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Detecting submarine groundwater discharge with synoptic surveys of sediment resistivity, radium, and salinity

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Detecting submarine groundwater discharge with synoptic surveys of sediment resistivity, radium, and salinity

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[1] A synoptic geophysical and geochemical survey was used to investigate the occurrence and spatial distribution of submarine discharges of water to upper Nueces Bay, Texas. The 17 km survey incorporated continuous resistivity profiling; measurements of surface water salinity, temperature, and dissolved oxygen; and point measurements of dissolved Ra isotopes. The survey revealed areas of interleaving, vertical fingers of high and low conductivity extending up through 7 m of bay bottom sediments into the surface water, located within 100 m of surface salinity and dissolved Ra maxima along with peaks in water temperature and lows in dissolved oxygen. These results indicate either brackish submarine groundwater discharge or the leakage of oil field brine from submerged petroleum pipelines. **Citation:** Breier, J. A., C. F. Breier, and H. N. Edmonds (2005), Detecting submarine groundwater discharge with synoptic surveys of sediment resistivity, radium, and salinity, *Geophys. Res. Lett.*, *32*, L23612, doi:10.1029/2005GL024639.

1. Introduction

[2] Direct discharge of groundwater (fresh, brackish, or saline) to bays and estuaries is a significant source of water and nutrients to the coastal ocean [*Moore*, 1999]. Submarine discharges have been detected in numerous areas using seepage meters and surface water enrichments in tracers such as Ra, Rn, and CH_4 [e.g., *Burnett et al.*, 2001; *Charette et al.*, 2003]. In some cases these submarine discharges clearly consist of advected groundwater; however, additional possibilities include seawater recirculation, density driven convection, the release of sediment pore water due to sediment compaction or resuspension, or leakage of oilfield brines from submerged petroleum pipelines [*Rama and Moore*, 1996; *Krest et al.*, 1999; *Simmons et al.*, 1991]. A complete understanding of the implications of submarine water discharge requires that we treat these sources separately and identify and quantify their individual contributions.

[3] Locating and determining the source of a suspected submarine discharge is difficult because there is significant spatial and temporal variability in the flux [*Burnett and Dulaiova*, 2003]. Current techniques used to measure submarine discharge do not adequately relate estimates at large and small scales. While natural chemical tracers are useful at estimating total discharge to an area they cannot be used to pinpoint the source of discharge because mixing weakens and spatially integrates the signal. Conversely, while direct measurements with seepage meters can be used to measure discharge at a point they do not capture spatial variation in the system and can miss significant localized discharges altogether. Additional techniques that can provide more detailed spatial and temporal data are needed to complement existing measurements.

[4] Sediment resistivity profiling is a common geophysical technique that can delineate transitions between sediment facies as well as salinity gradients within bay bottom sediments. The application of sediment resistivity measurements to investigating submarine groundwater discharge is relatively new [e.g., *Bratton et al.*, 2004; *Swarzenski et al.*, 2004; *Turner and Acworth*, 2004]. In August 2004, we conducted a study of Nueces Bay using continuous resistivity profiling with synoptic sampling of dissolved Ra isotopes, salinity, water temperature, and dissolved O_2.

[5] Our goals in this study were to 1) further develop the application of continuous resistivity profiling and synoptic geochemical measurements for submarine discharge studies and 2) apply it to our continuing investigation of submarine discharge to Nueces Bay, Texas. Our previous surveys of dissolved Ra in Nueces Bay revealed generally high dissolved Ra activities particularly at the head of the bay. A Ra mixing model indicated a submarine water discharge similar in magnitude to the Nueces River discharge (J. A. Breier and H. N. Edmonds, High ^{226}Ra and ^{228}Ra activities in Nueces Bay, Texas indicate submarine saline discharges, submitted to *Marine Chemistry*, 2005, hereinafter referred to as Breier and Edmonds, submitted manuscript, 2005); this discharge is larger than expected given the arid conditions, low hydraulic gradient, and small tidal range. We hypothesized that this Ra flux could be supported by density driven convection [*Simmons et al.*, 1991] of hypersaline marsh water or by leakage of oilfield brine from submerged petroleum wells and pipelines (Breier and Edmonds, submitted manuscript, 2005). Both of these possibilities would be seen as vertical fingers of higher conductivity on a conductivity profile (inverted resistivity profile) and should be coincident with high salinity and dissolved Ra in the overlying surface waters.

2. Methods

2.1. Study Area

[6] Nueces Bay (1m mean depth) is a secondary bay of the Corpus Christi Bay system of Texas. At its western end, the Nueces River delta comprises a low area of salt marshes, mudflats, and shallow water (Figure 1). The Nueces River outlet on the south shore and White's Point peninsula on the

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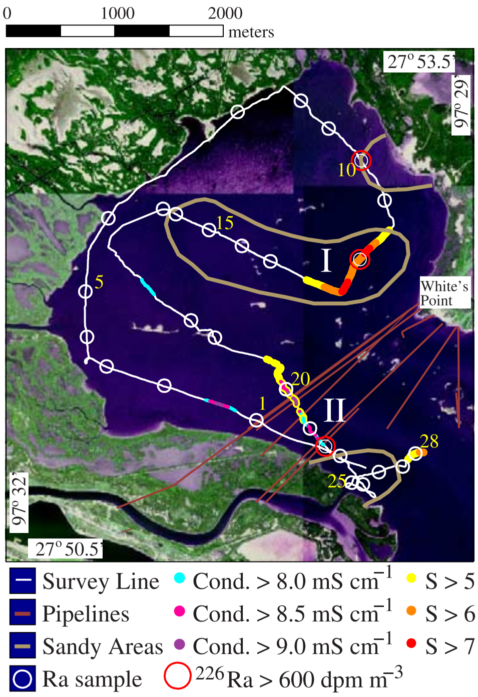

Figure 1. Survey with Ra samples marked by white circles (every fifth and last sample labeled). Highest activity Ra samples are marked by red circles. Areas of high surface salinity are yellow to red and high mean subsurface conductivity are cyan to purple. Area I, west of White's Point, had subsurface conductivity features within 100 m of surface Ra, salinity, and water temperature highs and dissolved O_2 lows. Area II, containing several petroleum pipelines, had subsurface conductivity features, high Ra and surface salinity, and low dissolved O_2.

north shore define a sheltered portion of the bay adjacent to the delta. This portion of the bay was selected for resistivity profiling because of high dissolved Ra activities found during four previous Ra surveys (Breier and Edmonds, submitted manuscript, 2005). Nueces Bay experiences dramatic annual swings in salinity driven by high evaporation rates and periods of intense precipitation. During the summer, hypersaline conditions are common particularly in the salt marsh. Nueces Bay salinity is typically between 15 and 30 however this survey followed recent rain storms and salinity in the upper bay was 2 to 7.

2.2. Continuous Resistivity Profiling

[7] Continuous resistivity profiling is a controlled source electromagnetic technique for measuring the vertical and horizontal distribution of electrical resistivity in submarine sediments [*Jones*, 1999]. The bulk resistivity of sediments can be measured using a dipole-dipole electrode array, one dipole to create an electric current in the sediments and another to measure the resulting potential field. The depth of the measurement is proportional to the spacing of the dipoles. Surveys are conducted by translating the dipoles along the surface. In practice, dipole spacing is varied by alternating between different electrode pairs and in the case of marine studies surveying can be done continuously by towing the electrode array behind a boat. Actual resistivity at a specific depth and location is estimated using an inverse modeling algorithm similar to that used in seismic profiling.

[8] The study area was surveyed on 14 August 2004 using an Advanced Geosciences (AGI) Marine Supersting R8-IP resistivity meter with a towed array of 8 electrodes. The survey (Figure 1) focused on the shoreline looking for evidence of density driven circulation. The river mouth and channel were also carefully surveyed looking for changes in sediment structure associated with the river. Boat speed was kept below 4 km hr^{-1} to maintain electrode contact with the water. Position and water depth were recorded with resistivity data using a Lowrance GPS and sonar connected to the resistivity controller. Data were postprocessed with an inverse modeling algorithm developed by AGI. Resistivity results are reported as their inverse, conductivity (mS cm^{-1}), to facilitate comparison with surface salinity.

2.3. Ra Isotopes

[9] ^{226}Ra, ^{228}Ra, ^{224}Ra, and ^{223}Ra are members of the three naturally occurring radioactive decay series and are each the product of Th decay. Their enrichment in aquifer and sediment pore waters makes Ra isotopes natural tracers of groundwater discharge to the coastal ocean. Their range in half-life of 3.66 days to 1600 years renders them responsive to processes occurring at a variety of rates and time scales [*Rama and Moore*, 1996].

[10] Surface water samples (25 L) for dissolved Ra analysis (n = 28) were collected from approximately 30 cm below the surface while the boat was moving using a sampling loop continuously pumped at 2 L min^{-1}. Samples were filtered in the laboratory through a 1 μm polypropylene cartridge filter and the Ra extracted onto a subsequent column of MnO_2-impregnated acrylic fiber at a flow rate of less than 1 L min^{-1}. Short lived ^{224}Ra and ^{223}Ra were measured using the delayed coincidence counting method of *Moore and Arnold* [1996]. ^{226}Ra and ^{228}Ra were then measured on a high purity Ge well gamma detector following the procedure outlined by *Rutgers van der Loeff and Moore* [1999].

2.4. Additional Data

[11] Surface water salinity, temperature, and dissolved O_2 were recorded with a YSI model 6000 sonde, set in a flow cell in the surface water sampling loop. In April 2005, a ground truthing survey was conducted to classify the surficial bay bottom sediments at each Ra sample location. Sediment cores (50 cm) were used to visually classify deposits by silt, clay, and sand fraction. Locations of oyster reefs, pipelines, and emergent petroleum well heads were also noted.

3. Results and Discussion

[12] The entire 17 km long sediment conductivity profile, with details of notable sections, is shown in Figure 2. Conductivity varies in response to several factors (temperature, sediment type, pore water salinity, and porosity) and the inversion algorithm can produce false conductivity features from incorrect depth soundings. Therefore to avoid overinterpreting the profile, we have focused on the overall conductivity structure and on features which correlate with surface water data. Most of the survey profile consists of evenly stratified layers of lower conductivity surface waters

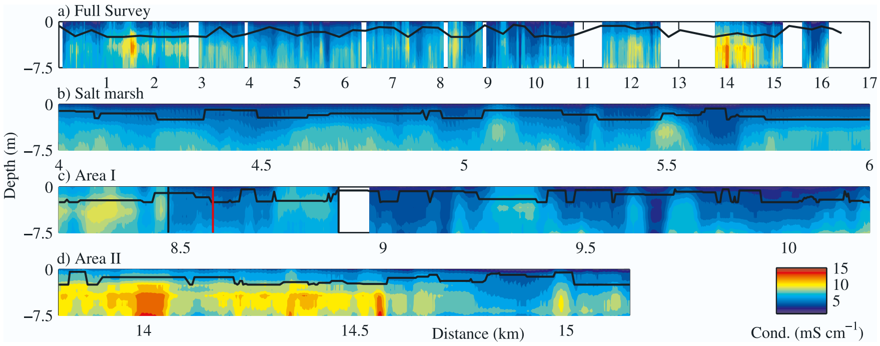

Figure 2. Results of the conductivity survey including a) the full survey path; b) a segment along the salt marsh shoreline; c) Area I, west of White's Point, with elevated surface salinity; and d) Area II containing pipeline indications and the Nueces River channel. In c), the location of the surface salinity maxima (S > 7) are indicated by vertical black lines and the survey maximum Ra activity (sample 12) by a vertical red line. Water depth is indicated by a black line in all panels.

and higher conductivity sediments (Figures 2a and 2b). This is consistent with low salinity surface waters overlying mud and clay sediments containing higher salinity pore water perhaps retained from past periods of higher salinity surface water. There is an area of low sediment conductivity (Figure 2c) in the center of the bay between km 8.5 and 11 (Figure 1, Area I). An area of high sediment conductivity (Figure 2d) occurs between km 13.5 and 14.7, with features which are probably buried petroleum pipeline cross-sections (Figure 1, Area II). The Nueces River channel cross section is also clearly visible near km 14.9 (Figure 2d). The interleaving low and high conductivity fingers in Area I at km 8.4, 8.8, 9.4, and 9.6 (Figure 2c) are suggestive of brackish water plumes discharging to the bay and appear to correspond with features in the surface water data. Similar features along the salt marsh (Figure 2b) do not correlate with the surface water data and are not discussed further as explained above.

[13] The conductivity fingers in Area I at km 8.4 and 8.8 extend from the bottom of the profile (7.5 m total depth) to the surface water and are within 100 m of the two surface salinity maxima (S > 7) at km 8.5 and 8.9 (Figures 1, 2c, and 3b). At these locations there are also peaks in surface water temperature and drops in dissolved O_2 (Figure 3). In addition sample 12 taken between these conductivity fingers had the highest dissolved Ra activity ($^{226}Ra > 600$ dpm m^{-3}) for all four isotopes (Figure 4). Such high spatial correlation between sediment conductivity and surface water chemistry suggests a submarine discharge in this area. Increased Ra and salinity (S > 5) along with decreased dissolved O_2 also occur from km 13.5 to 14.7 in Area II which contains the petroleum pipelines (Figures 2d, 3, and 4).

[14] It initially seems surprising that the strongest submarine discharge indications occurred in Area I as opposed to closer to the shoreline. Simple models predict that submarine groundwater discharge should be greatest at the shoreline where the hydraulic gradient is highest and bottom sediments are often more permeable; however, this neglects the actual complexity of coastal sediments [*Moore*, 1999]. In this case, ground truthing revealed an area in the bay center where sediments had a higher sand fraction than the margins (Figure 1). This corresponds with the area of low sediment conductivity between km 8.5 and 11, suggesting that the sandy, higher permeability sediments in this part of the bay are at least several meters deep. Sediments around the Nueces River and a portion of the north shore are also high in sand. Bottom sediments in the rest of the study area consist of low permeability silt, mud, and clay. Therefore groundwater discharge to the bay center vice the margins would be consistent with the actual bottom sediment distribution.

[15] The strong spatial correlation of sediment conductivity features with trends in surface water chemistry in Areas I and II suggests a causal relationship rather than a coincident source of surface water features such as tidal mixing or eddies. Possible connections between the sediment and surface water features include 1) brackish ground-

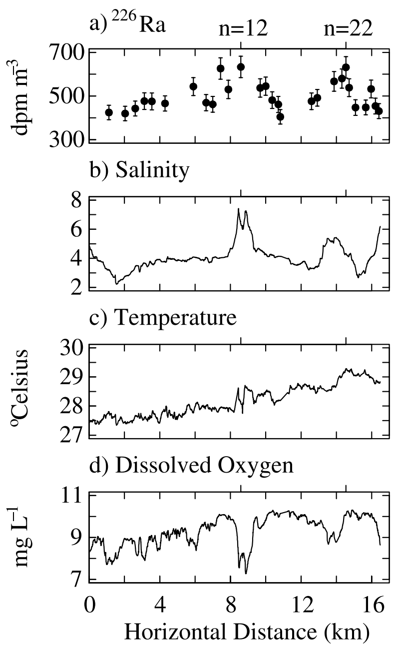

Figure 3. Results for a) dissolved ^{226}Ra (samples 12 and 22 are marked with ticks on all frames), b) surface salinity, c) water temperature, and d) dissolved O_2. Water temperature and dissolved O_2 generally increased during the course of the day. The influence of the Nueces River is apparent in the low surface salinity and dissolved ^{226}Ra activity near survey km 15.5; another surface salinity low near km 1.5 may be a plume or eddy of Nueces River water.

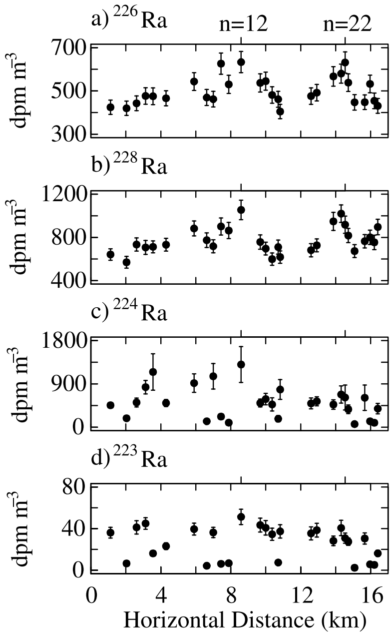

Figure 4. Results for dissolved a) ^{226}Ra, b) ^{228}Ra, c) ^{224}Ra, and d) ^{223}Ra. ^{226}Ra and ^{228}Ra activities exhibit similar trends, peaking in two locations. ^{223}Ra is nearly bimodal while ^{224}Ra shares both the trends of ^{223}Ra and those of ^{226}Ra and ^{228}Ra.

water discharge and 2) leakage of produced water from buried petroleum pipelines and wells. The known presence of pipelines in Area II suggests this as the source of the features we observed in this area. While the data in Area I are suggestive of brackish groundwater discharge, additional data such as seepage meter measurements or a time series of sediment resistivity and surface water chemistry measurements are necessary to determine whether the surface water features and conductivity fingers are directly related. Leakage of produced water from petroleum pipelines and wells in Area I is also possible. Such a brine would likely have all the characteristics seen in the surface water between km 8.4 and 8.9: high salinity, high dissolved Ra, elevated temperature, and low dissolved O_2. The mean dissolved ^{226}Ra activity of local produced water samples (n = 6) is 12,000 dpm m^{-3} [*Kraemer and Reid*, 1984]. Additional data such as the presence of hydrocarbons or low Br/Cl ratios are needed to conclude that pipeline or well leakage is occurring. Finally although we found little evidence of density driven convection at the shoreline of the salt marsh, we did not survey within the channels and bayous of the marsh, thus we cannot eliminate convection from the marsh as a discharge source.

4. Conclusions

[16] Synoptic surveying of sediment conductivity and surface water chemistry provided a more complete understanding of submarine discharges to Nueces Bay. Results suggest that at the head of Nueces Bay groundwater discharge and/or produced water leakage occurs largely in one, possibly two, relatively localized areas. This demonstrates how resistivity profiling can be used in a sequence of 1) chemical tracer assessments, 2) detailed synoptic surveys, and ultimately 3) targeted sampling and direct physical measurements. Future studies of Nueces Bay will focus on these areas looking for chemical evidence of produced water leakage from petroleum pipelines and direct physical measurements of seepage.

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