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Geophysical evidence for karst formation associated with offshore groundwater transport: An example from North Carolina

Rob L. Evans
Department of Geology and Geophysics, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts 02543, USA (revans@whoi.edu)

Dan Lizarralde
Earth and Atmospheric Sciences, Georgia Institute of Technology, 221 Bobby Dodd Way, Atlanta, Georgia 30332, USA

[1] Marine geophysical data from Long Bay, North Carolina, involving a novel combination of electromagnetic and high-resolution Chirp seismics, show evidence of submarine karst formation associated with what has been inferred to be a site of high-flux submarine groundwater discharge (SGD) a substantial distance offshore. Recently observed temperature and chemical signals from wells in this area provide the basis for the interpretation of the high-flux SGD here, and they also suggest a terrestrial source for the groundwater and thus a potentially important route for nutrient transport to the oceans. Our data indicate that karstification is localized to the high-flux zone, and we suggest that mixing of the chemically distinct (but saline) groundwater with seawater has resulted in the karstification. As karstification increases permeability and flux, a positive feedback would tend to progressively enhance submarine groundwater discharge. Our data reveal a significant local anomaly in apparent porosity: a dense block that may have initiated the local focusing of groundwater flow. Conditions favorable to the formation of similar locally punctuated sites of high-flux SGD are likely to exist along the mid to inner shelf of the southeastern United States, where carbonate aquifers are prevalent.

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1. Introduction

[2] The flux of nutrient-rich waters from land to the oceans is a fundamental component of biogeochemical cycles. This flux occurs through a variety of mechanisms: river input; groundwater discharge into estuarine marshes; and submarine groundwater discharge (SGD) directly through the seafloor. While riverine flux into the oceans is easily quantified, offshore groundwater transport and submarine discharge remain poorly understood. What is known is that groundwater exchange between land and sea occurs at many different levels and spans the continental shelf [e.g., *Kohout et al.*, 1988]. Discharge

from surficial aquifers at the shoreline [*Bear et al.*, 1999] is readily observed, and deeper aquifers are known to leak fresh water onto the seafloor at the shelf break, far offshore [e.g., *Robb*, 1984]. It also seems likely that aquifers at intermediate depths can leak groundwater in the mid-shelf. Some of these aquifers could be transporting terrestrial water offshore, while some may leak water that was emplaced during the last sea level lowstand and which was trapped as sea level rose [*Hathaway et al.*, 1979].

[3] Over the past decade, a series of regional scale studies using radionuclides (e.g., ^{226}Ra) as tracers for groundwater flux suggest that groundwater discharge may account for as much as ~30% of the total water flux into the coastal waters of the southeastern UNITED STATES [*Moore*, 1996; *Church*, 1996] and ~50% of the total nutrient flux [e.g., *Shaw et al.*, 1998; *Krest et al.*, 2000]. Understanding mechanisms of SGD is an important step in both verifying whether or not radionuclide inventories are accurate proxies for water and nutrient flux and, ultimately, in determining the importance of SGD to global-scale oceanic geochemical cycles. Although it is possible to extrapolate measured values of nearshore SGD flux throughout the southeastern U.S. inner shelf and account for the estimated flux on the basis of geochemical tracers [e.g., *Simmons*, 1992], this simplest of mechanisms is problematic because there is radionuclide evidence that substantial SGD discharge occurs beyond the inner shelf [*Moore and Shaw*, 1998], where flux via an unconfined aquifer could not be sustained.

[4] Groundwater discharge to the oceans can, in some cases, occur through locally punctuated high-flux regions, where it can act as an erosional agent, reshaping the seafloor through sapping processes nearshore [*Uchupi and Oldale*, 1994; *Driscoll and Uchupi*, 1997] or through chemical erosion [*Robb*, 1990]. Such erosion can potentially provide a positive feedback, increasing the flux of groundwater to the seafloor. An important example is the seafloor dissolution of limestone, or karstification. When terrestrial groundwater in a limestone aquifer mixes with seawater at a seafloor discharge zone, differences in ionic concentrations between the two fluids can lead to carbonate dissolution even when both fluids are initially saturated with respect to $CaCO_3$ [*Phillips*, 1991]. Sinkhole features observed offshore Florida have probably developed through a similar process [*Land and Paull*, 2000].

[5] In this paper, we present geophysical data collected across a locally punctuated, high-flux submarine groundwater discharge zone located in Long Bay, ~20 km offshore of the North Carolina coast (Figure 1). The geophysical data, from high-resolution seismic reflection and electromagnetic (EM) profiling, show that this location is strongly affected by karstification. This site was discovered during regional well installations designed to assess SGD. The results of sampling and logging temperature in those wells are given by *Moore et al.* [2002], which we summarize here. Wells near this site are unique relative to other locations in that they penetrated into an apparently confined, high-permeability zone where temperature fluctuations suggest significant tidally driven seawater/groundwater mixing, and thus high-flux SGD. The 4-m-deep wells show a stratigraphy consisting of 1–2 m of sands and clays overlying an approximately 2-m-thick high-porosity zone with a hard base, known to be limestone. Water pumped from the high-permeability zone is nutrient rich, chemically distinct from seawater, but with the same salinity, and it is significantly enriched in radium, suggestive of a terrestrial groundwater source. The ease with which water was pumped from this zone indicates permeabilities consistent with very large void space, karst like conditions. The clay layer is thought to act as an impermeable cap, restricting exchange between water in the high-porosity zone and the ocean at this particular location. Despite this, temperature measurements made in the well show a uniform basal temperature, but within the high-porosity zone a semidiurnal temperature variation was observed that is in phase with the local tides. Tidal pumping of warm seawater into this cavity at high tide, from still undiscovered locations, and discharge of cool groundwater from the limestone at low tide is the mechanism proposed to provide the temperature oscillation.

2. Long Bay Survey

[6] Long Bay sits within the Mid-Carolina Platform High [*Riggs and Belknap*, 1988], a topographic

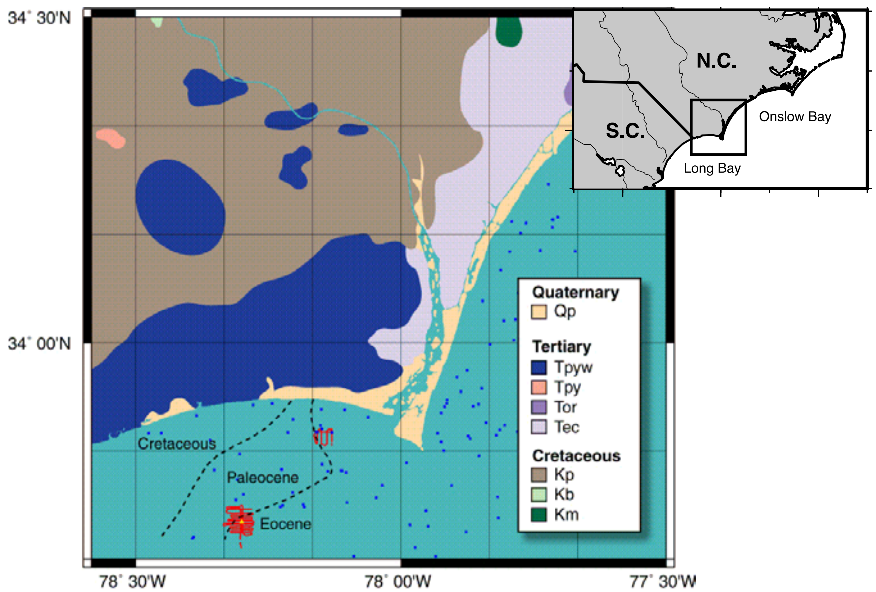

Figure 1. Map of Long Bay, North Carolina with interpreted offshore extension of regional geological units based on a series of vibracores (blue squares) [*Hoffman*, 1997]. Our main survey grid (red) and the *Moore et al.* [2002] wells are in the southwest, possibly at the boundary between a Paleocene sequence and the Eocene Castle Hayne limestone (Tec); this boundary position is consistent with the core data, but farther west than Hoffman's interpretation. A second series of lines (also red) were run across a known Castle Hayne outcrop. The other key unit in our interpretation is the Cretaceous Peedee formation (Kp).

feature that has played a major role in sediment supply to the shelf. Seafloor outcrops range from Cretaceous in the northwestern corner of the bay to Pliocene at the shelf edge. The bay has abundant hard bottom conditions with frequent Paleocene and Eocene limestone outcrops within the survey area. Our geophysical survey consisted of a grid of transects designed to constrain the geometries (seismic) and bulk physical properties (EM) of the sedimentary units in the vicinity of the well sites described above to a depth of ~30 m below the seafloor (Figure 2). The seismic reflection profiles were obtained using an EdgeTech chirp sonar (SB-0512), towed several meters above the seafloor, and transmitting a 1–7 kHz, swept frequency pulse with match filtering of the returns which we display as instantaneous amplitude in Figure 3. Details of the EM system used in the survey are given by *Evans et al.* [1999, 2000]. Briefly, it is a frequency domain magnetic dipole-dipole array with a transmitter and three receivers, which are spaced 4 m, 13 m and 40 m behind the transmitter. The system is towed along the seafloor at speeds of 1–2 knots and makes a measurement of seafloor resistivity every 10 m or so along track. Porosity is linked to electrical resistivity through the nonlinear empirical *Archie*'s [1942] law,

$$\rho_m = \rho_f \theta^{-m}, \tag{1}$$

where ρ_m is the measured resistivity (Ωm), ρ_f is the pore fluid resistivity (Ωm), θ is the sediment porosity, and m is a free parameter that typically varies between 1.4 and 1.8 for marine sediments [*Jackson et al.*, 1978]. Higher electrical resistivities generally imply lower porosity. The exponent m serves to describe how well the seawater is connected throughout the pore-space, with lower values of m reflecting higher connectivity. Other factors can bias the estimates of porosity from Archie's law. The most important of these is fresh water (described below), the presence of which will cause an underestimate in porosity. Clays can cause problems for interpreting terrestrial EM data, although their impact on bulk conductivity is minimal when the pore fluid is as conductive as seawater [*Wildenschild et al.*, 2000]. The raw data from the system are presented as apparent

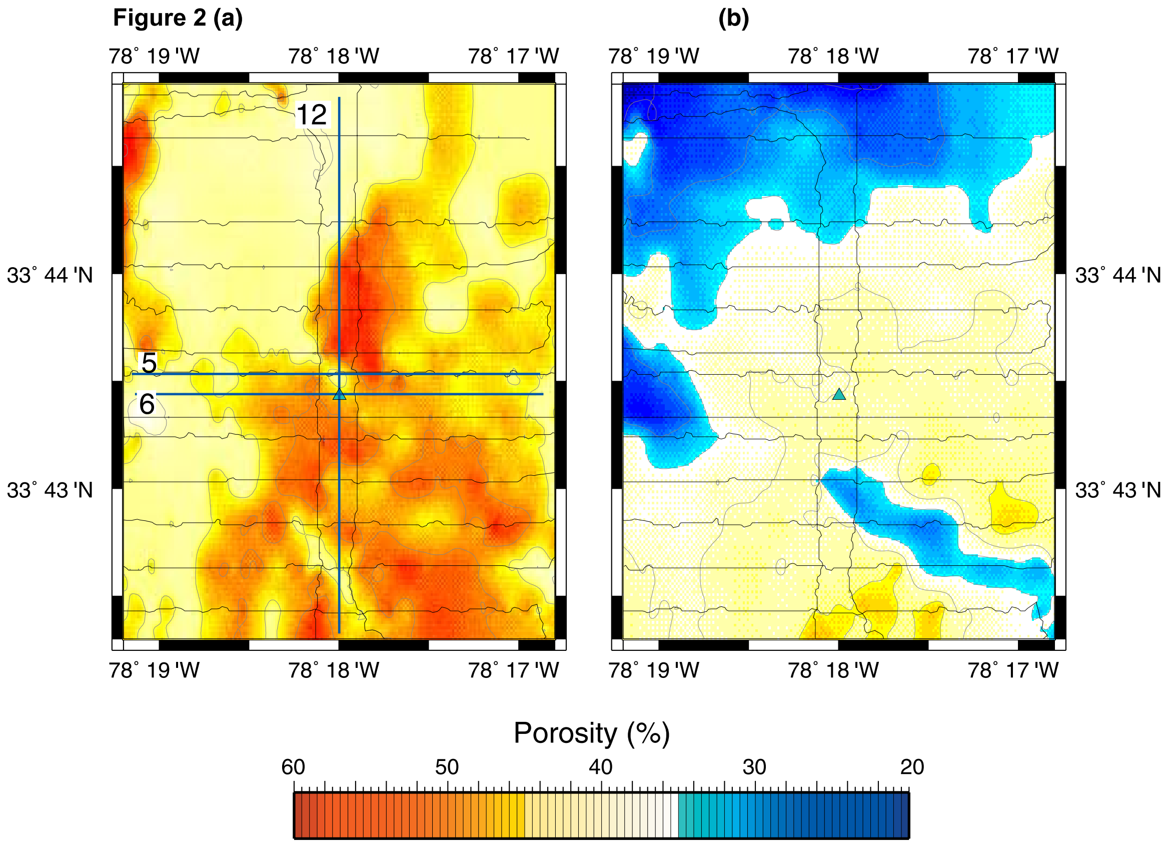

Figure 2. Contour maps of apparent porosity on the (a) 13-m and (b) 40-m receivers throughout our main survey region. EM survey lines are as shown. Two additional seismic lines (6 and 12) were run directly over the well sites. Note the NW-SE trend of increasing porosity. The influence of the limestone bench (see text) can be seen as the SE trending blue region at the lower right of (b). Lines 5, 6 and 12 (blue lines in (a)) are those for which raw data is shown in Figure 3. EM data shown in Figure 3 are from the closest line to the east (line 12) and to the south (line 6) as we were unable to tow the EM system directly through the well sites (green triangle).

porosities, one for each of the three receivers, and for convenience we choose a fixed value of m, typically 1.8. These apparent porosities are weighted averages over the depths to which the receiver is sensitive: for example the 4-m receiver is a weighted average over the top 2–2.5 m of seafloor [*Evans*, 2001], while the farthest receiver probes to about 20-m depth. Previous studies have demonstrated that the EM system measures physical properties that can be closely related to seismic stratigraphy [*Evans et al.*, 2000] and also that it might respond to zones of fresh groundwater [*Evans et al.*, 1999; *Hoefel and Evans*, 2001]. In the present case, however, it is important to note that all samples from within the wells have the same salinity as seawater and that there is no evidence of freshwater seeping through the seafloor. This means that variations in the subbottom resistivity structure can be safely interpreted as due to lithologic changes or to changes in porosity. Furthermore, EM and seismic data collected further north off Wrightsville Beach have been used in concert with hydrologic modeling to constrain the distance that freshwater can be seen offshore in the Castle Hayne to be around 1–2 km-substantially closer to shore than the present survey area (A. E. Mulligan et al., The role of paleochannels in groundwater-seawater exchange, submitted to *Journal of Hydrology*, 2002).

[7] The seismic reflection data can be used to outline the stratigraphic framework of the survey region and to delineate contacts between different geological units. The geology of the upper 30 m in

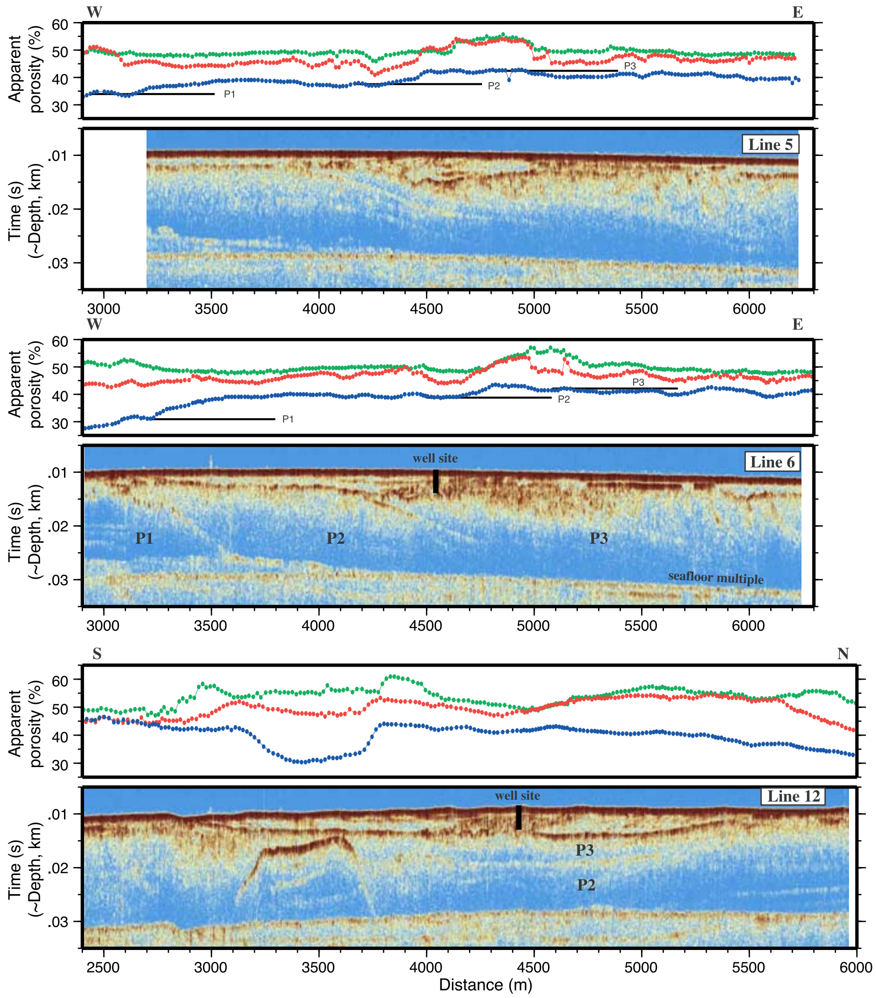

Figure 3. Controlled-source EM data plotted as apparent porosities for the 4-, 13-, and 40-m receivers (red, green and blue) and chirp seismic data for Lines 5, 6 and 12 (Figure 2). Location of the *Moore et al.* [2002] well site is indicated. The geologic setting consists of a 1- to 2-m-thick clayey layer overlying a sequence of beds P1, P2, and P3. The 40-m EM receiver suggests these layers have distinct bulk properties. The surface of the P3 layer is highly disturbed, in some locations this disturbance is quite punctuated, and the uppermost portion of the P3 layer has in places a ‘‘moth-eaten’’ reflection character. These features are consistent with karst formation. Note that the EM and seismic data for Lines 6 and 12 are not exactly coincident, as we avoided towing the EM system directly across the well installation (see Figure 2). Approximate depth scale assumes a seismic velocity of 2 km/s.

the survey region is dominated by a ~20-m-thick, apparently progradational sequence that strikes approximately NE-SW (Figure 3). This unit is overlain by a ~1- to 2-m-thick layer of sands and clays, and overlies a subhorizontal surface that dips toward the southeast. Two prominent boundaries are identified within the progradational interval, dividing the interval into three main units (P1, P2 and P3). The EM data measure bulk properties that can be interpreted in the light of the seismic data, but we caution that interpretation of structures based solely on apparent porosity is risky. For the most part, the apparent resistivity of the 40-m receiver reflects the response of the progradational interval, and this response suggests a slightly different porosity for each of the units, with the apparent porosity increasing from ~27 to 39 to 41% in ramplike fashion across the unit boundaries. This trend is clearly observed in the gridded 40-m receiver apparent porosities of Figure 2, where apparent porosity progressively increases toward the southeast. The existence of porosity contrasts within this interval and the strength of the reflections from the unit boundaries indicate that the units are distinct in physical properties, though the differences are small. The uppermost portion of the P3 unit, which can be seen clearly on Line 12 (Figure 3) from ~2900 m to ~5500 m, and from ~4250 m eastward on Line 6 (Figure 3), exhibits an eroded, "moth-eaten" appearance near its western contact and distinct, void-like drop outs in reflectivity along its upper eastward surface that are consistent with the dissolutional erosion of limestone. Although the erosional surface of this unit appears as a channel-like feature in individual profiles, examination of both E-W and N-S profiles indicates that it is in fact a local depression. This feature is associated with a marked increase in shallow apparent porosity, with a response that tends to dominate the signal in the southeastern quadrant of the 40-m receiver apparent porosity map (Figure 2b). Beneath the southern end of this shallow depression, and to the southeast of the well sites, an extremely strong bench-like reflector is seen (Line 12, Figure 3, from 3200 m to 3650 m). This reflector is almost certainly a dense, relatively impermeable limestone block, with a gently dipping top surface and steep sides. Raised apparent porosities on the 13-m and 40-m receiver surround this feature, although apparent porosities are dramatically reduced on top of it.

[8] The EM data cannot unequivocally confirm the existence of the thin high-porosity zone, between 2- and 4-m depth, in which porosity is as high as 90% [*Moore et al.*, 2002]. The 40-m receiver response suggests a P3-unit apparent porosity of ~40% around the well sites. However, we have also measured the seafloor EM response at a location closer to land, northeast of the well sites (Figure 1), where the Castle Hayne (thought to be correlative with the P3 unit) is known to outcrop. At this location, both the 13-m and 40-m receivers indicate substantially lower apparent porosity values, in places as low as 15% on the 40-m receiver. This suggests that the apparent porosity values seen on the 40-m receiver in the main survey area have been raised by the effects of shallow layers, but there is ambiguity as to how higher porosities might be distributed within the near surface. Simple 1-D models show that a 2-m-thick, 90%-porosity layer starting at a depth of 1.5 m below the seafloor and underlain by a 20%-porosity layer yields an apparent porosity for the 40-m receiver of 40% as seen, but this value can also be obtained simply by assuming that the porosity of the entire P3 unit and overlying sands and clays is around 40%. The true porosity distribution likely lies somewhere between the end-members described, as the substantial near surface erosion suggests shallow porosity, and the persistence of anomalous seismic reflectivity to at least 10 m below the P3 surface suggests a deepening of porosity enhancement.

3. Groundwater Flux, Karstification, and Offshore Transport

[9] *Moore et al.* [2002] suggest that the shallow high-permeability zone identified in their ~4-m-deep push-core wells is a site of substantial ocean/groundwater exchange, and that this type of high-flux offshore setting, given a sufficient number distributed across the shelf, may represent a significant component of the terrestrial-to-ocean nutrient flux. Our geophysical data bear on this hypothesis in two ways. First, our data reveal karst-like features that are most dramatically expressed within about 1 km of the wells of interest, suggesting that karstification and high-flux ocean/groundwater exchange are systematically linked. Second, observations of local contrasts in bulk physical properties between subsurface geologic units suggest a mechanism for groundwater flow focusing that could lead to a punctuated zone of dissolution. Local porosity contrasts within the progradational unit will tend to redirect and focus the flow of groundwater percolating upward through this layer. Flow is likely to be easier through the P3 unit in the southeast than through the P1 unit in the northeast. At a smaller scale, flow within the P3 unit would tend to be focused around the apparently massive bench-like feature. It is possible, then, that contrasts in bulk aquifer properties have served to focus groundwater flow, leading to a positive feedback between flow focusing, shallow karstification, and local flux. In addition, the continuous, undisturbed character of the uppermost sedimentary layer, which in places overlies what appears to be large, cavern like features,

suggests that karstification occurred beneath this capping unit. This capping unit is a local feature, and its presence may have helped to create a broader, more diffuse mixing region, enabling the onset of the mixing/karstification/flux feedback process. We do not see obvious breaches of this unit, which are presumably required to explain the extensive exchange of seawater into the high-porosity zone. There are regions of raised porosity on the 4-m receiver (e.g., ~3000 m and ~3900 m on Line 12, Figure 3), which might correspond to areas where seawater can enter the subsurface, but this interpretation is speculative. Thus inferences based on our observations provide a plausible scenario for the formation of some number of local high-flux SGD areas, wherever conditions are favorable within the carbonate aquifers that dominate the southeastern U.S. coastal zone. Confirmation of these models, however, will require detailed drilling and sampling of the subsurface throughout the region.

[10] Ocean/groundwater exchange in the survey area involves seawater mixing with chemically and thermally distinct groundwater [*Moore et al.*, 2002], and our data suggest that this mixing results in chemical dissolution of the limestone unit within which the mixing occurs. The groundwater flux has been identified on the basis of elevated radium in the water. *Moore et al.* [2002], following earlier work of *Moore* [1996], suggest that the radium is picked up at the saltwater/freshwater front onshore, suggesting significant offshore transport of groundwater to this site. An alternative explanation is that the radium is mined locally from the limestone in at least one of two ways. The radium may arise from water trapped within the limestone at the last sea level lowstand, or, because uranium can replace calcium in $CaCO_3$ in a limestone and because radium is a decay product of uranium, elevated radium may be a byproduct of the dissolution process irrespective of previously trapped pore water. Our results provide a plausible mechanism for release of a local source of radium, but they do not in themselves suggest a local versus distal radium source. If the elevated radium arises from a local source, then observed correlations of radium with nutrients, such as nitrogen and phosphorous, would reflect the chemistry of the locally trapped water and/or dissolution products, and so this question could be addressed with additional geochemical data. It is important to note, however, that a local source of radium does not preclude a distal source of groundwater, which would provide an explanation for the correlation between radium and nutrients observed by *Moore et al.* [2002], since higher land-to-ocean groundwater (and nutrient) fluxes will result in greater dissolution and hence radium released to the ocean.

[11] Groundwater transport a considerable distance offshore requires a feasible route and a sustained hydraulic gradient, and would likely occur within one or more of the major coastal aquifers. Our data provide information on the structural relationships beneath the site that appear to support the model proposed by *Moore et al.* [2002] in which their wells bottom in an offshore extension of the Eocene Castle Hayne limestone aquifer, an important, productive onshore aquifer. Well cuttings and the karst-like features observed in the seismic data strongly suggest that P3 is a carbonate unit, and it is possible to interpret this unit to be the westernmost portion of the Castle Hayne on the basis of regional offshore wells and an offshore extrapolation of the westernmost onshore boundary of this unit (Figure 1). While this is a plausible interpretation, it is unlikely that the Castle Hayne could transmit groundwater from land to this location without considerable mixing with seawater along the way. The impermeable, capping clay layer near the well sites is a local feature, and the Castle Hayne is known to outcrop on the seafloor at locations closer to shore. If terrestrial groundwater is transported in a confined aquifer to this location, then that aquifer likely lies beneath the progradational sequence, possibly the Pee Dee or Cape Fear aquifer, and transported water percolates upward through the P3 unit at this location.

4. Conclusions

[12] A novel combination of offshore high-resolution seismic reflection and electromagnetic profiling provide complementary data sets that have enabled us to place constraints on an example of

locally punctuated high-flux ocean/groundwater exchange that is believed to represent submarine groundwater discharge. Bedform geometry and stratigraphy provided by the chirp seismic data show evidence of karstification associated with this high-flux site. The EM data reveal lateral bulk-property contrasts within the area that may serve to focus groundwater flow. Together, these observations suggest a relationship between flow focusing, carbonate dissolution, and high-flux SGD that is likely to exist at other locations along the southeastern U.S. shelf, providing efficient outlets for nutrient release into the oceans.

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