IODP³ INTERNATIONAL OCEAN DRILLING PROGRAMME

SCIENTIFIC PROSPECTUS
IODP^3 Expedition 506S:

SIGNALS: Stratigraphic InteGration of North Atlantic Legacy Sites

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INTERNATIONAL OCEAN DRILLING PROGRAMME

IODP³ Expedition 506S Scientific Prospectus

SIGNALS: Stratigraphic InteGration of North Atlantic Legacy Sites

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Abstract

The North Atlantic plays a crucial role in regulating global climate due to its proximity to major ice sheets and sensitivity to changes in the Atlantic Meridional Overturning Circulation (AMOC). Over millennial and orbital timescales, the region has experienced abrupt climate shifts with significant global implications. Despite the wealth of sediment cores recovered from North Atlantic legacy sites through International Ocean Discovery Program (IODP) and predecessor programs, many remain underutilized due to challenges in stratigraphic correlation and integration. IODP^3 Expedition 506S “SIGNALS – Stratigraphic InteGration of North Atlantic Legacy Sites” aims to synthesize and integrate these legacy records into a coherent, four-dimensional stratigraphic framework to provide a regional reconstruction of past climate variability on millennial to orbital timescales since the late Miocene.

SIGNALS will enhance stratigraphic correlation, refine age models, and synchronize proxy datasets for multiple legacy sites across the North Atlantic spanning a wide range of climatic and bathymetric gradients. The expedition will capitalize on advanced methods, including machine learning and signal correlation algorithms, to rapidly produce high-resolution data by automated processing of core images, point counting, and precise stratigraphic correlation. The IODP^3 Expedition 506S Science Team will work collaboratively to produce training datasets to refine AI models, stratigraphic correlation methods, and age models.

SIGNALS will address methodological issues associated with estimating uncertainty in stratigraphic correlations and the limits of temporal resolution at each site given varying sedimentation rates, bioturbation, and sampling frequency. Furthermore, we will develop process models to understand how orbitally-driven climatic changes are expressed as cycles in the stratigraphic record of each site. By analyzing high-resolution geochemical and sedimentological proxies in a robust stratigraphic framework, the expedition will reconstruct climate evolution and ocean circulation changes across the North Atlantic since the late Miocene. It will focus on major climatic transitions and provide robust regional paleoclimate data for numerical modelling and assimilation studies.

Beyond research advancements, SIGNALS will foster collaboration by developing user-friendly computational tools, training early-career researchers, and making data publicly accessible through open repositories. The expedition will contribute to other programmes, such as PAGES PMIP, TIMES, Beyond-EPICA Oldest Ice, by providing robust paleoclimatic information for assimilation and comparison. SIGNALS aligns with key objectives of the 2050 Science Framework, including: Earth’s Climate System, Feedbacks in the Earth System, Tipping Points in Earth History, and Global Cycles of Energy and Matter. Additionally, it addresses the themes of

Technology Development and Big Data Analytics through machine learning applications and automated data collection.

Plain Language Summary

The North Atlantic Ocean plays a major role in shaping regional and global climate through its effect on the transport of heat and salt through the global ocean. This region has experienced dramatic climate shifts, including the abrupt warming and cooling events that coincided with growth of ice sheets and changes in deep ocean circulation. These changes affected the movement and storage of heat, salt, and carbon in the deep ocean, influencing Earth's climate on both long and short timescales. Understanding how and why these shifts occurred in the past is relevant to future climate change given warnings of a potential slowdown of the Atlantic deep overturning circulation in response to global warming.

IODP^3 Expedition 506S aims to integrate sediment core data from key legacy sites recovered by deep-sea drilling expeditions across the North Atlantic. No one location fully captures past climate change and thus one major goal of the expedition is to align data from multiple drill sites to develop a regional picture. The IODP^3 Expedition 506S Science Team will develop and apply advanced computational tools for signal alignment and image analysis to more accurately correlate climatic signals at a higher resolution than previously possible. The expedition will also develop user-friendly tools and resources to train the next generation of paleoclimate researchers. The methods and data will be shared openly, allowing scientists worldwide to build on this work.

Understanding the history of climate change in the North Atlantic is important because similar processes continue to shape our climate today. Studying past ocean and climate interactions will help us better anticipate future changes, especially those related to rising temperatures, melting ice sheets, and disruptions in deep ocean circulation. The knowledge gained from the expedition will contribute to global efforts to understand climate change by providing a synthesis of regional paleoclimatic data that can be used as input to numerical climate models.

Introduction

The North Atlantic is one of the most climatically variable and sensitive regions in the oceans as it is prone to mode jumps in the Atlantic Meridional Ocean Circulation (AMOC). Its proximity to the North American, Greenland, and European ice sheets makes it particularly susceptible to ice discharge and associated freshwater forcing to the ocean. On millennial timescales, the North Atlantic experiences abrupt climate change with global implications that have been hypothesized to be due to variations in surface heat/salt transport and strength of the AMOC, which plays a fundamental role in deep-water circulation and CO_2 storage. On orbital timescales, North Atlantic cores contain strong evidence for glacial-interglacial climate change and cyclic variations in sediment lithology related to changing Earth's orbital parameters, providing excellent "clocks" through cyclostratigraphy. On yet longer time scales, tectonic events such as the isolation of the Mediterranean in the latest Miocene (Messinian), Pliocene closure of the Isthmus of Panama, closure of the Bering Sea (Otto-Bliesner et al., 2017), and subsidence of the Greenland-Iceland-Scotland Ridge (Robinson et al., 2011; Sinnesael et al., 2025) may have affected North Atlantic heat and salt transport and, thereby, global climate.

While many ODP/IODP expeditions have recovered continuous, high-resolution sediment sequences in the North Atlantic, a comprehensive integration of these legacy sites remains incomplete. These cores contain distinct signals of orbital- and suborbital-scale climate variability but have not been fully exploited because they have not been properly correlated and integrated across the entire North Atlantic, both spatially and bathymetrically.

IODP^3 Expedition 506S "SIGNALS - Stratigraphic InteGration of North Atlantic Legacy Sites" will integrate North Atlantic Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program/International Ocean Discovery Program (IODP) legacy sites into a common stratigraphic framework and complete proxy data sets. We aim to apply traditional and innovative stratigraphic methods to legacy materials from key North Atlantic ODP/IODP sites for the late Miocene-Quaternary on orbital (104-105) and millennial (103) time scales.

Stratigraphic correlation and chronology are at the heart of the SIGNALS expedition because it is a prerequisite for interpreting past climate history, and identifying the forcings and dynamics of climate change. The expedition will synchronize records across multiple North Atlantic sites (**Figures 1 and 2**) to answer key paleoclimate questions regarding orbital- and millennial-scale climate variability from the late Miocene to present. Climate variability will be placed in an orbitally-tuned chronologic framework with robust estimates of stratigraphic and temporal uncertainty. The unified framework will provide the basis for generation and synthesis of new and existing proxy data by members of the IODP[3] Expedition 506S Science Team. It will also permit refinement of the ages of isotopic, biostratigraphic and magnetostratigraphic chronologies across the North Atlantic and interface with broader geochronologic initiatives such as Time Integrated Matrix for Earth Sciences (TIMES) (Westerhold et al., 2024).

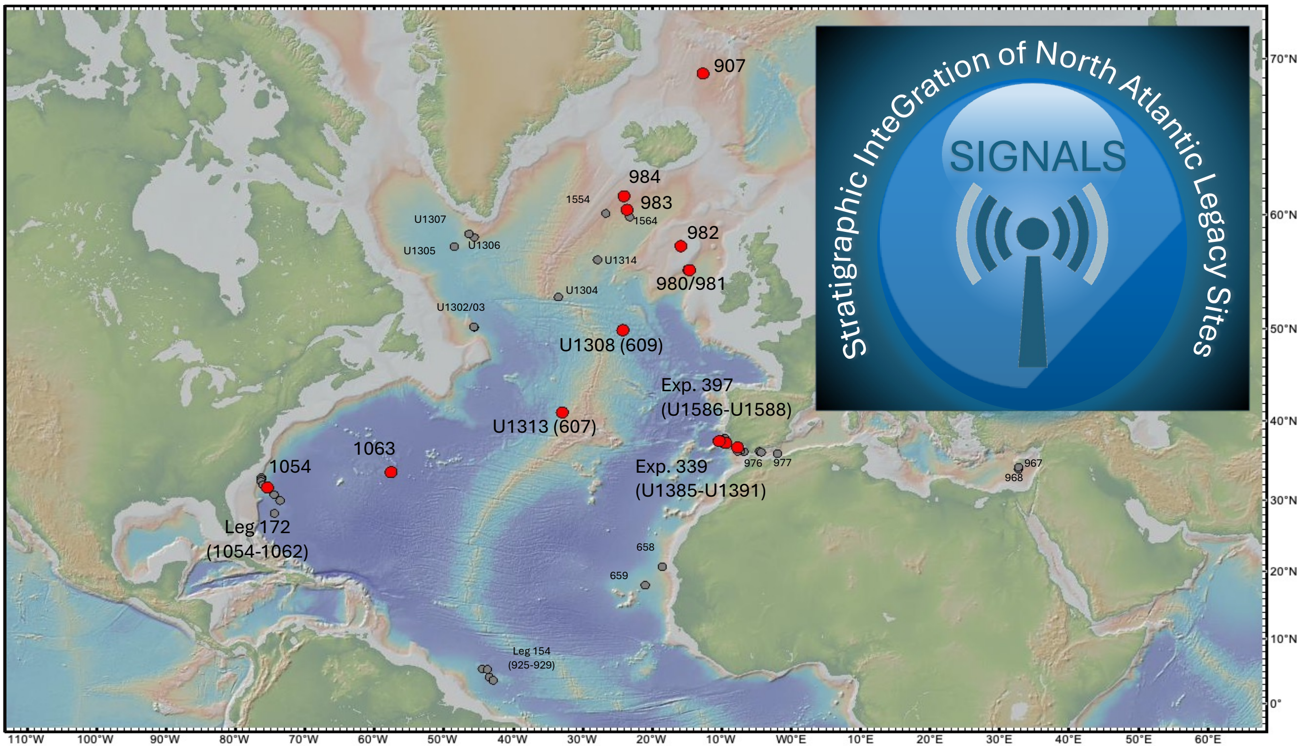

Figure 1. SIGNALS sites in the North Atlantic. Red circles indicate anchor sites that will be used for establishing correlations to other sites (gray circles). All sites chosen have multiple holes drilled and spliced composite sections for stratigraphic continuity. This figure was made with GeoMapApp (https://www.geomapapp.org).

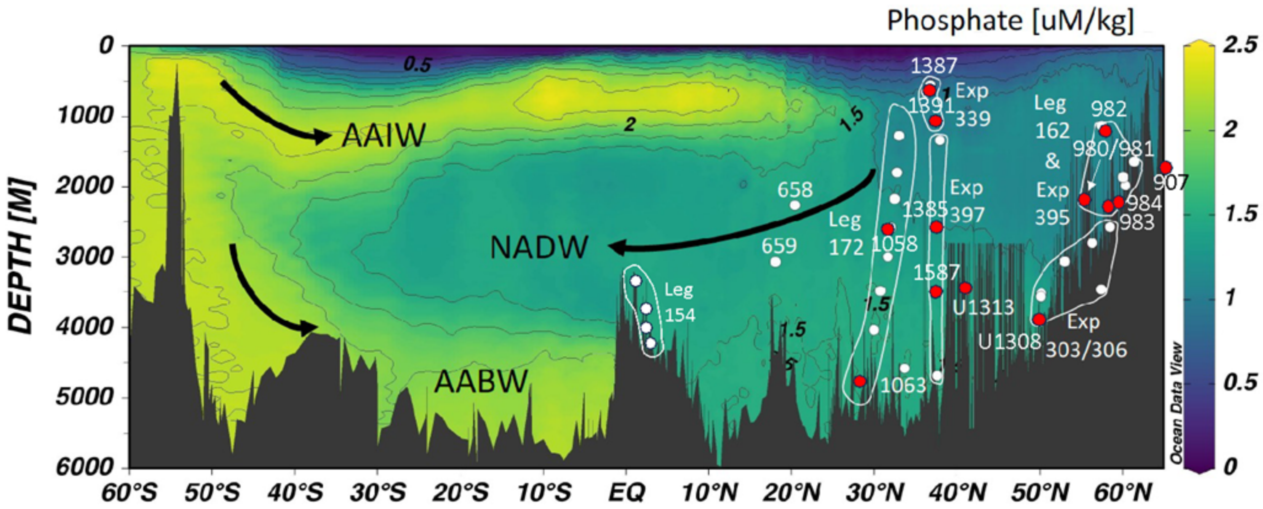

Figure 2. Depth distribution of SIGNALS sites spanning a range of water depths from 560 to 4600 m, intersecting each of the major subsurface water masses to reconstruct Atlantic intermediate- and deep-water circulation. The sites span the deep eastern and western Atlantic basins. White lines encompass ODP/IODP Legs/Expedition sites that were drilled as depth transects. Red circles represent anchor sites as in Figure 1. This figure was made with Ocean Data View (https://odv.awi.de/).

Background

North Atlantic Scientific Drilling

Given the potential role of the North Atlantic in influencing the global climate system, scientific ocean drilling has focused on recovering deep-sea sediments that are suitable for the study of past climate change at orbital- and millennial-scale resolution. In 1983, Deep Sea Drilling Project (DSDP) Leg 94 was a seminal expedition that used the Hydraulic Piston Corer (HPC) to recover continuous sequences from the Ice Rafted Detritus (IRD) belt of the North Atlantic (Ruddiman, 1977; Ruddiman et al., 1987), sometimes also referred to as the “Ruddiman IRD belt”. Leg 94 scientists recognized that sediment is invariably missing at core breaks and used core photographs to construct stratigraphic splices between holes (Ruddiman et al., 1987). The sites recovered during Leg 94 have become cornerstones of paleoceanographic research -- so much so that three of these legacy sites (607, 608, 609) were re-occupied during Integrated Ocean Drilling Program (IODP) Expeditions 303 and 306 (U1308, U1312 and U1313, respectively). In particular, Site 607 (U1313) featured prominently in the early identification and dating of oxygen isotope stages in the Late Pliocene to Pleistocene (Ruddiman et al., 1986, 1988, 1989; Raymo et al., 1989) and has been used in countless paleoceanographic studies. The resolution of the Site 607 isotope record is low by modern standards and fails to capture the full amplitude of the glacial-interglacial signal, suborbital variability, or the true shape of the cycles (**Figure 3**). New oxygen isotope results have been produced on only part of the U1313 record, focusing mainly on the Pleistocene to Late Pliocene (e.g., Voelker et al., 2010; Ferretti et al., 2015; Bolton et al., 2010, 2018; Naafs et al., 2020; Catunda et al., 2021), and should be completed back into the Miocene considering the importance of this site for oxygen isotope stratigraphy.

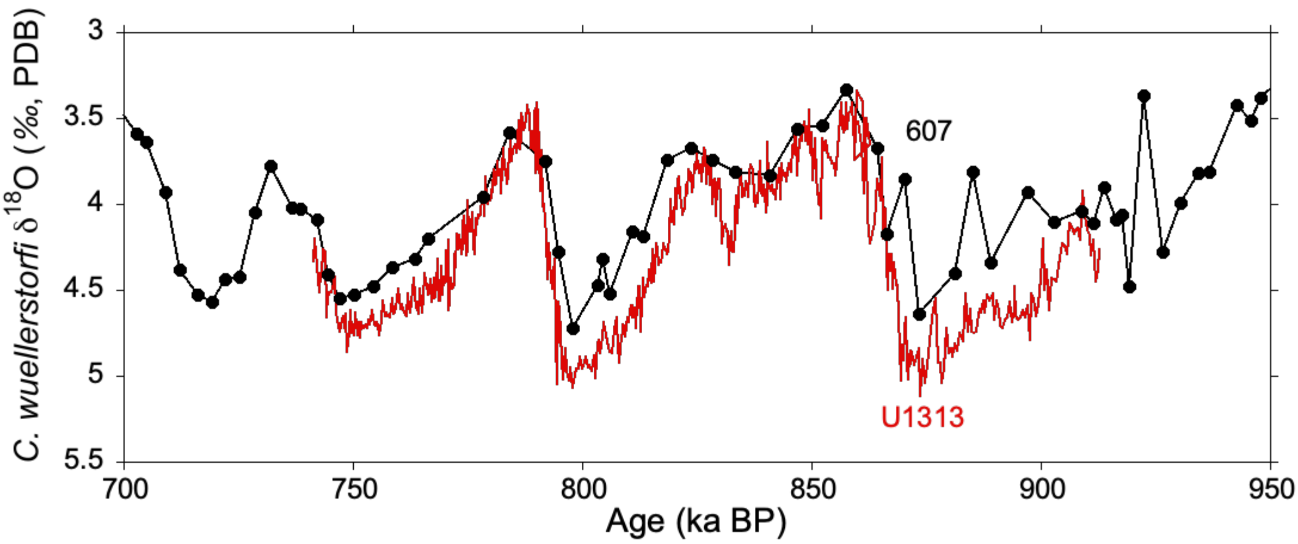

Figure 3. Comparison of the original benthic oxygen isotope record of Site 607 (sampled at 15 cm resolution; Ruddiman et al., 1989) and the same interval at higher resolution from Site U1313 (sampled at 1 cm resolution; Ferretti et al., 2015).

Beginning in the early 1990s, observations of abrupt climate change during the last glacial period in Greenland, (e.g., Dansgaard et al., 1993) sparked a search for similar variability in marine sediments of the North Atlantic. Millennial climate variability (MCV) in North Atlantic sediments was first identified in variations in sediment color and the abundance of the polar foraminifer *Neogloboquadrina pachyderma* (presented as % NPS) at DSDP Site 609 (Broecker et al., 1990; Bond et al., 1992, 1993). The continued quest for high-resolution records capable of resolving MCV led to the targeting of North Atlantic sediment drifts for drilling, which have elevated mean sedimentation rates in the range of 10–20 cm/ky. During ODP Leg 162, four sites (980, 981, 983 and 984) were drilled on sediment drifts south of Iceland (Feni, Björn and Gardar Drifts). These sequences have yielded invaluable insight into the nature of MCV in the North Atlantic beyond the limits of the ice cores (Raymo et al., 1998; McManus et al., 1999; Raymo, 1999; Flower et al., 2000; Kleiven et al., 2003; Barker et al., 2021). Further south, sequences with high deposition rates were recovered during ODP Leg 172 in the northwest Atlantic between ~30° and 35°N (Keigwin et al., 1998). Those sites were designed to trace orbital and MCV in the Gulf Stream region of the subtropical gyre and within the deep western boundary undercurrent (Thunell et al., 2002; Weirauch et al., 2008; Channell et al., 2012a; Billups and Scheinwald, 2014; Kaiser et al., 2019). IODP Expeditions 303 and 306 re-occupied some of the classic Leg 94 sites and further exploited other sediment drifts (particularly, the Eirik and Gardar Drifts) (Channell et al., 2006). It also drilled Orphan Knoll in the Labrador Sea which records Heinrich events related to surges of the Hudson Strait Ice Stream (e.g., Channell et al., 2012b). Most recently, International Ocean Discovery Program (IODP) Expedition 395 drilled contourite drift deposits on the flanks of the Reykjanes Ridge (Sites U1554 and U1562 on the Björn Drift and U1564 on Gardar Drift) (Parnell-Turner et al., 2025).

North Atlantic sediment drifts have proved to be invaluable drilling targets for obtaining sedimentary sequences capable of resolving MCV over long periods of time. This strategy was extended to the SW Iberian Margin, including the Gulf of Cadiz and Portuguese Margin, which is a well-established location where sediments accumulate at high rates. IODP devoted three expeditions (339, 397 and 401) to recovering an unrivalled set of high-resolution late Miocene-Holocene sequences, which together form a legacy archive. The sites form a complete depth transect from 560 to 4692 meters below sea level (m b.s.l.), spanning all the major subsurface water masses of the eastern North Atlantic. At intermediate depths (~500 to 1400 m b.s.l.), the Iberian margin is particularly sensitive to fluctuations in Mediterranean Outflow Water as recorded by sediment drift deposits of the Contourite Depositional System (CDS) (Hernandez-Molina et al., 2006, 2016). Below 1400 m b.s.l., benthic foraminifer proxies are sensitive to changes in temperature and ventilation of deep water related to the relative influence of North Atlantic and Antarctic-sourced bottom waters. At the surface, variations in alkenone sea-surface temperature (SST) and planktic foraminifer $\delta^{18}O$ record changes in the North Atlantic subtropical gyre and resemble Greenland ice core temperatures whereas benthic foraminifer $\delta^{18}O$ variations resemble Antarctic ice core temperatures (Shackleton et al., 2000, 2004). In particular, IODP Site U1385 has provided a detailed record of MCV during glacial periods spanning the last 1.5 Ma (**Figures 4 and 5**), which is a critical interval for comparison to the Antarctic ice core recently recovered by the Beyond EPICA-Oldest Ice project (https://www.beyondepica.eu/en/).

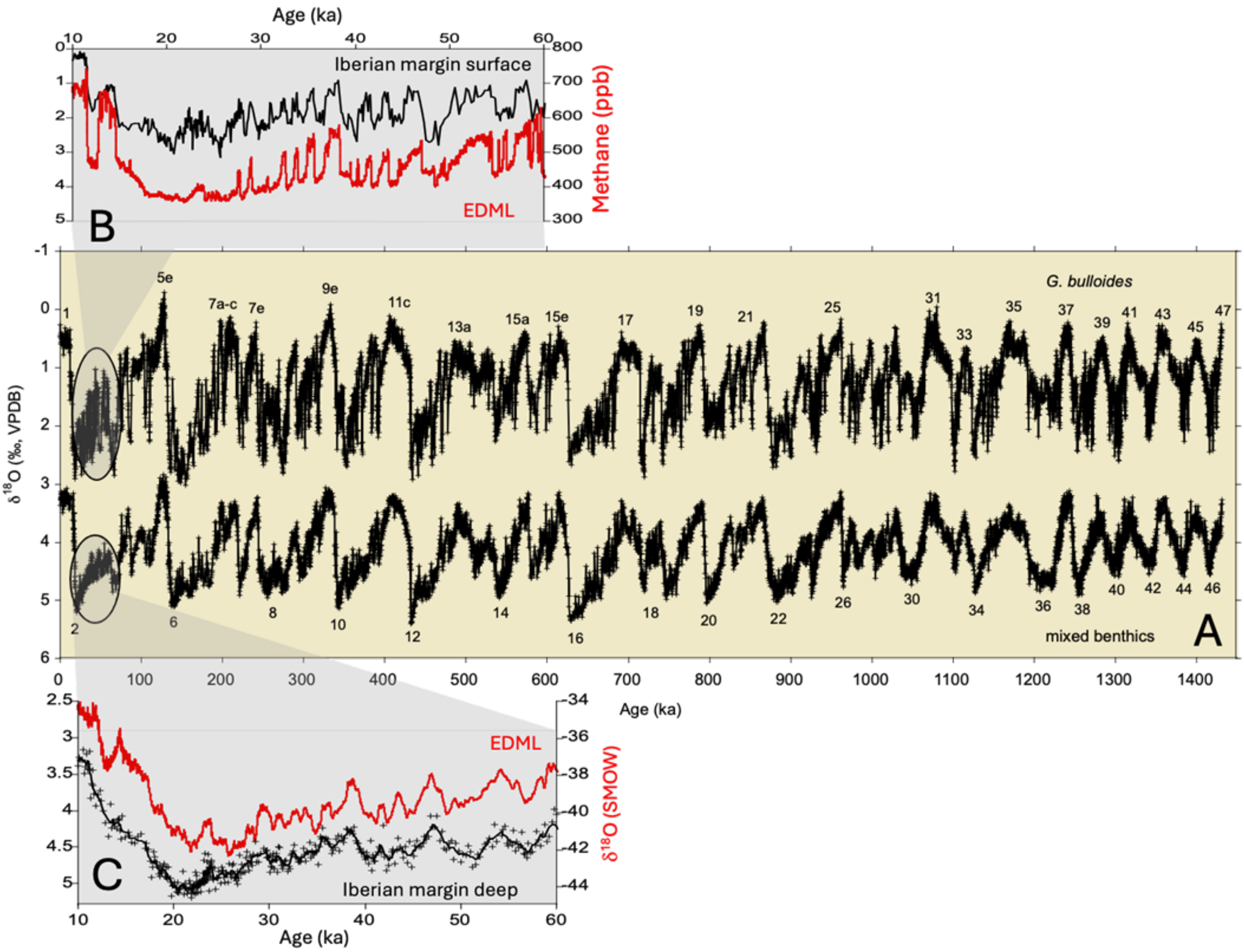

Figure 4. (A) Planktic (surface) and benthic (deep) oxygen isotope record of Site U1385 for the past ~1.5 million years (Hodell et al., 2023, 2025). (B) Planktic $\delta^{18}O$ compared to the WAIS Divide methane record which follows Northern Hemisphere temperature variations. (C) Benthic $\delta^{18}O$ compared to the $\delta^{18}O$ record from the WAIS Divide ice core, which reflects temperature variations in Antarctica (WAIS Divide Project Members, 2015).

Previous work has documented the continuous nature of sedimentation at the sites targeted, and provided high-resolution, non-destructive proxy measurements for initial stratigraphic assessments and alignments, generally reliable magnetic stratigraphies, and clear evidence of millennial and orbital variability in initial data sets (e.g., Grützner et al., 2002; Giosan et al., 2002; Channell et al., 2012a,b; Channell and Hodell, 2013; Obrochta et al., 2014; Grant et al., 2022). SIGNALS will build upon the large amount of high-quality work already produced on North Atlantic sites from the Late Miocene to present by filling critical gaps at key sites with, for example, additional data such as X-ray fluorescence (XRF) scanning and additional proxy measurements.

Orbital chronostratigraphy

The recognition of pervasive orbitally-induced cyclicity in sedimentation and paleoclimatic proxies revolutionized high-resolution stratigraphy and geochronology (Shackleton et al., 1990; Hilgen, 1991). Orbital stratigraphy ('astrochronology") provides the backbone timescales for assessing rates of changes in the past, and for understanding how changes in the earth's orbit influenced climate. North Atlantic sediments often display lithological alternations suitable for orbital tuning (e.g., Wilkens et al., 2017; Crocker et al., 2022; Hodell et al., 2024). XRF and color image scanning are ideally suited for developing large, integrated databases where sites can be orbitally dated and correlated. The framework will be validated by stable isotopic, biostratigraphic and magnetostratigraphic data. It is only with such careful stratigraphic work that important aspects such as regional versus basin-wide paleoceanographic changes can be assessed. The millennial-resolved sediment profiles are contained within the orbital chronostratigraphy in a nested hierarchy, which is pertinent to understanding how the climate system interacts across timescales (both upscale and downscale).

Millennial Climate Variability

Quaternary marine stratigraphy has witnessed a progressive trend towards higher resolution records spurred by the recognition of MCV in Greenland ice cores. With the move towards higher resolution studies, a new calibre of sediment archives was required with a high level of chronological precision. A number of IODP expeditions targeted locations where sedimentation rates were high enough to delineate millennial (or in exceptional cases centennial) climate variability.

Long records of IRD (or its proxies) exist for many sites across the North Atlantic but correlation of individual events across the "Ruddiman IRD belt" remains uncertain. The occurrence of an IRD layer at a particular location is dependent on proximity to source, transport of icebergs by wind and currents and their survivability, which is related to size, sea ice extent and SST. The absence of IRD at one site does not necessarily preclude its presence and associated freshwater forcing elsewhere. For example, "Heinrich Events" that are rich in detrital carbonate derived from Paleozoic bedrock underlying Hudson Strait (Heinrich, 1988; Broecker et al., 1992; Hemming, 2004) are not always present north of the IRD belt. To the south on the Iberian margin and Bermuda Rise, IRD is only sporadically present and instead stadial/interstadial changes are marked by changes in sediment composition and proxy geochemical data (e.g., planktic foraminifer $\delta^{18}O$, SST, % *N. pachyderma*).

What is lacking is a synthesis of MCV proxies (e.g., XRF, IRD, % *N. pachyderma*, planktic foraminifer δ^{18}O, SST) across sites in the North Atlantic. MCV at a single site may not be representative of the North Atlantic as a whole. Cores from different regions across the IRD belt may have a different expression of MCV in both the magnitude and temporal pattern of change (**Figure 5**). Indeed, many long records of MCV are needed to determine the regional patterns of the time-varying climate signals across the North Atlantic.

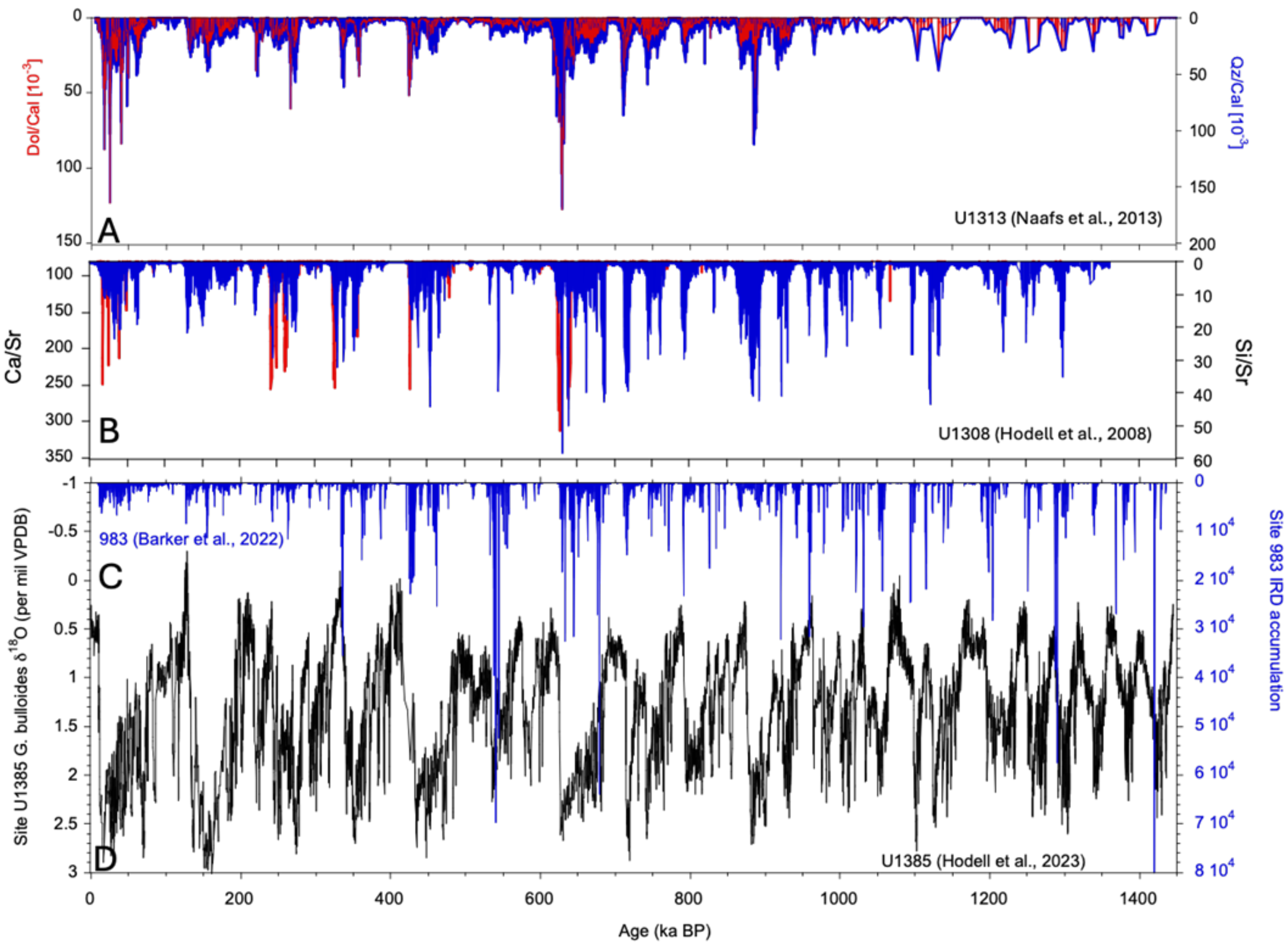

Figure 5. Comparison of IRD records and proxies from Site U1313 at 41ºN (A) (Naafs et al., 2013), U1308 at 50ºN (B) (Hodell et al., 2008) and Site 983 at 61.4ºN (C) (Barker et al., 2022) and the planktic foraminifer δ^{18}O record of Site 339-U1385 at 37ºN (D) (Hodell et al, 2023). Red proxy IRD signals in A and B indicate the presence of detrital carbonate with the greatest peaks associated with Heinrich events.

Scientific Objectives

Stratigraphy is the backbone of paleoclimate research that underpins the interpretation of all proxy records. Without a robust stratigraphical framework, paleoenvironmental observations and interpretations remain ambiguous and of limited use. A precise stratigraphy is the main factor limiting our ability to determine phase relationships (lead-lags) among various variables in the atmosphere-ocean system, which is essential for testing causal mechanisms of global climate change.

IODP[3] Expedition 506S aims to construct a comprehensive, 4-D stratigraphic framework to study climate variability across the North Atlantic on orbital and millennial timescales since the late Miocene. By integrating legacy data from ODP/IODP drill sites, we will refine stratigraphic correlations and chronologies and link proxy records across multiple locations along climatic and bathymetric gradients to evaluate the role of the North Atlantic in global ocean-climate interactions.

Paleoclimatic/Paleoceanographic Objectives

1. **Reconstructing North Atlantic Climate Evolution** – Investigate how the Earth transitioned from the warm Miocene to the glacial-interglacial cycles of the Pleistocene, with a focus on orbital-scale climate variability and feedbacks in relation to forcing by tectonics and greenhouse gases.
2. **Causes of cyclic sedimentation** – Develop process models to understand how orbitally-driven climatic processes are expressed as cycles in the stratigraphic record of each site. Understand how cyclicity evolved at each site/region as background conditions changed from Late Miocene to present.
3. **Understanding Millennial-Scale Climate Variability (MCV)** – Reconstruct the timing and spatial patterns of abrupt climate change since the Late Pliocene intensification of Northern Hemisphere glaciation (iNHG) and their relationship to a changing AMOC.
4. **Climate Variability across Timescales** – Characterise the interactions of millennial, orbital and longer timescale climate variability as orbital, glacial and tectonic boundary conditions changed since the Late Miocene.
5. **Linking Surface, Intermediate and Deep Ocean Changes**– Examine how variations in SST, IRD deposition, and deep-water circulation influenced past climate shifts and carbon cycle dynamics. How did Mediterranean Outflow Water and AMOC affect heat and salt transport in the ocean, and what was the role of the North Atlantic in triggering or amplifying global climatic changes?

Methodological Objectives

1. **Data Collection** – fill data gaps at key anchor sites and provide robust frameworks to refine the existing biostratigraphic and paleomagnetic stratigraphies.
2. **Construct 4-D Framework** – Establish a synchronized, multi-proxy stratigraphic framework for North Atlantic sites, including uncertainty estimates in stratigraphic correlations and age models.

3. **Assess Temporal Resolution** – Evaluate the limits of temporal resolution at each site given varying sedimentation rates, bioturbation, and sampling frequency.
4. **Marine-Ice-Terrestrial correlations** – Precisely correlate climate signals in marine sediment cores to the polar ice cores and terrestrial records to link oceanic, atmospheric, and terrestrial climate and environmental changes.
5. **Advance Stratigraphic Correlation Techniques** – Develop and apply automated signal correlation algorithms to synchronize sediment records at orbital and suborbital timescales, along with estimated uncertainties.
6. **Core Imaging, Computer Vision & Deep Learning** – Process high-resolution core images using neural networks to automatically segment and remove unwanted disturbances such as those resulting from bioturbation, redox changes, and core disturbance.
7. **Links to other initiatives** – Contribute the North Atlantic data to global ocean data integration initiatives and data-paleoclimate modelling initiatives (TIMES, PAGES working groups, PMIP-Interglacials, etc.).

TIMES (Time Integrated Matrix for Earth Sciences) is a global program with the aim of synchronizing age models for particularly important geological climate records from the past 100 million years (Westerhold et al., 2024). The current PAGES (Past Global Changes) working groups (https://pastglobalchanges.org/science/current-wg) most relevant to the SIGNALS expedition are CVAS (Climate Variability across scales) and PlioMioVAR (Pliocene and Miocene climate variability over glacial-interglacial timescales).

Alignment to 2050 Science Framework

These goals address Strategic Objectives (SO) posed by the 2050 Science Framework including: *Earth's Climate System* (SO3), *Feedbacks in the Earth System* (SO4), *Tipping Points in Earth History* (SO5), and *Global Cycles of Energy and Matter* (SO6). Furthermore, SIGNALS is relevant to several of the Enabling Elements of the science plan including: *Land to Sea* (EE2) - through correlation of terrestrial and ice core sequences to marine sediment records; *Technology Development and Big Data Analytics* (EE4) - through proposed machine learning applications and automated data collection. SIGNALS will also train a new generation of early career scientists in methods of modern stratigraphy and AI-assisted data generation (EE1).

Sampling and Analysis Strategy

Targeted Legacy Resources

The strategic goals of the SIGNALS expedition will be achieved using legacy core material and data covering a wide spatial and bathymetric range in the North Atlantic (**Figures 1 and 2**; Table 1). We will first construct the stratigraphic framework and chronologies of North Atlantic legacy sites, followed by integration of existing and new proxy data. The selected ODP/IODP sites range from 4.2 to 61.4°N latitude and 74.5°W to 32.8°E longitude (**Figure 1**), across the modern Polar, Subpolar and Subtropical gyres and the glacial IRD belt of the North Atlantic. The sites span a range of water depths from 560 to 4600 m (**Figure 2**) and are well placed to study how changes in intermediate and deep ocean circulation affect climate. For more recent IODP expeditions, we will interact and collaborate with the respective science parties to avoid overlap with ongoing research projects.

We have identified a list of sites where stratigraphic synchronization can be accomplished in a 3-year period (Table 1). Our choice of priority sites was guided by location, age and continuity of the stratigraphic section, availability of data from previous work, and gaps in data and/or knowledge. All sites will be incorporated into the SIGNALS stratigraphic framework, but the priority sites merit additional analysis (at minimum XRF, image processing). Some sites already have extensive work completed, including stratigraphic reanalysis and chronology back into the Pliocene or Miocene and are designated as reference sites (Table 1). We have compiled information on all known postcruise XRF data and identified gaps that need to be filled. Flexibility in site priority is important because it may become clear that some sites already have enough data and others require additional work once the expedition begins. We recognize that the initial scope of work is limited to a 3-year period, but the SIGNALS expedition is a seed project that we anticipate will continue to grow beyond the current funding period as new materials and resources become available. We expect the 4D stratigraphic framework developed as part of SIGNALS will be used to address many other research questions involving time series or time slice approaches (e.g., syn/diachrony of biostratigraphic events).

Multiple holes were drilled at each of the anchor sites and shipboard composite sections established, suggesting complete recovery of the sequences; however, revisions of splices are likely necessary for some sites – beyond those already known (e.g., U1313: Naafs et al., 2020; U1385: Hodell et al., 2015; U1387: Voelker et al., 2018; U1391: Abrantes et al., 2017). We will focus on archive halves (including existing u-channels of archive halves) for stratigraphic correlation using non-destructive methods (e.g., XRF scanning, core images, physical properties, paleomagnetism), supplemented by available measurements on discrete samples (e.g., stable isotope, bio-, and magneto-stratigraphic signals and datums). Where material is unavailable and sediment has been depleted from primary splice sections due to heavy sampling, alternate splices will be constructed.

Table 1. List of sites with basal ages of the section, available stratigraphic control, and average sedimentation rate. Priority sites are marked by bold type whereas others are designated as reference sites. All sites will be incorporated into the 4-D stratigraphic framework.

Site	Water depth (m)	Bottom depth (m b.s.f.)	Bottom age	Available stratigraphic control	Average sedimentation rate [cm/ky]
907	1800	224.1	<14.3 Ma	P-Mag; Biost.	1.7
980	2171	121.6	<1 Ma	Iso-B; Biost.	12
981	2173	320.31	>4.5 Ma	Iso-B; Biost.	7.6
982	1135	614.9	<19 Ma	Iso-B; P-Mag; Biost.	2.5 (Pleisto./L. Plio.); 4.7 (E. Plio./L. Mio.)
983	1983	260.85	ca. 2 Ma	Iso-B; P-Mag; Biost.	14.2
984	1648	523.26	≥ 2.61 Ma	Iso-B; P-Mag; Biost.	15.5
1058	2996	164.59	<1.4 Ma	Iso-P; Tuning; P-Mag	14.5
1063	4584	418.44	<3.3 Ma	P-Mag; Iso-B	17.6 – 30
U1308	3871	279.9	<6 Ma	Iso-B; P-Mag; Biost.	8.6
U1313	3426	308.6	<6 Ma	Iso-B; Iso-P; P-Mag; Biost.	4.3; 13.5 (Miocene)
U1385 [339,397]	2578	400	<5 Ma	Iso-B; P-Mag; Biost.	11
U1391	1073	671.5	<3.4 Ma	Iso-B; Iso-P; P-Mag; Biost.	13 – 39.8
Reference Sites					
U1587	3481	567.9	ca. 8.3 Ma	P-Mag; Biost.	6.8
U1387	559	870	ca. 5.7 Ma	Iso-P; Iso-B; Biost.; P-Mag;	25 (Pleist.); 15 (Plio./Mioc.)
U1304	3065	243.9	<1.9 Ma	Iso-B; P-Mag; Biost.	8.3
U1314	2800	279.5	<2.9 Ma	Iso-B; P-Mag; Biost.	7.5 – 10.8
U1305	3460	287.1	<1.8 Ma	Iso-P; Biost.; P-Mag	17.6
U1306	2272	309.3	ca. 2 Ma	Iso-P; P-Mag; Biost.	15.6
U1307	2575	162.6	≤3.6 Ma	Iso-P; Iso-B; P-Mag; Biost.	4.9
U1303	3518	93.9	<1 Ma	Iso-B; Iso-P; P-Mag	14.7
U1302	3560	107.1	<1.16 Ma	Iso-B; Iso-P; P-Mag	14.7
607	3426	307.45	>5.3 Ma	Iso-B; P-Mag; Biost.	4.3
609	3871	354.7	<7 Ma	Iso-B; P-Mag; Biost.	8.6
659	3070	273.8	>23 Ma	Iso-B; Tuning	2.1
967	2553	600.3	>5.1 Ma	Tuning; Iso-P	2.8
968	1961	302.7	>3.6 Ma	Tuning; Biost.	4.5
925	3052	2017	>20 Ma	Iso-B; Biost.; P-Mag	2.2
926	3610	1331.1	>14.4 Ma	Iso-B; Biost.; P-Mag	2.2
927	3327	840.7	>14.4 Ma	Iso-B; Biost.; P-Mag	2.2
928	4023	960.1	>11.4 Ma	Iso-B; Biost.; P-Mag	2.4

Iso-B/P: benthic/planktonic foraminifera stable isotope data; Biost.: Biostratigraphic data; P-Mag: Paleomagnetic chronostratigraphy

The SIGNALS strategy is to construct the 4-D stratigraphic framework of integrated North Atlantic sites that will then be used to host proxy data for paleoclimatic and paleoecological interpretation. In preparation of the expedition and implementation plan, we have prepared asset tables listing the core materials needed to construct the framework, mainly consisting of new XRF analysis, line-scan imaging and stable isotopes needed to supplement existing data, and images/physical property measurements stored in the LIMS (https://web.iodp.tamu.edu/LORE/) and JANUS (http://www-odp.tamu.edu/database/) databases. Many of the high priority sites have been partially XRF scanned and we propose to fill data gaps to the extent possible in the 3-yr period. Existing u-channels of archive halves will be scanned at other XRF facilities to the extent possible to decrease pressure on the Bremen Core Repository (BCR) instrumentation (however, no new u-channels will be taken). Line-scan digital images will be captured for older ODP cores. Individual sample requests by IODP[3] Expedition 506S Science Team members will be made for any additional discrete samples needed for biostratigraphic or other proxy data generation. We will use samples previously taken whenever possible and any new samples will be taken from working or non-permanent archive halves (including alternative splices).

Sampling and Data Sharing Strategy

All applicants applying for membership of the SPARC Expedition Science Team should refer to the *Sample, Data, and Obligations Policy* (https://iodp3.org/documents/sample-data-obligations-policy/). This document outlines the policy for distributing scientific ocean drilling samples and data to research scientists, curators, and educators. The document also defines the obligations that recipients of samples and data incur. The SPARC Co-Chief Scientists, in discussion with the Curators of the Core Repositories, will work with the entire SPARC Expedition Science Team to develop a formal Implementation Plan once the team is assembled following the open Call for Participation. The Implementation Plan will include:

- detailed plans for collaboration between SPARC Expedition Science Team members and how this will be facilitated and managed to promote focused research and progress (e.g., plans for in-person sampling at the Core Repositories, frequency of dedicated virtual and in-person meetings of the Science Team), and how results will be disseminated.
- outline discussions held with the Curators of the Core Repositories regarding the availability of core materials and plans for accessing and using repository facilities.
- plans for obtaining additional funding to complete the research, if this cannot be achieved using the €300,000 SPARC award.
- a Gantt chart showing the timelines for the research, key milestones and deliverables.

Every member of the SPARC Expedition Science Team will be obligated to carry out scientific research for the expedition and publish the results, by contributing to the production of the SPARC

Expedition Summary and Results in the *Proceedings of the International Ocean Drilling Programme* and by publishing in other scientific journals. All SPARC Expedition Science Team members are required to submit their own detailed research plans and associated sample/data requests via the *Sample, Data, and Research Request Manager* (SDRM) system (https://web.iodp.tamu.edu/SDRM/#/) in order to receive samples to work on. However, sample requests must be provided to the SPARC Expedition Co-Chief Scientists prior to submission to allow them to coordinate sampling efforts, avoid duplications and resolve sampling conflicts between Science Team members. However, subsequent sharing of allocated samples between SPARC Expedition Science Team members to facilitate integrated analyses will be encouraged.

Virtual Platform

Previous IODP expeditions have included a physical platform (R/V *JOIDES Resolution*, D/V *Chikyu*, other mission specific platforms) where the expedition science team could interact, collect data, share experience and work towards accomplishing expedition goals. For IODP^3 Expedition 506S, we propose a dedicated virtual workspace that will function as the expedition's platform — providing real-time communication, coordination, and data-sharing infrastructure for the Science Team. Slack® (https://slack.com) is the virtual platform of preference because it offers a dynamic, searchable platform for real-time messaging, structured discussion threads, file exchange, and integration with analytical and data-management tools. It will ensure that all members remain connected across time zones and institutions, fostering efficient, transparent, and inclusive collaboration.

This digital environment will provide structured channels for each working group (e.g., stratigraphic correlation, XRF data, image analysis, machine learning, chronology, etc.) for focused discussions and data sharing. Expedition documentation, meeting notes, and draft figures will be archived within relevant channels to create a centralized, searchable record of progress. Slack® will be integrated with cloud storage platforms (e.g., shared Google® Drive or institutional repositories) to facilitate data sharing and collaborative editing of documents. The Slack® workspace will also host a regularly updated expedition dashboard summarizing current milestones, deadlines, and deliverables to maintain momentum and a visible timeline.

Regular virtual meetings will be organized via video-conference platforms (e.g., Zoom® or Microsoft Teams®) and announced through Slack®. These meetings will focus on reviewing progress, discussing preliminary results, and aligning analytical efforts across teams.

Slack® will thus underpin the coordination and synthesis of the overall research effort by:

- Enabling rapid communication and troubleshooting across distributed teams.

- Providing a persistent record of decisions and workflows.
- Facilitating cross-disciplinary discussion between stratigraphers, developers, and data scientists.
- Ensuring all Science Team members have equitable access to information and updates.
- Supporting onboarding and training of early-career scientists through dedicated Q&A and resource channels.

This virtual collaboration model ensures that the collective expertise of the international SIGNALS Science Team is effectively harnessed, coordinated, and drawn together into a coherent research program, culminating in shared publications, data products, and open-access computational tools.

Virtual Expedition Organizational Structure

The SIGNALS Virtual Science Operations Environment will be organized around working groups (**Figure 6**). All activities will be coordinated through the Slack® workspace, which will function as a virtual workspace, linking scientists, data systems, and analytical tools in real time.

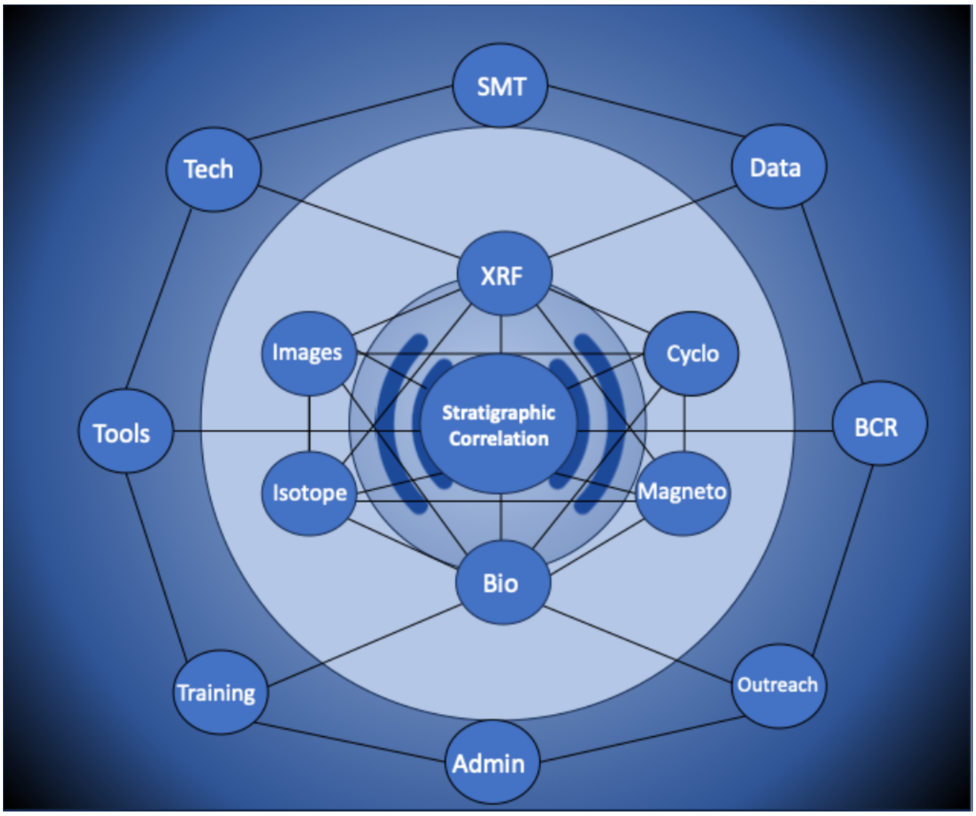

Figure 6. SIGNALS organisational chart with stratigraphic correlation as its central theme supported by an inner circle of cyclo-, magneto-, bio- and stable isotope-stratigraphy as well as XRF and image analysis. The outer circle supports the central core mission including the science management team (SMT), data management, Bremen Core Repository (BCR), outreach, grant administration, training, and development of advanced tools and technologies.

The **Leadership and Coordination Group** will consist of a science management team, project manager and repository and will be responsible for coordinating the expedition and fostering communication within and among the working groups (Table 2).

Table 2: Leadership and Coordination Group

Subteam	Key Tasks
Science management team	Scientific direction, integration across teams, and reporting. Overall scientific coordination, ensuring objectives are met.
Expedition Project Manager	Scheduling, tracks progress and deliverables, maintains communication flow between groups, promotes harmony among the Science Team.
Repository Liaison	Coordinates activities and scheduling with BCR

The **Stratigraphic Correlation Working Group** is the scientific heart of the expedition. It will be divided into two nested teams addressing different temporal scales but operating within a shared framework (Tables 3 and 4).

Table 3: Stratigraphic Correlation Working Group

Teams	Objective	Key Tasks
Millennial-scale Correlation Team	Synchronization of high-resolution proxy records (1–10 ky).	• Identify and align millennial-scale events across the Ruddiman IRD Belt and adjacent latitudes. • Correlate sediment drift and margin sites across latitudinal transects. • Link marine sequences with Greenland/Antarctic ice-core and speleothem records. • Assess uncertainty and temporal resolution limits.
Orbital-scale Correlation Team	Construct an orbitally tuned, basin-scale stratigraphic framework (20–400 ky).	• Apply astrochronologic tuning using precession, obliquity, and eccentricity cycles. • Integrate biostratigraphic and paleomagnetic markers with orbital tuning. • Quantify uncertainty and phase relationships between orbital parameters and sediment signals. • Process models to explain orbital cyclicity for each site.

Table 4: Science Working SubGroups

Subteam	Key Tasks
Stratigraphy & Chronology	Construct 4-D stratigraphic framework, correlation across sites, age models, uncertainty quantification.
XRF and Geochemical Analysis	Fill data gaps, integrate XRF datasets, establish calibration standards, best-practice data archiving, interpret element ratios.
Core Imaging & Computer Vision	Process digital line-scan images, develop AI segmentation models, validate color reflectance data.
Paleomagnetism & Biostratigraphy	Review and refine magneto- and biostratigraphic correlations, integrate with chronologic framework.
Millennial Climate Variability	Synthesize high-resolution proxies, identify millennial-scale events, integrate with ice core data.
Cyclostratigraphy & Astrochronology	Apply astrochronologic tuning, evaluate cyclicity drivers, model sedimentary periodicity.

The **Advanced Method Development Group** is the technical part of SIGNALS. It will develop automated, quantitative, and reproducible tools that underpin stratigraphic correlation. This group works jointly with both correlation teams to ensure methodological consistency and reproducibility (Table 5).

Table 5: Advanced Method Development Group

Subteam	Key Tasks
Automated Stratigraphic Alignment	Develop probabilistic and Bayesian alignment tools (e.g., dynamic programming, HMM, BIGMACs).
Computer Vision & Image Segmentation	Train AI models for color correction, feature extraction, and recognition of sedimentary events.
Signal and Noise Analysis	Quantify temporal resolution, apply Gaussian Process modelling, and filter core signals.
Tool Integration & Distribution	Maintain shared code repositories (GitHub®) and produce open-source training materials.

The **Technical and Analytical Support Group** will maintain digital infrastructure, visualization capabilities, ensure all analytical data and tools are well documented, training resources to support all scientific and data workflows (Table 6).

Table 6. Technical and Analytical Support Group

Subteam	Key Tasks
Systems Administrator	Manages Slack® integrations, cloud storage, and security.
Training & Documentation Coordinator	Prepares tutorials, user guides, and onboarding materials.

The **Data Management and Integration Group** will serve as the backbone of the SIGNALS network — compiling, standardizing, and integrating data from legacy and new analyses (Table 7).

Table 7: Data Management and Integration Group

Subteam	Key Tasks
Site Data Leads	Oversee compilation of site-specific legacy datasets and new XRF/imaging data.
Legacy Data Compilation	Aggregate and standardize datasets from ODP/IODP/DSDP sources.
Integration Hub	Merge site datasets into basin-wide stratigraphic and temporal frameworks.
Metadata & Quality Control	Enforce FAIR principles and ensure reproducibility and traceability.

The **Outreach and Communication Group** will disseminate scientific outputs, promote open science, and maintain community engagement (Table 8).

Table 8: Outreach and Communication Group

Team	Key Tasks
Outreach and Communication Group	Expedition summary and journal articles. Release of datasets and software. Coordination with other programs and working groups (TIMES, PAGES) Training workshops, media communication, and student engagement.

The **Administration Group** will provide financial, institutional, and logistical oversight through the grant-holding host institution, ensuring accountability, transparency, and operational support (Table 9).

Table 9: Administration Group

Team	Key Tasks
Administrative support	Manage grant finances, contracts, and reporting. Oversee travel logistics, reimbursements, and event organization. Support the Leadership and Coordination Team in budgeting for analyses, outreach, and data hosting. Coordinate with the Bremen Core Repository and IODP[3] on compliance and reporting.

In summary, these groups will work together to accomplish the main scientific goals of IODP[3] Expedition 506S (Table 10).

Table 10: Summary of Structure Aligned to Main Objective

Organizational Level	Primary Function	Connection to Goal
Coordination Team	Oversight and integration	Ensures consistent cross-scale strategy
Stratigraphic Correlation (Millennial)	Event-scale synchronization	High-resolution alignment of proxy records
Stratigraphic Correlation (Orbital)	Orbital-scale framework	Astrochronologic integration across sites
Method Development	Tool creation and automation	Enables reproducible, quantitative alignment
Technical & Analytical Support	Infrastructure & visualization	Supports interoperability and training
Data Management & Integration	Data backbone	Builds unified multi-site datasets
Outreach & Communication	Dissemination & engagement	Shares outcomes, tools, and training
Administration		Financial and institutional oversight

Analytical Techniques and Methodologies

Stratigraphic correlation (between holes and among sites) will be accomplished mainly using non-destructive, automated measurements used to characterize physical properties and elemental composition of sediment cores (e.g., line-scan images, color reflectance, Gamma Ray Attenuation Porosity Evaluation, magnetic susceptibility, natural gamma radiation, XRF scanning, and down-hole logging).

XRF Scanning

The introduction of commercial core scanning XRF instruments in 2003 revolutionized the stratigraphic correlation of ODP/IODP cores by allowing non-destructive analysis of the elemental composition of sediment at high spatial resolution. In addition, XRF elemental ratios provide vital information for detecting IRD layers in North Atlantic cores (e.g., Hodell et al., 2008; Channell et al., 2012b), identifying MCV (Hodell et al., 2023) and orbital variations in sediment composition used for astronomical tuning. The *JOIDES Resolution* did not have an XRF core scanner onboard and thus data collection was a postcruise research activity. Many of the key legacy North Atlantic sites have been partially scanned but some remain incomplete. We compiled the information on existing published and other available XRF data (to our knowledge) and propose to fill these data gaps by scanning cores for the high-priority legacy sites (to the extent possible in a 3-year period).

Core Images

Ever since ODP Leg 200, core section images have been captured using digital line scanners. Digital images provide the highest resolution (0.1 mm) data that we will ever collect, yet this resource remains terribly underutilized (exceptions include Wilkens et al., 2017, Crocker et al., 2022 among others). However, bioturbation, voids, cracks, redox zones, and drilling disturbance often result in noisy color signals that complicate their use in stratigraphic correlation. Advances in the field of computer vision offer the potential to automatically correct for these disturbances and vastly improve the signal-noise ratio of color data (e.g., Fazekas et al., 2017; Obrochta et al., 2020; 2022). SIGNALS will use deep learning-based tools for processing linescanner core images to produce nominally undisturbed color records along the composite sections of each site (see sections “Assessing signal-to-noise, stratigraphic alignments and temporal resolution” and “Computer Vision and Deep Learning” below). These ultra-high resolution data will be invaluable for correlating between holes at the same site, correlating between sites (e.g., Obrochta et al., 2014; top of **Figure 7**), and assessing the stratigraphic and temporal resolution of each site.

Prior to the introduction of a digital imaging system aboard the *JOIDES Resolution*, core photographs (digital or film) were taken of the sections of each core using a "core table" for older DSDP/ODP/IODP expeditions. Although color information can be recovered from these images (e.g., **Figure 7** and Wilkens et al., 2017), inconsistent lighting and parallax make standardization difficult. Archive halves of the high-priority sites will be scanned in Bremen using a digital line scan camera system, and a computer-vision based system, developed at Akita University (Japan), which contains additional processing features.

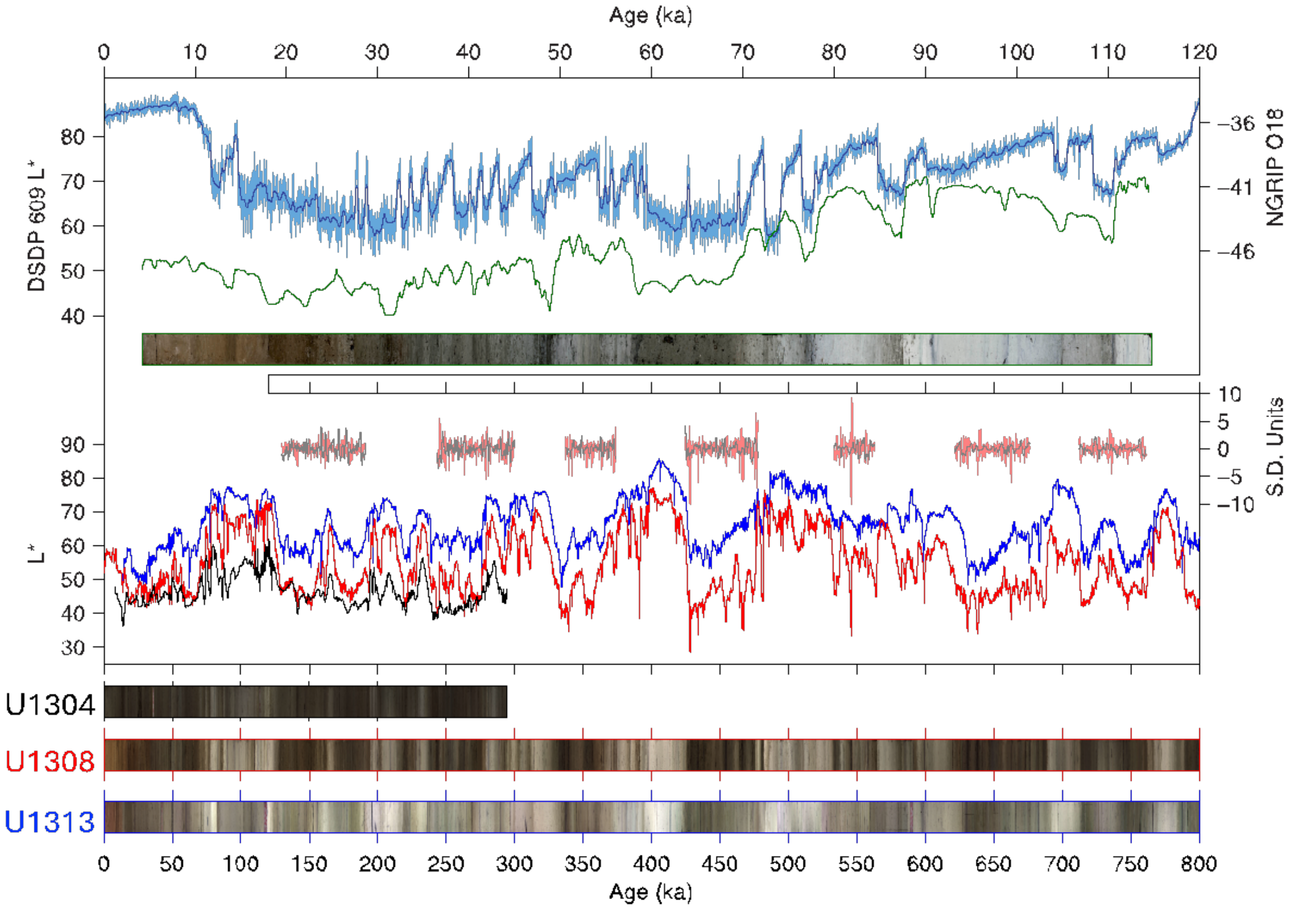

Figure 7. (Top) Correlation of sediment lightness (L*) at Site 609 (later redrilled as Site U1308) to North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ with a composite image created from the "core table" photograph and manually corrected for parallax. (Middle) Comparison of sediment lightness among Sites U1313 (41 °N), U1308 (50 °N) and U1304 (53 °N). (Lower) Core images of the three sites. Note the smoothing of the 609 L* data relative to millennial variability recorded in the NGRIP $\delta^{18}O$ record which can be simulated using a low-pass filter of the NGRIP record (see Figure 9).

Evaluation of Composite Sections

Shipboard stratigraphic correlation is often done under rushed conditions using physical properties data measured at varying resolution. Post cruise reanalysis of shipboard stratigraphic splices inevitably uncovers errors that include skipping or duplication of parts of the sequence. Furthermore, standard ODP/IODP practice involves shifting entire cores by a fixed distance and splicing sections from different holes together to form a composite section. Using this approach, cores between holes are correlated only at the splice tie points as no stretching or squeezing is permitted with the IODP Correlator software used onbard at the time of the expeditions. The splice continues down hole and accumulates offsets, so that the composite depth grows significantly relative to the driller's depth, creating an artificial depth scale (meters composite depth or core composite depth below seafloor). As part of IODP[3] Expedition 506S, we will use XRF scanning, core image and physical properties data to review the splices for each site and stretch and squeeze sections between holes to produce a revised composite depth scale. The CODD (Code for Ocean Drilling Data) software will also be evaluated for this purpose (Wilkens et al., 2017) along with other options such as Match (Lisiecki and Lisiecki, 2002) and BIGMACS (Lee et al., 2023). Rigorously assessing the reliability of existing composite sections is important for developing off-splice composites where primary splice sections are depleted from sampling. Data analysis may also help prioritize sites or stratigraphic intervals where more time and resource-consuming analyses are needed (e.g., XRF, stable isotopes, SST proxies, refining biostratigraphy or magnetostratigraphy). Additionally, downhole logs (where available) will be integrated into composite section generation (Lofi et al., 2016; de Vleeschouwer et al., 2017).

A few examples of the benefits of high resolution stratigraphic re-analysis illustrate the potential progress to be made. Drury et al. (2018) conducted XRF scanning of ODP Site 982, a North Atlantic site containing key records of Middle Miocene to present oceanographic change. The precision of XRF data allowed them to convincingly show that the shipboard splice contained both significant gaps and a major omission. The end result was a robust isotopic record that differed by several 100 kyr from what was originally thought. Wilkens et al. (2017) reviewed the splices of Leg 154 sites drilled on the Ceara Rise. Although most changes were minor several were large enough to affect age models based on orbital tuning. Similarly, Hilgen (2025) recently used XRF scans to revise the stratigraphy of Pacific IODP Site U1337 and showed that the original splice was in error by some 400 kyr. While such large errors may not be the rule, we cannot at present align most North Atlantic records to the level of 5 kyr precision (orbital-scale processes) or better (scale of millennial processes).

Integrated millennial-scale stratigraphy across the North Atlantic

SIGNALS will correlate millennial events in high-sedimentation-rate sites across the North Atlantic (**Figure 1**). We will synchronize these events where possible with the polar ice core records in Greenland and Antarctica (similar to approaches shown in **Figure 3**) and with speleothem records from Europe and Asia using a probabilistic algorithm for continuous proxy-data alignment (Muschitiello et al., 2020; Muschitiello and Aquino-Lopez, 2024; Lee et al., 2023). As shown in **Figure 5**, a similar signal is recorded in the North Atlantic across a wide range of latitudes. Some sites (e.g., 983, 1058, U1308, U1385) have very long, millennial-resolved proxy records that extend back to the Early Pleistocene (Barker et al., 2021, 2022; Hodell et al., 2015, 2023; Weirauch et al., 2008; Billups and Scheinwald, 2014), but the millennial events at these sites have yet to be precisely correlated across latitudes. Integrating proxy records of MCV across the North Atlantic is vital for linking low-latitude and high-latitude processes and evaluating the role of freshwater forcing in MCV, and their potential impact on regional and global climate (**Figure 5**).

Indeed, the leading hypothesis to explain MCV is changes to the AMOC because of its sensitivity to mode jumps that can be triggered by changes to the surface-water density in North Atlantic source areas of deep-water formation. Testing this hypothesis requires a network of integrated marine records across the North Atlantic (**Figure 1**).

Cyclostratigraphy and Geochronology for the Quaternary-Late Miocene

Most of the sedimentary sequences obtained through scientific ocean drilling in the Atlantic contain striking evidence of cyclicity paced by orbital variations. In particular, lithological cycles often mimic the eccentricity modulation expected from precessional forcing (**Figure 8**), far more than might be expected from stable isotopic profiles that are typically dominated by 41 kyr-obliquity cycles for most of the Miocene and Pliocene (Lisiecki and Raymo, 2005). The strong precession cycle is a boon to stratigraphy because the eccentricity modulated signal is a far better tuning target than the rather monotonic obliquity signal (Shackleton et al., 1990; Liautaud et al., 2020). In addition, because the precessional period is 50% shorter than obliquity, successful tuning to this rhythm inherently increases temporal precision. With a purely precession-tuned time scale, the timing of glacial terminations and inceptions in the benthic $\delta^{18}O$ signal can be independently assessed relative to changing obliquity.

A major goal will thus be to improve the chronology of both millennial and orbital-scale signals by astrochronology (see Meyers, 2019). Astrochronological tuning of sedimentary cycles promises to improve the dating of stable isotope signals, which often are quite noisy and difficult to tune or align precisely in the Pliocene prior to the iNHG. Improvements in dating will yield fresh insights into the pacing of cryospheric variation, North Atlantic circulation, benthic CO_2 storage, and paleoecology and evolution.

Cyclicity in Atlantic sedimentation also raises important questions about the causal mechanism(s) by which orbitally-induced changes in insolation are conferred to the sediment record. Potential processes could involve oscillations in carbonate production (e.g., latitudinal shifts in ecological provinces and/or shifts in dominant plankton groups, Lawrence et al., 2013, McIntyre et al., 1989), the corrosivity of bottom water to carbonate (dissolution), and dilution by clastic material, which may be erosional, eolian, fluvial, or ice-rafted in origin (Grützner and Higgins, 2010; Hodell et al., 2008; de Castro et al., 2021; Crocker et al., 2022; Sinnesael et al., 2025). Each of these processes may change over time, along with the evolution of global climates and the growth of Northern Hemisphere ice sheets. Thus, the origin of Atlantic lithological cycles is a paleoclimatic as well as stratigraphic problem that needs to be explored.

The IODP[3] Expedition 506S Science Team will focus on dissecting the origin of stratigraphic cycles by synthesizing existing and generating new measurements to fill gaps (e.g., SST, stable isotopes, microfossil assemblages and preservation, nannofossil assemblages, detrital (clay) mineralogy and isotope geochemistry, deep water chemical proxies) that will lead to process-based models to explain how orbitally-driven climatic processes are expressed as cycles in the stratigraphic record of each site.

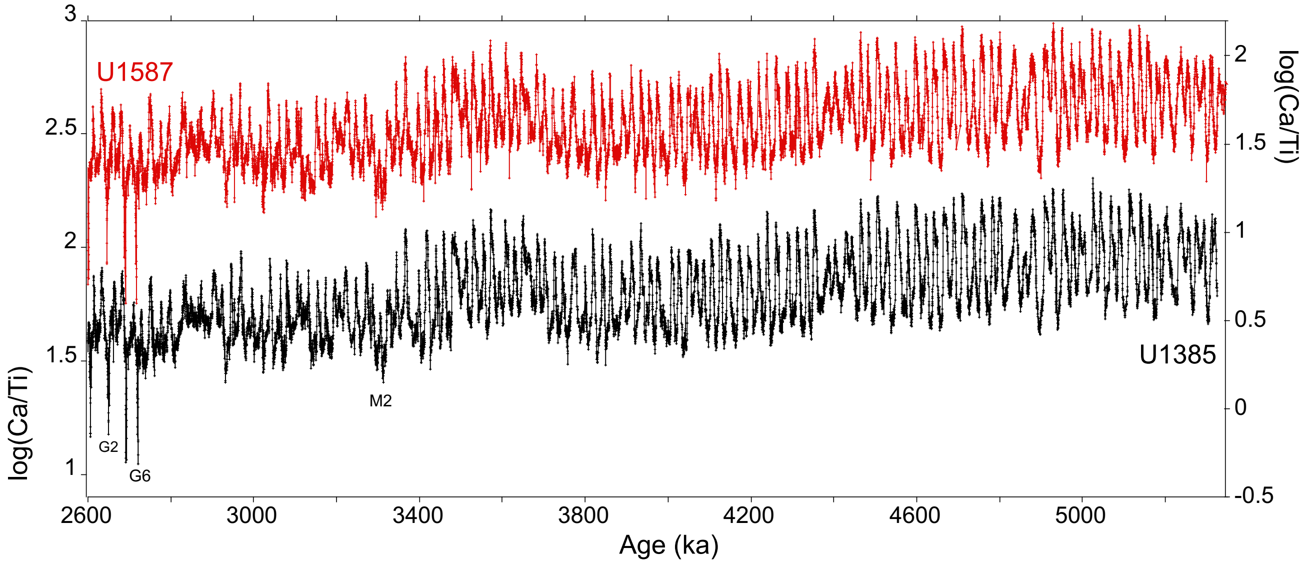

Figure 8. Ca/Ti record measured by XRF at Site 397-U1385 (black line) tuned to precession (red line) whose amplitude is modulated by eccentricity. Gray shade highlights prominent eccentricity minima. (Hodell et al., 2025).

Climate Interactions Across Timescales

Results from IODP Expedition 397 suggest that MCV began with the iNHG in Marine Isotope Stage (MIS) G6 (~2.75 Ma) in the latest Pliocene (**Figure 8**) and remained a persistent feature of glacial climate throughout the Quaternary (Hodell et al., submitted). The MCV is nested within the orbitally-driven glacial-interglacial cycles. Understanding how the climate system interacts across these timescales (both upscale and downscale) is important for understanding Ice Age climates. How do processes on orbital timescales affect MCV and, in turn, how does MCV affect orbital timescales? For example, orbital configuration may modulate the amplitude and/or frequency of MCV. Some MCV may be related to harmonics or combination tones of the orbital cycle (Hagelberg et al., 1994; Ferretti et al., 2015). MCV provides a source of deterministic noise on orbital time scales that may be important for phase locking the climate system to the orbital cycles. As part of SIGNALS, we will apply higher-order time series techniques (bispectral analysis, etc.) to better understand energy-transfer mechanisms across a broad range of timescales (e.g., Liebrand and de Bakker, 2019, Liebrand et al., 2023).

Evolving earth boundary conditions might also underlie mode switches (frequency and/or amplitude) in the expression of orbital cyclicity. Important candidates to be investigated by SIGNALS include the Late Miocene global cooling and rise on land of grassland and savanna ecosystems (Herbert et al., 2016), the isolation of the Mediterranean from ~6.5 to 5.235 Ma (Messinian Salinity Crisis), uplift of the Isthmus of Panama (Haug and Tiedemann, 1998; O'Dea et al., 2016), and subsidence of the Greenland-Iceland-Scotland Ridge (Robinson et al., 2011; Parnell-Turner et al., 2015; Sinnesael et al., 2025). The expression of these events in North Atlantic temperature gradients, heat transport, and deep and intermediate circulation are not well known.

Assessing signal-to-noise, stratigraphic alignments and temporal resolution

Sediment profiles represent low-pass filters of climatic/oceanographic signals whose cut-off frequency is dependent upon sedimentation rate, bioturbation, compaction, coring/drilling disturbance, and sampling frequency (Anderson, 2001; Zeeden et al., 2020; **Figure 9**). Before signals can be correlated between sites and interpreted, it is essential to understand how primary stratigraphic signals are smoothed (reduced amplitude) or distorted by these processes. This will be assessed empirically by evaluating the coherency of signals within and between sites (e.g., Low-pass filters of the Greenland $\delta^{18}O$ record with cut-off frequencies from 1–14 kyr (increasing from bottom to top). Sedimentation rate, bioturbation and sampling frequency act to smooth paleoclimatic signals. Note the signal distortion marked by attenuation and complete loss of high-frequency variations with increasing cut-off frequency, which simulates decreasing sedimentation rate and increasing bioturbation (Zeeden et al., 2020). Chapman and Shackleton, 1998) and using numerical bioturbation models (Hülse et al., 2022; Trauth et al., 2013).

All stratigraphic and paleoclimatic signals have uncertainties ("error"). These uncertainties can blur the true amplitude of paleoclimatic variability, distort the alignment of records in depth and time, and limit the detection of the orbital-scale periodicity that is pervasive in marine records. We will take advantage of new tools being applied to signal analysis under the umbrella of "Gaussian Process" (GP) modelling (see Rasmussen and Williams, 2006), a form of non-parametric estimation or data prediction. This approach underpins advances in artificial intelligence (AI) and machine learning, and brings a rigorous method for identifying patterns in data with noise. The GP process is very effective at assessing the signal-to-noise ratio of proxy data. It can be used on both equally and unequally spaced data. For noisy data, the prediction value of adjacent points is poor, and the most likely estimate will lie near the mean of the measurements (**Figure 10**).

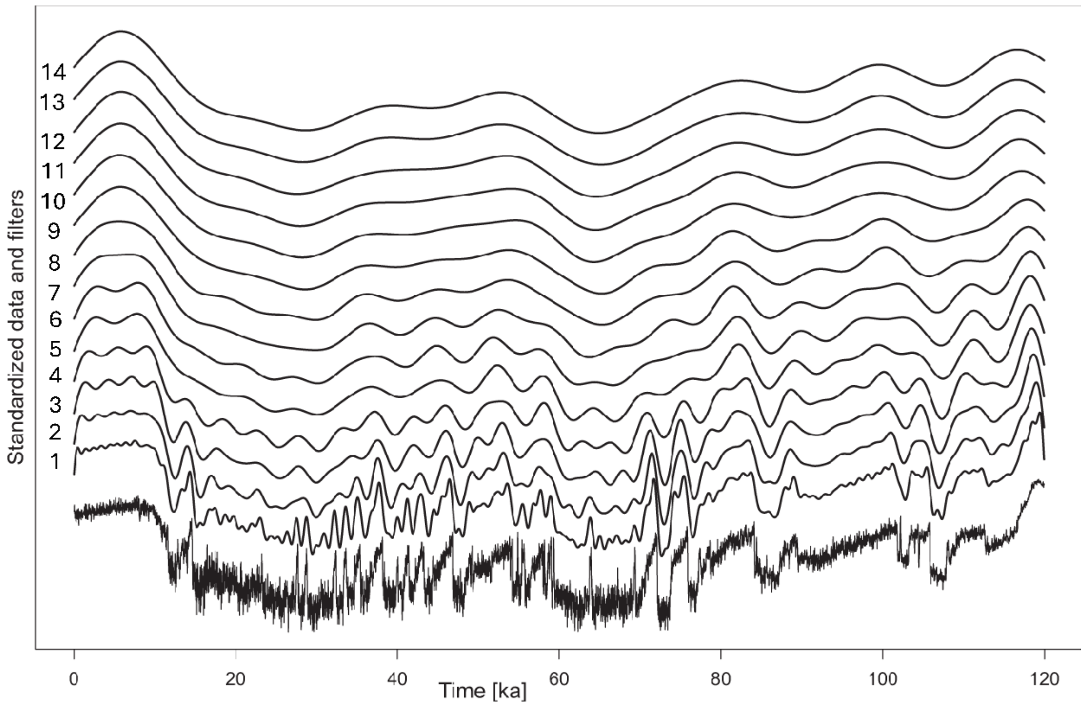

Figure 9. Low-pass filters of the Greenland δ^{18}O record with cut-off frequencies from 1–14 kyr (increasing from bottom to top). Sedimentation rate, bioturbation and sampling frequency act to smooth paleoclimatic signals. Note the signal distortion marked by attenuation and complete loss of high-frequency variations with increasing cut-off frequency, which simulates decreasing sedimentation rate and increasing bioturbation (Zeeden et al., 2020).

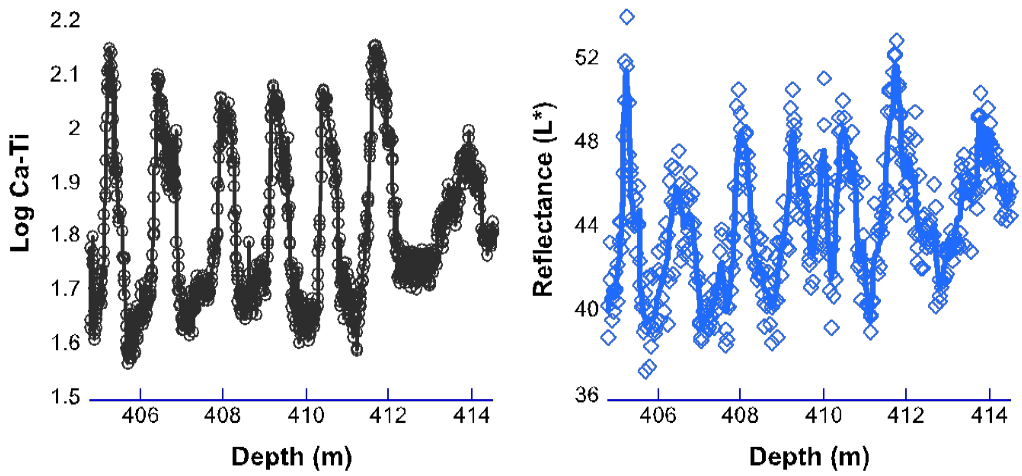

Figure 10. Gaussian Process Modelling of two non-destructive measurements of the same cored interval from Site U1587 (Zarikian et al., 2025). Open symbols denote "raw" measurements while the heavy lines show Gaussian Process fits to the data (GPy Python library https://gpy.readthedocs.io/en/deploy/GPy.core.html). Note that the dispersion of the measured L* parameter (color reflectance; a proxy for carbonate content) to the GP fit is greater than for the scanning XRF measurement of the log of Calcium to Titanium (which is also highly correlated to calcium carbonate).

We will form a working group to advance newer developments in signal alignment (see section "Virtual Expedition Organizational Structure" above). Proponent and Science Team member Tim Herbert has considerable experience with dynamic programming as a solution to the alignment problem, having worked with Lorraine Lisiecki in the first application of the Match algorithm (Lisiecki and Lisiecki, 2002; Lisiecki and Herbert, 2007). The subsequent introduction of probabilistic alignment using a Hidden Markov Model (HMM) permitted a better assessment of the uncertainty in stacked records (Lin et al., 2014), resulting in "ProbStack" (Ahn et al., 2017). A new software package named BIGMACs combines Bayesian age models and stacks (Lee et al., 2023). We will adapt these and other advanced techniques and incorporate them into user-friendly software packages. Online tutorials will be developed to disseminate them to the scientific ocean drilling community and, as part of the SIGNALS expedition, we will train a new generation of early career scientists in their use.

Computer Vision and Deep Learning

SIGNALS will use deep learning-based tools for processing linescanner core images to improve the signal-to-noise ratio and calculate nominally undisturbed color reflectance records. Proponent and Science Team member Stephen Obrochta and colleagues are a leading group in computer segmentation of coring images using machine learning (Fazekas et al., 2017; 2023), which automatically removes secondary color artefacts from images (i.e., different spots in the scanned image related to bioturbation, voids, drilling disturbance, iron oxides, reduced sulfur minerals, etc.). The artefacts can make color data extremely noisy, which is why they need to be removed before further analysis. Manual removal of these imperfections is extremely time consuming but the nature of the problem readily lends itself to automating the process using computer vision. Another issue is the images must be precisely cropped to the curated lengths in order to calculate an accurate depth scale for the extracted color information. Otherwise, the color depth scale will drift away from other high-resolution datasets. It is impractical to manually do this for every core section applicable to this proposal. Thus, we used a combination of neural networks and computer vision to automate this task (Fazekas et al., 2023).

The computer vision-based method is currently available for download on GitHub (**https://github.com/stephenobrochta/CoreAlign**). Convolutional neural networks require training and validation using images where artefacts have been manually identified (**Figure 11A**). The IODP[3] Expedition 506S Science Team will participate in producing these training data sets at the proposed study sites. **Figure 11B** shows segmentation results successfully identifying disturbed pixels in a sediment core. (i.e., this image patch was not included in the training data but used to assess the validity of the segmentation). Once removed, the color data can be further cleaned using Gaussian process modelling described above.

Computer vision is also applicable to identifying and counting particles in sediment coarse fraction. Counting IRD in sediment samples has been a mainstay of Quaternary paleoceanographic studies in the North Atlantic. Using AI models for image analysis and segmentation to automatically recognize and count IRD would tremendously add to the number of long IRD records available (e.g., Barker et al., 2021, 2022). The IODP[3] Expedition 506S Science Team will produce training data sets and apply these automated methods to rapidly generate IRD records at several of the high-priority North Atlantic sites within and outside of the North Atlantic IRD belt. The records will also be used to test the reliability of using elemental ratios measured by XRF scanning as a proxy for IRD (Hodell et al., 2008).

Figure 11. (A) Identification of bioturbation features as part of a training set for automatic recognition using machine learning (Fazekas et al., 2017; Obrochta et al., 2020; 2022). (B) (Left) an image patch of a sediment core that was not included in the training dataset but was (Middle) manually masked. (Right) The trained network was then used to successfully segment the image. Note that the manual masking is coarse due to the time required, but the segmentation result is finer and more precise.

Staffing

Staffing of the IODP[3] Expedition 506S Science Team involves a competitive process following an open Call for Participation published on the IODP[3] website (**https://iodp3.org**). Applications are evaluated by the scientific ocean drilling Programme Member Offices, with staffing nominations taking into account both the scientific background of applicants, the scientific needs of the expedition, and programmatic national, gender and career-stage balances.

SIGNALS will bring together a multidisciplinary Science Team of researchers (Table 11). The team will include specialists spanning the full range of disciplines needed to correlate North Atlantic legacy sites across millennial and orbital timescales to create an integrated stratigraphic network. Each participant will be assigned to one or more working groups (see section "Virtual Expedition Organizational Structure" above) according to expertise and interests, ensuring that both millennial and orbital correlation objectives are addressed collaboratively and coherently.

Table 11: List of areas of expertise needed for SIGNALS

Field / Expertise	Role or Focus Area
Stratigraphy & Chronology	Multi-proxy correlation and chronology at millennial and orbital time scales. Marine, ice-core, terrestrial integration.
Cyclostratigraphy & Astrochronology	Orbital tuning, spectral analysis, and time-series evaluation.
Sedimentology and Process Modelling	Depositional processes, cyclic stratigraphy, and facies analysis.
Geochemistry (XRF, Isotopes, Biomarkers)	Proxy generation, calibration, and inter-site consistency.
Paleomagnetism & Biostratigraphy	Magnetostratigraphic and micropaleontologic age control.
Computational Geoscience / Data Science	Quantitative correlation tools, probabilistic modelling, error analysis, and signal processing.
Computer Vision & Image Analysis	Machine-learning approaches for core imaging and feature extraction.
Data Management and Assimilation	Metadata curation, repository integration, and data interoperability, Data-Model Integration

SIGNALS is committed to fostering an equitable, inclusive, and diverse research environment. Applications are welcomed from scientists of all backgrounds, career stages, and nationalities. Selection will reflect IODP^3's principles of diversity, gender balance, early-career participation, and equitable access to scientific opportunities. Final staffing decisions will ensure a diverse, interdisciplinary, and balanced Science Team capable of delivering the integrated scientific objectives of the expedition. We strongly encourage applications from early career researchers and those researchers who have or still are working on the target sites listed in Table 1.

Outlook

IODP^3 Expedition 506S "SIGNALS" is the beginning of the scientific journeys outlined in this Prospectus. Staffing and meetings will be structured as much as possible to engage the next generation of scientists who may not have the opportunity to sail on a *JOIDES Resolution*-type vessel for some time, and to catalyze multi-investigator studies that will take advantage of the stratigraphic syntheses proposed by SIGNALS using a new generation of proxy and modelling studies. Among opportunities envisioned are "hackathons" and stratigraphic "boot camps" utilizing software and mathematical approaches developed over the course of the expedition. We aim to emulate the flow of data typical of shipboard participation and the potential for collaborations during and following SIGNALS. We will also use international meetings to highlight the work of SIGNALS and to entrain others in the community to the follow-up work that will be needed to fully accomplish the goals set by this expedition. Towards the end of the 3-year funded period we plan to host a dedicated conference session at an international meeting (EGU, AGU) and/or a special topical conference to highlight the research outcomes of the expedition.

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