Onshore-Offshore Drilling and Sampling to Understand Freshwater Resources along the New England Continental Shelf: An IODP-ICDP Workshop

May 22-23, 2017

Woods Hole, MA, USA

Steering Committee

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Executive Summary

This IODP(USSSP)-ICDP sponsored drilling workshop (22-23 May 2017) was convened with the overall objectives to develop a new operational plan for IODP Proposal 637 that addresses fiscal constraints identified by the ECORD Facilities Board and to establish the value of an onshore component of the project. The workshop included input and participation from 32 researchers from academia, government, industry, IODP (ESO), and ICDP (CDSCO).

The following are the key outcomes of the workshop:

1) Three offshore sites (MV-8A, MV-4C, and MV-3C or MV-5B), with one site per hole for coring, wireline logging, and sampling, can meet all of the science objectives of IODP Proposal 637. A three-site program with one site per hole should align with the fiscal constraints of a mid-cost project.
2) Dating of waters and geochemical analyses can mostly be completed by standard IODP porewater sampling. Pump tests are desired to collect sufficient hydrogeological information (hydraulic conductivity, storativity) and large enough water volumes for krypton age dating.
3) A separate proposal will be submitted to ICDP to collect onshore data that define stand-alone science but are also complementary to the objectives of IODP Proposal 637.

Follow up activities from the workshop include providing an addendum to the IODP for Proposal 637 (submitted Fall 2017), writing a new proposal to ICDP for onshore drilling to complement the IODP drilling (to be submitted January 2018), and to develop strategies for community engagement and outreach (ongoing).

Introduction and Background

Freshwater resources, particularly groundwater, are declining due to over-exploitation and climate change [Barlow, 2003; Aeschbach-Hertig and Gleeson, 2012]. Stresses on groundwater systems are increasing due to population growth and associated urbanization [Richey et al., 2015]. Coastal aquifer systems are especially vulnerable because of sea-level rise and over-pumping influences the position of the freshwater-salt water interface [Ferguson and Gleeson, 2012; Post et al., 2013]. However, there is growing evidence that passive margin sediments host large volumes of paleo-freshwater (up to 10^5 km^3 globally and 1300 km^3 offshore New England [Cohen et al., 2010]) that were emplaced during the past 2 million years [Edmunds, 2001]. Groundwater studies of North America and Europe show that large volumes of fresh paleo-groundwater were emplaced during Pleistocene glaciations and are not in hydrologic/geochemical equilibrium with current meteoric recharge [Person et al., 2003, 2007, 2012; Lemieux et al., 2008; Jiráková et al., 2011; McIntosh et al., 2012; Neuzil, 2012; Post et al., 2013]. Continental sedimentary basins and passive margins were influenced by the Laurentide ice sheet and aquifer-ice sheet coupling may explain emplacement 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 carbon-14 and noble gas ages [Morrisey et al., 2010; Darling, 2011; Klump et al. 2008; Schlegel et al., 2011] and oxygen isotope data [Rozanski, 1985; Vaikmae et al., 2001; Darling, 2004; Négrel and Petelet-Giraud, 2011; McIntosh et al., 2012; van Geldern et al., 2014]. These observations motivated numerous modeling 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]. In addition, recent IODP drilling offshore New Jersey (IODP Expedition 313 [Mountain et al., 2010]) has revealed non-equilibrium conditions, but documents significant impact from modern meteoric recharge [van Geldern et al., 2013].

To further understand the dynamics of these onshore-offshore hydrologic systems, we propose to focus on the coupling between glacial dynamics, sea-level variations, and groundwater flow for the US Atlantic continental shelf offshore Martha's Vineyard, MA (Figure 1). The shelf experienced glaciations in the late Pleistocene in combination with sea-level change throughout the entire 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 that reaches depths of several hundred meters below the sea floor (mbsf) (Figure 2) [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]. Additionally, Nantucket Island, offshore MA, USA, has freshwater deeper than 500 meters below sea level (mbsl), which is out of equilibrium with modern sea level [Kohout et al., 1977; Folger et al., 1978; Marksamer et al., 2007]; however, the origin, the extent, and the emplacement mechanisms of this freshwater offshore Massachusetts, USA, are not fully understood.

Several 2D and 3D numerical modeling studies have predicted freshwater distributions for the continental shelf offshore New England. These models incorporated sea-level change and ice sheets as boundary conditions in an effort to explain salinity patterns observed below Nantucket Island, and to predict the volume and distribution of offshore freshwater [Person et al., 2003; Marksamer et al., 2007; Cohen et al., 2010; Siegel et al. 2014]. These models demonstrate the range of freshwater distributions and their sensitivity to sea-level variations and glacial loading as well as to permeability architecture. IODP Proposal 637 was designed to sample these freshwaters, to determine their extent, and to characterize hydrologic properties of the sediments. This would allow us to improve our model constraints and to evaluate the origins of these freshwaters.

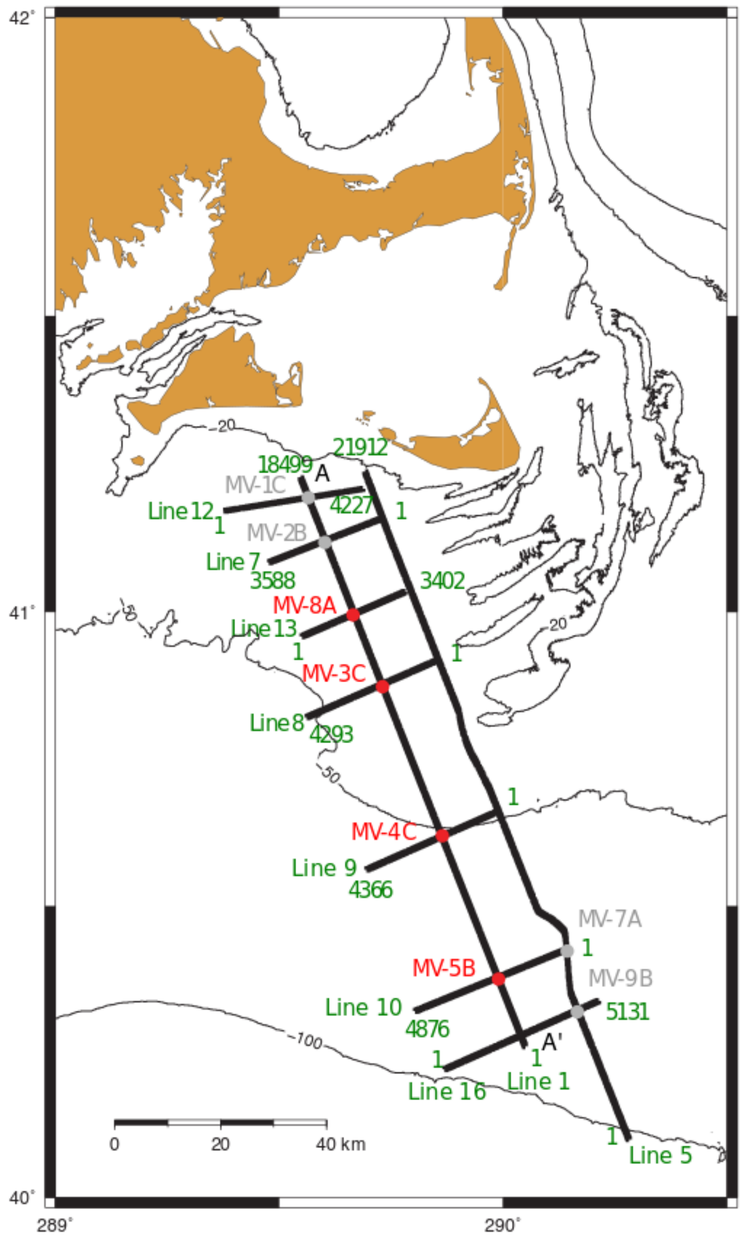

Figure 1. Basemap of IODP 637 study region including proposed sites (primary sites = solid red circles and red numbers; alternate sites = solid grey circles and grey numbers) high-resolution MCS data (black lines, green line numbers), and CDPs (green numbers).

Additionally most studies of chemical fluxes to coastal regions have focused on modern, shallow, nearshore processes. Salinity data from New England and elsewhere in the world suggest that large-scale flushing of continental shelf sediments during the Pleistocene may have been associated with significant episodic fluxes of nutrients (e.g., nitrogen [N], phosphorous [P]) and greenhouse gases (notably methane) to the oceans, biosphere, and atmosphere. Thus the continental shelf environment may be important for global biogeochemical cycles. Currently, knowledge of the time-dependent nature and primary driving forces of these fluxes is lacking. Of importance are the rates of regeneration of the products of organic matter decomposition after flushing. Also, modern continental shelf environments frequently contain substantial amounts of methane and other products of organic matter decomposition such as bicarbonate, ammonium and phosphate. Discharge of high N groundwater may drive N-limited coastal ecosystems towards P-limitation. Virtual absence of methane in the upper 400 m of the New Jersey shelf (ODP Sites 1071, 1072; AMCOR sites 6009, 6010, 6011, 6020) suggests low methane production rates; yet ^{13}C isotopes of authigenic siderites and calcites indicate that methanogenesis did occur in the past. Apparently, complex biogeochemical processes affect production rates and should be unraveled to evaluate the role of fluid fluxes in continental shelves in biogeochemical cycles. Understanding the timing and rates of flushing as well as the source of fluids are critical to developing biogeochemical models that depend on the distribution and concentration of pore fluid nutrients.

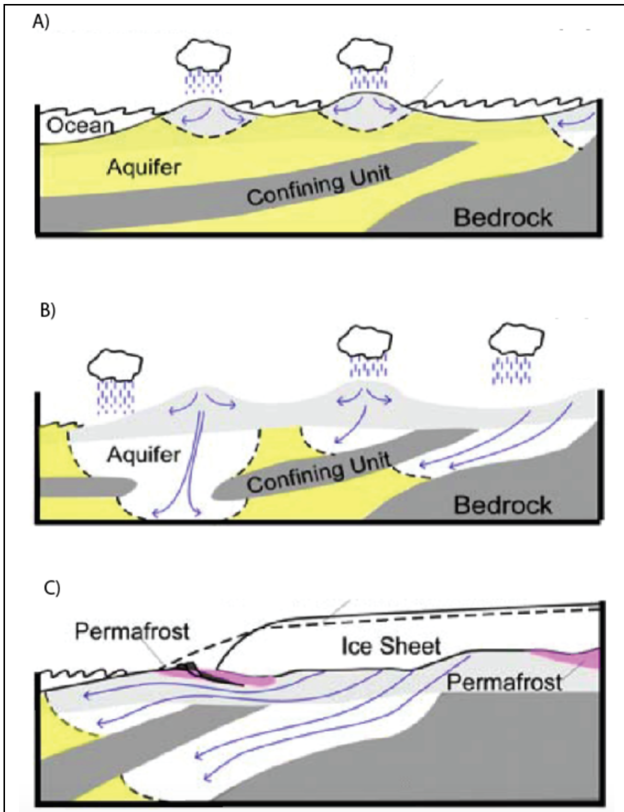

Figure 2. Conceptual models of freshwater emplacement. Freshwater-saturated sediments are light gray and white; saltwater-saturated sediments are yellow. The freshwater-saltwater interface is marked with a dashed blacked line. A) Meteoric recharge under current sea-level conditions produces a small lens of freshwater under islands. B) Meteoric recharge to exposed aquifers and increased gradient during sea-level lowstand 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; Siegel et al., 2014].

Globally, offshore fresh groundwater occurs also at many other locations below the continental shelves [Post et al., 2013]. These aquifers are prospective water reserves for densely populated, near-shore regions. Understanding the processes during emplacement of the fresh water lens offshore New England, as proposed by IODP Proposal 637, will also lead to a better fundamental understanding of this hydrogeological phenomena worldwide and its impact on biogeochemical cycling. This is essential for protection and for a sustainable management of these valuable resources in the near future and for better understanding biogeochemical cycling in shelf environments.

History of IODP Proposal 637: New England Shelf Hydrogeology

IODP Proposal 637 (https://docs.iodp.org/Proposal_Cover_Sheets/637-Full2_Person_cover.pdf) was originally submitted in 2004 with the objectives to understand the origin and volumes of freshwater beneath the New England continental shelf by addressing the following questions:

1) What is the distribution of freshwater, fluid pressures, and temperatures across the Atlantic continental shelf in New England?
2) How old is the groundwater and when was it emplaced?
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 distribution and can this distribution and the age patterns be unraveled through hydrogeological process models?
4) Do fluid pressures reflect the current fluid density distribution and modern sea level or are overpressuring mechanisms (e.g., rapid sediment loading) involved?
5) What are the current concentrations and production rates of methane and nutrients in shelf sediments? What controls them?
6) What are the rates of decomposition of sedimentary organic matter and which redox processes/microbial communities are involved? Which factors determine the spatial distribution and activity of microbial communities in the shelf?
7) What are the magnitudes of the long-term fluxes of methane and nutrients from the shelf due to periodic flushing during the Pleistocene?
8) Does the emplacement of ice sheet meltwaters in confined aquifers create a unique environment for methane?

The initial proposal was well received and highly ranked within IODP. Additional data collection and proposal revisions and addenda helped develop a solid scientific drilling proposal that advanced to the ECORD Facilities Board (EFB). Within the EFB, the proposal has been in the holding bin because of the very high cost associated with the operational plan.

Since the original submission of Proposal 637, multiple new discoveries and assessments of offshore freshwater have been made including offshore New Jersey (IODP Exp. 313 [Mountain et al., 2010]), offshore New Zealand (Exp. 317 [Fulthorpe et al., 2011]), offshore Alaska (Exp. 341 [Jaeger et al., 2014]), and offshore electromagnetic surveys (see Workshop Presentations section). In addition to these studies, there are increasing water demands globally and thus a need to understand the emplacement mechanisms and volumes of offshore freshwater as a primary step to addressing how these resources could be produced and used. Therefore Proposal 637 is gaining global momentum to target offshore freshwater resources with a process-based approach that will improve our understanding of this global resource. Unlike previous drilling projects that sampled freshwater as a result of other science objectives, Proposal 637 is specifically designed to constrain the onshore-offshore hydrogeologic system.

Workshop Goals and Objectives

The overall objective of the workshop was to develop a new operational plan for IODP Proposal 637 that meets fiscal constraints noted by the ECORD Facilities Board and to establish the value of an onshore component of the project. The approach to accomplish this was to address the following workshop goals.

1) Develop ideal sampling and measurement plan for hydrogeology, geology, geophysics, geochemistry, and microbiology across the shoreline and the shelf;
2) Define onshore operations/experiments that improve assessment of the science questions and to increase the overall science of the project;
3) Prioritize order of operations including site order and site depths; and
4) Formulate specific plans for pursuing non-IODP funds, including a full proposal to ICDP, and to expand education and outreach activities for the project.

To achieve the workshop goals, the workshop included input and participation from 32 researchers from academia, government, industry, IODP (ESO), and ICDP (CDSCO) (Appendix I and Appendix II).

Workshop Presentations

A central aspect to the workshop was science presentations that motivate freshwater resource studies on continental margins, that summarize existing observations and data for freshwater at locations around the world with an emphasis on the New England continental shelf, and that outline opportunities to expand and to achieve the science goals with onshore and offshore drilling. Below we summarize the presentations; most presentations are archived as PDF documents on the project websites through the ICDP (http://cape-cod.icdp-online.org/) and through the USSSP (http://usoceandiscovery.org/workshop-ne-freshwater-resources/).

Alicia Wilson (University of South Carolina) presented "Submarine Groundwater Discharge and Continental Shelves" which provided a context for the scales of onshore-offshore flow systems and submarine groundwater discharge. Wilson noted that previous oceanic studies of ^{228}Ra suggests a significant contribution of submarine groundwater discharge (SGD) into the ocean, and that SGD likely exceeds river discharge. With the potential size of this flux, it is surprising that so few studies have directly addressed this active hydrogeological system. Wilson emphasized that heat can be used as a tracer to better constrain the magnitude of SGD and that it varies at seasonal time scales. Wilson concluded with the indication that many driving forces can operate on SGD systems and more systematic onshore-offshore studies including drilling, sampling, monitoring, and modeling are required to improve our understanding of SGD.

Mark Person (New Mexico Tech) gave a history of New England continental shelf hydrogeology in a presentation entitled "Insights into Continental Shelf Hydrologic Systems in New England using Mathematical Models." This talk introduced the potential driving mechanisms for freshwater on New England's continental shelf including meteoric recharge during sea-level lowstands, recharge beneath ice sheets, and infiltration beneath glacial lakes. Person linked these mechanisms to the glacial history of the region, and then discussed the state of numerical modeling for constraining fluid flow dynamics. These models include variable-density groundwater flow, diffusion, ice sheet loading, sediment loading, and lithospheric flexure. Salinity and hydraulic head model results were presented in context of existing onshore wells and far-offset AMCOR wells. Existing models include 2D dip transects as well as regional 3D models from New Jersey to Maine. These models provide testable predictions on salinity and pressure that could be tested with drilling and sampling. Models could be adapted to look at groundwater age for additional testing with drilling and sampling. The tests of these models could help us better understand the dynamics of this system and to better understand the limitations of the models and what data are essential to improving the predictive capability of onshore-offshore hydrologic models.

Robert van Geldern (Friedrich-Alexander-Universität Erlangen-Nürnberg) presented "Stable isotope geochemistry of pore waters from the New Jersey shelf: fluid origin" to demonstrate the value of focused pore fluid geochemical analyses for understanding the source of offshore freshwater. van Geldern first introduced the analytical techniques used for stable isotope analyses and how these approaches can be used to differentiate between modern water and paleowater. This was demonstrated for an onshore study in Germany and then for an offshore study from New Jersey (IODP Exp. 313). Results from Exp. 313 showed a more complex geometry of the offshore freshwater lens than was inferred from AMCOR drilling and modeling studies. Their stable isotope and pore water geochemical results indicate three water sources: meteoric freshwater, marine seawater, and deep-sourced brines. This suggests that freshwater is from a modern source and not from Pleistocene glacial meltwater. Another intriguing aspect to these results was the integration with sediments showing that freshwater exists in the confining units and saltwater exists in the permeable, sand units. van Geldern concluded that these new results drive a need for re-evaluating the groundwater models and additional data collection to validate model parameters.

Todd Jarvis (Oregon State University) gave a presentation entitled "Proposed Center for Ocean-Aquifer Studies (COASt): Marine Studies Initiative at OSU." Jarvis emphasized that offshore freshwater is a global phenomenon, however the west coast of the United States is missing from current and proposed studies. He emphasized that we need to expand our thoughts on funding models and need to augment our approach from science-based analyses to use-inspired studies. The proposed study is looking at Stonewall Bank within five miles of Oregon Coast through a multi-disciplinary, multi-user approach. He noted that we should aim for new approaches to funding large-scale (order $100M) studies of this vital research by working with high levels of government, private companies, and private foundations. To do this we need to expand our communication to scientists, society, businesses, and politicians.

Aaron Micallef (University of Malta) introduced us to another offshore groundwater project entitled "MARCAN – A 5 yr research project investigating groundwater and its role in landscape evolution." The MARCAN project was motivated by the fact that scientists have long been studying the interaction of groundwater in shaping terrestrial landscape, but little-to-no in-depth analysis has been done on how groundwater shapes submarine environments. Specific questions to address include what are the rates of groundwater weathering and erosion? what are the resulting morphologies? how can we use morphologies to infer process? how do the dynamics and spatial patterns of offshore groundwater influence submarine morphology? and what are they linkages between offshore groundwater and glacial-interglacial cycles? MARCAN sets out to define the groundwater dynamics and their importance in submarine geomorphology through field and modeling studies. Field studies will be offshore New Zealand where IODP Expedition 317 observed offshore freshwater in a siliciclastic environment and offshore Malta in a carbonate environment. Micallef then summarized the recent and extensive marine survey offshore New Zealand where they collected seven controlled-source electromagnetic data (BGR HYDRA system), multi-channel seismic data (300-m streamer, 24 channels), and TOPAZ data (2-6 kHz). In addition to the geophysical surveys CTD casts, piston/gravity coring, and seafloor photography were done. Data are currently being processed and integrated to better understand this system.

Brandon Dugan (Colorado School of Mines) gave a historical summary of IODP Proposal 637 in a talk entitled "A Shallow Drilling Campaign to Assess the Pleistocene Hydrology, Geomicrobiology, Nutrient Fluxes, and Freshwater Resources of the Atlantic Continental Shelf". This presentation laid out the origin of Proposal 637 from the early AMCOR work that documented offshore freshwater along the US Atlantic Margin, modeling studies that looked at different modes of freshwater emplacement (modern meteoric recharge, meteoric recharge during sea level lowstands, and glacially emplaced freshwater). The talk documented the modeling improvements that benefited from high resolution seismic surveys that redefined the stratigraphy and the extent of glaciation, both of which affect the timing and amount of emplaced freshwater. Continued model refinements have allowed re-assessment of proposed sites, ultimately suggesting fewer sites can accomplish the science goals. The final modeling work will be to take advantage of the high resolution seismic data and the recently collected electromagnetic data to make quantitative predictions that can be tested by drilling of three offshore sites. The talk also noted that onshore wells will capture modern meteoric recharge and potentially paleo freshwater at depth thus an onshore component can help define the age of the flow system and its dynamics but also constrain how well the onshore and offshore systems are linked.

Dugan then provided an overview of the existing site survey data for Proposal 637. He first introduced the low-resolution data up which the original proposal was based. Then he presented a site-by-site summary of the high-resolution seismic data across each proposed primary drill site to show the drilling targets and to summarize the geological evolution. He noted that all sites shown and multiple alternates where already approved by EPSP, but noted alternate drill sites could be pursued based on discussion about science objectives for each site. In this line of discussion there was a note that the goals of the offshore transect are to capture one freshwater endmember, the transition zone between freshwater and seawater, and one seawater endmember.

Kerry Key (Lamont-Doherty Earth Observatory) presented a summary of an NSF-funded controlled-source electromagnetic (CSEM) and magnetotelluric (MT) survey that they completed offshore New Jersey and offshore Martha's Vineyard. Key first introduced the CSEM and MT technology and then the surveys. The survey offshore New Jersey covered the sites drilled by Exp. 313 to test the techniques in a zone where offshore freshwater had been directly sampled and where core and log data exist. The survey offshore Martha's Vineyard was done along the transect of sites proposed in Proposal 637 to help identify freshwater distribution with depth and laterally which will be used to help finalize drilling sites and operations for the Martha's Vineyard drilling transect. The data show resistivity structures indicative of freshwater offshore New Jersey and offshore Martha's Vineyard that can be correlated with stratigraphic architecture. Conclusions are that these methods are very effective for mapping out freshwater zones and for locating drilling locations and depths for the drilling offshore Martha's Vineyard.

Carole Johnson (US Geological Survey) presented "Combined use of transient electromagnetics, passive seismic, and nuclear magnetic resonance methods to characterize an unconsolidated aquifer on Cape Cod, Massachusetts." This provided a summary of the USGS work that has been completed onshore to engage discussions of linking onshore and offshore hydrology and for assessing how onshore techniques might be employed offshore. The motivation for the USGS work was to demonstrate the effectiveness of integrating geophysical surveys for hydrogeologic investigations. Survey types include horizontal to vertical spectral ratio, transient electromagnetic methods, gamma and electromagnetic induction logging, and nuclear magnetic resonance logging. Johnson introduced the basic mechanics of each survey type and showed example data for imaging basement structure, subsurface resistivity, and well characterization and interpretation. One exciting notion was how NMR data can be used to interpret porosity and hydraulic conductivity thus providing essential information for hydrogeologic flow studies. The hydraulic conductivity was shown from the NMR tool and how it compared with model results, with an overall good match. The conclusion was that combined geophysical techniques are valuable for understanding hydrogeologic systems including stratigraphic and basement architecture and aquifer properties.

Laura Brothers (US Geological Survey) presented an overview presentation on "USGS Coastal and Marine Work: Martha's Vineyard and Southern New England." This talk provided great insights to the existing regional data collected by the USGS, ongoing surveys by the USGS, and products the USGS produces in near-shore environments. Brothers started with the goals of the USGS Coastal and Marine Geology program including proving reliable, impartial scientific information, understanding coastal and submerged lands, and understanding the geologic processes that create, modify, and maintain this coastal and submerged lands. The USGS has coastal activities around North America, but in their offshore Massachusetts work was emphasized. In collaboration with the Massachusetts Office of Coastal Zone Management, they are defining the geological framework of the coastal zone (<3 nautical miles) of Massachusetts. This work includes mapping the seafloor with chirp seismic, swath bathymetry, backscatter, and grab samples. The work informs decisions on offshore development and on habitat monitoring. Brothers noted the numerous products available from this project and that they are all accessible online, and pointed out key data sets for south of Martha's Vineyard. Brothers then introduced a project to characterize the Southern New England Mud Patch and how it relates to studies on post-last glacial maximum sea-level studies and submarine slope stability studies. Stepping back to a larger perspective, Brothers introduced the CO2 sequestration project that is ongoing with re-analysis of seismic data collected along the US East Coast from 1975-1995. The next topic introduced was seep analyses work where the survey is using water column and subsurface data to image seeps in the water column and linking them to subsurface plumbing systems. Brothers than moved to onshore studies by the USGS where glacial geology is being characterized and onshore and offshore glacial data are being integrated for Massachusetts. The USGS work related to wind energy was summarized including the use of high-resolution geophysical surveys and how similar surveys could be used to characterize drill sites and to interpret near-surface geology and geologic processes. Multiple data products were presented showing the fidelity of the data, its spatial extent, and how it is used to infer geologic processes. In summary, there are numerous data sets that will help link the onshore and offshore systems, but there is room for drilling and sampling to improve control on age constraints and age-unit thicknesses. Brothers concluded with details on the in-house equipment that the USGS has available for coastal mapping.

Mark Person (New Mexico Tech) presented "Drilling History on the Cape & Islands" as an example of what can be done to address the local hydrogeological system and its dynamics. Person motivated the regional hydrogeology with examples of glacial extent and deformation along the Cape and Islands and with observations of offshore freshwater found through AMCOR drilling in the 1970s. Person emphasized that this science can and should be accomplished in cooperation with local water companies that have interest in fully understanding the local freshwater system especially in times of increasing demand. Wannacomet Water Company (Nantucket Island) has contributed to studies of the Nantucket in consultation with Person's group. Rotasonic drilling, petrophysical studies, isotope studies, and modeling work that resulted from this collaboration documented complex geology and distribution of confining units along Nantucket have created a complicated distribution of freshwater beneath the island with freshwater that ranges in age from Holocene to late Pleistocene. Person concluded from this onshore work that if the aquifer-aquiclude system of Nantucket is representative of the region, water from the offshore environment can be produced for decades, and offshore drilling is required to validate this assessment.

Jennifer McIntosh (University of Arizona) introduced opportunities to use tracers to understand mechanisms of meteoric recharge into saline aquifers and to characterize microbial processes in organic-rich sediments. McIntosh first introduced terrestrial studies of glacier-groundwater interactions including disequilibrium salinity conditions. She then introduced approaches and challenges to dating these groundwaters using carbon, helium, hydrogen, and krypton. Within this context she noted the linkages between dating the waters and defining the recharge mechanisms. McIntosh then discussed how carbon isotope work can be used to look at early onset of methanogenesis and AOM. The talk concluded with a summary of additional measurements that could be used to better understand methanogenesis, metabolic pathways, and microbial processes. One key takeaway message was that multi-tracer approaches are the best avenue to understand groundwater dynamics and microbial processes.

Ken Miller (Rutgers University) provided an overview of MSP research along the continental shelf in a presentation entitled "Lessons from the NJ/MAT Sea-level Transect." Miller started by emphasizing these projects can take a lot of time and a lot of perseverance by the proponent team, but upon success high-quality science is attainable. The talk started with the motivation to test stratigraphic models and to better understand sea-level change and the long-standing history of this project which started in 1987. The project advanced with seismic data collection on onshore/offshore drilling as part of ODP Leg 150/150X. Safe drilling practices however, delayed this drilling including evaluation by the safety panel, risk of shallow biogenic gas, reaction policies and rates for pressure kicks, and difficult lithologies for drilling. All of these issues had to be fully addressed, and in some instances repeatedly, to move forward with NJ drilling. Eventually Leg 150/150X was drilled (1993/1994) to produce a great record of icehouse sequence boundaries. From this, the idea for Leg 174A was developed based on collection of new, high-res seismic. Leg 174A had drilling and recovery problems in shallow water, but did collect sequence timing information on a slope site. To improve shelf recovery, and MSP project was developed and ranked very highly. After numerous setbacks, IODP Exp. 313 was scheduled and drilled. A jackup was used to improve control of the drillstring, and this, with casing, improved recovery and ability to collect logging data. This resulted in nice ties of seismic to cores to logs and added significant new information to sequence evolution and extended our knowledge of sea-level change as recorded in seismic and sediments. Miller provided numerous examples of the quality of data that can be acquired in this environment with the right platform, and then how these data can be integrated.

Dave Smith (IODP ESO) provided a general overview on how an MSP moves forward after scheduling. He did this by presenting the summary of planning for IODP Expedition 381: Corinth Active Rift Development. ESO starts by deciding what equipment will be needed and the requests bids for vessels. In most cases, they start with a standard vessel and outfit it for drilling and sampling. In the case of Exp. 381, they secured a Fugro vessel that was more than capable and ready for drilling. This fortunate event is the result of industry downturn. Smith than summarized that offshore a minimal science party is used to make only the minimum measurements at sea which generally are limited to ephemeral (geochemistry, microbiology) and hazard measurements. Core splitting and full analyses are done at a post-expedition sampling party at the Bremen Core Repository. Smith did mention that in the case of Proposal 637 where specialized downhole fluid sampling is proposed, the science party could be changed during operations to ensure expertise for ephemeral and hazard sampling and expertise for fluid/hydrogeologic sampling. The details of this, however, need to be formalized during planning. Smith also discussed vessel sizing as controlled by water depth, sampling needs, and wireline vs LWD logging. This helped inform discussions related to operations for Proposal 637.

Renee Martin-Nagle (University of Strathclyde) provided another important perspective for consideration "Offshore freshwater: Governing a new resource." Martin-Nagle noted that as we are addressing the science of freshwater resources, we should also investigate how this resource may be governed. Water use and water stresses are increasing and models predict they will continue, indicating that offshore freshwater will be a critical component in the future, however, no approaches to governance exist. Martin-Nagle has started investigating three possible ways in which the resource may be governed: (1) UN convention on the Law of the Sea; (2) customary laws for land-based freshwater; and (3) customary practices of offshore oil and gas. She reviewed each of these models, and then concluded with questions for future investigation including should offshore resources be governed globally, regionally, or individually? will states limit sovereignty over trans-boundary aquifers for humanitarian or economic reasons? and should aquifers with land-linkages be treated differently than isolated offshore aquifers? In summary, these questions will need to be addressed as we start to utilize these offshore resources.

Science and Technology Needs

Central to the workshop presentations were numerous discussions about the science and technology needs for the project. Plenary and small-group discussions were continuous throughout the meetings and breaks, and here we distill the discussion to four questions that dominated and were crucial to moving this project forward. The questions were:

1) Is logging while drilling needed?
2) What is necessary to date the waters?
3) Which sites and to which depths provide the highest confidence of addressing the science questions?
4) What do onshore data provide?

Is logging while drilling needed?

The original proposal requested the use of logging-while-drilling (LWD) to obtain the highest quality petrophysical data in shelf sediments as traditional wireline logging has problematic in shelf sediments, such as documented on ODP Leg 174A [Austin et al., 1998]. Of particular importance is getting high quality density, porosity, and resistivity logs for assessing transport properties and for ground-truthing the electromagnetic and magnetotelluric surveys. Logging data will also be integrated with well test data and standard IODP core and porewater analyses. While LWD data would provide high quality downhole data, the costs of LWD tools are high. IODP Exp. 313 [Mountain et al., 2010], however, demonstrated that a drilling-coring-wireline logging-casing plan provides useful logging data and maintains the integrity of the hole for deeper drilling, sampling, and logging. In discussions on the necessary data, the workshop team determined that standard core measurements of moisture and density and porewater analyses for water chemistry coupled with wireline logging for resistivity and density provide more than sufficient information to ground-truth the electromagnetic and magnetotelluric data as the core and porewater data will provide regular and precise porosity and chemistry data that can be enhanced by wireline logs. The porosity and chemistry data also provide essential constraints for numerical models that will be augmented by wireline logging data. Thus the team concluded that standard coring, sampling, and wireline logging will provide the required data.

In association with the logging discussion, the workshop team also addressed the need for downhole hydrologic testing (pump tests). The overall consensus was that pump tests are important for constraining the hydrologic properties, especially in the sand-rich intervals as where core recovery is expected to be low which precludes shore-based hydrogeological testing on cores. Discussion of the pump tests also related to feasibility and integration with the casing plan. More detailed scoping on casing and screen is needed, but the overall consensus is that a casing-screening plan can be designed to keep all operations in a single hole at each site.

What is necessary to date the waters?

One important aspect to testing the origin of offshore freshwater is obtaining age data on the water. At the simplest level, these data provide temporal constraints on the origin of the freshwater which can be used to refine groundwater flow models, to test emplacement mechanisms, to evaluate flow pathways, and to predict the modern dynamics of the flow system. The first issue addressed was which waters to date. It was concluded that we should date the freshwater and the seawater endmembers as well as the mixed waters to help understand the age of the freshwater and the seawater and to help understand the mixing of the waters.

The primary approaches for age dating discussed were krypton (^{81}Kr), helium (^{4}He), carbon (^{14}C), tritium (^{3}H), oxygen ($\delta^{18}O$), and a full suite of noble gases from the porewater samples from traditional IODP porewater samples (core squeezing of intact intervals with good recovery – most likely confining units) and from pumping tests (intervals of poor recovery – most likely aquifer units). In addition, strontium ($^{87}Sr/^{86}Sr$) analyses are desired as they can provide constraints on the origin of the freshwater and on flow pathways. To get the best constrains on water ages, multiple age-dating approaches should be employed. Most of the dating techniques can be done with porewater samples from core squeezing, allowing us to bracket the age and origin of fluids in the confining units where core recovery should be good. The exception to this is krypton work which requires larger water volumes, which will have to be collected from pumping tests. Pumping tests, however, also provide fluids from intervals of poor recovery facilitating analyses of all the isotopes and of the formation hydrologic properties. Thus a combined approach of core squeezing and pumping tests in a single hole allows collection of all the data needed for age and origin assessment. It also provides enough fluids for rare earth elemental (REE) analyses allowing improved constraints on global geochemical cycles and on the contribution of REEs to the ocean via submarine groundwater discharge (SGD). This in turn allows a better understanding of SGD volumes, which are not well constrained.

Which sites and to what depths?

A significant component to IODP Proposal 637 is drilling and sampling the freshwater endmember, the seawater endmember, and the transition between the end members. The original plan was to drill six sites, each consisting of three holes, to ensure we captured the spectrum of conditions and were able to collect samples for hydrogeology, sedimentology, and biogeochemistry. The number of days required for this was cost prohibitive so a primary objective of the workshop was to re-evaluate the science questions in conjunction with refined numerical models and electromagnetic and magnetotelluric data to assess the minimum number of sites and holes required to meet the science objectives.

The numerical modeling data suggested that three sites could accomplish the drilling objectives, and the electromagnetic and magnetotelluric data helped guide a revised operational strategy for drilling three sites (and one hole at each site) to meet the science objectives. The new proposed drilling strategy is to first drill MV-8A to 550 mbsf (Figures 1,3) to sample the freshwater endmember which is predicted to be bounded on top and bottom by seawater. MV-8A has been approved by EPSP to 350 mbsf, so the depth extension needs to be evaluated by the EPSP. The second site to be drilled will be MV-4C to 550 mbsf (Figures 1,3) which could be the seawater endmember based on numerical modeling results or the freshwater-seawater transition based on electromagnetic and magnetotelluric data. MV-4C has been approved by EPSP to a depth of 650 mbsf. If MV-4C is the seawater endmember, the third site to be drilled would be MV-3C to 550 mbsf (Figures 1,3) to sample the freshwater-seawater transition. MV-3C has been approved to 550 mbsf by the EPSP. If MV-4C samples the freshwater-seawater transition, the third site to be drilled would be MV-5B to 550 mbsf (Figures 1,3) to sample the seawater endmember, as predicted by models and the electromagnetic and magnetotelluric data. MV-5B has been approved to a depth of 650 mbsf by the EPSP.

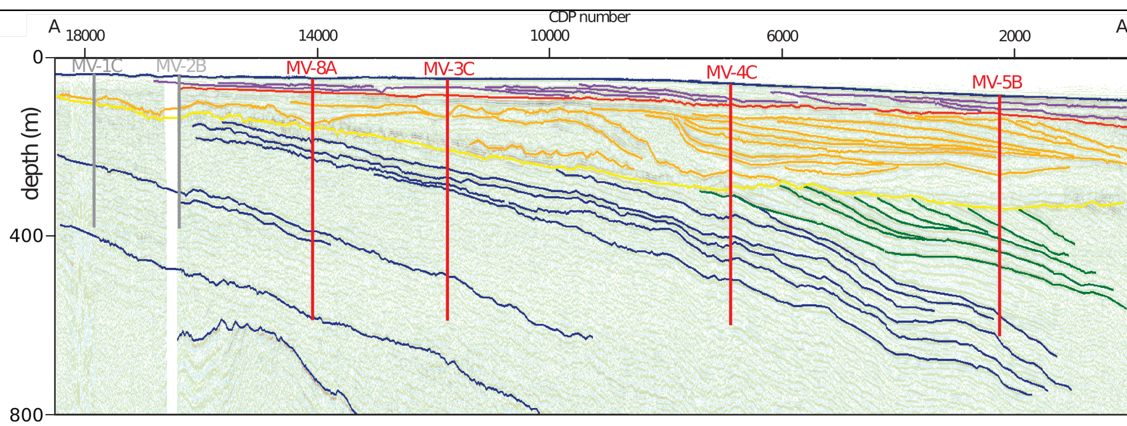

Figure 3. Depth-converted and interpreted seismic line A-A' (located in Figure 1) showing location and proposed depths of primary sites MV-8A, MV-3C, MV-4C, and MV-5B (red lines, red numbers). Also shown are locations and proposed depths for alternate sites MV-1C and MV-2B (grey lines, grey numbers). Details on seismic processing and interpretation are provided in Siegel et al. [2012].

After deciding on the operational strategy that allows for three sites, we discussed how many holes were needed at each site. Given that coring and logging would be done in a single hole, the discussion centered on whether a second hole was required for pump tests and microbiological sampling. The group quickly converged on the idea that microbiological samples could be taken in the coring and logging hole as is commonly employed within IODP. More lengthy discussions focused on the logistics of completing pump tests in the same hole. Ultimately the group decided that with appropriate scoping, a casing plan could be developed that would allow pump tests to be completed in the coring and logging hole. The group is optimistic that all operations can be completed in a total of three sites with one hole at each site.

What do onshore data provide?
An objective of the workshop was to determine the value added for adding an onshore component to the drilling. Initial thoughts were that an onshore site would provide direct access to modern recharge, could isolate the transition from modern water to paleo-freshwater, and might facilitate the removal of some offshore sites to reduce overall costs. After evaluating the numerical flow models, the electromagnetic data, and the magnetotelluric data, it was determined that three offshore sites were sufficient to characterize the entire offshore system, and would keep the project in the estimated budget for a mid-cost project. This limited the amount of discussion for onshore sites, but it was determined that a separate proposal would be developed for ICDP as a stand-alone, but complementary, onshore drilling project. The onshore proposal will focus on three discrete issues: (1) characterizing the hydrogeological properties of the sediments to better understand the permeability architecture; (2) evaluating the spatial variability of freshwater on Martha's Vineyard and/or Nantucket including any potential transitions from modern freshwater to paleo-freshwater; and (3) collecting basement material to contribute to our overall understanding the central Atlantic magmatic province.

Expanding the Community and Science Impact
As this project has matured from conceptual model to full proposal, our need to broaden the science community was noted. Through participants in the workshop, we have developed a network of scientists interested in the project that includes physical hydrogeologists, onshore hydrogeologists, marine geologists and geophysicists, hydrogeochemists, biogeochemists, sedimentologists, and stratigraphers. Ultimately this has expanded the potential science footprint of this project from a dedicated marine hydrogeology project to assess freshwater emplacement mechanisms to now include nutrient cycling, rare earth element cycling, biogeochemical processes, and sea-level cycles as recorded in a glaciated region. So, the workshop helped refine the overall drilling approach and expanded the science impact. We are optimistic that this broadening of interest will produce a large pool of applicants to participate in the drilling and the post-expedition science.

Society, Education, and Outreach
Another discussion of importance at the workshop was integrating this project with the local community to inform them and educate them about coastal freshwater and to engage them in the science to improve relations for before drilling. This would help drilling but also set the stage for post-drilling engagements. Four primary groups were targeted for assisting with the community outreach and education: USGS, Massachusetts Coastal Zone Management, Massachusetts Geological Survey, and WHOI. Each of these organizations has ties to the study area and has positive experiences working with the communities. We felt this was a strong starting point. Point contacts were identified for each organization. Additionally we decided that two activities should be pursed. The first is the development of a one-page white paper that summarizes the proposed work and its value to society. This could then be distributed to stakeholder and regional community

groups. A second activity is to work with the identified agencies to plan town hall meetings where the science project will be discussed and proponents will be available for questions. The white paper will be developed soon and then distributed. Town-hall like activities will have to be planned later depending on scheduling of Proposal 637.

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Appendix I: Workshop Agenda

Onshore-Offshore Drilling and Sampling to Understand Freshwater Resources along the New England Continental Shelf: An IODP-ICDP Workshop

May 22, 2017

8:00-8:30 Breakfast
8:30-8:45 Introductions and Workshop Objectives [B. Dugan]
8:45-10:15 Onshore-Offshore Freshwater
- submarine groundwater discharge [A. Wilson]
- New England hydrogeology studies [M. Person]
- New England geochemistry studies [R. van Geldern]

10:15-10:45 Coffee Break
10:45-11:30 Onshore-Offshore Freshwater
- Ocean-Aquifer Studies at Oregon State University [T. Jarvis]
- New Zealand surveys [A. Micallef]

11:30-12:00 Group Discussion – science questions, data needs
12:00-13:15 Lunch
13:15-14:30 History of IODP Proposal 637 [B. Dugan]
14:30-15:15 Existing Data and Studies
- seismic data [B. Dugan]
- electromagnetics [K. Key]

15:15-15:45 Coffee Break
15:45-17:00 Existing Data and Studies
- onshore data [C. Johnson]
- coastal zone data and survey capabilities [L. Brothers]

Adjourn for day, dinner on own

May 23, 2017

8:00-8:30 Breakfast
8:30-8:45 Recap of day one [B. Dugan]
8:45-9:15 Onshore wells [M. Person]
9:15-10:00 Science Needs at Onshore and Offshore Wells
- water and gas geochemistry/isotopes [J. McIntosh]
- sedimentology and sea level [K. Miller]
- discussion

10:00-10:30 Coffee Break
10:30-11:15 Small group discussions
11:15-12:30 Lunch
12:30-13:30 Group Discussion – review and revise science questions, summarize science and technology needs and challenges, set science priorities potential sites
13:30-14:15 Expected Costs and Opportunities for Funding [B. Dugan]
14:15-14:45 Summary of ESO Planning and Facilities [D. Smith]
14:45-15:15 Coffee Break
15:15-15:30 Governing a new resource [R. Martin-Nagle]
15:30-16:00 Education and Outreach
- community outreach, freshwater resource education, social media presence

16:00-17:00 Closing Discussion - plan for proposals to ICDP and other funding sources

Appendix II: List of Participants and Contributors

Workshop Participants and Contributors

Boutt, Dave – University of Massachusetts, Amherst
Brothers, Laura – U.S. Geological Survey
Chaanda, Mohammed – University of Plymouth (UK)
Clarke, Leon – Manchester Metropolitan University (UK)
Deyassa Daddi, Gaddissa – Wollega University (Ethiopia)
Dugan, Brandon – Colorado School of Mines
Evans, Rob – Woods Hole Oceanographic Institution
Jarvis, Todd – Oregon State University
Jayaraju, Nadimikeri – Yogi Vemana University (India)
Johannesson, Karen – Tulane University
Johnson, Carole – U.S. Geological Survey
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Kiro, Yael – Lamont-Doherty Earth Observatory
Lane, Jr., John – U.S. Geological Survey
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