Large submarine aquifers on the US Atlantic continental shelf

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\section*{SUMMARY}
Submarine groundwater beneath continental shelves may be a significant global phenomenon, yet little is known about the distribution of these fresh and brackish water bodies. Borehole data provide direct evidence of submarine groundwater, but their sparse locations are unable to characterize the lateral extent of offshore aquifers. Here, we present data from a pilot study of large-scale electromagnetic (EM) surveying of offshore groundwater on the US Atlantic continental shelf. We collected a total of 410 line kilometers of surface-towed controlled source EM data and 18 stations of passive magnetotelluric data in shore perpendicular surveys located off New Jersey and off Martha’s Vineyard. Our data reveal laterally continuous low conductivity zones consistent with brackish aquifers within the top 500m of sediment that extend up to 98 km offshore, providing the first constraints on the lateral distribution of this groundwater. The distributions of brackish and saline water imaged via EM methods are consistent with co-located borehole measurements from IODP Expedition 313 off New Jersey. Furthermore, combining our EM results with seismic stratigraphic interpretations reveals structural controls on freshwater distribution.

\textbf{Keywords:} Marine EM, Joint Inversion, Submarine Groundwater

\section*{INTRODUCTION}

Fresh and brackish waters have been identified in boreholes drilled on continental shelves worldwide, yet their distribution, origin, and interactions with the surrounding submarine environments is not yet well understood (Post et al. 2013). One modeling study estimates $3 \times 10^5$ km$^3$ of freshwater may exist within continental shelves (Cohen et al. 2010), but considerable uncertainty exists due to a lack of observational data. Brackish and briny waters have been observed in several boreholes drilled on the US Atlantic continental shelf. The earliest indications come from a scattering of boreholes made across the margin in the 1970’s as part of the Atlantic Continental Margins Coring (AMCOR) project (Hathaway et al. 1979). A more focused drilling survey, IODP Expedition 313 (Mountain et al. 2010), off the coast of New Jersey identified a more complex groundwater system within the shelf, revealing sharply alternating layers of saline and fresh water within the top 600m of sediment (Mountain et al. 2010; Lofi et al. 2013).

\section*{MARINE EM SURVEY AND METHODS}

In order to investigate the distribution of submarine groundwater in continental shelves, we collected controlled source electromagnetic (CSEM) and magnetotelluric (MT) data to image electrical resistivity structure of shallow crust off the coasts of central New Jersey and Martha’s Vineyard. The New Jersey survey was collocated with IODP Expeditions 313 boreholes to provide a comparison of directly measured salinity with resistivity structure derived from EM inversions. The survey off of Martha’s Vineyard was designed to provide the first observational data of offshore groundwater for this area, as the only borehole evidence of freshwater exists onshore Martha’s Vineyard and Nantucket. Survey layout is shown in Figure 1.

In both survey locations we recorded seafloor MT and CSEM data using a sparse array of ten broadband EM receivers deployed at 10 to 20 km spacing. The shallow water depths on the continental shelf permitted the additional use of a 336m long surface-towed CSEM transmitter antenna fol-
owed by four EM receivers at offsets of 600m - 1380m from the transmitter. This allowed us to collect short-offset, surface-towed CSEM data continuously along all profiles. The antenna transmitted an alternating 100 A current using a complex binary waveform with a fundamental frequency of 0.25 Hz that was designed to provide a wider frequency spectrum of high amplitude harmonics than is produced by a simple square wave (Myer et al. 2011). This surface towed system is ideal for detecting resistive freshwater as it was designed for high resolution imaging in the near surface (Sherman et al. 2017). CSEM response functions for frequencies of 0.25 Hz - 48.25 Hz for each surface towed receiver were obtained by processing measured electric field time series as outlined by Myer et al (2011). Data were robustly stacked into 60 sec bins.

Figure 1: Map of electromagnetic survey of the US Atlantic continental shelf. Red lines show the surface-towed CSEM profile. Blue squares show MT receiver locations. IODP Expedition 313 borehole locations are labeled and shown as green circles. Yellow triangles show locations for AMCOR wells.

Seafloor MT receivers recorded horizontal electric and magnetic field time series for 3-5 days and were processed into impedance responses using a robust array processing method to estimate impedances (Egbert 1997). Due to the shallow water depths (20 to 150 m) and generally favorable sea state, we obtained good MT responses from \(10^{-4}\)Hz up to 100 Hz, greatly exceeding the typical maximum recoverable frequency of 0.1-1Hz for broadband receivers deployed at ocean depths of 4 to 1 km, respectively.

2D INVERSION RESULTS

We inverted our data for 2D isotopic resistivity structure using MARE2DEM (Key 2016), a freely-available goal-oriented adaptive finite-element inversion code for 2D electromagnetic modeling. The surface-towed CSEM data consisted of the 0.75 and 1.75 Hz harmonics and the MT data consists of periods below 100 seconds. In order to evaluate the relative merits of both data types, we carried out independent inversions of the surface-towed CSEM and seafloor MT data, then jointly inverted the two data types together.

Figure 2 shows the three different inversion models for our shore-to-shelf New Jersey profile. In both locations the independent surface-towed CSEM and MT data was fit to root-mean squared misfit (RMS) 1.0 using 1% and 5% error floors, respectively. For the jointly inverted data sets, the New Jersey profile uses MT error floors of 10% and fits the data to RMS 1.4. For Martha’s Vineyard, the MT error floors remain at 5% and fit the data to RMS 1.4.

The surface-towed CSEM inversion in Figure 2 identifies a large scale resistive feature in the upper 500 m of sediments from the survey origin to 90 km offshore. The resistor is continuous laterally until 50-60 km position, where it abruptly jumps to shallower depths. In general, the resistive feature is fairly smooth looking, except for a few small scale resistors on the seafloor where the data’s lateral and depth resolution is highest.

The MT inversion in Figure 2 also recovers the resistive feature, although it is not as laterally uniform as the CSEM inversion. The magnitude of the resistor is also lower, but this is expected due to the saturation effect of MT responses for a thin resistive layer between conductors. At positions greater than 73 km and depths of around 500 m, the MT inversion recovers an extensive conductive feature about 200 m thick.

The joint inversion shows the same resistivity trend as the independent inversions, but with more sharply defined geometries (see Figure 2). It is possible there are two separate resistive bodies separated at 53 km, rather than an upward shift as the boundary may be smoothed over in our inversion. In the rest of our text we focus on our interpretations on joint inversions results from both survey areas.
Recent borehole data allow a direct comparison of our inversion model from off New Jersey with chlorinity data from the IODP Expedition 313 (Figure 3). The locations of the high and low resistivity features seen in our inversion correspond well with low and high chlorinity concentrations, respectively. However, due to the diffusion nature of EM soundings, our data cannot resolve the sharply alternating layers of brackish and briny waters observed in the upper 200m of the boreholes. We interpret resistive values (warm colors in Figures 2, 3, and 4) to be indicative of freshwaters and conductive values to be indicative of saltier waters.
Joint inversions of shore-to-shelf edge profiles off of New Jersey and Martha’s Vineyard (Figure 4) reveal resistive bodies extending out to 93 - 98 km offshore. The highest resistivity values, and therefore freshest pore waters, appear closest to shore for both profiles, indicating this water likely connects and is potentially recharged onshore. When overlaying depth migrated seismic reflection data (G. Mountain, personal communication, B. Dugan, personal communication) and specific sequence boundaries (M. Steckler, personal communication), the freshwater appear stratigraphically capped for both locations. Furthermore, both locations show the terminus of the freshwater colocated with the onset of clinoform structures. Both locations show deeper conductive features that do not correlate with any stratigraphic boundaries.

**CONCLUSION**

We have demonstrated marine EM methods successfully map shallow submarine groundwater. Our results constrain the lateral and depth extent of the freshwater in both New Jersey and Martha’s Vineyard. In both locations, the fresh water aquifer geometries seem to be structurally controlled by clinoforms and sequence boundaries. Although separated by 300 km, the similarity of the offshore extent of both aquifers suggests the entire shelf in this region may contain abundant freshwater. The lateral and depth constraints on groundwater off the US Atlantic coast provided by this study may be used to guide modeling studies determining the relative importance of stratigraphy, sea level changes, and ice sheet dynamics for paleo-freshwater emplacement.

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