initial profiling and to re-appraise the most promising targets for dating

906 of the 1104 preliminary samples were taken forward to further laboratory analyses (this equates to 82% of the dataset).

From this, we obtained the first indication of bulk mineral / luminescence behaviour, which were promising: OSL sensitivities ranged from 110 to 1.48×10^6 counts Gy-1. 81% of aliquots returned an OSL sensitivity >1000 counts Gy^{-1} and, 91% of aliquots, a sensitivity >500 counts Gy^{-1}. Recuperation was, in general, low with a mean value of 6.7 ± 11.0 % (error expressed here, and elsewhere, as standard deviation); 66% of aliquots returned a recuperation value <5%. Recycling ratios were, in general, good with a mean of 1.04 ± 0.35; with 82% of aliquots returning recycling ratios within ± 0.1 error of unity. By substituting the 1st regenerative dose for the natural dose in each dependent SAR curve, and comparing this nominal normalised value to the known given dose, pseudo-dose recovery 'ratios' are obtained for each sample. The mean value for pseudo-dose recovery was 1.07 ± 0.26.

OSL apparent doses ranged from 0.1 to >100Gy; relatively few aliquots returned apparent doses in the sub-Gy region (<4%), and <7% returned apparent doses in excess of 60Gy. With the exception of ELF012, the dynamic range in apparent doses down core is in the range of 10^2 to 10^3, which attests to long sediment chronologies and moreover the preservation of stratigraphy in these cores (which partly addresses challenge 2: post-deposition sediment mixing). These analyses suggest the cores, and/or parts of the cores, where apparent doses are low and likely to return early Holocene depositional ages, and where apparent doses are high, which in a low dose rate environment would correspond to late Pleistocene and earlier dates. Earlier, with reference to the luminescence stratigraphies shown in Figure 12.3, we suggested the parts of cores ELF012 and ELF022, where we might expect sedimentation to be slow and gradual, or episodic and rapid. Both these trends are reproduced in the calibrated laboratory dataset. Across the 6m length of core in ELF012, the progression in apparent doses is from 4 to 5Gy; whereas for the 20cm thickness of unit 22-4 in ELF022, apparent doses increase from 6 to 22Gy. With any estimate of environmental dose rate, this implies that the sediments in ELF012 represent a short chronology (and rapid deposition), whereas, a considerable chronology (and slow sedimentation) is represented in ELF022.

The detail in this is illustrated using the example of ELF001A. All 61 samples from this core were taken forward to preliminary laboratory characterisation. As before, key observations, and inferences from these, are tabulated in supplementary data.

Unit 1A-1 is characterised by variable OSL apparent doses in the range 0.7 to 1.7Gy (with one high dose outlier, trending to in excess of 20Gy), with poor paired reproducibility between aliquots, and no stratigraphic coherence. The sensitivity distribution is also heterogeneous, varying across two orders of magnitude.

In contrast, units 1A-2 and 1A-3 show a progression in OSL apparent doses with depth, through 21 to 90cm, from 1.7Gy to 5.7Gy. The paired reproducibility between aliquots is good: apparent doses reproduce within error between 30 and 55cm and 70 and 85cm. The sensitivity distribution is less heterogeneous, varying across a single order of magnitude. This supports the hypothesis raised at sampling: unit 1A-1 is modern and mobile, units 1A-2 and 1A-3 record some chronology and stratigraphy is preserved.

Across the unit 1A-3 / 1A-4 boundary, there is a step increase in OSL apparent doses, from 5.7Gy to in excess of 10Gy. Even withstanding large variations in environmental dose rate across this boundary, this attests to a large temporal break between these units. From 90 to 109cm, apparent dose estimates are inverted, from c. 14 to 10Gy. The fine-grained sandy silts of unit 1A-4 are characterised by lower luminescence sensitivities than the coarser-grained sands of units 1A-1 to 1A-3. In the original interpretation, it had been assumed that the step-change in net signal intensities across the boundary reflected a change in provenance; but the lower signal intensities returned from unit 1A-4 reflect in part the lower sensitivities of these sediments.

The sensitivity and apparent dose distributions for units 1A-5 and 1A-6 are complex, varying on the 5 to 10cm scale: between 109 and 119cm, apparent dose values are consistent at c. 10Gy, with good paired reproducibility; from 121 to 129cm, apparent doses show a normal dose-depth progression, from 9.5-10Gy to >12Gy, with poor reproducibility between aliquots; from 136 to 146cm, some scatter is noted in apparent doses, which vary between 6 and 13Gy; from 150 to 155cm, apparent dose values are consistent at c. 8Gy. Paired reproducibility is variable: although the lower doses in each couplet show better paired reproducibility (varying within 10%), and the higher dose outliers in each, poorer reproducibility (diverging by up to 50%). There are several interpretations to this, successive waves may have entrained more 'old' sediment as they moved inland, or alternatively, 'old' buried and un-zeroed sediment from deeper water and/or beach were sequentially cut into and entrained by later waves. In either scenario, zeroing of the luminescence signals during tsunami-transport was variable, from partial to good.

Across the unit 1A-6 / 1A-7 boundary, there is a step increase in apparent dose values to 10 to 13Gy, consistent with a temporal break. From 200cm depth in core, there is another step-increase in apparent doses to values fluctuating around 14.5Gy. This corroborates the hypothesis raised at sampling of a lithostratigraphic division in unit 1A-7 that must correspond to a change in depositional conditions.

This stage of the investigations provided the further temporal (and spatial) frameworks for each of the investigated cores, providing insights on the depositional histories, and indicating the parts of the cores, and units, amenable for OSL dating. Subsequent to this, the luminescence stratigraphies were reviewed, dating priorities discussed with colleagues in the *Europe's Lost Frontiers* team, and targets/sedimentary units identified for OSL dating.

Stage 3 – Quantitative quartz SAR OSL dating

Dating priorities differ from core to core, covering deposits from a range of palaeo-environments from mudflats, estuarine mudflats to terrestrial shorelines and fluvial deposits (Figure 12.2).

In regard to reporting luminescence ages in this, and subsequent volumes in the *Europe's Lost Frontiers* monograph series, the data generated during all stages will be appended to the relevant chapter. The supplementary data will be reported in the following format: 1. luminescence stratigraphies; 2. representative decay and dose response curves; 2. equivalent dose determinations/distributions; 4. dose rate determinations; and 5. OSL depositional ages, with a commentary on geomorphological and/or palaeo-environmental significance.

Equivalent dose determinations

Standard mineral preparation procedures as routinely used in OSL dating were used to extract sand-sized quartz from each sample (cf. Kinnaird *et al.* 2017a, 2017b). Further technical details are provided in supplementary data. Variable quartz yields necessitated the need to explore several grain size fractions, typically 90-150 and 150-250µm.

Equivalent doses (De) were determined by OSL using a single aliquot regenerative dose (SAR) OSL protocol (cf. Murray and Wintle 2000; Sanderson and Kinnaird 2019: supplementary data).

Quartz from the *Europe's Lost Frontiers* cores was characterised by a range of responses, reflecting regional variations in lithofacies, mineralogy and depositional setting. As standard in the SAR OSL protocol, individual aliquots, or equivalent doses were only taken forward to analysis if they passed strict SAR acceptance criteria: a.) Sensitivities had to exceed >1000 counts per Gy; b.) Recuperation had to be < 10% of the natural signal (it was typically < 5%); c.) Recycling ratios had to be within 10% of unity; d.) pseudo-dose recovery ratios had to be within 10% of unity and/or e.) aliquots had to show no significant IRSL response associated with anomalous equivalent doses.

In general - and as observed in the exploratory laboratory dataset - the *Europe's Lost Frontiers* quartz was responsive to SAR OSL: approximately 70% of measured aliquots passed SAR acceptance criteria. Mean sensitivities were in the range 3400 ± 260 and 3650 ± 520 counts Gy^{-1}, for the 150-250µm and 90-150µm grain size fractions, respectively. Recuperation remained low, 6.2 ± 5.3 and 4.2 ± 2.2 %. Recycling ratios were within error of unity, 1.02 ± 0.02 and 1.02 ± 0.03, as were pseudo-dose recovery ratios, 0.99 ± 0.02 and 1.00 ± 0.03. IRSL response was variable, with mean responses of 17.4 ± 20.0 and 18.4 ± 28.1%, but equivalent dose varied independently of IRSL response.

Unsurprisingly, equivalent dose distributions were variable, with depositional setting and bleaching potential, contributing to dispersion in De values. Discrete equivalent dose distributions were appraised for homogeneity, and, where stratigraphic associations are established, different combinations of merged datasets explored. Average values of over-dispersion were 30.9 ± 17.5 and 32.3 ± 20.3 % for the 150-250 and 90-150µm fractions respectively.

Dose rate determinations

Activity concentrations of potassium, uranium and thorium were estimated from high-resolution gamma spectrometry (HRGS) measurements, conducted at the Environmental Radioactivity Laboratory at the School of Biological and Environmental Sciences, University of Stirling, and inductively-coupled plasma mass spectrometry (ICPMS), at the StAiG laboratories at the School of Earth and Environmental Sciences, University of St Andrews and at Activation Laboratories, Canada. For a number of cores, semi-quantitative element concentrations of K, U and Th as obtained by X-ray Fluorescence core scanning where available down-core. Core scanning by X-ray Fluorescence was undertaken at Aberystwyth University.

These data were used to determine infinite matrix dose rates for alpha, beta and gamma radiation, using the conversion factors of Guérin *et al.* (2011), grain-size attenuation factors of Mejdahl (1979) and attenuated for moisture content. 'Fractional water' values, ranged between approximately 8 and 40% of dried weight (mean, 23 ± 7%; n= 129), and 'saturated' values, between 12 and 50% of dried weight (mean, 30 ± 11%).

The Doggerland samples had, in general, low activity with K, U and Th concentrations ranging between 0.2 and 3.1%, 0.2 and 8.4ppm and 0.6 and 15.40ppm, respectively (with mean values of 1.5 ± 0.6 % K, 1.7 ± 1.2ppm U and 5.6 ± 3.5ppm Th; n = 132). The ratio of Th:U ranged between 1.07 and 7.05, with a mean of 3.4 ± 0.9; approximately 80 % of the samples measured returned typical Th:U ratios, 3.2 ± 0.5 (n = 103). For the 29 samples with atypical Th:U ratios, further investigations have been instigated to explore disequilibrium in the uranium decay series and determine time-dependent dose rates. These samples have not been taken forward to dating and are excluded from further discussion.

Beta dose rates from HRGS were in the range 0.9 to 1.1mGy a^{-1}; and from ICPMS, 0.4 to 2.5mGy a^{-1}, with a mean estimate of 1.2 ± 0.5mGy a^{-1}. Wet gamma from HRGS were in 0.5 to 1.0mGy a^{-1}; and from ICPMS, 0.2 to 1.6mGy a^{-1}, with a mean estimate of 0.6 ± 0.3mGy a^{-1}.

The contributions from the cosmic dose were modelled after Sanderson and Kinnaird (2019), by combining latitude and altitude specific dose rates (0.17 ± 0.01mGy a^{-1}), with time-dependent corrections for water depth and overburden (for the period the terrestrial sediments accumulated). Consideration was given to the palaeo-environment(s) of deposition: a.) for sediments sampled from shallow-marine to offshore deposits, the depth of water above the deposit would have attenuated the cosmic dose contribution to a few percent of the total dose; b.) similarly, for the shoreline and nearshore deposits rapidly flooded in inundation (100s of years), the contribution as percent would be low; c.) it is only for the terrestrial deposits, that the cosmic dose contribution needed to be modelled.

Total environmental dose rates to the 90-150µm, HF-etched quartz were in the range 0.7 to 3.3mGy a^{-1}, with a mean estimate of 1.8 ± 0.7mGy a^{-1}.

Age determinations

Depositional ages were calculated for discrete depths in each core using standard micro-dosimetric models, with uncertainties that combined measurement and fitting errors from the SAR OSL analysis, dose rate evaluation uncertainties, and allowance for the calibration uncertainties of the sources and reference materials.

In each core, consideration was given to:

1. the luminescence stratigraphies generated at sampling, and the stratigraphic progressions and/or temporal breaks implied
2. the sensitivity and apparent dose distributions determined during preliminary laboratory analysis
3. the equivalent dose distributions obtained at discrete depths, which were appraised for homogeneity
4. the combined distributions from across lithostratigraphic units, which were appraised for homogeneity, when the luminescence profiles suggested stratigraphic coherence. Different permutations of the assimilation of equivalent doses to obtain the burial dose were also considered, including weighted combinations and statistical dose models (Guérin *et al*. 2017)
5. the variations in radionuclide concentrations down core, the gradients and/or breaks in dosimetry, and in estimating environmental dose rates to the positions of the dating samples
6. depositional ages, which were calculated for discrete units, and when considerations 1 to 5 suggested stratigraphic coherence, conventional statistical and/or Bayesian approaches used to assimilate depositional ages for stratigraphic units and/or events

To illustrate this, we return to the example of core ELF001A. The dating priorities identified in this core were: 1.) the top of unit 1A-7 (at 155cm depth), well-laminated fine-grained sandy silts deposited under estuarine mudflat conditions; 2.) the base of unit 1A-6, the 'tsunami' deposit (at 151cm); 3.) the base of unit 1A-4, well-laminated fine-grained sandy silts deposited under more open marine estuarine mudflat conditions (at 108cm).

Thirteen sub-samples from across these stratigraphic units were taken forward to dating: four of these were from the top of unit 1A-7 at depths in core of 155, 160, 170 and 190cm; a further four were taken through unit 1A-6 at depths of 136, 140, 146 and 150cm; two from unit 1A-5 at depths of 110 and 117cm; and four from unit 1A-4 at depths of 95, 100, 100 and 105cm.

Figure 12.6 presents the equivalent dose distributions as Abanico plots for units 1A-4, -5, -6 and -7. Given the evolving depositional environment from estuarine mudflat to high-energy marine, to estuarine mudflat, a range of responses were expected: but fortuitously, the equivalent dose distributions showed reasonable homogeneity, and good internal consistency. Values of overdispersion ranged between 10.3 and 37.3 %, with a mean of 20.5 ± 8.3 %. The samples with the most pronounced heterogeneity, were those located close to lithological boundaries and / or transitions in palaeo-environments (i.e. top of unit 1A-7, immediately beneath tsunami deposit = 37.3 %; base of unit 1A-5 = 33.7%). Table 12.1 lists the apparent dose estimates (90-150µm) determined for discrete depths down-core in ELF001A (these were calculated using a central dose model in the R package luminescence). The apparent dose estimates for the 90-150 and 150-250µm fractions are shown relative to each other in Figure 12.7.

The apparent dose values correlate well with the apparent dose-depth profile obtained for ELF001A (R^2 = 0.943).

Down-core variations in radionuclide concentrations for ELF001A are shown in Figure 12.8, together with the estimates of the environmental dose rate to the HF-etched, 90-150µm quartz fractions. Unsurprising given the contrasting lithologies and diverse environmental conditions, radionuclide concentrations vary with position in core: the highest concentrations observed in K, Th and U are from the estuarine mudflats, both at the base of unit 4 and the top of unit 7 (> 1.5 % K, >3.5 Th ppm, > 1.7 U ppm); concentrations drop off through unit 5 of the tsunami deposit (from 1.3 to 0.8 % K, 5.6 to 4.3ppm Th, 1.8 to 1.2 U ppm); and are lowest in unit 6 of the same deposit (min 0.8 % K, 2.5 Th ppm, 0.8 U ppm). K, U and Th concentrations are most variable in unit 6. Throughout, Th:U ratios remain typical at 3.2 ± 0.7.

Total environmental dose rates vary down core: unit 4, comprising the estuarine mudflats with open marine affinities, is characterised by dose rates in the range 1.5 to 2.7mGy a^{-1}; unit 5 of the tsunami deposit by dose rates in the range 1.0 to 1.4mGy a^{-1}; unit 6 of the same deposit, 1.0 to 1.5mGy a^{-1}; and unit 7, 1.8 to 2.2mGy a^{-1}.

Individual sediment ages range from 9.2 ±1.4 ka at the top of unit 1A-7, to between 8.3 ±1.1 ka to 7.9 ±0.5 ka within units 1A-5 and -6, to 7.2 ±0.5 ka immediately above (base of unit 1A-4); with statistical combinations suggesting depositional ages for units 1A-5 and -6 between 8.0 to 8.2 ka (Table 12.2). The combined age of 8.14 ± 0.29 ka for units 1A-5/-6 is consistent with the hypothesis suggested above that these are tsunami deposits related to the Storegga Slide. Final inundation of Doggerland in the position of this core did not occur to 7.16 ± 0.50 ka, and together with the multi-proxy evidence from ELF001A, this shows that the landscape temporarily recovered after the Storegga tsunami.

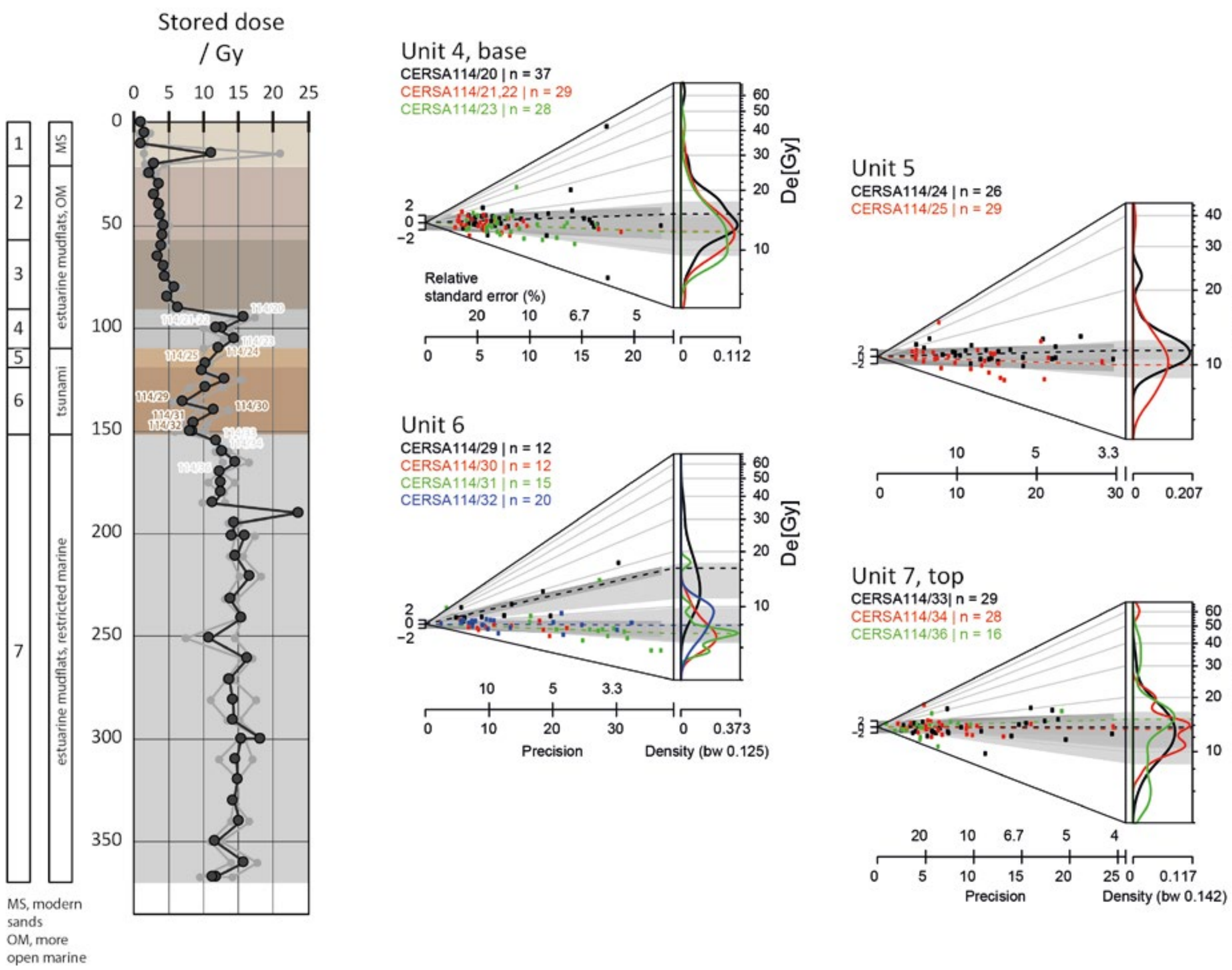


Figure 12.6 De distributions for ELF001A, 90-150µm, shown relative to the stratigraphy of the core. Units for ELF001A as discussed in the text.

CERSA ID	Depth /cm	Unit		Apparent dose / Gy
114/20	95	Unit 4, estuarine mudflats		8.36 ± 0.53
114/21	100			15.60 ± 1.07
114/22	100			12.74 ± 0.40
114/23	105			12.55 ± 0.72
114/24	110	5	Tsunami	11.45 ± 0.32
114/25	117			10.66 ± 0.89
114/29	136	Unit 6		13.34 ± 0.99
114/30	140			7.19 ± 0.31
114/31	146			7.48 ± 0.66
114/32	150			8.30 ± 0.35
114/33	155	7, EM-RM		15.14 ± 1.81

Table 12.1 Stored dose estimates for the 90-150µm quartz fractions from ELF001A (lab code, CERSA114).

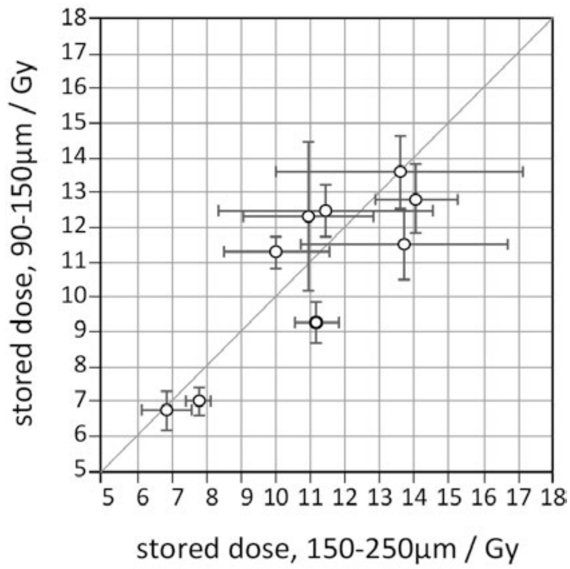


Figure 12.7 Stored dose estimates for the 90-150µm and 150-250µm quartz fractions.

Discussion

As demonstrated through core ELF001A, work progressed successively through a three-staged approach, from initial screening of the core stratigraphies at sampling (stage 1), through calibrated characterisation of these stratigraphies in the laboratory (stage 2), towards final quartz SAR OSL dating (stage 3). Through OSL, a chronology and sedimentation history were established for early to mid-Holocene deposits in this core, providing a temporal framework to pin palaeo-environmental interpretations and reconstructions.

This demonstrates the potential of OSL for dating the ELF core sediments. It also illustrates the added value in contextualising the luminescence stratigraphy across the entirety of the core, and how stratigraphic breaks and progressions aid in interpreting depositional sequences and histories. At the broad scale, the calibrated datasets show the cores, and/or parts of cores, where apparent doses are low, suggesting that for these units/intervals, the sediment is likely to return later Holocene dates. Larger apparent dose estimates, which in a low dose rate environment would correspond with substantially older dates, potentially record late Pleistocene ages. At a higher resolution, intricate fluctuations in apparent doses and sensitivities with depth: 1.) inform on sedimentation rates, 2.) suggest the chronology to the unconformities and hiatuses identified in the cores, and 3.) provide temporal (and spatial) frameworks to aid sedimentological and palaeoenvironmental interpretations. Through, a critique of this data, we are able to select the units and/or parts of the cores which hold most promise for dating, mitigating the challenges associated with partial bleaching, bioturbation, and other depositional and environmental conditions (challenges 1 to 4 above).

In further justification of this approach, the apparent doses obtained through preliminary laboratory characterisation broadly correlate with the apparent dose estimates obtained in full quartz SAR OSL dating (Figure 12.9a). There is a degree of variability down-core, and also between cores, but this is unsurprising given the range of lithologies sampled.

The final phase of OSL investigations on the ELF cores from Doggerland is still ongoing. At the time of print, 103 samples have been subjected to full quantitative quartz SAR OSL, providing temporal constraints on final inundation of Doggerland, and the early Holocene and late Pleistocene palaeo- environments and geographies (Figure 12.9b). This includes new constraints on inundation: at the position of core ELF001A, inundation was complete by 7.16 ± 0.50 ka; at ELF003, inundation is dated to between 7.93 ± 1.11 to 7.21 ± 0.98 ka, most probably at 7.71 ± 0.51 ka; and at ELF022, between 8.33 ± 0.91 and 7.37 ± 0.73 ka, with weighted combinations suggesting inundation by 7.84 ± 0.42 ka. For ELF045, a *terminus post quem* is provided by the end of tidal mudflat accumulation at 8.19 ± 0.96 ka.

The sediment chronologies for Doggerland extend back to approximately 14,000 to 15,000 years (Figure 12.9b), providing the temporal framework to interpret the late post-glacial landscape. From the onset of the freshwater sequence in core ELF034 to 12.67 ± 0.93 ka, to constraining the open estuary environment in core ELF045 to at least 13.39 ± 0.85 ka (bottom of unit not encountered), and shoreline deposits at the base of

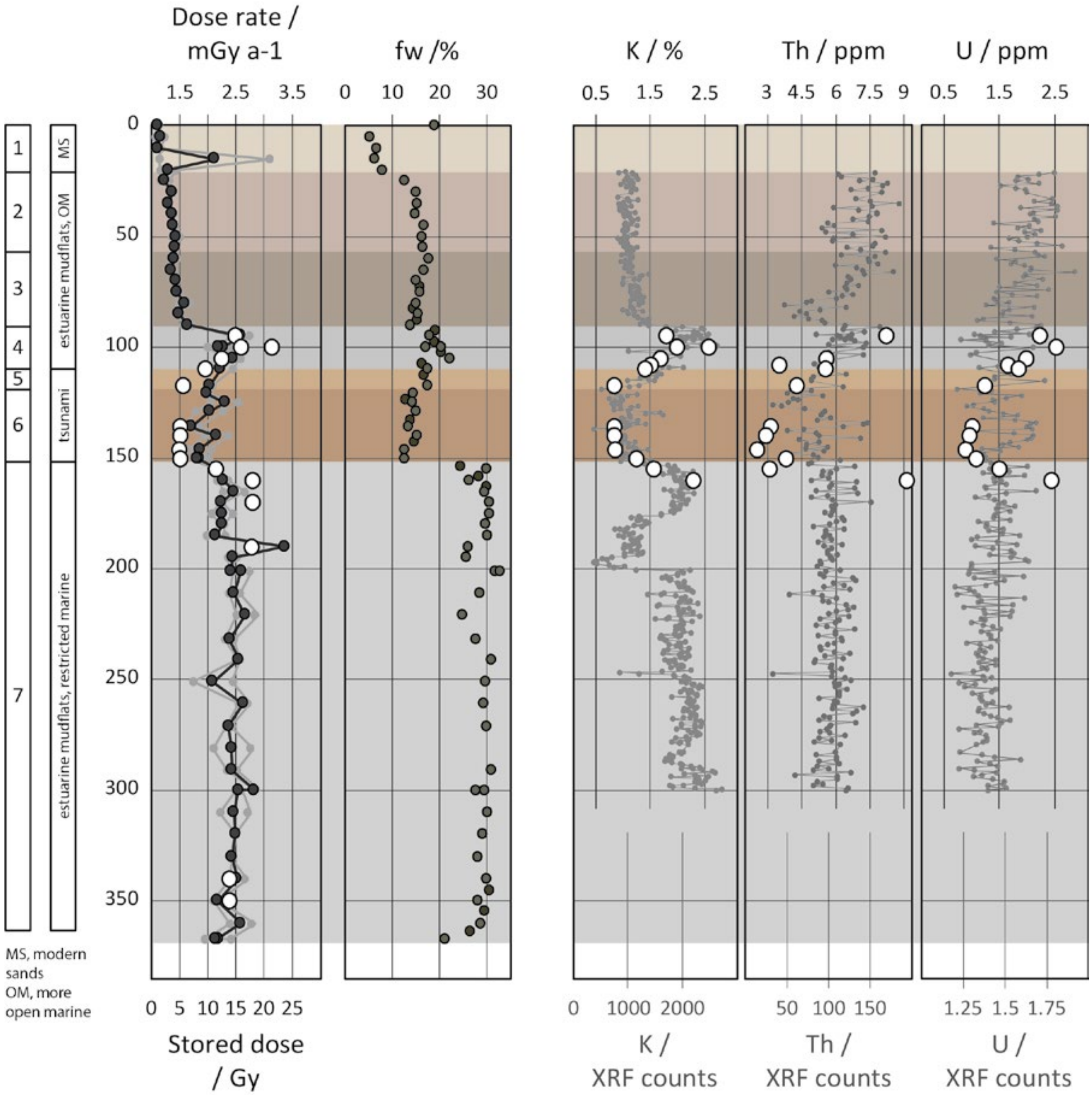


Figure 12.8 Dosimetry of core ELF001A: semi-quantitative and absolute down-core variations in radionuclide concentrations.

Unit no.	Description / context	from samples	Age / ka
1A-4	laminated fine sands and silts; estuarine mudflats – open marine	114/21, 114/22	6.03 ±0.22
		114/23	7.16 ±0.50
1A-5	grey silty fine sands, with shells; tsunami deposit	114/24, 114/25	8.22 ±0.43
1A-6	grey medium sands, v common shell fragments, small stones; tsunami deposit	114/29, 114/30, 114/31, 114/32	8.04 ±0.43
1A-5 and 6		114/24, 114/25, 114/29, 114/30, 114/31, 114/32	8.14 ±0.29

Table 12.2 Weighted combinations of OSL depositional ages for ELF001A.

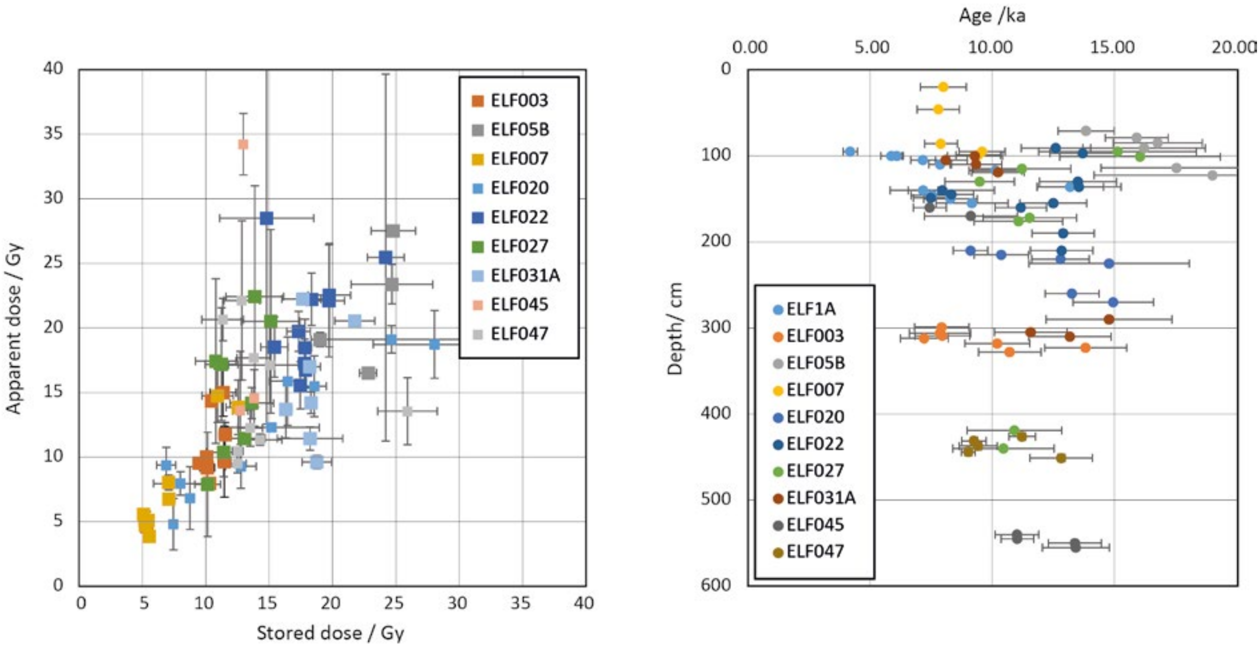


Figure 12.9 (left) Apparent vs stored dose estimates for discrete depths in core across a subset of sampled cores, encompassing terrestrial, littoral and marine deposits; (right) Quartz SAR OSL depositional ages shown relative to depth in core for the same subset of cores.

ELF003 to between 13.82 ± 1.68 ka to 10.20 ± 1.33 ka, with the weighted combination at 11.21 ± 1.04 ka.

OSL is also contributing to reconstructions for the period 14-7 ka, which is the period the sea is encroaching Doggerland, and palaeo-environments and geographies are rapidly evolving. Dating the development of strandlines at the Silver Pit, as preserved in core ELF027 between approximately 0.6 and 6.4m depth to 10.63 ± 0.74 ka. Providing temporal constraints for transgressions and regressions, such as 'dating' the transition from a littoral to more open marine, tidal mudflat setting at 4.3-4.4m depth in core ELF047 to after 9.11 +- 0.23 ka, or 'bracketing' the open estuarine environment in ELF045 to between 13.39 ± 0.85 ka to at least 10.97 ± 0.53 ka. OSL is also providing constraints on the terrestrial environments identified in core i.e. core ELF020, records the development of a wetland on a late-glacial landscape. The base of the wetland sequence is dated to 13.02 ± 1.26 ka, near contemporaneous, with disturbance to the underlying till, 37cm beneath palaeo-surface on which wetlands developed at 13.26 ± 1.10 ka.

Conclusions

Luminescence investigations of the *Europe's Lost Frontiers* sedimentary cores from Dogger Bank are contributing to a high-resolution chronological framework for the terrestrial, near-shore and off-shore environments of Doggerland.

Chapter 13

Building chronologies for Europe's Lost Frontiers: Radiocarbon dating and age-depth modelling

Derek Hamilton and Tim Kinnaird

Introduction

Key to reconstructing the palaeo-geographies and environments of Doggerland is a detailed chronological framework. This has been achieved here, by the generation of high-resolution chronologies for 22 of the recovered cores from the Outer Dowsing Deep region of the southern North Sea, constructed from radiocarbon dates of organic layers (*n* = 165) and shells (*n* = 13) and optically stimulated luminescence dates from sediment (*n* = 139). The chronologies span the period from the Late Glacial (14,000–15,000 BP) to final inundation between 8200 and 7200 BP, the period in which the sea is encroaching Doggerland, and palaeo-geographies and environments were rapidly evolving (Walker *et al.*, this volume: chapter 5; Fitch this volume: chapter 4).

Constructing these chronologies was not straightforward. Taphonomic and technical challenges impact the development and reliability of radiocarbon-based chronologies for the organic-rich sections of the cores. This chapter will focus on the complex interplay between the taphonomic and technical challenges, the thought-process that is involved in understanding the potential and real effects, and detail the protocols put in place to mitigate for the challenges above through the presentation of some age-depth models for specific priority cores.

The challenges associated with OSL dating, with reference to the submerged landscape of Doggerland, and potential solutions to these, are discussed in a companion chapter in this monograph (see Kinnaird *et al.* this volume). Here, the potential for partial bleaching, post-depositional mixing and stable dose rate conditions, are discussed in relation to the age-depth models.

Radiocarbon dating organic layers in the ELF cores

Accelerator mass spectrometry (AMS) has drastically reduced the sample sizes needed for radiocarbon dating and this has enabled archaeologists and palaeo-environmentalists to use a wider range of materials than was previously possible. When considering typical palaeo-environmental sequences in bogs and fens, the most common sample type remains to be the actual peat, usually in a well-humified form, but it is also now possible to radiocarbon date terrestrial seeds, identifiable herbaceous plant material, and very small fragments of waterlogged wood. These sample types are all affected by physical processes (including reburial or redeposition) and/or chemical alteration that is dependent on the context from which they were recovered and the mechanism by which they were transported into that context (Lowe and Walker 2000). As such, it is important to consider the different potential problems that might occur with the dating of various fractions of peat (humic acid and humin being the two regularly dated fractions) and the different types of plant macrofossils. Because different sample types have their own specific potential problems, the radiocarbon programme employed should always have consistency between results as its foremost aim.

Considering the different sample types

As stated above, there are three primary elements of a peat core that generally are processed for radiocarbon dating. The first is the actual peat, either the leaves and stems or the well-humified remains (humin fraction); the second is the humic acid that is the by-product of the decomposition from a living peat to a humified peat soil; and the third is associated plant macrofossils from other plants growing in/on the peat.

Humic Acid and humin fractions

The dating of peat and the reliability of the resultant dates from various fractions (e.g. humin, humic acids, etc.) has been a topic of contention in the literature (see Blaauw *et al.* 2004; Kilian *et al.* 1995, 2000; Shore *et al.* 1995). While the concerns predate the regular use of AMS dating, the issues were seen as less problematic previously due in large part to the larger sample sizes required for radiometric dating (Mook and Waterbolk 1985; Waterbolk 1971).

The two most commonly dated fractions from peat samples are the humin (i.e. alkali and acid insoluble organic detritus) and the humic acids (i.e. alkali soluble and acid insoluble matter). As the humin fraction is composed of the actual organic detritus, the resultant date from measuring this fraction is subject to many of the same processes that affect the dating of macrofossils in the same type of environment. First, organic material that forms all or part of the humin fraction could be in-washed, which would result in a date that potentially is too old relative to its depth. Second, contamination of this material by geological age carbon (e.g. coal, hard-water error) would have the same effect, though modern pre-treatment methods make this a less common problem. The humin fraction can also be too young, if for example the environment is prone to wet-dry episodes or bioturbation, allowing intrusive material to work its way down the sediment column. Since the humin fraction is not necessarily homogenous, it is often avoided for dating on its own by AMS as the smallest contamination would greatly affect the resultant measurement.

The humin fraction can also sometimes be divided into the coarse (>250μm) and fine (<250μm) fraction. According to the research of Dresser (1971), only the fine humin fraction from blanket and reedswamp peats consistently produces reliable dating. However, Bartley and Chambers (1992) argue that the entire humin fraction should be used. It is important to stress once more that, because of the various scientific opinions regarding the fractions of peat that can be reliably dated and site-specific factors, consistency between different types of measurements is sought within a robust radiocarbon dating programme.

The second peat fraction that is often dated are referred to as the humic acids, which are the *in-situ* products of plant decay. Although they are produced *in situ* and imply stability of the ground surface, it has been shown that they can be mobile in groundwater, both vertically and horizontally (Shore *et al.* 1995). Their mobility is often considered to be limited as they are insoluble in highly acidic environments (Baglieri *et al.* 2014). However, in weakly acidic and slightly alkali peatlands (e.g. minerotrophic fens) humic acids should be expected to be more mobile with fluctuations in groundwater. Therefore, humic acids cannot be relied upon to always correctly date the level from which they were collected either, but because they are homogenous, they are often preferred over the humin fraction for dating by AMS.

In some cases, when there is not enough material for dating of separate fractions, the humic acid and humin fractions can be bulked together to provide an average date for all the organic material in that level, but there is little reason to do this given the small samples needed for AMS dating. Therefore, it is preferable to have the dates on the two fractions as this provides the data necessary for using replication as a measure of consistency. When the dates on two fractions are obtained, if they are statistically consistent, a weighted average can be taken before calibration as described in Ward and Wilson (1978). In most cases this creates a date that is more reliable. However, if the two results are not statistically consistent then the data need to be re-evaluated, in an attempt to determine which sample more reliably relates to the date of peat formation at the level under consideration, and methods for this include further dating and age-depth modelling discussed below.

Plant macrofossils

The dating of plant macrofossils in a peat core is primarily concerned with sampling the non-humified remains in the core – the identifiable leaves and stems of the moss or identifiable remains of other plants that grew on the peat surface. The taphonomic relationship between a sample and its context is the most hazardous link in dating, since the mechanisms by which a sample came to be in its context are a matter of interpretative decision rather than certain knowledge. Being identifiable and short-lived, the actual non-decomposed material is advantageous for dating. However, simply being able to identify a sample does not ensure it is a 'good' sample for dating and preference should be given to sample materials that can be argued to represent the plants that were part of the active peatland surface. By doing this, extra care is being taken to minimize the dating of either reworked or intrusive materials.

Consistency between dates

When developing a chronology for a palaeo-environmental sequence, as stated above, consistency between the dates is a key consideration since this lends support to the interpretation of a layer being stable over time and not containing reworked or intrusive material. When considering the two dated peat fractions (humic acid and humin fractions), a *t*-test is performed on the radiocarbon measurements to determine if they could represent the same radiocarbon age. It is also possible, where the peat is not completely humified, to date a third element from the same level – a plant macrofossil such as leaves of sphagnum or twiggy pieces of heather. This result can then be compared to the two fractions. Ideally, where the three dates are possible, the results will be consistent, giving greater confidence in the results on just one or two elements of the core in other levels.

A second method used to evaluate the consistency of the dates within a core, is evaluation of the radiocarbon results and their relative stratigraphic order. For a peat deposit that has not suffered the in-wash of reworked material, been prone to wet-dry episodes, or been manipulated through other natural or anthropogenic

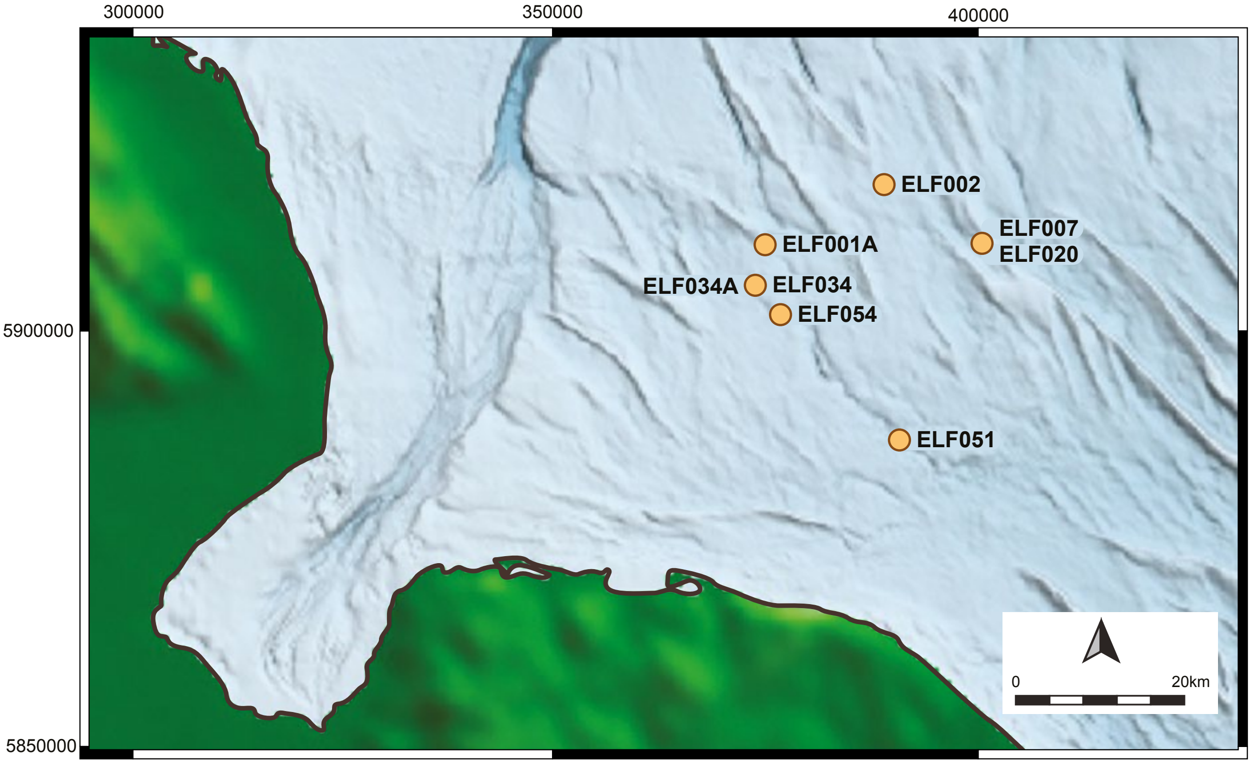


Figure 13.1 Locations of cores mentioned in this chapter.

activities, the radiocarbon results should follow the general order of oldest at the bottom and youngest at the top. Deeper cores with only a few dates will generally follow this trend, but as the sampling becomes more concentrated across a core or within a specific region, there is a higher likelihood that age reversals will be identified.

Whenever there is inconsistency between a set of measurements from a single level or from across a set of levels in a core, it is necessary to determine the physical or chemical processes that may have led to one or more results to be 'incorrect' – that is to be inconsistent with the true age for the depth from which it came. The process is a reflexive one that is not always straightforward and can often lead to either a series of age-depth models (e.g. minimum age vs maximum age) or even the exclusion of a large number of results. No matter the final age-depth model that is developed for a sequence, what is most important at this stage is full transparency in the thought process that led to accepting and rejecting each individual result.

Constructing age-depth models for *Europe's Lost Frontiers*

In constructing the age-depth models for the *Europe's Lost Frontiers* project all of the potential issues and concerns noted above were taken into consideration. As the peat being dated was once the active land surface, the usual natural and anthropogenic processes applied to peat cores from such things as blanket bogs or palaeochannels were considered when evaluating the consistency of the dates. Additionally, processes associated with the inundation and submergence of the peat, as well as its subsequent burial under a mass of minerogenic sediment and water, were considered. Finally, the age-depth models produced for the project contain both radiocarbon-dated organic layers and OSL-dated sediments, and so specialists from both dating techniques worked together in evaluating the results as the two techniques had very different potential problems.

Methodological details

Samples of peat (humic acid and humin fractions), waterlogged wood, identifiable plant macrofossils, and marine shell were submitted to Beta Analytic and the Scottish Universities Environmental Research Centre (SUERC). Samples indicated by the Beta- lab code were submitted to Beta Analytic where they were pretreated following methods found on their website (https://www.radiocarbon.com/pretreatment-carbon-dating.htm) and dated by accelerator mass spectrometry (AMS). Beta Analytic round all uncalibrated radiocarbon ages to the nearest ten years, according to the Trondheim convention (Stuiver and Polach 1977; Stuiver and Kra 1986) and assign a conservative minimum error of ±30 ^{14}C years. Samples indicated by the SUERC- lab code

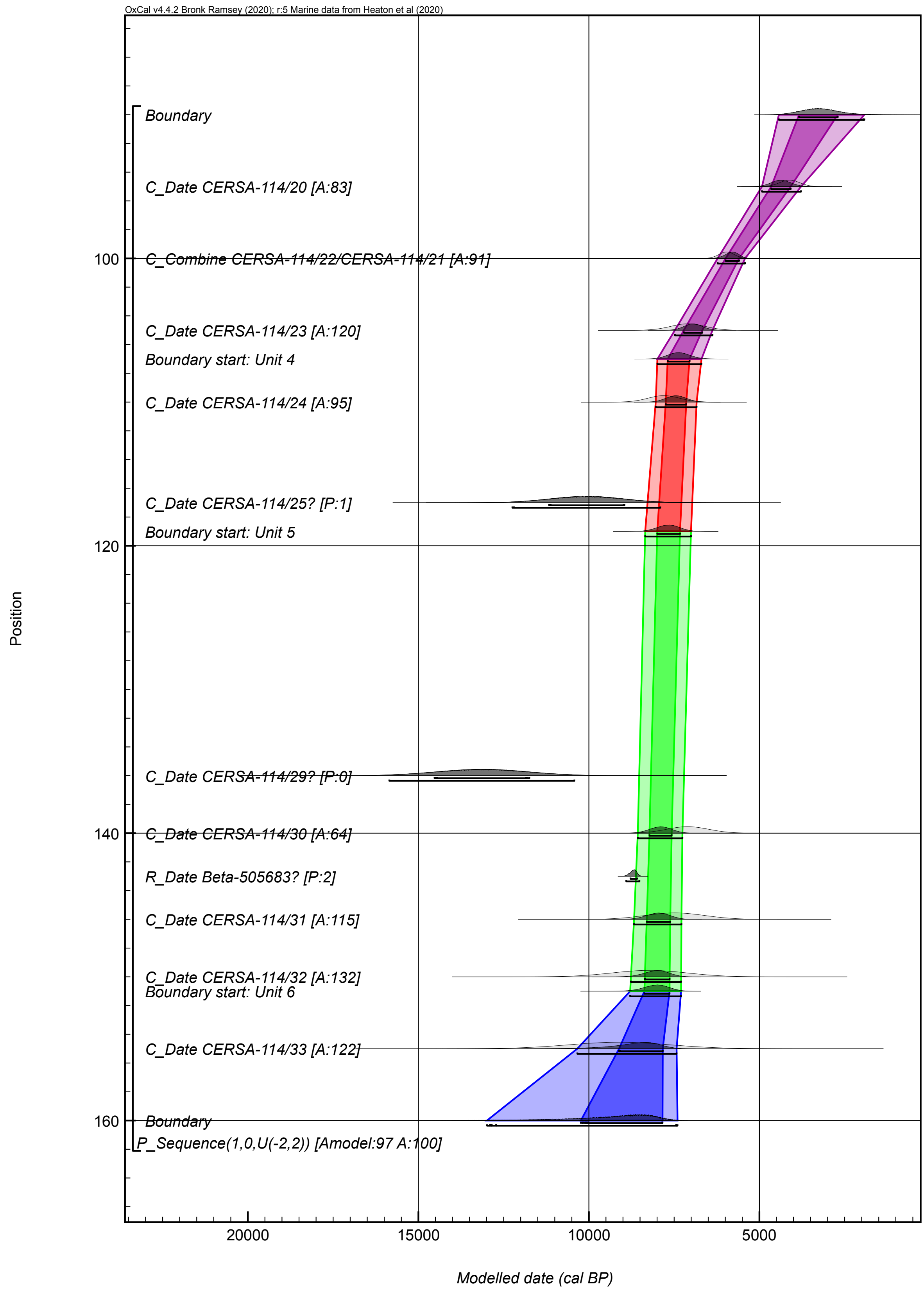


Figure 13.2 Age-depth model for ELF001A. Each distribution represents the relative probability that an event occurred at some particular time. For each OSL measurement two distributions have been plotted, one in outline, which is the original result, and a solid one, which is based on the chronological model use. The other distributions correspond to aspects if the model. For example, 'start: Unit 5' is the estimated date that this litho-stratigraphic change occurred, based on the dating results. The large square 'brackets' along with the OxCal keywords define the overall model exactly.

were pretreated and measured by accelerator mass spectrometry (AMS), following the methods of Dunbar *et al.* (2016). The SUERC lab maintains rigorous internal quality assurance procedures, and participation in international inter-comparisons (Scott *et al.* 2010) indicate no laboratory offsets; thus, validating the measurement precision quoted for the radiocarbon ages.

Radiocarbon ages were calibrated in OxCal v4.3 (Bronk Ramsey 1995; 1998; 2001; 2009) using the internationally agreed terrestrial calibration curve (IntCal20, Reimer *et al.* 2020) or marine calibration curve (Marine20, Heaton *et al.* 2020), where appropriate for the carbon reservoir associated to each sample type. For marine shell samples, a local marine reservoir correction (ΔR) of -140 ±91 years, was calculated using the ^{14}Chrono Centre database (http://calib.org/marine/) and the ten nearest data points to 55.1369' N, 3.4086' W.

Results

Age-depth models were developed in OxCal following the methods presented in Bronk Ramsey (2008). The following cores contained either marine shell or peat sequences that were sampled, radiocarbon dated, and age-depth modelled in OxCal: ELF001A, ELF002, ELF007, ELF020, ELF034 and 034A, ELF051, and ELF054 (Figure 13.1). The age-depth modelling process for ELF001A, ELF007, and ELF034 are discussed in some detail here as they provide highlights of the challenges faced with many of the cores.

ELF001A

The dated sequence for core ELF001A covers the depths between 95 and 155cm. This 60cm of sediment was dated with 11 OSL samples taken from ten depths and a single marine shell. The figure (Figure 13.1) provides an 'easy-to-read' view of an age-depth model and highlights one of the more common complications when dating marine sediments and shell, notably incomplete bleaching of the sediments for luminescence dating and the increased likelihood for reworked shell to be incorporated into the deposits. CERSA-114/32 chronologically through to CERSA-114/24 were taken from Units 5 and 6, which have been shown to represent material chronological associated with the Storegga slide (see Kinnaird *et al.* this volume for more detail on the OSL dating from ELF001A). It is perhaps not unsurprising that the age-depth model might indicate that some of the OSL dates (CERSA-114/25 and -114/29) are earlier than should be expected, given the other stratigraphic constraints in the model. These dates are most likely affected by incomplete bleaching of the sediments. Furthermore, the radiocarbon-dated marine shell (Beta-505683) appears to be slightly earlier than expected, when compared to the modelled luminescence dates, which also suggests it is reworked from slightly earlier deposits.

ELF007

The dating from ELF007 combined both radiocarbon dating on the humic acid and humin fractions of peat layers, but also luminescence dates from overlying sediment deposits. The radiocarbon dated peat was at a depth of approximately 194–215cm in the core, while the OSL dates were made on sediments in the range of 20–99cm. Figure 13.3 shows what can be considered a 'well-behaved' age-depth model, as the model shows a steady development of peat and accumulation of sediment over a period of *740–2280 years* (*95% probability*; Difference between *ELF007-20* and *14C - 215*cm). This equates to an average of 0.09–0.26cm/yr for the entire dated length of the core. Additionally, the only age reversal occurs at 194cm in the core, with 'R_Combine 14C - 194cm' being older than expected given its depth. The two dates on the humic acid (SUERC-89344; 8352 ±29 BP) and the humin fraction (SUERC-89348; 8491 ±29 BP) are not statistically consistent (T'=11.5; df=1; T_{crit}(5%)=3.8; Ward and Wilson [1978]) and have been excluded from the modelling.

ELF034

The final chronological model demonstrates some of the more challenging aspects of producing age-depth models for the *Europe's Lost Frontiers* core sequences. The full model is shown in Figure 13.4 and like ELF007 contains both radiocarbon-dated peat and OSL-dated sediments. However, unlike ELF007 which had a clear separation between the radiocarbon and OSL-dated materials, ELF034 has OSL-dated sediments on both sides of the peat and even interleaved with the peat near the base of the core. The full dated portion of the sequence covers the depths between 15 and 235cm in the core.

Firstly, the bottom five pairs of radiocarbon dates – at depths 180, 183, 193, 202, and 209cm – all fail their tests for statistical consistency. In each case, the humin fraction is considerably older than the humic acid, and initially it was felt that excluding the humin fractions would be the better option as residual organic material is thought to be more likely than mobile humic acids. However, when that was done, there was an age-reversal in the humic acid dates (Figure 13.5) at 185, and in fact the reversal was present at this depth in the humin fractions as well. Since there were OSL dates interleaved with the radiocarbon dates, two models were then constructed to investigate the maximum age, represented by the radiocarbon-dated humin, and the minimum, represented by the radiocarbon-dated humic acids. However, neither set of the results was in agreement with the OSL dates, which were all

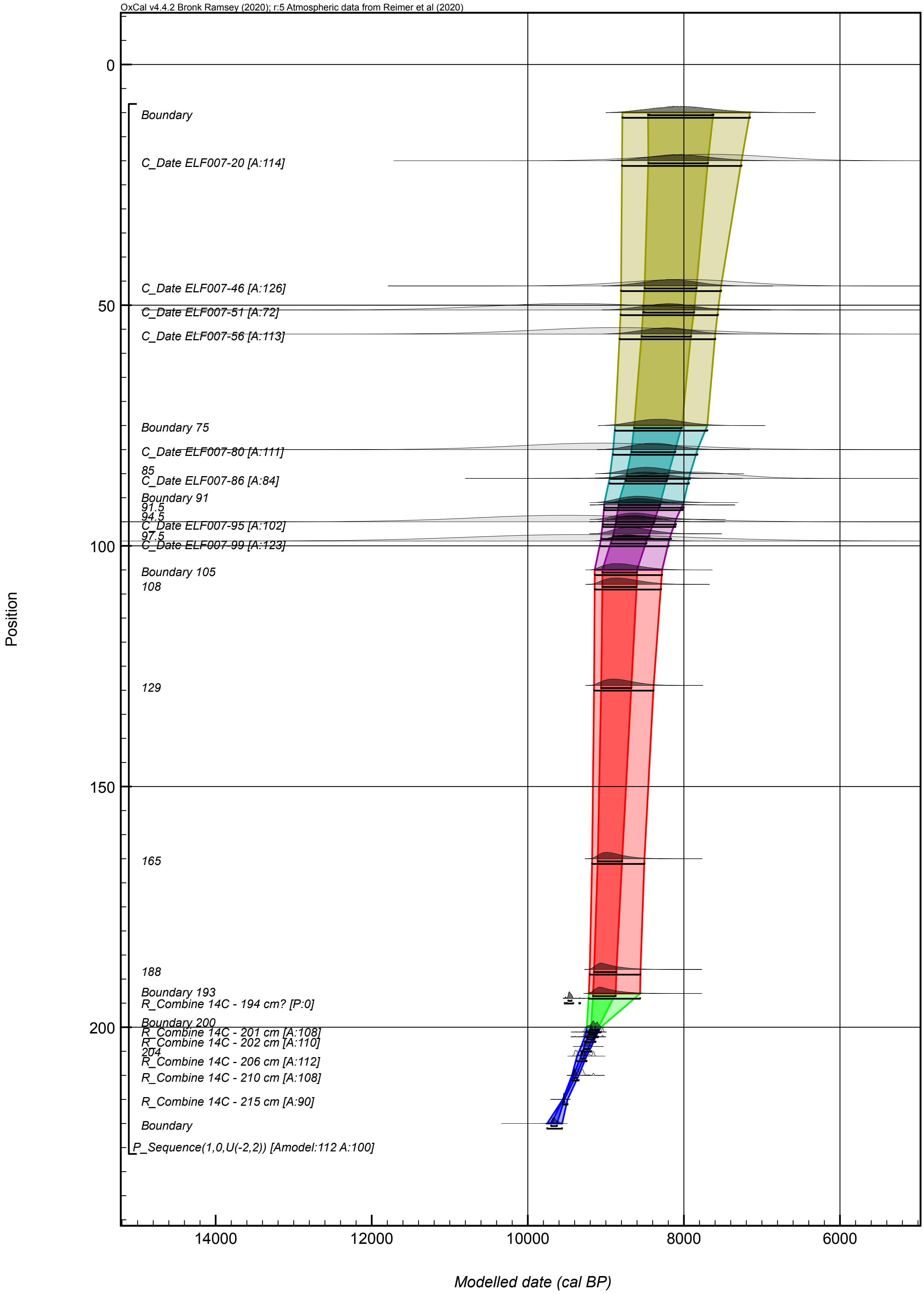


Figure 13.3 Age-depth model for ELF007. The model is described in Figure 13.2, with the exception that the outline of the radiocarbon dates is based on the simple calibration of those measurements, whereas the solid ones are the result of the modelling.

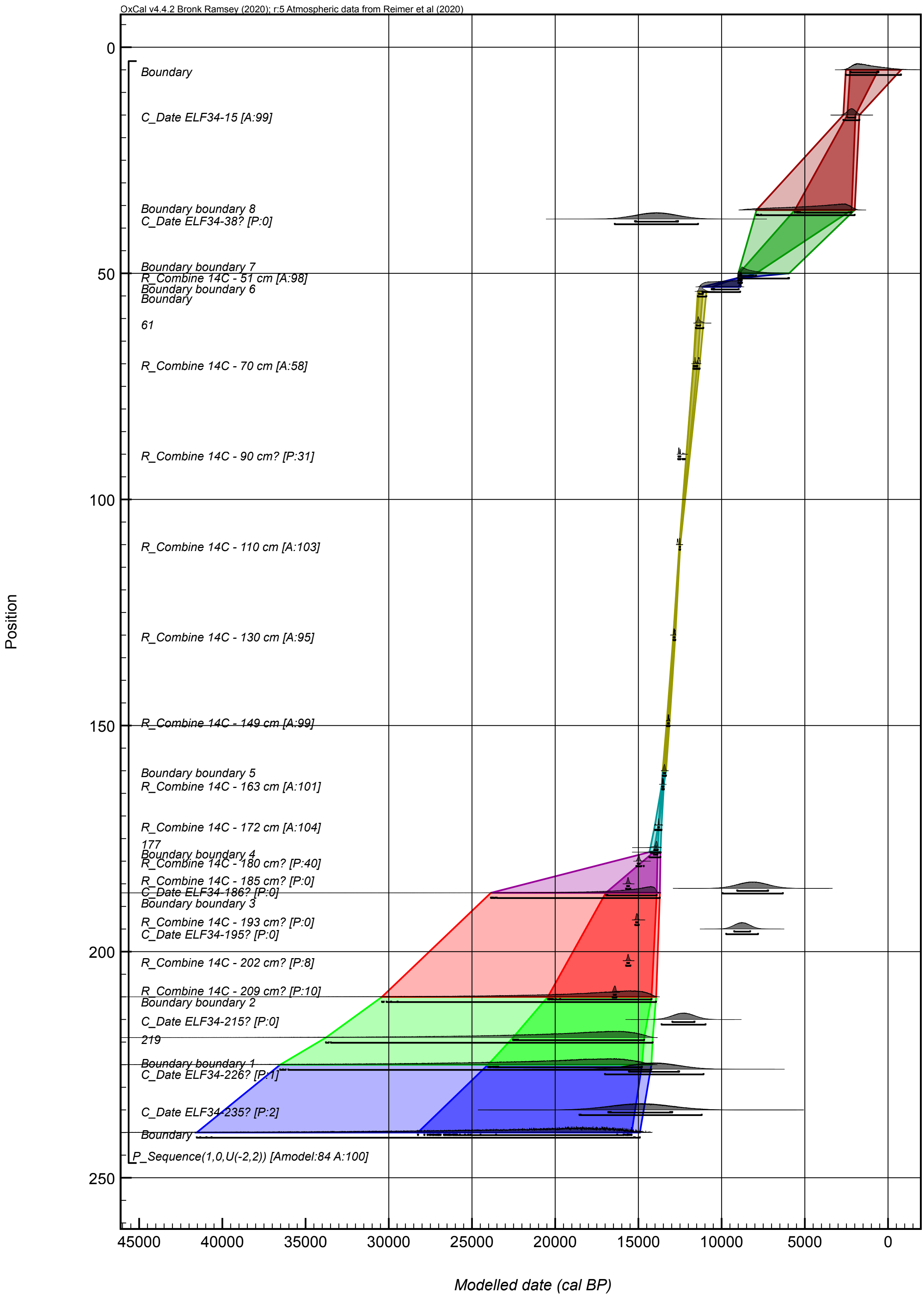


Figure 13.4 Age-depth model for ELF034. The model is as described in Figures 13.2 and 13.3.

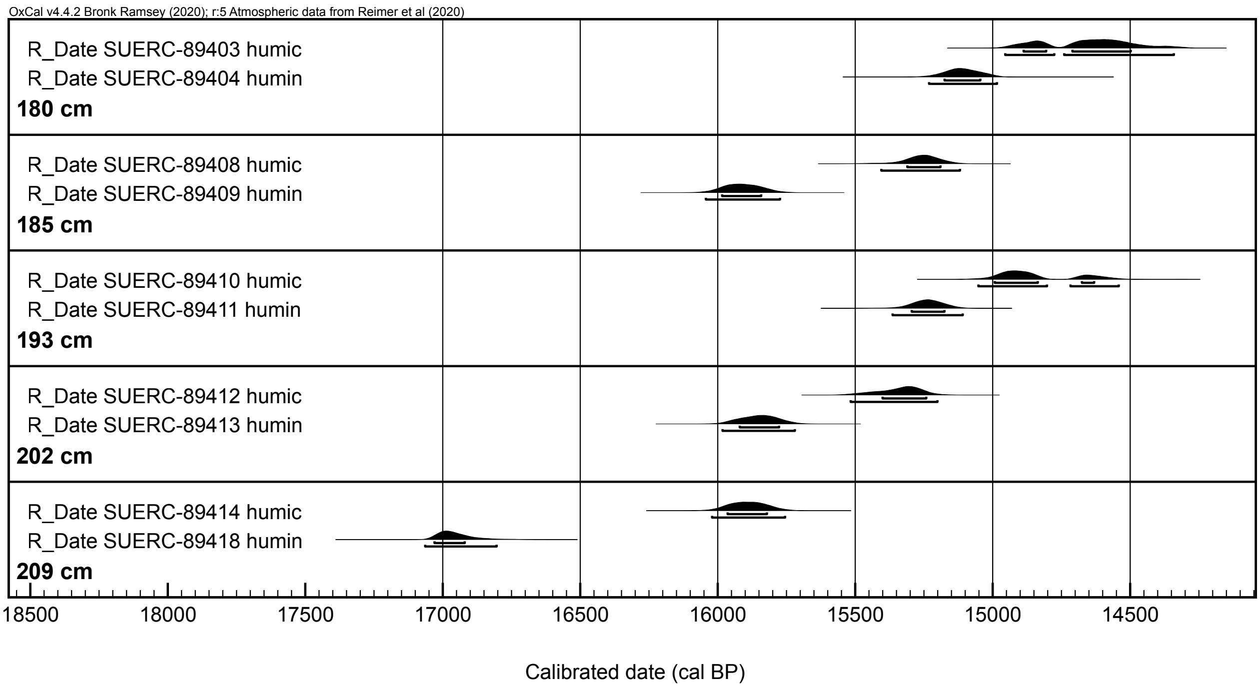


Figure 13.5 Calibrated humin fraction and humic acid pairs for depths 180, 185, 193, 202, and 209cm in core ELF034.

younger than expected. This technical reasons for this discrepancy are discussed in more detail in Kinnaird *et al* (this volume). It was decided that the modelling would take a conservative approach and the dates below 172cm were all excluded from the modelling. The result is that the age-depth model extrapolates the model from above 172cm and increases the error moving back in time. The relationship between the OSL dates and both the humic acid and humin fraction that were radiocarbon dated can be seen in Figure 13.6, which shows these probabilities in relation to the 95% and 68% probability model ranges in the lower portion of the model. It is reassuring that the radiocarbon dates from 193, 202, and 209cm depth appear to be consistent with the age-depth model trajectory, with further work between specialists likely to lead to better understanding of the taphonomic processes at work in this section of core, which will assist in better assessing the quality of the humic acid and humin dates, and thus help to refine the dating of this core.

Discussion

The aim of this chapter was to provide an overview of the radiocarbon dating programme that was implemented as part of the *Europe's Lost Frontier* project and to present some of the challenges involved not just in the radiocarbon dating but in bringing together ^{14}C dates with luminescence dates in combined age-depth models. The physical and taphonomic processes that affect the overall quality of a final age-depth model are often not fully presented in published research, and so it was felt this chapter was well-situated to use the challenges of this specific project to give a flavour of not just the hurdles but how they might be mitigated or further explored.

What was not covered was how the resultant age-depth models are used to provide a set of chronological frameworks for interpreting the proxy data of the specialists as this detail will be presented in a later volume in the *Europe's Lost Frontiers* series. In Figures 13: 2-4, there are labels along the y-axis that are either the word 'Boundary' followed by a number (representing the depth at which there was an identified litho-stratigraphic change) or numbers on their own (representing the depth of a probability). The associated probability in the figures is a product of the modelling process and not represented by a specific scientific date. The 'Boundaries' provide break-points for changes in the rate of deposition (sediment) or accumulation (peat), while the simple depth that is labelled is a 'Date' query in OxCal and returns a probability density estimate for the date of that layer. The 'Date' queries are inserted into the model at the request of the other specialists. Unlike the 'Boundaries', which are factored into the mathematical modelling, the 'Date' queries do not have a direct effect on the final model result. It is with the probabilities from these 'Boundary' and 'Date' parameters that the full narrative of *Europe's Lost Frontier* will be born.

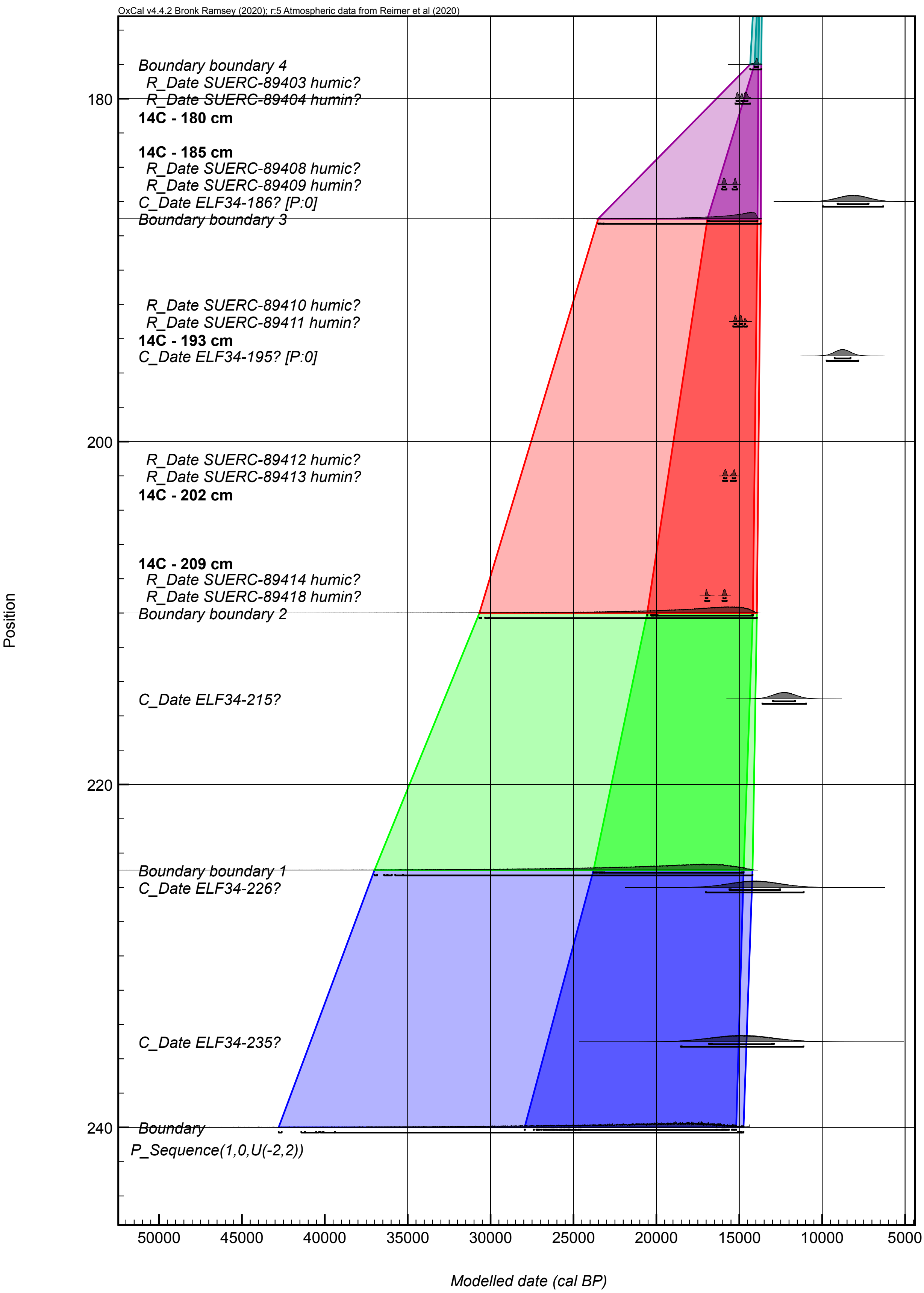


Figure 13.6 Detail of the bottom of the age-depth model for ELF034. In this detail the humin fraction and humic acid dates at each level have been plotted side-by-side, rather than combined as in Fig 13.4, to show the relationship of each result to the conservative model results for the bottom of the core.

Chapter 14

Simulating a drowned landscape: A four-dimensional approach to solving problems of behaviour and scale

Phil Murgatroyd, Eugene Ch'ng, Tabitha Kabora and Micheál Butler

Introduction to simulation within Europe's Lost Frontiers

Attempts to understand the landscape and environment of the area known as Doggerland face a number of significant challenges. Mapping based on seismic geophysics is extensive but coverage is not complete, can be of variable quality and resolution, and only provides relative dating evidence. Data gained from cores taken from the seabed can provide absolute dating, but this has its own constraints. Extrapolating the core data out to provide answers to questions regarding the whole landscape faces a variety of problems, principally those regarding taphonomy. The ways in which the complex processes operating within the Doggerland environment interact with each other, and then are subsequently expressed in the seismic and core data, are poorly understood. This lack of understanding becomes particularly critical when dealing with evidence of human interactions with their environs. In the absence of significant finds of worked artefacts, which are unlikely given the scale of the area and probable density of population, we would have to unpick the data, revealed by techniques such as sedimentary DNA analysis, soil geochemistry or palynology, for such clues. Yet human behaviours may be transitory, and may not be detected via conventional archaeological techniques, which often use coarse spatial and temporal resolutions. Furthermore, evidence of human activity may be contained within a combination of different types of evidence and may not be possible to find by examining a single type of data in isolation. A method is required to bridge the gap between the natural and anthropogenic processes which operated in Doggerland and the data which we have collected. This must be achieved in a manner which would allow us to identify instances in which these processes leave evidence in multiple data sources. This would, in turn, provide a critically important step forward in our ability to understand a complex, changing environment, about which we have relatively sparse data.

In order to address these challenges, the project has sought to develop models of the landscape and human activity which can be used to simulate the processes of relative sea-level rise, along with patterns of landscape response and human activity over the early Holocene period. There are two issues associated with such a goal. Firstly, finding a way of combining a few data rich points with an extensive terrain model, and then ensuring that this is represented in four dimensions. The temporal resolution should be able to cover the short timescales of anthropogenic processes along with the longer time scales associated with environmental change as reflected in the archaeological data.

The simulations of the *Europe's Lost Frontiers* project aim to combine maps created from seismic geophysics data with environmental data from coring. The seismic mapping provides an extensive terrain model, while the cores provide rich data sources (Bates *et al.* this volume; Fitch this volume: chapter 4), but from a limited number of points across the landscape of Doggerland. Combining these two types of data will present both technical and archaeological problems, particularly when dealing with the change over time. These four-dimensional aspects come into play when utilising seismic data that spans extensive time periods in which features such as rivers, lakes and coastlines have changed. Indeed, change is the predominant characteristic of the Doggerland landscape as, between the end of the last Ice Age to its eventual inundation, parts of it are likely to have developed from tundra to scrubland, then forest, wetland and finally inundation.

Traditional forms of archaeological research and presentation can be incompatible with continuous processes of change. The coarse spatial and temporal resolutions of archaeological data have resulted in similarly coarse categories within which these data are allocated. Labels such as 'Mesolithic', 'hunter-gatherer', 'wetland' and 'coastal' are useful simplifications but are likely to hide much fine detail which may be significant. Time is commonly split into periods based on certain defining characteristics. Within Doggerland, or its fringes, human behaviours characteristic of the Mesolithic are likely to give way (how? why?) to those which are characteristic of the Neolithic. In a landscape of constant change, how relevant is it to ask questions such as 'what was the environment like in the Mesolithic?' or, 'where was the coastline of Doggerland at the point of the Mesolithic/Neolithic transition?'. Doggerland is a landscape of continuous change regarding the processes of inundation, the processes of the natural environment and the behaviours of its human population. Every spot of Doggerland was coastline at some point, albeit only briefly in some locations. Behaviours characteristic of both the Mesolithic and the Neolithic could have been carried out on the same day, maybe by the same communities. The coarse categories used by archaeologists are often a product of the coarseness of the underlying data. With this in mind, a more sophisticated way of dealing with continuous processes would be an advantage. Such an approach would allow a finer resolution than terms such as 'Mesolithic', 'Neolithic' and provide a more complex view of the landscape than covered by terms such as 'terrestrial', 'wetland' and 'marine'.

Archaeological computer simulation is a method which deals primarily with processes. It can model systems from the bottom up, defining the attributes and behaviours of small elements within a system and governing their interactions. Essentially a way of testing certain aspects of hypotheses, it provides a digital sandbox within which entities and processes can be defined and then observed in order to detect changes over time (below and Figure 14.6). The extensive terrain model created by the seismic mapping team can act as a base upon which hypothetical ecological environments can be created, then the processes that act within these environments can be modelled over time to determine their effects. This can be done both with and without simulated human occupation. The results of these hypothetical scenarios are compared with each other to detect patterns that can be characteristic of certain behaviours. These results can also be compared to the data from the cores to determine whether patterns of data within the cores are comparable to those from the simulations. The core data can therefore be used as validation for the models. It is important to note that if a model's results compare well with the core data that it does not necessarily follow that the model is an accurate representation of the environment of Doggerland. 'All models are wrong' wrote George Box and we must appreciate the role of probability, equifinality and epifinality in interpreting the results. But Box continued by saying 'some models are useful'(Box 1979: 202).

A note on terminology

There are a number of terms used by practitioners of simulation and these can vary slightly in their usage across disciplines. A model is a representation of an object or system, in which some elements have been abstracted out, commonly because these elements are either deemed to be unimportant or unmodellable. Simulations are models which operate over time, allowing for the observation of their processes and the analysis of their output (Sokolowski and Banks 2011: 3). Although simulations do not necessarily require the involvement of digital computers (Bratley, Fox and Schrage 2011: 2), computers are ideal environments in which to build simulations. The encapsulation of the model in a computer programming language is an explicit and precise version of that model and this form of model can be run by the computer to create a version of the model which operates over time, making it a simulation.

Many computer simulations within archaeology are agent-based models (ABMs) (Cegielski and Rogers 2016). These are a specific type of simulation containing individual software entities (agents) which operate and interact in a virtual environment according to their own inbuilt rules. This architecture makes them ideal for building simulations of human behaviours due to their structure mirroring that of human groups. The terms 'model', 'simulation' and 'ABM' tend to be used interchangeably, and usually refer to a computer programme, especially in an area such as archaeology in which most simulations are ABMs running in a digital environment.

An exceptionally brief history of simulation in archaeology

The use of computer simulation in archaeological research is not a recent development. Archaeologists first became interested in computer simulation in the late 1960s with the emergence of the 'New Archaeology'. Enthused by system theories research and cybernetics, researchers including Clarke (1970), and Doran (1970) began to popularise similar modelling techniques in archaeology. Clarke characterised models as the use of machines to put our conceptual (cognitive) models into practice. The use of such models in archaeology continued throughout the 1970s although attitudes began to change during the 1980s, where their usefulness was questioned with the development of post-processual theory. A number of influential simulations were however created including Mithen's investigation of Mesolithic hunter-gatherer foraging (1988) and Reynolds' cultural algorithms to model resource scheduling of hunter-gatherers (1987).

During the early 1990s, the emergence of the new field of complexity theory began to popularise the utility of simulation in archaeology once again. Within this, complex adaptive systems allowed for the investigation of social developments within simulations, with systems components becoming more human-focussed. Researchers were slowly beginning to adopt the agent-based modelling (ABM) approach, which had been popularised in other fields. Cegielski and Rogers' graph of published ABMs since 2000 highlights this trend (2016).

The development of a number of platforms for modelling complexity, and ever-increasing computing capacity also aided in this renewal, taking advantage of multiple CPUs (Scheutz and Schermerhorn 2006; Shook, Wang and Tang 2013). A number of thematic trajectories for ABMs have been apparent over the last decade including the integration of environmental processes with human interactions (Crema 2014; e.g. Barton *et al.* 2018), complex social structures (Crabtree *et al.* 2017; Del Castillo *et al.* 2014), and formation processes of the archaeological record (Barton and Riel-Salvatore 2014; Davies, Holdaway and Fanning 2016; Rubio Campillo, Cela and Hernàndez Cardona 2012). The emergence of GPGPUs (General-Purpose Graphics Processing Units) that supports massively parallel and distributed processing, including using the GPU for visualisation, looks likely to support the next steps in modelling complexity (Richmond *et al.* 2010; Laville *et al.* 2012).

Most of the simulation used in the *Europe's Lost Frontiers* project relies on the modelling of complex systems. A complex system is one in which the overall behaviour of the system depends on interactions between the individual elements, or agents, which constitute the system and the environment within which they work (e.g. Corning 2002; Resnick 1997). The global state resulting from the collective behaviour from the interactions of agents is termed emergence (Holland 1998; Johnson 2002). Although these often arise from simple rules at the level of the individual agent, the interactions between the agents themselves and between the agents and their environment generates complexity that is often impossible to model using top-down approaches, such as rule-based models that have been used in GIS systems. The study of complexity in nature has been a growing area of scientific research from the second half of the 20th century, but the work of previous researchers such as Adam Smith, Friedrich Engels and Charles Darwin all touch on some of the central ideas of emergence such as the self-organisation of systems with no overall controller (Corning 2002: 18). The term 'emergence' as it relates to a specific process has been around since the 19th century although it was in the 1920s that it became widely discussed across a range of sciences (Goldstein 1999: 53).

Simulation in Europe's Lost Frontiers

The usefulness of the models within *Europe's Lost Frontiers* lies in three main areas:

1. The models represent a vital first step in formalising our assumptions about the landscape of Doggerland. The models form a definite, describable set of processes that are intended to appropriately represent the processes at work in the environment at the time. This allows others to critique our models and, if desired, alter our models themselves and run their own simulations. The same digital environment in which we construct and test our hypotheses can be used by others. Initial assumptions can be tested, and counter arguments can likewise be tested in an ongoing iterative process, both within and between groups of researchers.
2. The models can be used to demonstrate to specialists and the wider public the processes that are believed to have been at work in the landscape and environment of Doggerland, as well as demonstrating the ability of these computer simulation techniques to represent these four-dimensional landscapes and data in a four-dimensional way.
3. Computer simulation can work at temporal and spatial resolutions that are often not dealt with in conventional archaeological research. In building hypotheses, and therefore models, from the bottom-up, we can simulate processes operating on models with high granularity (Lorenz 1963), and within a much smaller spatial and temporal scale than is done when looking at coarse resolution archaeological data over the *longue duree* (Bintliff 1991). This gives us the ability to see short-term and long-term changes from the viewpoint of a single human lifespan.

One model to rule them all? A single model or many different ones?

With all this in mind, is it possible to create one model to simulate the whole landscape from the retreat of the glaciers to the final inundation? The answer to this question depends on the research questions and the resources available, whether these resources come in human, data, software or hardware form. As a result, the answer is usually 'no'. Instead, we think that multiple simulations initialised within a range of parameters that can generate parallel models that we can view as progressive trends would provide us with adequate information for testing hypotheses. This, with awareness that all models have 'sensitive dependence on initial conditions', i.e. the butterfly effect in Chaos Theory (Lorenz 1972).

A single model that represents the development of the whole of Doggerland from 13,000 BC to 6000 BC, with enough time resolution to cope with seasonal changes and enough spatial resolution to model the detail of landscape inundation, would have massive requirements in terms of development time, storage and processing. A cellular environment covering the whole of Doggerland at a resolution of 1m would have something in the region of 315,000,000 cells (a 350km x 300km area with approximately 30% land). If these cells each required 1Kb of storage space, the resulting environment would require around 36GB of disk space. A simulation requiring the recording of the environment over time would require 36GB per simulation 'tick' which would result in storage of around 750TB for the environment alone if it ran for one tick per day for 7000 years. This hypothetical scenario ignores the many methods and techniques available to reduce storage requirements, but these cannot completely eliminate the problems associated with simulating large areas at fine resolution. Likewise, the time taken to run a simulation is relevant. A simulation that requires many hours, or maybe even days, to run might be feasible if the number of scenarios to be modelled were limited, but it would prove impractical during development of larger, more complex scenarios. Typically, there is an extensive testing and verification process to be completed before useful simulations can be performed. The testing phase usually requires many more runs of the simulation than are used for actual experimentation once the models are finalised. For this reason, models that can be run in a short period of time, and then analysed similarly quickly, will drastically reduce development time beyond any benefits provided by shorter processing time of the final, published scenarios.

Techniques within computer science can be used to get around some of these constraints but issues of scalability become important. Environments do not necessarily have to be stored and manipulated in a raster format covering every square metre of the target area, nor does every event or system have to be recorded at the finest possible resolution, e.g. running models within OpenGL coordinate systems that can be represented by fractions and not limited by pixel cells, using non-lossy compression techniques for storing model states, etc. However, there are fundamental problems with models that incorporate both small-scale events and large spatial resolutions that need to be overcome. This can be achieved in the design of the model or in its implementation. A design-centred approach would seek to separate individual systems into smaller chunks. These can be implemented as individual models with lower processing requirements. An implementation-centred approach would use software and hardware technologies that enabled faster processing. In *Europe's Lost Frontiers* we use novel software approaches in high performance distributed computing environments, both with and without GPGPU processing, and an approach to model design that splits the whole of Doggerland and its processes into specific, constrained scenarios.

While Einstein may not have said 'everything should be made as simple as possible, but no simpler' as widely quoted, he did say 'the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience' (Einstein 1934: 165), which is less snappy but functionally identical. Therefore, modelling the whole of Doggerland, when only a small area is required, is wasteful of time and resources, while modelling a rich landscape of resources and behaviours when the research questions can be answered with simpler, more abstract, models is also inefficient. With this in mind, we need to restrict our research questions to scenarios we can practically model with the resources available.

The two research questions being addressed with computer simulation within the *Europe's Lost Frontiers* project are:

1. What does the landscape inundation look like at a human scale?
2. How could we see evidence for human behaviours within the sediment cores?

What does the landscape inundation look like at a human scale?

Although there has been significant development relating to the availability of sea-level index points in the North Sea (Clark *et al.* 2018), the effects of the process of landscape inundation over the area of Doggerland are poorly understood. This especially applies to how this process was experienced by the inhabitants. A primary reason for this gap is that landscape inundation processes are studied more at the millennial/centennial scale rather than at the decadal/annual scale that influences human activity, particularly regarding sea-level changes. A useful method of data downscaling is required to enable both the ability to examine events occurring over shorter timescales and to examine the effects of the downscaling itself (Contreras *et al.* 2019).

The effects of inundation should not be restricted to the movement of the coastline, as other landscape changes such as increasing salinity of the water table potentially have significant effects for both human, plant and animal inhabitants. How this might have altered patterns of behaviour is unclear. It seems likely that some areas will have changed quickly, yet others may have stayed fairly static for several generations, but there is little data to base conclusions upon. Models of inundation calibrated by the project's dating programme give us a way to assess which areas are likely to experience rapid change and what effects this would have on the environment that humans would have to live within, compared to areas in which the change is more gradual.

How can we see evidence for human behaviours in the sediment cores?

Although analysis of the cores is still ongoing, they are already a rich source of data, albeit one that provides only around 78 data points within a vast landscape of millions of square metres. Multiple types of evidence act as proxies for the environment around the core locations. Although worked artefacts that provide direct evidence of human behaviour have been found over the years, including by *Europe's Lost Frontiers* (Missiaen *et al.* 2021), these offer insufficient information regarding human behaviours across time and space in Doggerland. More indirect sources of supplementary data can include pollen profiles that suggest human-altered landscapes or evidence of micro-organisms associated with domesticated animals or crops (Smith *et al.* 2015). How the evidence in the cores relates to the wider landscape is critical in identifying the effects of human behaviour, however evidence for human behaviour in cores may not be obvious and may result from particular combinations of different proxies.

The addition of a system which can model taphonomic effects and can keep track of processes of erosion and deposition enables us to construct 'virtual cores' which can be taken anywhere within the landscape and examined in similar ways to the actual cores (Barton *et al.* 2018). By incorporating a taphonomic layer within the models, underlying the simulations of the landscape, we can model different types of human activity, or no human activity at all, and core the virtual landscape created within the model. This may not only allow the identification of indirect markers of human activity, not obvious from simply analysing the cores one proxy at a time, but also allow the examination of the effects of different sampling strategies, including that strategy used to position the cores.

Simulation design

To simulate the landscape of Doggerland, the models need to be designed, and an infrastructure, which can run these models as they change through time, needs to be created. A model is an abstraction of a system, ideally with relevant aspects left in and unnecessary aspects removed. The more complex a model is, the longer it will take to implement and the more errors there are liable to be within. This means the model should be as simple as required to give us the necessary data, but no simpler. This process starts with the question, 'what do we want the model to tell us?'

As one of our key research questions regards the inundation of the landscape at a human scale, we will ultimately need models that we can use to simulate the processes within the landscape that affect the resources that humans need or want. This will include aspects such as the location of the coastline and the environments that are associated with it, such as salt marshes and the intertidal zone; although the systems included in each individual model will be dictated by the specific question being asked. Further inland, environments will react to both the changing environments of the coastal areas and to the changing weather. These changes will affect the flora and fauna inhabiting the landscape and will also affect the terrain itself via processes of erosion and deposition. Human behaviour will also affect both the environment and its non-human inhabitants.

These models will involve a series of subsystems (Figure 14.1):

Terrain

The terrain of the Doggerland landscape will result in variability in the patterns of inundation as different topographies will respond at different rates to the rising sea level. In addition, erosion and deposition processes will have variable effects on the terrain. The data received from the seismic mapping programme need not directly equate to land surfaces as lived on by the inhabitants of Doggerland. Processes of preservation, erosion and deposition ensure that the seismic data contains evidence of the land surfaces rather than being the surfaces themselves. Land that has been eroded away, both before and after inundation, is lost to us but areas where this has occurred can be identified, albeit without complete certainty. Maps can be built of the areas which are considered to be contemporary land surfaces and where there are gaps, fill surfaces can be generated in ways that plausibly fit with the surrounding seismic and geological data. This will not give a single, unified land surface that corresponds to a specific date, but it will enable the generation of multiple plausible terrains, each with greater or lesser certainty attached to them. This will provide a useful addition to the seismic mapping component of the project as well as forming plausible bases for subsequent simulation. Those simulations may even suggest refinements to the previously assigned probabilities for our generated land surfaces.

The generation of land surfaces will involve the simulation of the processes of erosion and deposition. These are not just the mechanisms from which to create a land surface that may have existed at some point, but they will also have been ongoing processes throughout the history of Doggerland. Processes of erosion and deposition are particularly important within simulations with a taphonomic component, as movement of sediment can also equate to movement of environmental evidence.

Climate

The climate has an effect on the landscape, flora and fauna of Doggerland. Global temperatures will affect sea levels while local conditions will affect the growing conditions of plants. Rainfall will affect erosion and deposition processes related to rivers and streams. Climate data may be regional and of a coarse temporal resolution, especially compared to the resolution of the simulations being processed, but it is possible to create plausible data at a finer resolution if required by the simulation.

Sea Level

Sea level will be related to climate and have wide ranging effects on other systems. The sea level will ensure some areas of the landscape are unavailable for colonisation by flora, fauna or humans, although the seas and coastline will provide significant resources. Salinity will affect water sources and ecosystems, which will also have an effect on humans, animals and plants.

Flora

The plant life of Doggerland has already been studied, both directly and via coarse modelling (Gearey *et al.* 2017), but the data within the *Europe's Lost Frontiers* cores will provide a new set of plant species to place within the Doggerland landscape. Plants will affect processes of erosion and deposition and will provide food and resources for animals and humans.

Fauna

The fauna of Doggerland (Van der Plicht *et al.* 2016), like the flora, has been studied previously but this project, especially the sedaDNA component, provides a significant development in our understanding of what inhabited the project study area. Fauna provide a technical challenge to the computer simulation of Doggerland due to their mobile nature. This mobility also means they have more in common with the humans of Doggerland than other aspects of the environment in that they can react to change by rapidly moving to different areas. This movement can then subsequently change aspects of the environment, especially the flora. In addition, animals such as beavers can directly alter natural environments as a direct or indirect result of their actions.

Humans

That humans inhabited Doggerland between the end of the last Ice Age and its eventual submergence is not in doubt. Finds such as the Colinda harpoon (Godwin and Godwin 1933) (actually probably part of a leister for catching fish or eels) and the worked flint found within the study area provide direct evidence of a human population. However, the lifestyle of these humans has left very little direct evidence within the Doggerland landscape, although evidence for their behaviours can be found in comparable environmental and technological contexts throughout Europe and beyond. Exactly what these behaviours are will depend on the goal of the specific simulation being run. If we are looking at the contexts within which the adoption of Neolithic technologies may be beneficial, the behaviours may be tightly restricted in order to study the effects of individual changes. When examining the taphonomy of evidence and the effect of sampling strategies, this behaviour may be simple and static. When looking at human responses to inundation, these behaviours will have to be flexible. Due to the richness of human society and the many ways humans have developed to cope with changing circumstances, these behaviours will always be heavily abstracted when compared to reality. This will make them 'wrong' in the sense that George Box referred to, but hopefully also 'useful'.

Taphonomy

Closely related to the erosion and deposition processes of the terrain system, taphonomic processes also encompass such things as the dispersal of pollen by the wind and the deposition of DNA by the life, death and decay of an animal. The taphonomic system is designed to bridge the gap between a four-dimensional simulation of multiple processes within a landscape and the understanding of the results of these processes. We understand the real world of Doggerland through the seismic data and the cores, we are not able to directly see the natural and anthropogenic behaviours that produced this data. Within the simulations we are also able to view indirectly the results of our simulated processes via virtual cores through the deposits created by the taphonomic system. This allows direct comparisons between the simulation data with the real-world data to be made. Due to the uncertainty surrounding many taphonomic processes, this will provide comparative, rather than absolute, data.

The taphonomic system will provide the following four benefits:

1. allow easier comparison between the simulations and the real world
2. enable specialists who are unfamiliar with computer simulation to understand the results in a format which they are familiar with
3. enable greater understanding of how taphonomic processes act on the sedimentary and seismic data
4. assess the impact of different sampling strategies, allowing the comparison of conclusions drawn from different core locations placed in the same dataset

This is not a completely novel approach. Taphonomic processes have been modelled independently of overarching societal simulations (Davies, Holdaway and Fanning 2016) and have also been used for the purpose of providing data in formats accessible to specialists in the manner planned for *Europe's Lost Frontiers* (Barton *et al.* 2018). The addition of an extra layer of uncertainty may be unwelcome and will drastically expand the parameter space of the models, but it will also increase the accessibility of the data and the uses to which the models can be put. This will increase the impact of the modelling portion of the project.

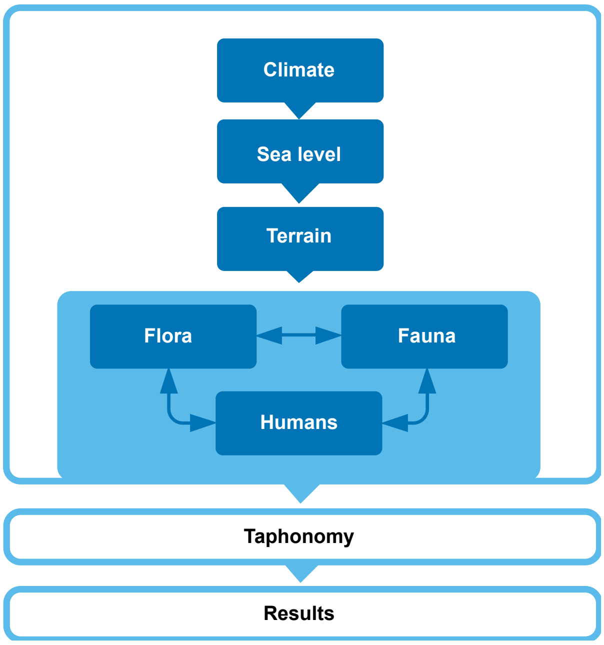


Figure 14.1 The simulation conceptual framework.

The simulation infrastructure

The software platform within which the simulations are created has to be chosen to fit the requirements of the project, the computing resources available and the technical skills of the project team. Due to the existing competencies of the modelling team, the simulations use bespoke software written in the C++ programming language, libraries and APIs (application programming interface). Several packages have been created within the project to suit different purposes. These include a quadtree-based terrain system, a quadtree-based agent interaction framework, interactive visualisation package, forest dynamic modelling software, a landscape modelling sandbox with optional real time visualisation and a very large-scale modelling infrastructure which can handle hundreds of thousands of software agents using the GPU. As all are written in C++ and use a restricted set of external libraries, code written in one platform can easily be imported into the others if required, particularly between the three packages which do not rely on code written to take advantage of NVIDIA CUDA GPU cores.

3D visualisation

The 3D visualisation package was developed by Eugene Ch'ng, primarily as a way of demonstrating the use of a quadtree-based approach to subdividing the landscape and agent-interaction into processes that can be managed by both the CPU and GPU. This allows the user to navigate through the landscape via a user interface which allows real-time control of a camera, through which the landscape is viewed (Figure 14.2). This was easily modified so it could also show the results of the sea-level rise simulation, allowing the user to navigate through the landscape as the sea-level changes were occurring.

Forest dynamic modelling

Developed by Micheál Butler as part of his PhD research, this package simulates forest stand dynamics on an individual tree basis, converting existing methods of simulating the growth of trees to an individual-based modelling framework. Although it has a visualisation component to assist in debugging, the primary output is in the form of text files which can be subsequently analysed. They can also be used by 3D modelling software to create visualisations (Figure 14.3).

Landscape modelling

Developed by Phil Murgatroyd, this package is the primary framework for simulation within the project, and consists of just enough infrastructure to make debugging, running and analysing the simulations practical. Although it is able to be run with a simple graphical output, provided as a means of debugging the simulation, its primary focus is to generate analysable text and image outputs (Figure 14.4), from which results can be produced. The graphical output can be switched on or off via a command line argument, ensuring that it can be run in non-graphical environments such as the University of Bradford's High-Performance Computing Cluster. It also enables faster processing due to the removal of the need to allocate resources to real-time graphical outputs.

Very large-scale modelling

Developed by Eugene Ch'ng, the very large-scale modelling infrastructure uses NVIDIA CUDA and OpenGL technology to run large scale agent-based simulations on the processors of commercial PC graphics cards. This allows the use of simulations with hundreds of thousands of agents (Figure 14.5). Having the capability to run simulations at such scale raises the issue of how to analyse the results from such simulations. This is assuming that such models can be designed, debugged and verified within the constraints of the project.

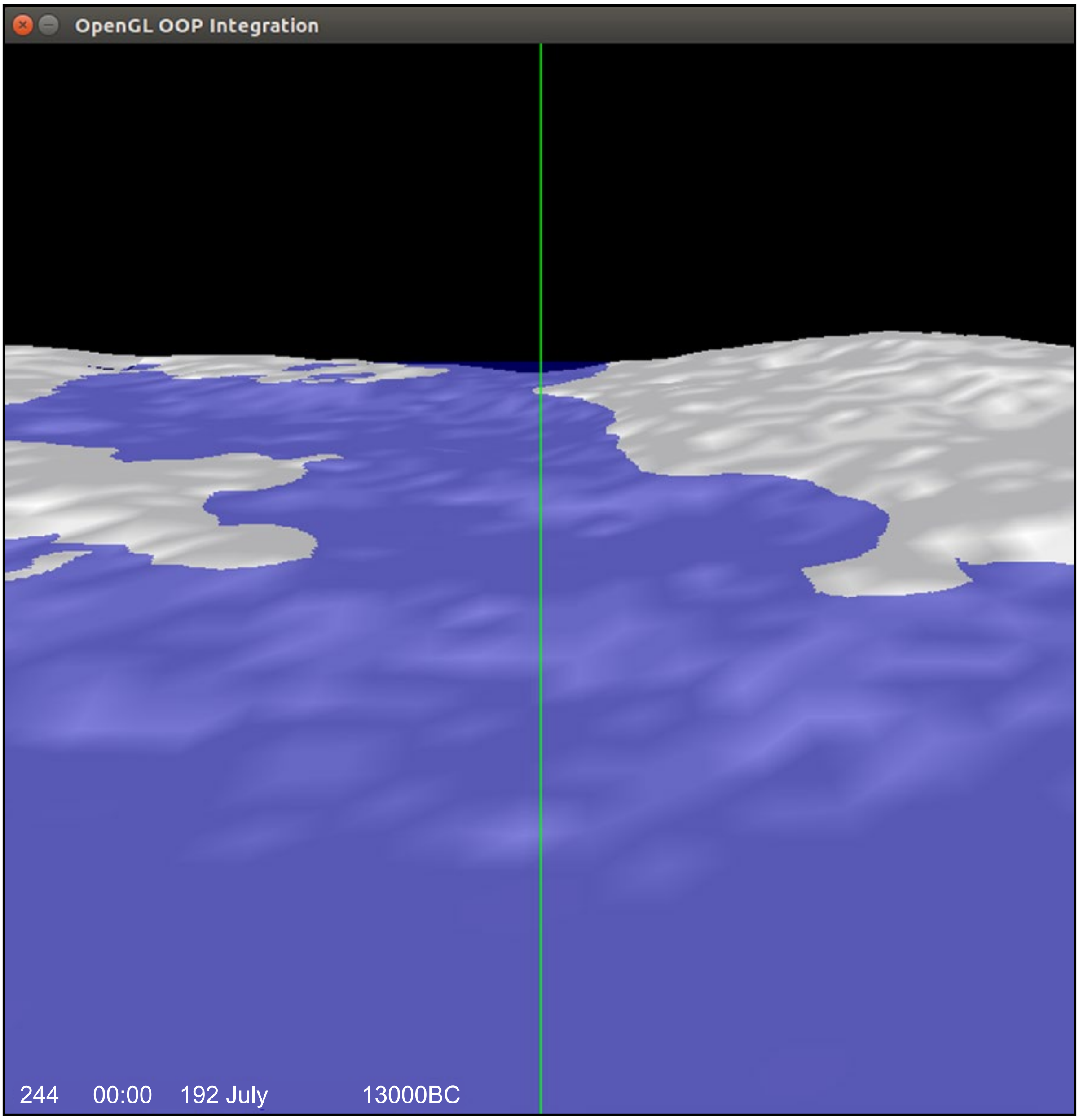


Figure 14.2 3D visualisation package, showing part of the Southern River valley terrain with simulated sea level.

Outputs and dissemination

The outcomes of the project as a whole will include further monographs, including one dedicated to the simulation component of *Europe's Lost Frontiers*, along with articles in academic journals. These formats are two-dimensional, consisting of static words and images on paper, statistical graphs, and increasingly, on computer screens. One of the outcomes of the taphonomic modelling will be to provide output that can be usefully included in such formats, increasing the accessibility of our results, particularly among archaeologists familiar with such data sources. Simulated pollen diagrams, output from the models using pollen dispersal and taphonomic modelling, can be easily compared with actual pollen diagrams from the cores from the North Sea, and are easily included in traditional publications.

However, the data and the models are four-dimensional and involve complex processes interacting with each other and the environment. These processes need to be documented, and the standards for this all rely on the written word, but in order for people to understand the interaction of these processes the models developed need to be user-friendly, well-documented and accessible to the public. If specialists and the interested lay person are able to see the processes at work, see how they interact and maybe even influence those interactions, a barrier to understanding the project

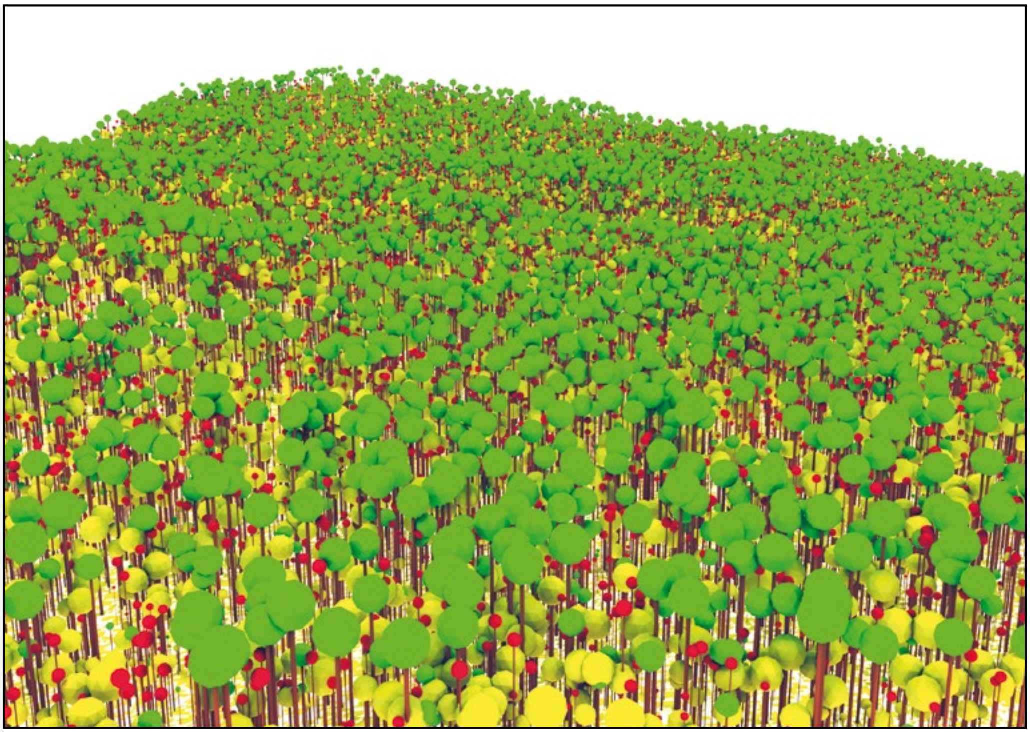


Figure 14.3 A 3D render of the output of the forest dynamic modelling package.

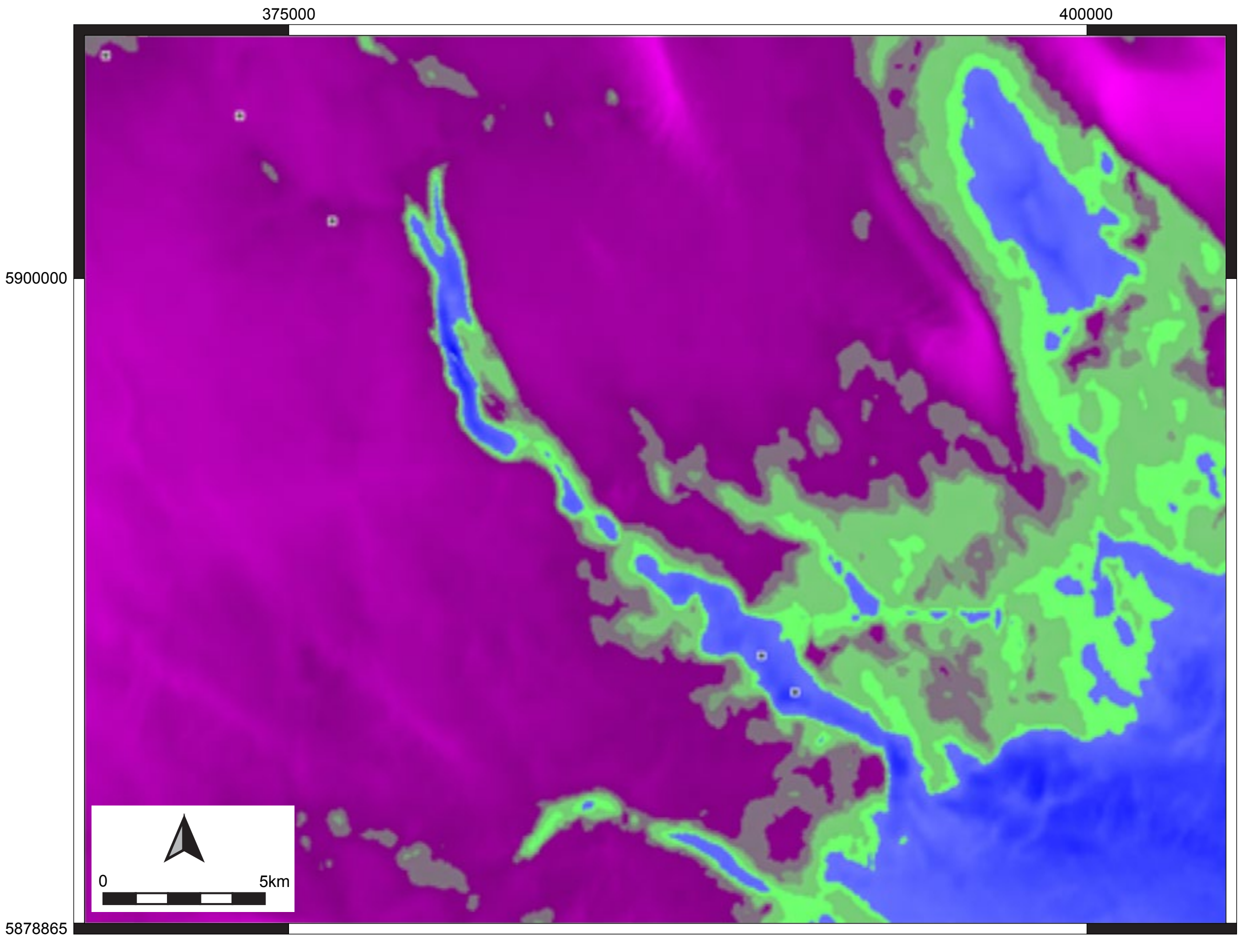


Figure 14.4 Graphical output from the landscape modelling package showing areas with differing amounts of inundation over time.

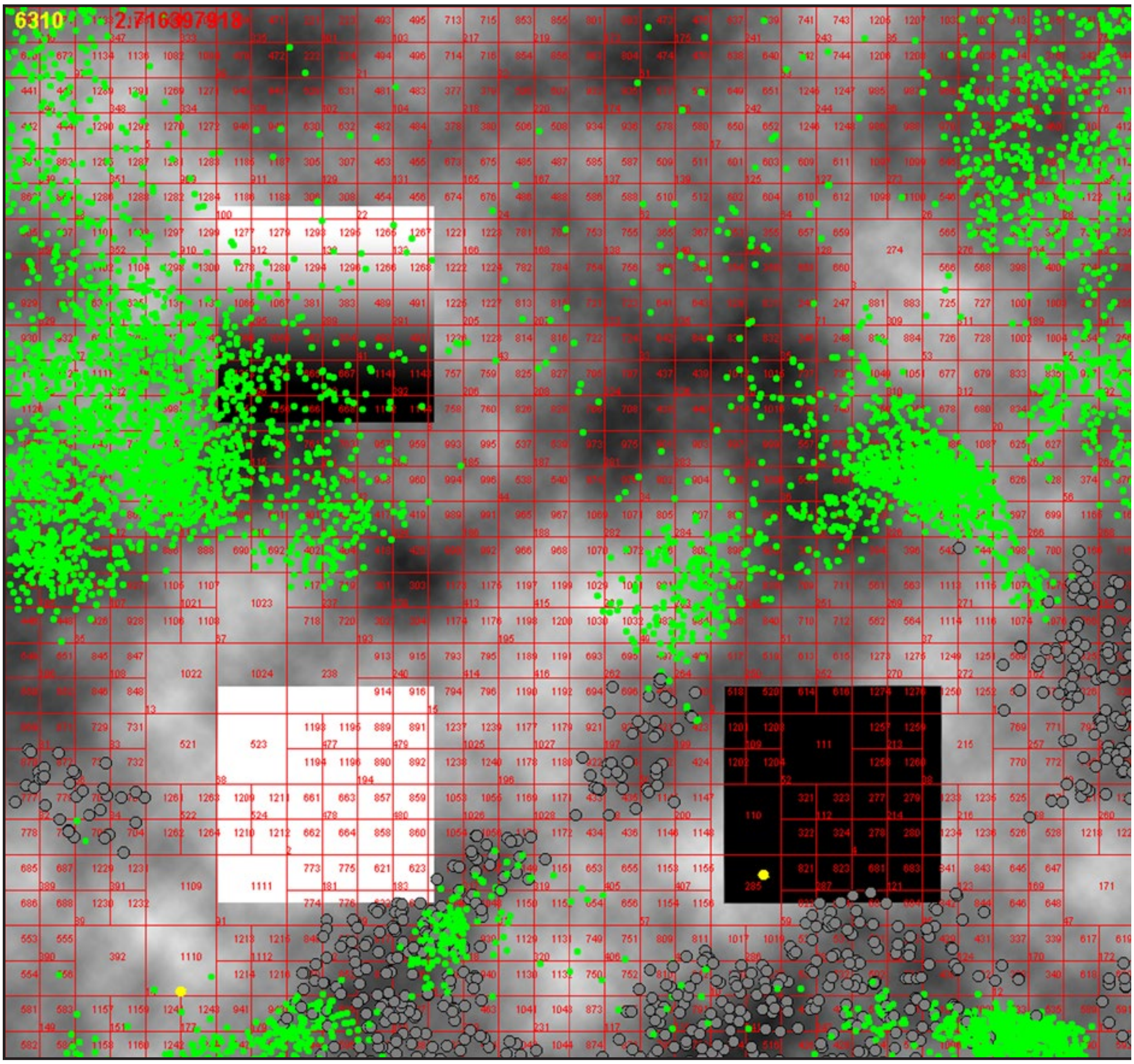


Figure 14.5 A screenshot of the quadtree-based large-scale modelling infrastructure, showing herbivore agents responding to resources in a landscape. The red squares show the dynamic partitioning of the environment resulting from the quadtree structure.

and its results will be reduced. With this in mind, the models used in the project will be made freely available for download in a format that can be easily used by as many people as possible. This will mean depositing the models with open repositories designed to curate models, such as that provided by the COMSES network.

Nevertheless, making the models available and maximising accessibility are two different tasks, with radically different costs in time and resources. Without the kind of user interface (UI) and user experience (UX) development commonly found in commercial software and games, such as tutorials, tooltips, official documentation and user-generated content such as videos and wikis, the models will remain accessible to only a niche audience. It is hoped that the resources can be made available at some point in the future to support development of the surrounding infrastructure. In doing so, access to the models can transcend a specialist audience, which has both the technical skills to compile C++ code and the interest to understand out how they work, to being accessible to anyone with a computer and a passing interest in the subject matter.

Dissemination in person

Illustrating the project's use of computer simulation to more general audiences has already been done using the project's Augmented Reality (AR) sandbox (Figure 14.6, 14.7). AR sandboxes are a relatively recent technology whereby a box of sand is scanned with a Microsoft X-Box Kinect sensor to create an array of height values that can be used as a simulated landscape. This can then be processed, and the resulting image projected back onto the surface of the sand using an LCD projector. This has been developed at the University of California, Davis (UCDavis), and has been used both for public events and teaching, frequently to illustrate the flow of water over a land surface (Reed *et al.* 2016; Woods *et al.*, 2016). *Europe's Lost Frontiers* has used the same hardware setup specified in the AR sandbox created at UCDavis, but we have written new software based on the J4K Java library (Barmpoutis 2013) with Microsoft's Kinect SDK to use the sandbox to demonstrate archaeological ABM principles to public audiences.

The AR sandbox has proven itself to be a very useful way of engaging with non-specialist members of the public, introducing them to computer simulation and explaining why it is part of the project. It has been used at public events around the country and has proven popular with all ages, down to infants who need to be propped up by parents at 90 degrees in order to play with the 'coloured sand'. The simulations that it runs model a dynamic environment of climate, flora, fauna and humans. All these systems interact so that altering one affects the others. This allows users to interact with a complex system and provides a starting point for discussions regarding the project's work in Doggerland, complex systems modelling and environmental archaeology. This ability for members of the general public to interact with an engaging exhibit that is able to prompt discussion, in whichever areas interest them, has proven to be a useful tool for public engagement.

Figure 14.6 The ELF Augmented Reality sandbox.

How modelling fits into the project timetable

The modelling component of the *Europe's Lost Frontiers* project was originally scheduled to run for the final three years of the project, from 2017 – 2020, although this has been extended to 2021 due to delays caused by the coronavirus pandemic. Scheduling the modelling towards the end of the project was done to enable it to take advantage of the environmental and seismic data being produced by the other areas of the project. The design and programming of the models is carried out at the University of Bradford, using the infrastructure designed at the University of Nottingham, Ningbo, China. Environmental processes and human behaviours are specified by the project's researchers. These are then incorporated into models, which are run and the results analysed.

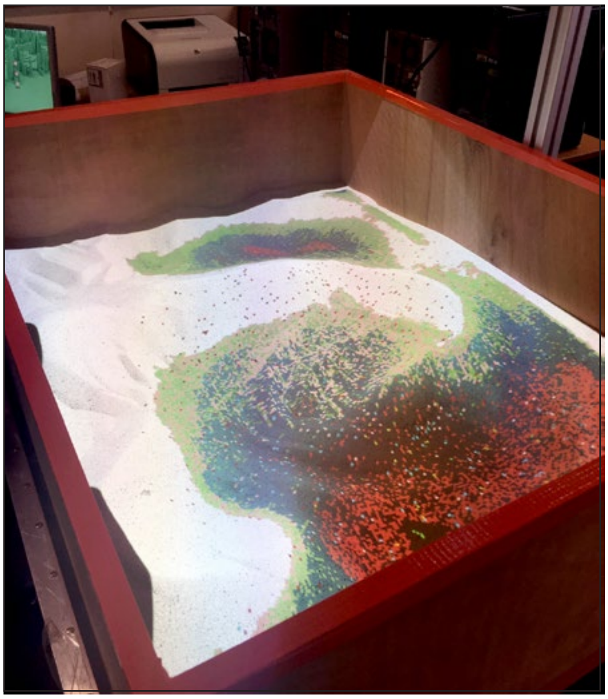


Figure 14.7 The ELF Augmented Reality sandbox in use.

Model 1.1 – Sea-level change

The first set of models produced by the project focus on environmental changes, including landscape inundation. Understanding the processes of inundation is a vital first step towards assessing how human communities would have reacted to change. This includes not only the changes in the shoreline but also how this would have affected resource availability, both in the intertidal zone and further inland. One benefit of simulation is the ability to model processes that occur in the modern world and therefore can be studied at a human scale which is often hard to detect within archaeological contexts. How the landscape changed on a scale detectable to the humans who lived within it is important to understanding how humans reacted to the changing landscape.

The first model in the *Europe's Lost Frontiers* simulation component is one that focuses on sea-level change, incorporating processes working at different scales. It models the interaction of short-term and long-term processes on a seismic-based model of the Southern River Valley (Figure 14.8).

Aims

This model has two main aims:

1. to combine various datasets to provide a way of visualising both short-term and long-term sea-level fluctuations
2. to provide a base for future modelling of landscape inundation and beyond

The ability to examine the interactions of short-term and long-term processes will assist research into how the environment responds to this driver and also provide context for project hypotheses regarding the changing landscape. Model 1.2, which deals with changing ground conditions and plant communities, will be built upon the foundations laid by this model.

Design

The model can simulate a single water level at a minimum temporal resolution of one hour. This allows simulation of daily tides and short-term weather effects. Simulating a single water level across the whole study area means that if the water level effecting a whole landscape is required, effects that cause differing relative sea levels across an area, such as those caused by local topography, will not be explicitly modelled and must be considered as part of the interpretation of the results instead.

The model output consists of a single water level which is derived as the sum of the following modelled processes:

- lunar tide
- solar tide
- atmospheric pressure
- wind

Lunar tide

The lunar tide is created by combining two high and low tides per lunar day to replicate the rotation of the moon around the earth with two smaller high and low

Figure 14.8 The Model 1.1 simulation study area.

tides per anomalistic month to replicate the movement of the moon from perigee to apogee and back.

Solar tide

The magnitude of the solar tide depends on both the rotation of the earth relative to the sun and the elliptical orbit of the earth round the sun. The effect of the solar tide is around half of the effect of the lunar tide. The component of the solar tide depends on the rotational speed of the earth and therefore results in two tides per 24 hours. A further, smaller effect is caused by the elliptical orbit of the earth around the sun every 365.25 days.

Atmospheric pressure

The atmospheric pressure at any particular location in the distant past is obviously impossible to recreate exactly, but the effects of atmospheric pressure are predictable. Each hectopascal (millibar) of atmospheric pressure away from 1013 increases or decreases the sea level by 1cm. Currently within the model, this is modelled by using record high and low pressures recorded at a reference point (Cromer, Norfolk), as bounds for a randomly altering distribution centred around the average (see Figure 14.7).

Wind

The effects of wind on sea level are highly dependent on coastal morphology and the direction and strength of the wind. An onshore wind will increase sea level at the coast, whereas an offshore wind will decrease it. Obviously, any model of wind strength, direction and effects will have to be highly abstracted and yet wind can be a significant contributor to major events such as storm surges. Within the model, the wind strength is tied to the atmospheric pressure, with higher winds falling low pressure conditions than rising high pressure. Direction is random but can depend on prevailing wind directions and local topography once individual sites and their surroundings are selected. There does not seem to be good data regarding how much the wind effect contributes to sea level, so a determination of wind speed is made based on atmospheric conditions and an effect is calculated, based on direction, within a 3m range.

Base water level

The base water level is the base level upon which the other effects are added or subtracted. It allows long-term relative sea-level change to be represented by using data from published reconstructions at different locations. This data can be taken from any source and can either be run as a constant curve or with a small component of random annual variation introduced.

The base water level can be estimated from sea-level reconstructions. These show that sea level within the *Europe's Lost Frontiers* study area was *c.* 100m lower today than during the Last Glacial Maximum (LGM) at approximately 20,000 BP (Figure 14.9). During the early Holocene, temperatures rapidly increased (Smith *et al.* 2011) resulting in the melting of glaciers and release of meltwater into oceans and seas. Reconstructions of relative sea-level change utilising Glacial Isostatic Adjustment models, including those by Bradley *et al* (2011) and Shennan, Bradley and Edwards (2018), provide information on the rate of sea-level rise which varied over time. Using these sea-level reconstructions, the changes in base water levels and the influence on tides can be visualised in both the short-term and long-term temporal scale.

Initially between 21,000-18,000 BP the rate of sea-level rise was below 1mm/yr, however as glaciers began to melt as the overall global temperature rose, the rate of sea-level rise also increased (Figure 14.9). The rate of sea-level rise between 18,000-11,000 BP averaged 2-5mm/yr, increasing to ~12mm/yr between 14,000-13,000 BP and between 11,000-8000 BP ranged from 7-13mm/yr. However, by 10,000 BP the global temperature rise begun to plateau (Marcott *et al.* 2013) and this coincided with a decrease in glacial melting and the rate of sea-level rise. After 7000 BP the rate of sea-level rise slowed to below 4mm/yr and by 2000 BP was less than 1mm/yr. This decrease in SLR coincided with a long-term cooling trend that began at around at *c.* 5000 BP of approximately 0.7° (Marcott *et al.* 2013).

Outputs

There are currently two ways of viewing the model's outputs: a text file giving simulated water levels and a 3D graphic visualisation of the landscape and sea level.

Text and graphs

Water levels can be simulated without any visualisation infrastructure and the results output to a text file (Figure 14.10). This can be then imported into Excel and used to create graphs. Without the need to display a landscape, the simulation runs rapidly, at approximately a thousand years per minute.

The graph of one year's data (Figure 14.11) shows the two spring and neap tides per month along with the increased variability in winter due to both atmospheric pressure and wind. As can be seen, the contribution of atmospheric pressure is a minor part of the overall sea level, but it is the atmospheric pressure and wind components that add 'noise' to the relatively regular signal contributed by the solar and lunar tides.

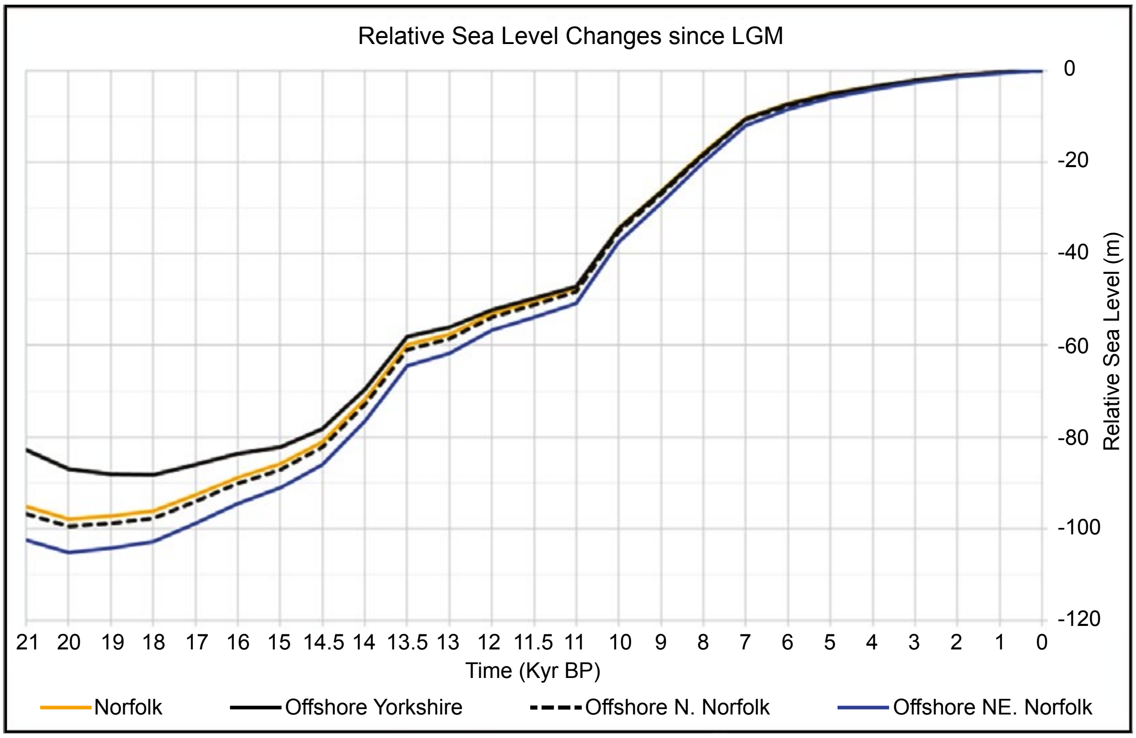


Figure 14.9 Relative sea-level change over the last 21,000 years in the North Sea region from Glacial Isostatic Adjustment (GIA) model reconstructions (Bradley *et al.* 2011; Shennan, Bradley and Edwards 2018).

The graph of 14 years' data (Figure 14.12) shows the difference between the more turbulent winter weather and the calmer summer weather. In the simulation results presented here, the long-term sea-level change forms an insignificant part of the total sea-level change.

These graphs seem to indicate a wider variability than is found in reference data from coastal sites such as Cromer. In the short term, this is useful in that it serves to highlight the patterns in the data. More thought needs to be put into how individual sites are likely to compare to available reference datasets. While some factors such as atmospheric pressure have predictable effect sizes, others such as lunar and solar tide and wind depend on local factors, such as local topography and bathymetry, and would therefore benefit from a model that takes local factors into account.

Ongoing development

Some of the elements that make up the water height data are crudely modelled, whether because the best available models are too complex and computationally expensive to run or that the data does not exist to allow more sophisticated models to be made. Each comparative dataset is taken at a point that will not correspond exactly to any point in the Doggerland landscape. It is not our task to exactly replicate the water level at any given spot over thousands of years at hourly resolution. Rather we are attempting to assist in unpicking which factors are most significant and to provide a base from which a plausible model of landscape inundation can be built. For this reason, the water level has to exhibit the *kind of* variation that may have been seen in Doggerland, rather than the *actual* variation. If this water level model is plausible and defensible for the purposes for which we will use it then it will be a 'useful' model, even if it is a 'wrong' model.

Further work

The sea-level model is just one element in the interaction network of processes, and it can be studied on its own or reused within further models. One conclusion from Model 1.1 as it currently stands, is that long-term sea-level changes seem to be drowned out (so to speak) by shorter term effects. To what extent would the inhabitants of the Southern River Valley have realised they were living within a landscape that was being inundated? Looking at the graphs of sea level produced by the model it seems possible that they may not have been aware of such processes. But the inhabitants of Doggerland did not experience their landscape via graphs, but from within the real world and in real time. The location of the sea is just one aspect of a changing landscape and it may have been other changes that were the most noticeable signs of climatic change.

Hour	Day	Year	waterHeight	baseWaterHeight	lunar	luneff	solar	soleff	atmeffect	windeffect	windspd
01:00	1	13000BC	0.210788	0	0.454668	0.09879	0.26612	0.099454	0.01	-0.52	3
02:00	1	13000BC	-0.208545	0	0.132002	0.098185	0.099454	0.099454	0	-0.44	2
03:00	1	13000BC	1.03212	0	-0.19066	0.097581	-0.06721	0.099454	0.01	1.28	5
04:00	1	13000BC	-0.36721	0	-0.51333	0.096976	-0.23388	0.099454	0.01	0.37	5
05:00	1	13000BC	-1.00654	0	-0.836	0.096371	-0.40055	0.099454	-0.01	0.24	2
06:00	1	13000BC	-1.55369	0	-0.64981	0.095766	-0.23388	0.099454	0.01	-0.68	5
07:00	1	13000BC	-0.435563	0	-0.32835	0.095161	-0.06721	0.099454	-0.01	-0.03	0
08:00	1	13000BC	-0.487439	0	-0.00689	0.094556	0.099454	0.099454	0.01	-0.59	3
09:00	1	13000BC	0.340683	0	0.314563	0.093951	0.26612	0.099454	0	-0.24	2
10:00	1	13000BC	0.738807	0	0.63602	0.093347	0.432787	0.099454	-0.02	-0.31	1
11:00	1	13000BC	1.54693	0	0.957476	0.092742	0.599454	0.099454	-0.02	0.01	1
12:00	1	13000BC	0.608128	0	0.905342	0.092137	0.432787	0.099454	0	-0.73	5
13:00	1	13000BC	-0.0412045	0	0.582675	0.091532	0.26612	0.099454	0.01	-0.9	4
14:00	1	13000BC	-0.930537	0	0.260009	0.090927	0.099454	0.099454	0.01	-1.3	4
15:00	1	13000BC	-0.99987	0	-0.06266	0.090322	-0.06721	0.099454	0.01	-0.88	4
16:00	1	13000BC	-0.00920278	0	-0.38532	0.089717	-0.23388	0.099454	0.01	0.6	4
17:00	1	13000BC	-1.70854	0	-0.70799	0.089113	-0.40055	0.099454	0.01	-0.61	4
18:00	1	13000BC	-1.42621	0	-0.79233	0.088508	-0.23388	0.099454	-0.01	-0.39	1
19:00	1	13000BC	-0.568087	0	-0.47087	0.087903	-0.06721	0.099454	0.01	-0.04	3
20:00	1	13000BC	-0.819963	0	-0.14942	0.087298	0.099454	0.099454	0.02	-0.79	3
21:00	1	13000BC	-0.22184	0	0.172039	0.086693	0.26612	0.099454	0.03	-0.69	4
22:00	1	13000BC	1.26628	0	0.493495	0.086088	0.432787	0.099454	0.05	0.29	3
23:00	1	13000BC	1.95441	0	0.814952	0.085483	0.599454	0.099454	0.07	0.47	3
00:00	2	13000BC	1.94559	0	1.03335	0.084879	0.432241	0.098907	0.07	0.41	3
01:00	2	13000BC	0.126257	0	0.710683	0.084274	0.265574	0.098907	0.05	-0.9	4
02:00	2	13000BC	-1.01308	0	0.388017	0.083669	0.098907	0.098907	0.06	-1.56	5
03:00	2	13000BC	0.407591	0	0.06535	0.083064	-0.06776	0.098907	0.05	0.36	2
04:00	2	13000BC	-0.0217414	0	-0.25732	0.082459	-0.23443	0.098907	0.05	0.42	2
05:00	2	13000BC	-1.91107	0	-0.57998	0.081854	-0.40109	0.098907	0.07	-1	3
06:00	2	13000BC	-2.15707	0	-0.90265	0.081249	-0.23443	0.098907	0.05	-1.07	4
07:00	2	13000BC	-1.07116	0	-0.6134	0.080645	-0.06776	0.098907	0.07	-0.46	5
08:00	2	13000BC	0.676966	0	-0.29194	0.08004	0.098907	0.098907	0.07	0.8	5
09:00	2	13000BC	0.745089	0	0.029516	0.079435	0.265574	0.098907	0.07	0.38	5
10:00	2	13000BC	0.403212	0	0.350971	0.07883	0.432241	0.098907	0.06	-0.44	4
11:00	2	13000BC	1.28134	0	0.672428	0.078225	0.598907	0.098907	0.08	-0.07	4
12:00	2	13000BC	1.77612	0	0.993884	0.07762	0.432241	0.098907	0.06	0.29	3
13:00	2	13000BC	1.48426	0	0.83869	0.077015	0.265574	0.098907	0.06	0.32	3
14:00	2	13000BC	0.694931	0	0.516024	0.07641	0.098907	0.098907	0.06	0.02	3

Figure 14.10 Table of data showing headings.

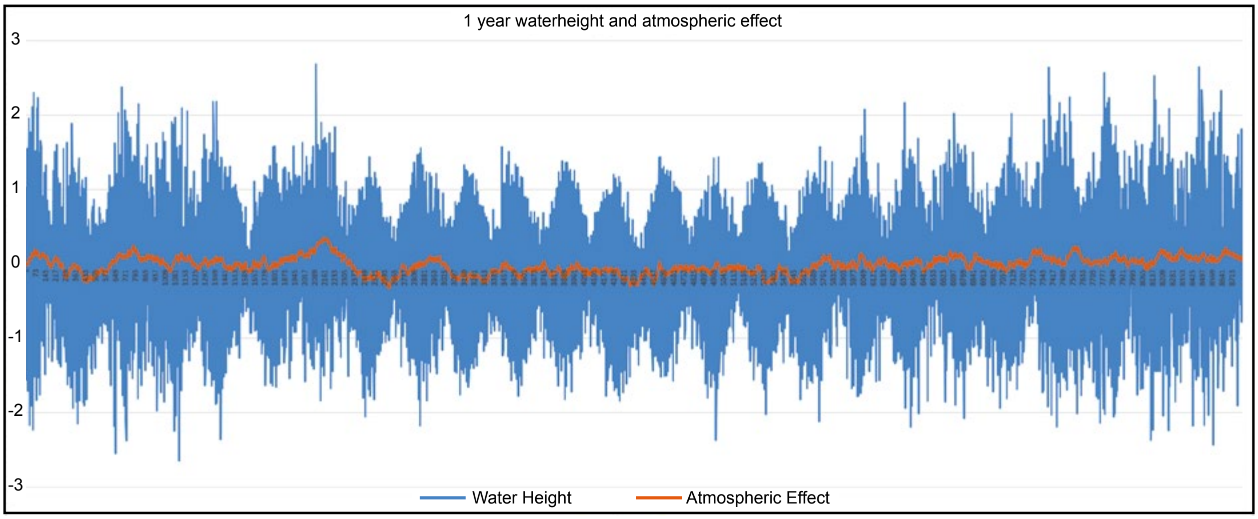


Figure 14.11 Graph showing one calendar year's data of water height and atmospheric pressure effect.

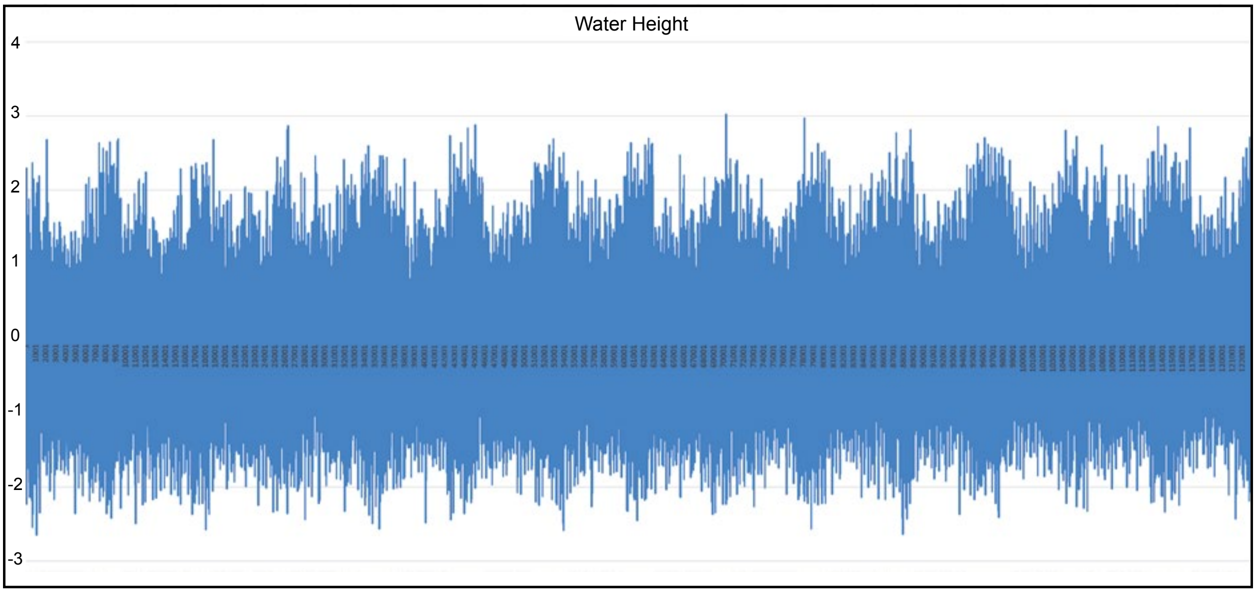


Figure 14.12 Graph showing 14 year's water height data.

With this in mind, Model 1.2 will incorporate simulated environmental areas within the landscape in order to assess whether the reduced volatility of the limits of these zones is likely to make the changing climate more or less noticeable than the volatile, noisy data from the sea level.

Model 1.1 also produces identical results for each point in the Doggerland landscape of the same height. This ignores local effects such as geology, wave action and the effects of river systems and therefore has limited ability to develop hypotheses regarding how the changing shape of Doggerland affected the inundation of Doggerland. This model will form one of two branches that diverge after the implementation of Model 1.2. Once we have a model in which a landscape contains simulated environmental areas that respond to changing sea level, we can use this as a base for developing further models. Model 2 is an examination of how the changing landscape could have affected human inhabitants. Model 3 makes the simplified changing landscape more complex with the addition of processes of erosion and deposition. Appropriate aspects of Models 2 and 3 can be recombined into a model in which human behaviour takes place in a changing landscape that involves taphonomic processes, Model 4. Models 2, 3 and 4 are likely to consist of various submodels which add processes to the base provided by Model 1 (Figure 14.13).

Model 1.2 – A Changing Environment

The representation of a virtual coastal and terrestrial landscape allows for the exploration of the effects of sea-level change, the patterns of inundation across the landscapes and how visible these changes were over time. Terrestrial landscapes and coastal shorelines respond to changes in sea level and sea-level change in a variety of ways, some of which are temporary or short term while others are persistent and can result in long-term landscape changes. Shoreline and landscape responses to sea-level change fall into three main categories: erosional response; landward migration or overstepping; and in-situ drowning of the shoreline (Pretorius *et al.* 2019). These responses range from changing coastal hydrodynamics and eco-geomorphology, transformation of inland terrestrial environments to estuarine/saltmarsh and marine environments, as well as inundation and submersion of the landscapes as sea level encroaches further inland. The effect of sea-level rise on coastal areas includes wetland inundation, increased shoreline erosion and increased flooding during storm events (Passeri *et al.* 2015). Sea-level rise affects the terrestrial ecosystems through:

- submersion/drowning/flooding of coastal and inland landscapes
- coastal erosion from waves
- retreat of saltmarshes and estuarine ecosystems further inland which leads to loss of inland woodlands and leads to more open environments
- changing water table as groundwater levels rise leading to formation of waterbodies further inland where drainage is impeded

Sea-level change can result in the migration of estuaries inland, increased effect of storm surges due to erosion of sandbanks, rising ground water table/levels, and formation of marshes or lakes where the groundwater is close to the surface (Leary 2009) and can also result in increased salinity in an estuary and coastal freshwater aquifer. However, these responses tend to be variable

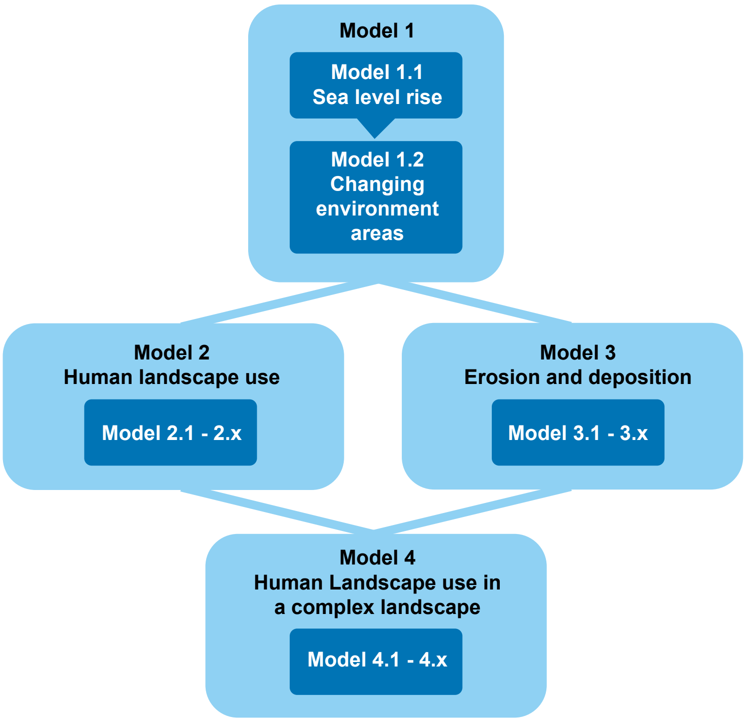


Figure 14.13 Flowchart of the Europe's Lost Frontier models.

depending on the coastal topography. For example, in low-lying coastal landscapes tidal ranges would stay the same or decrease where there are no impediments to these landscapes flooding (Lee, Li and Zhang 2017), resulting in an increase in the extent of tidal flooding across the landscape. The effect of sea-level change on the Doggerland landscape can be explored through four main processes (Passeri *et al.* 2015):

1. coastal hydrodynamics (tidal and fluvial)
2. coastal morphodynamics
3. marshland responses
4. groundwater changes

Of these, marshland responses and the effects of groundwater changes will be incorporated into Model 1.2, with coastal hydrodynamics and morphodynamics forming part of Model 3.

Marshland response

Coastal marshes occupy the intertidal areas at elevations near the mean high tide levels. Wetland extent, productivity, and inundation frequency and duration is affected by the platform elevation relative to the sea surface elevation (Morris *et al.* 2002: 2869). Saltmarsh development is influenced by the rates of sea-level rise, tides and tidal regimes, wind-wave action, sediment supply and vegetation establishment (Tonelli, Fagherazzi and Petti 2010). Saltmarshes are influenced by inundation events at different temporal scales. These may be short term or constant i.e. tides, intermittent storm surges, and long term i.e. sea-level change and tsunamis, making Model 1.1 a suitable base to build upon. The effect of sea-level rise on marshes include (Passeri *et al.* 2015):

- tidal inundation due to sea-level change effects on sediment deposition which affects accretion and vegetation production
- increased hydroperiods due to increased tidal ranges can affect sediment transport – where inorganic sediments are deposited marsh elevation increases (vertical accretion); however, if organic sediments are deposited, they increase vegetation stress, lower biomass production, decrease accretion and can increase the hydroperiod
- vegetation biomass productivity contributes to flow damping i.e. limits erosion, leads to increased accretion
- if sedimentation does not keep pace with sea-level change (where sea-level change is fast), the marsh drowns or becomes submerged and converts to a subtidal ecosystem; where sea-level change is slow it can increase settling on marsh surfaces and biomass production; where marsh development keeps pace with SLR it can migrate landwards at a similar pace as erosion – vertical accretion or landward migration is dependent on inundation, sedimentation and plant growth (Borchert *et al.* 2018)

- increased tidal inundation increases saltwater intrusion affecting vegetation productivity; where saltmarsh vegetation invades freshwater communities that experience increased saltwater intrusion, plants not tolerant of salt die out and are replaced with more salt-tolerant species (Grenfell *et al.* 2016)
- higher tidal prisms can result in saltwater intrusion further inland of the estuaries where the tidal saltwater zone moves further upstream.
- Increased flooding further upstream.

Marshland response and fluvial dynamics are important in understanding changes to estuaries from sea-level change. As discussed above, marsh landscapes can respond to sea-level change through vertical and horizontal accretion that is dependent on fluvial dynamics of water and sediment discharge, tidal effects on sediment transport, vegetation dynamics and sediment deposition and erosion (Crosby *et al.* 2016; Morris *et al.* 2002; Phillips 2018). If a marsh is to keep pace with rising sea level, the positive vertical rate of accumulation must be greater or equal to the rate of total subsidence plus the local sea-level trend (Cahoon 2015). Stability of these systems relies on an equilibrium between the elevation of the saltmarsh's sediment surface with mean sea level as shown by models of accretion based on mass balance (Morris *et al.* 2002; Temmerman *et al.* 2003; French 2006).

The sea-level model implemented in Model 1.1 provides a sound base to create simulated marshlands that respond to inundation events of both short term and long term, with the erosive effects of wave action and the accumulation and supply of sediment being implemented in Model 3.

Groundwater changes

As sea level rises, groundwater levels are affected with the water table rising, leading to the formation of pools, lakes, marshes and bogs where the drainage stagnates (Ward and Larcombe 2008). Sea-level change also affects groundwater resources where tidal flooding extends further inland, resulting in reduced vegetation productivity where water resources become brackish. In addition, saltwater intrusion into fresh-groundwater resources could further affect the productivity of saline-intolerant vegetation (Passeri *et al.* 2015), leading to:

- freshwater migration landward due to differences in densities
- landwards migration of vegetation due to stress and decreased productivity as water resources become brackish

Changes in groundwater provide the basis for the next step back from the coastline to the terrestrial landscape with regards to Model 1.2. They allow us to create a coarsely modelled complete environment which can form the base for human activity.

Conclusion

The overall workflow of the simulation component of *Europe's Lost Frontiers* takes the form of a potentially endless, iterative cycle. Individual components are added to models to allow us both to look at how each system works and how each system interacts with those that have been implemented. This creates an ever-increasing parameter space which will be impossible to fully explore. Nevertheless, it allows us not only to progress with the task of creating a full featured landscape sandbox within which to test hypotheses, but also to go back and alter previously researched components, refining our models, both mental and computational. We will be able to examine the interaction of short-term and long-term processes that affect sea level, but we will also be able to examine the effect each can have on each of the subsequently modelled systems. This approach has been successfully attempted in the Village Ecodynamics Project (Kohler and Varien 2012). This study produced a variety of models over the 13 years of its existence, and beyond. It also combined computer simulation and traditional archaeology in order to shed new light on an entire landscape over hundreds of years and its models provided both a jumping off point for further models and a way of producing new data that prompts a re-evaluation of previously modelled hypotheses.

By utilising this approach, the hypotheses regarding the inundation of Doggerland within the *Europe's Lost Frontiers* project are made explicit and testable through the models described here. The processes and data on which we base these hypotheses will be transparent and the models that incorporate these processes can be modified and run by other researchers. The results will be displayed via formats already accessible to researchers and the general public. This will include simulated pollen diagrams and cores that will present the results of the simulation in ways that are directly comparable to the data provided by more traditional forms of archaeological research. The taphonomic models that underpin these outputs will support researchers in examining existing hypotheses of taphonomy in environmental and archaeological contexts. In this way we hope to make our hypotheses accessible and comprehensible to both archaeological researchers and the general public, and to demonstrate that computer simulation is an essential component of submerged landscape research.

Chapter 15

Greetings from Doggerland? Future challenges for the targeted prospection of the southern North Sea palaeolandscape

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Pilgrim felt his feet transparent on the deck, a sailor
treading uplands sixty fathoms back; saw nettled deer tracks
pooling, inch by sodden inch, into a whaler's channel;
inlands islanded and highlands turned to shipping hazards.
Jo Bell, Doggerland (2015)

The introductory chapter of this volume began with a quote from John Clare, England's quintessential poet of rural change and the romantic memory of things past. In this, the final chapter, we turn to Jo Bell's equally emotive poem, Doggerland. Here the poet considers our relationship with the palaeolandscapes of the North Sea within the context of what, increasingly, appears to be unavoidable climate change. In the seven years that have lapsed since Bell's cautionary poem was published, social media tags have morphed from #ClimateChange to #ClimateCrisis and, as this volume goes to press, the world has suffered a series of climatic disasters. Catastrophic heat waves and forest fires have scorched the American west, the Australian bush, southern Europe and Siberia; devastating floods have occurred from Germany to China. Polar ice continues to melt at some of the fastest rates recorded in recent history. Climate outcomes, some of which were discussed as avoidable in Europe's Lost World, the final volume of the NSPP (Gaffney 2009: chapter 5), are now deemed 'Irreversible for centuries to millennia' in the most recent IPCC report (IPCC 2021: Table 4.10). Anthropogenic climate change is unequivocal and affects every part of the world (IPCC 2021: SPM 12). The extent and impact of such change is such that, in some senses they can now be compared with the inexorable natural changes faced in the past (Burroughs 2008), although the potential scale of anthropogenic change in recent centuries now appears to exceed the normal range of post glacial fluctuation (NASA 2022).

It is apparent that many aspects of archaeological research must increasingly be undertaken with respect to the new climatic normal. Whilst such issues will be discussed in greater detail in the final volume of the project, climate change is now so rapid that it will inevitably affect archaeological research currently occurring in the North Sea, as well as that planned for the future. In such a context it seems appropriate that a provisional statement on future marine palaeolandscape research is provided at this early stage of publication.

As was illustrated in the introductory archaeology chapters to this volume, our understanding of the palaeogeography of the early Holocene landscape has been a vital pre-requisite for targeted archaeological prospection in the North Sea (Gaffney and Fitch this volume; Walker *et al*. this volume). Without this knowledge our capacity to anticipate discovery largely becomes a matter of chance and good fortune (Spikins and Engen 2007). Whilst the positive results of chance are an intrinsic part of archaeological discovery, the last two decades of research have transformed our understanding of Doggerland to the point where we may now at least be more hopeful of future attempts at targeted prospection (Missiaen *et al*. 2021). Up till now, the key to providing the outline detail of the elusive landscape associated with early Holocene Doggerland, outlined within *Europe's Lost Frontiers* (Gaffney *et al.* 2009), has been access to data not usually available through conventional archaeological protocols. Massive datasets, largely acquired in support of the development of offshore energy reserves of oil and gas, have underpinned research (Gaffney *et al*. 2007). The analysis of this data has only been possible thanks to the integration of a diverse array of specialists within the *Europe's Lost Frontiers* team, and the collaboration of colleagues from other research establishments. Here we would specifically note the work of the Flemish Marine Institute (VLIZ) and the Dutch Geological Service (TNO). Moreover, such an undertaking would not be possible at all were it not for the willingness of private industrial stakeholders to share their data and facilitate such research in the first place. The support of PGS and Royal Haskoning and their provision of unfettered access to survey data, acquired or merged at the cost of millions of dollars, has been the bedrock of research undertaken by *Europe's Lost Frontiers*. At the time of writing, the relative lack of direct archaeological funding from UK sources for this work, following the demise of the Aggregates Levy scheme, contrasts significantly with the funding provided through the European Research Council, or the access to research vessels provided through European partners (Gaffney and Fitch this volume). How we build on these achievements, as nations around the world also begin to explore their coastal shelves, is now an urgent, academic question.

Where next?

Coastal states around the world, including those countries surrounding the North Sea basin, are urgently looking to harness offshore wind energy as a means of reducing carbon emissions and establishing a green power source infrastructure. The British government recently pledged their aim to have all homes powered by offshore windfarms by 2030 (UK Govt, 2020), and equally ambitious targets were outlined by nations across the globe at the recent COP26 conference. Within UK waters this requires rapid and massive expansion of turbine installation in areas that largely accord with early Holocene Doggerland. As this publication goes to press, it is becoming clear that these rapid changes may be exacerbated following the geopolitical crisis resulting from the iniquitous Russian invasion of Ukraine. In such a situation, areas that we might hope to investigate are now at risk of being damaged or rendered inaccessible as a result of greatly expanding offshore energy infrastructure (Figure 15.1).

This clarion call for future archaeological research is amplified, as noted in Walker *et al.* (this volume), through the results of the BRITICE-Chrono project

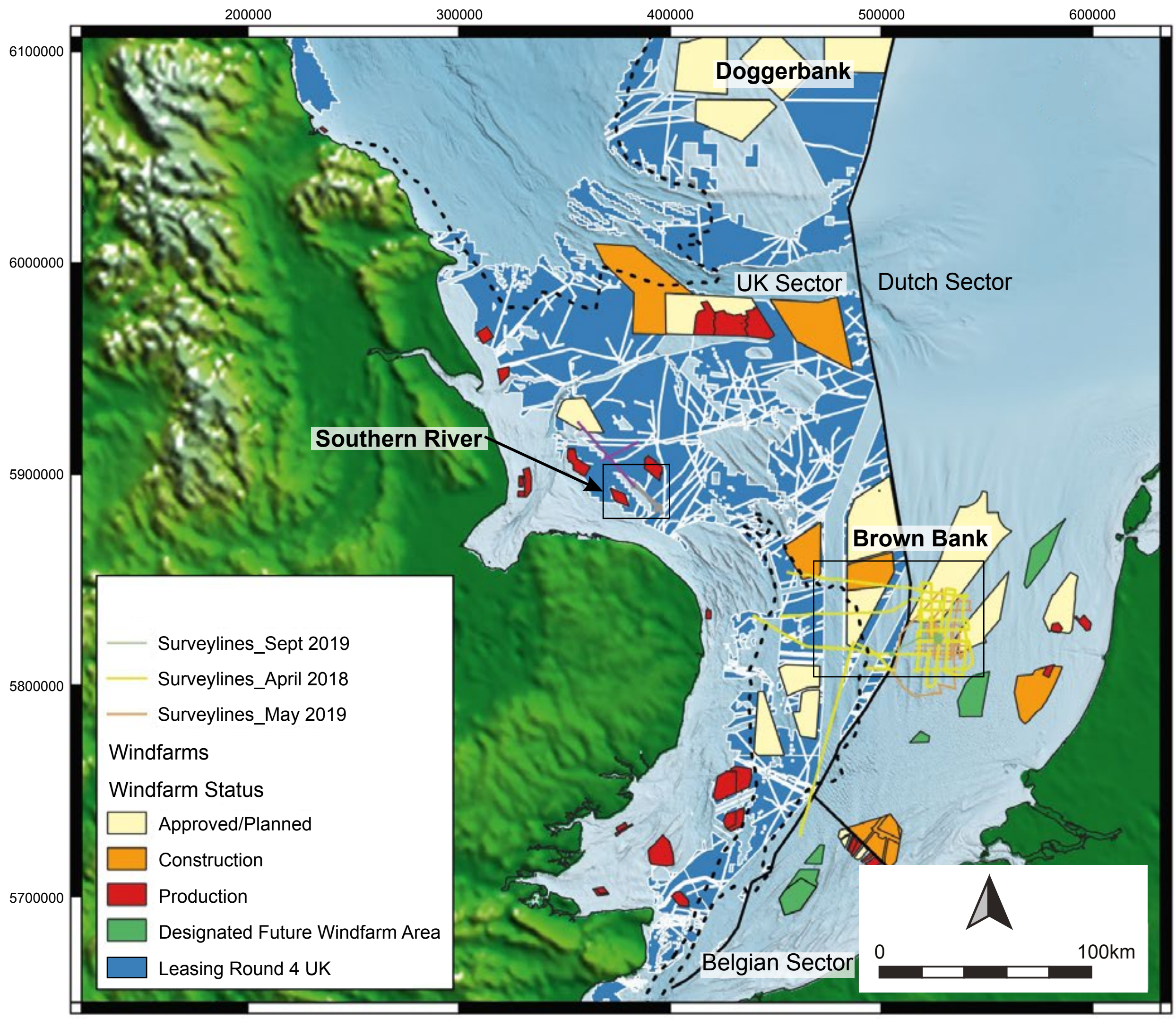

Figure 15.1 Areas designated for windfarm development within UK and Belgian waters and survey lines associated with the Brown Bank and Southern River study areas (The Crown Estate ©, bathymetry derived from EMODNET. Topography derived from ETOPO)

(Roberts *et al.* 2018). These demonstrate that, aside from coastal margins, postglacial Doggerland did not extend much north of the Dogger Bank throughout the Late Pleistocene and Early Holocene. In contrast to earlier reconstructions of the area of Doggerland, we must now accept that evidence for palaeolandscape settlement during this period, and any material culture correlates, will essentially be constrained to those areas that will be most impacted by planned offshore development. However, whilst nearshore sites exist, and offshore finds have been made through chance recovery (Peeters and Amkreutz 2020), evidence for settlement or *in-situ* activity from offshore waters (>12 nautical miles from the coast) has yet to be found in the North Sea, or indeed globally (Walker *et al*. this volume).

Ultimately, whilst we now know much about the physical landscape of Doggerland, our understanding of the cultural landscape has not progressed substantially since the early 20th century (Waed 2014; Ward *et al.* 2014). This situation persists despite decades of offshore development and planned archaeological mitigation (The Crown Estate 2014). The lack of direct evidence for archaeological settlement, or *in-situ* activity, in a landscape that must have been densely populated, and in areas we presume to be subject to uniquely favourable preservation, is a significant heritage issue.

Initially, it must be recognised that the intensity of development activity in the North Sea has been associated with extensive archaeological impact assessments undertaken in advance of development (COWRIE 2011; The Crown Estate 2021). Given the level of activity, and the general absence of *in-situ* archaeology, this may suggest that current approaches to development mitigation of this unique landscape are not always appropriate to the nature of the problem. Rapid change may be required to provide adequate mitigation and support for the development of the green energy resource we so badly need. It is some concern that, amongst the North Sea basin nations, only Belgium has fully committed to the curation of marine heritage beyond the 12 nautical mile zone (Dromgoole 2020). With respect of the UK, the country has provisionally agreed to recognise the 2001 *UNESCO Convention of the Underwater Cultural Heritage* as best practise. However, whilst heritage management guidance for this particular area has been developed (e.g. Pater 2020), these guidelines are essentially based on the currently available data and are reactive to commercial development and chance finds (The Crown Estate 2014). The lack of substantive archaeological evidence over much of the southern North Sea ensures that this unique, shared European heritage, has little formal protection or substantive guidance to support preservation, mitigation or documentation in the face of the massive development proposed.

There are, however, positives in the current situation. A major outcome of the palaeogeographic research programmes of the past two decades has been that we have now reached a point where archaeological survey of the deeper waters of the offshore zone may at last be becoming feasible. Moreover, international decarbonisation and development strategies are also key to gaining access to the seabed. The current documentation of large parts of the North Sea, in anticipation of offshore development, will prove an invaluable asset to future archaeological planning (Royal Haskoning DHV nda). We may now have a unique opportunity to test methods of archaeological prospection across parts of the Doggerland landscape that would otherwise have been prohibitively expensive to explore. Collaboration between private stakeholders, archaeologists and heritage professionals is essential if we wish to survey and record deep-water archaeological assets that may be at risk from development (Bailey *et al.* 2020a). In the absence of obligated protection, or curation of submerged prehistory through formal legislation, much future work on the prehistoric archaeology of the offshore zone will require the goodwill and the cooperation of green energy developers, in much the same way that, 15 years ago, the work of the NSPP was dependent upon the outputs of oil and gas exploration and the generosity of companies including PGS.

Given this situation, it is imperative that we continue to develop and maintain a thriving dialogue between researchers, commercial groups, national and regional curators and governmental legislators, in order to assess how the future of North Sea prehistory might be managed in the face of extreme change. In doing so we will ensure that our collective North Sea heritage may be protected or recorded for future generations as, for example in the Belgian SeArch initiative (Missiaen *et al.* 2017; Thal *et al.* 2018).

Making targeted archaeological survey a possibility

In support of an increasingly collaborative approach to exploring the North Sea, it should be noted that the results of commercially driven research in the nearshore, such as the Yangtze Harbour project (Moree & Sier 2015), or UK research projects run by independent trusts, as at Bouldnor Cliff (Momber *et al.* 2011), add substantively to the historic and emerging datasets which underpin our perception of settlement and archaeological potential. The continuing recovery of 'chance' finds within the North Sea also demonstrates the opportunity for research in the area. Indeed, the case for targeted archaeological survey and directed investigation of potential sites within offshore waters should now be considered both practical and an archaeological necessity. Previously considered impossible, our ability to reconstruct localised landscapes, along with the increasing datasets of archaeological finds (Bailey *et al.* 2020b), suggest that we should be confident that if research activities attract appropriate funding, and access to the seabed is secured, then despite the expense of working at sea, such aspirations may soon be realised (Missiaen *et al.* 2021).

The Southern River Valley find

In April-May 2019, an event occurred that might be compared to Pilgrim Lockwood's historic find of the Colinda harpoon; memorialised in Jo Bell's poem introducing this final chapter. A joint expedition was undertaken by members of the *Europe's Lost Frontiers* team (Simon Fitch and Andrew Fraser), and a team from the Flemish Marine Institute (VLIZ), who also facilitated access to the Belgian Navy research vessel RV Belgica. A small part of that expedition was aimed at the survey of the Southern River valley, an underwater palaeochannel located some 20km off the East Anglian coast (Figure 15.2; Fitch *et al.* this volume: chapter 6; Bates *et al.* this volume). This estuary would have existed for some time as part of an established coastline on the Doggerland littoral (Walker *et al.* 2020; Sturt *et al.* 2013). The head of the river approaches the location for the project sediment core associated with evidence for the Storegga Tsunami, ELF001A (Gaffney *et al.* 2020). It is, coincidentally, also in the vicinity of the Colinda harpoon discovery, near the Leman and Ower banks. The Southern River is a topographic feature previously identified by the *Europe's Lost Frontiers* team as potentially key to locating deposits that might contain archaeological material. The pilot survey set out to assess the archaeological potential of the estuary of the valley and, during the course of the survey, a small hammerstone fragment was recovered from a Gilson dredge survey (Figure 15.2).

Provenance of the find

The Gilson Dredge was used to sample top-layer sediments from the seabed over the Southern River estuary to corroborate mapping data and assess whether conditions were favourable for recovery of archaeological material or deposits. Such a method has produced successful results when deployed on the Belgian continental shelf (http://www.vliz.be/en/gilsondredge). Sample collection transects were restricted to 200m in length, to provide some constraint over the provenance of prospective finds. These transects were located on the basis of project mapping, which allowed for the targeting of specific areas based upon microtopography. All recovered samples were sorted on deck by archaeologists and geologists.

The hammerstone fragment was recovered from a transect following seismic line SR7 (Figure 15.3). Seismic Line SR7 trends south west to north east across what would have been the Southern River estuary mouth during the Early-to-Middle Mesolithic. This was judged to be an ideal location for the prospection of archaeological material (Hall 2014). Dredge line SR7 started at the south western bank of the palaeochannel

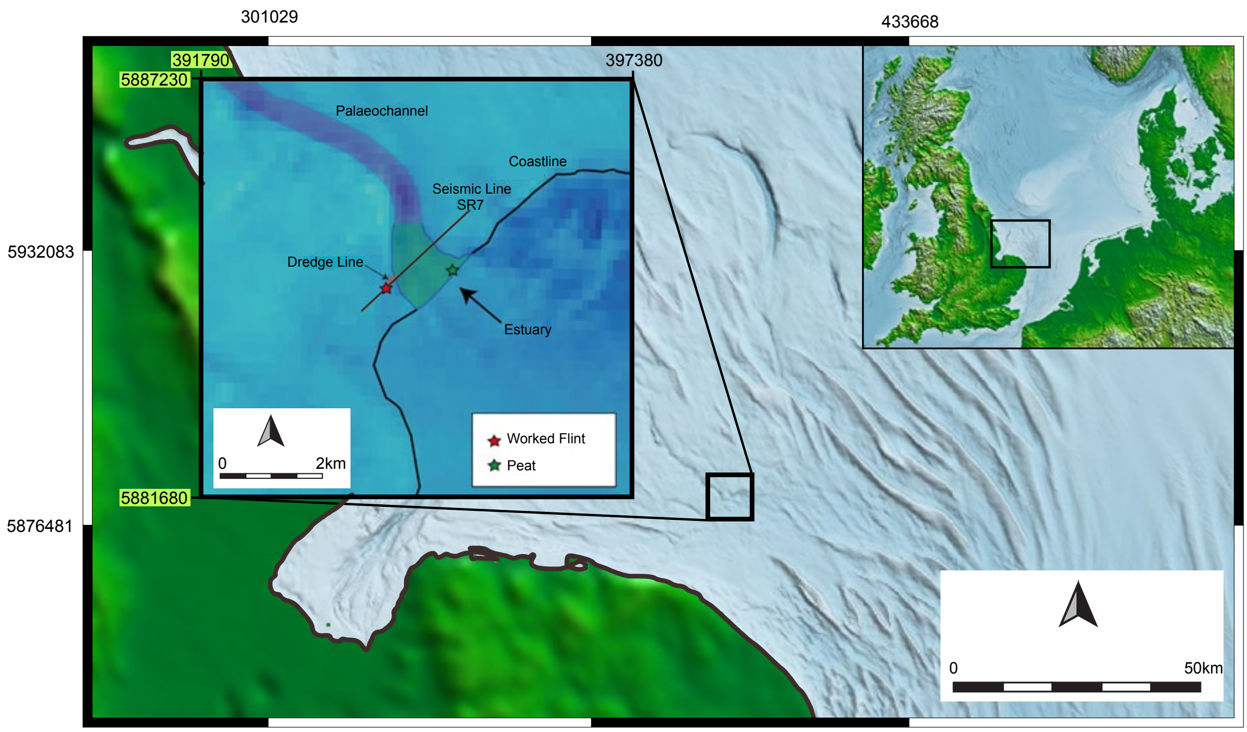

Figure 15.2 Survey on the Southern River estuary

before terminating just after reaching the edge of the channel. Although a precise location for the artefact cannot be given, we can be confident of the general locus from which it was recovered and also, thanks to the nature of the dredge, that it came from a surface or near-surface deposit. Whilst it is recognised that the geomorphological context of the Southern River Estuary is complex and still requires detailed study (Bates *et al*. this volume), radiocarbon dating of core sediments from the vicinity of the transect (VC51) indicate that top sediments in this area were emergent in 9000-8000 BP (Missiaen *et al.* 2021: 8). This gives reasonable grounds to believe that the fragment was recovered from, and probably deposited within, an early Holocene context.

Description of the Southern Valley find

The piece weighs 42.7g, measures 60mm × 49mm, and is 15mm at its greatest width (Figure 15.3). The dorsal surface has a reddish-brown, possible gloss patination (Howard 2002), while the ventral face of the flint is predominantly unpatinated with extensive brown speckling and some later marine concretions. The dimorphic patination and concretion might reflect the surficial exposure of the ventral face. The dorsal surface is devoid of cortex and is entirely covered by small flake scars with the exception of an area at the proximal end, measuring 28mm × 9mm, which is covered by pecking marks. These are consistent with the macroscopic indications of use-wear associated with a hammerstone. On the ventral surface there are two bulbs of percussion, both adjacent to pecking on the dorsal surface. One has a pronounced bulb of percussion but is terminated with a hinge fracture. Ten millimetres to the left of this is the second, much less pronounced bulb of percussion, which was responsible for the detachment of the flake.

The size of the flake and the extent of its dorsal pecking suggests that the hammerstone from which it was detached could have been quite a substantial size. Such a large piece would be unusual in many prehistoric assemblages, and is anomalous within a Mesolithic industry. Such traditions have an emphasis on blade technologies associated with soft hammers and indirect percussion. Hammerstones are not frequently noted in the British Mesolithic, but they do feature prominently in some other European assemblages, such as at the Mesolithic/Neolithic 'occupation phase 2 (5040-4940 cal BC)' at Hardinxveld-Giessendam, De Bruin, a Swifterbant site in the Netherlands (Devriendt 2014: 238).

Broader significance

Numerous Palaeolithic and Mesolithic finds have been located or recovered from Doggerland (Bailey *et al.* 2020a; Long *et al*. 1986; Tizzard *et al*. 2015), but all those recovered from offshore areas (>12 nautical miles from the shore) have been chance discoveries, or the results of work informed by such finds. This hammerstone fragment constitutes, to the best of our knowledge, the first offshore artefact to be found through targeted archaeological prospection without *a priori* artefactual indication of archaeological presence. Given this context, the recovery of this artefact is a significant moment in the prospection of submerged prehistoric landscapes from the offshore zone, and in this sense contrasts significantly with Pilgrim Lockwood's famous find. Although currently only a single artefact, this was recovered during a very limited expedition, cut short by inclement weather and hazardous sea conditions. However, with increasingly extensive mapping, and a better appreciation of the topographic and stratigraphic context of such mapping, it should be expected that many more finds will be recovered if there is continuing investment into archaeological survey and prospection of the area.

Further work is certainly needed to confirm the presence of a more substantial assemblage, and to directly date and provenance any further finds. However, the potential context of the artefact remains an enticing prospect given the circumstances of its recovery. It should also be noted that organic material, probably associated with a fossil forest, was also recovered from the Brown Bank during the same expedition (Louwe Kooijmans 1970; Missiaen *et al*. 2021; Verhart 1995). This suggests that the area also has significant archaeological potential and may retain well preserved landscape deposits. Together, these finds suggest that we are entering a phase of exploration in which direct prospection of areas of archaeological interest may at last become feasible.

Given such finds, and the plans for rapid development of the landscapes studied by *Europe's Lost Frontiers*, a statement on the results of the project may be useful even though this is prior to full publication. It is to be hoped that this will inform the urgent debate that will be necessary to respond to proposed development:

- The *Europe's Lost Frontiers* project has demonstrated the ability to reconstruct landscape evolution over time and to a resolution not previously possible. This has led to the possibility that the characterisation of landscape histories on a localised scale may now be possible in some areas. There remain, however, caveats in the interpretation of data at scales that are commensurate with archaeological settlement or patterns of behaviour. Despite this, the results of the project demonstrate that we may be able to locate areas in Doggerland that might i) have favourable preservation, ii) be accessible for

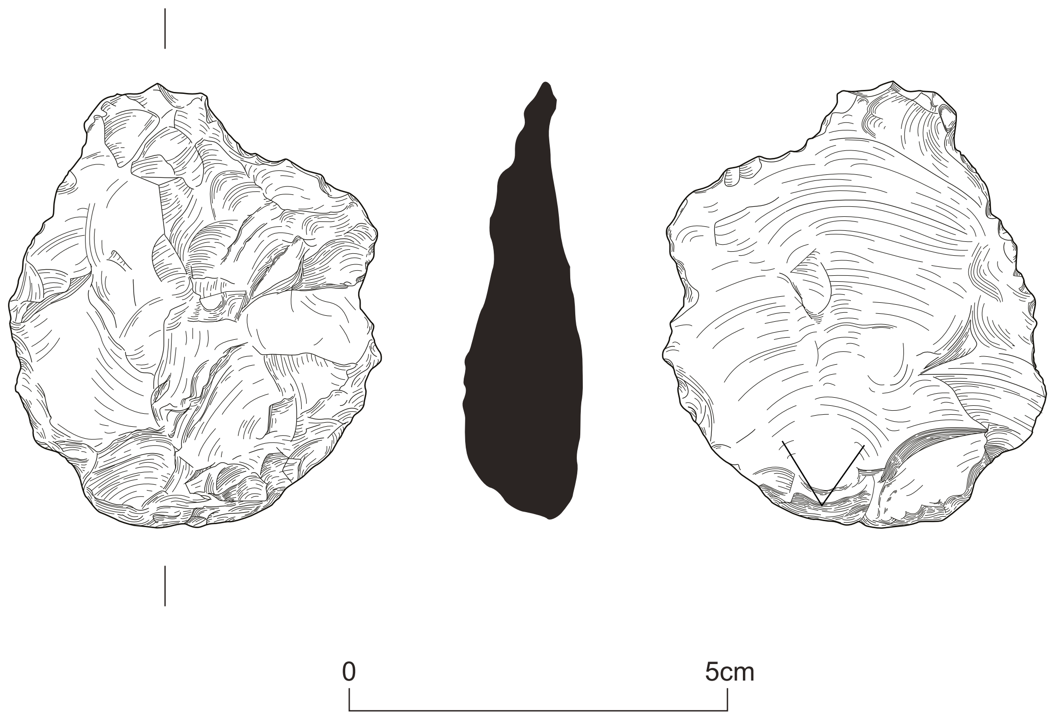

Figure 15.3 A flint hammerstone fragment, approximately 50mm wide, was retrieved during a 2019 survey of the Southern River valley (offshore north of the Norfolk coast) from (or near) a surface dated to 8827±30 cal BP SUERC-85715 (Missiaen *et al.* 2021). Scanned image courtesy of Tom Sparrow.

investigation using appropriate equipment, and iii) have been a location favoured at some point by hunter-fisher-gatherers during the Final Palaeolithic and Early Mesolithic.

- Much of the area we predict to be most favourable for archaeological prospection aligns with that assigned for proposed offshore development. This provides a unique opportunity to work with green energy providers and curators to ensure that our response to climate change in the present need not have excessively deleterious impacts on a uniquely shared part of our European prehistoric heritage, that also contains some of the best records of past responses to climate change.
- It is only through multinational, collaborative research, in cooperation with the private sector, that has made the work of the NSPP and *Europe's Lost Frontiers* projects possible. The solution to identifying, investigating and curating marine prehistory in the future will be equally dependent on professional working relationships with appropriate stakeholders (Arnott & Baggaley 2012; Bicket 2011; BMAPA & English Heritage 2003; 2005; COWRIE 2007; 2011; Dellino-Musgrave *et al.* 2009; Evans *et al.* 2009; Flatman & Doeser 2010; Flemming *et al.* 2014; Flemming 2002; 2004; Firth 2015; Heamagi 2016; Maarleveld 1998; 2020; Missiaen *et al.* 2017; Peeters *et al.* 2009; 2019; 2020; Pater 2020; Satchell 2017; 2018; Salter *et al.* 2014; Sturt *et al.* 2017; The Crown Estate 2013; 2016; 2021; Wenban-Smith 2002; Wessex Archaeology 2017).

Implications for future landscape research

Throughout the *Europe's Lost Frontiers* project, it has been apparent that Doggerland contained a very dynamic landscape, rapidly evolving and changing through time. The evidence for landscape change, from coring and seismic mapping, will be presented in later project volumes (Bates *et al.* this volume; Fitch *et al.* this volume: chapter 4). The results of these studies will carry major implications for future archaeological, geological and geographical research in the area. There are, however, four immediate archaeological issues that follow from the results of *Europe's Lost Frontiers* and the imminent consequences of extensive offshore development in the area (Walker *et al.* this volume):

The first of these concerns the relative stability of the northern coastline of Doggerland compared to other areas of the landscape. For many years, archaeologists have hypothesised that Doggerland extended to the far north, even as far as the Norwegian Trench. The present research, combined with data from Glørstad (2016), clearly indicates that this was not the case. The persistence of the coastline in a much diminished Doggerland has clear implications for the study of the Late Palaeolithic. Issues relating to the nature of cross-cultural connections and the occupation of areas, including Scotland, may now need to be re-assessed (cf. Ballin and Bjerck 2016).

A second issue relates to the effect of the marine inlet in the south of the project study area, and the increasing evidence for a marine presence earlier than previously considered. The existence of such a feature may go some way to explain the distribution of Mesolithic artefacts (Walker *et al*. this volume: Figure 5.3). Previously considered a function of human activity or random recovery, it is no longer surprising that no major clusters of Mesolithic artefacts have been found in the area. Key artefacts, such as the Leman and Ower point, and indeed the flint found at Southern River, are now seen to occur in areas which fringe this inlet. Whilst this absence of artefacts supports the evidence that early marine inundation of this area made it inaccessible to Mesolithic groups, the lack of earlier late Palaeolithic material within the landscape may suggest that this may have been exposed to more intense marine erosion for a longer period, thus explaining a relative absence of related material in this area.

The third issue arising from new landscape mapping follows from the identification of three main flooding routes through the Doggerland landscape: the Outer Silver Pit, the Elbe, and the southern inlet. These are clearly the primary vectors of flooding and, as we begin to understand the implications of the inundation process, a more complex pattern of landscape development is emerging which raises significant questions for our understanding of the Mesolithic occupation of Doggerland. The most immediate, visual implication of new Doggerland is that nearly all the rivers in the British, Danish, German and Dutch sectors, and on the Dogger Bank itself, must act as routeways to, and through, this region. Within a broader context, and if we expand this to cover the extended, terrestrial catchments of these river systems, then this landscape could potentially act as a focus for a vast area of Mesolithic, north west Europe. As primary communication routes these features must have stimulated travel, trade and facilitated contact between communities over a very large area (Gaffney *et al.* 2009). The impact of these corridors on human occupation and migration patterns remains to be explored, but previous research has indicated the significant implications for the grouping and cultures in the area caused by landscape change (Fitch 2011). More detailed research into the nature of inundation and its impacts on its occupants may therefore hold the key to a fuller understanding of life in north west Europe during the Mesolithic. It is therefore a necessity that future research incorporates these areas into our archaeological narratives, as it offers the potential to add significant new insights into trade and cultural development during this period of change.

The fourth issue involves the resolution of data now available for study. Whilst previously unimaginable detail of the landscape of Doggerland is now being revealed, challenges remain in understanding the landscape in relation to local sea-level history. The sea-level models in the marine zone generally rely on relatively widely spaced index points, yet it is increasingly apparent from studies on land that detailed, local sea-level histories are required to fully understand issues associated with rates of inundation and coastline formation. Comparison of the current results to existing maps, e.g. Coles 1998 or Gaffney 2007, demonstrates that there is a far greater complexity present within the landscape than has previously been appreciated or modelled. New data, including that of the modelling programme undertaken by *Europe's Lost Frontiers* will assist in the refinement of both current models and our understanding of the landscape (Murgatroyd *et al*. 2022).

The value of resolving these issues is significant. The importance of coastlines as key resource areas, for instance, has long been understood in terrestrial or near shore contexts (Bell 2007). Provision of improved information from the North Sea will support archaeologists and sea-level modellers to understand the effects of marine inundation on past human populations in a manner previously impossible. Such information may also provide results that are useful for studies of future sea-level rise.

Looking back, moving forward

From the preceding text, it should be clear that the archaeology of submerged prehistoric landscapes has been revolutionised in recent decades. Without doubt, this is partly driven by advancements made in technology. The developments we have witnessed in remote sensing are, perhaps, the clearest evidence for such change. However, the capacity for archaeologists to visualise and model these data is also significant (Fitch *et al*. 2007; Fitch this volume: chapter 4); Murgatroyd *et al*. this volume). The development of novel environmental analyses should also be clear and is most evident in the relatively recent prominence of sedaDNA as a high-potential investigative technique (Allaby *et al*. this volume). We can be certain that future technology development will continue to underpin exploration. In a world driven by 'Big Data', the information generated by extensive marine prospection must rank near the top in archaeological terms. These are, however, emerging technologies. We are only at the beginning of understanding how to integrate these data more effectively, although we should be confident that new aggregated datasets will dramatically enhance our capacity to interpret the exponentially complex landscapes of Doggerland.

Unsurprisingly, since Coles classic paper in 1998, research undertaken in the North Sea by many archaeologists, has been widely recognised as critical for understanding the prehistory of north west Europe, both for the Early Holocene, and much further back in time. However, the North Sea is by no means the only place where this is true, although it does remain the best studied submerged palaeolandscape. Elsewhere, prehistorians are engaging with the realities and potential of underwater archaeological evidence in a way that simply was not the case 25 years ago. These groups are also studying other, frequently larger, landscapes and facing similar technical and interpretative challenges. The submerged Pacific coastal plain is increasingly popular as a hypothesised means for the pioneering peopling of the Americas (Braje *et al.* 2019; Davis and Madsen 2020). Similarly, the submerged coastlands of East Africa and the South Asian subcontinent have figured prominently in recent discussions of hominin dispersals including 'Out of Africa' (Erlandson and Braje 2015). Projections of Sundaland at its fullest extent indicate a vast amount of habitable land for the first peoples as they explored Island South East Asia. It seems increasingly apparent that these and the submerged coastlines of the Sahul must have played an important role in facilitating the early colonisation of the antipodean archipelago (Benjamin *et al.* 2020; Crabtree *et al.* 2021).

Coupled with the archaeological significance of these landscapes, is the recognition of just how much land has been lost to the sea over time, and the acknowledgement that this is neither a unilinear nor a final process (Dobson 2014). Whilst future sea-level rise is inevitable, the sea has not risen uniformly around the world. It has risen in some areas, and receded in others, and will continue to do so. Understanding these processes allows academics, and archaeologists specifically, to inform society more broadly as to just how much of the prehistoric landscape is submerged and effectively lost, but also how peoples in the past have dealt with similar challenges.

Whilst it should be clear that any assessment of the value of marine palaeolandscape research is entangled within the politics of contemporary climate challenges, it should not be forgotten that this debate has not been restricted to engagement with the general public or private stakeholders. One of the most important obstacles to overcome has been winning over our own field (Bailey 2004). In reviewing past archaeological literature, it is not difficult to find acknowledgement that submerged landmasses must have been important (Jacobi 1976; Morrison 1980; Smith 1992), although this was usually in respect of what they connected rather than their implicit value as inhabited landscapes. Such debate was also before the North Sea seabed had actually become the subject of general archaeological interest, rather than as an archaeological curiosity (e.g. Louwe Kooijmans 1980: 115-116; 1970). In such a context, the relative inaccessibility of these areas, and the technical barriers to their study, had reduced them being either a known unknown or excluded from consideration altogether (see Coles 1998 for critique).

Dissatisfaction with such a position has also driven research. A good example of such a position can be found in discussion related to the peopling of the Americas. In 1992, Norman Easton discussed the Coastal Migration Theory for the earliest peopling of the Americas. He suggested three methodological problems, previously perceived by some to be insurmountable, and which had historically challenged the investigation of submerged marine prehistory. These are: i) whether it is possible to find archaeological evidence in the submarine environment, ii) whether post-depositional degradation might have rendered any archaeological material impossible to evaluate, and iii) whether, if a site with archaeological integrity was found, it would be possible to carry out controlled excavations (Easton 1992: 34).

We are now approaching the position that it is possible to find archaeological material in the submarine environment, although knowing where to look remains an ongoing process of refinement. We know that some areas with excellent conditions of preservation can yield materials of interest, and that these materials can be excavated and recovered with at least some control. While contemporary discussions consider the place of submerged prehistory in archaeological and anthropological theory (Lemke 2021), it is still worth remembering that just thirty years ago, it was not widely recognised that such a pursuit was viable or even worthwhile (Easton *et al.* 2021).

The progress that has been made in recent decades demonstrates the change in attitudes towards the significance and potential of the submerged prehistoric record within the archaeological community. It is now vital that we look ahead and plan, within the community, how we may best deal with future challenges. Currently, the most pressing challenge marine palaeolandscape research faces globally, will be the desire to develop infrastructure in the offshore zone, and particularly through the establishment of windfarms in pursuit of greener energy. Having come so far in our understanding of the palaeogeography of Doggerland, it is imperative that we seek to minimise the risk of damage or loss to the archaeological landscape incurred by development, and foster a working relationship with the energy providers who are seeking to develop much of the area that we consider of archaeological significance. Action is urgently needed, in accordance with the urgency with which governments around the world are seeking to invest in such enterprises. If we do not take the opportunity to establish a working relationship with government agencies, developers and national curators, then the move to capitalise on offshore infrastructure development will pose a significant obstacle to future research. If such a dialogue is established, then these strategic developments will present a tremendous opportunity, and a means to continue developing our research and knowledge of Doggerland, and submerged landscapes around the world.

Chapter 16

Supplementary data to 'The archaeological context of Doggerland during the Final Palaeolithic and Mesolithic' by Walker, Gaffney, Fitch, Harding, Fraser, Muru and Tingle

James Walker, Vincent Gaffney, Simon Fitch, Rachel Harding, Andrew Fraser, Merle Muru and Martin Tingle

A note on sites and findspots mentioned in Chapter 5

Sites and findspots within this chapter, and Figure 5.4 specifically, relate to entries from the SplashCOS database listed as either Mesolithic or Palaeolithic-Mesolithic in typo-chronological affinity. The Michelsburg axes from the vicinity of the Brown Bank are also included here. These are diagnostically younger in age, and anomalous by their being the only Neolithic finds known from well beyond the nearshore zone. Two further Neolithic findspots (two single polished axes) reported from the northern coast of the Doggerbank have been excluded from representation as they lack reliable provenance (see Tables 5.1 and 5.2). The stratified site spots in Figure 5.4 refer to Seaton Carew (1) on the northeast coast of England, the Yangtze Harbour site (2) at Maasvlakte 2, and Bouldnor Cliff (3). Although not part of the southern North Sea landscape, Bouldnor is marked, along with the middle Palaeolithic excavations at Area 240 (4), as areas of importance/interest also discussed in the text. The other areas highlighted for reference in the text include the Southern River Valley (5), and the Brown Bank. Various Neolithic sites adjacent to contemporary shorelines were not included. Palaeolithic sites or findspots of indeterminate age were also excluded, with the exception of the excavations at Area 240. Sites and findspots from inland waters were excluded as out of scope. This includes examples from rivers in Essex, the Thames Estuary, upriver from the Rhine-Meuse Delta, and from the interior of the Limfjord estuary in Denmark.

The findspots and sites presented in the Figures from this chapter may vary in precision of location. Some findspots may also refer to multiple locations. For these reasons, Figure 5.4 should be considered a selective guide to the late and Postglacial archaeology of Doggerland, rather than a comprehensive representation. Nevertheless, it illustrates that most known sites/findspots are located in territorial seas (nearshore waters), that the overwhelming majority of these are unstratified findspots rather than stratified deposits, and that most offshore findspots cluster around the southern Marine inlet, the Brown Bank and the waters between East Anglia and lowland Europe.

Chapter 17

Supplementary data to ‘Constructing sediment chronologies for Doggerbank, North Sea’ by Kinnaird, Bates, Bateman and Srivastava

Tim Kinnaird, Martin Bates, Rebecca Bateman and Aayush Srivastava

Luminescence screening measurements (Figures 12.3 and 12.4)

Cores were spilt under subdued light conditions at sample preparation facilities at the University of Wales Trinity Saint David, Lampeter. One half of the core was half retained for sedimentological and palaeotonological analyses and the other, used for OSL sampling and profiling. Sedimentological descriptions of all cores were completed ahead of OSL sampling and profiling.

Cores were sampled by the author TK, during three visits to Lampeter: cores ELF001A, 002, 005B, 012 and 019 were sampled in November 2017; cores ELF003, 007, 022, 027, 031A, 034, 039, 040A, 042, 044A, 045, 047, 049, 051, 053, 054, 059, 060 in September-October 2018; and core 020 in January 2020 (Kinnaird and Bates 2018).

Bulk sediment samples were appraised using portable OSL equipment (Sanderson and Murphy 2010), using the methodology of Kinnaird *et al.* (2017) and Turner *et al.* (2021).

Sample preparation and analysis

Sample preparation and OSL analysis was undertaken under safe light conditions at the luminescence laboratories at the School of Earth and Environmental Sciences, University of St Andrews. Sample preparation for inductively-coupled plasma mass spectrometry (ICPMS) was undertaken in class-100 metal-free clean rooms at the STAiG laboratories, University of St Andrews. High-resolution gamma spectrometry (HRGS) measurements were made at the Environmental Radioactivity Laboratory at the School of Biological and Earth Sciences, University of Stirling. Core scanning by X-ray Fluorescence was undertaken at Aberystwyth University.

Mineral Preparation of Quartz

Standard mineral preparation procedures as routinely used in OSL dating were used to extract sand-sized quartz from each sample (cf. Kinnaird *et al.* 2017).

The subset of samples taken forward to laboratory analysis (stage 2, OSL screening and characterisation), were subjected to rapid mineral preparation procedures (cf. Kinnaird *et al.* 2017; Turner *et al.*, 2021), including wet sieving to obtain the 90-250µm fraction and repeated hydrochloric (HCl) and hydrofluoric (HF) acid washes / etches to concentrate ‘quartz’ and/or ‘polyminerals’. HF-etched quartz was dispensed to disc in duplicate.

The subset of samples taken forward to full quartz SAR OSL dating (stage 3) were subjected to further mineral purification procedures (cf. Kinnaird *et al.* 2017; Turner *et al.* 2021). Samples were wet-sieved to obtain the 90-250µm size fraction, then treated in 1M HCl for 10 minutes, followed by 40% HF for 40 minutes, and a further treatment in 1M HCl for 10 minutes. The HF-etched fractions were then density separated in LST heavy liquids at concentrations of 2.64 and 2.74gcm-3, to obtain concentrates of feldspar (< 2.64gcm-3), quartz (2.64-2.74gcm-3) and heavy minerals (>2.74gcm-3). The quartz concentrates were re-sieved at 150µm.

Preparation of Samples for HRGS

HRGS measurements were performed on dried, composite bulk samples, generated using bulk sediment from the position of the dating sample, but also, sediments from the adjacent layers in the stratigraphy. 10-20g quantities of sediment from horizons of interest were dried to a constant weight in an oven set at 50°C, then amalgamated by weighing out discrete quantities of sediment based on the distance between the relative positions of the dating and bulk sediment samples.

Preparation of Samples for ICPMS

ICPMS measurements were performed on dried, homogenised sub-samples of sediment taken from discrete horizons in the core. 15-20g of sediment were taken from each sample, then ground and homogenised using a Tema Machinery Disc Mill. 2g sub-samples were treated in a furnace set at 1000 °C for 6 hours. 50mg quantities of sediment from each sub-sample were prepared for ICPMS using total rock digestion by Ammonium Bifluoride (Zhang *et al.* 2002). This method was implemented here, as 1.) 50mg of rock powder and 200mg of NH_4HF_2 powder into 7ml screw-top Teflon vials; 2.) which were then, capped and heated at 230°C

Observations from initial luminescence screening / pOSL	Inferences from pOSL	Observations from calibrated luminescence screening	Inferences from calibrated dataset
unit 1A-1, 0.00-0.21m			
- fluctuating OSL intensities between 1.75 and 5.30 × 10^5 counts, with no stratigraphic coherence. - low depletion indices, <1.3	- modern, mobile sands - low depletion indices suggest material poorly bleached, and signals include residuals	- stored doses range between 0.7 and 1.6Gy, with no stratigraphic coherance	- **modern, mobile sands**
unit 1A-2, 0.21 – 0.67m; unit 1A-3, 0.67-0.90m			
- no progression in OSL intensities with depth, fluctuate between 1.08 × 10^5 and 1.44 × 10^6 counts - higher depletion indices than observed in 1A-1 - signal-depth progression from 6.01 × 10^5 to 9.26 × 10^6 counts - higher depletion indices than observed in 1A-1, *c*.1.7	- recent sands - with stratigraphic coherence - low sedimentation rate	- progression in stored dose values with depth, from *c*.1.6Gy to 6-7Gy - good reproducibility between aliquots - sensitivities drop off through unit from × 10^4 to 10^5 counts Gy^{-1}	- **recent sands** - in situ, coherent stratigraphy - 'short' chronology - 'slow' sedimentation rate - well-bleached at deposition
unit 1A-4, 0.90-1.09m			
- inverted signal-depth progression from 5.71 to 4.96 × 10^6 counts - lowest depletion indices observed in core aside from 1A-1	- tidal mudflat - step change in OSL intensities, implies different provenance - low depletion indices suggest material poorly bleached, and signals include residuals	- 'spike' in stored dose values, >14Gy - poor reproducibility between aliquots - sensitivities continue to drop off, × 10^4 counts Gy^{-1}	- tidal mudflats - quartz/feldspar sourced from a different provenance - poor to partial bleaching at deposition
unit 1A-5, 1.09-1.19m; unit 1A-6, 1.19-1.51m			
- inverted signal-depth progression from 2.21 to 1.28 × 10^6 counts - lower signal intensities correlate with higher depletion indices - 1.21-1.29m: normal signal-depth progression from 8.05 to 8.76 × 10^5 counts - 1.36-1.40m: inverted signal-depth progression from 1.24 × 10^6 to 8.09 × 10^5 counts - 1.46-150m: inverted signal-depth progression from 1.31 × 10^6 to 8.90 × 10^5 counts - cyclicity to depletion indices – first influx >1.6, then 1.5	- tsunami deposit 1; waning flow or new wave? - tsunami deposit 2; evidence of multiple waves: *cyclicity* to intensities and depletion ratios: 1. first influx of sediment, low OSL intensity and high depletion index; 2. then, higher intensities and lower depletion indices - note, signal intensities vary over similar magnitude and range, common provenance	- stored dose values consistent at *c.* 10Gy - good reproducibility between aliquots - 1.21-1.29m: normal age-depth progression from 9.5-10Gy to >12Gy; poor reproducibility between aliquots - 1.36-1.46m: some scatter to Des, between 6 and 13Gy - 1.50-1.55m: stored dose values consistent at *c.* 8Gy - cyclicity to sensitivity, in magnitude and range – first influx > × 10^4 counts Gy^{-1}, then × 10^3 counts	**- tsunami deposit: evidence of multiple waves** - cyclicity to luminescence proxies: first influx, well-bleached and characterised by > sensitivities (and > depletion indices); waning flows, only partial bleached and characterised by < sensitivities (and < lower depletion indices)
unit 1A-7, 1.51-3.51m			
- 1.55-1.80m, signal intensities drop from 1.24 × 10^6 to 5.78 × 10^5 counts; - 1.80-2.00m, signal intensities increase from 5.78 × 10^5 to 1.16 × 10^6 counts; - from 2.00m, intensities fluctuate between 2.40 × 10^5 and 1.59 × 10^6 counts, with a mean of 5.89 × 10^5 counts	- tidal mudflats - with stratigraphic coherence from 1.55 to 2.00m - no 'prolonged' chronology to the unit	- 1.55-2.00m: stored dose values fluctuate between 10 and 13Gy - from 2.00m, stored dose values fluctuate around a mean of 14.5Gy	- tidal mudflats - poor to partial bleaching at deposition - no 'prolonged' chronology

Table 17-1. Observations / inferences from preliminary OSL screening and subsequent calibrated OSL characterisation, example ELF001A

in an electric oven for 3hr; 3.) following cooling, 2 ml of HNO_3 was added, and the vials capped and fluxed at 160°C for 1hr; 4.) after 1 hour, the vials were opened and evaporated to near dryness on the hotplate; 5.) then, 2ml of 6M HCl was added and fluxed at 140°C for 6 hours; 6.) after the 6 hours, the vials and evaporated to near dryness on the hotplate; 7.) the final residue was then taken up in 1mL of 2% (v/v) HNO_3.

Calibrated luminescence measurements (Figures 12.3 and 12.5)

Calibrated luminescence screening methods, as previously utilised by Kinnaird *et al.* (2017) were used to generate stored sensitivity- and dose-depth profiles for core ELF001a. Luminescence sensitivities (photon counts per Gy) and stored dose (Gy) were evaluated on paired aliquots of HF-etched quartz, using procedures modified from Burbidge *et al.* (2007), Sanderson *et al.* (2003) and Kinnaird (2017).

All OSL measurements were carried out using either a Risø TL/OSL DA-20 (Risø 2) or DA-15 (Risø 3) automated dating system, equipped with a $^{90}Sr/^{90}Y$ β-source for irradiation (dose rates at time of measurement, 1.10 and 0.03Gy/s, respectively) blue LEDs emitting around 470nm and infrared diodes emitting around 830nm for optical stimulation. OSL was detected through 7.5mm of Huoya U-340 filter and detected with a 9635QA photomultiplier tube. OSL was measured at 125°C for 60s. The OSL signals, *Ln* and *Lx*, used for equivalent dose (De) determinations were obtained by integrating the OSL counts in the first 2.4s and subtracting an equivalent signal taken from the last 9.6s. The protocol implemented here involved a readout of the natural signal, followed by a 1Gy test dose, then readouts of the regenerated cycles following a series of nominal doses between 5 and 120Gy, each with a subsequent 1Gy test dose. For all, OSL followed a preheat of 220°C, and was measured at 125°C for 60s.

Apparent dose estimates were made in Luminescence Analyst v.4.31.9, using dose response curves forced through zero and the two to three normalized regenerative points with an exponential function.

Equivalent dose determinations (Figures 12.6 and and S1.1)

Equivalent dose (De) determinations were determined using a single-aliquot regenerative dose (SAR) method (Kinnaird *et al.* 2017; Murray and Wintle 2000). The SAR OSL protocol was implemented here, using five regenerative doses (nominal doses of 1, 2.5, 5, 10 and 30Gy), with additional cycles for zero dose, repeat or 'recycling' dose and IRSL dose.

Data reduction and De determinations were made in Luminescence Analyst v.4.31.9. Individual decay curves were scrutinised for shape and consistency. Dose response curves were fitted with an exponential function, with the growth curve fitted through zero and the repeat recycling points. Error analysis was determined by Monte Carlo Stimulation.

Dose rate determinations (Figure 12.8)

HRGS measurements

All sample handling, processing and analysis were undertaken in accordance, and in compliance with ERL protocols LS03.1, 03.2 & 03.6 and LS08. HRGS measurements were performed using a 50% relative efficiency 'n' type hyper-pure Ge detector (EG&G Ortec Gamma-X) operated in a low background lead shield with a copper liner. Standard laboratory efficiency calibrations were used, derived from GE Heathcare Ltd QCY48 Mixed Radionuclide Spike and DKD RBZ-B44 ^{210}Pb spike. All absolute efficiency calibrations were corrected for variations in sample density and matrix. Sample counts for HRGS were for 80-85ks, interleaved with background counts for 200ks. Nuclide specific estimates for U and Th decay series nuclides were assessed relative to measurement precision, then weighted combinations used to estimate mean activity concentrations (Bq kg^{-1}) and elemental concentrations (% K and ppm U, Th) for the parent activity. The activity concentrations of potassium, uranium and thorium were converted into infinite-matrix dose rates, using the conversion factors of Guérin *et al.* (2011), and grain-size attenuation factors of Mejdahl (1979).

ICPMS measurements

50mg quantities of sediment from each sub-sample were prepared for ICPMS using total rock digestion by Ammonium Bifluoride (Zhang *et al.* 2002), adapted to include additional fluxes in hot HCl and HNO_3. Samples were prepared by gravimetric serial dilution at 10 and 1000x in 0.4 M HNO3:0.02 M HF, for analysis of U and Th, and K, respectively. ICPMS analyses were conducted on two Aligent systems, the 7500 or the 8900 ICP-MS instruments. Samples and standards were introduced through a PFA spray chamber in 0.4 M HNO3:0.02 M HF using a self-aspirating nebuliser (100μL min-1). Analytical calibration standards (0.1, 1, 10, 100 and 500ppb for all elements) were prepared by gravimetric serial dilution from 10ppm certified stock multi-element solutions (Agilent) in 0.4 M HNO3:0.02 M HF. Inter-calibration between counting and analogue detection modes was performed prior to each analytical session. Reference materials from IAG, USGS, MINTEK were prepared and run in batch with unknown samples. Again, concentrations of potassium, uranium and thorium were converted into infinite-matrix dose rates, using conversion factors and grain-size attenuation factors.

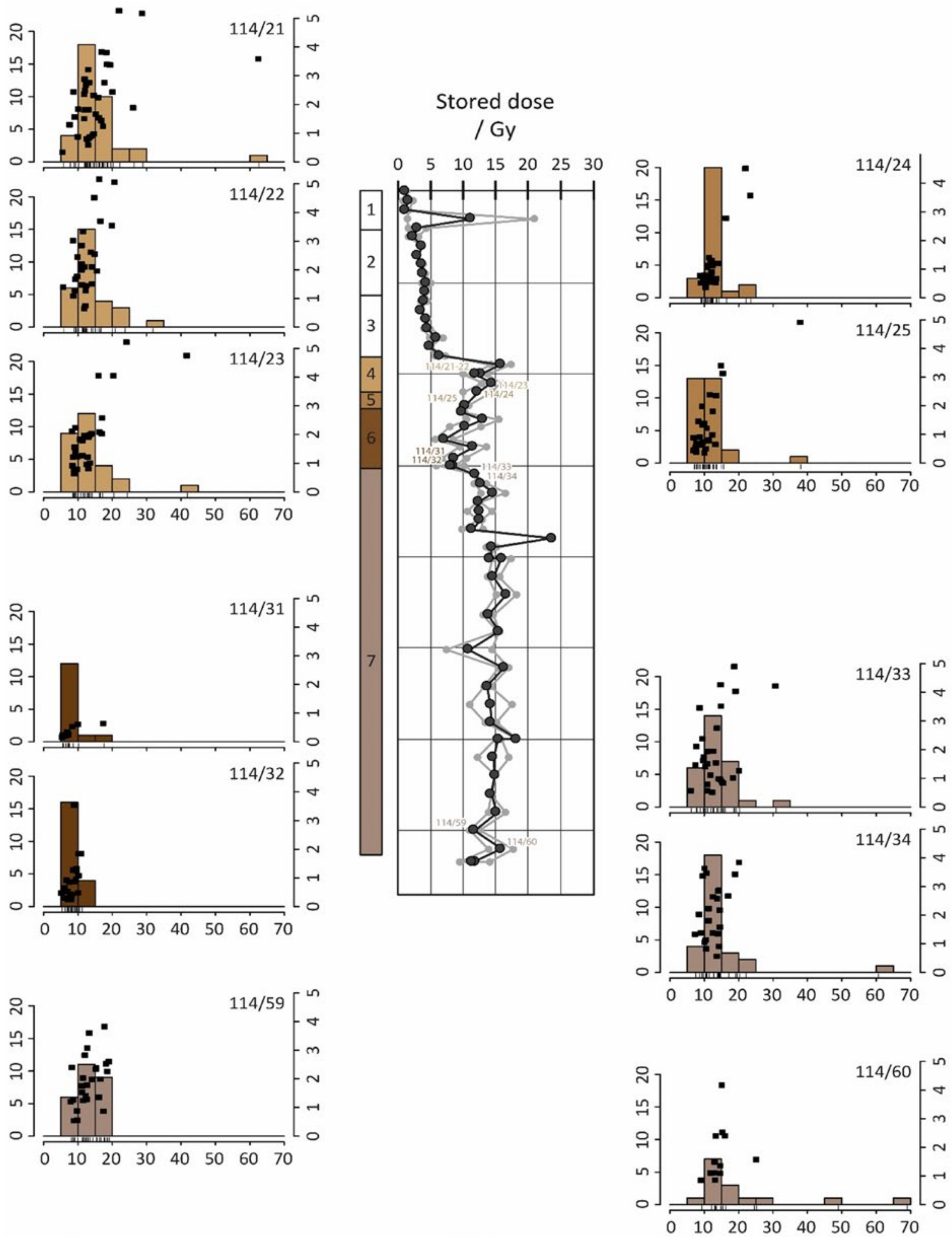

Figure 17.1 Equivalent dose distributions for units 4, 5, 6 and 7 from ELF001A as histogram plots

Bibliography

Aaris-Sorensen, K. 2009. *Diversity and dynamics of the mammalian fauna in Denmark throughout the last glacial-interglacial cycle, 115–0 kyr BP*. London: Wiley-Blackwell.

Adams, J., *et al.* 2011. *Maritime and Marine Historic Environment Research Framework*. York: Archaeology Data Service. https://doi.org/10.5284/1000148

Ahmed, E., *et al.* 2018. Archaeal community changes in late glacial lake sediments: Evidence from ancient DNA. *Quaternary Science Reviews* 181: 19-29.

Aitken, M.J. 1958. Magnetic Dating - I. *Archaeometry* 1 (1): 16-20.

Aitken, M.J. 1983. Dose rate data in SI units. *PACT: Journal of the European Study Group on Physical, Chemical and Mathematical Techniques Applied to Archaeology* 9: 69-76.

Alappat, L., *et al.* 2010. Establishing the late Pleistocene-Holocene sedimentation boundary in the southern North Sea using OSL dating of shallow continental shelf sediments. *Proceedings of the Geologists' Association* 121(1): 43-54.

Ali, J.R., C. King and E.A. Hailwood 1993. Magnetostratigraphic calibration of early Eocene depositional sequences in the southern North Sea Basin, in E.A. Hailwood and R.B. Kidd (eds) *High Resolution Stratigraphy* (Geological Society London Special Publication 70): 99-125. London, Geological Society.

Alsos, I.G., *et al.* 2016a. Sedimentary ancient DNA from Lake Skartjørna, Svalbard: Assessing the resilience of arctic flora to Holocene climate change. *The Holocene* 26: 627-642.

Alsos, I.G., *et al.* 2016b. The role of sea ice for vascular plant dispersal in the Arctic. *Biology Letters* 12: 2016026420160264. http://doi.org/10.1098/rsbl.2016.0264

Allcock, A.L., *et al.* 2017. Molluscs (Phylum Mollllusca), in P.J. Hayward and J.S. Ryland (eds) *Handbook of the Marine Fauna of North-West Europe*: 455-602. 2nd Edition. Oxford: Oxford University Press.

Amkreutz, L., *et al.* 2017. Meer Dan Bijvangst! De Prehistorische Archaeologie Van De Noordzee. *Cranium* 34: 34-47.

Amkreutz, L., *et al.* 2018. What lies beneath. late Glacial human occupation of the submerged North Sea landscape. *Antiquity* 92 (361): 22-37. https://doi.org/10.15184/aqy.2017.195

Amkreutz, L. and M. Spithoven 2019. Hunting Beneath the Waves. Bone and Antler points from North Sea Doggerland off the Dutch Coast, in D. Groß, *et al.* (eds) *Working at the sharp end: From Bone and Antler to Early Mesolithic Life in Northern Europe* (Untersuchungen und Materialien zur Steinzeit in Schleswig-Holstein und im Ostseeraum 10): 338-404. Kiel/Hamburg: Wachholtz Verlag. https://doi.org/10.23797/9783529018619-16

Amkreutz, L. and S. van der Vaart-Verschoof (eds) 2021. *Doggerland. Verdwenen wereld in de Nordzee*. Leiden: Sidestone Press.

Andersen, K., *et al.* 2012. Meta-barcoding of 'dirt' DNA from soil reflects vertebrate biodiversity. *Molecular Ecology* 21: 1966-1979.

Andersen, S.H. 2005. En glittestok fra Dogger BankeNordsøen. *Kuml* 54 (54): 9-15.

Andersen, S.H. 2013. *Tybrind Vig: Submerged Mesolithic settlements in Denmark*. Aarhus: Aarhus University Press.

Anderson-Carpenter, L.L., *et al.* 2011. Ancient DNA from lake sediments: bridging the gap between paleoecology and genetics. *BMC Evolutionary Biology* 11: 30. https://doi.org/10.1186/1471-2148-11-30

Anderson, R. and B. Rowson 2020. *Annotated List of the Non-Marine Mollusca of Britain and Ireland*. London: The Conchological Society.

Arnott, S.H.L. and P.A. Baggaley 2012. The Role of Archaeology in Offshore Site Investigation for Renewable Developments. Paper presented at the Offshore Site Investigation and Geotechnics: Integrated Technologies - Present and Future, London, UK, September 2012.

Armitage, S.J. 2015. Optically stimulated luminescence dating of Ocean Drilling Program core 658B: Complications arising from authigenic uranium uptake and lateral sediment movement. *Quaternary Geochronology* 30: 270-274.

Armitage, S.J. and R.C. Pinder 2017. Testing the applicability of optically stimulated luminescence dating to Ocean Drilling Program cores. *Quaternary Geochronology* 39: 124-130.

Athersuch, J., D.J. Horne and J.E. Whittaker 1989. Marine and brackish water ostracods. *Synopsis of the British Fauna (New Series)*, no. 43. Leiden: E.J. Brill (for the Linnaean Society of London and The Estuarine and Brackish-water Sciences Association).

Avery, R.S., *et al.* 2017. A new Holocene record of geomagnetic secular variation from Windermere, UK. *Earth and Planetary Science Letters* 477: 108-122.

Baglieri, A., *et al.* 2014. Chemical and spectroscopic characterization of insoluble humic acid fractions at different pH values. *Chemical and Biological Technologies in Agriculture* 1: 1-11.

Bahorich, M. and S. Farmer 1995. The coherence cube. *The Leading Edge* 14: 1053-1058.

Bailey, G. 2004. The wider significance of submerged archaeological sites and their relevance to world prehistory, in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research

Report 141): 3-10. York: English Heritage/Council for British Archaeology.

Bailey, G.N. and N.C. Flemming 2008. Archaeology of the continental shelf: Marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews* 27: 2153-3165.

Bailey, G.N., J. Harff and D. Sakellariou (eds) 2017. *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20). Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1

Bailey, G., *et al.* 2020a. The Archaeology of Europe's Drowned Landscapes: Introduction and Overview, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 1-26. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_1

Bailey, G., *et al.* 2020b. Appendix: The SPLASHCOS Viewer, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 537-542. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2

Bailey, G., *et al.* 2020c. Great Britain: The Intertidal and Underwater Archaeology of Britain's Submerged Landscapes, in G. Bailey, *et al.* (eds), *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 189-219. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_10

Bailey, G., S.H. Andersen and T.J. Maarleveld 2020d. Denmark: Mesolithic Coastal Landscapes Submerged, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 39-76. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_3

Ballin, T.B. 2017. Rising waters and processes of diversification and unification in material culture: the flooding of Doggerland and its effect on north-west European prehistoric populations between *c.* 13,000 and 1500 cal BC. *Journal of Quaternary Science* 32: 329-339.

Ballin, T.B. and H.B. Bjerck, 2016. Lost and found twice: discussion of an early post-glacial single-edged tanged point from Brodgar on Orkney, Scotland. *Journal of Lithic Studies* 3: 1-20.

Ballin, T.B., *et al.* 2018. *A Late Hamburgian settlement in southern Scotland – its lithic artefacts and natural environment*. Oxford: Archaeopress.

Bálint, M., *et al.* 2018. Environmental DNA time series in ecology. *Trends in Ecology and Evolution* 33 (12): 945-957.

Barmpoutis, A. 2013. Tensor body: Real-time reconstruction of the human body and avatar synthesis from RGB-D. *IEEE transactions on cybernetics* 43 (5): 1347-1356.

Bartley, D.D. and C. Chambers 1992. A pollen diagram, radiocarbon ages and evidence of agriculture on Extwistle Moor, Lancashire. *New Phytologist* 121: 311-320.

Bang-Andersen, S. 1995a. Mesolithic man and the rising sea spotlighted by three tapes-transgressed sites in SW Norway, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monograph 53): 113-121. Oxford: Oxbow Books.

Bang-Andersen, S. 1995b. The Mesolithic of Western Norway: prevailing problems and possibilities, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monograph 53): 107-112. Oxford: Oxbow Books.

Barton, N. and A. Roberts 2004. The Mesolithic Period in England: Current Perspectives and New Research, in A. Saville (ed.) *Mesolithic Scotland and its Neighbours. The early Holocene Prehistory of Scotland, its British and Irish context, and some Northern European Perspectives*: 339-358. Edinburgh: Society of Antiquaries of Scotland.

Barton, C.M., *et al.* 2018. Risk and resilience in the late glacial: A case study from the western Mediterranean. *Quaternary Science Reviews* 184: 68-84.

Barton, C.M. and J. Riel-Salvatore 2014. The formation of lithic assemblages. *Journal of Archaeological Science* 46: 334-352.

Bateman, M.D. 2015. The application of luminescence dating in sea-level studies, in I. Shennan, A.J. Long, and B.P. Horton (eds) *Handbook of Sea-level Research*. Chichester: John Wiley and Sons.

Bateman, M.D., *et al.* 2007. Detecting post-depositional sediment disturbance in sandy deposits using optical luminescence. *Quaternary Geochronology* 2 (1-4): 57-64.

Bateman, M.D., *et al.* 2003. Investigations into the potential effects of pedoturbation on luminescence dating. *Quaternary Science Reviews* 22 (10-13): 1169-1176.

Batt, C.M., *et al.* 2017. Advances in archaeomagnetic dating in Britain: New data, new approaches and a new calibration curve. *Journal of Archaeological Science* 85 (Supplement C): 66-82.

Battram, N.M., *et al.* 2015. Organic matter biomarker analysis as a potential chemostratigraphic tool for late Pleistocene tills from the Hudson Bay Lowlands, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 418: 377-385.

Bayless, S., *et al.* 2015. Assessing environmental DNA in lake water and ice. *Scientia* 6: 39.

Behre, K-E. 2007. A new Holocene sea-level curve for the southern North Sea. *Boreas* 36: 82-102.

Bell J. 2015. A climate change poem for today: Doggerland by Jo Bell, The Guardian, viewed 09 December 2021, <https://www.theguardian.com/environment/2015/may/21/a-climate-change-poem-for-today-doggerland-by-jo-bell>.

Bell, M. 2007. *Prehistoric coastal communities: the Mesolithic in Western Britain* (CBA Research Report 149). York: Council for British Archaeology.

Bell, T., A. O'Sullivan and R. Quinn 2006. Discovering ancient landscapes under the sea. *Archaeology Ireland* 20 (2): 12-17.

Bell, M., *et al.* 2013. The Mesolithic, in J. Ransley, *et al.* (eds) *People and the Sea: a maritime archaeological research agenda for England* (CBA Research Report 171): 30-49. York: Council for British Archaeology.

Bellemain, E., *et al.* 2013. Fungal palaeodiversity revealed using high-throughput metabarcoding of ancient DNA from arctic permafrost. *Environmental Microbiology* 15: 1176-1189.

Bennett, K.D. 2015. Comment on 'Sedimentary DNA from a submerged site reveals wheat in the British Isles 8000 years ago'. *Science* 349: 247. https://doi.org/10.1126/science.aab1886

Benjamin, J. 2010. Submerged Prehistoric Landscapes and Underwater Site Discovery: Re-evaluating the 'Danish Model' for International Practice. *Journal of Island and Coastal Archaeology* 5: 253-270.

Benjamin J., *et al.* (eds) 2011. *Submerged Prehistory*. Oxford: Oxbow Books.

Benjamin, J., *et al.* 2020. Aboriginal artefacts on the continental shelf reveal ancient drowned cultural landscapes in northwest Australia. *PLos ONE* 15(7) e0233912.

Berger, G.W. 2006. Trans-arctic-ocean tests of fine-silt luminescence sediment dating provide a basis for an additional geo-chronometer for this region. *Quaternary Science Reviews* 25: 2529-255.

Bērziņš, V. 2020. Transformations of coast and culture. A view from the Latvian shore of the Baltic, in A. Schülke (ed.) *Coastal Landscapes of the Mesolithic. Human engagement with the coast from the Atlantic to the Baltic Sea*: 98-116. Abingdon: Routledge.

Bevins, R.E., *et al.* 2020. Constraining the provenance of the Stonehenge 'Altar Stone': Evidence from automated mineralogy and U-Pb zircon age dating. *Journal of Archaeological Science 120*: 105-188.

Binford, L.R. 1980. Willow Smoke and Dogs' Tails: Hunter-Gatherer Settlement Systems and Archaeological Site Formation. *American Antiquity* 45: 4-20.

Binford, L.R. 2001. *Constructing Frames of Reference. An analytical method for Archaeological Theory building using ethnographic and environmental data sets.* Berkley: University of California Press.

Bintliff, J.L. 1991. '*The Annales' School and Archaeology*. New York: New York University Press.

Bicket, A. 2011. *Submerged Prehistory: Marine ALSF Research in Context* (Marine Aggregate Levy Sustainability Fund Science Monograph Series 5): J. Gardiner (ed.) MEPF 10/P150. Edinburgh: Wessex Archaeology

Bicket, A.R., *et al.* 2017. Exploring Holocene palaeogeography in the 'white ribbon': a Mesolithic case study from the Northumberland coast. *Journal of Quaternary Science* 32: 311-328.

Bicket, A. and L. Tizzard 2015. A review of the submerged prehistory and palaeolandscapes of the British Isles. *Proceedings of the Geologist's Association* 126: 643-663.

Bissett, A., *et al.* 2005. Isolation, amplification, and identification of ancient copepod DNA from lake sediments. *Limnology and Oceanography: Methods* 3: 533-542.

Bjerck, H.B. 1995. The North Sea Continent and the pioneer settlement of Norway, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monograph 53): 131-144. Oxford: Oxbow Books.

Bjerck, H.B. 2019. What could the 'Sea Ice Machine' do to its People? On Late glacial Doggerland, Marine Foraging, and the Colonisation of Scandinavian Seascapes. *Environmental Archaeology* 26 (1): 51-63. https://doi.org/10.1080/14614103.2019.1642673

Blaauw, M., J. van der Plicht and B. val Geel 2004. Radiocarbon dating of bulk peat samples from raised bogs: non-existence of a previously reported 'reservoir effect'? *Quaternary Science Reviews* 23: 1537-1542.

Blankholm, H.P. 2008. Southern Scandinavia, in G. Bailey and P. Spikins (eds) *Mesolithic Europe*: 107-131. Cambridge: Cambridge University Press.

Blondel P., and B.J. Murton 1997. *Handbook of Seafloor Imagery*. Chichester: John Wiley and Sons.

Blackburn, J. 2019. *Time Song: Searching for Doggerland*. London: Jonathan Cape.

BMAPA and English Heritage 2003. *Marine aggregate dredging and the historic environment: guidance note*. London: British Marine Aggregate Producers Association and English Heritage.

BMAPA and English Heritage 2005. *Protocol for reporting finds of archaeological interest*. London: British Marine Aggregate Producers Association and English Heritage.

Boere, A., *et al.* 2011. Preservation potential of ancient plankton DNA in Pleistocene marine sediments. *Geobiology* 9 (5): 377-393.

Boessenkool, S., *et al.* 2012. Blocking human contaminant DNA during PCR allows amplification of rare mammal species from sedimentary ancient DNA. *Molecular Ecology* 21: 1806-1815.

Boessenkool, S., *et al.* 2014. Use of ancient sedimentary DNA as a novel conservation tool for high-altitude tropical biodiversity. *Conservation Biology* 28: 446-455.

Bondevik, S., S.K. Stormo and G. Skjerdal 2012. Green mosses date the Storegga tsunami to the chilliest decades of the 8.2 ka cold event. *Quaternary Science Reviews* 45: 1-6.

Bonsall, C. and C. Smith 1989. Late Palaeolithic and Mesolithic bone and antler artefacts from Britain: First reactions to accelerator dates. *Mesolithic Miscellany* 10 (1): 33-38.

Borchert, S.M., *et al.* 2018. Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. *Journal of Applied Ecology* 55 (6): 2876-2887.

Box, G.E. 1979. Robustness in the strategy of scientific model building. *Robustness in Statistics* 1: 201-236.

Bradley, R. 2007. *The Prehistory of Britain and Ireland* (Cambridge World Archaeology). Cambridge: Cambridge University Press.

Bradley, R., *et al.* 2016. Maritime Havens in Earlier Prehistoric Britain. *Proceedings of the Prehistoric Society* 82: 2016, 125-159.

Bradley, S.L., *et al.* 2011. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science* 26: 541-552.

Braje, T.J., *et al.* 2019. Fladmark + 40: What have we learned about a potential Pacific Coast Peopling of the Americas? *American Antiquity* 85: 1-21.

Braker, G., *et al.* 2000. Nitrite reductase genes (nirK and nirS) as functional markers to investigate diversity of denitrifying bacteria in Pacific Northwest marine sediment communities. *Applied and Environmental Microbiology* 66: 2096-2104.

Bratley, P., B.L. Fox and L.E. Schrage 2011. *A guide to simulation*. New York: Springer Verlag (Springer Science and Business Media).

Breivik, H.M., G. Fossum and S. Solheim 2018. Exploring human responses to climatic fluctuations and environmental diversity: Two stories from Mesolithic Norway. *Quaternary International* 465: 258-275.

Brendryen, J., H. Haflidason and H.P. Sejrup 2010. Norwegian Sea tephrostratigraphy of marine isotope stages 4 and 5: prospects and problems for tephrochronology in the North Atlantic region. *Quaternary Science Reviews* 29 (7-8): 847-864.

Briggs, A.W., *et al.* 2007. Patterns of damage in genomic DNA sequences from a Neandertal. *Proceedings of the National Academy of Sciences* 104: 14616-14621.

Briggs, K., K. Thomson and V. Gaffney 2007. A Geomorphological Investigation of Submerged Depositional Features within the Outer Silver Pit, southern North Sea, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea*: 43-60. Oxford: Archaeopress.

Bronk Ramsey, C. 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. *Radiocarbon* 37: 425-430.

Bronk Ramsey, C. 2001. Development of the radiocarbon calibration program. *Radiocarbon* 43: 355-363.

Bronk Ramsey, C. 2008. Deposition models for chronological records. *Quaternary Science Reviews* 27: 42-60.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337-360.

Brown A., *et al.* 2018. Late glacial/early Holocene palaeoenvironments in the southern North Sea Basin: new data from the Dudgeon offshore wind farm. *Journal of Quaternary Science* 33 (6): 597-610.

Brennand, M. and M. Taylor 2003. The survey and excavation of a Bronze Age timber circle at Holme-next-the-Sea, Norfolk, 1998-9. *Proceedings of the Prehistoric Society* 69:1-84

Brown, M. 1986. *Indefatigable Sheet (53N o2E): Quaternary Geology*. HMSO, London.

Buckland, P.I. and P.C. Buckland 2006. *BugsCEP Coleopteran Ecology Package* (IGBP PAGES/World Data Centre for Paleoclimatology Data Contribution Series # 2006-116. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA), viewed 28 November 2021, <http://www.ncdc.noaa.gov/paleo/insect.html> or <http://www.bugscep.com>.

Buglass, J. 1994. A Neolithic fish weir in Cleveland? *Nautical Archaeology Newsletter* 4.

Bunch M., V. Gaffney and K. Thomson 2007. Coordinating Marine Survey Data Sources, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea*: 11-22. Oxford: Archaeopress.

Burbidge, C.I., *et al.* 2007.Survey of Palaeolithic sites by luminescence profiling, a case study from Eastern Europe. *Quaternary Geochronology* 2 (1): 296-302.

Burkitt, M.C. 1932. A Maglemose Harpoon dredged up recently from the North Sea. *Man* 32: 118.

Burroughs, W.J. 2008. *Climate Change in Prehistory. The end of the reign of chaos*. Cambridge: Cambridge University Press.

Bush, R.T. and F.A. McInerney 2013. Leaf wax n-alkane distributions in and across modern plants: implications for paleoecology and chemotaxonomy. *Geochimica et Cosmochimica Acta* 117: 161-179.

Bynoe, R., J. Dix and F. Sturt 2016 Of mammoths and other monsters: historic approaches to the submerged Palaeolithic. *Antiquity* 90 (352): 857-875. https://doi.org/10.15184/aqy.2016.129

Bynoe, R. 2018 The submerged archaeology of the North Sea: Enhancing the Lower Palaeolithic record of northwest Europe. *Quaternary Science Reviews* 191: 1-14. https://doi.org/10.1016/j.quascirev.2018.05.002

Cahoon, D.R. 2015. Estimating relative sea-level rise and submergence potential at a coastal wetland. *Estuaries and Coasts* 38 (3): 1077-1084.

Carpelan, C. 2008. On the history and recent studies of the 'Antrea Net Find'. *Iskos* 16: 88-127.

Carreira, R.S., *et al.* 2016. Distribution and characterization of organic matter using lipid biomarkers: a case study in a pristine tropical bay in NE Brazil. *Estuarine, Coastal and Shelf Science* 168: 1-9.

Cameron, T.D.J., *et al.* 1992. *United Kingdom offshore regional report: the geology of the Southern North Sea*. London: Her Majesty's Stationary Office for the British Geological Survey.

Campbell, C. 2013. *Campbell's Atlas of Oil and Gas Depletion*. Berlin: Springer Verlag.

Cegielski, W.H. and J.D. Rogers 2016. Rethinking the role of agent-based modelling in archaeology. *Journal of Anthropological Archaeology* 41: 283-298.

Chapman, H.P. and M.C. Lillie 2004. Investigating 'Doggerland' through analogy: the example of Holderness, East Yorkshire (UK), in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research Report 141): 65-69. York: English Heritage/ Council for British Archaeology.

Chemostrat Multiclient Report NE118. Integrated Stratigraphic and Provenance Study undertaken on the Lower Palaeocene Successions (T10 - T38) within the Faroe-Shetland Basin. Welshpool: Chemostrat Ltd.

Chen, J., *et al.* 2019. Lipid biomarker as indicator for assessing the input of organic matters into sediments and evaluating phytoplankton evolution in upper water of the East China Sea. *Ecological Indicators* 101: 380-387.

Chester, R. 2009. *Marine Geochemistry.* Chichester: John Wiley and Sons.

Childe, V.G. 1931. The Forest Cultures of Northern Europe: a study in evolution and diffusion. *The Journal of the Royal Anthropological Institute of Great Britain and Ireland* 61: 325-348.

Childe, V.G. 1957. *The Dawn of European Civilisation.* London: Routledge and Kegan Paul.

Childe, V.G. 1958. *The Prehistory of European Society.* Middlesex: Penguin Books.

Ch'ng, E., T.K. Kabora and P.S. Murgatroyd (eds) forthcoming (2022) *Modelling Doggerland: The simulations of Europe's Lost Frontiers* (Europe's Lost Frontiers Volume 4). Oxford: Archaeopress.

Christiansen, B.C., *et al.* 2009. Identification of green rust in groundwater. *Environmental Science and Technology* 43 (10): 3436-3441.

Claassen, C. 1998. *Shells.* Cambridge: Cambridge University Press.

Clark, C. 1970. *The economics of subsistence agriculture.* 4th ed. London: MacMillan.

Clark, C.D., *et al.* 2018. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British-Irish Ice Sheet. *Boreas*, 47(1): 11-e8. https://doi.org/10.1111/bor.12273

Clark, C.D., *et al.* 2021 Timing, pace and controls on ice sheet retreat: an introduction to the BRITICE-CHRONO transect reconstructions of the British–Irish Ice Sheet. *Journal of Quaternary Science*: 673-680.

Clark, J.G.D. 1932. *The Mesolithic Age in Britain.* Cambridge: Cambridge University Press.

Clark, J.G.D. 1936a. *The Mesolithic Settlement of Northern Europe. A study of the food-gathering peoples of Northern Europe during the early post-glacial period.* Cambridge: Cambridge University Press.

Clark, J.G.D. 1936b. The Separation of Britain from the Continent. *Proceedings of the Prehistoric Society* 2: 239.

Clark, J.G.D. 1972. *Star Carr: A Case Study in Bioarchaeology* (Addison-Wesley Module in Anthropology 10). Reading, Massachusetts: Addison-Wesley.

Clark, J.G.D. 1978. Neothermal Orientations, in P. Mellars (ed.) *The Early Postglacial Settlement of Northern Europe: An Ecological Perspective*: 1-11. London: Gerald Duckworth and Co Ltd.

Clelland, S.-J. and C.M. Batt 2012. Geomagnetic secular variation as recorded in British lake sediments and its application to archaeomagnetic studies. *Physics of the Earth and Planetary Interiors* 194-195: 85-97.

Cohen, K.M., P.L. Gibbard and H.J.T. Weerts 2014. North Sea palaeogeographical reconstructions for the last 1 Ma. *Netherlands Journal of Geoscience* 93: 7-29.

Cohen, K.M., *et al.* 2017. The North Sea, in N.C. Flemming, *et al.* (eds) *Submerged Landscapes of the European Continental Shelf. Quaternary Palaeoenvironment*: 147-186. Chichester: John Wiley and Sons.

Coles, B.J. 1998. Doggerland: a speculative survey. *Proceedings of the Prehistoric Society* 64: 45-81.

Coles, B.J. 1999. Doggerland's loss and the Neolithic, in B. Coles, J. Coles and M.S. Jørgensen (eds) *Bog bodies, sacred sites and wetland archaeology* (WARP occasional paper 12): 51-58. Exeter: Wetland Archaeology Research Project.

Coles, B.J. 2000. Doggerland: the cultural dynamics of a shifting coastline, in K. Pye and J.R.L. Allen (eds) *Coastal and Estuarine Environments: sedimentology, geomorphology and geoarchaeology* (Geological Society Special Publications 175): 393-402. London: The Geological Society.

Collard, M., *et al.* 2010. Radiocarbon evidence indicates that migrants introduced farming to Britain. *Journal of Archaeological Science* 37: 866-870.

Collins, L.G., *et al.* 2012. Palaeomagnetic and biostratigraphic dating of marine sediments from the Scotia Sea, Antarctica: First identification of the Laschamp excursion in the Southern Ocean. *Quaternary Geochronology* 7: 67-75.

Conneller, C. 2004. Becoming deer: corporeal transformations at Star Carr. *Archaeological Dialogues* 111: 37-56.

Conneller, C., *et al.* 2016. The Resettlement of the British Landscape: Towards a chronology of Early Mesolithic lithic assemblage types. *Internet Archaeology* 42.

Conneller, C.J. and T.F.G. Higham 2015. The early Mesolithic colonisation of Britain: preliminary results, in N. Ashton and C.R.E. Harris (eds) *No stone unturned: papers in honour of Roger Jacobi*: 157-166. London: Lithic Studies Society.

Contreras, D.A., *et al.* 2019. From paleoclimate variables to prehistoric agriculture: Using a process-based agro-ecosystem model to simulate the impacts of Holocene climate change on potential agricultural productivity in Provence, France. *Quaternary International* 501: 303-316.

Corning, P.A. 2002. The re-emergence of 'emergence': A venerable concept in search of a theory. *Complexity* 7 (6): 18-30.

Cook, H.E., *et al.* 1975. IV. Methods of sample preparation, and X-ray diffraction data analysis, X-ray mineralogy laboratory, Deep Sea Drilling Project, University of California, Riverside. *Initial reports of the Deep Sea Drilling Project* 28: 999-1007.

Coolen, M.J., *et al.* 2004. Combined DNA and lipid analyses of sediments reveal changes in Holocene haptophyte and diatom populations in an Antarctic lake. *Earth and Planetary Science Letters* 223: 225-239.

Coolen, M.J., *et al.* 2006. Ancient DNA derived from alkenone-biosynthesizing haptophytes and other algae in Holocene sediments from the Black Sea. *Paleoceanography* 21 (1): PA1005 https://doi.org/10.1029/2005PA001188

Coolen, M.J. and J. Overmann 2007. 217,000-year-old DNA sequences of green sulfur bacteria in Mediterranean sapropels and their implications for the reconstruction of the paleoenvironment. *Environmental Microbiology* 9: 238-249.

Conneller, C. and G. Warren 2006. *Mesolithic Britain and Ireland: New Approaches*. Cheltenham: The History Press.

Cook, P.J. 1991. Spurn Sheet (53N - 00E) *Quaternary Geology*. Southampton: Ordnance Survey.

Corinaldesi, C., *et al.* 2011. Preservation, origin and genetic imprint of extracellular DNA in permanently anoxic deep-sea sediments. *Molecular Ecology* 20: 642-654.

Corinaldesi, C., F. Beolchini and A. Dell'Anno 2008. Damage and degradation rates of extracellular DNA in marine sediments: implications for the preservation of gene sequences. *Molecular Ecology* 17: 3939-3951.

Cotterill, C.J., *et al.* 2017. The evolution of the Dogger Bank, North Sea: a complex history of terrestrial, glacial and marine environmental change. *Quaternary Science Reviews* 171: 136-153.

COWRIE 2007. Historic environment guidance for the offshore renewable energy sector. Wessex Archaeology on behalf of COWRIE Ltd (project reference ARCH-11-05), viewed 12 October 2021, <https://www.wessexarch.co.uk/sites/default/files/field_file/COWRIE_2007_Wessex_%20-%20archaeo_%20guidance_Final_1-2-07.pdf>.

COWRIE 2011. J. Gribble and S. Leather for EMU Ltd. 2011. Offshore Geotechnical Investigations and Historic Environment Analysis: Guidance for the Renewable Energy Sector. Commissioned by COWRIE Ltd (project reference GEOARCH-09), viewed 12 October 2021, <https://www.historicenvironment.scot/media/2376/2011-01-offshore-geotechnical-investigations-and-historic-environment-analysis-guidance-for-the-renewable-energy-sector.pdf>.

Crabtree, S.A., *et al.* 2017. How to make a polity (in the Central Mesa Verde region). *American Antiquity* 82 (1): 71-95

Crabtree, S.A., *et al.* 2021 Landscape rules predict optimal superhighways for the first peopling of Sahul. *Nature Human Behaviour* 5: 1301-1313. https://doi.org/10.1038/s41562-021-01106-8

Cram, F.M., *et al.* 2014. A New Integrated Approach to the Subdivision of the Rotliegend and Upper Carboniferous, Offshore Netherlands and Germany, in *Conference Proceedings, 76th EAGE Conference and Exhibition 2014, June 2014, Vol. 2014*: 1-5. Amsterdam: European Association of Geoscientists and Engineers. https://doi.org/10.3997/2214-4609.20141134

Crema, E.R. 2014. A simulation model of fission-fusion dynamics and long-term settlement change. *Journal of Archaeological Method and Theory* 21 (2): 385-404.

Cribdon, B., *et al.* 2020. PIA: More Accurate Taxonomic Assignment of Metagenomic Data Demonstrated on sedaDNA From the North Sea. *Frontiers in Ecology and Evolution*. 8: Article 84. https://doi.org/10.3389/fevo.2020.00084

Crombé, P. 2019. Mesolithic projectile variability along the southern North Sea basin (NW Europe): Hunter-gatherer responses to repeated climate change at the beginning of the Holocene. *PLoS ONE* 14: e0219094.

Crombé, P. and B. Vanmontfort 2007. The Neolithisation of the Scheldt basin in western Belgium, in A. Whittle and V. Cummings (eds) *Going over: the Mesolithic-Neolithic transition in north-west Europe* (Proceedings of the British Academy 144): 263-285. Oxford: Oxford University Press.

Crombé, P. and E. Robinson. 2017. Human resilience to Lateglacial climate and environmental change in the Scheldt basin (NW Belgium). *Quaternary International* 428B: 50-63.

Crombé, P. and E. Robinson 2019. European Mesolithic: geography and culture, in C. Smith (ed.) *Encyclopedia of Global Archaeology*: 1-23. Cham: Springer.

Crombé, P., *et al.* 2011. Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolothic land use in northwest Belgium. *Journal of Anthropological Archaeology* 30: 454-471.

Crombé, P., *et al.* (eds) 2009. *Chronology and Evolution Within the Mesolithic of North-West Europe. Proceedings of an International Meeting, Brussels, May 30th-June 1st 2007*. Newcastle: Cambridge Scholars.

Crosby, S.C., *et al.* 2016. Salt marsh persistence is threatened by predicted sea-level rise. *Estuarine, Coastal and Shelf Science* 181: 93-99. https://doi.org/10.1016/j.ecss.2016.08.018

Croudace, I.W., A. Rindby and R.G. Rothwell 2006. ITRAX: description and evaluation of a new multi-function

X-ray core scanner. *Geological Society, London, Special Publications* 267 (1): 51-63.

Croudace, I.W., and R.G. Rothwell 2015. Micro-XRF Studies of Sediment Cores. Developments in Paleoenvironmental Research. *Developments in Paleoenvironmental Research 1-21.*

Crump, S.E., *et al.* 2019. Arctic shrub colonization lagged peak postglacial warmth: Molecular evidence in lake sediment from Arctic Canada. *Global Change Biology* 25: 4244-4256.

Cummings, V. and C. Fowler 2016. *The Neolithic of the Irish Sea: materiality and traditions of practise*. Oxford: Oxbow.

Cunningham, A., J. Wallinga and P. Minderhoud 2011. Expectations of scatter in equivalent-dose distributions when using multi-grain aliquots for OSL dating. *Geochronometria* 38 (4): 424-431.

Cunliffe, B. 2001. *Facing the Ocean: the Atlantic and its peoples*. Oxford University Press. Oxford.

van Dam, H., A. Mertens and J. Seinkeldam 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology* 28 (1): 117-133.

Dalrymple, R.W., B.A. Zaitlin and R. Boyd 1992. Estuarine facies models; conceptual basis and stratigraphic implications. *Journal of Sedimentary Research* 62: 1130-1146.

David, E. 2006. Contributions of the bone and antler industry for characterising the Early Mesolithic in Europe, in C.-J. Kind (ed.) *After the Ice: Settlements, Subsistence and Social Development in the Mesolithic of Central Europe. Proceedings of the International Conference, Rottembourg, 9th-12th September 2003* (Materialhefte zur Archäologie in Baden-Württemberg 78): 135-146. Stuttgart: Konrad Theiss Verlag.

Davies, S.J., H.F. Lamb and S.J. Roberts 2015. Micro-XRF core scanning in palaeolimnology: recent developments, in I. Croudace and R. Rothwell (eds) *Micro-XRF Studies of Sediment Cores* (Developments in Paleoenvironmental Research 17): 189-226. Dordrecht: Springer https://doi.org/10.1007/978-94-017-9849-5_7

Davies, B.J., *et al.* 2011. Provenance and depositional environments of quaternary sediments from the western North Sea Basin. *Journal of Quaternary Science* 26: 59-75.

Davies, P. 2008. *Snails: Archaeology and Landscape Change*. Oxford: Oxbow.

Dabney, J., M. Meyer and S. Pääbo 2013. Ancient DNA damage. *Cold Spring Harbor Perspectives in Biology* 5: a012567.

Davis, L.G. and Madsen, D.B. 2020. The coastal migration theory: formulation and testable hypotheses. *Quaternary Science Reviews* 249: 106605.

D'Costa, V.M., *et al.* 2011. Antibiotic resistance is ancient. *Nature* 477: 457-461.

Davies, B., S.J. Holdaway and P.C. Fanning 2016. Modelling the palimpsest: an exploratory agent-based model of surface archaeological deposit formation in a fluvial arid Australian landscape. *The Holocene* 26 (3): 450-463.

Dawson, A., S. Bondevik and J.T. Teller 2011. Relative timing of the Storegga submarine slide, methane release, and climate change during the 8.2 ka cold event. *The Holocene* 21 (7): 1167-1171.

De Boer, E.J., *et al.* 2014. Climate variability in the SW Indian Ocean from an 8000-yr long multi-proxy record in the Mauritian lowlands shows a middle to late Holocene shift from negative IOD-state to ENSO-state. *Quaternary Science Reviews* 86: 175-189.

De Clercq, M. 2018. Drowned landscapes of the Belgian Continental Shelf: implications for northwest European landscape evolution and preservation potential. Unpublished PhD dissertation, Ghent University.

Dekker, J., *et al.* 2020. Human and cervid osseous materials used for barbed point manufacture in Mesolithic Doggerland. *Journal of Archaeological Science (Reports)* 35: article 102678. https://doi.org/10.1016/j.jasrep.2020.102678

Del Castillo, F., *et al.* 2014. Modelling mechanisms of cultural diversity and ethnicity in hunter-gatherers. *Journal of Archaeological Method and Theory* 21 (2): 364-384.

Dell'Anno, A. and R. Danovaro 2005. Extracellular DNA plays a key role in deep-sea ecosystem functioning. *Science* 309: 2179.

Dellino-Musgrave, V., S. Gupta and M. Russell 2009. Marine Aggregates and Archaeology: a Golden Harvest? *Conservation and Management of Archaeological Sites* 11: 29-42.

DeMott, W.R., J.R. Edington and A.J. Tessier 2004. Testing zooplankton food limitation across gradients of depth and productivity in small stratified lakes. *Limnology and Oceanography* 49 (4 part 2): 1408-1416.

Denys, L. 1991-92. *A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements: I. Introduction, ecological code and complete list*. Service Geologique de Belgique Professional Paper 246.

Denys, L. 1994. Diatom assemblages along a former intertidal gradient: a palaeoecological study of a subboreal clay layer (western coastal plain, Belgium). *Netherlands Journal of Aquatic Ecology* 28 (1): 85-96.

Devriendt, I. 2008. Becoming Neolithic. The Mesolithic-Neolithic transition and its impact on the flint and stone industry at Swifterbant (the Netherlands). *Documenta Praehistorica* XXXV: 131-141.

Devriendt, I. 2014. *Swifterbant Stones. The Neolithic Stone and Flint Industry at Swifterbant (the Netherlands): from stone typology and flint technology to site function* (Groningen Archaeological Studies 25). Groningen: Barkhuis and Groningen University Library.

Dewing, E. 2012. Mesolithic coastal community perception of environmental change in the southern North Sea basin. Unpublished PhD dissertation, University of Southampton.

Dill, H.G. 2001. The geology of aluminium phosphates and sulphates of the alunite group minerals: a review. *Earth-Science Reviews* 53 (1-2): 35-93.

Dixit, S.S., *et al.* 1999. Assessing water quality changes in the lakes of the northeastern United States using sediment diatoms. *Canadian Journal of Fisheries and Aquatic Sciences* 56: 131-152.

Dobson, J.E. 2014. Aquaterra Incognita: Lost Land Beneath the Sea. *Geographical Review* 104: 123-138.

Doran, J. 1970. Systems theory, computer simulations and archaeology. *World Archaeology* 1 (3): 289-298.

Douvere, F., A. Vanhulle and J. Schrijvers 2007. The role of marine spatial planning in sea use management: The Belgian case. *Marine Policy* 31: 182-191.

Dove, D., *et al.* 2017. Phased occupation and retreat of the last British-Irish Ice Sheet in the southern North Sea: geomorphic and seismostratigraphic evidence of a dynamic ice lobe. *Quaternary Science Review.* 163: 114-134.

Domaizon, I., *et al.* 2017. DNA-based methods in paleolimnology: new opportunities for investigating long-term dynamics of lacustrine biodiversity. *Journal of paleolimnology* 58: 1-21.

Dresser, P.Q. 1971. A study of sampling and pre-treatment for radiocarbon dating. Unpublished PhD dissertation, Queen's University Belfast.

Dromgoole, S. 2020. Continental Shelf Archaeology and International Law, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 485-495. Cham: Springer.

Duller, G.A. 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas* 37 (4): 589-612.

Dunbar, E., *et al.* 2016. AMS ^{14}C dating at the Scottish Universities Environmental Research Centre (SUERC) Radiocarbon Dating Laboratory. *Radiocarbon* 58: 9-23.

Durcan, J.A. 2019. Luminescence Dating, in S. Elias (ed.) *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.12105-0

Durcan, J.A., *et al.* 2010. Testing the use of range-finder OSL dating to inform field sampling and laboratory processing strategies. *Quaternary Geochronology* 5 (2-3): 86-90.

EAA 2013. European Association of Archaeologists, European Archaeological Heritage Prize 2013, viewed 6 August 2021, <https://www.e-a-a.org/EAA/Prizes___Awards/Heritage_Prize/2013/EAA/Navigation_Prizes_and_Awards/Heritage_Prize_2013.aspx>

Eadie, G. and C. Waddington 2013. Rescue recording of an eroding inter-tidal peat bed at Low Hauxley Northumberland (6109). Archaeological Research Services Report 2013/17, viewed 27 January 2022, <http://www.archaeologicalresearchservices.com/projects/Low%20Hauxley%20Footprints%20&%20Peat%20Deposit.pdf>

Einstein, A. 1934. On the method of theoretical physics. *Philosophy of Science* 1 (2): 163-169.

Eisma D., J.H.F. Jansen and T.C.E van Weering 1979. Sea-floor morphology and recent sediment movement in the North Sea, in R.T.E Oele-Schotenhelm and A.J. Wiggers (eds), *The Quaternary History of the North Sea* (Symposium Universitatis Upsaliensis Annum Quingentesimum Celebrantis): 217-231. Uppsala: Uppsala University

Easton, N.A. 1992. Mal de Mer above Terra Incognita, or, 'What ails the Coastal Migration Theory?'. *Arctic Anthropology* 29: 28-41.

Easton, N.A., C. Moore and A.R. Mason. 2021. The archaeology of submerged prehistoric sites on the North Pacific Coast of North America. *The Journal of Island and Coastal Archaeology* 16: 118-149.

Elbaum, R., *et al.* 2009. New methods to isolate organic materials from silicified phytoliths reveal fragmented glycoproteins but no DNA. *Quaternary International* 193: 11-19.

Ellwood, *et al.* 2008. High-resolution magnetic susceptibility and geochemistry for the Cenomanian/Turonian boundary GSSP with correlation to time equivalent core. *Palaeogeography, Palaeoclimatology, Palaeoecology* 261 (1-2): 105-126.

Emery, A. 2020. Glacial and postglacial landscape evolution at the Dogger Bank since the Last Glacial Maximum. Unpublished PhD dissertation, University of Leeds.

Emery, A.R., *et al.* 2019. Topographic and hydrodynamic controls on barrier retreat and preservation: An example from Dogger Bank, North Sea. *Marine Geology* 416: 105981. https://doi.org/10.1016/j.margeo.2019.105981

EMODNET 2021. European Commission Directorate-General for Maritime Affairs and Fisheries (DG MARE), European Marine Observation and Data Network (EMODnet) data portal, viewed 3 June 2021, <https://emodnet.eu/en>.

Engen, M. and P. Spikins 2007. 'A Needle in a Haystack?': Perspectives on prospection for submerged Mesolithic sites, in C. Waddington and K. Pedersen (eds) *Mesolithic Studies in the North Sea Basin and Beyond. Proceedings of a conference held at Newcastle in 2003:* 25-32. Oxford: Oxbow Books.

Enghoff, I.B. 1995. Fishing in Denmark during the Mesolithic Period, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monograph 53): 67-74. Oxford: Oxbow Books.

English Heritage and Atkins Heritage 2009. *ALSF Dissemination: Benchmark Report Theme 4A. Rich Deposits - Aggregates Extraction, Research and the*

Knowledge Pool. York: Archaeology Data Service. https://doi.org/10.5284/1000116

Epp, L.S., *et al.* 2012. New environmental metabarcodes for analysing soil DNA: potential for studying past and present ecosystems. *Molecular Ecology* 21: 1821-1833.

Erdtman, G. 1925. Some micro-analyses of 'Moorlog' from the Doggerbank. *Essex Naturalist* 21: 107-112.

Erlandson, J.M. and T.J. Braje 2015. Coasting out of Africa: The potential of mangrove forests and marine habitats to facilitate human coastal expansion via the Southern Dispersal Route. *Quaternary International* 382: 31-41.

Evans, A.M., A. Firth and M. Staniforth 2009. Old and New Threats to Submerged Cultural Landscapes: Fishing, Farming and Energy Development. *Conservation and management of archaeological sites* 11: 43-53.

Evans, J.G. 1972. *Land Snails in Archaeology*. London: Academic Press.

Everett R, *et al.* 2020. MetaDamage Tool: Examining post-mortem damage in sedaDNA on a metagenomic scale, *EGU General Assembly 2021*, online, 19-30 April 2021, EGU21-2906, https://doi.org/10.5194/egusphere-egu21-2906

Fagan, B. 2013. *The Attacking Ocean. The Past, Present, and Future of Rising Sea Levels*. London: Bloomsbury.

Fang, X. and H.G. Stefan 1998. Temperature variability in lake sediments. *Water Resources Research* 34: 717-729.

Fearn, M.L. 1998. Phytoliths in sediment as indicators of grass pollen source. *Review of Palaeobotany and Palynology* 103: 75-81.

Ficetola, G.F., *et al.* 2015. Replication levels, false presences and the estimation of the presence/absence from eDNA metabarcoding data. *Molecular Ecology Resources* 15: 543-556.

Ficken, K.J., *et al.* 2000. An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. *Organic Geochemistry* 31 (7-8): 745-749.

Finlay, A.J., *et al.* 2012. Trace element fingerprinting of ceramic building material from Carpow and York Roman fortresses manufactured by the VI Legion. *Journal of Archaeological Science* 397: 2385-2391.

Firth, A. 2013. Submerged Prehistory in the North Sea, in B. Ford, D.L. Hamilton and A. Catsambis (eds) *The Oxford Handbook of Maritime Archaeology*: 786-808. Oxford: Oxford University Press.

Firth, A. 2015. Risks, resources and significance: navigating a sustainable course for marine development-led archaeology. *Bulletin of the Australian Institute of Maritime Archaeology* 39: 1-8.

Fischer, A. 1993. *Stenalderbopladser i Smålandsfarvandet. Stone Age settlements in the Småland Bight. A theory tested by diving*. Copenhagen: Miljøministeriet, Skov- og naturstyrelsen.

Fischer, A. 1995. *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monographs 53). Oxford: Oxbow.

Fischer, A. 2004. Submerged Stone Age - Danish Examples and North Sea potential, in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research Report 141): 21-36. York: English Heritage/Council for British Archaeology.

Fischer, A. 2007. Coastal fishing in Stone Age Denmark – evidence from below and above the present sea level and from human bones, in N. Milner, O.E. Craig and G.N. Bailey (eds) *Shell Middens in Atlantic Europe*: 54-69. Oxford: Oxbow Books.

Fischer, A. 2018. The qualities of the submarine Stone Age, in A. Fischer and L. Pedersen (eds) *Oceans of Archaeology* (Jutland Archaeological Society Publications 101): 180-191. Aarhus: Aarhus University Press.

Fischer, A. and L. Pedersen (eds) 2018. *Oceans of Archaeology* (Jutland Archaeological Society Publications 101). Aarhus: Aarhus University Press.

Fitch, S. 2011. The Mesolithic Landscape of the Southern North Sea. Unpublished PhD dissertation, University of Birmingham.

Fitch, S. 2013. Time and Tide: modelling the effects of landscape change on population support in the Southern North Sea, in E. Ch'ng, V. Gaffney and H. Chapman (eds) *Visual Heritage in the Digital Age*: 275-296. London: Springer.

Fitch, S. and V. Gaffney 2011. *West Coast Palaeolandscapes Survey (WCPS)*. Birmingham Archaeology Project No.1997 Ref: Document No: WCPS-1997-3b, viewed 27 July 2021, <https://archaeologydataservice.ac.uk/archives/view/wcpp_eh_2013/downloads.cfm>.

Fitch, S., *et al.* 2007. An Atlas of the Palaeolandscapes of the Southern North Sea, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland: the Mesolithic Landscapes of the Southern North Sea*: 67-91. Oxford: Archaeopress.

Fitch S., V. Gaffney and K. Thomson 2007a. Heritage Management and the North Sea Palaeolandscapes Project, in V. Gaffney, K. Thompson and S. Fitch (eds) (2007) *Mapping Doggerland: the Mesolithic landscapes of the southern North Sea*: 105-118. Oxford: Archaeopress.

Fitch S., V. Gaffney and K. Thomson 2007b. Merging Technologies: The integration and visualisation of spatial data sets used in the project, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland: the Mesolithic Landscapes of the Southern North Sea*: 33-42. Oxford: Archaeopress.

Fitch, S., V. Gaffney and K. Thomson 2007c. In Sight of Doggerland: From speculative survey to landscape exploration. *Internet Archaeology* 22. https://doi.org/10.11141/ia.22.3

Fitch, S., V. Gaffney and K. Thomson 2007d. Heritage Management and the North Sea Palaeolandscapes

Project, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland: the Mesolithic Landscapes of the Southern North Sea*: 105-118. Oxford: Archaeopress
Fitch S., *et al.* 2011. Between the lines: enhancing methodologies for the exploration of extensive, inundated palaeolandscapes, in D.C. Cowley (ed.) *Remote sensing for archaeological heritage management*. (EAC Occasional Paper. Occasional Publication of the Aerial Archaeology Research Group No. 3): 173-204. Brussels: Europae Archaeologiae Consilium.
Fitch S., R. Harding and R. Bates forthcoming. The Southern River: a detailed geomorphic examination of a submerged North Sea Palaeochannel, in S. Fitch, R. Bates and V.L. Gaffney (eds) *Europe's Lost Frontiers: Seismic Survey and Landscape Archaeology* (Europe's Lost Frontiers Volume 2). Oxford: Archaeopress.
Fitch, S., E. Ramsey and R. Cutler 2009. QNHER: Qatar Marine report. Unpublished report by the University of Birmingham for the Qatar Museums Authority (QMA). Report deposited with QMA, Doha.
Fitch, S., K. Thomson and V. Gaffney 2005. late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research* 64 (2): 185-196.
Flatman, J. 2011. What the walrus and the carpenter did not talk about: maritime archaeology and the near future of energy, in M. Rockman and J. Flatman (eds) *Archaeology in Society*: 167-192. New York: Springer. https://doi.org/10.1007/978-1-4419-9881-1_13
Flatman, J. and J. Doeser 2010. The International Management of Marine Aggregates and its Relation to Maritime Archaeology. *The Historic Environment* 1: 160-184.
Fletcher, P. 2015. Discussions on the possible origin of Europe's First Boats – 11,500 BP. *Atti Della Accademia Peloritana Dei Pericolanti – Classe Di Scienze Fisiche, Matematiche E Naturali* 93 (2): A1. https://doi.org/10.1478/AAPP.932A1
Flemming, N.C. 2002. *The scope of Strategic Environmental Assessment of North Sea areas SEA3 and SEA2 in regard to prehistoric archaeological remains*. Report for the Department of Trade and Industry (UK). TR_014.
Flemming, N.C. (ed.) 2004a. *Submarine prehistoric archaeology of the North Sea: research priorities and collaboration with industry* (CBA Research Report 141). York: English heritage/Council for British Archaeology.
Flemming, N.C. 2004b. The prehistory of the North Sea floor in the context of Continental Shelf archaeology from the Mediterranean to Nova Zemlya, in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research Report 141): 11-20. York: English Heritage/Council for British Archaeology.
Flemming, N.C., *et al.* 2014. *Land beneath the waves: submerged landscapes and sea level change. A joint geoscience-humanities strategy for European continental shelf prehistoric research* (European Marine Board Position Paper 21). Ostend: European Marine Board
Flemming, N.C., *et al.* 2017. *Submerged Landscapes of the European Continental Shelf: Quaternary Paleoenvironments*. Chichester: Wiley-Blackwell.
Folloni, S., *et al.* 2012. Detection of airborne genetically modified maize pollen by real-time PCR. *Molecular Ecology Resources* 12: 810-821.
Fortin, D., *et al.* 2013. Destructive and non-destructive density determination: method comparison and evaluation from the Laguna Potrok Aike sedimentary record. *Quaternary Science Reviews 71*: 147-153.
Fossum, G. 2020. Specialists facing climate change. The 8200 cal BP event and its impact on the coastal settlement in the inner Oslo fjord, southeast Norway, in A. Schülke (ed.) *Coastal Landscapes of the Mesolithic. Human engagement with the coast from the Atlantic to the Baltic Sea*: 178-200. Abingdon: Routledge.
Fraser, A. 2021. Analysis and Pattern Mapping of Organic Interfaces by means of Seismic Geophysical Technologies to Investigate Archaeological Palaeolandscapes Beneath the Southern North Sea. Unpublished PhD dissertation, University of Bradford.
Fruergaard, M., *et al.* 2015. Tsunami propagation over a wide, shallow continental shelf caused by the Storegga slide, southeastern North Sea, Denmark. *Geology* 43 (12): 1047-1050.
French, J. 2006. Tidal marsh sedimentation and resilience to environmental change: exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems. *Marine Geology* 235 (1-4): 119-136.
Funnel, B. M. 1995. Global sea-level and the (pen) insularity of late Cenozoic Britain, in R.C. Preece (ed.) *Island Britain: a Quaternary Perspective*: 3-13. London: Geological Society.
Gaffney, V.L. and M. Tingle 1984. The tyranny of the site: method and theory in field survey off-site land use. *Scottish Archaeological Review* 3: 134-140.
Gaffney, V.L., *et al.* 2017. Doggerland and the Lost Frontiers Project (2015-2020), in G.N. Bailey, J. Harff, and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 305-320. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_20
Gaffney, V., S. Fitch and D. Smith 2009. *Europe's Lost World. The Rediscovery of Doggerland* (CBA Research Report 160). York: Council for British Archaeology.
Gaffney, V., K. Thompson and S. Fitch (eds) 2007. *Mapping Doggerland: the Mesolithic landscapes of the southern North Sea*. Oxford: Archaeopress.
Gaffney, V., *et al.* 2011. *Between the Salt Water and the Sea Strand. Report prepared for the National Atmospheric and Oceanographic administration* (University of Birmingham Project No. 2052, NOAA Reference Document No. NOAA-2052-2b). Birmingham Archaeology.

Gaffney, V., *et al.* 2020. Multi-proxy characterisation of the Storegga tsunami and its impact on the early Holocene landscapes of the southern North Sea. *Geosciences* 10: 270. https://doi.org/10.3390/geosciences10070270

Galbraith, R.F., *et al.*1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry* 41 (2): 339-364.

Gale, N.H., *et al.* 1999. Natural variations detected in the isotopic composition of copper: possible applications to archaeology and geochemistry. *International Journal of Mass Spectrometry* 184 (1): 1-9.

García, V.H., *et al.* 2019. Late Quaternary tectonics controlled by fault reactivation. Insights from a local transpressional system in the intermontane Lerma valley, Cordillera Oriental, NW Argentina. *Journal of Structural Geology* 128: 103875.

Garrow, D. and F. Sturt 2011. Grey waters bright with Neolithic argonauts? Maritime connections and the Mesolithic-Neolithic transition within the 'western seaways' of Britain, *c.* 5000-3500 BC. *Antiquity* 85: 59-72. https://doi.org/10.1017/S0003598X00067430

Gearey, B.R., *et al.* 2012. From Small Things to Big Pictures? Possibilities and Problems in Studying the Environmental Archaeology of the Southern North Sea, in R. Adams and J. Grattan (eds) *Keys to the Future: Geoarchaeology in the 21st Century*.

Gearey, B., *et al.* 2017. Multi-proxy palaeoecological approaches to submerged landscapes: a case study from 'Doggerland', in the southern North Sea, in M. Williams, *et al.* (eds) *The Archaeological and Forensic Applications of Microfossils: A Deeper Understanding of Human History* (The Micropalaeontological Society, Special Publications): 35-53. London: Geological Society.

Gendel, P. 1987. Socio-Stylistic Analysis of Lithic Artefacts from the Mesolithic of Northwestern Europe, in P. Rowley-Conwy, M. Zvelebil and H.P. Blankholm (eds) *Mesolithic Northwest Europe: Recent TrendsI*: 65-73. Sheffield: John R. Collis.

Gibbard, P.L. 1988. The history of the great northwest European rivers during the last three million years. *Philosophical Transactions of the Royal Society, London. Series B* 318: 559-602. https://doi.org/10.1098/rstb.1988.0024

Gibbard, P.L., *et al.* 1991. Early and early Middle Pleistocene correlations in the southern North Sea Basin. *Quaternary Science Reviews* 10 (1): 23-52. https://doi.org/10.1016/0277-3791(91)90029-T

Giguet-Covex, *et al. 2014.* Long livestock farming history and human landscape shaping revealed by lake sediment DNA. *Nature Communications* 5: 3211. https://doi.org/10.1038/ncomms4211

Ginolhac, A., *et al.* 2011. MapDamage: testing for damage patterns in ancient DNA sequences. *Bioinformatics* 27: 2153-2155.

Glimmerveen, J., *et al.* 2004. The North Sea project: the first palaeontological, palynological, and archaeological results, in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research Report 141): 43-52. York: English Heritage/Council for British Archaeology.

Glørstad, H. 2013. Where are the Missing Boats? The Pioneer Settlement of Norway as Long-Term History. *Norwegian Archaeological Review* 46: 57-80.

Glørstad, H. 2016. Deglaciation, sea-level change and the Holocene colonization of Norway, in J. Harff, G. Bailey and F. Lüth (eds) *Geology and Archaeology. Submerged Landscapes of the Continental Shelf* (Geological Society Special Publication 411): 9-25. Bath: The Geological Society Publishing House.

Glørstad, H., *et al.* 2020. Norway: Submerged Stone Age from a Norwegian Perspective, in G. Bailey, *et al.* (eds). *The Archaeology of Europe's Drowned Landscapes*: 125-140. Cham: Springer.

Glørstad, H., J. Gundersen and F. Kvalø, 2017. The Northern Coasts of Doggerland and the Colonisation of Norway at the end of the Ice Age, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 285-304. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_19

Godwin, H. 1943. Coastal Peat Beds of the British Isles and North Sea. Presidential Address to the British Ecological Society. *Journal of Ecology* 31. 199-247.

Godwin, H. 1945. Coastal Peat-Beds of the North Sea Region, as Indices of Land- and Sea-Level Changes. *The New Phytologist* 44: 29-69.

Godwin, H. and M.E. Godwin 1933. British Maglemose harpoon sites. *Antiquity* 7: 36-48.

Griffiths, S. and E. Robinson 2018. The 8.2 ka BP Holocene climate change event and human population resilience in northwest Atlantic Europe. *Quaternary International* 465: 251-257.

Goldstein, J. 1999. Emergence as a construct: History and issues. *Emergence* 1 (1): 49-72.

Graham, R.W., *et al.* 2016. Timing and causes of mid-Holocene mammoth extinction on St. Paul Island, Alaska. *Proceedings of the National Academy of Sciences* 113: 9310-9314.

Groningen 2020. Resurfacing Doggerland. Environment, humans and material culture in a postglacial drowning landscape, University of Groningen, viewed 10 January 2021, <https://www.rug.nl/let/onze-faculteit/actueel/nieuwsberichten-2020/resurfacing-doggerland-environment-humans-and-material-culture-in-a-postglacial-drowning-lands?lang=en>.

Grenfell, S.E., *et al.* 2016. Will a rising sea sink some estuarine wetland ecosystems? *Science of the Total Environment* 554: 276-292.

Grøn, O. 2006. Does the future of investigations in Mesolithic and Neolithic peat bog settlements lie under water? *Notae Praehistoricae* 26: 1-8.

Grøn, O. and O. Kuznetsov 2003. Ethno-archaeology among Evenkian forest hunters. Preliminary results and a different approach to reality!, in L. Larsson, *et al.* (eds) *Mesolithic on the Move. Papers presented at the Sixth International Conference on the Mesolithic in Europe, Stockholm, 2000*: 216-221. Oxford: Oxbow.

Guérin, G., N. Mercier and G. Adamiec 2011. Dose-rate conversion factors: update: *Ancient Thermo Luminescence* 29: 5-8.

Guilderson, T.P., P.J. Reimer and T.A. Brown 2005. The Boon and Bane of Radiocarbon Dating. *Science* 307 (5708): 362-364.

Gupta, S., *et al.* 2004. Submerged palaeo-Arun River: Reconstruction of prehistoric landscapes and evaluation of archaeological resource potential. Report for English Heritage, viewed 16 October 2021, <https://www.researchgate.net/publication/280831782_Submerged_palaeo-Arun_River_Reconstructuion_of_prehistoric_landscapes_and_evaluation_of_archaeological_resource_potential>.

Gurney, S.D. and K. White 2005. Sediment magnetic properties of glacial till deposited since the Little Ice Age maximum for selected glaciers at Svartisen and Okstindan, northern Norway. *Boreas* 34 (1): 75-83.

Gusick A.E., *et al.* 2021. Above and Below the Waves: Advances in the Search for a late Pleistocene Colonization of California's Islands, in M.F. Napolitano, J.H. Stone and R.J. Di Napoli (eds) *The Archaeology of Island Colonization: Global Approaches to Initial Human Settlement*: 105-131. Gainesville: University Press of Florida.

Haile, J., *et al.* 2007. Ancient DNA chronology within sediment deposits: Are paleobiological reconstructions possible and is DNA leaching a factor? *Molecular Biology and Evolution* 24: 982-989.

Haile, J., *et al.* 2009. Ancient DNA reveals late survival of mammoth and horse in interior Alaska. *Proceedings of the National Academy of Sciences* 106: 22352-22357.

Hall, K. 2014. Locating Potential Mesolithic Fish Sites in Britain using Predictive Modelling: Applying the 'fishing site model' to British conditions, in F.W.F. Foulds, *et al.* (eds) *Wild Things. Recent Advances in Palaeolithic and Mesolithic Research*: 175-184. Oxford: Oxbow.

Haltia-Hovi, E., N. Nowaczyk and T. Saarinen 2010. Holocene palaeomagnetic secular variation recorded in multiple lake sediment cores from eastern Finland. *Geophysical Journal International* 180 (2): 609-622.

Hansen, A.J., *et al.* 2006. Crosslinks rather than strand breaks determine access to ancient DNA sequences from frozen sediments. *Genetics* 173: 1175-1179.

Hamblin, R.J.O. 1992. *United Kingdom offshore regional report: The geology of the English Channel.* London: Her Majesty's Stationary Office for the British Geological Society.

Hammer, O., *et al.*2016. Agderia - a postglacial lost land in the southern Norwegian North Sea. *Norwegian Journal of Geology* 96: 43-60.

Hansson, A., *et al.* 2018. A submerged Mesolithic lagoonal landscape in the Baltic Sea, south-eastern Sweden - early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. *Quaternary International* 463: 110-123.

Haouchar, D., *et al.* 2014. Thorough assessment of DNA preservation from fossil bone and sediments excavated from a late Pleistocene-Holocene cave deposit on Kangaroo Island, South Australia. *Quaternary Science Reviews* 84: 56-64.

Harding, R., *et al.* forthcoming. Surveying the early Holocene geomorphology of Cardigan Bay: archaeological potential and future directions, in S. Fitch, R. Bates and V.L. Gaffney (eds) *Europe's Lost Frontiers: Seismic Survey and Landscape Archaeology* (Europe's Lost Frontiers Volume 2). Oxford: Archaeopress.

Harff, J., G. Bailey and H. Lüth 2016. *Geology and Archaeology: Submerged Landscapes of the Continental Shelf* (Geological Society of London Special Publication 411). London: Geological Society.

Härnström, K., M. Ellegaard, T.J. Andersen and A. Godhe 2011. Hundred years of genetic structure in a sediment revived diatom population. *Proceedings of the National Academy of Sciences* 108: 4252-4257.

He, J., *et al.*2016. Composition and Distribution Characteristics and Geochemical Significance of n-Alkanes in Core Sediments in the Northern Part of the South Yellow Sea. *Journal of Chemistry*: Article 4741939. https://doi.org/10.1155/2016/4741939

Heamagi, C. 2016. Hornsea Project One Offshore Wind Farm Revised Archaeological WSI Offshore Generation Assets. Unpublished report by Maritime Archaeology Ltd. Archaeology Data Service. https://doi.org/10.5284/1051472

Heaton, T., *et al.* 2020. Marine20 - the marine radiocarbon age calibration curve (0-55,000 cal BP), *Radiocarbon* 62 (4): 779-820. https://doi.org/10.1017/RDC.2020.68

Hebsgaard, M.B., *et al.* 2009. The Farm Beneath the Sand'- an archaeological case study on ancient 'dirt' DNA. *Antiquity* 83: 430-444. https://doi.org/10.1017/S0003598X00098537

Heckenberger, M.J., *et al.* 2003. Amazonia 1492: Pristine Forest or Cultural Parkland? *Science* 301: 1710-1714.

Heiri, O., A.F. Lotter and G. Lemcke 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25 (1): 101-110.

Hendy, N.I. 1964. *An introductory account of the smaller algae of the British coastal waters. Part V: Bacillariophyceae (Diatoms)* (Fisheries Investigation Series I). London: Her Majesty's Stationary Office.

Hennekam, R. and G. De Lange 2012. X-ray fluorescence core scanning of wet marine sediments: methods to improve quality and reproducibility of high-resolution paleoenvironmental records. *Limnology and Oceanography: Methods* 10 (12): 991-1003.

Hepp, D.A., *et al.* 2017. Tributaries of the Elbe Palaeovalley: Features of a Hidden Palaeolandscape in the German Bight, North Sea, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 211-222. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_14

Hepp, D.A., *et al.* 2019. How a river submerges into the sea: a geological record of changing a fluvial to a marine palaeoenvironment during early Holocene sea level rise. *Journal of Quaternary Science* 34 (7): 581-592.

Van Heteren, S., *et al.* 2014. Reconstructing North Sea Palaeolandscapes from 3D and high-density 2D seismic data: An overview. *Netherlands Journal of Geosciences* 93 (1/2): 31-42.

Hijma, M.P. and K.M. Cohen 2019. Holocene sea-level database for the Rhine-Meuse Delta, The Netherlands: Implications for the pre-8.2 ka sea-level jump. *Quaternary Science Reviews* 214: 68-86.

Hijma, M.P., *et al.* 2012. Pliestocene Rhine-Thames landscapes: geological background for hominin occupation of the southern North Sea region. *Journal of Quaternary Science* 27 (1): 17-39.

Hill, J., *et al.* 2014. How does multiscale modelling and inclusion of realistic palaeobathymetry affect numerical simulation of the Storegga Slide tsunami. *Ocean Modelling* 83: 11-25. https://doi.org/10.1016/j.ocemod.2014.08.007

Hill, J., *et al.* 2017. *Was Doggerland catastrophically flooded by the Mesolithic Storegga tsunami?* arXiv:1707.05593 [physics.ao-ph]

Hillhouse, J. and A. Cox 1976. Brunhes-Matuyama polarity transition. *Earth and Planetary Science Letters* 29 (1): 51-64.

Holmlund. J., Nilsson, B. and Rönnby, J. 2017. Joint Explorations of the Sunken Past: Examples of Maritimne Archaeological Collaboration Between Industry and Academia in the Baltic, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 53-64. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_4

Hounslow, M.W. 2018. GM4Edit - a program for managing magnetometer data v5.3.

Hjelstuen, B.O., *et al.* 2017. Evidence of an ice-dammed lake outburst in the North Sea during the last deglaciation. *Marine Geology* 402: 118- 130.

Hofreiter, M., *et al.* 2001. DNA sequences from multiple amplifications reveal artifacts induced by cytosine deamination in ancient DNA. *Nucleic Acids Research* 29: 4793-4799.

Hofreiter, M., *et al.* 2003. Molecular caving. *Current Biology* 13 (18): R693-5 PMID 13678604. https://doi.org/10.1016/j.cub.2003.08.039

Holford, S., K. Thomson and V. Gaffney 2007. Salt tectonics in the Southern North Sea: controls on late Pleistocene-Holocene geomorphology, in V. Gaffney, K. Thompson and S. Fitch (eds) *Mapping Doggerland: the Mesolithic landscapes of the southern North Sea*: 61-66. Oxford: Archaeopress.

Holland, J.H. 1998. *Emergence: from chaos to order*. Boston: Addison-Wesley Longman

Howard, C.D. 2002. The Gloss Patination of Flint Artifacts. *Plains Anthropologist* 47: 283-287.

Hublin, J.-J., *et al.* 2009. Out of the North Sea: the Zeeland Ridges Neandertal. *Journal of Human Evolution* 57: 777-785.

Ingham, E., *et al.* 2017. Volcanic records of the Laschamp geomagnetic excursion from Mt Ruapehu, New Zealand. *Earth and Planetary Science Letters* 472: 131-141.

IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, viewed 12 October, 2021, <https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/>

Jacobi, R. 1976. Britain inside and outside Mesolithic Europe. *Proceedings of the Prehistoric Society* 42: 67-84.

Jacobs, Z. 2008. Luminescence chronologies for coastal and marine sediments. *Boreas* 37 (4): 508-535.

Jain, M., A.S. Murray and L. Botter-Jensen 2004. Optically stimulated luminescence dating: how significant is incomplete light exposure in fluvial environments? *Quaternaire* 15 (1-2): 143-157.

Jakobsson, M., 2003. Optically Stimulated Luminescence dating supports central Arctic Ocean cm-scale sedimentation rates. *Geochemistry, Geophysics, Geosystems* 4 (2). https://doi.org/10.1029/2002GC000423

Jarvis, I., and K.E. Jarvis 1992. Inductively coupled plasma-atomic emission spectrometry in exploration geochemistry. *Journal of Geochemical Exploration* 44 (1-3): 139-200.

Jelgersma, S. 1979. Sea-level changes in the North Sea basin, in E. Oele, R.T.E. Schüttenhelm and A.J. Wiggers (eds) *Impacts of Sea-Level Rise on European Coastal Lowlands* (Institute of British Geographers Special Publication Series 27): 1-35. Oxford: Blackwell Scientific.

Johnson, S. 2002. *Emergence: The connected lives of ants, brains, cities, and software*. New York: Simon and Schuster.

Johnson, S.S., *et al.* 2007. Ancient bacteria show evidence of DNA repair. *Proceedings of the National Academy of Sciences* 104: 14401-14405.

Jonsson, M., P.M. Astrup and C. Skriver 2019. Thor offshore wind farm, North Sea. Archaeological Analysis. Holstebro Kommune: De Kulturhistoriske Museer.

Jónsson, H., *et al.* 2013. MapDamage2.0: fast approximate Bayesian estimates of ancient DNA damage parameters. *Bioinformatics* 29 (3): 1682–1684. https://doi.org/10.1093/bioinformatics/btt193

Jones, A.P., M.E. Tucker and J.K. Hart 1999. *The description and analysis of Quaternary stratigraphic field sections* (Quaternary Research Association Technical Guide No. 7). London: Quaternary Research Association.

Jöns, H., *et al.* 2020. Germany: Submerged Sites in the South-Western Baltic Sea and the Wadden Sea, in G. Bailey, *et al.* (eds). *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 95-124. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_5

Jørgensen, T., *et al.* 2012a. A comparative study of ancient sedimentary DNA, pollen and macrofossils from permafrost sediments of northern Siberia reveals long-term vegetational stability. *Molecular Ecology* 21: 1989-2003.

Jørgensen, T., *et al.* 2012b. Islands in the ice: detecting past vegetation on Greenlandic nunataks using historical records and sedimentary ancient DNA Meta-barcoding. *Molecular Ecology* 21: 1980-1988.

Karikalan, R., R. Sathasivam and S. Rakkiannan 2020. XRD analysis in Gundar river estuary and beach sediments of Mookaiyur area, Ramanathapuram district, South India. *International Journal of Engineering Research and Technology (IJERT)* 9: 340-344.

Katari, K. and L. Tauxe 2000. Effects of pH and salinity on the intensity of magnetization in redeposited sediments. *Earth and Planetary Science Letters* 181 (4): 489-496.

Kelly, R.L. 1995. *The Foraging Spectrum. Diversity in Hunter-Gatherer Lifeways*. London: Smithsonian Institution Press.

Kenward H.K. 1978. *The Analysis of Archaeological Insect Assemblages: A New Approach* (Archaeology of York 19/1). London: Council for British Archaeology for York Archaeological Trust.

Kenward H.K. and A.R. Hall 1995. *Biological Evidence from Anglo-Scandinavian Deposits at 16-22 Coppergate* (The Archaeology of York 14/7). London: Council for British Archaeology for York Archaeological Trust.

Kenward, H.K., A.R. Hall and A.G. Jones 1980. A tested set of techniques for the extraction of plant and animal macrofossils from waterlogged archaeological deposits. *Science and Archaeology* 22: 3-15.

Kerney, M.P. 1999. *Atlas of the Land and Freshwater Molluscs of Britain and Ireland*. Colchester: Harley.

Killeen, I., D. Aldridge and G. Oliver 2004. *Freshwater Bivalves of Britain and Ireland*. Ambleside: Freshwater Biological Association.

Kilian, M.R., J. van der Plicht and B. van Geel 1995. Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* 14: 959-966.

Kilian, M.R., J. van der Plicht and B. van Geel 2000. ^{14}C wiggle matching of raised bog deposits and models of peat accumulation. *Quaternary Science Reviews* 19: 1011-1033.

Kim, Y.-G., *et al.* 2007. *Oceanobacillus profundus* sp. nov., isolated from a deep-sea sediment core. *International Journal of Systematic and Evolutionary Microbiology* 57: 409-413.

King, J., *et al.* 1982. A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: Some results from lake sediments. *Earth and Planetary Science Letters* 59 (2): 404-419.

Kinnaird, T.C. and M. Bates 2018. Characterising the luminescence stratigraphies of cores ELF1A and ELF19, Europe's Lost Frontiers. CERSA Luminescence Report, University of St Andrews.

Kinnaird, T.C., *et al.* 2017a. Optically-stimulated luminescence profiling and dating of historic agricultural terraces in Catalonia (Spain). *Journal of Archaeological Science* 78: 66-77.

Kinnaird, T.C., *et al.* 2017b., Chronostratigraphy of an eroding complex Atlantic round house, Baile Sear, Scotland. *Journal of Coastal and Island Archaeology* 14 (1): 46-60.

Kirkels, F.M.S.A., B. Jansen and K. Kalbitz 2013. Consistency of plant-specific n-alkane patterns in plaggen ecosystems: A review. *The Holocene* 23 (9): 1355-1368.

Kistler L. (2012) Ancient DNA Extraction from Plants, in B. Shapiro and M. Hofreiter (eds) *Ancient DNA: Methods and Protocols* (Methods in Molecular Biology 840). Humana Press. https://doi.org/10.1007/978-1-61779-516-9_10

Kistler, L., *et al.* 2015. Thermal age, cytosine deamination and the veracity of 8000 year old wheat DNA from sediments. *bioRxiv*: 032060. https://doi.org/10.1101/032060

Kistler, L., *et al.* 2017. A new model for ancient DNA decay based on paleogenomic meta-analysis. *Nucleic Acids Research* 45 (11): 6310-6320. https://doi.org/10.1093/nar/gkx361

Kohler, T.A. and M.D. Varien 2012. *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. Berkeley: University of California Press.

Konare, H., *et al.* 2010. Loss on ignition: measuring soil organic carbon in soils of the Sahel, West Africa. *African Journal of Agricultural Research* 5 (22): 3088-3095.

Korte, M., *et al.* 2011. Reconstructing the Holocene geomagnetic field. *Earth and Planetary Science Letters* 312 (3): 497-505.

Kovacheva, M., *et al.* 2014. Extended and revised archaeomagnetic database and secular variation curves from Bulgaria for the last eight millennia. *Physics of the Earth and Planetary Interiors* 236: 79-94.

Krammer, K. and H. Lange-Bertalot 1986-1991. *Subwasserflora von Mitteleuropa*. Bacciliarophyceae: 2 (1) Naviculaceae; 2 (2) Bacillariacceae, Epithemiaceae, Surirellaceae; 2 (3) Centrales, Fragilariaceae, Eunotiaceae; 2 (4) Achnanthaceae. Stuttgart: Fischer.

Krüger, S., *et al.* 2017. Life in Doggerland - palynological investigations of the environment of prehistoric hunter-gatherer societies in the North Sea Basin. *Quaternary Science Journal* 66: 3-13.

Laj, C. and J.E.T. Channell 2007. Geomagnetic Excursions, in M. Kono (ed.) *Treatise on Geophysics* 5: 373 - 416. Amsterdam: Elsevier. https://doi.org/10.1016/B978-044452748-6.00095-X

Lambeck, K. 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hyro-isostatic rebound. *Journal of the Geological Society* 152: 437-448.

Laraminie, F.G. 1989a. *Silverwell Sheet (54N 02E): Seabed Sediments and Holocene Geology*. London: Her Majesty's Stationary Office.

Laraminie, F.G. 1989b. *Silverwell Sheet (54N 02E): Quaternary Geology.* London: Her Majesty's Stationary Office.

Larrasoaña, J., *et al.* 2014. Paleomagnetic and paleoenvironmental implications of magnetofossil occurrences in late Miocene marine sediments from the Guadalquivir Basin, SW Spain. *Frontiers in Microbiology* 5. https://doi.org/10.3389/fmicb.2014.00071

Last, W.M. and J.P. Smol (eds) 2006. *Tracking environmental change using lake sediments 2: physical and geochemical methods* (Developments in Paleoenvironmental Research 2). Dordrecht: Springer. https://doi.org/10.1007/0-306-47670-3

Laville, G., *et al.* 2012. Using gpu for multi-agent multi-scale simulations, in S. Omatu *et al.* (eds) *Distributed Computing and Artificial Intelligence* (Advances in Intelligent and Soft Computing 151): 197-204. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-28765-7_23

Law, M. 2017. Numerical approaches to land snail palaeoecology, in M. Allen (ed.) *Molluscs in Archaeology*: 48-64. Oxford: Oxbow.

Layton, R. and Rowley-Conwy, P. 2013. Wild Things in the North? Hunter-Gatherers and the tyranny of the colonial perspective. *Anthropologie* 51 (2): 213-230. http://www.jstor.org/stable/26272448

Leary, J. 2009. Perceptions of and responses to the Holocene flooding of the North Sea lowlands. *Oxford Journal of Archaeology* 28: 227-237.

Leary, J. 2011. Experiencing Change on the Prehistoric Shores of Northsealand: an anthropological perspective on early Holocene sea-level rise, in J. Benjamin, *et al.* (eds) *Submerged Prehistory*: 75-84. Oxford: Oxbow.

Leary, J. 2015. *The remembered land: surviving sea-level rise after the last Ice Age. Debates in archaeology*. London: Bloomsbury.

Lee, S.B., M. Li and F. Zhang 2017. Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans* 122 (5): 3917-3938.

Lejzerowicz, F., *et al.* 2013. Ancient DNA complements microfossil record in deep-sea subsurface sediments. *Biology Letters* 9: 20130283.

Lekens, W.A.H., *et al.* 2005. Laminated sediments preceding Heinrich event 1 in the Northern North Sea and Southern Norwegian Sea; origin, processes and regional linkage. *Marine Geology* 216: 27-50.

Lemke, A. 2021. Submerged prehistory and anthropological archaeology: Do underwater studies contribute to theory? *Journal of Island and Coastal Archaeology* 16: 5-26.

Leo, R.F. and P.L. Parker 1966. Branched-chain fatty acids in sediments. *Science* 152 (3722): 649-650.

Levis, C., *et al.* 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science* 355: 925-931.

Lewis, C.F.M., *et al.* 2012. Lake Agassiz outburst age and routing by Labrador Current and the 8.2 cal ka cold event. *Quaternary International* 260: 83-97.

Limburg, P.A. and L.J. Weider 2002. 'Ancient' DNA in the resting egg bank of a microcrustacean can serve as a palaeolimnological database. *Proceedings of the Royal Society of London B (Biological Sciences)* 269: 281-287. https://doi.org/10.1098/rspb.2001.1868

Limpenny, S.E., *et al.* 2011. *The East Coast Regional Environmental Characterisation*. Cefas Open Report 08/04, published by the Marine Aggregate Levy Sustainability Fund.

Lindahl, T. and B. Nyberg 1972. Rate of depurination of native deoxyribonucleic acid. *Biochemistry* 11: 3610-3618.

Linsen, D., *et al. 2014.* Mineralogical study of surface sediments in the western Arctic Ocean and their implications for material sources. 极地研究 25 (3-English): 192-203.

Long, D., *et al.* 1986. The sedimentary record of climatic variation in the southern North Sea (and discussion). *Philosophical Transactions of the Royal Society. London* Ser. A B 318: 523-537.

Long, D., C.R. Wickham-Jones and N.A. Ruckley 1988. A flint artefact from the northern North Sea, in D.A. Roe (ed.) *Studies in the Upper Palaeolithic of Britain and Northwest Europe* (BAR International Series 296): 55-62. Oxford: British Archaeological Report Publishing.

Lord, T.C., J.A. Thorp and P. Wilson 2015. A wild boar dominated ungulate assemblage from an early Holocene natural pit fall trap: Cave shaft sediments in northwest England associated with the 9.3 ka BP cold event. *The Holocene* 26: 147-153. https://doi.org/10.1177/0959683615596837

Lorenz, E. 1972. Predictability: Does the flap of a butterfly's wing in Brazil set off a tornado in Texas? Paper presented at the annual meeting of the American Association for the Advancement of Science, Washington, DC. https://eapsweb.mit.edu/sites/default/files/Butterfly_1972.pdf

Lorenz, E.N. 1963. Deterministic nonperiodic flow. *Journal of Atmospheric Sciences* 20 (2): 130-141.

Louwe Kooijmans, L.P. 1970. Mesolithic bone and antler implements from the North Sea and the Netherlands. *Berichten van de Rijksdienst voor Oudheidkundig Bodemonderzoek* 20-21: 27-73.

Louwe Kooijmans, L.P. 1980. Archaeology and Coastal Change in the Netherlands, in F.H. Thompson (ed.) *Archaeology and Coastal Change* (Society of Antiquaries of London Occasional Paper New Series I): 106-133. London: Society of Antiquaries of London.

Louwe Kooijmans, L.P. 2007. The gradual transition to farming in the lower Rhine basin, in A. Whittle and V. Cummings (eds) *Going over: the Mesolithic-Neolithic transition in north-west Europe* (Proceedings of the British Academy 144): 287-309. Oxford: Oxford University Press.

Lowe, J.J., and M.J.C. Walker 2000. Radiocarbon dating the last glacial-interglacial transition (^{14}C ka BP) in terrestrial and marine records: the need for new quality assurance protocols, *Radiocarbon* 42 (1): 53-68. https://doi.org/10.1017/S0033822200053054

Lu, L., *et al.* 2001. Quantitative X-ray diffraction analysis and its application to various coals. *Carbon* 39 (12): 1821-1833.

Lumsden, G.I. 1986. *California Sheet (54N 0E): Quaternary Geology*. London: Her Majesty's Stationary Office.

Lund, S., D. Oppo and W. Curry 2017. Late Quaternary paleomagnetic secular variation recorded in deep-sea sediments from the Demerara Rise, equatorial west Atlantic Ocean. *Physics of the Earth and Planetary Interiors* 272: 17-26.

Lund, S.P., *et al.* 2005. Deep-sea sediment records of the Laschamp geomagnetic field excursion (~41,000 calendar years before present). *Journal of Geophysical Research: Solid Earth* 110 (B4). https://doi.org/10.1029/2003JB002943

Luoto, T.P. and A.E.K. Ojala 2017. Meteorological validation of chironomids as a paleotemperature proxy using varved lake sediments. *The Holocene* 27 (6): 870-878.

Lydolph, M.C., *et al.* 2005. Beringian paleoecology inferred from permafrost-preserved fungal DNA. *Applied and Environmental Microbiology* 71: 1012-1017.

Maarleveld, T.J. 1998. *Archaeological heritage management in Dutch waters: exploratory studies* (Scheepsarcheologie V). Leiden: Nederlands Instituut voor Scheeps- en onderwaterArcheologie / ROB (NISA).

Maarleveld, T.J. 2020 Beam Trawlers and Bones: A reflection on Dutch Fisheries, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 521-536. Cham: Springer.

Macan, T.T., 1977. *A Key to the British Fresh- and Brackish-Water Gastropods, with notes on their Ecology* (FBA Scientific Publications 13). Ambleside: Freshwater Biological Association.

Mackereth, F.J.H. 1971. On the variation in direction of the horizontal component of remanent magnetisation in lake sediments. *Earth and Planetary Science Letters* 12 (3): 332-338.

Madsen, A.T., *et al.* 2005. Optically stimulated luminescence dating of young estuarine sediments: a comparison with 210Pb and 137Cs dating. *Marine Geology* 214 (1-3): 251-268.

Madsen, A.T., *et al.* 2011. A new method for measuring bioturbation rates in sandy tidal flat sediments based on luminescence dating. *Estuarine, Coastal and Shelf Science* 92 (3): 464-471.

Maher, B.A. 2007. Environmental magnetism and climate change. *Contemporary Physics* 48 (5): 247-274.

Maher, B.A. and D.F. Hallam 2005. Palaeomagnetic correlation and dating of Plio/Pleistocene sediments at the southern margins of the North Sea Basin. *Journal of Quaternary Science* 20 (1): 67-77.

Maldegem, E.V., *et al.* 2021. Population collapse or human resilience in response to the 9.3 and 8.2 ka cooling events: A multi-proxy analysis of Mesolithic occupation in the Scheldt basin (Belgium). *Journal of Anthropological Archaeology* 64: 101348.

MALSF 2010. Marine Aggregate Levy Sustainability Fund (MALSF): Achievements and Challenges for the Future. Report by British Marine Aggregate Producers Association (BMAPA). https://tethys.pnnl.gov/sites/default/files/publications/MALSF_2010.pdf

Maity, S.K. and R. Maiti 2016. Understanding the sediment sources from mineral composition at the lower reach of Rupnarayan River, West Bengal, India-XRD-based analysis. *GeoResJ* 9-12: 91-103. https://doi.org/10.1016/j.grj.2016.09.004

Manninen, M.A. 2014. *Culture, Behaviour, and the 8200 cal BP Cold Event: Organisational Change and Culture Environment Dynamics in Late Mesolithic Northern Fennoscandia* (Monographs of the Archaeological Society of Finland 4). Helsinki: Archaeological Society of Finland.

Marathe, R.B. 2012. XRD and SEM analysis of Tapti river sediment: a case study. *Archives of Applied Science Research* 4 (1): 78-84.

Marcel J.L., *et al.* 2019. middle Palaeolithic complex technology and a Neanderthal tar-backed tool from the Dutch North Sea. *Proceedings of the National Academy of Sciences of the United States of America* 116: 22081-22087.

Marchand, G. 2007. Neolithic fragrances: Mesolithic-Neolithic interactions in western France, in A. Whittle and V. Cummings (eds) *Going over: the Mesolithic-Neolithic transition in north-west Europe* (Proceedings of the British Academy 144): 225-242. Oxford: Oxford University Press.

Marcott, S.A., *et al.* 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science* 339 (6124): 1198-1201.

Marincea, Ş. and D.-G. Dumitras 2005. First reported sedimentary occurrence of berlinite (AlPO4) in phosphate-bearing sediments from Cioclovina Cave, Romania Comment. *American Mineralogist* 90 (7): 1203-1208.

McCartan, S.B., *et al.* (eds) 2009. *Mesolithic Horizons Volumes 1 and 2: Papers presented at the seventh International Conference on the Mesolithic in Europe, Belfast 2005*. Oxford: Oxbow Books.

Meisch, C. 2000. *Freshwater Ostracoda of Western and Central Europe* (Suẞwasserfauna von Mitteleuropa Band 8/3). Heidelberg and Berlin: Spektrum Akadamischer Verlag.

Mejdahl, V. 1979. Thermoluminescence dating: Beta-dose attenuation in quartz grains. *Archaeometry* 29 (1): 61-72. https://doi.org/10.1111/j.1475-4754.1979.tb00241.x

Mellars, P.A. 1970. An antler harpoon-head of 'Obanian' affinities from Whitburn, Co. Durham. *Archaeologia Aeliana* 48: 337-346.

Mellars, P. 1987. *Excavations on Oronsay. Prehistoric human ecology on a small island*. Edinburgh: Edinburgh University Press.

Meylemeans, E., *et al.* 2018. The oldest cereals in the coversand area along the North Sea coast of NW Europe, between ca. 4800 and 3500 cal BC, at the wetland site of 'Bazel- Sluis' (Belgium). *Journal of Anthropological Archaeology* 49: 1-7.

Meziane, T. and M. Tsuchiya 2000. Fatty acids as tracers of organic matter in the sediment and food web of a mangrove/intertidal flat ecosystem, Okinawa, Japan. *Marine Ecology Progress Series* 200: 49-57.

Michoux, S. 2020 How geometallurgical outcomes could be used and by whom. Training course

Milner, N., C. Conneller and B. Taylor 2018a. *Star Carr. Volume 1: a persistent place in a changing world*. York: White Rose Press. https://doi.org/10.22599/book1

Milner, N., C. Conneller and B. Taylor 2018b. *Star Carr. Volume 2: studies in technology subsistence and environment*. York: White Rose Press. https://doi.org/10.22599/book2

Missiaen, T., *et al.* 2017. The SeArch Project: Towards an Assessment Methodology and Sustainable Management Policy for the Archaeological Heritage of the North Sea in Belgium, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 415-424. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_27

Missiaen T, *et al.* 2018. Archaeological prospection of the nearshore and intertidal area using ultra-high resolution marine acoustic techniques: results from a test study on the Belgian coast at Ostend-Raversijde. *Geoarchaeology* 33 (3): 386-400. https://doi.org/10.1002/gea.21656

Missiaen T., *et al.* 2021.Targeting the Mesolithic: Interdisciplinary approaches to archaeological prospection in the Brown Bank area, southern North Sea. *Quaternary International* 584: 141-151.

Mithen, S.J. 1988. Modeling hunter-gatherer decision making: complementing optimal foraging theory. *Human Ecology* 17 (1): 59-83.

Mithen, S. 2000. *Hunter-gatherer landscape archaeology. The Southern Hebrides Mesolithic Project 1988-1998* (Volumes 1 and 2). Cambridge: McDonald Institute Monographs.

Mithen, S.J. 2003. *After the Ice: A Global Human History, 20,000 - 5000 BC*. London: Weidenfeld and Nicolson.

Mithen, S. and K. Wicks 2021. Population level models for testing hunter-gatherer resilience and settlement response to the combined impact of abrupt climatic events and sea level change: A case study from the Holocene of northern Britain. *Quaternary Science Reviews* 265: 107027.

Mithen, S., K. Wicks and I. Berg-Hansen 2020. The Mesolithic coastal exploitation of western Scotland: The impacts of climate change and use of favoured locations, in A. Schulke (ed.) *Coastal Landscapes of the Mesolithic. Human engagement with the coast from the Atlantic to the Baltic Sea*. Abingdon: Routledge. 147-178.

Mithen, S., *et al.* 2015. A Lateglacial archaeological site in the far north-west of Europe at Rubha Port an t-Seilich, Isle of Islay, western Scotland: Ahrensburgian-style artefacts, absolute dating and geoarchaeology. *Journal of Quaternary Science* 396-416.

Moe Astrup, P. 2018. *Sea-Level Change in Mesolithic southern Scandinavia. Long and short-term effects on society and the environment*. Moesgaard: Jutland Archaeological Society.

Moe Astrup, P., *et al.* 2020a. Underwater Shell Middens: Excavation and Remote Sensing of a Submerged Mesolithic site at Hjarnø, Denmark. *The Journal of Island and Coastal Archaeology* 15 (4): 457-476.

Moe Astrup, P. 2020b. The role of coastal exploitation in the Maglemose culture of southern Scandinavia - marginal or dominant?, in A. Schülke (ed.) *Coastal Landscapes of the Mesolithic. Human engagement with the coast from the Atlantic to the Baltic Sea*: Abingdon: Routledge. 26-42.

Mol, D., *et al.* 2006. The Eurogeul-first report of the palaeontological, palynonological and archaeological investigations of this part of the North Sea. *Quaternary International* 142-143: 178-185.

Momber G., *et al.* 2021. New evidence from Bouldnor Cliff for technological innovation in the Mesolithic, population dispersal and use of drowned landscapes, *Quaternary International* 584: 116-128. https://doi.org/10.1016/j.quaint.2020.11.048

Momber, G., *et al.* 2011. Mesolithic *occupation at Bouldnor Cliff and the submerged prehistoric landscapes of the Solent* (CBA Research Report 164). York: Council for British Archaeology.

Momber, G. and H. Peeters 2017. Postglacial Human Dispersal and Submerged Landscapes in North-West Europe, in G.N. Bailey, J. Harff and D. Sakellariou (eds)

Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf (Coastal Research Library 20): 321-334. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_21

van Montfrans, H.M. 1971. Palaeomagnetic dating in the North Sea Basin. *Earth and Planetary Science Letters* 11 (1): 226-235.

Mook, W.G. and H.T. Waterbolk 1985. *Radiocarbon dating: a publication of the Sub-committee for Archaeology of the Standing Committee for the Humanities*. Strasbourg: European Science Foundation.

Moore, J. 2003. Beyond hazelnuts and into the forest, in L. Bevan and J. Moore (eds) *Peopling the Mesolithic in a northern environment*. (British Archaeological Report International Series 1157): 53-58. Oxford: Archaeopress.

Moree, J.M. and M.M. Sier (eds) 2015. Part 1. Twenty metres deep! The Mesolithic period at the Yangtze Harbour site - Rotterdam Maasvlakte, the Netherlands. early Holocene landscape development and habitation, in *Interdisciplinary Archaeological Research Programme Maasvlakte 2, Rotterdam* (BOORrapporten 566): 15-350. Rotterdam: Bureau Oudheidkundig Onderzoek Rotterdam, Gemeente Rotterdam.

Morris, J.T., *et al.* 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83 (10): 2869-2877.

Morrison, A. 1980. *Early Man in Britain and Ireland*. London: Croom Helm.

Munyikwa, K., T.C. Kinnaird and D.C. Sanderson 2020. The potential of portable luminescence readers in geomorphological investigations: a review. *Earth Surface Processes and Landforms*. 46: 131-150.

Murgatroyd, P., M. Butler and V. Gaffney 2022. The Europe's Lost Frontiers Augmented Reality sandbox: Explaining a 2.5 million Euro project using play sand, in E. Ch'ng *et al.* (eds) Visual Heritage: Digital Approaches in Heritage Science (Springer Series on Cultural Computing). Cham: Springer. https://doi.org/10.1007/978-3-030-77028-0_12

Murphy, P. 2007. *The Submerged Prehistoric Landscapes of the Southern North Sea: Work in Progress*. *Landscapes* 8: 1-22.

Murray, A.S. and A.G. Wintle 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32 (1): 57-73.

Murray, J.W. 2006. *Ecology and applications of Benthic Foraminifera*. Cambridge: Cambridge University Press.

Muru, M., *et al.* 2017. Sea level changes and Neolithic hunter-fisher-gatherers in the centre of Talinn, southern coast of the Gulf of Finland, Baltic Sea. *Holocene* 27: 917-928.

Narayan, H., *et al.* 2012. Synthesis, characterization and ac-conductivity measurements of polyaniline based composites with fly-ash and clinker. *Journal of Materials and Environmental Science*. 3 (1): 137-148.

NASA 2022. Jet Propulsion Laboratory, California Institute of Technology, Climate change: how do we know?, viewed 27 September 2021, <https://climate.nasa.gov/evidence/>.

Nelson, M., T. Rittenour and H. Cornachione 2019. Sampling methods for luminescence dating of subsurface deposits from cores. *Methods and Protocols* 2 (4): 88.

Neubauer, W. and A. Hinterleitner 1997. 3D-interpretation of postprocessed archaeological magnetic prospection data. *Archaeological Prospection* 4: 191-205.

Nguyen, T.T., L.J. Janik and M. Raupach 1991. Diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy in soil studies. *Soil Research* 29 (1): 49-67.

Niekus, M.J.L.Th., 2006. A geographically referenced 14C database for the Mesolithic and the early phase of the Swifterbant culture in the Northern Netherlands. *Palaeohistorica* 47/8: 41-99.

Niekus, M.J.L.Th., *et al.* 2015. Flint and other stone, in J. Moree and M.M. Sier (eds) Part 1. Twenty metres deep! The Mesolithic period at the Yangtze Harbour site – Rotterdam Maasvlakte, the Netherlands. early Holocene landscape development and habitation, in *Interdisciplinary Archaeological Research Programme Maasvlakte 2, Rotterdam* (BOORrapporten 566): 147-200. Rotterdam: Bureau Oudheidkundig Onderzoek Rotterdam, Gemeente Rotterdam.

Nilsson, A., R. Holme, M. Korte *et al.* 2014. Reconstructing Holocene geomagnetic field variation: new methods, models and implications. *Geophysical Journal International* 198 (1): 229-248.

Nilsson, B., A. Sjöström and P. Persson 2018. Seascapes of stability and change: the archaeological and ecological potential of the early mesolithic seascapes with examples from Haväng, in SE Baltic, Sweden, in P. Persson (eds) *Ecology of Early Settlement in Northern Europe Conditions for Subsistence and Survival: The Early Settlement of Northern Europe, Volume 1*: 335-352. Sheffield: Equinox Publishing.

Nymoen, P. and B. Skar 2011a. Paradis - og andre indikasjoner på sub-marine lokaliteter fra mesolittisk tid langs den norske Sørlandskyst, in P.G. Norseng (ed.) *Norsk Maritimt Museums Årbok 2010*: 91-115. Oslo: Norsk Maritimt Museum

Nymoen, P. and B. Skar 2011b. The Unappreciated Cultural Landscape: indications of submerged Mesolithic settlement along the Norwegian southern coast, in J. Benjamin, *et al.* (eds) *Submerged Prehistory*: 38-54. Oxford: Oxbow.

Ogram, A., *et al.* 1988. DNA adsorption to soils and sediments. *Environmental Science and Technology* 22: 982-984.

Olesik, J.W. 1991. Elemental analysis using ICP-OES and ICP/MS. *Analytical Chemistry* 63 (1): 12A-21A.

Olley, J., G. Caitcheon and A. Murray 1998. The distribution of apparent dose as determined by optically stimulated luminescence in small aliquots of fluvial quartz: implications for dating young sediments. *Quaternary Science Reviews* 17 (11): 1033-1040.

Olley, J.M., G.G. Caitcheon and R.G. Roberts 1999. The origin of dose distributions in fluvial sediments, and the prospect of dating single grains from fluvial deposits using optically stimulated luminescence. *Radiation Measurements* 30 (2): 207-217.

Olley, J.M., A. Murray and R.G. Roberts 1996. The effects of disequilibria in the uranium and thorium decay chains on burial dose rates in fluvial sediments. *Quaternary Science Reviews* 15 (7): 751-760.

Orlando, L., A. Ginolhac and E. Willerslev 2013. Recalibrating Equus evolution using the genome sequence of an early Middle Pleistocene horse. *Nature* 499: 74-78.

Oswalt, W.H. 1973. *Habitat and Technology. The Evolution of Hunting*. New York: Holt, Rinehart and Winston, Inc.

Özmaral, A. 2017. Climatically controlled sedimentary processes on continental shelves. Unpublished PhD dissertation, University of Bremen.

Pancost, R.D. and C.S. Boot 2004. The palaeoclimatic utility of terrestrial biomarkers in marine sediments. *Marine Chemistry* 92 (1-4): 239-261.

Pansu, J., *et al.* 2015. Reconstructing long-term human impacts on plant communities: an ecological approach based on lake sediment DNA. *Molecular Ecology* 24: 1485-1498.

Papenmeier, S., and H.C. Hass 2020. Revisiting the Paleo Elbe Valley: Reconstruction of the Holocene, Sedimentary Development on Basis of High-Resolution Grain Size Data and Shallow Seismics. *Geosciences* 10 (12): 505. https://doi.org/10.3390/geosciences10120505

Parducci, L., *et al.* 2015. Proxy comparison in ancient peat sediments: pollen, macrofossil and plant DNA. *Philosophical Transactions of the Royal Society B* 370: 20130382.

Parducci, L., *et al.* 2017. Ancient plant DNA in lake sediments. *New Phytologist* 214: 924-942. https://doi.org/10.1111/nph.14470

Parducci, L., *et al.* 2019. Shotgun Environmental DNA, Pollen, and Macrofossil Analysis of Lateglacial Lake Sediments From Southern Sweden. *Frontiers of Ecology and Evolution* 7 https://doi.org/10.3389/fevo.2019.00189

Parfitt, S.A., R.W. Barendregt M. Breda *et al.* 2005. The earliest record of human activity in northern Europe. *Nature* 438: 1008-1012.

Passeri, D.L., *et al.* 2015. The dynamic effects of sea level rise on low-gradient coastal landscapes: A review. *Earth's Future* 3 (6): 159-181.

Pater, C. 2020. Seabed Infrastructure Projects, Underwater Cultural Heritage and The Environmental Assessment Process: The UK Example, in G. Bailey, N. Galanidou, H. Peeters, H. Jöns and M. Mennenga (eds), *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 509-519. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_26

Pavón-Carrasco, F.J., *et al.* 2014. A geomagnetic field model for the Holocene based on archaeomagnetic and lava flow data. *Earth and Planetary Science Letters* 388: 98-109.

Peacock, J.D. 1995. Late Devensian to early Holocene palaeoenvironmental changes in the Viking Bank area, northern North Sea. *Quaternary Science Reviews* 14: 1029-1042.

Pedersen, L. 1995. 7000 years of fishing: stationary fishing structures in the Mesolithic and afterwards, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monograph 53): 75-86. Oxford: Oxbow Books.

Pedersen, L., A. Fischer and B. Aaby 1997. *The Danish Storebælt since the Ice Age: man, sea and forest.* Copenhagen: A/S Storebætsforbindelsen.

Pedersen, M.W., *et al.* 2013. A comparative study of ancient environmental DNA to pollen and macrofossils from lake sediments reveals taxonomic overlap and additional plant taxa. *Quaternary Science Reviews* 75: 161-168.

Pedersen, M.W., *et al.* 2015. Ancient and modern environmental DNA. *Philosophical Transactions of the Royal Society B* 370: 20130383. https://doi.org/10.1098/rstb.2013.0383

Pedersen, M.W., *et al.* 2016. Postglacial viability and colonization in North America's ice-free corridor. *Nature* 537: 45-49.

Peeters, H. 2006. Sites, landscapes and uncertainty: on the modelling of the archaeological 167 potential and assessment of deeply buried Stone Age landscapes in the Flevoland polders (the Netherlands), in E. Rensink and H. Peeters (eds) *Preserving the Early Past: Investigation, selection and preservation of Palaeolithic and Mesolithic sites and landscapes.* (Nederlandse Archeologische Rapporten 31): 167-184. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Peeters, H., P.L. Murphy and N. Flemming 2009. *North Sea prehistory research and management framework.* Amersfoort: Rijksdienst Voor Cultureel Erfgoed / English Heritage.

Peeters, H. and L. Amkreutz 2020. The Netherlands: Probing into the Submerged Prehistoric Archaeology, Landscapes and Palaeontology of the Dutch Continental Shelf, in G. Bailey, *et al.* (eds), *The Archaeology of Europe's Drowned Landscapes* (Coastal Research Library 35): 157-173. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_8

Peeters, H., G. Bailey and N. Galanidou 2020a. The Legal, Historical and Industrial Context of Underwater Heritage: Introduction, in G. Bailey, *et al.* (eds) *The Archaeology of Europe's Drowned Landscapes* (Coastal

Research Library 35): 485-494. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_24

Peeters, H., F. Sturt and K. Westley 2020b. The Atlantic Margin and the North Sea: Introduction, in G. Bailey, *et al.* (eds), *The Archaeology of Europe's Drowned Landscapes*. (Coastal Research Library 35): 143-155. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_7

Peeters, J.H.M. 2011. How wet can it get? Approaches to submerged prehistoric sites and landscapes on the Dutch Continental Shelf, in J. Benjamin, *et al.* (eds) *Submerged Prehistory*: 55-64. Oxford: Oxbow.

Peeters, J.H.M. and G. Momber 2014. The southern North Sea and the human occupation of northwest Europe after the Last Glacial Maximum. *Netherlands Journal of Geosciences* 93: 55-70.

Peeters, J.H.M., *et al.* 2015. Synthesis, in J. Moree, and M.M. Sier (eds) Part 1. Twenty metres deep! The Mesolithic period at the Yangtze Harbour site – Rotterdam Maasvlakte, the Netherlands. early Holocene landscape development and habitation, Rotterdam, in *Interdisciplinary Archaeological Research Programme Maasvlakte 2, Rottedam* (BOORrapporten 566): 287-318. Rotterdam: Bureau Oudheidkundig Onderzoek Rotterdam, Gemeente Rotterdam.

Peeters, J.H.M., *et al.* 2019. *North Sea Prehistory Research and Management Framework (NSPRMF) 2019. Retuning the research and management agenda for prehistoric landscapes and archaeology in the Dutch sector of the continental shelf* (Nederlandse Archeologische Rapporten 63). Amersfoort: Cultural Heritage Agency of the Netherlands.

Perdaen, Y., P. Crombé and J. Sergant 2008. Lithic Technology and the Cultural Identity of Early Mesolithic Groups. *Current Anthropology* 49: 317-327.

Pettitt, P. and White, M. 2012. *The British Palaeolithic. Human Societies at the edge of the Pleistocene World*. Abingdon: Routledge.

PGS 2021. Petroleum Geo-Services, Case studies, 'Nearer, Denser, Longer: The Barents Sea solution', viewed 3 August 2021, <https://www.pgs.com/publications/case-studies/hammerfest/>.

Phillips, J.D. 2018. Environmental gradients and complexity in coastal landscape response to sea level rise. *Catena* 169: 107-118.

Pieters, M., *et al.* 2018. Belgium - finds from trawl fishing, dredging and beach walking, in A. Fischer and L. Pedersen (eds) *Oceans of Archaeology* (Jutland Archaeological Society Publications 101): 89-93. Aarhus: Aarhus University Press.

Pieters, M., *et al.* 2020. Belgium: Prehistoric and Protohistoric Archaeology in the Intertidal and Subtidal Zones of the North Sea, in G. Bailey, *et al.* (eds), The Archaeology of Europe's Drowned Landscapes (Coastal Research Library 35): 175-188. Cham: Springer. https://doi.org/10.1007/978-3-030-37367-2_9

Pietramellara, G., *et al.* 2009. Extracellular DNA in soil and sediment: fate and ecological relevance. *Biology and Fertility of Soils* 45: 219-235.

Plets, R., *et al.* 2007. Characterization of buried inundated peat on seismic (Chirp) data, inferred from core information. *Archaeological Prospection* 14 (4): 261-272.

Plets, R., *et al.* forthcoming, in S. Fitch, R. Bates, and V.L. Gaffney (eds). *Europe's Lost Frontiers: Seismic Survey and Landscape Archaeology* (Europe's Lost Frontiers Volume 2). Archaeopress. Oxford.

Poinar, H.N. and A. Cooper 2000. Ancient DNA: do it right or not at all. *Science* 5482: 1139.

Poinar, H.N., *et al.* 2006. Metagenomics to paleogenomics: large-scale sequencing of mammoth DNA. *Science* 311: 392-394

Polymeris, G.S., *et al.* 2009. Luminescence dating of the top of a deep water core from the NESTOR site near the Hellenic Trench, east Mediterranean Sea. *Quaternary Geochronology* 4: 68-81.

Porter, T.M., *et al.* 2013. Amplicon pyrosequencing late Pleistocene permafrost: the removal of putative contaminant sequences and small-scale reproducibility. *Molecular Ecology Resources* 13: 798-810.

Poulton, S.W., P.W. Fralick, and D.E. Canfield 2010. Spatial variability in oceanic redox structure 1.8 billion years ago. *Nature Geoscience* 3: 486-490.

Praeg, D. 1997. Buried fluvial channels: 3D-seismic geomorphology, in T.A. Davies, *et al.* (eds) *Glaciated Continental Margins: An Atlas of Acoustic Images*: 162-163. London: Chapman and Hall.

Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin - high resolution from low frequencies. *Journal of Applied Geophysics* 53: 273-298.

Prescott, J.R. and J.T. Hutton 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations. *Radiation Measurements* 23 (2): 497-500.

Pretorius, L., *et al.* 2019. Outer- to inner-shelf response to stepped sea-level rise: Insights from incised valleys and submerged shorelines. *Marine Geology 416*: 1-14. [105979]. https://doi.org/10.1016/j.margeo.2019.105979

Preusser, F. and H.U. Kasper 2001. Comparison of dose rate determination using high-resolution gamma spectrometry and inductively coupled plasma-mass spectrometry. *Ancient Thermo Luminescence* 19 (1): 19-23.

Price, T.D. 1985. Affluent Foragers of Mesolithic Southern Scandinavia, in T.D. Price and J.A. Brown (eds) *Prehistoric Hunter-Gatherers. The Emergence of Cultural Complexity*: 341-363. London: Academic Press Inc.

Price. T. D. 2015. *Ancient Scandinavia. An Archaeological History from the First Humans to the Vikings*. Oxford: Oxford University Press.

Prins, L.T. and K.J. Andresen 2019. Buried late Quaternary channel systems in the Danish North Sea - Genesis and geological evolution. *Quaternary Science Reviews* 223: 105943. https://doi.org/10.1016/j.quascirev.2019.105943

Prosser, C.M. and B.M. Hedgpeth 2018. Effects of bioturbation on environmental DNA migration through soil media. *PloS One* 13: e0196430.

Ramasamy, V., P. Rajkumar and V. Ponnusamy 2009. Depth wise analysis of recently excavated Vellar river sediments through FTIR and XRD studies. *Indian Journal of Physics* 83 (9): 1295-1308.

Raniello, R. and G. Procaccini 2002. Ancient DNA in the seagrass *Posidonia oceanica*. *Marine Ecology Progress Series* 227: 269-273.

Ransley J., *et al.* 2014. *People and the Sea: a maritime archaeological research agenda for England* (CBA Research Report 171). York: Council for British Archaeology.

Ratcliffe, K.T., A.M. Wright and K. Schmidt 2012. Application of inorganic whole-rock geochemistry to shale resource plays: an example from the Eagle Ford Shale Formation, Texas. *The Sedimentary Record* 10 (2): 4-9.

Rawlence, N.J., *et al.* 2014. Using palaeoenvironmental DNA to reconstruct past environments: progress and prospects. *Journal of Quaternary Science* 29: 610-626.

Reed, D.C., *et al.* 2006. Steady-state tracer dynamics in a lattice-automaton model of bioturbation. *Geochimica et Cosmochimica Acta* 70 (23): 5855-5867.

Reed, S., *et al.* (2016), Augmented reality turns a sandbox into a geoscience lesson, Eos, 97, Published 26 July 2016, viewed 18 October 2019. https://doi.org/10.1029/2016EO056135

Rielley, G., *et al.* 1991. The biogeochemistry of Ellesmere Lake, UK—I: source correlation of leaf wax inputs to the sedimentary lipid record. *Organic Geochemistry* 17 (6): 901-912.

Reid, C. 1913. *Submerged Forests*. London: Cambridge University Press.

Reide, F. 2014. The Resettlement of Northern Europe, in V. Cummings, P. Jordan and M. Zvelebil (eds) *The Oxford Handbook of the Archaeology and Anthropology of Hunter-Gatherers*: 556-581. Oxford: Oxford University Press.

Riede, F. and J.B. Pedersen 2018. late Glacial Human Dispersals in Northern Europe and Disequilibrium Dynamics. *Human Ecology* 46: 621-632.

Reimer, P.J., *et al.* 2020. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0-55 cal kBP). *Radiocarbon* 62: 725-757.

Resnick, M. 1997. *Turtles, termites, and traffic jams: Explorations in massively parallel microworlds*. Cambridge, Massachusetts: The MIT Press.

Reynolds, R.G. 1987. A production system model of hunter-gatherer resource scheduling adaptations. *European Journal of Operational Research* 30 (3): 237-239. https://doi.org/10.1016/0377-2217(87)90063-4

Rittenour, T.M. 2008. Luminescence dating of fluvial deposits: applications to geomorphic, palaeoseismic and archaeological research. *Boreas* 37 (4): 613-635.

Richmond, P., *et al.* 2010. High performance cellular level agent-based simulation with FLAME for the GPU. *Briefings in Bioinformatics* 11 (3): 334-347.

Rivkina, E., E. Friedmann, C. McKay and D. Gilichinsky 2000. Metabolic activity of permafrost bacteria below the freezing point. *Applied and Environmental Microbiology* 66: 3230-3233.

Roberts, A.P. 2008. Geomagnetic excursions: Knowns and unknowns. *Geophysical Research Letters* 35 (17): L17307.

Roberts, D.H., *et al.* 2018. Ice marginal dynamics of the last British-Irish Ice Sheet in the southern North Sea: Ice limits, timing and the influence of the Dogger Bank. *Quaternary Science Reviews* 198: 181-207.

Roberts, H.M. and G.A.T. Duller 2004. Standardised growth curves for optical dating of sediment using multiple-grain aliquots. *Radiation Measurements* 38 (2): 241-252.

Roberts, H.M., J.A. Durcan and G.A.T. Duller 2009. Exploring procedures for the rapid assessment of optically stimulated luminescence range-finder ages. *Radiation Measurements* 44 (5): 582-587.

Rolph, T.C., L. Vigliotti and F. Oldfield 2004. Mineral magnetism and geomagnetic secular variation of marine and lacustrine sediments from central Italy: timing and nature of local and regional Holocene environmental change. *Quaternary Science Reviews* 23 (14-15): 1699-1722.

Rosentau, A., *et al.* 2021. A Holocene relative sea-level database for the Baltic Sea. *Quaternary Science Reviews* 266: 107071.

Rothwell, R., and I. Croudace 2015. Twenty Years of XRF Core Scanning Marine Sediments: What Do Geochemical Proxies Tell Us?, in I. Croudace and R. Rothwell (eds) *Micro-XRF Studies of Sediment Cores* (Developments in Paleoenvironmental Research 17). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9849-5_2

Round, F.E., R.M. Crawford and D.G. Mann 2007. *The Diatoms: Biology and Morphology of the Genera*. Cambridge: Cambridge University Press.

Rowley-Conwy, P. 1983. Sedentary hunters: the Ertebølle example, in G. Bailey (ed.) *Hunter-gatherer economy in prehistory. A European perspective*: 111-126. Cambridge: Cambridge University Press.

Rowley-Conwy, P. 1996. Why didn't Westropp's 'Mesolithic' catch on in 1872? *Antiquity* 70: 940 -944.

Rowley-Conwy, P. 1998. Cemeteries, seasonality, and complexity in the Ertebølle of southern Scandinavia, in M. Zvelebil, L. Domanska and R. Dennell (eds) *Harvesting the sea, farming the forest: The emergence of Neolithic societies in the Baltic region*: 193-202. Sheffield: Sheffield Academic Press.

Rowley-Conwy, P. 2002. Time, change and the archaeology of hunter-gatherers: how original is the

'Original Affluent Society'?, in C. Panter-Brick, R.H. Layton and P. Rowley-Conwy (eds) *Hunter-Gatherers. An Interdisciplinary Perspective*: 39-72. Cambridge: Cambridge University Press.

Rowley-Conwy, P. 2013. Homes without houses? Some comments on an Ertebølle Enigma, in G. Bailey, K. Hardy and A. Camara (eds) *Shell Energy: Mollusc Shells as Coastal Resources*: 137-154. Oxford: Oxbow.

Royal Haskoning NDA. Archaeological Data Service Digital Resource, Royal Haskoning DHV unpublished report series, viewed 27 September 2021, <https://archaeologydataservice.ac.uk/library/browse/series.xhtml?recordId=10548&recordType=GreyLit>.

Rubio Campillo, X., J.M. Cela and F.X. Hernàndez Cardona 2012. Simulating archaeologists? Using agent-based modelling to improve battlefield excavations. *Journal of Archaeological Science* 39 (2): 347-356.

Saarinen, T. 1999. Palaeomagnetic dating of Late Holocene sediments in Fennoscandia. *Quaternary Science Reviews* 18 (7): 889-897.

Sagnotti, L. 2013. Demagnetization Analysis in Excel (DAIE). An open source workbook in Excel for viewing and analyzing demagnetization data from paleomagnetic discrete samples and u-channels. *Annals of Geophysics* 56 (1): 1-9.

Salomonsen, I., and K.A. Jensen 1994. Quaternary erosional surfaces in the Danish North Sea. *Boreas* 23: 244-253.

Salter, E., P. Murphy and H. Peeters 2014. Researching, Conserving and Managing Submerged Prehistory: National Approaches and International Collaboration, in A.M. Evans, J.C. Flatman and N.C. Flemming (eds) *Prehistoric Archaeology on the Continental Shelf: A Global Review*: 151-172. New York: Springer.

Salter, S.J., *et al.* 2014. Reagent and laboratory contamination can critically impact sequence-based microbiome analyses. *BMC Biology* 12: 87.

Sanderson, D.C.W., 2003. Luminescence dating of anthropogenically reset canal sediments from Angkor Borei, Mekong Delta, Cambodia. *Quaternary Science Reviews* 22: 1111-1121.

Sanderson, D.C. and T.C. Kinnaird 2019. Optically Stimulated Luminescence Dating as a Geochronological Tool for Late Quaternary Sediments in the Red Sea Region in *Geological Setting, Palaeoenvironment and Archaeology of the Red Sea*: 685-707. Cham. Springer.

Sanderson, D.C.W. and S. Murphy 2010. Using simple portable OSL measurements and laboratory characterisation to help understand complex and heterogeneous sediment sequences for luminescence dating. *Quaternary Geochronology* 5 (2): 299-305.

Satchell, J. 2017. Education and Engagement: Developing understanding and appreciation of submerged prehistoric landscapes, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 391-402. Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_25

Saville, A. 2009. Gordon Childe in Print. *European Journal of Archaeology* 12: 247-275.

Scheutz, M. and P. Schermerhorn 2006. Adaptive algorithms for the dynamic distribution and parallel execution of agent-based models. *Journal of Parallel and Distributed Computing* 66 (8): 1037-1051.

Schlumberger oil field glossary, 2022 Schlumberger Limited, 'Compton scattering', viewed 3 September 2021, <https://glossary.oilfield.slb.com/en/terms/c/compton_scattering>.

Schmidt, C., *et al.* 2018. Copper complexation and solubility in high-temperature hydrothermal fluids: A combined study by Raman, X-ray fluorescence, and X-ray absorption spectroscopies and ab initio molecular dynamics simulations. *Chemical Geology* 494: 69-79.

Schock, S.G. 2004. Remote Estimates of Physical and Acoustic Sediment Properties in the Southern China Sea Using Chirp Sonar Data and the Biot Model. *IEEE Journal of Oceanic Engineering* 29 (4): 1218-1230.

Schulke, A. (ed.) 2020. *Coastal Landscapes of the Mesolithic. Human engagement with the coast from the Atlantic to the Baltic Sea*. Abingdon: Routledge.

Scott, E.M., G.T. Cook and P. Naysmith 2010. A report on phase 2 of the Fifth International Radiocarbon Intercomparison (VIRI). *Radiocarbon* 52: (3), 846-858. https://doi.org/10.1017/S0033822200045938

Seersholm, F.V., *et al.* 2020. Rapid range shifts and megafaunal extinctions associated with late Pleistocene climate change. *Nature Communications* 11: 2770.

Séveno, N.A., *et al.* 2002. Occurrence of reservoirs of antibiotic resistance genes in the environment. *Reviews in Medical Microbiology* 13 (1): 15-27.

Shennan, I., S.L. Bradley and R. Edwards 2018. Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum. *Quaternary Science Reviews* 188:143-159.

Shennan, I. and B. Horton 2002. Holocene land and sea-level changes in Great Britain. *Journal of Quaternary Science* 17 (5-6): 511-526.

Shennan, I., *et al.* 2000. Modelling western North Sea palaeogeographies and tidal changes during the Holocene, in I. Shennan and J.E. Andrews (eds) *Holocene land ocean interactions and environmental change around the North Sea* (Geological Society Special Publication 166): 299-319. London: Geological Society.

Shennan I., G. Milne and S. Bradley 2012. Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *Journal of Quaternary Science* 27: 64-70.

Sheridan A. 2015. Neolithic connections along and across the Irish Sea, in V. Cummings and C. Fowler

(eds) *The Neolithic of the Irish Sea: materiality and traditions of practice*: 9-20. Oxford: Oxbow.
Shook, E., S. Wang and W. Tang 2013. A communication-aware framework for parallel spatially explicit agent-based models. *International Journal of Geographical Information Science* 27 (11): 2160-2181.
Shore, J.S., D.D. Bartley, and D.D. Harkness 1995. Problems encountered with the ^{14}C dating of peat. *Quaternary Science Reviews* 14: 373-383.
Shumway, G. 1960. Sound Speed and Absorption Studies of Marine Sediments by a resonance method. *Geophysics* 20 (2): 451-467.
Sikes, E.L., *et al.* 2009. Sources of organic matter in a coastal marine environment: evidence from n-alkanes and their δ13C distributions in the Hauraki Gulf, New Zealand. *Marine Chemistry* 113 (3-4): 149-163.
Silverman, H. 2011. *Contested Cultural Heritage: Religion, Nationalism, Erasure, and Exclusion in a Global World*. Springer-Verlag New York.
Sjerup, H.P., C.D. Clark. and B. O. Hjelstuen 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea. *Geology* 44: 355-358.
Skar, B., *et al.* 2016. A Submerged Mesolithic Grave Site Reveals Remains of the First Norwegian Seal Hunters, in Bjerck, H.B., *et al.* (eds). *Marine Ventures. Archaeological Perspectives on Human-Sea Relations*: 225-239. Sheffield: Equinox Publishing.
Skoglund, P., *et al.* 2014. Separating endogenous ancient DNA from modern day contamination in a Siberian Neandertal. *Proceedings of the National Academy of Sciences* 111: 2229-2234.
Sjögren, P., *et al.* 2017. Lake sedimentary DNA accurately records 20th century introductions of exotic conifers in Scotland. *New Phytologist* 213: 929-941.
Slon, V., *et al.* 2017. Neandertal and Denisovan DNA from Pleistocene sediments. *Science* 356: 605-608.
Smart, D.J.Q. 2003. *Later Mesolithic Fishing Strategies and Practices in Denmark* (British Archaeological Report International Series 1119). Oxford: Archaeopress. https://doi.org/10.30861/9781841713281
Smith, B. 2019. *Doggerland*. London: HarperCollins 4th Estate.
Smith, C. 1992. *Late Stone Age Hunters of the British Isles*. Abingdon: Routlege.
Smith, C.I., *et al.* 2003. The thermal history of human fossils and the likelihood of successful DNA amplification. *Journal of Human Evolution* 45: 203-217.
Smith O., *et al.* 2015. Sedimentary DNA from a submerged site provides evidence of wheat in the British Isles 8000 years before present. *Science* 347 (6225): 998-1001. https://doi.org/10.1126/science.1261278
Snowball, I., *et al.* 2007. Varve dated Holocene palaeomagnetic secular variation and relative palaeointensity stacks for Fennoscandia. *Earth and Planetary Science Letters* 255 (1): 106-116.
Sokolowski, J.A. and C.M. Banks 2011. *Principles of modelling and simulation: a multidisciplinary approach*. Hoboken, NJ: John Wiley and Sons.
Sønstebø, J., *et al.* 2010. Using next-generation sequencing for molecular reconstruction of past Arctic vegetation and climate. *Molecular Ecology Resources* 10: 1009-1018.
Sparvath, K.S. 2012. Maritime Archaeology and Offshore Wind Farms. Unpublished MA dissertation, University of Southern Denmark.
Spikins, P. and Engen, M. 2007. Putting Predictive Models Underwater, Challenges New Perspectives and Potential of GIS Based Predictive Models in Submerged Areas, in F. Niccolucci and S. Hermon (eds) *Beyond the Artifact. Digital Interpretation of the Past. Proceedings of the CAA2004. Prato 13-17 April 2004*: 266-272. Hungary: Archaeolingua.
Spithoven, M. 2019. De biografie van de Mesolithische kleine benen spitsen met weerhaken uit de Noordzee. *Cranium* 36: 60-68.
Srinivasan, A. and S. Bandyopadhyay 2016. *Advances in Polymer Materials and Technology*. Boca Raton: CRC Press. https://doi.org/10.1201/9781315371054
Stapert, D., L. Johansen and M.J.L.Th. Niekus, 2013. A bifacial tool of the Neanderthals from Ameland, the Netherlands. *Netherlands Journal of Geosciences* 92: 181-192.
Steffens, G.S., *et al.* 2004. The use of near-seafloor 3D seismic data in deepwater exploration and production, in R.J. Davies, *et al.* (eds) *3D Seismic Technology: Application to the Exploration of Sedimentary Basins* (Geological Society of London Memoirs 29): 35-43. London: Geological Society. https://doi.org/10.1144/GSL.MEM.2004.029.01.04
Stephenson, A. 1993. Three axis alternating-field demagnetization of rocks and the identification of NRM, GRM, and anistropy. *Journal of Geophysical Research - Atmospheres* 98 (B1): 373-381.
Stoker, M.S., P.S. Balson, D. Long and D.R. Tappin 2011. *An overview of the lithostratigraphical framework for the Quaternary deposits on the United Kingdom continental shelf* (British Geological Survey Research Report RR/11/03, v. 48). Keyworth: British Geological Survey.
Stoker, M.S., *et al.* 1983. Palaeomagnetic evidence for early Pleistocene in the central and northern North Sea. *Nature* 304 (5924): 332-334.
Stoker, M.S., D. Long and J.A. Fyfe 1985. *A revised quaternary stratigraphy for the central North Sea* (British Geological Survey Research Report 17) London: Her Majesty's Stationary Office.
Stokes, S., *et al.* 2003. Alternative chronologies for Late Quaternary (Last Interglacial-Holocene) deep sea sediments via optical dating of silt-sized quartz. *Quaternary Science Reviews* 22 (8-9): 925-941.
Street, M. 1989. *Jager und Schamanen, Bedburg-Konigshoven ein Wohnplatz am Niederrhein vor 10000 Jahren*. Mainz: Verlag der Romisch-Geranishce Zentralmuseums.

Sturt, F., D. Garrow and S. Bradley 2013. New models of North West European Holocene palaeogeography and inundation. *Journal of Archaeological Science* 40: 3963-3976.

Sturt, F. and R. Van de Noort 2013. The Neolithic and Early Bronze Age, in J. Ransley, *et al.* (eds) *People and the sea: a maritime archaeological research agenda for England* (CBA Research Report 171): 50-92. York: Council for British Archaeology.

Sturt, F. 2015. From sea to land and back again: understanding the shifting character of Europe's landscapes and seascapes over the last million years, in A. Anderson-Whymark, D. Garrow and F. Sturt (eds) *Continental Connections. Exploring cross-Channel relationships from the Mesolithic to the Iron Age*: 7-27. Oxford: Oxbow Books.

Sturt, F., J. Dix and M.J. Grant 2017. The history of Industry-Linked Research in English Waters: Lessons for the Future, in G.N. Bailey, J. Harff and D. Sakellariou (eds) *Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf* (Coastal Research Library 20): 425-436 Cham: Springer. https://doi.org/10.1007/978-3-319-53160-1_28

Sturt, F., *et al.* 2017. *Determining Potential: Onshore/Offshore Prehistory. Historic England Project 6918.* York: Archaeology Data Service. https://doi.org/10.5284/1041582

Sturt, F., *et al.* 2018. The next frontiers in research on submerged prehistoric sites and landscapes on the continental shelf. *Proceedings of the Geologist's Association* 129: 654-683.

Stuiver, M., and H.A. Polach 1977. Reporting of ^{14}C data. *Radiocarbon* 19: 355-363.

Stuiver, M. and R.S. Kra 1986. Editorial comment. *Radiocarbon* 28: ii.

Su, Y., *et al.* 2013. Mineral magnetic study of lacustrine sediments from Lake Pumoyum Co, southern Tibet, over the last 19ka and paleoenvironmental significance. *Tectonophysics* 588: 209-221.

Szczuciński, W., *et al.* 2016. Ancient sedimentary DNA reveals past tsunami deposits. *Marine Geology* 381: 29-33.

Taberlet, P., *et al.* 2006. Power and limitations of the chloroplast trn L (UAA) intron for plant DNA barcoding. *Nucleic Acids Research* 35: e14-e14.

Tappin, D.R., *et al.* 2011. *The Humber Regional Environmental Characterisation* (British Geological Survey Open Report OR/10/54). Keyworth: British Geological Survey. http://nora.nerc.ac.uk/id/eprint/15037/

Tarling, D.H. 1983. *Palaeomagnetism: Principles and Applications in Geology, Geophysics and Archaeology*. London: Chapman and Hall Ltd.

Tauxe, L., K.P. Kodama and D.V. Kent 2008. Testing corrections for paleomagnetic inclination error in sedimentary rocks: A comparative approach. *Physics of the Earth and Planetary Interiors* 169 (1-4): 152-165.

Tauxe, L., J.L. Steindorf and A. Harris 2006. Depositional remanent magnetization: Toward an improved theoretical and experimental foundation. *Earth and Planetary Science Letters* 244 (3-4): 515-529.

Taylor, B. 2018. Subsistence, Environment and Mesolithic Landscape Archaeology. *Cambridge Archaeological Journal* 28: 493-510.

Taylor, M., *et al.* 2018. The Wooden Artefacts, in N. Milner, C. Conneller and B. Taylor (eds) *Star Carr. Volume 2: studies in technology, subsistence and environment*: 367-418. York: White Rose University Press. https://doi.org/10.22599/book2.o

Temmerman, S., *et al.* 2003. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. *Marine Geology* 193 (1-2): 151-169.

Thal, J., S. Feldmann and J.P. Brock 2019a. Geological Desk Study for the Ijmuiden Ver Wind Farm Zone. Arcadis Nederland B.V. and Geo-Engineering.org GmbH, 180017. Netherlands Enterprise Agency: RVO.nl Distribution.

Thal, J. 2019b. Geological *Desk Study for the Ten noorden van de Waddeneilanden Wind Farm Zone, Arcadis Nederland B.V. and Geo-Engineering.org GmbH*, 180017. Netherlands Enterprise Agency: RVO.nl Distribution.

Thal, J., *et al.* 2018. *Geological Desk Study for the Hollandse Kust (west) Wind Farm Zone*. Arcadis Nederland B.V. and Geo-Engineering.org GmbH, 180017. Netherlands Enterprise Agency: RVO.nl Distribution.

The Crown Estate 2014. *Protocol for Archaeological Discoveries: Offshore Renewable Projects*. Salisbury: Prepared by Wessex Archaeology on behalf of the Crown Estate. https://www.thecrownestate.co.uk/media/1782/ei-protocol-for-archaeological-discoveries-offshore-renewables-projects.pdf

The Crown Estate 2021. *Archaeological Written Schemes of Investigation for Offshore Wind Farm Projects*. Prepared by Wessex Archaeology on behalf of the Crown Estate. https://www.thecrownestate.co.uk/media/3917/guide-to-archaeological-requirements-for-offshore-wind.pdf

Thomson, D.F. 1939. The Seasonal Factor in Human Culture Illustrated from the Life of a Contemporary Nomadic Group. *Proceedings of the Prehistoric Society* 5: 209-221.

Thomson, K. and V. Gaffney 2007. 3D seismic reflection data, associated data and the development of the project methodology, in V. Gaffney, K. Thomson and S. Fitch (eds) *Mapping Doggerland, The Mesolithic Landscapes of the Southern North Sea*: 23-31. Oxford: Archaeopress.

Thompson, R., *et al.* 1980. Environmental applications of magnetic measurements. *Science* 207: 481 - 486.

Thompson, R., *et al.* 1992. The magnetic properties of Quaternary and Tertiary sediments in the southern North Sea. *Journal of Quaternary Science* 7 (4): 319-334.

Tizzard, L, *et al.* 2014. A middle Palaeolithic site in the southern North Sea: investigating the archaeology and palaeogeography of Area 240.

Journal of Quaternary Science 29: 698-710. https://doi.org/10.1002/jqs.2743

Tizzard, L., A.R. Bicket and D. de Loecker 2015. *Seabed prehistory: investigating the palaeogeography and Early middle Palaeolithic archaeology in the southern North Sea* (Wessex Archaeology report 35). Salisbury: Wessex Archaeology.

Tonelli, M., S. Fagherazzi and M. Petti 2010. Modeling wave impact on salt marsh boundaries. *Journal of Geophysical Research: Oceans* 115: C09028. https://doi.org/10.1029/2009JC006026

Tolan-Smith, C. 2003. Social interaction and settlement patterns in hunter-gatherer societies-applications of the 'amity-enmity' model, in L. Bevan and J. Moore (eds) *Peopling the Mesolithic in a Northern Environment* (British Archaeological Report International Series 1157): 113-118. Oxford: Archaeopress.

Topping, E.F. 2018. Magnetic Insights into the Chronology and Environment of Doggerland. Unpublished MSc dissertation, University of Bradford.

Torsvik, T.H., *et al.* 2012. Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews* 114 (3): 325-368. https://doi.org/10.1016/j.earscirev.2012.06.007

Torti, A., M.A. Lever and B.B. Jørgensen, 2015. Origin, dynamics, and implications of extracellular DNA pools in marine sediments. *Marine Genomics* 24: 185-196.

Trechmann, C.T. and A.S. Kennard 1936. Mesolithic flints from the Submerged Forest at West Hartlepool. *Proceedings of the Prehistoric Society* 2: 161-168.

Tresset, A., and J-D. Vigne 2007. Substitution of species, techniques and symbols at the Mesolithic-Neolithic transition in Western Europe, in A. Whittle and V. Cummings (eds) *Going over: the Mesolithic-Neolithic transition in north-west Europe* (Proceedings of the British Academy 144): 189-210. Oxford: Oxford University Press.

Tuorto, S.J., *et al.* 2014. Bacterial genome replication at subzero temperatures in permafrost. *International Society of Microbial Ecology (ISME) Journal* 8: 139-149. https://doi.org/10.1038/ismej.2013.140

Turner, G.M. and R. Thompson 1979. Behaviour of the earth's magnetic field as recorded in the sediment of Loch Lomond. *Earth and Planetary Science Letters* 42 (3): 412-426.

Turner, G.M. and R. Thompson 1981. Lake sediment record of the geomagnetic secular variation in Britain during Holocene times. *Geophysical Journal of the Royal Astronomical Society* 65 (3): 703-725.

Turner, G.M. and R. Thompson 1982. Detransformation of the British geomagnetic secular variation record for Holocene times. *Geophysical Journal of the Royal Astronomical Society* 70 (3): 789-792.

Turner, S., *et al.* 2021. Agricultural terraces in the Mediterranean: intensive construction during the later Middle Ages revealed by landscape analysis with OSL profiling and dating. *Antiquity* 95 (381): 773-790.

Tyler, G. and S. Jobin Yvon 1995. *ICP-OES, ICP-MS and AAS Techniques Compared.* (ICP Optical Emission Spectroscopy Technical Note 5). Longjumeau, France: Horiba Group

Underhill, J. 2007. The Geological Society, Obituaries (2001 onwards), Ken Thomson 1966-2007, viewed 23 July 2021, <https://www.geolsoc.org.uk/en/About/History/Obituaries%202001%20onwards/Obituaries%202007/Ken%20Thomson%201966-2007#>.

UK Government 2020. Energy demand reduction, News and communications, Press Release: New plans to make UK world leader in green energy, viewed 27 September 2021, <https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy>.

Vaezzadeh, V., *et al.* 2015. Forensic investigation of aliphatic hydrocarbons in the sediments from selected mangrove ecosystems in the west coast of Peninsular Malaysia. *Marine pollution bulletin* 100 (1): 311-320.

Van der Noort, R. 2011. *North Sea Archaeologies. A Maritime Biography, 10,000 BC - AD 1500.* Oxford: Oxford University Press.

Van der Noort, R. 2013. *Climate change archaeology: building resilience from research in the world's coastal wetlands.* Oxford: Oxford University Press.

van der Plicht, J., *et al.* 2016. Surf'n Turf in Doggerland: dating, stable isotopes and diet of Mesolithic human remains from the southern North Sea. *Journal of Archaeological Science: Reports* 10: 110-118. https://doi.org/10.1016/j.jasrep.2016.09.008

van der Werff, A. and H. Huls 1958-1974. *Diatomeeënflora van Nederland.* (Eight parts published privately by van der Werff). De Hoef (Utrecht), The Netherlands.

Verhart, L.B.M. 1987. Some preliminary notes on the barbed bone points from Europoort, the Netherlands. *Mesolithic Miscellany* 8 (1): 20-24.

Verhart, L.B.M. 1989. Mesolithic Barbed Points and Other Implements from the Europoort. *Mesolithic Miscellany* 10 (1): 24-26.

Verhart, L.B.M. 1995. Fishing for the Mesolithic. The North Sea: a submerged Mesolithic landscape, in A. Fischer (ed.) *Man and Sea in the Mesolithic. Coastal Settlement above and below present sea level. Proceedings of the International Symposium, Kalundborg, Denmark 1993* (Oxbow Monographs 53) 291-302. Oxford: Oxbow.

Verhart, L.B.M. 2004. The implications of prehistoric finds on and off the Dutch coast, in N.C. Flemming (ed.) *Submarine prehistoric archaeology of the North Sea. Research priorities and collaboration with industry* (CBA Research Report 141): 57-64. York: English Heritage/Council for British Archaeology.

Verhart, L.B.M. 2008. New Developments in the Study of the Mesolithic of the Low Countries, in G. Bailey and P. Spikins (eds) *Mesolithic Europe*: 158-181. Cambridge: Cambridge University Press.

Vigliotti, L. 2006. Secular variation record of the Earth's magnetic field in Italy during the Holocene: constraints for the construction of a master curve. *Geophysical Journal International* 165 (2): 414-429.

Vink, A., H. Steffen, L. Reinhardt and G. Kaufmann 2007. Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea). *Quaternary Science Reviews* 26: 3249- 3275.

Vos, P.C., *et al.* 2015. A staged geogenetic approach to underwater archaeological prospection in the Port of Rotterdam (Yangtzehaven, Maasvlakte the Netherlands): a geological and palaeoenvironmental case study for local mapping of Mesolithic lowland landscapes. *Quaternary International* 367: 4-31.

Vos, P.C. and H. de Wolf 1988. Methodological aspects of palaeo-ecological diatom research in coastal areas of the Netherlands. *Geologie en Mijnbouw, 67*: 31-40.

Vos, P.C. and H. de Wolf 1993. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands: methodological aspects. *Hydrobiologia* 269/270: 285-296.

Velgrakis, A.F., J.K. Dix and M.B. Collins 1999. Late Quaternary evolution of the upper reaches of the Solent River, Southern England, based upon marine geophysical evidence. *Journal of the Geological Society* 156: 73-87.

Waddington, C. 2007. *Mesolithic Settlement in the North Sea Basin: A Case Study from Howick, North-East England*. Oxford: Oxbow Books.

Waddington, C. 2015. A case for a secondary Mesolithic colonisation of Britain following rapid inundation of the North Sea Plain, in N. Ashton and C. Harris (eds) *No Stone Unturned: papers in honour of Roger Jacobi*: 221-232. Oxford: Oxbow Books.

Waddington, C. and C. Bonsall (eds) 2016. *Archaeology and Environment on the North Sea Littoral. A Case Study from Low Hauxley*. Bakewell: Archaeological Research Services Ltd.

Waddington, C. and K. Pedersen (eds) 2007. *Mesolithic Studies in the North Sea Basin and Beyond. Proceedings of a conference held at Newcastle in 2003*. Oxford: Oxbow Books.

Waddington, C. and K. Wicks 2017. Resilience or wipe out? Evaluating the convergent impacts of the 8.2 ka event and Storegga tsunami on the Mesolithic of northeast Britain. *Journal of Archaeological Science: Reports* 14: 692-714.

Walker, J., *et al.* 2020. A great wave: the Storegga tsunami and the end of Doggerland. *Antiquity* 94: 1409-1425. https://doi.org/10.15184/aqy.2020.49

Ward, G.K. and S.R. Wilson 1978. Procedures for comparing and combining radiocarbon age determinations: a critique. *Archaeometry* 20: 19-32.

Ward, I. 2014. Depositional Context as the Foundation to Determining the Palaeolithic and Mesolithic Archaeological Potential of Offshore Wind Farm Areas in the Southern North Sea. *Conservation and Management of Archaeological Sites* 16 (3): 212-235.

Ward, I., P. Larcombe and M. Lillie 2006. The dating of Doggerland - post glacial geochronology of the southern North Sea. *Environmental Archaeology: The Journal of Human Palaeoecology* 11: 207-218.

Ward, I. and P. Larcombe 2008. Determining the preservation rating of submerged archaeology in the post-glacial southern North Sea: a first order geomorphological approach. *Environmental Archaeology: The Journal of Human Palaeoecology* 13 (1): 59-83. https://doi.org/10.1179/174963108x279229

Ward, I., *et al.* 2014. Practical approaches to management of the marine prehistoric environment. *Netherlands Journal of Geosciences* 93: 71-82.

Waterbolk, H.T. 1971. Working with radiocarbon dates. *Proceedings of the Prehistoric Society* 37: 15-33.

Watters, M. 2006. Geovisualization: An Example from the Catholme Ceremonial Complex. *Archaeological Prospection* 13: 282-290.

WCPP 2011. *West Coast Palaeolandscape Project (Pilot Project)* University of Birmingham, viewed 12 October 2021, <https://doi.org/10.5284/1000398>.

WCPP 2013. *West Coast Palaeolandscapes Survey Main.* University of Birmingham, viewed 12 October 2021, <https://doi.org/10.5284/1018087>.

Weerts, H., *et al.* 2012. Finding the Needle in the Haystack by Using Knowledge of Mesolithic Human Adaptation in a Drowning Delta. *eTopoi Journal for Ancient Studies* 3: 17-24.

Weiß, C.L., *et al.* 2015. Contesting the presence of wheat in the British Isles 8000 years ago by assessing ancient DNA authenticity from low-coverage data. *Elife* 4: e10005.

Weltje, G.J., *et al.* 2015. Prediction of geochemical composition from XRF core scanner data: a new multivariate approach including automatic selection of calibration samples and quantification of uncertainties, in I.W. Croudace and R.G. Rothwell (eds) *Micro-XRF Studies of Sediment Cores. Developments in Paleoenvironmental Research*: 507-534. Dordrecht: Springer.

Wenban-Smith, F. 2002. *Palaeolithic and Mesolithic Archaeology on the Sea-bed: Marine Aggregate Dredging and the Historic Environment*. Salisbury: Wessex Archaeology on behalf of BMAPA (British Marine Aggregate Producers Association) and RCHME (Royal Commission on the Historical Monuments of England). https://bmapa.org/documents/palaeo_meso.pdf

Weninger, B., *et al.* 2008. The catastrophic final flooding of Doggerland by the Storegga Slide tsunami. *Documenta Praehistorica* 35: 1-24.

Wessex Archaeology 2017. *Norfolk Vanguard Offshore Wind Farm Marine Archaeological Technical Report*. Peterborough: Royal Haskoning DHV, viewed 12 October 2021, <https://archaeologydataservice.

ac.uk/library/browse/issue.xhtml?recordId=1179174&recordType=GreyLitSeries>.

Wessex Archaeology 2018. *Norfolk Boreas Offshore Windfarm Archaeological Assessment of Geophysical Data-Addendum*. Peterborough: Royal Haskoning DHV, viewed 12 October 2021, <https://archaeologydataservice.ac.uk/library/browse/issue.xhtml?recordId=1179183&recordType=GreyLitSeries>.

Weyrich, L.S., *et al.* 2017. Neanderthal behaviour, diet and disease inferred from ancient DNA in dental calculus. *Nature* 544: 357-361. https://doi.org/10.1038/nature21674

Whitehead, H. and Goodchild, H. 1909. Some notes on 'Moorlog' a peaty deposit from the Doggerbank in the North Sea. *Essex Naturalist* 16. 51-60.

Wickham-Jones, C. 2018. *Landscape Beneath the Waves. The archaeological investigation of underwater landscapes* (Studying Scientific Archaeology 4). Oxford: Oxbow Books.

Wicks, K. and S. Mithen 2014. The impact of the abrupt 8.2 ka cold event on the Mesolithic population of western Scotland: a Bayesian chronological analysis using 'activity events' as a population proxy. *Journal of Archaeological Science* 45: 240-269.

Wilkinson, T.J. and P.L. Murphy 1995. *The Archaeology of the Essex Coast, Volume I: The Hullbridge Survey* (East Anglian Archaeology Report 71). Chelmsford: Essex County Council Archaeology Section.

Willerslev, E., *et al.* 2003. Diverse plant and animal genetic records from Holocene and Pleistocene sediments. *Science* 300: 791-795. https://doi.org/10.1126/science.1084114

Willerslev, E. and A. Cooper 2005. Ancient DNA. *Proceedings of the Royal Society of London B (Biological Sciences)* 272: 3-16.

Willerslev, E., *et al.* 2004a. Long-term persistence of bacterial DNA. *Current Biology* 14: R9-R10.

Willerslev, E., A.J. Hansen and H.N. Poinar 2004b. Isolation of nucleic acids and cultures from fossil ice and permafrost. *Trends in Ecology and Evolution* 19: 141-147.

Willerslev, E., *et al.* 2007. Ancient biomolecules from deep ice cores reveal a forested southern Greenland. *Science* 317: 111-114.

Willerslev, E., J. Davison and M. Moora 2015. Fifty thousand years of Arctic vegetation and megafaunal diet. *Nature* 506: 47.

Wilmshurst, J.M., *et al.* 2014. Use of pollen and ancient DNA as conservation baselines for offshore islands in New Zealand. *Conservation Biology* 28: 202-212. https://doi.org/10.1111/cobi.12150

Wintle, A.G. and D.J. Huntley 1979. Thermoluminescence dating of a deep-sea sediment core. *Nature* 279 (5715): 710-712.

Wintle, A.G. and D.J. Huntley 1980. Thermoluminescence dating of ocean sediments. *Canadian Journal of Earth Sciences* 17 (3): 348-360.

Woodman, P. 2015. *Ireland's First Settlers: time and the Mesolithic.* Oxford and Philadelphia: Oxbow.

Wood, J.R., *et al.* 2018. Plant pathogen responses to late Pleistocene and Holocene climate change in the central Atacama Desert, Chile. *Scientific Reports* 8: 17208.

Woods, T.L., *et al.* 2016. Pilot study using the augmented reality sandbox to teach topographic maps and surficial processes in introductory geology labs. *Journal of Geoscience Education* 64 (3): 199-214.

WoRMS Editorial Team, 2020. World Register of Marine Species, An authoritative classification and catalogue of marine names, viewed 4 December 2021, http://www.marinespecies.org/

Wymer, J. 1991. *Mesolithic Britain*. Shire Archaeology.

Wymer, J.J. and C.J. Bonsall (eds) 1977. *Gazetteer of Mesolithic sites in England and Wales with a Gazetteer of Upper Palaeolithic sites in England and Wales* (CBA Research Report 22). London: Council for British Archaeology.

Xia, Z.-H., *et al.* 2008. Hydrogen isotope ratios of terrigenous n-alkanes in lacustrine surface sediment of the Tibetan Plateau record the precipitation signal. *Geochemical Journal* 42 (4): 331-338.

Xuan, C., J.E.T. Channell and D.A. Hodell 2016. Quaternary magnetic and oxygen isotope stratigraphy in diatom-rich sediments of the southern Gardar Drift (IODP Site U1304, North Atlantic). *Quaternary Science Reviews* 142: 74-89.

Yamamoto, M., F. Ohira and F. Kumon 2014. late Pleistocene variation in lignin and fatty acids from core TKN-2004 in a small mountain basin in central Japan. *Geochemical Journal* 48 (2): 207-217.

Yilmaz, O. 1987. *Seismic Data Processing*. Tulsa, Oklahoma: Society of Exploration Geophysicists.

Young, G. 2012. Birmingham Mail, News, Hundreds join protest at closure of University of Birmingham archaeology centre. viewed 23 July 2021, <https://www.birminghammail.co.uk/news/local-news/university-of-birmingham-archaeology-centre-closure-227043>.

Yu, S-Y., *et al.* 2010. Freshwater Outburst from Lake Superior as a Trigger for the Cold Event 9300 Years Ago. *Science*. 328 (5983): 1262-1266.

Zagwijin, W.H. 1989. The Netherlands during the Tertiary and Quaternary: a case history of coastal lowlands evolution. *Geologie en Mijnbouw* 68: 107-121.

Zander, A., *et al.* 2007. Optically stimulated luminescence dating of sublittoral and intertidal sediments from Dubai, UAE: Radioactive disequilibria in the uranium decay series. *Quaternary Geochronology* 2 (1-4), 123-128.

Zeng, H. 1994. Facies-guided 3D seismic modelling and reservoir characterization. Unpublished PhD dissertation, University of Texas at Austin.

Zeng, H. 2010. Stratal slicing: Benefits and challenges. *The Leading Edge* 29 (9): 1040-1047.

Zhang, D., *et al.* 2020. Denisovan DNA in late Pleistocene sediments from Baishiya Karst Cave on the Tibetan Plateau. *Science* 370: 584-587.

Zvelebil, M. 2008. Innovating hunter-gatherers: The Mesolithic in the Baltic, in G. Bailey and P. Spikins (eds) *Mesolithic Europe*: 18-59. Cambridge: Cambridge University Press.

Zvelebil, M. and J. Moore 2006. Assessment and representation: the informative value of Mesolithic landscapes, in E. Rensink and H. Peeters (eds) *Preserving the Early Past. Investigation, selection and preservation of Palaeolithic and Mesolithic sites and landscapes* (Nederlandse Archeologische Rapporten 31): 151-165. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Europe's Lost Frontiers was the largest, directed archaeological research project undertaken in Europe to investigate the inundated landscapes of the Early Holocene North Sea – the area frequently referred to as 'Doggerland'. Funded through a European Research Council Advanced Grant (project number 670518), the project ran from 2015 to 2021 and involved more than 30 academics, representing institutions spread geographically from Ireland to China. A vast area of the seabed was mapped, and multiple ship expeditions were launched to retrieve sediment cores from the valleys of the lost prehistoric landscapes of the North Sea. This data has now been analysed to provide evidence of how the land was transformed in the face of climate change and rising sea levels.

This volume is the first in a series of monographs dedicated to the analysis and interpretation of data generated by the project. Here, as a precursor to publication of the detailed results, we provide the context of the study and method statements. The following volumes will present the mapping, palaeoenvironment, geomorphology and modelling programmes of *Europe's Lost Frontiers*. The results of *Europe's Lost Frontiers* confirm that these landscapes, long held to be inaccessible to archaeology, can be studied directly and provide an archaeological narrative. This data will become increasingly important at a time when contemporary climate change and geo-political crises are pushing development within the North Sea at an unprecedented rate, and when the opportunities to explore this unique, heritage landscape may be significantly limited in the future.

Vincent Gaffney is Anniversary Chair in Landscape Archaeology at the University of Bradford and has undertaken research across many archaeological periods and in many parts of the world. Professor Gaffney was Principle Investigator on the ERC-funded, Advanced Grant project, *Europe's Lost Frontiers*. The results presented in this volume, and forthcoming project monographs, represent the culmination of nearly two decades of research in which he has been involved in the study of Doggerland, the submerged prehistoric landscape of the southern North Sea.

Simon Fitch is a UKRI Future Leaders Fellow at the University of Bradford. Dr Fitch led the seismic mapping aspect of *Europe's Lost Frontiers* and he has a longstanding interest in the study of submerged landscapes. His continuing research focuses upon submerged Mesolithic and late Palaeolithic landscapes worldwide and the investigation of the impacts of environmental and landscape change upon human populations during prehistory.

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