INTERNATIONAL OCEAN DRILLING PROGRAMME

SCIENTIFIC PROSPECTUS

IODP³/NSF Expedition 501: New England Shelf Hydrogeology

17 December 2024

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New England Shelf Hydrogeology

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Abstract

In many coastal settings worldwide, the distribution of freshwater within continental shelf sediments is far out of equilibrium with modern sea level. One of the most remarkable examples is found on the Atlantic continental shelf off New England where groundwater within shallow Pliocene-Pleistocene sand aquifers over 100 km offshore has low salinity (3000 mg/l or less). On Nantucket Island, a 514m deep borehole penetrating the entire Cretaceous-Tertiary sedimentary package shows considerable variations in salinity with extremely fresh (<1000 mg/l) water in sand aquifers, higher salinity (30-70% of seawater) in thick clay/silt layers, and intermediate-to-low salinity in thin confining units. Integrated Ocean Drilling Program Expeditions 313 (New Jersey Shallow Shelf) and 317 (Canterbury Basin New Zealand) also showed abrupt offshore freshwater-saltwater boundaries linked to lithology. This demonstrates the disequilibrium nature of such systems; diffusion tends to eliminate such patterns. Pore fluid within Pleistocene to upper Cretaceous sands beneath Nantucket Island are also found to be modestly overpressured, ~4m relative to the local water table.

We hypothesise that the rapid incursion of freshwater on the continental shelf in New England could have been caused by one or more of the following mechanisms: (1) meteoric recharge during Pleistocene sea-level lowstands including vertical infiltration of freshwater associated with local flow cells on the shelf; (2) sub-ice-sheet recharge during the last glacial maximum; and (3) recharge from pro-glacial lakes. We further hypothesise that the overpressures could be due to: (1) Pleistocene sediment loading; or (2) fluid density differences associated with emplacement of a thick freshwater lens over saltwater (analogous to excess pressures in the gas legs of petroleum reservoirs). We argue these different recharge mechanisms and overpressure models can be distinguished through drilling, coring, logging, and fluid sampling. Noble gas and environmental isotope data will be necessary to completely evaluate recharge models.

This work will extend our understanding of the current and past states of fluid composition, pressure, and temperature in continental shelf environments. It will help better constrain rates, directions, and mechanisms of groundwater flow and chemical fluxes in continental shelf systems. It will contribute to the development of new tools for measuring freshwater resources in marine environments. The apparent transient nature of continental shelf salinity patterns could have important implications for microbial processes and long-term fluxes of carbon, nitrogen, and other nutrients to the ocean. Successful drilling will test process-based models for shelf freshwater off New England. These models can then be applied to other shelf freshwater systems around the world.

Schedule for Expedition 501

Expedition 501 is based on International Ocean Discovery Program (IODP) drilling proposal 637-Full2 and Addenda 637-Add3, -Add7, and -Add8. Following ranking by the IODP Science Advisory Structure, the expedition was scheduled by the European Consortium for Ocean Research Drilling (ECORD) Facility Board as a Mission Specific Platform (MSP) expedition, to be implemented by the ECORD Science Operator (ESO). The expedition is scheduled from 1 May to a latest end date of 14 August 2025, with a total of 105 days available for the drilling, coring, and downhole measurements described in this report and on the ESO **Expedition 501 webpage**. The Onshore Operations (OSP) in Bremen is provisionally scheduled to start late 2025/2026 and last for a maximum of 4 weeks (dependent on core recovery).

The following links should be used in conjunction with this Scientific Prospectus:

- The Expedition 501 webpage will be periodically updated with expedition-specific information on the platform, facilities, coring strategy, measurements plan and schedule. The full proposal and addenda can be accessed **here**.
- General details about the offshore facilities provided by ESO are provided on the ESO-specific **webpages** on the MARUM website.
- General details about the onshore facilities provided by ESO are provided on the ESO-specific **webpages** on the MARUM website.
- The supporting site survey data for Expedition 501 are archived in the **IODP Site Survey Data Bank**. Please note that not all site survey data associated with this Expedition is publicly available.

Introduction

Coastal hydrological systems are important as they provide significant freshwater to coastal communities around the world. These resources are typically extracted by groundwater wells that produce from unconfined or confined aquifers with well screen depths of less than 100 m. In 2000, coastal groundwater production along the US Atlantic and Pacific coastlines was about 19.5 km^3 [Barlow and Richard, 2010]. To put this number in perspective, this represents about 2.4% of annual global groundwater withdraws of 800 km^3/yr [Konikow and Kendy, 2005]. Sea-level rise poses a unique issue to coastal freshwater sustainability [Werner and Simmons, 2009; Werner et al. 2013]. In this context, offshore freshened groundwater (OFG) systems that occur within continental shelves below sea level are of particular interest. The global occurrence of this offshore fresh and brackish groundwater along coastlines [Post et al., 2013] (**Figure 1**) is volumetrically significant, but not a well-studied future reserve for an increasing coastal population. Additionally, coastal freshwater resources are particularly susceptible to contamination due to their proximity to seawater [Post, 2005]. To date, the residence times of OFG systems are unknown. This leads to questions including: were they emplaced during the last glacial maximum (LGM) or do they represent some long-term average of Pleistocene low-stand sea-level conditions? Of further interest is a potential hydraulic connection to onshore meteorically recharged systems [Michael and Kahn, 2016]. It is currently unclear whether groundwater offshore New England is replenished through long-time scale flow paths through permeable crystalline basement rocks that crop out on the mainland or if these systems represent non-renewable reserves decoupled from the modern, active hydrologic cycle. As coastal populations continue to increase and sea-level rises, stresses on these vulnerable resources will also increase. It is therefore crucial to understand the hydrodynamics of these systems, to characterize their extent, to establish their relation to equilibrium conditions, and to define their potential as a resource.

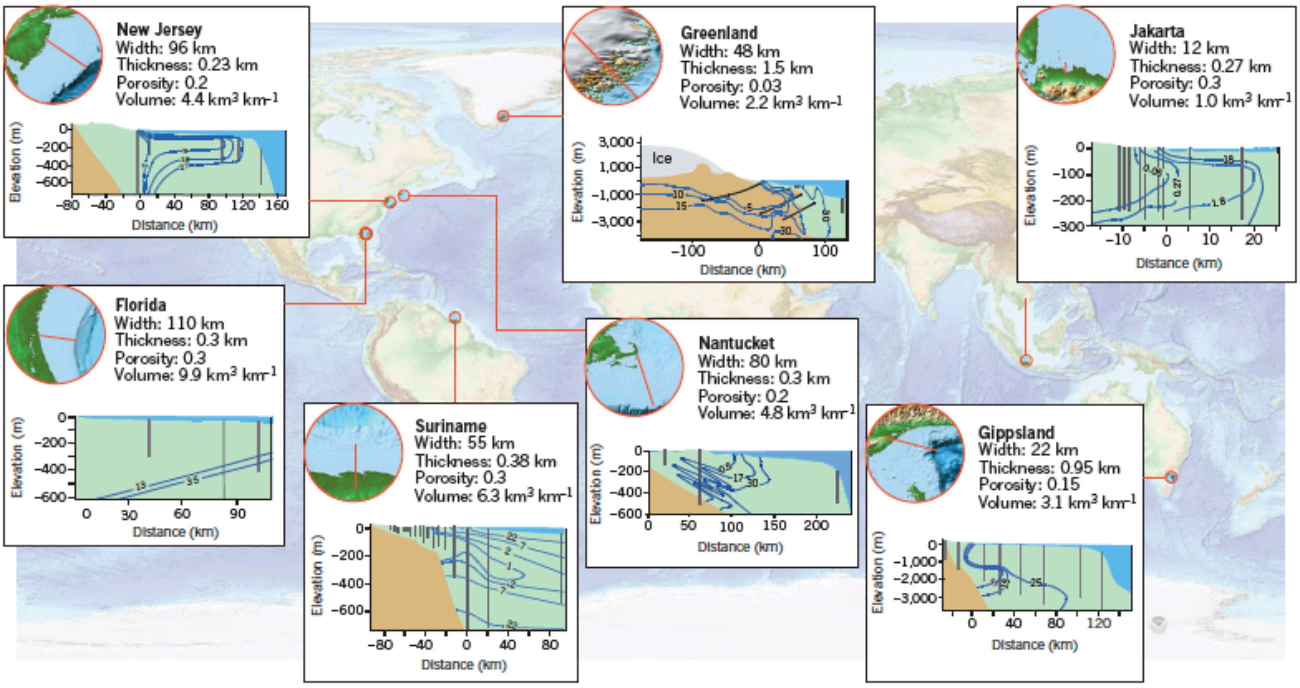

Figure 1. Offshore freshwater cross-sections around the world from Post et al. [2013]. Blue contour lines indicate total dissolved solid (TDS) concentrations in parts per thousand (ppt); horizontal and vertical axes of cross sections are distance (km) and elevation (m) relative to mean sea level; vertical grey lines indicate well locations where salinity is inferred from water samples and borehole logs.

The northeast coast of the United States is perhaps the best understood example of an offshore freshwater system with multiple studies trying to determine the origin and volume of offshore freshwater [e.g., Meisler et al., 1984; Person et al., 2003; Lofi et al., 2013]. Drilling campaigns beginning in the 1970s documented that the Atlantic continental shelf hosts vast quantities of OFG in sub-seafloor depths >100 m within marine clastic deposits [Hathaway et al., 1979]. Cohen et al. [2010] estimate that there are about 1300 km^3 of sequestered freshwater along the Atlantic continental margin between New Jersey and Maine; for perspective, the City of New York uses 1.5 km^3 of freshwater per year. However, little is known about the origin of this freshwater or the timing of fluid emplacement. Thus, the primary objectives of the proposed research are to understand the spatial distribution of OFG, emplacement mechanisms of OFG, porewater geochemistry, microbe diversity and activity, and anomalous pressure distribution. This project will characterize the OFG extent and the transition to seawater which may be linked to submarine groundwater discharge on the shelf-slope break [Skarke et al., 2014, 2018] and to anomalous freshwater onshore [Marksamer et al., 2007]. Globally, OFG occurs at many other locations below continental shelves (**Figure 1**) [Post et al., 2013], and these aquifers are prospective water reserves for densely populated, near-shore regions. Understanding the processes driving emplacement of the freshened water lenses offshore New England will also lead to a better fundamental understanding of this worldwide hydrogeological phenomenon and its impact on biogeochemical cycling. This is essential for protection and sustainable management of these valuable resources in the near future and for better understanding biogeochemical cycling in shelf environments.

Motivation and Need for Ocean Drilling

Prior drilling campaigns and paleohydrogeologic modelling studies provide evidence of freshwater extending far offshore along the North America Atlantic margin [e.g., Meisler et al., 1984]. This freshwater may provide a buffer to increased demand, especially during periods of intense drought. There is growing evidence that passive margin sediments host large volumes of paleo-freshwater, and it is hypothesized that these waters were emplaced during the past 2 million years as a result of Pleistocene glaciations [Edmunds, 2001; Person et al., 2003, 2007, 2012; Lemieux et al., 2008; Jiráková et al., 2011; McIntosh et al., 2012; Neuzil, 2012; Zhang et al. 2018]. Continental sedimentary basins and passive margins along the US Atlantic margin have been influenced by the Laurentide ice sheet and aquifer-ice sheet coupling may explain the emplacement of fresh groundwater to depths up to 1000 m [McIntosh and Walter, 2005; Bense and Person, 2008; McIntosh et al., 2011]. Evidence of glacially emplaced freshwater in basins comes from many sources, including ^{14}C and noble gas ages [Klump et al., 2008; Morrisey et al., 2010; Darling, 2011; Schlegel et al., 2011] and oxygen isotope data [Rozanski, 1985; Vaikmäe et al., 2001; Darling, 2004; Négrel and Petelet-Giraud, 2011; McIntosh et al., 2012; van Geldern et al., 2014]. These observations motivated numerous modelling studies that evaluated how sub-glacial meltwater may create non-equilibrium conditions and may drive freshwater deep into sedimentary basins [Person et al., 2007, 2012; Post et al., 2013; Siegel et al., 2014]. IODP drilling offshore New Jersey (IODP Expedition 313 [Mountain et al., 2009]) has revealed non-equilibrium salinity conditions, but also shows significant impact from modern meteoric recharge [van Geldern et al., 2013].

Multiple mechanisms have been proposed to explain the emplacement of freshwater within continental shelf sediments during glacial periods. Early studies focused on the shore-normal hydraulic gradient associated with primary topography of the continental shelf as the prime driving force for fresh water recharge during sea-level lowstands [Meisler et al., 1984] (**Figure 2**). Subsequently, Groen et al. [2000] argued that local flow systems associated with secondary topography of the subaerially exposed and incised shelf are essential to emplace meteoric water far out onto the continental shelf (**Figure 2**). Person et al. [2003] then emphasized the role of sub-ice-sheet recharge (**Figure 2**), whereas Mulligan and Uchupi [2003] and Person et al. [2012] suggested recharge from pro-glacial lakes (**Figure 2**). The mechanism proposed by Groen et al. [2000] would be particularly viable if confining units are discontinuous, a situation indicated by IODP Expedition 313 drilling off New Jersey [Mountain et al., 2009]. A problem that some of the above mechanisms face is that freshwater incursion far offshore is indicative of a permeable environment whereas observed (Nantucket, well 6001) and interpreted (offshore New Jersey) excess fluid pressures suggest a low-permeability environment [Dugan and Flemings, 2000; Marksamer et al., 2007; Lofi et al., 2013].

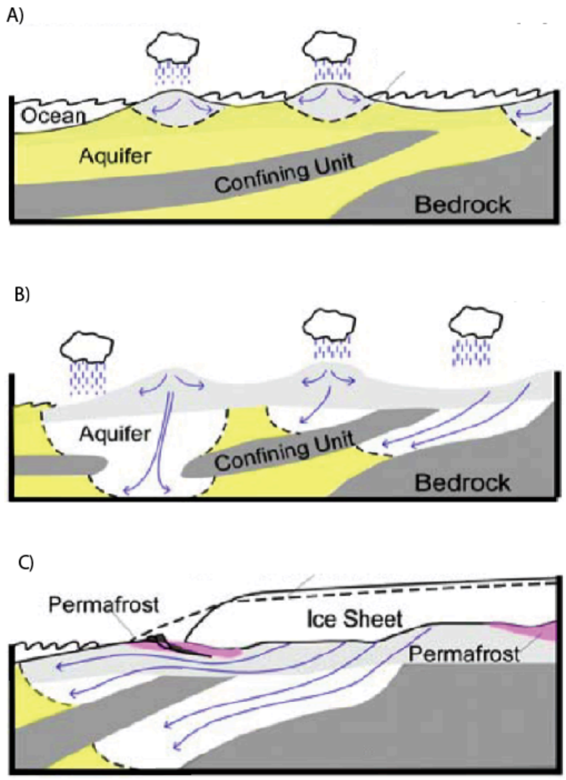

Figure 2. Conceptual models of freshwater emplacement. Freshwater-saturated sediments are light gray and white; saltwater-saturated sediments are yellow. The freshwater-saltwater interface is marked with a dashed blacked line. A) Equilibrium freshwater lens under present-day meteoric recharge produces a small lens of freshwater under islands [Glover, 1959]. B) Meteoric recharge to exposed aquifers and increased gradient during sea- level low-stand drives the freshwater-saltwater interface deeper and farther offshore [e.g., Kooi and Groen, 2001; Meisler et al., 1984]. C) Sub-ice sheet recharge during a glacial period; high pressure from glacial advances drives freshwater deeper and pushes the freshwater-saltwater interface farther offshore [e.g., Person et al., 2003; Marksamer et al, 2007; Siegel et al., 2014].

To better understand the dynamics of these onshore-offshore hydrologic systems, a dedicated hydrogeological expedition is required. We propose a transect drilling approach to focus on the interactions between glacial dynamics, sea-level variations, and groundwater flow along the US Atlantic continental shelf extending south from Massachusetts, USA (**Figures 3 and 4**). This shelf experienced a number of glaciations in the late Pleistocene in combination with sea-level change throughout the Pleistocene [Oldale and O'Hara, 1984; Uchupi et al., 2001; Siegel et al., 2012]. Glacial loading, sea-level fluctuations, and meteoric recharge processes have all been suggested as driving mechanisms that emplaced freshwater nearly 100 km offshore New Jersey down to depths of several hundred meters below the sea floor (mbsf) [Hathaway et al., 1979; Kohout et al., 1988; Cohen et al., 2010; Lofi et al., 2013; Post et al., 2013; van Geldern et al., 2013]. Dedicated drilling, coring, and analyses focused on the onshore-offshore hydrogeological system are required to fully understand emplacement processes and dynamics.

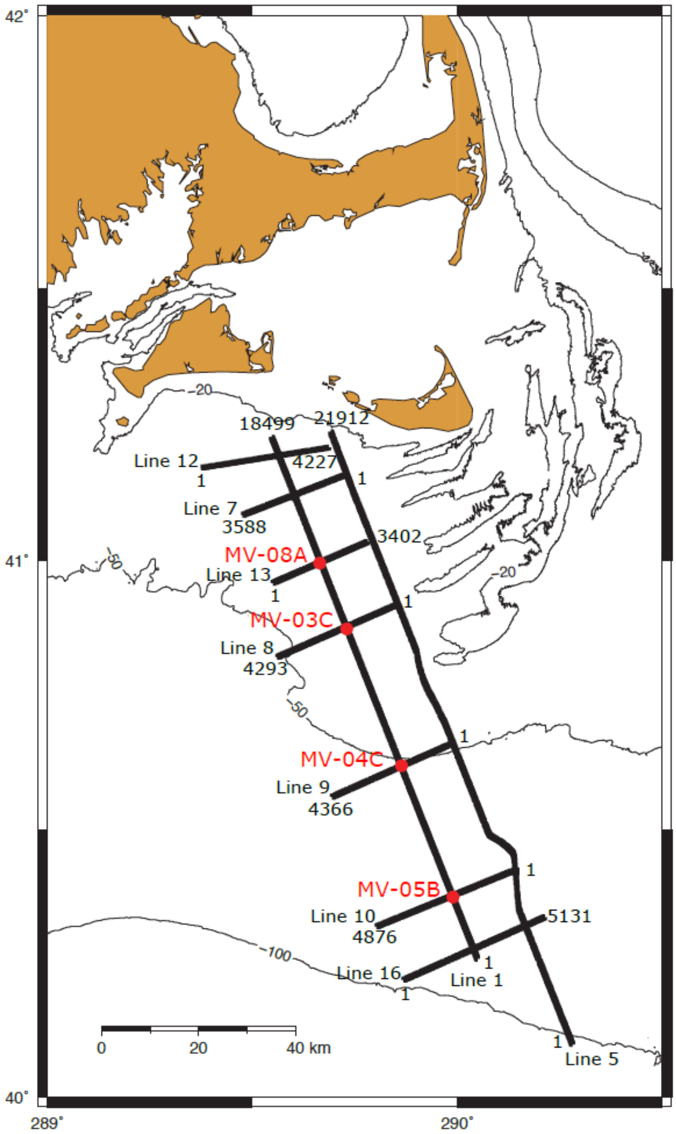

Figure 3. Basemap of IODP Drilling Proposal 637 study region including proposed sites (primary sites = solid red circles and red numbers; alternate sites = solid grey circles and grey numbers) high-resolution MCS data (black lines, green line numbers), and CDPs (green number). Cross section A-A' (Line 1) is shown in Figure 4.

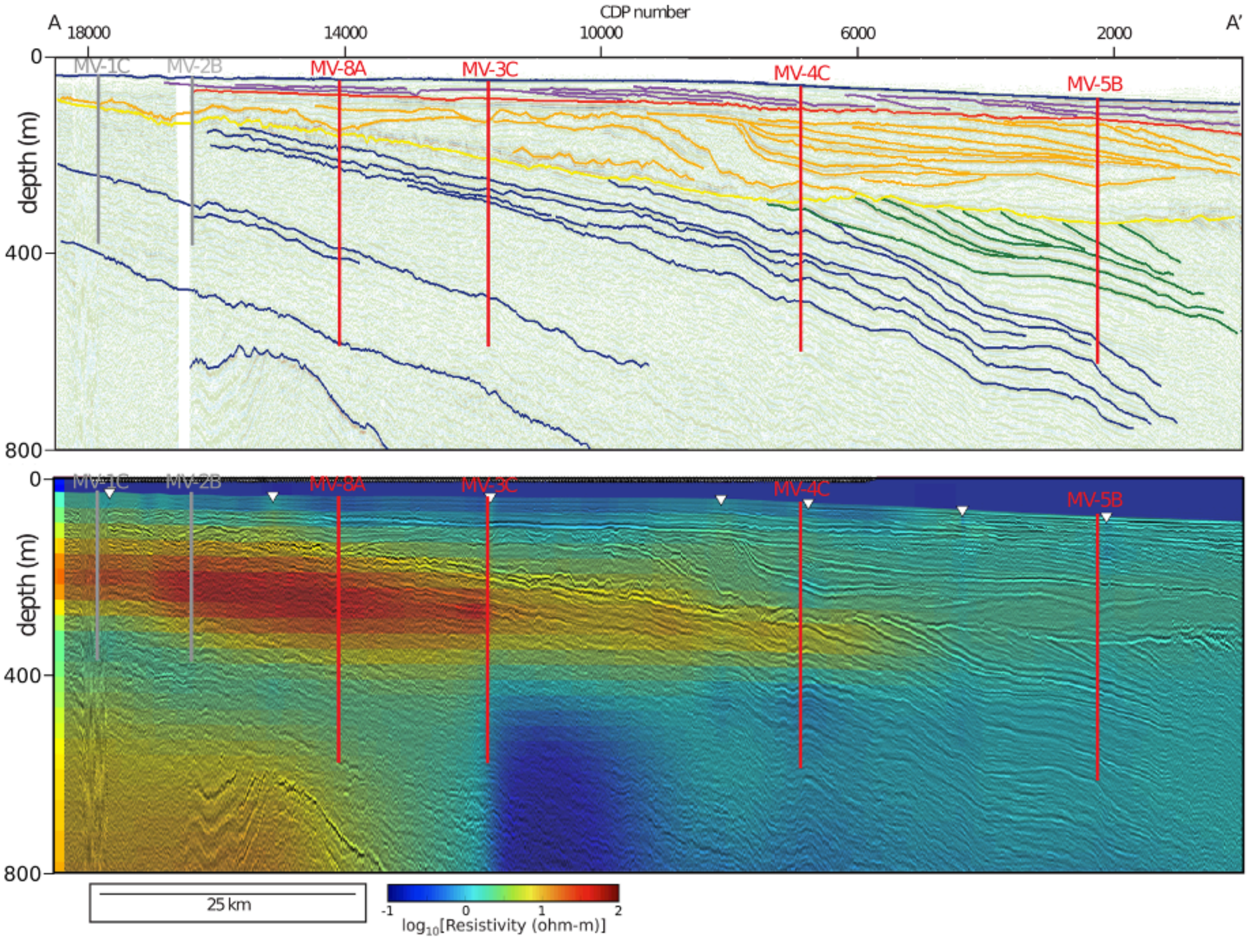

Figure 4. Top – Depth-converted and interpreted seismic line A-A' (located in Figure 3) showing location and proposed depths of primary sites MV-8A, MV-3C, MV-4C, and MV-5B (red lines, red numbers). Also shown are locations and proposed depths for alternate sites MV-1C and MV- 2B (grey lines, grey numbers). Details on seismic processing and interpretation are provided in Siegel et al. [2012]. Bottom – Resistivity profile based on joint inversion of controlled-source electromagnetic and magnetotelluric data overlain on depth-converted seismic line A-A' (located in Figure

Background

We argue that targeted drilling and coring including hydrogeochemical, microbiological, isotopic, and noble gas analysis and measurement of hydraulic properties and fluid pressures will yield a process-based understanding for the origin and volumes of offshore freshwater, how these fluids influence local and global biogeochemical cycles, and how they record climate cycles.

We propose a three-site, shallow-water drilling campaign on the Atlantic continental shelf off Martha's Vineyard, Massachusetts, USA, to test our hypotheses and to map offshore freshwater resources. Our transect takes advantage of boreholes on Martha's Vineyard (ENW-05) and Nantucket (6001), builds on previous Atlantic Margin Coring (AMCOR) and IODP analyses, and is motivated by geophysical observations (stratigraphy, resistivity). Our transect will provide samples from the interpreted freshwater, freshwater-seawater transition, and seawater zones allowing complete characterization of the OFG system. Based on paleohydrologic reconstructions, we developed 2D and 3D models of the freshwater distribution and predicted the freshwater-seawater transition is < 30 km offshore. Electromagnetic data suggest the transition may extend up to 80 km offshore. Drilling will directly test these geophysical interpretations and provide additional constraints for hydrogeological models.

Our drilling campaign will require one mission-specific platform (MSP). We propose a programme similar to IODP Expedition 313 [Mountain et al., 2009] to increase recovery in unconsolidated sand units and a casing/screening programme to facilitate collection of pristine pore fluid samples for geochemical and microbiological analyses. Post-expedition numerical models will include simulation of groundwater residence time and noble gas transport for comparison with field measurements. This highly interdisciplinary work will be one of the first focused hydrogeological-biogeochemical-microbiological studies of continental shelf systems.

Scientific Objectives

Primary Objectives and Assessment

Objective 1: What is the distribution of freshened water, fluid pressures, and temperatures across the Atlantic continental shelf in New England?
We will directly sample water chemistry, pressures, and temperatures across the freshwater zone, the freshwater-saltwater transition, and the seawater zone and characterize how they relate to the glacial loading history.

Objective 2: How old is the groundwater and when was it emplaced?
The deepest onshore freshwater is possibly Pleistocene in age and linked to glaciations. This will be tested with groundwater age analysis.

Objective 3: Was freshwater recharged by basal melting of large ice sheets, infiltration from large proglacial lakes, direct recharge from precipitation, or a combination of these processes? If the latter, what is their relative importance, and can their distribution and the age patterns be unravelled through hydrogeological process models?
Isotopic and age data and hydrologic parameter information that we will collect are required to fully constrain OFG system dynamics over time for the offshore component of this onshore-offshore freshwater system that may extend 80 km offshore.

Objective 4: What are the current concentrations and production/consumption rates of methane, nutrients, and rare Earth elements in shelf sediments? What controls them?

Nutrients and methane have been studied in the mid-continent and in near-shore environments. Our proposal targets offer a better understanding of an active shelf environment.

Objective 5: What are the rates of decomposition of sedimentary organic matter and which redox processes/microbial communities are involved? What sources of carbon do the shelf microbes utilize? Which factors determine the spatial distribution and activity of microbial communities in the shelf?
Dedicated organic matter sampling and microbiological analyses along our proposed transect are required to address these questions and will provide a first step to establishing how they change in the offshore environment.

Secondary Objectives and Assessment

Objective 6: Do fluid pressures reflect the current fluid density distribution and modern sea level or are overpressuring mechanisms (e.g., rapid sediment loading) involved?
Onshore well data suggest non-equilibrium fluid pressure. Documenting the vertical and horizontal pressure distribution on the shelf and linking it with process will test models for the origin of fluid overpressures as well as the timing of overpressure generation.

Objective 7: What are the magnitudes of long-term fluxes of methane and nutrients from the shelf due to periodic flushing during the Pleistocene?
We have developed process-based models for fluxes from the onshore to the offshore environment and drilling will provide model inputs (e.g., hydrological parameters) and test data for models (e.g., modern conditions that can be tested against forward models under different sea-level and glacial cycles).

Objective 8: Does the emplacement of ice sheet meltwaters in confined aquifers create a unique environment for methane?
Vertical and horizontal profiling of waters emplaced at different times and under different hydrological conditions will provide new information to address this question.

Objective 9: What is the sea-level history along this glaciated margin?
Integrating core age and lithology data with the sequence stratigraphy will contribute to addressing this question.

Assessing Objectives 1-3, 6 and 9 will provide new insights on shelf hydrogeology that will contribute to Strategic Objective (SO) 3 of the **2050 Scientific Framework**: Earth's Climate System (Ice sheets and sea-level rise), SO 4: Feedbacks in the Earth System (Ice sheet grounding and stability), SO 6: Global Cycles of Energy and Matter (Matter cycling: water, freshwater aquifers), and Enabling Element (EE) 2: Land to Sea (Fluid flow across the coastlines). Assessing Objectives 4 and 5 will provide new insights on shelf hydrogeology that will contribute to SO 1: Habitability and Life on Earth (Microbial influence on biogeochemical cycles), SO 6: Global Cycles of Energy and Matter (Matter cycling: water, freshwater aquifers, Matter cycling: carbon), Flagship Initiative (FI) 4: Diagnosing Ocean Health (Nutrient availability in the ocean), and FI 5: Exploring Life and its Origin (Defining the rules of microbial life). As a project with direct societal impact, it will also be an asset for EE1: Broader Impacts and Outreach.

Previous Drilling

No previous drilling has been done in this region. The Atlantic Margin Coring Project [Hathaway et al., 1979] had sites located more than 100 km from Expedition 501 sites.

Proposed Drilling

A significant component to IODP drilling proposal 637 is drilling and sampling the freshwater endmember, the seawater endmember, and the transition between the endmembers. The proposed drilling strategy is to drill MV-08A first to 550 mbsf (**Figure 4**). This will sample the freshwater endmember which is predicted to be bounded on top and bottom by seawater. The second site to be drilled will be MV-03C to 550 mbsf (**Figure 4**). This is likely the freshwater-seawater transition based on electromagnetic and magnetotelluric data. The third site to be drilled would be MV-04C to 550 mbsf (**Figure 4**) to sample the seawater endmember, as predicted by numerical models and electromagnetic and magnetotelluric data. Site MV-04C, however could have a small component of freshened water.

Proposed drill sites

Site Locations

Three primary sites, located in water depths ranging from approx. 40-50 m and with total penetration depths ≤550 m (**Table 1**).

Sediments are expected to be predominantly sand, silt and clay based on seismic interpretation and stratigraphic correlation with observations from IODP Expedition 313 [Mountain et al., 2009]. Sites have been selected to target resistivity anomalies interpreted to reflected freshened groundwater [Gustafson et al., 2019], drilling depth constraints and drilling time. To address the Scientific Objectives, the sites are specifically targeting:

- the freshwater endmember location, expected to be bounded above and below by seawater;

- the freshwater-seawater transition that is also expected to be bounded above and below by seawater;
- the seawater endmember which may have a small contribution of freshened water.

MV-08A: Proposed drilling to 550 m to capture the freshwater endmember, to assess the age of the freshened water, and to characterize microbial diversity and activity in the freshened water and the overlying and underlying seawater. The lithology and hydrogeological properties will also be defined to better understand different emplacement mechanisms.

MV-03C: Proposed drilling to 550 m to capture the onset of the freshwater-seawater transition, to assess the amount of freshwater and seawater mixing, and to characterize microbial diversity and activity in a system that may be increasing in salinity in the modern environment. The lithology and hydrogeological properties will also be defined to better understand the dynamics of this transition.

MV-04C: Proposed drilling to 550 m to capture the likely seawater endmember that was likely freshened in the past, to understand when this location became dominated by saltwater, and to characterize the microbial system that has gone from freshened water to seawater. There is the potential that this site will have a minor amount of freshened water.

MV-05B: Will not be drilled during Expedition 501. The site was originally targeted as the definitive seawater endmember, however the same objectives can be addressed with project budget and timeframe by drilling MV-04C.

Table 1. Location of and information for proposed primary sites. Sed = sediment; Bsm = basement.

Site Name	Position (Lat, Lon)	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
MV-08A (Primary)	40.9976 -70.3334	41	550	0	550	MV-8A will characterize the freshwater endmember.
MV-03C (Primary)	40.8746 -70.2697	42	550	0	550	MV-3C will characterize the freshwater-to-seawater transition zone of the transect.
MV-04C (Primary)	40.6185 -70.1370	52	550	0	550	MV-4C will likely characterize the seawater endmember.
MV-05B	40.3771 -70.0119	79	650	0	650	MV-5B will not be drilled as the objectives will be accomplished at MV-04C

Site survey data

The Expedition 501 study area has been surveyed by a grid of high-resolution, multi-channel seismic (MCS) data (**Table 2**) [Siegel et al., 2012]. Data were collected with a 45 in^3/105 in^3 generator-injector (GI) air gun and a digital streamer with 48 channels spaced at 12.5 m. Seismic processing included outside trace mute, bandpass filter, true amplitude recovery, f-k filter, radon filter, deconvolution in the tau-p domain, normal moveout (NMO) correction, post-stack deconvolution, Kirchhoff post-stack depth migration, and f-x deconvolution. In water depths of 50-150 m, the water bottom multiple has been sufficiently suppressed by processing. Stacking velocity analysis was performed every 500 m, and interval velocities were calculated based on the stacking velocities. The data achieves a horizontal and vertical resolution of 7 m. All sites have crossing MCS lines.

Controlled-source electromagnetic (CSEM) data and magnetotelluric (MT) data were collected along a transect that connects all sites (**Table 2**) [Gustafson et al., 2019]. Ten MT stations were collected by deploying broadband seafloor electromagnetic (EM) receivers. Surface-towed CSEM data were collected with a 336.9 m long dipole antenna broadcasting a 88 A current (doubly symmetric square waveform; 0.25 Hz fundamental frequency). In addition, four broadband EM receivers were surface-towed (offsets 600, 870, 1120, and 1380 m). Two-dimensional (2-D) resistivity models were determined by inverting CSEM and MT data jointly and independently using MARE2DEM, a freely-available goal-oriented adaptive finite-element inversion code.

Bathymetric data over the study sites comes from the NOAA National Geophysical Data Center.

Table 2. Geophysical site survey data used for the planning of Expedition 501. Seismic reflection data can be found **here**.

Source	Data Type	Distribution
Seismic Reflection		
Marine Geoscience Data System	High-resolution, multichannel seismic data. Digital.	Crossing lines at each site plus additional lines for regional context.
Electromagnetics		
Lamont-Doherty Earth Observatory	Controlled-source electromagnetic and magnetotelluric data. Digital.	Transect extending through MV-08A, MV-03C, and MV-04C.
Bathymetry		
NOAA National Geophysical Data Center	Bathymetric data. Digital.	Throughout study region

Operational Strategy

Drilling platform

The proposal calls for a drilling platform that can operate in shallow water and deep penetration. The Liftboat L/B *Hawk* has been contracted to undertake the drilling and coring. Coring will be performed using soil boring equipment cantilevered from the main deck using a top drive power swivel. The vessel has a cruise speed of 5 knots and total accommodation capacity of 34 people (including crew). The equipment includes a top drive surface coring rig with hands-free coring equipment, mud mixing and pumping unit, as well as other tools and accessories required to carry out the site investigation. Heave motion compensation will not be required as the secure positioning of the liftboat on the seabed will ensure the drill bit maintains a uniform pressure on the base of the borehole during drilling operations. An ample supply of drilling mud will be provided and a spare string of drill pipe, sufficient spare parts and other supplies required will be available. The drilling fluid used will be seawater and/or TP-012, a biodegradable polymer for use in brackish water.

Downhole depth control

Prior to commencing drilling operations, water depth is measured and adjusted to local Mean Sea Level (MSL). Water depth measurements will be performed using the drill string lowered onto the seabed. At this time, the ‘air gap’, (i.e., the distance between the drill floor and the water level) shall be measured to assist with the accurate determination of the drill be depth below seabed.

Coring Methodology

Wireline coring will be done using QD TECH 450 series tools. QD TECH offers a wide range of inner barrels to handle varied lithology. 450 Hydraulic Piston Core (HPC) inner assembly is for collecting soft sediments up to moderately stiff clay. 450 Extended Nose Punch Core (EXN) is an assembly for collecting core samples in sediment using direct push force. 450 “Alien” Flush – Extended Lithified/Rock Coring (ALN) is an Inner Tube Assembly for collecting core samples in harder formations that cannot be sampled using either of the two push style samplers. 450 Non-Coring Inner Assembly (NCA) inner tube assembly places a full-face drill bit within the main outer bit. Coring will commence using the Piston Corer (HPC) and will continue to be used until quality or penetration rate drops. At this point, the Nose Punch Corer (EXN) will be used, ideally until full depth. The ALN tool will be used if the limitations of the other tools are reached. The main suite uses a nominal diameter of 3.0” (76.2 mm) and polycarbonate plastic liners.

Typically, every core run will be 3 m in length, however, shorter core runs can be made if the formation is blocking the bit, or if it is too friable to withstand a 3-m run.

Backup tools providing cores in 83 mm and 61 mm diameter will also be made available. BLY PQ3 Core Barrel: Produces a 3-1/4" (83mm) core and BLY HQ3 Core Barrel: Produces a 2-3/8" (61mm) core.

All boreholes will be drilled using a 6-5/8” buttress casing trough the water column. The casing will be washed into the seabed to create a “riser” with a natural seal allowing the system to recirculate all drill fluids.

Uncased sections of boreholes are expected to naturally collapse shortly after operations are concluded. Thus, casing will be removed from at least the top-hole section, with natural collapse the preferred abandonment method.

Downhole Logging

In all MSP expeditions, the downhole logging programme, coordinated by the European Petrophysics Consortium (EPC), is an integral part of the offshore operation and is designed to help meet the expedition-specific scientific objectives and maximize scientific output.

The various coring strategies and resulting logging conditions (e.g., water depth, pipe and borehole diameter) on MSPs require an appropriate set of logging tools. The type of logging tools used, including super-slimline tools, memory-mode tools and standard oilfield tools, varies from expedition to expedition. For Expedition 501, logging services are contracted to the University of Montpellier (France). Their suite of slimline tools can be used alone or stacked in a toolstring, offering the possibility to collect multiple measurements in a single toolstring run. During the expedition, the Petrophysics Staff Scientists will liaise with the Co-Chief Scientists, Expedition Project Managers, the operational team, the Science Team and the logging engineers to ensure that the best decisions are made to address the scientific objectives, taking into consideration both time constraints and borehole conditions.

The tool suite available for Expedition 501 includes spectral and total gamma ray, sonic (P-wave velocity), formation conductivity and magnetic susceptibility, hydrogeological measurements (borehole fluid temperature and conductivity), caliper, and flow meter. The use of the entire tool suite is dependant of borehole conditions and stability. A novelty explored for this expedition is the use through PVC casing of Nuclear Magnetic Resonance (NMR) in order to characterise the porosity, and permeability (with calibration via post-expedition experiments), of the formation. The use of the NMR tool is dependent on the overall operational strategy.

For Expedition 501, two holes will be drilled at each site, one for coring and logging, and the other one to perform pumping tests. The plan is to acquire as much downhole logging data as borehole conditions safely allow, for the selected tools, in each cored hole. To address the scientific objectives, and based on the available tools, the ideal logging plan will include gamma ray, sonic, magnetic susceptibility, formation conductivity, borehole fluid properties and porosity. First, the spectral gamma ray log will be acquired through the drillpipe as soon as coring operations are complete. This step ensures the collection of a continuous dataset that can be used to 1) correlate downhole values to multi-sensor core logger (MSCL) gamma ray core values and 2) correlate different holes. Following that, depending on the operational strategy and borehole conditions, the other tools will be deployed. Once operations at the first hole are complete, a second hole will be drilled without coring, to perform pumping tests. If needed, the spectral gamma ray tool will be deployed through the drillpipe to confirm the main lithology and that the target intervals have been reached.

The Petrophysics Staff Scientist will be responsible for data processing, Quality Assurance/Quality Control (QA/QC) of data, and ongoing scientific support for data interpretation and research. The final set of downhole data (following the full QA/QC process) will be made available to the science team at the commencement of the Onshore Operations (OSP).

Groundwater Extraction Methodology

Intervals of interested will be screened using Standard Wireline Packer System (SWIPS). The SWIPS system includes hydraulically inflated packers and can be configured as a single or straddle packer system.

To ensure that the borehole conditions are most appropriate for pristine water sampling, each site will have a second borehole drilled for water extraction. If the conditions of the first borehole are favourable, an attempt may be made to extract water from the first (cored) borehole.

The initial water flow is expected to be artesian. In case of insufficient artesian flow, airlifting or swabbing techniques will be used. This is to preserve electric submersible pumps, which are unlikely to deal well with sand. Once the borehole is clean from sand, if needed, an Electrical Submersible Pump (ESP) will be lowered to as deep as 100 m below sea level. The pumping will continue until the water is deemed pristine and all the samples have been collected. A mini-Ruedi (portable mass spectrometer) will be used to identify when the water has reached pristine levels.

The wellhead attached to the ESP is equipped with “vampire ports” for collecting smaller fluid samples and measuring fluid pressures during pump tests.

As with cored boreholes, natural collapse will be preferred abandonment method.

Long-term condition monitoring

A seafloor borehole observatory may be installed in up to two sites. The Simple Cabled Instrument for Measuring Parameters in-situ (SCIMPI) will be installed at the conclusion of operations, before abandoning the borehole.

The tool, which is the length of the borehole, is deployed through the drill string and left inside the borehole. Ballasts and flotation devices keep the tool in place, while a command module extends a couple of metres above borehole. The system measures pressure, temperature, and resistivity at various pre-defined borehole depths.

Site priorities and contingency considerations

In this section, we provide an overview of operations including strategy and prioritisation for coring, logging, pump tests, and long-term monitoring, The planned order of operations is MV-08A then MV-03C, and finally MV-04C. MV-08A will be the first site as it is interpreted to contain significant amounts of freshened water which is the overarching target of the expedition. Operations in Hole A will include coring and logging to a maximum depth of 550 metres below seafloor (mbsf). Operations may be concluded at a shallower depth of porewater data show freshened water underlain by a consistent return to seawater salinity at depths shallower than 550 mbsf. Upon completion of Hole A, Hole B will be drilled for targeted pump tests and water sampling based on initial porewater chemistry data and borehole logging data. Pump tests will target zones that are sand-rich and contain freshened water. MV-03C will then be drilled to continue to assess the freshened water system as it transitions to seawater. The same Hole A and Hole B strategies used at MV-08A will be employed at MV-03C. MV-04C will be drilled last to sample the seawater endmember. MV-04C will only have one hole focussed on coring and logging. MV-04C could be shallowed significantly if no contribution of freshened water is determined by 400 mbsf. In the event that borehole conditions are problematic (1) logging will prioritize gamma radiation and formation conductivity and (2) the number of pump tests will be scaled back to accommodate one pump test at MV-08A and one at MV-03C. The installation of long-term borehole monitoring systems (SCIMPI) will be closely evaluated in the context of operational time and success of pump tests.

Core on Deck

As cores are recovered to deck, they will undergo initial labelling and sampling on a core bench, prior to delivery to the curation container. The operation will proceed using a changeover of inner core barrels to ensure continuity of the coring operation in as timely a fashion as possible. The deck operators will deploy an empty core barrel immediately after the previous one has been retrieved, then address the core removal and subsequent readying of that core barrel for re-use. As the cores will be collected in a plastic liner, the usual IODP curation procedures will be followed, and will be documented in the ESO Expedition 501 Core Curation, Initial Sampling and Analyses Handbook. After curation (and temperature equilibration), unsplit core sections and core catcher materials will be passed to the Science Team members for onboard description, physical properties measurements, analysis and sampling as described in “Science Operations” below.

Science Operations

A Sampling and Measurements Plan (SMP) for Expedition 501 has been prepared by ESO and the Co-Chief Scientists to meet the scientific objectives of IODP proposal 637-Full2 and Addenda 637-Add3, 637-Add7, and 637-Add82.

Offshore science activities

It is the nature of MSP expeditions that there is limited laboratory space and accommodation on the platforms compared to the larger research drilling vessels *JOIDES Resolution* and *Chikyu*, and as such there is no splitting of the cores at sea with only selected scientific analysis carried out onboard by a sub-set of the Science Team (in this case, c. 9 members). Science activities on the platform are confined to those essential for decision making at sea, core curation, measurement of ephemeral properties, securing of samples for pore water chemistry, and downhole logging. Cores will typically be cut into 1.5 m lengths for curation. Most of the scientific analyses are carried out during the Onshore Operations (OSP) in Bremen (Germany), when the cores are split.

The following is a summary of the offshore scientific activities (please refer to the Exp.501 Sampling and Measurement Plan and the online tutorial, to be made available following conclusion of Sample Allocation Committee (SAC) review):

- Basic curation, photography and labelling of core.
- All cores (>10 cm) will be measured on the multi-sensor core logger (MSCL; gamma density, *P*-wave velocity, electrical resistivity, magnetic susceptibility and natural gamma radiation).
- Core catcher ("CC") sampling, if available, for initial sedimentological, micropaleontological, petrophysical and/or structural characterization, including taking a CC image.
- Taking and storage of groundwater from various depths in drilled boreholes, on the assumption that the contractor and the Science Team are responsible for the equipment and sampling.
- Taking and proper storage of groundwater samples, again on the assumption that the contractor and the Science Team are responsible for the equipment and sampling, for gas analyses, and acquisition and splitting of groundwater samples.
- Groundwater geochemistry analysis and any other ephemeral properties agreed in the Sampling and Measurements Plan.
- Taking and proper storage of samples for gas analyses, and acquisition and splitting of pore-water samples.
- Pore-water geochemistry analysis and any other ephemeral properties agreed in the Sampling and Measurements Plan.
- Core storage.
- Downhole logging.
- Preliminary core-log-seismic integration using available downhole logging data and/or core physical properties data.
- Associated data management of all activities (see below).

In order to deliver the scientific requirements on the platform with a sub-set of the Expedition Science Team, a staffing plan has been devised. The plan requires flexibility of approach from all participants, with priority given to safety, core recovery, curation, and procedures for the measurement of ephemeral properties.

Report preparation will take place on board as required; the reports to be compiled include:

- Daily and weekly operational reports will be compiled by ESO and provided to the management and panels of ECORD and IODP[3], Science Team members and any other relevant parties. Scientific reports are provided by the Co-Chief Scientists. Summarised daily reports will be publicly available on the ESO website for any interested parties.

- Completion of the offshore sections of the Expedition Reports (primarily the ‘Methods’ chapter, but also recording of initial results from offshore observations, measurements, and analyses) will be undertaken by Offshore Science Team members and ESO staff.
- Press releases in line with ECORD outreach policy and Information for posting on the ESO expedition web site will be managed by the Communications Task Force.

Onshore science activities

The Onshore Operations (OO) will be held at the Bremen Core Repository (BCR) at the MARUM, Center for Marine Environmental Sciences, University of Bremen, Germany. The scientific work will follow the Sampling and Measurements Plan to be developed in conjunction with the Co-Chief Scientists. The majority of the scientific reporting for the Expedition is also undertaken during the Onshore Operations by Expedition Science Team members.

Details of the facilities that will be available for the Onshore Operations at the IODP Bremen Core Repository and MARUM laboratories can be found in the **Expedition 501 Sampling and Measurements Plan (SMP)** which will be made available following conclusion of the Sample Allocation Committee review. The Measurements Plan will take account of MSP specifications for QA/QC procedures. Additional facilities can be made available through continuing close co-operation with additional laboratories at the MARUM - Center for Marine Environmental Sciences, and the Department of Geosciences at the University of Bremen, all of which are situated nearby on campus.

The following briefly summarizes the Onshore Operations scientific activities:

- Prior to the Onshore Operations, thermal conductivity measurements will be taken on all cores (as appropriate) using a needle probe. Additional standard MSP physical properties measurements may be undertaken on whole cores at this time in the event offshore datasets are incomplete. This may be owing to time (natural gamma radiation) or permitting issues (gamma density). These measurements will be undertaken by ESO personnel;
- Core splitting - an archive half will be set aside as per Scientific Ocean Drilling programs procedure;
- Core description - ESO will provide a data-entry system that is standard to IODP[3] or Scientific Ocean Drilling programs. For data entry ESO will employ the Expedition mDIS (mobile Drilling Information System) that is entirely compatible with others being used in the Scientific Ocean Drilling programs. Please see Data Management below;
- High-resolution digital imaging, using a digital linescan camera system;
- Colour reflectance spectrophotometry, using a spectrophotometer;

- *P*-wave velocities measured on discrete samples, using an MSCL Discrete P-Wave system (MSCL-DPW);
- Moisture and density (MAD) on discrete samples, using a pycnometer;
- Core sampling for Expedition ("shipboard") samples (to produce MSP standard measurements data for the Expedition Report, e.g., petrophysical properties *P*-wave, moisture and density analyses);
- Smear slide preparation (undertaken by sedimentologists and/or micropaleontologists at regular intervals as required);
- Thin section preparation (as requested);
- Biostratigraphy;
- Inorganic geochemistry (whole-rock and pore fluid chemistry) and organic geochemistry;
- Bulk mineralogy – X-ray diffraction (XRD) analysis;
- Paleomagnetic measurements (as requested);
- Core sampling for personal post-expedition research - a detailed sampling plan will be devised after the scientists have submitted their revised sample requests following completion of the offshore Operations (please see 'Research planning: sampling and data sharing strategy' below). This will likely include whole round samples for experimental post-cruise analysis, taken prior to splitting of the cores. Sample allocation will be determined by the Sample Allocation Committee (SAC – see below for further details).

In view of the existing geographical distribution of all scientific ocean drilling programs (DSDP/ODP/IODPs) cores, it is understood that the Bremen Core Repository (BCR) will be the long-term location for the Expedition 501 cores.

Report preparation will take place during the OSP as required by ECORD. The reports to be compiled include:

- Weekly progress reports to ECORD and relevant parties. Scientific reports are provided by the Co-Chief Scientists.
- Expedition Summary compiled by the Expedition Science Team (submission to Copernicus publication at the end of the Onshore Operations).
- The Sites Reports compiled by the Expedition Science Team (submission to Copernicus publication services as soon as practically possible after the Onshore Operations).

For more information, please refer to **SMP link**, and also the online tutorial (to be made available following conclusion of the review by the SAC).

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Staffing

Scientific staffing is determined on the basis of task requirements and nominations from the **IODP Programme Member Offices**. ESO staffing is based on the need to carry out the drilling and scientific operations safely and efficiently (**Table 3**).

Table 3. Summary of Expedition Science Team and operator (ESO) personnel, Expedition 501.

ESO (21)	Expedition Science Team	
	Offshore Science Team	Expedition Scientists
2 ESO Expedition Project Managers (EPM) 1 ESO Operations Manager 1 Expedition Operations Manager 5 ESO Curators 2 ESO Geochemists 1 ESO Petrophysics Staff Scientist 4 ESO Petrophysicists 1 Logging Staff Scientist 2 ESO Data Managers 2 Logging Engineers	Offshore Science Team will be comprised of up to c.10 members of the Science Team at any one time, ensuring expertise onboard will meet expedition requirements.	Comprises the offshore and onshore science team members, Expedition Project Manager and Petrophysics Staff Scientist.
Offshore Team total (max. 26)		

Data Management

A data management plan for the expedition will be developed once the data requirements and operational logistics are finalised. The outline plan is that:

- The primary data capture and management system will be the **Expedition mobile Drilling Information System** (mDIS). mDIS is a database management application originally developed from collaboration with the International Continental Drilling Programme Operations Group (GeoForschungsZentrum Potsdam) with adaptions to ESO for capturing and curating metadata on geological cores and samples, drilling progress, and lithology on MSP Expeditions.
- The Expedition mDIS includes tools for data input, visualisation, report generation and data export.
- The database can be accessed directly by other interpretation or decision-making applications if required.
- A file server will be used for the storage of data not captured in the database (for example, documents and image files), and the inputs/outputs of any data processing, interpretation and visualization applications used during the expedition.
- On completion of the Offshore Operations of the expedition, the Expedition mDIS and the file system will be transferred to the BCR to continue data capture during the Onshore Operations.

- Between the end of the Offshore Operations and the start of the Onshore Operations the expedition scientists will have access to the data via a password-protected web site.
- On completion of the Onshore Operations, Expedition Scientists will continue to have access to all data through a password-protected web site throughout the moratorium period.
- During the moratorium, all metadata and data, apart from downhole logging data, will be transferred to PANGAEA data repository for long-term archiving.
- The Petrophysics Staff Scientist will manage the downhole logging data (including formation temperature measurements), MSCL data, and other physical properties data.
- Downhole logging data will be stored separately for processing and compositing and will be made available to the Science Team via the Log Database hosted by the Lamont-Doherty Earth Observatory. These data will be archived at the Lamont-Doherty Earth Observatory.
- After the moratorium, cores and samples will be archived at the BCR.
- After the moratorium, all the expedition data will be made accessible to the public.

Outreach

The IODP^{3} Communications Task Force (CTF) will be working to promote the Expedition and the science generated by this investigation into shelf hydrogeology. As guidance, the CTF have produced a communications plan that will be distributed to the Science Team prior to sailing. The main objectives are:

- To interact positively with the media, NGOs, Governments, and the general public to demonstrate the benefits of the IODP^{3}/NSF New England Shelf Hydrogeology scientific expedition, and IODP^{3} in general.
- To maximise the expedition’s publicity impact among scientists and the public.
- To ensure that all outreach is conducted in a consistent way.
- To promote scientific research in respect to the scientific goals.
- To successfully continue the media relationships which were established during the previous seven ECORD mission-specific platform and other IODP expeditions.

To facilitate the above, there will be a number of outreach activities being conducted throughout the Expedition.

Outreach activities before the start of the expedition:

- Develop a Communications Plan in close cooperation with Co-Chief Scientists, ECORD/ESO staff, especially the Expedition Project Manager(s).
- Produce and distribute an expedition flyer.
- Produce a media pack on the ESO website, including the expedition’s webpage and biographies of the Co-Chief Scientists and other members of the Science Team.

- Distribute a regional (New England) media release in parallel with the start-up media briefing.
- Organise ship visits for the media during mobilisation in New England, if possible.
- Prepare an outreach document for the Science Team, explaining their responsibilities.
- Produce a ‘Frequently asked questions’ document to distribute to the general public.
- Produce a guide to social media to distribute to the Science Team.
- Network with participants’ university media offices, particularly the Co-Chief Scientists’ host organisations.
- Produce an official expedition logo for use on all promotional materials.

Outreach activities during the Offshore Operations of the expedition:

- Maintain daily/weekly expedition logbook on ESO website (co-ordinated by ESO Outreach Manager).
- Publish media releases (in the case of special events / findings and, if appropriate, at the end of the expedition).
- Organise video coverage of the working processes on board the expedition vessel (B-roll footage), to be collected by ESO staff and Science Team members, when time allows.
- Promote the expedition through national and international media and organise interviews with Co-Chief Scientists and other Science Team members as necessary / requested.
- Promote social media blogs compiled by Science Team and ESO members.

Outreach activities during the Onshore Operations (date to be confirmed):

- Prepare background material to provide to the media.
- Hold a media day towards the end of the OSP.
- Publish an international media release (tentative results).
- Document activities with photos and video footage.

Outreach activities after the expedition

- Promotion at international conferences (booths, talks) for example at EGU and AGU / JpGU-AGU Meetings.
- General outreach to the media as scientific results of the expedition become available.
- Continued logging of any outreach activities undertaken by any of the Science Team members including interviews, blogs and abstracts submitted. ESO outreach team will depend on science party members to alert us to anything they do in addition monitoring international (mostly online) media.

Research Planning: Sampling and Data Sharing Strategy

All researchers requesting samples should refer to the Scientific Ocean Drilling programmes **Sample, Data and Obligations Policy**. This outlines the policy for distributing Scientific Ocean Drilling programmes samples and data to research scientists, curators, and educators. It also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of Co-Chief Scientists, Expedition Project Manager, and Scientific Ocean Drilling programmes Curator for Europe (BCR and MSPs) or offshore curatorial representative) will work with the entire Science Team to formulate an expedition-specific sampling plan for "shipboard" (expedition: offshore and OSP) and postcruise (personal post-expedition research) sampling.

Members of the Science Team are expected to carry out scientific research for the expedition and publish it. Before the expedition, all members of the Science Team are required to submit research plans and associated sample/data requests via the Sample, Data and Research Request Manager (SDRM) system **here** before the deadline specified in their invitation letters. Based on sample requests submitted by this deadline, the SAC will prepare a tentative sampling plan, which can be revised on the ship and once cores are split as dictated by recovery and cruise objectives. All post-cruise research projects should provide scientific justification for desired sample size, numbers, and frequency. The sampling plan will be subject to modification depending upon the material recovered and collaborations that may evolve between scientists during the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved. Modifications to the sampling plan and access to samples and data during the expedition and the 1-year post-expedition moratorium period require the approval of the SAC.

Offshore sampling will be restricted to that necessary for acquiring ephemeral data types which are critical to the overall objectives of the expedition and to preliminary lithological and biostratigraphic sampling to aid decision making at sea and planning for the OSP.

The permanent archive halves are officially designated by the Scientific Ocean Drilling programmes curator for BCR and MSPs. All sample frequencies and volumes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the expedition objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

If critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. A sampling plan coordinated by the SAC will be required before critical intervals are sampled.

The SAC strongly encourages, and may require, collaboration and/or sharing among the shipboard and shore-based scientists so that the best use is made of the recovered core. Coordination of post-cruise analytical programmes is anticipated to ensure that the full range of geochemical, isotopic, and physical property studies are undertaken on a representative sample suite. The majority of sampling will take place at the Onshore Operations in Bremen, and the SAC encourages scientists to start developing collaborations before and during the Expedition.

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