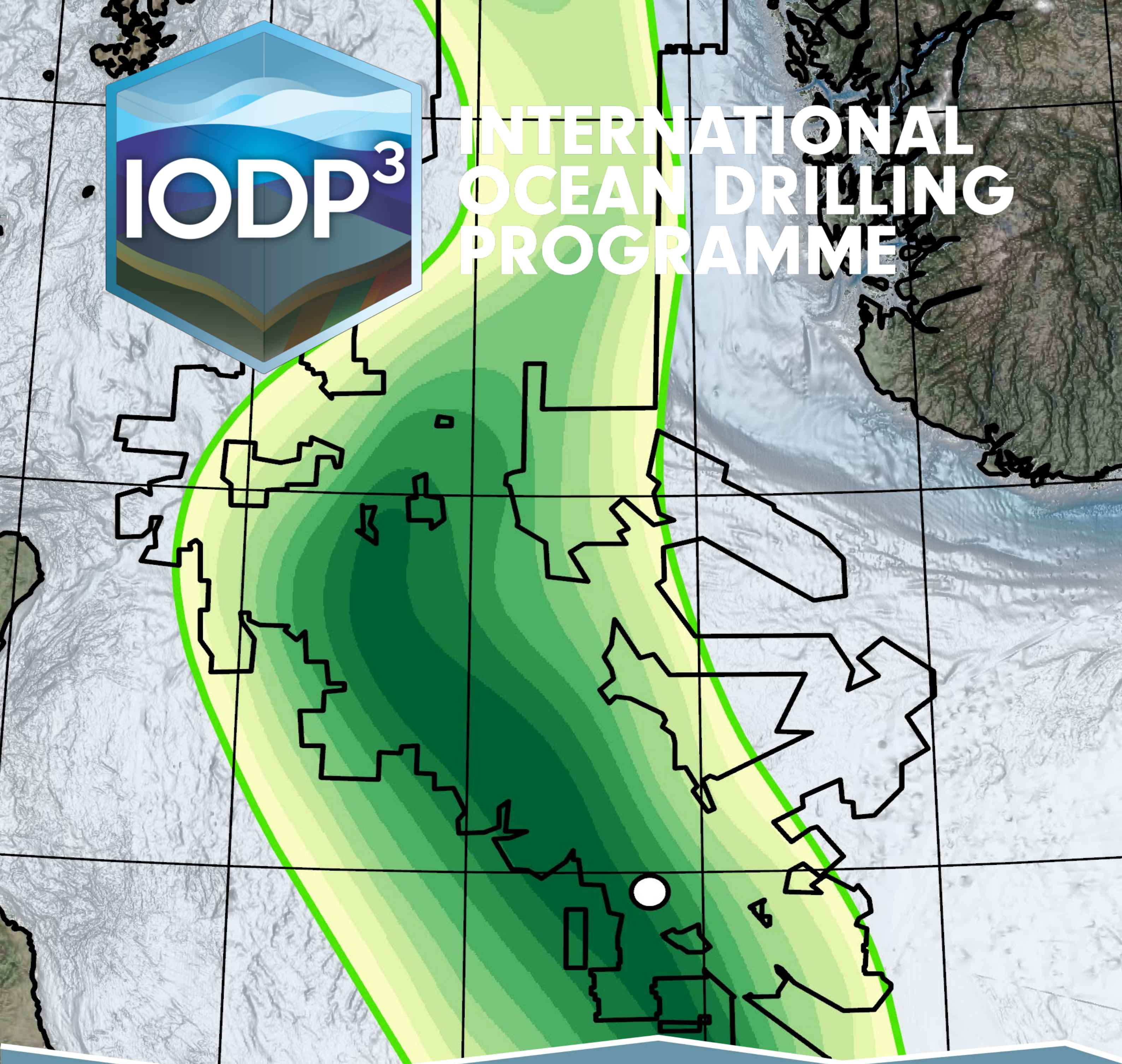

IODP³

INTERNATIONAL OCEAN DRILLING PROGRAMME

EXPEDITION OUTLINE

IODP³ Expedition GLACE-NS: Late Cenozoic Glaciers, Landscapes, Climates, and Ecosystems of the North Sea

11 September 2025

INTERNATIONAL OCEAN DRILLING PROGRAMME

IODP³ Expedition GLACE-NS: Expedition Outline

Late Cenozoic Glaciers, Landscapes, Climates, and Ecosystems of the North Sea

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****This is a condensed version of the original proposal, not the expedition scientific prospectus****

Introduction

Intensification of global glacial-interglacial cycles, marked by the onset of the Pleistocene (~2.6 Ma), was a critical climate transition as progressively more severe cold conditions triggered continental-scale Northern Hemisphere glaciation. While the last glacial cycle is increasingly well-understood, prior glaciations have little information about ice sheet margins, the underlying glacial- and morpho-dynamic controls, and how glacial variability was linked with climate and ecosystem changes. There is piecemeal evidence for some of these unknowns – e.g., landforms on the glaciated terrains of northwest Europe and North America suggest that, in some instances, Early Pleistocene ice sheets may have been comparable in size to those in the Late Pleistocene (Balco and Rovey 2010; Rea et al. 2018). However, with Early Pleistocene sea level lowstand estimates generally, but not always, ~50-60% of those in the Late Pleistocene (Miller et al. 2011; Jakob et al. 2020), such observations provide uncertainty on how they match up and, more broadly, the nature of Pleistocene climate-cryosphere evolution and its feedbacks relative to the preceding Pliocene global warmth. If we cannot fully understand the nuances of such discrepancies then it provides a limit on how effectively the past can be used as an analogue for the future.

The 600-km long North Sea Basin (NSB) transitioned through ~50 glacial-interglacial cycles – of varying lengths between the 41-kyr and 100-kyr worlds (**Figure 1**) – as it was infilled by an offset-stacked succession of largely muddy deep-to-shallow marine and terrestrial sediments (Lamb et al. 2018). Ample accommodation and high sediment fluxes combined to preserve a unique ~1.2-km-thick late Plio-Pleistocene succession that captures the co-evolution of glaciation and Europe's largest river systems in a shallow marine basin (Gibbard 1988; Rea et al. 2018). These sediments record palaeo-environment signatures from all over northwest Europe as they were sourced by multiple rivers and ice sheets connecting mid- and high-latitudes (**Figure 2a**). The interval also benefits from near-complete 3D- and 2D-seismic coverage (**Figure 2b**) and these data have revolutionised our understanding, providing paradigm shifts on patterns of basin infill and process dominance (Knutz 2010; Montelli et al. 2018; Rea et al. 2018). The northwest European Pleistocene ice sheets likely generated global-scale feedbacks that impacted the climate system, and nutrient/carbon exchange in the North Atlantic (Clark et al. 1999; Patton et al. 2017). Thus, the NSB Pleistocene sequence and the late Pliocene succession capturing the transition into it, provide a unique land-to-sea-to-ocean palaeo-climate archive across millions of years (Donders et al. 2018). Despite thousands of successfully-drilled exploration wells, industry operations rarely collected materials from the upper ~1.5 km, meaning this climate archive lacks samples to date and corroborate hypotheses, something that GLACE-NS hopes to resolve.

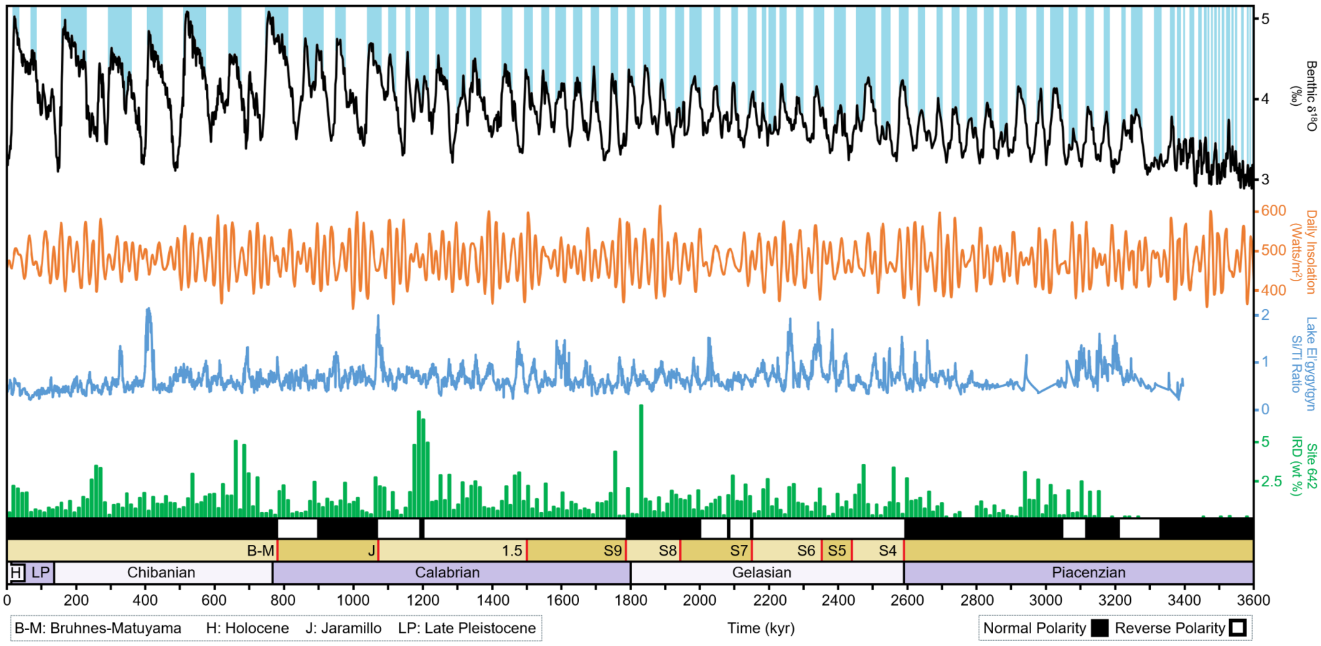

Figure 1. Proxy records – Black graph shows the global oxygen isotope record (Lisiecki and Raymo 2005), with blue bands indicating ice ages. Orange graph shows orbital variation influence on insolation that triggered glacial-interglacial cycles (Laskar et al. 2004). Blue graph is the productivity record at Lake El'gygytgyn, Siberia (Brigham-Grette et al. 2013). Green bars shows ice-rafted detritus documented on the mid-Norwegian margin (Krissek 1989). Seismic units (brown boxes) and age of key surfaces (labels with red lines) are shown.

Geological Setting

The NSB structural configuration results primarily from Late Jurassic-Early Cretaceous rifting and later regional uplift, followed by thermal cooling and subsidence (Jarsve et al. 2014). The basin is surrounded by land, except for a persistent northern link with the northeast Atlantic. Since the Neogene, up to 2 km of sediment accumulated in the Central Graben, of which up to ~1.2 km is Quaternary-aged (**Figure 2b**) and are largely undisturbed, except near salt diapirs (Knutz 2010). Basin-scale 3D-seismic data show that at ~2.6 Ma the North Sea formed an elongate depression with a narrow marine connection to the north (Lamb et al. 2018). North-westward progradation of shelf deltaic systems in the south and glaciogenic-linked progradation in the central/northern North Sea gradually infilled the Early Pleistocene basin with sediments from glaciation and the Baltic/Rhine-Meuse river systems (Lamb et al. 2017, 2018; Ottesen et al. 2018) (**Figure 2a**). Basin-scale age models have been developed from limited core materials (Kuhlmann and Wong 2008; Knutz 2010; Lamb et al. 2018) and allows subdivision of Early Pleistocene stratigraphy, from inception at ~2.6 Ma, to the Middle Pleistocene Transition (MPT – ~1.2-0.8 Ma).

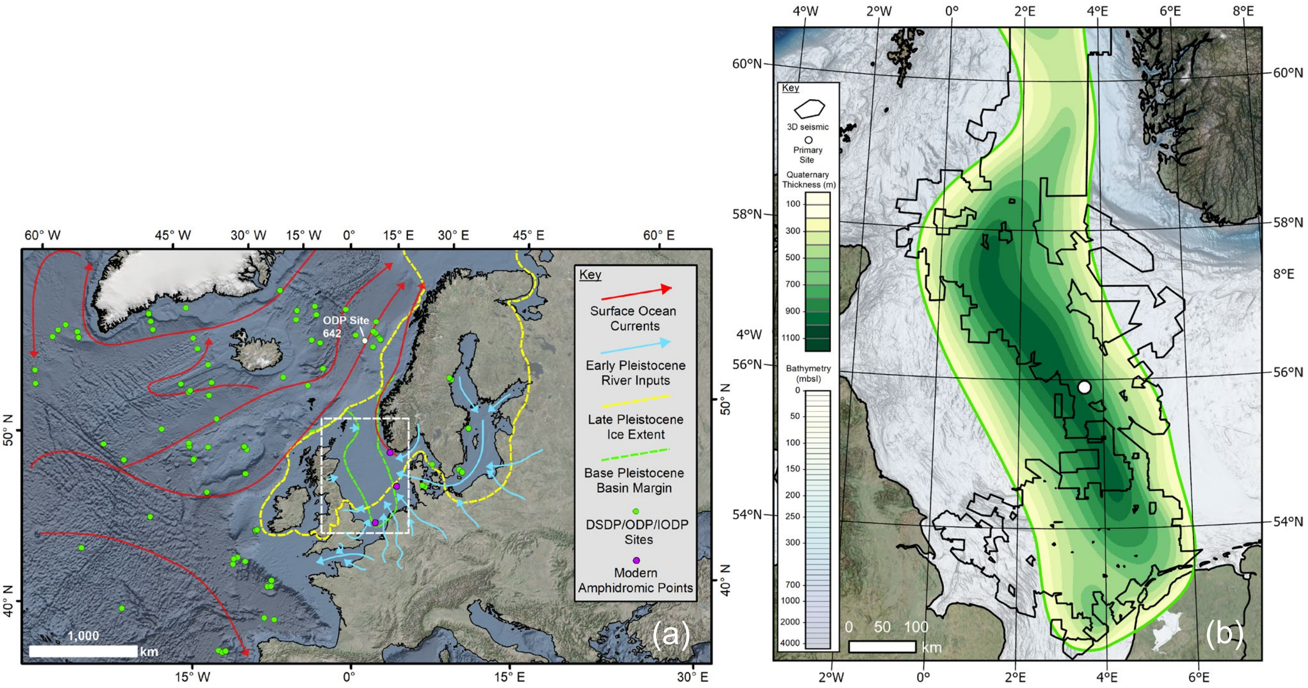

Figure 2. Study site – (**a**) Regional context showing Early Pleistocene river inflow into the North Sea (Gibbard 1988), Last Glacial Maximum ice extent (Hughes et al. 2016), and contemporary ocean surface currents. Purple dots show modern amphidromic points (Sinha and Pingree 1997). The map highlights the large geographical extent of NSB sediment transport pathways. Green dots show existing ocean drilling sites – note the North Sea absence. White box shows location of (**b**). ODP Site 642 from **Figure 1** is highlighted by the white circle. (**b**) Thickness map of NSB Quaternary section and the extent of industry data used to plan drill sites. 2D-seismic data are not displayed for clarity, but cover the entire basin.

The Plio-Pleistocene intensification of glaciation, which strengthened during the MPT, is preserved within the NSB. While direct glacial evidence is scarce (e.g., Graham et al. 2011), 3D-seismic data reveal extensive Early Pleistocene glacial landforms on clinoforms (e.g., Knutz 2010; Rea et al. 2018). However, limited chronological control from borehole A15-03 has led to contrasting interpretations. The 'extensive ice sheets' model puts the earliest ice advance from the British Ice Sheet into the central basin at the start of the Pleistocene at ~2.53 Ma, with the earliest confluence of the British and Fennoscandian ice sheets in the North Sea at ~1.87 Ma (Rea et al. 2018). In contrast, the 'restricted ice sheets' model suggests that, while the earliest Pleistocene Fennoscandian Ice Sheet reached the palaeo-shelf break beyond western Norway (Ottesen et al. 2018; Løseth et al. 2020), this ice sheet did not reach the centre of the basin until ~1.1 Ma (Ottesen et al. 2024). The contrasting interpretations provide significant uncertainty on glaciation extent and timing, limiting our ability to interrogate the causes and consequences of global climate shifts such as the MPT. From limited samples, key associations have been derived between ice sheet growth/decay and changes in sea surface temperatures, ecosystem extent (e.g., arboreal vegetation), and migration of Arctic surface water masses (Donders et al. 2018). In contrast to the Pleistocene, limited samples from the Pliocene show significant warmth compared to present (Kuhlmann et al. 2006; Dearing Crampton-Flood et al. 2020) with different flora and fauna that provide fundamental insights into a warm-state end member for the NSB.

Aims and Objectives

The NSB mid-latitude location, latitudinal range, complete 3D-seismic stratigraphic framework (architecture, facies, morphology), and the multiple catchments and processes feeding materials into a subsiding basin at different times with high sedimentation rates, provide a unique opportunity to unravel the palaeo-climatic and oceanographic evolution of northwest Europe in unprecedented detail. The NSB is, therefore, extremely well-suited for IODP[3] drilling. This campaign aims to investigate the NSB late Plio-Pleistocene succession and the environmental-ecological information it contains. This will help elucidate how Glaciers, Landscapes, Climates, and shallow marine and coastal Ecosystems evolved through a period of high-amplitude climate variability (**Figure 1**). The current North Sea has warmed at twice the global average and, therefore, has a non-linear response to climate forcing that needs quantification (Edwards et al. 2021; Holland et al. 2023). The regional climatic state cascades into nutrient cycling, ecosystem evolution, sediment transport, and carbon cycling in the North Sea and requires a greater knowledge on how these systems evolved through time periods of variable baseline characteristics (i.e., orbital parameters, ice sheets, climate, tipping points). This will improve knowledge on the fundamental mechanisms governing these processes, with strong relevance to contemporary and future change.

Objective 1: Glaciers – when, where, and how did ice sheets develop around the NSB?

Beyond the fact that icebergs and grounded ice occasionally entered the NSB, we know little about timing, origin, and characteristics (Newton et al. 2024). This uncertainty is important because ice sheet volumes impact global sea level reconstructions, our understanding of NSB connectivity with the North Atlantic, and how sensitive ice sheets were to different orbital and landscape settings. These are existential gaps in our knowledge of European palaeo-glaciology that profoundly impact our understanding of global Pleistocene glaciation. The first objective of a successful drilling campaign will be to provide knowledge on when Pleistocene ice sheet glaciations occurred in northwest Europe, where the ice sheets were centred, and how these ice sheets and their associated feedbacks evolved.

Objective 2: Landscapes – how did the landscapes around the NSB evolve?

The scale of the drainage networks flowing into the NSB from across northwest Europe, coupled with repeated glaciation, means that a coring campaign will provide insight on landscape evolution and its links with climatic changes across the European continent. The results will feed into conceptual discussions of global significance on topics such as the role of regolith in ice sheet development, the influence of ice sheets on tectonic movements, and the characteristics of the MPT. The second objective of a successful drilling campaign in the NSB will be to provide knowledge on how landscapes around the NSB evolved and impacted other parts of the Earth system through the late Plio-Pleistocene.

Objective 3: Climate – how did climate evolve across different time?

Insights on climate variability and vulnerability to perturbations, the large-scale structure of atmospheric-oceanographic circulation systems, rates/magnitudes of change, and how different Earth spheres interacted across different timescales, are all relevant to contextualising contemporary climate change and are of regional and global significance. The third objective of a successful drilling campaign in the NSB will be to provide knowledge on northwest European climate evolution over different climatological timescales, from within and across glacial-interglacial cycles and major global transitions like the MPT.

Objective 4: Ecosystems – how did ecosystems respond to climate changes and what can this tell us about thresholds relevant for contemporary and future biodiversity?

Documenting the timing, duration, and nature of ecosystem turnover events and understanding the role which climatic change plays in triggering the crossing of thresholds in biosphere responses is important. Climate records derived from proxies such as dust, pollen, leaf waxes, and micropalaeontology – which have been effective in the NSB (Noorbergen et al. 2015; Donders et al. 2018) – all provide information that links with other parts of the Earth-system (e.g., Objectives 1-3). This has direct implications for our understanding on the habitability of life on Earth and how this may relate to future ecosystem changes. The fourth objective of a successful drilling campaign in the NSB will be to provide knowledge on how ecosystems responded to past climatic tipping points and longer-term climatic changes.

GLACE-NS and the IODP 2050 Science Framework (2050-SF)

This proposal directly addresses the Strategic Objectives (SO) of the 2050 Science Framework by using the late Plio-Pleistocene record of the NSB to explore ecosystem resilience, biodiversity change, food web structures, and carbon cycling (SO-1), the role of biogeochemical processes, CO_2 sequestration, and microbial activity (SO-6), and the dynamics of feedbacks, tipping points, and ice-sheet evolution under different boundary conditions (SO-3 to SO-5). It contributes to the Flagship Initiatives (FI) by ground-truthing climate models to test climate sensitivity and variability (FI-1) and reconstructing changes in productivity, geochemistry, nutrient availability, and biodiversity across glacial–interglacial cycles (FI-4). It also fulfils the Enabling Elements (EE) by maximising scientific return through international and multidisciplinary collaboration (EE-1), integrating land-to-sea records from onshore and offshore drilling (EE-2), and generating geophysical, geochemical, and biological datasets that improve climate projections and contextualise modern change (EE-4). The NSB, never before drilled by IODP, offers a unique and essential archive to achieve these goals.

Drilling and Sampling Straettegy

Drilling and Logging Times

Recent drilling of the northwest Greenland glaciated margin (IODP Expedition 400) provided challenges for using advanced piston coring (APC) to penetrate compacted subglacial sediments (Knutz et al. 2024). The upper-most interval at the Primary site will consist of comparable subglacial sediments and might experience variable amounts of recovery (IODP Expedition 400 had >13%, while U1420/IODP Expedition 341 Bering Trough, U1521A/ODP Leg 374 Ross Sea, ODP Leg 188 Prydz Bay had up to ~65%). Thus, an APC would likely be refused within the first shot or two at these sites. To save time (from changing setup), it is proposed that a rotary core-barrel (RCB) will be used for the full target depth at the Primary site. Although RCB coring can result in loss of sandier intervals, it should maximise recovery of deeper mud-prone strata, particularly if compacted by ice loading. The shallower interval is comparatively better known than the more cohesive, mud-prone sediments beneath, which are the key target of GLACE-NS. IODP Expedition 400 drilled similar sediments, with a recovery of ~77%. In addition to coring, a standard suite of downhole logging will be performed.

Full Drilling Strategy

The Primary site will recover high-resolution records of the late Pliocene and Early Pleistocene interval, possibly down to ~4 Ma. Seismic reflection geometries and nearby well data suggest the target strata comprise muddy to fine-grained marine sediments, coarsening upwards due to progradation. The upper succession (above ~1.78 Ma) is expected to consist of unconsolidated fine-to-medium grained sands intercalated with clays. The succession deeper than 400 mbsf is expected to comprise interbedded silty clay/clays, silts, and very fine-to-medium-grained sands. Occasional limestone stringers may be expected. Evidence of iceberg scouring in the Early

Pleistocene topset strata (2.1-1.7 Ma) suggests ice-rafted debris could be present. Nearby Pleistocene gas reservoirs are clearly seen on the seismic data and have been avoided. The uppermost ~300 m is thought to comprise a heterolithic succession spanning the last ~500 kyr.

A ~30-day expedition using a Mission Specific Platform will target these predominantly mud-rich, late Plio-Pleistocene sequences at the Primary site in the Central North Sea. Valuable records will be obtained even if target depths are not reached, as these strata have rarely been sampled. The general operational plan is to conduct drilling and coring, then wireline logging. Previous IODP coring of glaciogenic sediments yielded recovery of 13-65% (see above). However, the lower latitude sites proposed here comprise mud-dominated strata buried at greater depths, with operations and cores at nearby gas reservoirs demonstrating the Pleistocene to be amenable to coring. During site selection, significant effort was made to limit the potential for sandy layers to disrupt recovery. Additionally, IODP Expedition 400 provides some justification to expect ≥70% recovery of the facies targeted from 2.8-0.78 Ma, at depths below ~400 mbsf. In the event of variable core recovery, a combination of techniques will be implemented for robust dating and interpretation of recovered sections. Downhole logs will be key for interpreting intervals with poor recovery.

Summary of Offshore Expected Measurements

Onboard analyses will provide first insights into the environmental history of the NSB, with post-cruise studies expanding these through detailed chronologies, biostratigraphy, and facies interpretations. Chronology will be developed initially offshore using standard biostratigraphy (foraminifera, coccoliths, diatoms, dinoflagellates, pollen, spores) and potentially palaeomagnetism and magnetic susceptibility, with higher-resolution work onshore. Palaeo-environments will be reconstructed from fossil assemblages to infer water conditions, sea-surface temperatures, sea ice cover, ecosystem changes, productivity, and terrestrial inputs, supplemented by pore fluid analyses and contamination-controlled sampling for microbiology. Sedimentology will document lithofacies across terrestrial to glacimarine settings using grain-size, mineralogy, smear slides, and core scanning, with initial carbon content estimates where possible. Wireline logging will provide physical property data and mitigate intervals of poor recovery.

Summary of Onshore Expected Analyses

Onshore, analyses will broaden to include stable isotopes ($\delta^{18}O$, $\delta^{13}C$, Mg/Ca) for temperature and salinity, palynology for vegetation and hydrology, and additional siliceous and organic microfossils. Biomarkers (HBIs, sterols, GDGTs, leaf waxes) and sedimentary DNA will be used to reconstruct sea ice, productivity, vegetation, and ecosystem diversity. Sedimentology will employ microscopy, XRD, SEM, and stratigraphic analyses to refine facies models, fluxes, and depositional histories. Geochemistry and provenance studies will use elemental data, isotopes, and mineral dating to track sediment sources, organic matter changes, and redox conditions. Together, these methods will deliver a high-resolution stratigraphy and palaeo-environmental framework for the late Plio-Pleistocene.

Summary of Analyses

A major goal of the drilling is to establish a robust Pleistocene chronology using palaeomagnetic reversal stratigraphy, biostratigraphy, geochemistry, palynology, tephrochronology, and radiometric dating, many of which have been successfully applied in the North Sea (e.g., Kuhlmann et al. 2006; Donders et al. 2018; Reinardy et al. 2018; Chauhan et al. 2022) (**Table 1**). This framework will enable all other workflow components to be integrated into a chronostratigraphic and seismic stratigraphic context. Sediment provenance will be constrained by bulk and clay mineralogy, trace and rare Earth elements, and single-grain thermochronology. Lithological, macro- and micro-fabric, and grain-size analyses will refine interpretations of depositional environments from ice-contact to glacimarine settings. Many methods have cross-cutting applications, and together will produce a powerful dataset for documenting glaciation, landscape transformation, climate change, and ecosystem turnover. These outputs will be integrated with numerical Earth-system models to test and calibrate their ability to reproduce past environmental change.

Expected Scientific Outcomes

A successful coring campaign will deliver the bullet points below, with specific research questions presented on **Table 2**:

- A late Pliocene and Pleistocene chronostratigraphic record of the NSB.
- Reconstruction of glaciation in the NSB and what form those glaciations took.
- Insights on the landscape dynamics and how infill of the NSB impacted other parts of the Earth-system, such as ice sheets and the Baltic and Rhine-Meuse river systems.
- Knowledge on how northwest European climate evolved through glacial-interglacial cycles, within individual cycles, the potential for tipping points, and the rates of change.
- Ecosystem reconstructions through different environmental changes, providing insights on speciation, extinction, longevity, turnover times, and response.
- Insight on how different Earth-system components interacted and their sensitivity through the transition into the Pleistocene ice-house and the subsequent glacial-interglacial cycles.
- These outcomes will provide the world’s most integrated record of glaciological, geological, climatological, and biological changes for the late Plio-Pleistocene.

Table 1. Research priorities – summary of methods to be used. Superscript numbering in the top table relates to facies in the bottom table and shows which methods are typically (green numbers) used for studying that facies – e.g., dinoflagellates are typically use to investigate marine facies. The red numbering represents facies that may potentially be studied using that method, depending upon what materials are present. The number 8 represents cases where the method may be applicable to the investigation of all the expected facies.

	Anticipated Methods	What information can be derived from these methods?
Palaeontology	**Biological tracers and indicators** • *Diatoms (fresh to marine)* [3,5,8] • *Dinoflagellates (marine)* [3,8] • *Forams (brackish to marine)* [2,3,7] • *Molluscs (fresh to marine)* [3,4,8] • *Non-pollen palynomorphs (fresh to brackish)* [5,7,2] • *Pollen and spores (land/fresh)* [4,6,8] • *Radiolaria (marine)* [3,2] **Isotopic and elemental analysis** • *Clumped isotopes (Δ_{47})* [2,3,8] • *Isotopes (O, C)* [8] • *Mg/Ca ratios* [2,3,8]	• Diatoms, dinoflagellate cysts, foraminifera, molluscs and pollen and spores and derived indices can be used to reconstruct past environmental conditions such as sea surface temperatures, salinity, nutrient levels, oxygen stress and vegetation types. Additional fresh water-derived palynomorphs (e.g. green algae) trace freshwater input. • Isotopes (such as $\delta^{18}O$ and $\delta^{13}C$) and Mg/Ca ratios in micro- and macrofossils and sedimentary materials can be used to infer past climate conditions, including temperature, precipitation, and ocean circulation patterns. $\delta^{18}O$ time series can detect successive glacial cycles and $\delta^{13}C$ clumped isotopes (Δ_{47}) provide reliable temperature estimates. • Analysis of isotopes and trace elements in micro/macro fossils can provide information about sediment provenance, transport pathways, and depositional environments. • Changes in fossil assemblages and organic material abundance can provide information about shifts in biodiversity, community structure, and ecosystem functions/dynamics through geological time. • Radiometric dating ($^{40}Ar/^{39}Ar$) can determine the age of carbonate fossils, helping establish timescales/correlations.
Biomarkers and Sedimentary DNA	**Microbial markers** • *Methanogens* [5,6,3] • *Nucleic acids (DNA or RNA)* [5,6,8] **Sterol/Lipid biomarkers** • *Glyceraldehyde (GDGTs)* [5,6,8] • *HBIs* [3,8] • *n-alkanes (leaf waxes)* [4,7,8] • *Sterols* [5,6,8]	• A wide range of sterol and lipid biomarkers can be used to reconstruct past environmental conditions such as mean air and sea surface temperatures, precipitation, soil pH, vegetation types/traits, pelagic productivity, sea ice cover, and terrestrial inputs. • Methanogens can indicate anaerobic microbial activity in ancient environments, while nucleic acids (eDNA or eRNA) can provide information about genetic diversity and microbial communities in sediments. • Indices based on n-Alkanes (leaf waxes) and other organic compounds can be used to trace the sources of organic matter in sediments, higher plant abundance and, with alkane-δD, provide insight of past hydrological regimes. • Organic compounds can provide information about environmental redox conditions, including the presence of oxygen or anaerobic conditions.
Sedimentology	**Mineralogical and microscopic** • *Mineralogy* [8] • *Petrographic microscopy* [8] • *Scanning electron microscopy* [8] **Palaeo-magnetics** • *NRM* [1,8] **Petrophysical** • *Penetrometer & shear vane* [1,3,8] • *Wireline logs* [8] **Stratigraphic** • *Lithofacies* [8] • *Micro-morphology* [8] • *Particle size analysis* [8] • *Thickness* [8]	• Lithofacies descriptions support the interpretation of sedimentary facies and depositional environments, helping to provide insight on sediment transport processes and landscape evolution. • Micro-morphology and particle size characteristics can be used to document sedimentary fabrics, biogenic structures, and sediment grain size classification (e.g., ice-rafted detritus), all of which provide insight on transport processes and interpretation of the depositional environments. • The metrics derived from individual geological units/facies, such as thickness and age, can provide information on how sedimentation fluxes changed through time and how this relates to interpretations of the environmental conditions preserved in the stratigraphy. • Mineralogical and petrographic analysis can identify mineral composition, providing insights into the origin, provenance, diagenesis, weathering/transport history, and depositional environments. • Petrophysical data can provide information on the variability in composition and physical attributes of the sediments (and any fluids), which aid stratigraphic interpretation and correlation, as well knowledge on the geotechnical properties.
Geochemistry, Mineralogy, and Provenance Analysis	**Chemical** • *Carbon analyses* [8] • *Elemental ratios* [3,7,8] • *Pore water analysis* [3,7,8] • *Rare Earth elements* [8] • *Redox-sensitive elements* [8] • *Trace elements* [8] **Dating and Chronostratigraphy** • *Dating* [8] • *Fission-track* [8] • *Tephrochronology* [8] **Isotopic** • *Stable and radiogenic* [8] **Mineralogical** • *X-ray diffraction & fluorescence* [8]	• Carbonate and organic/inorganic carbon measurements provides insights into carbonate deposition/dissolution, past biological productivity, carbon cycling, and environmental conditions. • Elemental ratios and analyses (e.g., Mg/Ca, trace, REE) inform us about past environmental conditions and processes like temperature and salinity, weathering and sediment provenance. • Redox-sensitive elements and pore water analysis can reveal past oxygen levels, redox conditions, diagenetic processes, and fluid-rock interactions in sedimentary environments. • Dating techniques (e.g., amino acid racemisation, $^{40}Ar/^{39}Ar$, U-Pb, tephrochronology, and magneto-stratigraphy can determine the age of minerals and fossils, and by extension, geological units, as well as facilitating correlations between different sites and existing records. • Isotopes (stable/radiogenic) are used for dating, palaeo-climate reconstruction, and sediment provenance. • Mineralogical analyses (X-ray diffraction/fluorescence): Identify elemental and mineral composition, aiding in trace element identification and providing insights into crystal structure, clay minerals, and geological history.

Chronological Methods and Approximate Resolution		
• Agglutinated forams: 100 ka – 1 Ma • Amino acid racemisation: 100 ka • Benthic forams: 100 ka – 1 Ma • Calcareous fossils: 10 ka – 100 ka • Diatoms: 100 ka – 1 Ma	• Dinoflagellate cysts: 100 ka – 1 Ma • Foraminifera isotopes: 1 ka – 10 ka • Magnetic excursions: 1 ka – 100 ka • Magnetic reversals: 5-500 ka • Optically stimulated luminescence: 10 ka – 100 ka	• Orbital tuning: 10 ka • Palaeo-intensity: 1 ka – 10 ka • Palaeo-secular variation: 1 ka • Planktic forams: 100 ka – 1 Ma • Radiocarbon: 1 ka

Main Expected Facies Types	
1) Glacial – poorly-sorted sediments with a mix of clay, silt, sand, gravel, and erratics; meltwater deposits are well-sorted sands and gravels.	**5)** Lacustrine – fine-grained muds and silts with occasional dropstones from nearby glacial activity.
2) Glaciomarine – fine-grained muds, isolated clasts (dropstones), and layers of coarse material (ice-rafted detritus).	**6)** Peat and organic-rich – peat layers or potential land surfaces with significant vegetation and organic material preservation.
3) Marine – well-sorted sands/silts (shallow marine), fine-grained muds (deeper environments), and fossil-rich layers indicative of interglacial highstand environments.	**7)** Transitional – mixed sands, silts, and clays with tidal laminations; well-sorted coastal sands showing wave or tidal influence.
4) Fluvial/Deltaic – coarse-grained sands and gravels in channel deposits, laminated muds in floodplains, and cross-bedded sands in deltas.	Method and facies association: **TYPICALLY USED** **POTENTIALLY USED**

Table 2. New knowledge – questions that a successful drilling campaign will seek to answer.

Glaciers	- What evidence is there for the first advance of ice into the basin and where did it come from? - Can we reconstruct the number and extent of those advances? - How did ice sheet geometries and behaviours vary between the 41 kyr and 100 kyr worlds? - How sensitive were the European ice sheets in the NSB to changes in boundary conditions – e.g., did infill of the basin promote ice sheet confluence, was it a precondition? - Do we see evidence for rapid ice sheet collapse through meltwater signals in the NSB and how is this manifested in the sedimentary record? - Is there evidence for different magnitudes of rapidity in ice sheet changes and variability in the contributing factors – i.e., are some changes internally driven by ice dynamics, are some driven by oceanographic forcing, or are they predominantly driven by insolation changes? - What evidence is there for the so-called missing glaciations of the Middle Pleistocene? - How do ice sheet changes in the NSB relate to broader climatic changes?	Landscapes	- How did sources of fluvio-deltaic sediments in the NSB and their transport history change? - Can changes in sediment supply and provenance be linked to regional climatic and hydrological cycle changes? - In the different parts of the NSB, what were the relative contributions of glacial and fluvial processes and how did they vary across glacial-interglacial cycles and within individual cycles? - Can the glacial sediments be used to reconstruct provenance and transport pathways? - What evidence is there for the interaction between wider landscape evolution and ice sheet geometries within the NSB? - Is there evidence for rapid landscape changes and what facilitated this? - Are cycles of erosion around the margins of the North Sea enough to explain evidence of tectonic movements within it? - Is regolith observed, and if so, where did it come from, when did it first appear, and when did it cease to be deposited in the NSB?
Climates	- How did the climate of the NSB evolve across the Pliocene-Pleistocene boundary? - Is there evidence for rapid climate changes or polar amplification during deglaciations of the NSB? - At what stage do feedback loops reach a tipping point and break down, and do they do so at global and/or regional scales? - What was the climate response of northwest Europe to the MPT? - Can we reconstruct the polar storm track positions and link this with European climate change? - How does oceanography of the North Sea evolve and how much freshwater is exported into the Norwegian Sea? - Do we see evidence of climatic or oceanographic variability that can be linked to changes in the strength of the Atlantic Meridional Overturning Circulation? - What role do global teleconnections play in the evolution of European glacial-interglacial climates and what linkages are there with other regional changes?	Ecosystems	- How did vegetation types change through time and what linkages were there with changes in the prevailing climate and CO_2? - Is there evidence for synchronicity in styles of vegetation change across different glacial-interglacial cycles? - What insights are there on turnover times, ecosystem resilience, and diversification through long- and short-term climate changes in marine and terrestrial habitats? - Can the impact of glaciation on carbon burial through multiple glacial-interglacial cycles be quantified? - What evidence is there for super interglacials and how resilient were communities during them? - Did dead zone development occur and how did it impact marine biodiversity and ecosystem functioning? - Are there differences in how marine and terrestrial ecosystems evolved during climate turnovers? - Can the marine and terrestrial species be used to tell us more broadly about oceanic, atmospheric, and hydrologic changes around the NSB and northwest Europe?

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