Estuarine, Coastal and Shelf Science (2001) **52,** 179–189
doi:10.1006/ecss.2000.0718, available online at http://www.idealibrary.com on IDEAL®

Impact of Low Salinity Porewater on Seafloor Electromagnetic Data: A Means of Detecting Submarine Groundwater Discharge?

F. G. Hoefel[a] **and R. L. Evans**[b,c]

[a]*MIT/WHOI Joint Program in Oceanography, Woods Hole, MA 02543, U.S.A.*
[b]*Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, U.S.A.*

Received 4 January 2000 and accepted in revised form 4 September 2000

Submarine groundwater discharge has been recognized as an important process in coastal and shelf environments, but, due to the diffuse nature of the process, methods to identify and map zones of discharge still need development. Vertical profiles of subseafloor salinity from two locations off the east coast of the U.S. and from a coastal embayment in Cape Cod, MA, have been used to model seafloor electromagnetic (EM) responses to changes in porewater salinity. Ordinarily, porewaters of salinity close to that of seawater will be electrically conductive. Replacement of this conductive porewater by a body of fresh groundwater will reduce the electrical conductivity of the porewater and, hence, that of the seafloor. Based on *in situ* measurements of porewater salinity and reasonable estimates of sediment porosity, our modelling quantifies the changes in EM apparent porosity measurements that might be expected over coastal and nearshore regions of fresh water discharge. Given the results obtained, we demonstrate that existing EM technology might be used to map zones of fresh water in conjunction with other methods.

Keywords: electromagnetic (EM); submarine groundwater discharge; groundwater; porosity

Introduction

Submarine groundwater discharge (SGWD) plays a potentially important role in the oceanic environment, both as a major geochemical supply to the ocean (Church, 1996; Moore & Shaw, 1998; Shaw *et al.*, 1998) and as an agent of seascape evolution (Driscoll & Uchupi, 1997). However, the extent to which submarine groundwater discharge (SGWD) occurs through subsurface routes across continental margins remains controversial. Because of the diffuse nature of subsurface fluid advection and the difficulty in recognizing and quantifying its importance, few investigators have attempted to assess the fluid flux (Moore & Shaw, 1998). Global estimates of SGWD fluxes based on hydraulic pressure gradients and transmission coefficients along the world's coasts range from 0·01 to 10% of surface water runoff (Church, 1996). Nevertheless, many studies have documented the occurrence of offshore freshwater springs (Naimi, 1965; Kohout, 1966; Barans & Henry, 1984; Emery & Uchupi, 1972; Moore & Shaw, 1998) and of fresh or low salinity groundwater discharge to coastal embayments and continental shelves (Hathaway *et al.*, 1979; Kohout *et al.*, 1988; Cable *et al.*, 1997; Cambareri & Eichner, 1998; Uchyiyama *et al.*, 2000). Locally, the use of geochemical tracers naturally enriched in groundwater, such as Ba, ^{226}Ra and its daughter product, ^{222}Rn, has been proven to be a more effective approach to identify and quantify the process, despite several limitations of the method (e.g. Cable *et al.*, 1996; Moore & Shaw, 1998; Moore, 1996; Tsunogai *et al.*, 1996; Corbett *et al.*, 1997).

Fresh- to low-salinity porewater in offshore shelf strata can originate either from direct submarine groundwater discharge from confined aquifers (Church, 1996) or by the trapping of remnant fresh groundwater that infiltrated shelf sediments during the last glacial maximum (LGM), 18 000 years ago (Hathaway *et al.*, 1979). Submarine groundwater discharge occurs whenever an aquifer has a hydrostatic potential above sea level and is hydraulically connected to the sea through permeable sediment layers, whereas groundwater from unconfined aquifers seeps along coastal areas. Direct measurements of freshwater distribution beneath the seafloor are limited to point sampling in wells or in the vicinity of seeps, while indirect methods include the use of geochemical tracers and temperature signals in order to detect zones of discharge (e.g. Banks *et al.*, 1996).

---

[c]E-mail: evans@hera.whoi.edu

0272–7714/01/020179+11 $35.00/0

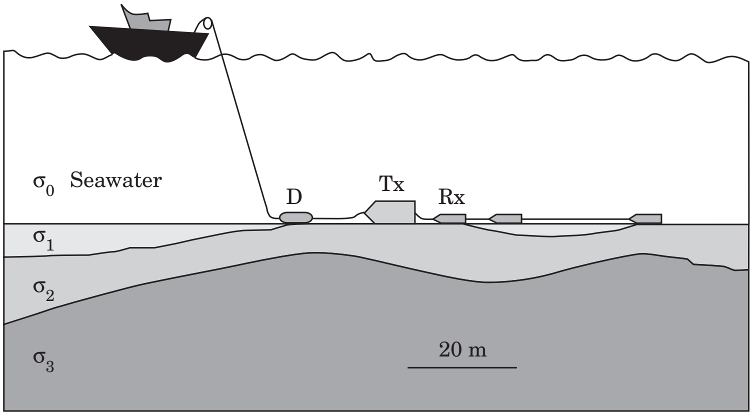

FIGURE 1. A schematic of the towed EM system considered in the present study. The system forms a 50 m long array on the seafloor consisting of a depressor unit (D), a transmitter (Tx), and three receivers (Rx) 4 m, 13 m and 40 m away from the transmitter respectively.

Geophysical techniques, which have the capability to map large areas of the seafloor, are generally not sensitive to changes in porewater salinity. Nevertheless, the salinity dependence of seawater conductivity (or resistivity) suggests that this might provide a means of identifying zones of fresh water. In terrestrial environments, the application of geo-electrical and electromagnetic (EM) techniques has proven to be useful in groundwater exploration and detection of saline and fresh water (e.g. Roy & Elliot, 1980; Fitterman & Stewart, 1986; Anthony, 1992; Ruppel *et al.*, 2000). The complication of such methods is that while the bulk conductivity of sediments depends heavily on the porewater conductivity, it is also dependent on the porosity of the sediment matrix. Thus, seafloor EM techniques, tailored to measure resistivity of marine sediments, will respond to changes in porewater salinity, in sediment porosity or to both. However, given proper knowledge of the local geology, in many circumstances changes in sediment porosity can be distinguished from changes in porewater salinity. A particular dataset of EM measurements collected offshore of Northern California displayed seafloor resistivities far too high to be explained by changes in sedimentary porosity only, raising the possibility that the survey had imaged a region of freshwater discharge.

In the present study we demonstrate the conditions under which EM methods can be used to directly detect the presence of submarine groundwater discharge. In order to address the issue, we use sub-bottom porewater salinity-depth profiles of coastal and nearshore areas to generate synthetic EM records. Although EM measurements can be designed in several different ways, in this paper our discussion and modelling refer to one particular system configuration that provides continuous resistivity profiles of the top 20 m of the seafloor (e.g. Cheesman *et al.*, 1993; Evans *et al.*, 1999).

Physical reasoning and equipment

Seafloor EM methods use the physics of induction to provide an increased sensitivity to changes in seafloor properties compared to conventional resistivity techniques. For full details and summaries of marine EM induction methods, the reader is referred to Chave *et al.* (1987), Cheesman *et al.* (1987) and Constable (1990).

The system we have employed consists of a transmitter, which generates time varying magnetic fields over a range of frequencies, and three receivers, tuned to measure these magnetic fields, that are towed at fixed distances behind the transmitter (Figure 1) (Cheesman *et al.*, 1993; Evans *et al.*, 1999). At a given frequency, the strength of magnetic fields decays away from the transmitter as a function of the conductivity of the seafloor, decaying more rapidly in more conductive media. Therefore, given that the frequencies are chosen appropriately, a measured signal will have primary sensitivity to changes in seafloor properties and will not be greatly affected by the overlying conductive seawater. Each receiver is tuned to record three frequencies, and the information in each consists of a magnetic field amplitude and phase. Thus, the set of raw measurements consists of nine amplitude and phase values at each transmission station along a tow-line. The system is dragged along the bottom at speeds of 1–2 knots and makes a set of readings approximately every 10 m along track. It is possible to take a set of amplitude and phase values and invert these for a resistivity-depth profile. In practice, a more

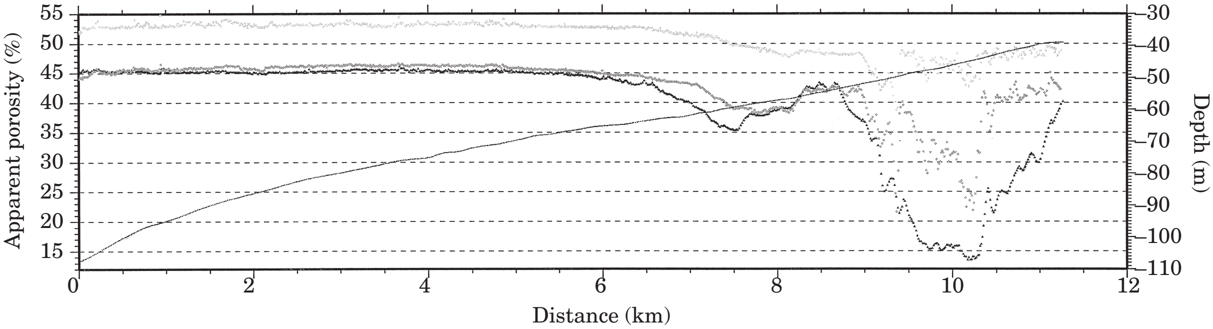

FIGURE 2. Typical apparent porosity EM profile measured across the Northern California shelf, from west to east (Evans *et al.*, 1999). The lightest upper line represents data from the 4 m receiver, the middle line represents measurements of the 13 m receiver, and the third line represents data from the 40 m receiver. The thin line represents the local depth.

efficient and straightforward way of looking at the data is to take the three amplitudes and phases recorded by each receiver and find the best fitting apparent resistivity for each. An apparent resistivity is the resistivity of the uniform seafloor halfspace that would best reproduce the observed response. Since all the recorded values have associated errors, and the seafloor is not a half-space, this is only an approximation, but the apparent resistivity does provide a reasonable average resistivity over the depth of sensitivity of each receiver. In general, a receiver that is a distance L away from the transmitter will be sensitive to structure over a depth range up to about $0{\cdot}5L$ below the seafloor. By having receivers spaced 4, 13 and 40 m behind the transmitter, we are able to obtain information over the top 20 m of seafloor. The apparent resistivity of the 4 m receiver provides average structural information about the uppermost 2 m of seafloor, the 13 m averages over about 6–7 m, while the 40 m receiver averages over the top 20 m of seafloor. EM propagation in the oceanic environment is a diffusive process, and thus the technique does not generate detailed spatial images of the subsurface structure as provided by seismic reflection profiles. However, the method does provide both lateral and vertical estimates of the bulk physical properties of the sea-floor (Evans *et al.*, 1999), and it is especially powerful when used in concert with high resolution seismic profiling methods (Mosher & Law, 1996).

The seafloor resistivity can be related to sediment porosity by Archie's Law (Archie, 1942), given by:

$$\rho_m = \rho_f \phi^{-m} \quad (1)$$

where ρ_m is the measured resistivity (Ωm); ρ_f is the interstitial fluid resistivity (Ωm), which is a well known function of temperature and salinity; ϕ is the porosity and m is a free parameter typically between 1·4 and 1·8 (Jackson *et al.*, 1978). A typical profile of apparent porosity estimates is illustrated in Figure 2. When interpreting EM seafloor data, it is assumed that the interstitial fluid is seawater. Although, for most cases, interstitial salinity displays little variation, close to freshwater seeps or concentrated brine pools the salinity dependence of resistivity may become more important. Consequently, the occasional presence of fresh water within sediment pores, which is much more resistive than seawater, will yield lower apparent porosity estimates that are in fact related to the increase of interstitial fluid resistivity rather than to changes in sedimentary structure.

Evidence of fresh/low salinity groundwater signature in EM data

Results of an EM survey conducted on the Eel River shelf, offshore Northern California, show extremely low apparent porosity measurements (as low as 10% on the 40 m receiver) that are hard to be explained by changes in sediment porosity (Figure 3) (Evans *et al.*, 1999). The low apparent porosities were observed on the inner shelf at water depths less than 60 m. Even though the 40 m receiver recorded the lowest apparent porosity values, the 13 m and 4 m receivers also recorded relatively low values, indicating that the low apparent porosities extend upward in the sediment column to within 1–2 m beneath the seafloor. Such low porosities are unlikely to occur within sediments in the high deposition rate environment of this portion of the shelf. Evans *et al.* (1999) ruled out the effects of the underlying Tertiary and Cretaceous basement rocks or the effects of high consolidation of the sediments as the cause for the anomalously low apparent porosities. The authors suggested three explanations for the measured high resistivities: (a) calcium carbonate precipitation as methane migrates to the seafloor; (b) occurrence of low salinity groundwater within sediment pores or (c) free gas in the sediment.

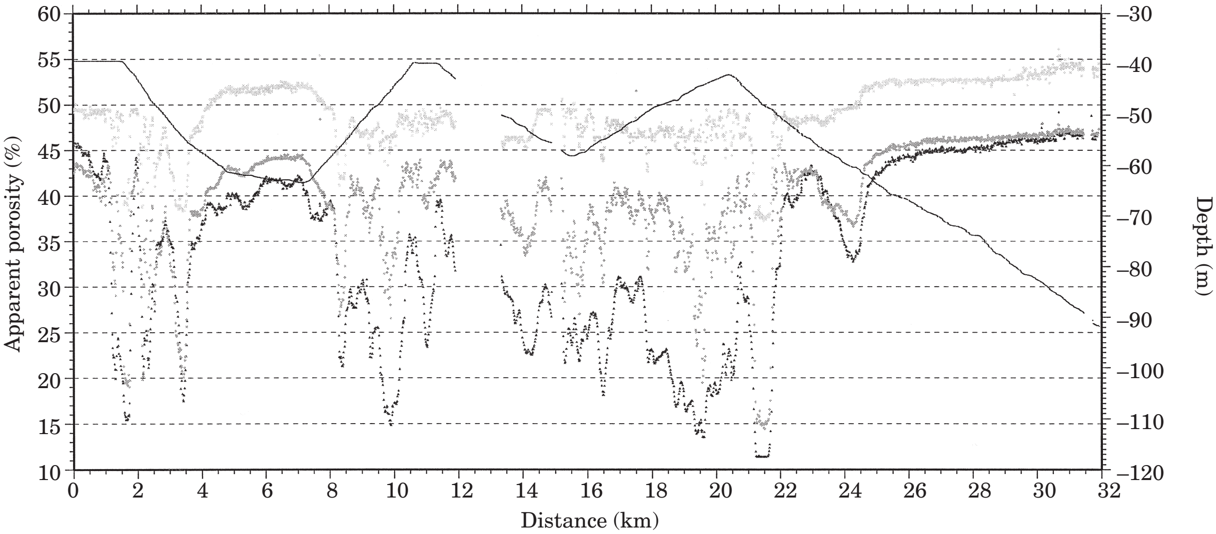

Figure 3. Low apparent porosities measured off Northern California (after Evans *et al.*, 1999). See Figure 2 for legend.

Additional observations are required in order to prove whether fresh water is the cause of the high resistivities measured off California. Our aim is to demonstrate that fresh water is a geologically feasible explanation.

The discrepancy between real porosity and apparent porosity predicted by the EM system that could arise due to changes in porewater salinity was shown by Evans *et al.* (1999) for two porewater salinities. A porewater salinity of 9·4 (resistivity = 1 Ωm) would cause a sediment with a true porosity of 40% to have an apparent porosity of only 17% (Figure 4). As the porewater becomes fresher (salinity = 0·72), it would cause the porosity to appear to be less than 5%. This relationship alone suggests that freshwater discharge along the California Margin could explain the low apparent porosities zone associated with the observed resistivity pattern. The remaining issue is whether porewater salinities this fresh are realistic in the subsurface, or whether mixing would occur to such an extent that the porewater would have a conductivity indistinguishable from that of seawater.

In situ **measurements of fresh and low salinity porewater within shallow marine sediments**

Hathaway *et al.* (1979) drilled 19 cores on the continental shelf from Cape Cod, MA, to Northern Florida and noted that fresh or slightly brackish waters occur along much of the Atlantic continental shelf. In general, very low salinities (less than 1·8) are found at distances of less than about 16 km off the Delaware-Maryland-New Jersey coast but as much as 120 km off the Florida coast. As noted by the authors, the salinity profile measured offshore Maryland at a water depth of 20 m, shown in Figure 5, is typical of sites where an aquifer containing relatively fresh water underlies a confining bed of low permeability. The same pattern was observed on Georges Bank about 250 km off the Massachusetts coast, but caving and collapse of Pleistocene glacial-outwash sands and gravels stopped the drill at relatively shallow depths. The most striking documentation of low salinity water along the continental shelf was obtained in a transect of five core holes across the shelf east of Barnegat Light, New

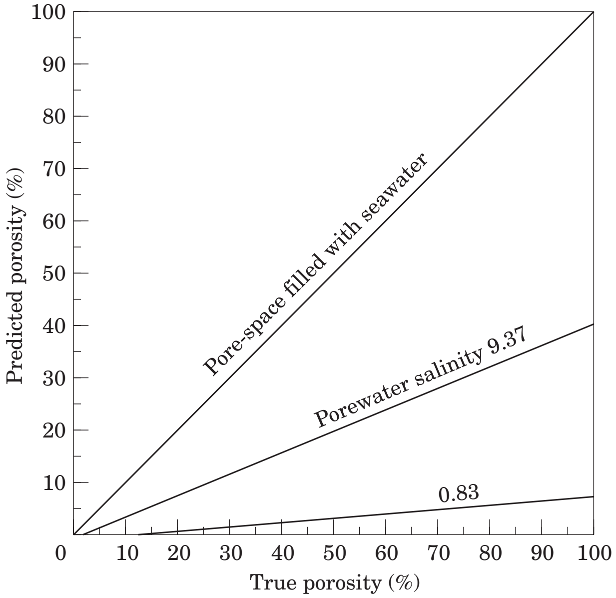

Figure 4. Relation between predicted porosity and true porosity as a function of interstitial fluid salinity (from Evans *et al.*, 1999).

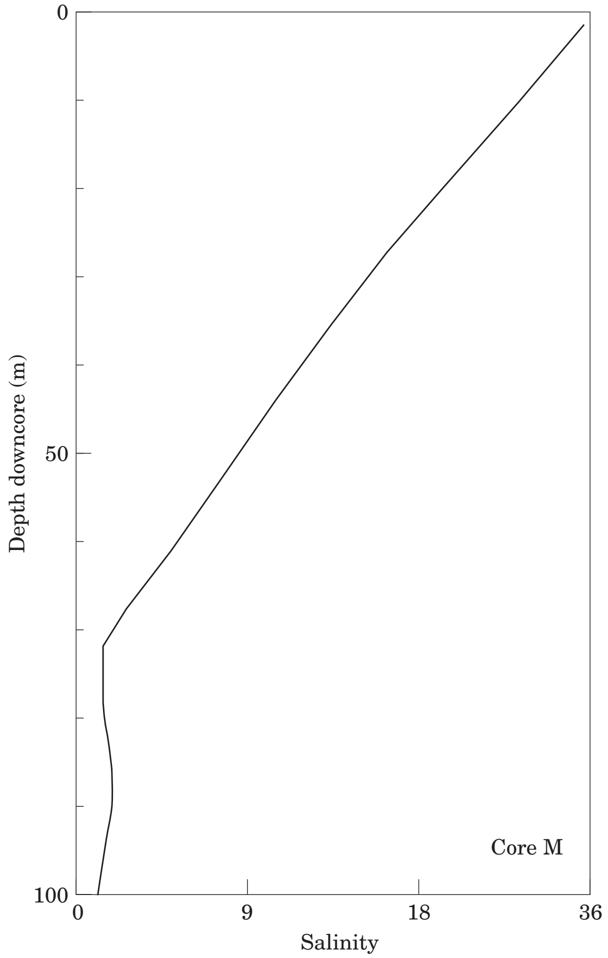

FIGURE 5. Typical sub-bottom salinity-depth profile of sites where an aquifer containing relatively fresh water underlies a confining bed of low permeability. This core was collected offshore Maryland at a depth of 20 m (after Hathaway *et al.*, 1979).

Jersey. The salinity cross-section illustrated in Figure 6 shows that relatively fresh groundwater (salinity=9) forms a flat-lying lens extending more than 100 km offshore to water depths over 75 m. The minimum salinity value found was 1·5. The crossing of lithologic and stratigraphic boundaries by the isohalines and the extent of low salinity water far offshore New Jersey and Massachusetts suggest that, in the Northern and Middle Atlantic segments, relict Pleistocene waters are responsible for the observed phenomena (Hathaway *et al.*, 1979).

The occurrence of freshwater in the subsurface has also been documented in coastal environments. Based on salinity measurements of groundwater samples collected from wells, Cambareri and Eichner (1998) present an alongshore cross-section of submarine groundwater beneath Waquoit Bay, Cape Cod, MA (Figure 7). The salinity of the bay water ranged between 26 and 30 during a tidal cycle. Along well #2 fresh groundwater (salinity=1) was found 4·5 m below mean sea level and, along wells #3 and #4, fresh water was found at approximately 13·5 m below sea level. Such porewater salinities reflect the discharge of fresh water from the unconfined Cape Cod Aquifer, which is 100 to 120 m thick beneath Waquoit Bay. The aquifer is bounded by marine water at its margins and less permeable deposits of till and bedrock below (LeBlanc *et al.*, 1986; Cambareri & Eichner, 1998).

Modelling low salinity groundwater signatures on EM data

In order to assess the impact of fresh or low salinity porewater on EM measurements, six sub-bottom salinity-depth profiles presented previously were used to model EM responses. The profiles (or cores) were selected as representative of realistic situations of SGWD, although in some cases their structure was simplified for modelling purposed [Figure 8(a)]. The methods followed in our modelling are illustrated in Figure 9.

For each given profile (or core) considered, resistivity values of discrete layers down the profile were computed, using the salinity records to determine the porewater conductivity (Perkin & Lewis, 1980). Assuming a homogenous porosity structure of 42% for all profiles and based on the porewater resistivity values obtained from the salinity profiles, Archie's Law (Equation 1) was then used to compute the measured resistivity of each layer. The porosity assumption is consistent with surface (top 20 m) sand sized sediments that are expected to occur on inner continental shelves and is based on values seen off the New Jersey margin in an EM survey (Evans *et al.*, 2000). Although in normal circumstances porosity will decrease with depth, we have chosen to keep it constant in order to clearly demonstrate the impact of porewater salinity variation on the data. According to studies presented by Cheesman *et al.* (1993) and Evans *et al.* (1999), the free parameter *m* was set to 1·8.

When interpreting seafloor measurements, Archie's Law is used to convert measured resistivity to porosity, under the assumption that the interstitial fluid salinity is that of seawater. If this latter assumption is wrong, and the porewater is fresher than seawater, then, as mentioned above, the porosity will be underpredicted. To assess more fully the extent of such underprediction, we solved Archie's Law for porosity using the measured resistivities obtained in the

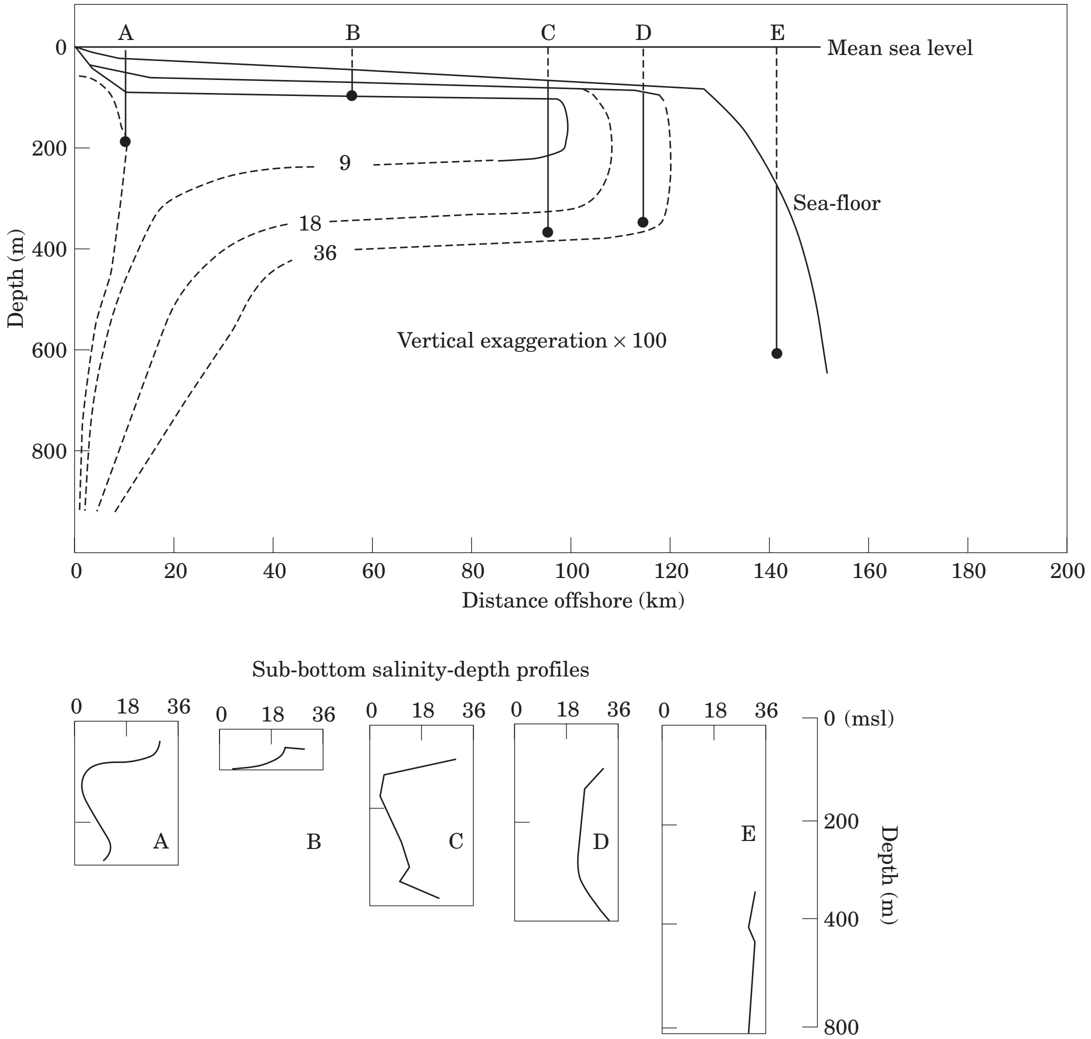

Figure 6. Sub-bottom salinity-depth cross-section of the continental shelf off New Jersey, Eastern U.S. Relatively fresh groundwater forms a flat-lying lens extending more than 100 km offshore. The porewater salinity contours presented are based on porewater salinity measurements down the cores indicated by letters A through E (after Hathaway *et al.*, 1979).

previous step under the assumption that the interstitial fluid is seawater (low resistivity). Not surprisingly, the computed apparent porosities differ significantly from our chosen sediment porosity of 42·5% [Figure 8(a)].

The next step in our analysis aims to show how field data might appear as the EM system transitions from a region with normal porewater salinity to a fresh water bearing region. Using the profiles shown in Figure 8(a) we constructed a series of pseudo-2D resistivity models. The model was discretized onto a grid with 20 columns. Columns 1–10 are described by a reference porewater salinity-depth profile, and columns 11–20 represent the anomalous salinity profile. For the profiles offshore the Eastern U.S. shelf, we have assumed a uniform salinity structure as the reference profile, whereas the anomalous profile is the freshwater bearing structure. When modelling the data from Waquoit Bay we have constructed profiles that reflect the porewater salinity variation in adjacent wells, and in this case both profiles are freshwater bearing regions. At each depth interval in each column of the model, we performed a lateral averaging of log (resistivity) between columns using a Gaussian weighting function. For example, in column 5 the closest lateral change in resistivity occurs in column 11, and, in this case, the weighting function is constructed to return the original column 5 resistivity profile. Closer to the boundary between the two parts of the model, in columns 8–12, the weighted resistivities represent a lateral average between the two models. After this averaging is performed, and

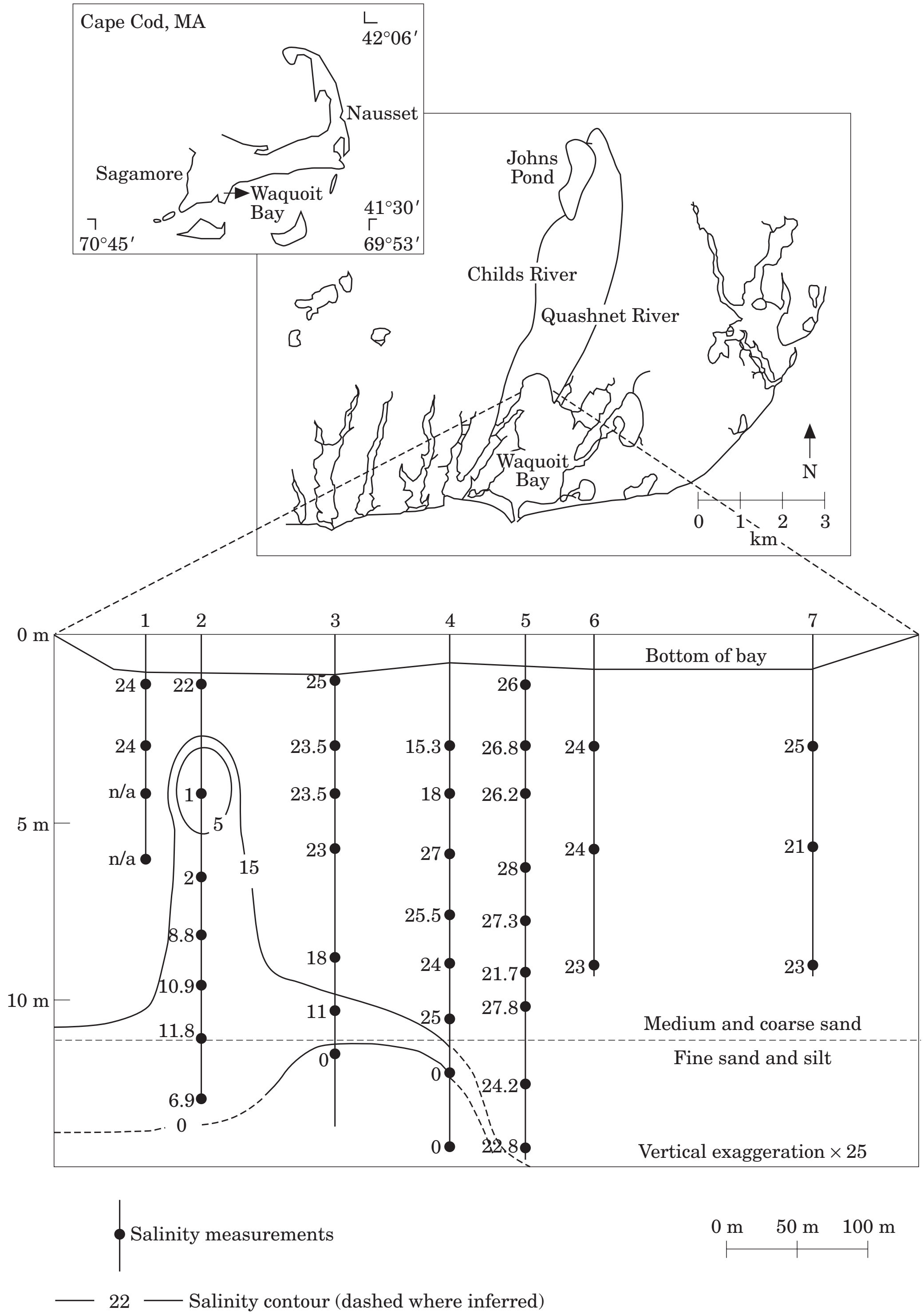

FIGURE 7. Well locations and salinity measurements of porewater beneath Waquoit Bay, MA, displaying the presence of fresh and low salinity groundwater within sediments pores (after Cambareri & Eichner, 1998).

new resistivity-depth profiles for each column are obtained, each column is treated as a 1D resistivity profile, and the magnetic field amplitudes and phases that the towed EM system would record above such a 1D layered structure are calculated. This method is not a true 2D response calculation as the horizontal spatial scale is not well determined and is dependent on the Gaussian weighting function, nor is it clear that

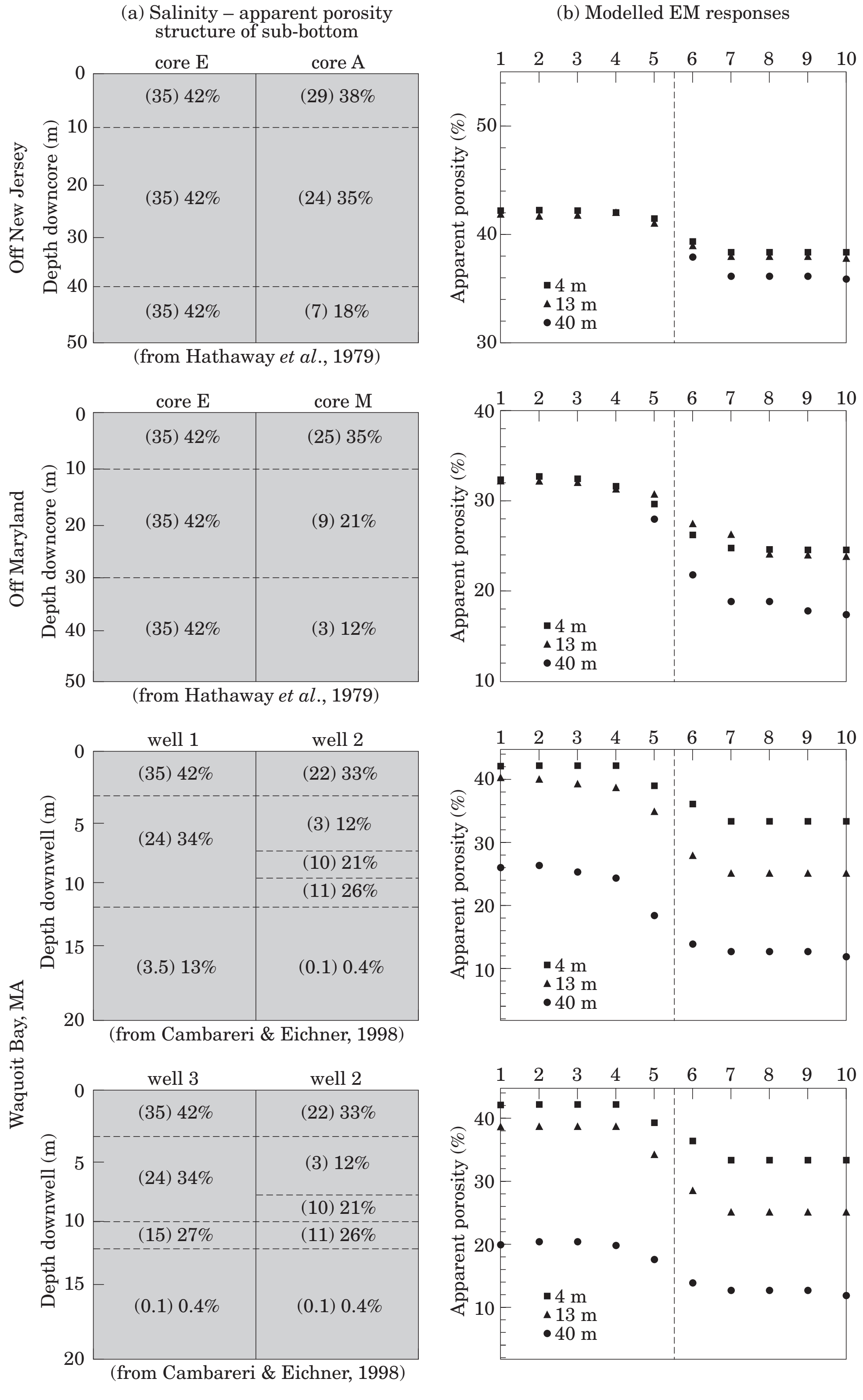

FIGURE 8. (a) Salinity-apparent porosity structure of the sub-bottom profiles used to model EM responses to the presence of fresh and low salinity porewater. Salinity values are in parenthesis followed by the corresponding apparent porosity values. Note that the vertical scale of the profiles vary between profiles off the U.S. East coast and Waquoit Bay, MA. (b) Synthetic EM responses to the sub-bottom salinity-depth profiles illustrated in (a). The vertical axis represents apparent porosity and the horizontal axis represent the space coordinate. The distance between points is approximately 20 m. Points 1 to 5 represent the left core modelled, and points 6 to 10 represent the right core modelled. Only 10 of the 20 points calculated are shown. Occasions where the 13 m receiver response is higher than the 4 m receiver reflect the addition of numerical noise to the synthetic data and indicate that the system is capable of a resolution of 1–2% in apparent porosity.

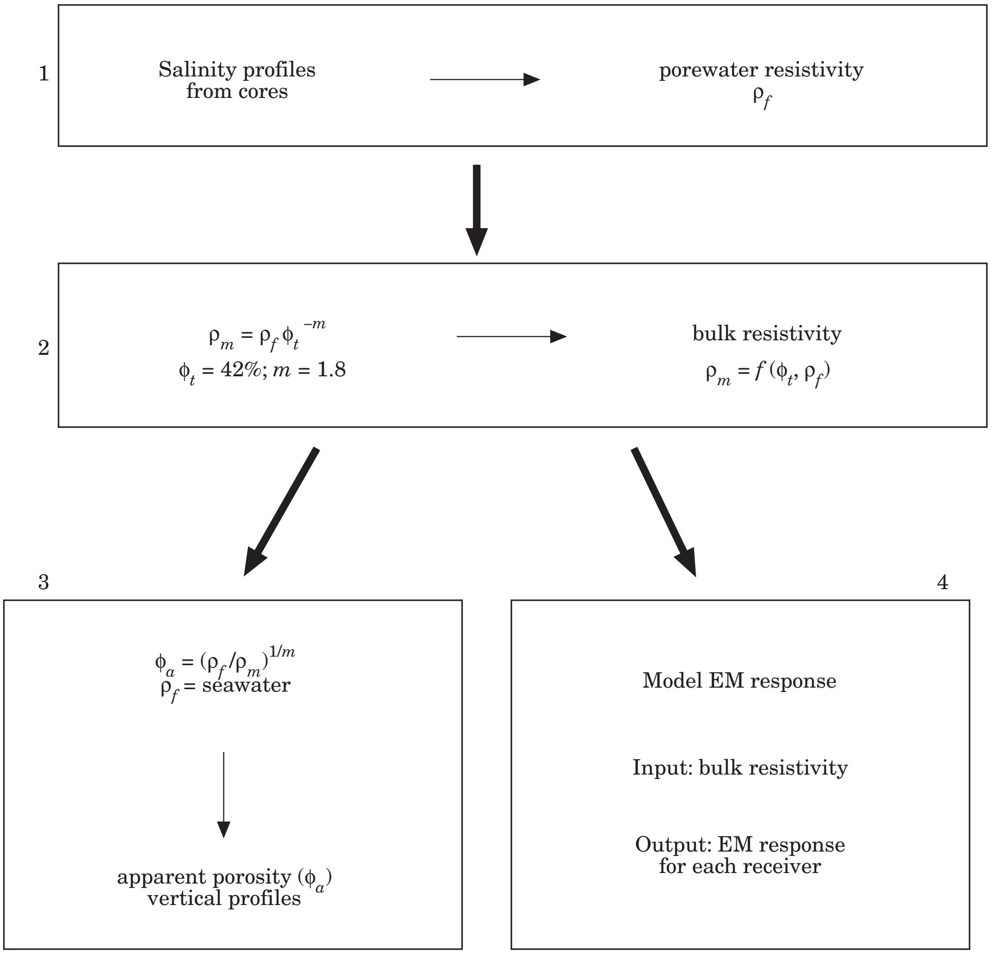

FIGURE 9. Flow diagram of the methodology followed in the present study.

the process of averaging log (resistivity) results in accurate responses. However, field data are seen to be well behaved as the system crosses lateral changes in resistivity, and our numerical approach produces responses that mimic the observed behaviour and that are correct at the edges of the model, for each 1D profile (Evans *et al.*, 2000). Appropriate errors, based on field data, were applied to the synthetic amplitudes and phases calculated across the model. The amplitude and phase values for each receiver were then inverted for an apparent resistivity and from there to an apparent porosity using our standard field techniques.

The net result of this process is a series of apparent porosity profiles for each of the three receivers shown in Figure 8(b). As expected, the most prominent responses were obtained across the Waquoit Bay section, where the lowest salinities were measured (minimum of 0). Since the system resolves the structure of the uppermost 20 m of the seafloor only, it does not respond to the very low salinity layers present in the cores off New Jersey and off Maryland below 30 m. This aquifer should be detectable further across the shelf where it approaches and eventually discharges onto the seafloor.

Discussion

The EM response models presented show that interstitial fresh and low salinity water do have a significant impact on measured apparent porosities. Porosity profiles that otherwise would have a constant value of 42% were imaged as complex structures, with vertical and horizontal variations, showing porosity values as low as 12% in the Waquoit Bay models. The U.S. east shelf cores models do not show such extreme values because the very low salinity layers are located below the maximum vertical penetration capability of the EM system. However, porewater salinities ranging between 29 and 9 still generate appreciable porosity variations, of around 9%. Even though there is ambiguity in the identification of freshwater signals in apparent porosity measurements, apparent porosity changes due to SGWD are expected to be spatially abrupt and too large to be explained by a drop in formation porosity alone; especially if co-located seismic data show a generally layered structure.

Based on the modelling results presented, very low salinity waters (between 0 and 10) would have to be present within the top 20 m of the sediments to cause the observed response in California. Even though none of the cores analysed by Hathaway *et al.* (1979) show such salinity structure (low salinity water was detected mainly below 10 m to 20 m downcore), it has become evident that substantial fresh water lies trapped within the sediments across the U.S. eastern continental shelf. Additionally, global occurrence of offshore artesian seeps have been documented by many authors (Barans & Henry, 1984; Kohout *et al.*, 1988; Moore & Shaw, 1998; Kohout, 1966; White & Ross, 1979; Emery & Uchupi, 1989; Driscol & Uchupi, 1997). The presence of fresh or low salinity groundwater within the top 20 m of continental shelf sediments is thus a viable possibility and should not be discarded to explain the very low apparent porosities recorded across the northern California shelf. The Californian coast is more tectonically modified and faulted than the east coast, potentially providing conduits for submarine groundwater release. Cores and tracers studies in the area are required to test the described hypothesis.

Even though EM measurements alone are not enough to confirm the presence of fresh to low salinity porewater within sediments, it has been demonstrated that low salinity porewater does have a measurable impact on EM data, suggesting the tool is a potentially viable means of detecting submarine groundwater discharge. The main advantage of such a method is the possibility of surveying large areas of shelf and coastal environments in a relatively short time. Thus EM could provide important information for the detection of areas of occurrence of SGWD that later could be surveyed through more specific and quantitative methods such as geochemical tracers. It is important to keep in mind, though, that limitations to the use of methods like geochemical tracers may also limit the use of EM to detect SGWD. As discussed by Moore and Shaw (1998), direct injections of subsurface fluids from coastal aquifers onto the continental shelf cause large chemical anomalies in the bottom water on the shelf, but in many circumstances these fluids are a mixture of groundwater and seawater that has reacted with aquifer solids. Since the extent of mixing between fresh and seawater is not known, we have no guarantee that SGWD events will always present a detectable salinity signal to the EM system. In some cases, even though there is no detectable salinity signal, the ability of EM to measure sub-bottom porosity may be useful in determining the sub-bottom hydrology.

Conclusions

The presence of low salinity porewater within sediments is a plausible explanation for the low apparent porosity response of the EM survey off Northern California, but corroboration of this hypothesis still depends on additional data such as cores and geochemical groundwater tracers studies.

Modelled EM responses for porewater salinity vertical profiles indicate that fresh or low salinity porewater has a significant effect on EM data. For a true porosity of 42·5%, the modelled apparent porosities decrease as much as 11% with interstitial salinities close to 0·5. Even though salinity values must range between 1 and 10 within the top 20 m of the sediment column to produce EM apparent porosity estimates of the order of 10%, interstitial salinity variations from 22 to 29 are enough to produce EM responses 10% to 4·5% less than the true porosity of the sediment. Field data as well as additional studies considering varying porosity structures are necessary to improve our quantitative understanding of the impact of low salinity porewater on EM data.

Acknowledgements

We would like to thank Billy Moore and Prof. Antonio Stefanon for their helpful reviews. FGH is funded by a fellowship from CNPq—Brazil. RLE received support from ONR grant N00014-98-1-0507 through the office of Dr J. Kravitz. WHOI contribution number 10356.

References

Anthony, S. S. 1992 Electromagnetic methods for mapping freshwater lenses on Micronesian atoll islands. *Journal of Hydrology* **137,** 99–111.

Archie, G. E. 1942 The electrical resistivity log as an aid in determining some reservoirs characteristics. *Journal of Petroleum Technology* **5,** 1–8.

Banks, W. S. L., Paylor, R. L. & Hughes, W. B. 1996 Using thermal-infrared imagery to delineate ground-water discharge. *Ground Water* **34,** 434–443.

Barans, C. A. & Henry, V. J. 1984 A description of the shelf edge ground fish habitat along the southeastern United States. *Northeast Gulf Science* **7,** 77–96.

Cable, J. E., Burnett, W. C., Chanton, J. P. & Weatherly, L. G. 1996 Estimating groundwater discharge into the northeastern Gulf of Mexico using radon-222. *Earth and Planetary Science Letters* **144,** 591–604.

Cable, J. E., Burnett, W. C. & Chanton, J. P. 1997 Magnitude and variations of groundwater seepage along a Florida marine shoreline. *Biogeochemistry* **38,** 189–205.

Cambareri, T. C. & Eichner, E. M. 1998 Watershed delineation and ground water discharge to a coastal embayment. *Ground Water* **36,** 626–634.

Corbett, D. R., Brunett, W. C., Cable, P. H. & Clark, S. B. 1997 Radon tracing of groundwater input into Par Pound, Savannah River Site. *Journal of Hydrology* **203,** 209–227.

Cambareri, T. C. & Eichner, E. M. 1998 Watershed delineation and ground water discharge to a coastal embayment. *Ground Water* **36,** 626–634.

Corbett, D. R., Burnett, W. C., Cable, P. H. & Clark, S. B. 1997 Radon tracing of groundwater input into Par Pound, Savannah River Site. *Journal of Hydrology* **203,** 209–227.

Chave, A. D., Constable, S. C. & Edwards, R. N. 1987 Electrical exploration methods for the seafloor. In *Electromagnetic Methods in Applied Geophysics* vol. 2, Application. (Nabighiam, M., ed.), Society of Exploration Geophysics, Tulsa, pp. 931–966.

Cheesman, S. J., Edwards, R. N. & Chave, A. D. 1987 On the theory of sea-floor conductivity mapping using transient electromagnetic systems. *Geophysics* **52,** 204–217.

Cheesman, S. J., Law, L. K. & St. Louis, B. 1993 A porosity survey in Hecate Strait using a seafloor electro-magnetic profiling system. *Marine Geology* **110,** 245–256.

Church, T. M. 1996 An underground route for the water cycle. *Nature* **380,** 579–580.

Constable, S. C. 1990 Marine electromagnetic induction studies. *Surveys in Geophysics* **11,** 303–327.

Driscoll, N & Uchupi, E. 1997 The importance of gas and groundwater seepage in landscape and seascape evolution. *Thalassas* **13,** 35–48.

Emery, K. O. & Uchupi, E. 1972 The Western North Atlantic: Topography, rocks, structure, water, life and sediments. American Association of Petroleum Geologists Memoirs, 532 pp.

Emery, K. O. & Uchupi, E. 1984 The Geology of the Atlantic Ocean. Springer-Verlag, New York, 1050 pp.

Evans, R. L., Law, L. K., St. Louis, B. & Cheesman, S. 1999 The shallow porosity structure of the Eel River shelf, northern California: results of a towed electromagnetic survey. *Marine Geology* **154,** 211–226.

Evans, R. L., Law, L. K., St. Louis, B. & Cheesman, S. 2000 Buried Paleo-channels on the New Jersey Continental Margin: channel porosity structures from electromagnetic surveying. *Marine Geology* **170,** 381–394.

Fitterman, D. V. & Stewart, M. T. 1986 Transient electromagnetic sounding for groundwater. *Geophysics* **51,** 995–1005.

Hathaway, J. C., Poag, C. W., Valentine, P. C., Miller, R. E., Schultz, D. M., Manheim, F. T., Kohout, F. A., Bothner, M. H. & Sangrey, D. A. 1979 U.S. Geological Survey Core Drilling on the Atlantic Shelf. *Science* **206,** 515–527.

Jackson, P. D., Taylor-Smith, D. & Stanford, P. N. Resistivity-porosity particle shape relationships for marine sands. *Geophysics* **43,** 1250–1268.

Kohout, F. A. 1966 Submarine springs. In *The Encyclopedia of Oceanography* (Fairbridge, R. W., ed.). Reinhold, New York, pp. 878–883.

Kohout, F. A., Meisler, F. W., Johnston, R. H., Leve, G. W. & Wait, R. L. 1988 *Hydrogeology of the Atlantic Continental Margin*, (Sheridan, R. E. & Grow, J. S., eds). The Geological Society of America, Boulder, CO, pp. 463–480.

LeBlanc, D. R., Guswa, J. H., Frimpter, M. H. &Londquist, C. J. 1986 *Groundwater Resources of Cape Cod, Massachusetts.* U.S. Geological Survey Hydrologic Investigations Atlas 692, 4 plates.

Mosher, D. & Law, L. K. 1996 Application of concurrent marine EM and marine seismic high resolution profiling, British Columbia, Canada. *Journal of Environmental and Engineering Geophysics* **1,** 215–228.

Moore, W. S. 1996 Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. *Nature* **380,** 612–614.

Moore,, W. S. & Shaw, T. J. 1998 Chemical signals from submarine fluid advection onto the continental shelf. *Journal of Geophysical Research* **103,** 21543–21552.

Naimi, A. I. 1965 *The ground water of northeastern Saudi Arabia*. Fifth Arab Petroleum Congress, Cairo, March 16–23, 1965, 26 pp.

Perkin, R. G. & Lewis, E. L. 1980 The Practical salinity scale 1978: fitting the data. *I.E.E.E. Journal of Oceanography Engineering* **5,** 9.

Roy, K. K. & Elliot, H. M. 1980 Resistivity and IP survey for delineating saline water and fresh water zones. *Geoexploration* **18,** 145–162.

Ruppel, C., Schultz, G. & Kruse, S. 2000 Anomalous freshwater lens morphology on a strip barrier island. *Groundwater* **38,** 872–881.

Shaw, T. J., Moore, W. A., Kloepper, J & Sochaski, M. A. 1998 The flux of barium to coastal waters of the southeastern USA: the importance of submarine groundwater discharge. *Geochimica et Cosmochimica Acta* **62,** 3047–3054.

Tsunogai, U., Ishibashi, J., Wakita, H., Gamo, T., Masuzawa, T., Nakatsuka, T., Nojiri, Y. & Nakamura, T. 1996 Fresh water seepage and pore water recycling on the seafloor: Sagami trough subduction zone, Japan. *Earth and Planetary Science Letters* **138,** 157–168.

Uchiyama, Y., Nadaoka, K., Rolke, P., Adachi, K. & Yagi, H. 2000 Submarine groundwater discharge into the sea and associated nutrient transport in a sandy beach. *Water Resources Research* **36,** 1467–1479.

White, R. S. & Ross, D. A. 1979 Tectonics of the Western Gulf of Oman. *Journal of Geophysical Research* **84,** 3479–3489.