CONTINUOUS-RESISTIVITY PROFILING FOR COASTAL GROUND-WATER INVESTIGATIONS: THREE CASE STUDIES

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Abstract

Continuous-resistivity profiling (CRP) was used at three sites to investigate submarine ground-water discharge (SGD) and to delineate the subsurface saltwater/freshwater interface. At the first site, in Georgetown, South Carolina, CRP was used to locate possible areas of SGD in the Winyah Bay estuary. The data show evidence of SGD in the Pee Dee River, feeding into Winyah Bay, at approximately the location of the forest/marsh boundary. In Waquoit Bay, Massachusetts, CRP was used to further map the extent of SGD already measured by sea floor seepage meters and to delineate the subsurface saltwater/freshwater boundary. The data show evidence for a focused ground-water plume beneath the bay that may extend 350 meters (m) out from the shore. Finally, CRP was used in Orleans, Massachusetts, to verify a ground-water model prediction of freshwater-saturated sediments underlying an area of Cape Cod Bay, just west of Rock Harbor. The data support the prediction of freshwater-saturated sediments beneath the bay. Results from all three sites show the value of CRP in coastal ground-water investigations.

Introduction

Ground water-ocean interactions are important processes that have recently begun to draw the attention of oceanographers and hydrologists alike. Although it has long been recognized that submarine ground-water discharge (SGD) is an important pathway for nutrients to reach the ocean, recent observations demonstrate that SGD often contains higher concentrations of nutrients than surface waters (Burnett et al., 2002). This observation has significant implications for terrestrial contaminant transport to the ocean and also affects estuarine-scale geochemical cycles, estuarine circulation and mixing, biological habitats, watershed flow modeling, and even municipal water supply planning.

Investigations of ground water-ocean interactions have used geochemical tracers or hydrologic models to constrain the volume of ground-water discharge to the ocean (Moore, 1995, 1999; Church, 1996). Moore (1995, 1999) concluded that coastal ground-water seeps may be more prevalent than previously believed, because estimates from radium isotope methods showed greater fluxes of ground water than were calculated by hydrologic methods. Analytical and numerical models of ground-water discharge have predicted discharge decreasing with distance from shore (Reilly and Goodman, 1985); however, site-specific studies using a dense grid of seepage meters have shown extreme spatial and temporal variability in discharge (Michael et al., 2002).

The application of geophysical methods to ground-water investigations has been established as a successful tool for defining aquifer characteristics and for imaging certain physical properties of ground water (Zohdy et al., 1990). Near-surface geophysical methods have been used in coastal ground-water studies, especially for monitoring saltwater intrusion. Because electrical conductivity is affected by salinity (Archie, 1942), electrical methods such as electromagnetic induction and resistivity imaging lend themselves particularly well to coastal ground-water investigations because of the sharp contrast in conductivity between saltwater and freshwater.

In the three case studies presented in this paper, continuous resistivity profiling (CRP) has been used to identify or confirm areas of SGD, and to delineate the saltwater/freshwater interface by detecting changes in conductivity in the marine environment. This method has previously been applied in Delaware coastal bays for detecting areas of ground-water seeps (Manheim et al., 2002).

Methods

CRP data were collected in Winyah Bay, South Carolina, from March 2 – 9, 2002, in Orleans, Massachusetts, on March 21, 2002, and in Waquoit Bay, Massachusetts, on June 13, 2002. Echo sounder data were collected in tandem with CRP data to constrain water depth at all three sites. Direct water column temperature and conductivity measurements were taken at Winyah Bay and Waquoit Bay. Data were geo-referenced at all sites through real-time GPS integration with echo sounder and CRP data.

Continuous Resistivity Profiling

A SuperSting Marine[1], manufactured by Advanced Geosciences, Inc., was used for the resistivity measurements. The system is an eight-channel resistivity and induced-polarization meter with a maximum current output of 2 amps. The meter operates in a "continuous" mode by injecting current and measuring eight-voltage potentials simultaneously every 2.8 seconds as the survey vessel moves forward. Electrodes are towed on the surface of the water behind the boat, and survey speeds are generally kept around 2 or 3 knots to maximize the density of data points collected. Stacking measurements is not possible in the continuous collection mode because of the physical inability to exactly repeat survey lines. Noisy data are filtered out by setting appropriate signal to noise ratio thresholds. At Winyah Bay and Orleans, an electrode streamer consisting of 11 graphite electrodes, spaced 10 m apart, was used for data collection. In Waquoit Bay, an electrode streamer with 11 stainless steel electrodes spaced 2 m apart was used for data collection. As a result of the smaller electrode spacing at Waquoit Bay, the depth of investigation was much shallower than at the other two sites. Graphite electrodes were used where possible because, unlike stainless steel, graphite has proven to be highly resistant to the oxidation caused by the injection of electrical current in saltwater environments. Due to the geometry of the electrode streamers used, a dipole-dipole array was used for the data collection. In the continuous profiling set-up, dipole-dipole array data are collected by assigning two fixed current electrodes and measuring voltage potentials between electrode pairs in the remaining electrodes.

Echo Sounder Profiling

To constrain the water depth, depth data from an echo sounder were collected. Echo sounders determine depth by measuring the two way travel time of a sound wave through the water column. In Winyah Bay, a Knudsen 320bp echo sounder was used in tandem with CRP data collection. This system operates at 50 and 200 kHz and is controlled by an external PC. At the two Massachusetts sites, a Lowrance XMS echo sounder, operating at 192 kHz, was used. Position data are imported directly into the PC and merged real-time with echo sounder data. For both depth instruments, geo-referenced echo sounder data are merged with geo-referenced CRP data later in the processing process.

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[1] The use of firm, trade, and brand names is for identification purposes only and does not constitute the endorsement of the U.S. Government.

Conductivity, Temperature, and Depth Measurements

Conductivity, temperature, and depth (CTD) measurements were taken at discrete locations along survey lines in Winyah Bay and Waquoit Bay using an Ocean Sensors OS200 CTD. Where applicable, the conductivity data were incorporated into the inversion process to constrain inverse resistivity models.

Data Processing and Interpretation

Data were processed using an iterative least-squares inversion method (deGroot-Hedlin and Constable, 1990; Sasaki, 1992) to create a model of subsurface resistivity by inverting the apparent resistivity data. A commercial software program, RES2DINV, was used for all data processing. At the Waquoit Bay site, where sufficient depth and water column conductivity data were available, the inversion was constrained by assigning model blocks of the water column to the average conductivity values as measured by CTD probes at various locations along the survey line. The constrained model blocks are held as absolute and not allowed to change during the inversion process. Constraining the model in this way increases the accuracy and resolution of the inverse model. Because of the computing capabilities required with large volumes of data in individual CRP lines, longer lines were divided into smaller sections and each individual section was inverted separately, even though this increased the amount of boundary edge artifacts.

The inverted data are displayed as a cross section of resistivity that approximates the true subsurface resistivity distribution (Loke, 1997). Information about the subsurface is interpreted from the distribution of areas of high and low resistivity. Errors in the inversion can be caused by gaps in the data and/or noisy data; the effect of these errors is amplified as the depth increases. Also, resistivity anomalies seen at the edges of inverted sections do not represent true subsurface features; these anomalies are the result of boundary edge artifacts. Robust inversion results are assured by using quality-control checks to filter out noisy data.

Winyah Bay, South Carolina

Site Description and Background

Winyah Bay, in southeastern South Carolina (**Figure 1**), is a partially mixed Coastal Plain estuary. The Winyah Bay watershed is one of the largest estuarine ecosystems on the East coast and drains approximately 121,000 square kilometers (km^2) (Blood and Vernberg, 1992). Freshwater to the estuary is received mainly through the Pee Dee, Waccamaw, and Sampit Rivers. Evidence for freshwater discharge to marsh areas at the forest-marsh boundary has been documented (Thibodeau, 1997); however, no evidence of SGD has been recorded. CRP data were collected to look for the presence of SGD in Winyah Bay.

Results

Data were collected on two lines in Winyah Bay (**Figure 1**). Line WB18 was collected midway down gradient in the estuary near Mud Bay as representative of background data in the bay. Line WB21 was collected to look for evidence of SGD. The inverted resistivity sections are shown in **Figure 2**.

Line WB18 shows relatively horizontal layering with resistivity ranging from approximately 1 ohm-meter (Ω-m) to 14 Ω-m (**Figure 2A**). The water bottom, as measured by the echo sounder, does not represent an abrupt change in resistivity, implying that the bottom sediment is fully saturated with sea water and has a relatively high porosity. As expected, resistivity increases with depth. This is interpreted to be decreasing porosity in response to increasing compaction, in agreement with Archie's

Relation, which says that resistivity is a function of pore-water salinity, porosity, and saturation (Archie, 1942).

Line WB21 contains a resistivity anomaly interpreted to be caused by SGD (**Figure 2B**). The anomaly, approximately 500 m from the southwest end of the line, shows a highly resistive body (≈ 50 Ω-m) extending through the thickness of the section. Where this anomaly is not present, a layer of low resistivity is found confined between two layers of higher resistivity. The bottom of the water column corresponds to the bottom of the upper-most resistive layer. The less resistive areas (blue) found directly beneath the water column are interpreted to be sediment saturated with more saline water. Based on this interpretation, the resistive body that extends through the thickness of the section (red) is inferred to be freshwater discharge.

Evidence from the Pee Dee River hydrograph, along with an estuary-scale salinity profile indicates that this situation is geologically feasible. Salinity and temperature for Winyah Bay are shown in **Figure 3**. These data were collected 5 days prior (March 3, 2002) to data collection of CRP line WB21 (March 8, 2002). At the location of WB21, the salinity was 4 to 5 parts per thousand (ppt) (corresponding to ≈ 0.002 Ω-m at 12.5ºC). The discharge hydrograph for the Pee Dee River for February through April, 2002 is shown in **Figure 3C**. A spring freshet occurred on or about March 8, the day of the CRP survey. Before this, discharge was significantly less for several weeks. On the day of the CRP survey, surface salinities were measured to be 0 ppt; salinities at WB21 were 4 to 5 ppt or greater at least 5 days before the CRP survey and probably for weeks prior. Therefore, it is likely that the bed sediments were saturated with water that was more saline than the water in the water column. The resistive anomaly in the middle of line WB21 is interpreted to represent an area of freshwater discharge where the sediment is saturated with freshwater from ground-water discharge.

Waquoit Bay, Cape Cod, Massachusetts

Site Description and Background

Waquoit Bay, between the towns of Mashpee and Falmouth on Cape Cod, Massachusetts (**Figure 4**), is a part of the National Estuarine Research Reserve system. Waquoit Bay is relatively shallow, on average less than 1 m, and approximately 3.3 km^2 in size. Freshwater enters the estuary through four principal sources: the Quashnet/Moonakis River, Red Brook, Childs River, and through SGD.

Submarine discharge in Waquoit Bay has been investigated by Valiela et al. (1990), Cambareri and Eichner (1998), and Charette et al. (2001). Saltwater and freshwater discharge in the near-shore environment of Waquoit Bay has been well constrained by a grid of seepage meters. Results from the seepage meter study performed by Michael et al. (2002) are shown in **Figure 5**. Michael et al. (2002) study found focused areas of discharge at the head of the bay, extending offshore for approximately 60 m. The maximum discharge was mostly saline water at approximately 40 m offshore. Near-shore discharge was found to be approximately 35% freshwater. CRP was used at this location to further delineate areas of SGD and to provide insight into the depth structure of the saltwater/freshwater interface.

Results

CRP data were collected on two lines in Waquoit Bay (**Figure 4**). Line WQ1 aligns parallel to the shore and line WQ2 is perpendicular to the shore. During the CRP data collection, resistivity values also were measured directly from the water column at discrete points along profile lines. The average measured water column resistivity is 0.25 Ω-m, and this value along with the measured depths has been used to constrain the inversions shown in **Figure 6**. Line WQ1 crosses over an area of measured high

SGD at approximately the center of the line. At this location, a high resistivity anomaly (5 Ω-m) is present in the inverted resistivity profile. Like the discharge measured by seepage meters, the resistivity anomaly is extremely focused (less than 10 m in width). The anomaly extends vertically from approximately 3 m below the water surface to the bottom of the section (8 m). In addition to this anomaly, another high resistivity zone is present in the western end of the section. This anomaly is wider (at least 60 m) and has a high resistivity of approximately 7 Ω-m. No seepage meter data are available from this location.

The resistivity anomaly observed in the middle of the CRP section corresponds almost exactly to the location of discharge measured by seepage meters in 2000; however, the resistivity of this anomaly is low relative to fresh water. This could be due to mixing of the water bodies and/or the inability of the geophysical method to resolve the true resistivity of such a focused target.

Line WQ2 extends perpendicular to the shore and crosses the same lateral position where high SGD is measured with seepage meters and where a resistivity anomaly is observed in line WQ1. In WQ2, a high resistivity layer is observed beneath the subsurface extending out from the beach approximately 350 m. The high resistivity layer is approximately 5 m below the water surface and the resistivity ranges from approximately 7 to 2 Ω-m. This layer is interpreted as less saline water underlying the more saline bay water. The decrease in resistivity in the layer as the distance from the shore increases is consistent with the interpretation that the elevated resistivity is due to the presence of less saline ground water. As the ground water moves farther from the shore, it progressively mixes more with bay water, resulting in a decrease in the resistivity.

Cape Cod Bay, Orleans, Massachusetts

Site Description

Rock Harbor is located on the western shore of Cape Cod on Cape Cod Bay in Orleans, Massachusetts (**Figure 7**). The area directly offshore from the harbor is relatively shallow, on average 1 to 3 m deep, and has a shallow gradient, resulting in tidal flats that may extend for up to 2 km offshore. The Cape Cod aquifer, consisting of glacially deposited sand and gravel, underlies Rock Harbor and extends offshore. Bedrock is located approximately 120 m below ground surface.

Results

A CRP line was collected offshore from Rock Harbor in Orleans, extending about 700 m into the bay (**Figure 7A**). Echo sounder data also were collected on the same line. The inverted resistivity section is shown in **Figure 7B**.

Ground-water model simulations predict bayward (west) flow of freshwater in the sediments underlying Cape Cod Bay just offshore of Rock Harbor (Masterson, 2002). This flow is simulated as part of the Nauset Flow Cell, which is one of six regional flow cells on Cape Cod. In the area where the CRP data were collected, the freshwater-saturated sediment of the Cape Cod aquifer is confined by a thick deposit of glaciolacustrine silt and clay, which extends offshore, preventing the freshwater from discharging into the bay (Masterson, 2002). In 2000, a coring investigation confirmed the presence of freshwater below Rock Harbor (McCobb and LeBlanc, 2002).

On the inverted resistivity section, an area of high resistivity (approximately 30 to 50 Ω-m) in the center and southeastern portion of the section is interpreted to be freshwater-saturated sediment underlying saline bay water. The strong contrast in resistivity only several meters below the seabed provides evidence for freshwater-saturated sediments. As in Winyah Bay line WB18 (**Figure 2**), no contrast in resistivity is observed at the water bottom. This implies that the subsurface, above the confined freshwater, is fully saturated with saline bay water, and that freshwater is not discharging upwards through the confining layer of glaciolacustrine silt and clay at this location.

Conclusions

Results from the three sites described in this paper show the potential use of CRP for finding regions of submarine ground-water discharge and delineating the subsurface saltwater/freshwater interface in coastal ground-water investigations. The accuracy and resolution of CRP data interpretation are improved when the data inversion is constrained by direct water column depth and conductivity measurements. As in all geophysical investigations, the usefulness of CRP data is greater when employed as part of a suite of complimentary geophysical tools such as electromagnetic induction and seismic profiling. Because CRP data can be collected quickly and over large areas, the technique is useful for rapid site assessment, and may be effectively used to locate appropriate areas for seepage meter placement. As more research efforts are directed toward studying the dynamics of coastal watershed systems, the utility of CRP in coastal ground-water investigations will likely continue to increase.

Acknowledgments

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References

1. Archie, G.E. (1942), "The electrical resistivity log as an aid in determining some reservoirs characteristics", *Journal of Petroleum Technology*, 5, pp 1-8.
2. Blood, E.R., and F.J. Vernberg (1992), "Characterization of the physical, chemical and biological conditions and trends in Winyah Bay and North Inlet Estuaries: 1970-1985", in *Characterization of the physical, chemical and biological conditions and trends in three South Carolina estuaries: 1970-1985*, v 2, Charleston, SC, South Carolina Sea Grant Consortium.
3. Burnett, B., J. Chanton, J. Christoff, E. Kontar, S. Krupa, M. Lambert, W. Moore, D. O'Rourke, R. Paulsen, C. Smith, L. Smith, and M. Taniguchi (2002), "Assessing methodologies for measuring groundwater discharge to the ocean", *EOS*, 83, n 11, pp 117-123.
4. Cambareri, T.C. and E.M. Eichner (1998) "Watershed delineation and ground water discharge to a coastal embayment", *Ground Water*, 36:4, pp 626-634.
5. Charette, M.A., K.O. Buesseler, and J.E. Andrews (2001), "Utility of radium isotopes for evaluating the input and transport of groundwater-derived nitrogen to a Cape Cod estuary", *Limnol. Oceanogr*, 46(2), pp 465-470.
6. Church, T.M. (1996), "An underground route for the water cycle", *Nature,* 380, pp 579-580.
7. deGroot-Hedlin, C. and S. Constable (1990) "Occam's Inversion to Generate Smooth, Two-Dimensional Models from Magnetotelluric Data", *Geophysics*, 55, pp 1613-1624.

8. Loke, M.H. (1997), "Electrical imaging surveys for environmental and engineering studies – a practical guide to 2D and 3D surveys", unpublished short training course notes, Penang, Malaysia, Universiti Sains Malaysia.
9. Manheim, F.T., D.E. Krantz, D.S. Snyder, and B. Sturgis (2002), "Streamer resistivity surveys in Delmarva coastal bays", in *Symposium on the Application of Geophysics to Engineering and Environmental Problems*, Las Vegas, NV, Feb 10-14, 2002, Proceedings: Wheat Ridge, Colo., Environmental and Engineering Geophysical Society, CD-ROM.
10. Masterson, John (2002), oral personal communication.
11. McCobb, T.D., and D.R. Leblanc (2002), "Detection of fresh ground water and a contaminant plume beneath Red Brook Harbor, Cape Cod, Massachusetts, 2000", *Water Resources Investigation Report*, U.S. Geological Survey.
12. Michael, H.A., J.S. Lubetsky, and C.F. Harvey (2002), "Characterizing submarine groundwater discharge: a seepage meter study in Waquoit Bay, Massachusetts", *Geophysical Research Letters*, In press.
13. Moore, W.S. (1995), "Radium isotopes in coastal waters on the Amazon shelf", *Geochimica et Cosmochimica Acta*, 59, n 20, pp 4285-4298.
14. Moore, W.S. (1999), "The subterranean estuary: a reaction zone of ground water and sea water", *Marine Chemistry*, 65, pp 111-125.
15. Reilly, T.E. and A.S. Goodman (1985), "Quantitative analysis of saltwater-freshwater relationships in groundwater systems – a historical perspective", *Journal of Hydrology*, 80: pp 125-160.
16. Sasaki, Y. (1992), "Resolution of resistivity tomography inferred from numerical simulation", *Geophysical Prospecting*, v. 40, pp 453-464.
17. Thibodeau, P.M. (1997), "Groundwater flow dynamics across the forest-salt marsh interface; North Inlet, South Carolina", Doctoral Dissertation, University of South Carolina, Columbia, SC, pp 278.
18. Valiela, I., J. Costa, K. Foreman, J.M. Teal, B.L. Howes, and D.G. Aubrey (1990), "Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters", *Biogeoch,* 10, pp 177-197.
19. Zohdy, A.A.T., G.P. Eaton, and D.R. Mabey (1990), "Application of surface geophysics to ground-water investigations", in *Techniques of water-resources investigations of the United States Geological Survey*, Book 2, Chapter D1, U.S. Government Printing Office, Denver, CO, pp 115.

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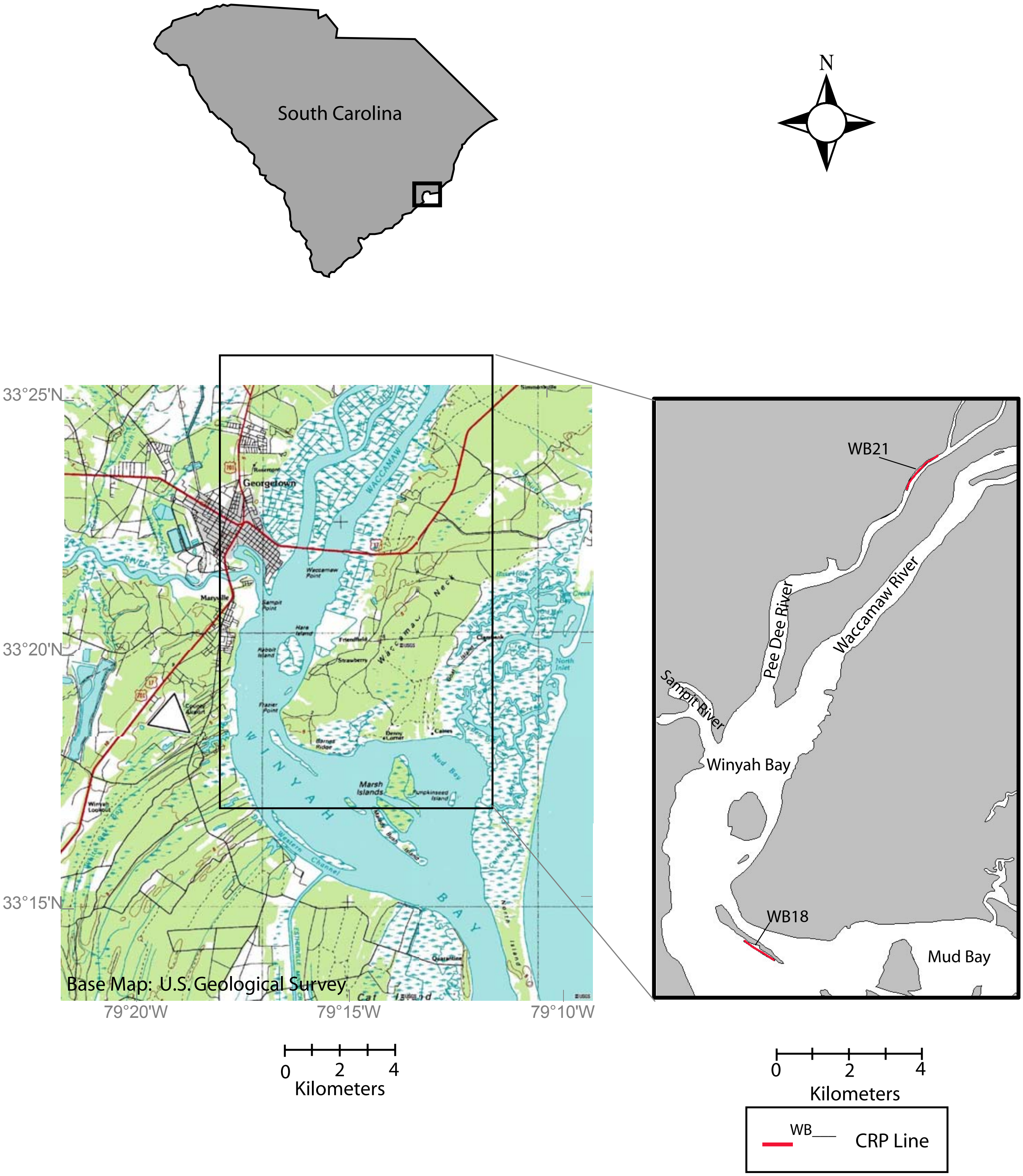
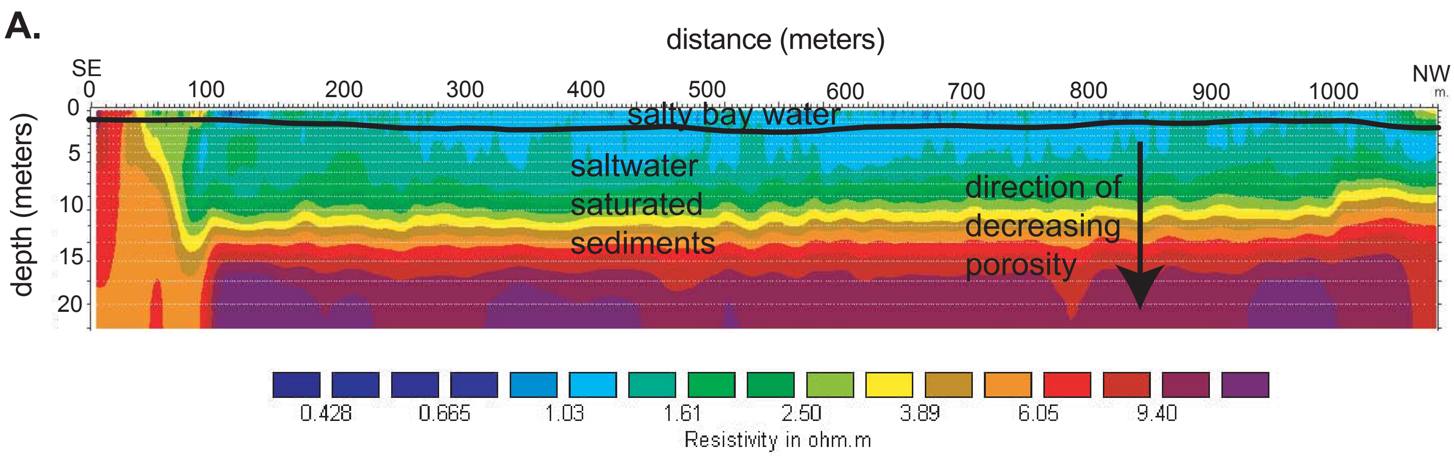


Figure 1. Locations of CRP lines WB18 and WB21 in Winyah Bay, South Carolina.

Winyah Bay, 2002, Resistivity Profiles WB18 and WB21



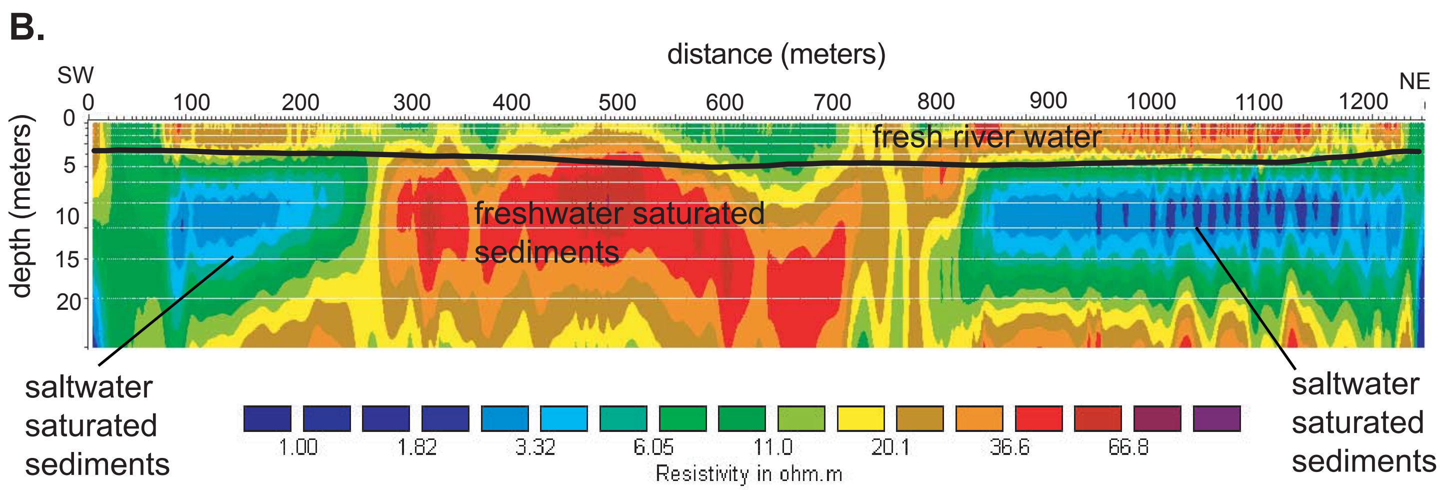


Figure 2. Inverted resistivity section WB18 with interpretations (A) and WB21 with interpretations (B). The inverted model displayed for WB18 is the third iteration with a root mean squared error (RMSE) of 3.3%. The inverted model displayed for WB21 is the fifth iteration with an RMSE of 4.3%. Water bottom measured by an echo sounder is plotted as a dark line.

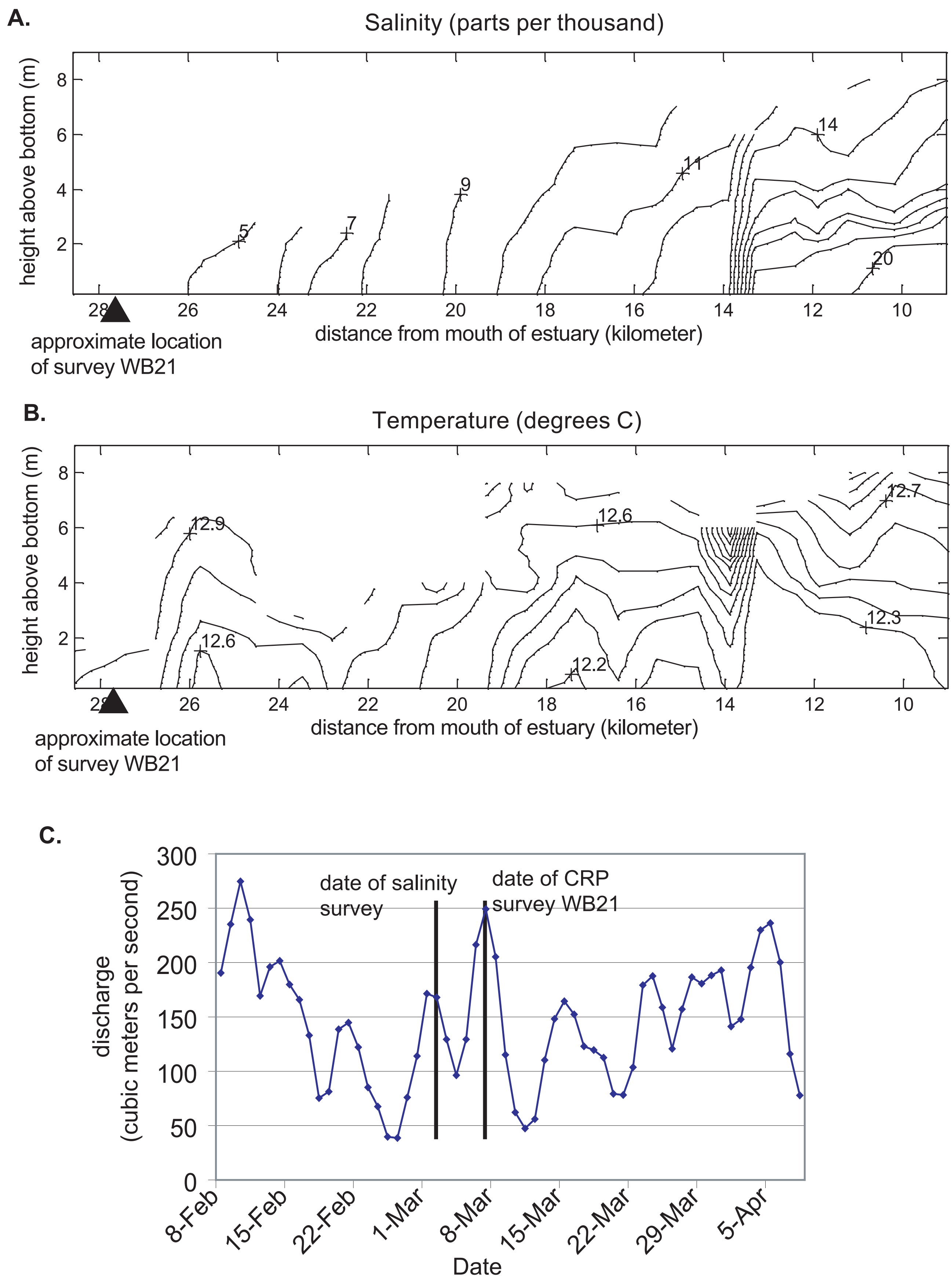


Figure 3. Salinity (A) and temperature (B) profiles of Winyah Bay on March 3, 2002. Average daily stream flow (C), Pee Dee River USGS Gaging Station 02131000 (at Peedee, South Carolina).

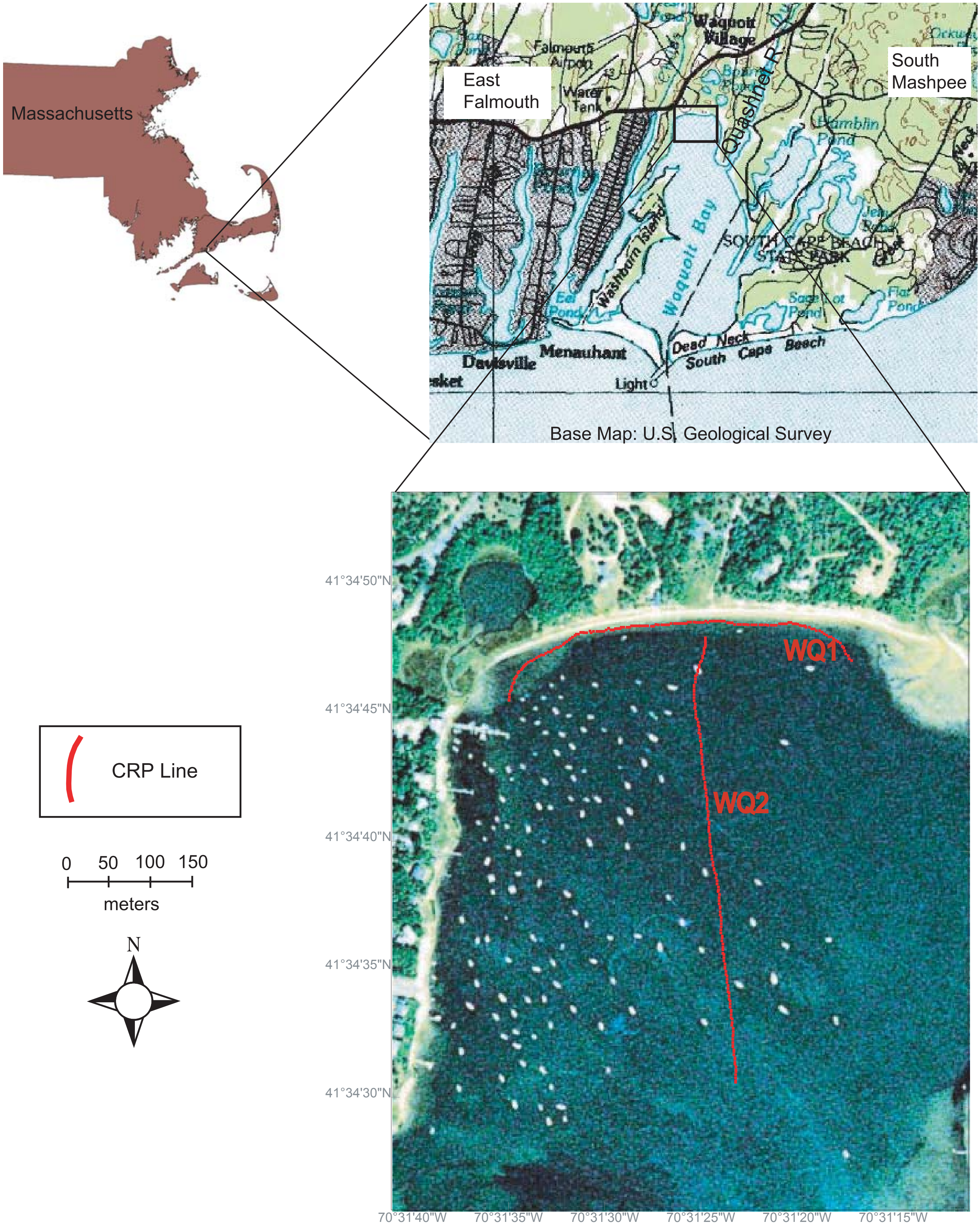


Figure 4: Waquoit Bay, Massachusetts, showing locations of geophysical surveys

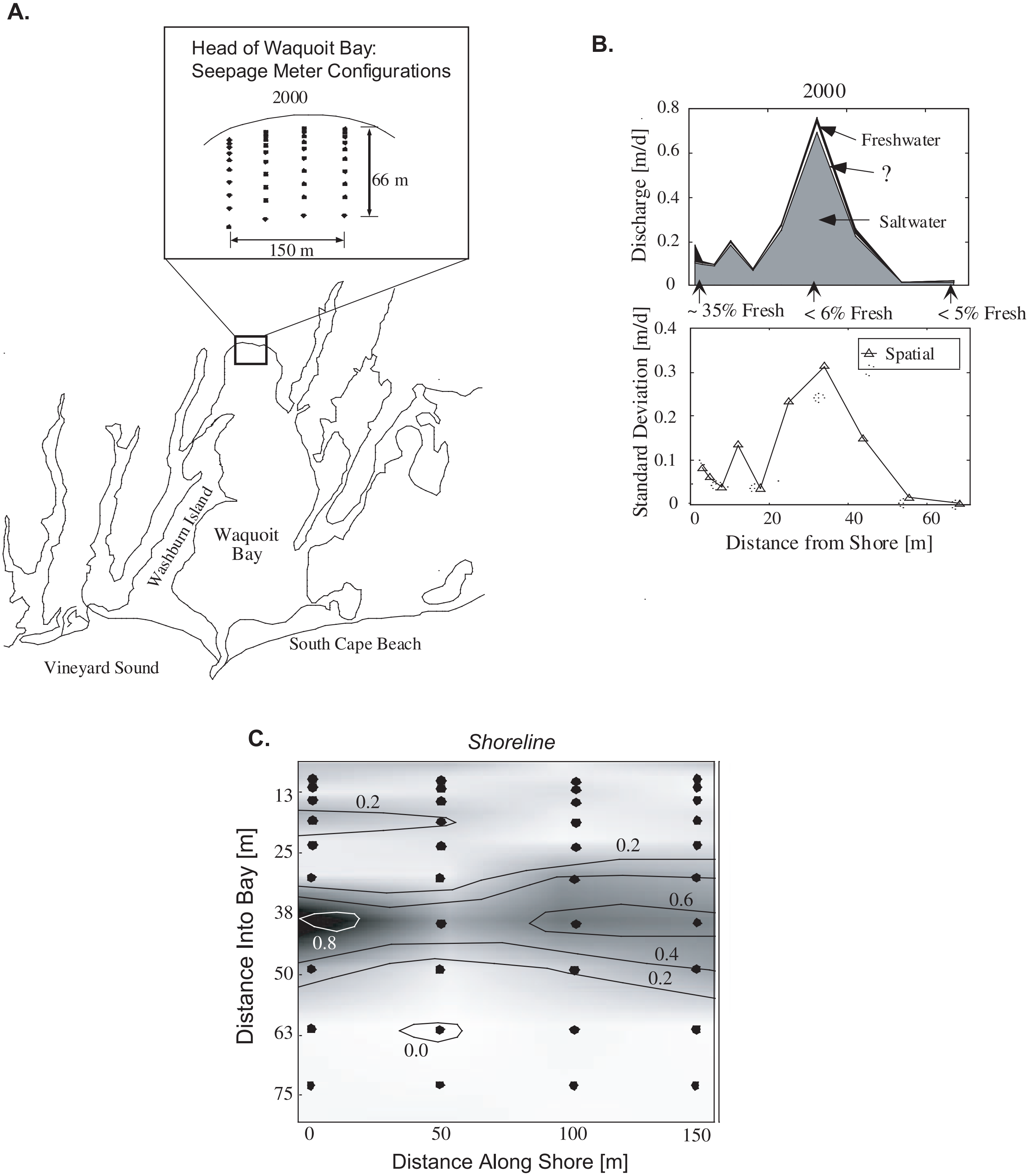


Figure 5: Results of seepage meter study in Waquoit Bay by Michael et al. (2002). Figure and data reprinted with permission. (A) Location of seepage meters (B) distribution of freshwater and saltwater in discharged water with distance from shore, and (C) time-averaged ground-water discharge in meters per day.

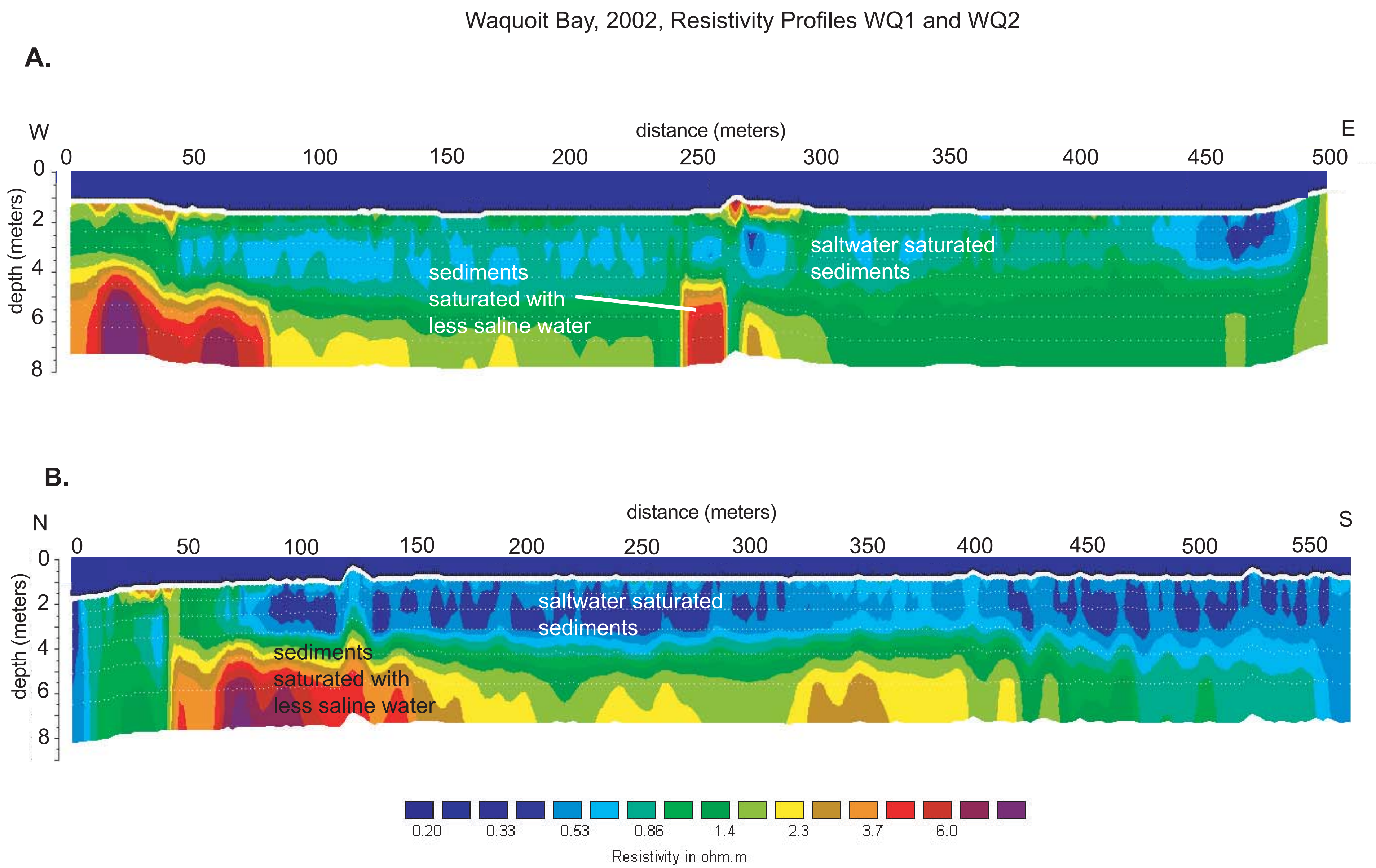


Figure 6. Inverted resistivity section WQ1 (A) (alongshore) and WQ2 (B) (offshore). The inverted model displayed for WQ1 is the third iteration with a root mean squared error (RMSE) of 2.9%. The inverted model displayed for WQ2 is the third iteration with an RMSE of 4.6%. Both sections have been inverted with the water column resistivity constained to 0.25 ohm-meter. A white line marks the water bottom as recorded by an echo sounder.

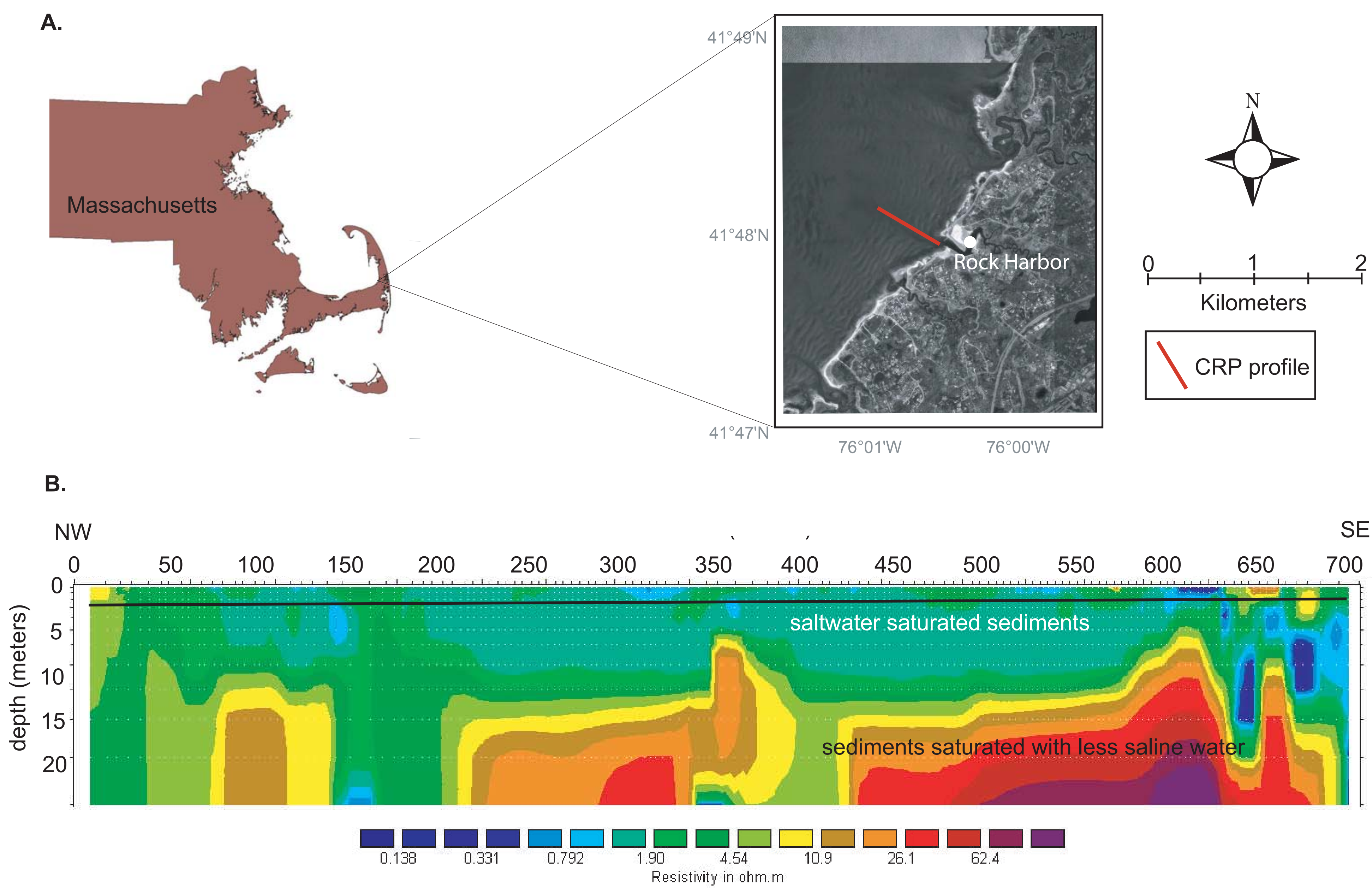


Figure 7. Site map and location of CRP line outside of Rock Harbor, Orleans, Massachusetts (A), and inverted CRP section (B). The inverted model displayed is the sixth iteration with a root mean squared error (RMSE) of 3.9%. Water bottom, as measured by an on-board echo sounder is plotted as a dark line. Depths and distances are plotted in meters.