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Data was interpreted for a one-dimensional conductivity structure with an iterative least-square scheme. The electrical properties interpreted from the EM measurements have been compared with the available bottom-towed EM soundings in the area.

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CONTROLLED SOURCE ELECTROMAGNETIC SOUNDING OFF THE COAST OF EUREKA CALIFORNIA

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Abstract: Controlled electromagnetic (EM) measurements were conducted with a ship-towed electric bipole source and fixed electric and magnetic field sensor units that were deployed on the seafloor in 62 meters of water near Eureka, California. The objective was to determine the electrical properties of the marine sediments to depths greater than 20 meters. The survey site was positioned in a region that had been investigated by numerous shallow geologic/geophysical studies.

Data was interpreted for a one-dimensional conductivity structure with an iterative least-square scheme. The electrical properties interpreted from the EM measurements have been compared with the available bottom-towed EM soundings in the area.

Keywords: Magnetic and Electric Fields, Sediment Conductivity, Controlled Source EM, Layered Electromagnetic Inversion.

1. INTRODUCTION

This work was conducted off the coast of northern California near Humbolt Bay. The area is currently being studied by researchers brought together by the Office of Naval Research (ONR) to develop a better understanding of the relationship between depositional processes and the strata that reside in the geologic record. The ONR program, STRATAFORM [1], is focused on understanding the spatial and temporal relationship of geologic processes to the strata being created. A suite of oceanographic measurements and bottom core samples have been taken over the past two years to characterize the shelf environment and the local sedimentation characteristics at the site.

The coastal region geology is an active tectonic setting with frequent earthquakes and a narrow continental shelf. Much of the area has a complicated history due to the nearby Mendocino triple junction formed by the intersection of the North American, Gorda, and Pacific plates [2]. A high-resolution sidescan [3] identifies the shelf to have very smooth topography, which most likely results from the high influx of terrigenous sediments carried by the Eel and Mad rivers. Some long scale features do exist on the shelf. A dominant sediment bulge from outflow at the mouth of the Eel river appears to be associated with a secondary depositional feature [3] extending to the north along the coast for more than 20 km. This secondary sediment feature has a few meters relief and correlates with the location of recent cumulative flood deposits suggesting that it is caused by the cumulative effect of a short term process (floods). To the north, a similar feature is observed from the Mad River with a secondary depositional feature extending southward and into the area of our measurements.

The objective of our work is to determine the electrical conductivity structure at this site and relate the electrical properties to the sediment type and stratigraphic structure. The electrical properties of sediments are closely related to the pore structure and interstitial fluid of the sediments. In this paper we will focus on the measurements and the initial efforts for inversion of the measurements to sediment electrical properties.

The electromagnetic measurements were completed using a portable source and fixed receivers that provided multi-frequency data over a continuous range of separations. The recording instruments consisted of three autonomous ocean magnetotelluric systems (OMS) deployed on the bottom. These instruments were deployed in approximately 62 meters of water near a site of extensive oceanographic and sediment transport studies by other investigators. An electric bipole source was towed through the water across the OMS array. The source was a 10.75 meter long grounded current source towed 220 meters behind the vessel to avoid coupling the source field with the ship. Acoustic transponders on the tow-body were used to monitor the position and depth of the towed source. A "star" pattern of profile lines shown in Fig. 1 were traversed across the receiver array to investigate the lateral variability of the electrical properties. Letters on Fig. 1 designate the way-points for the traverses, and the OMS Array is located at way-point A.

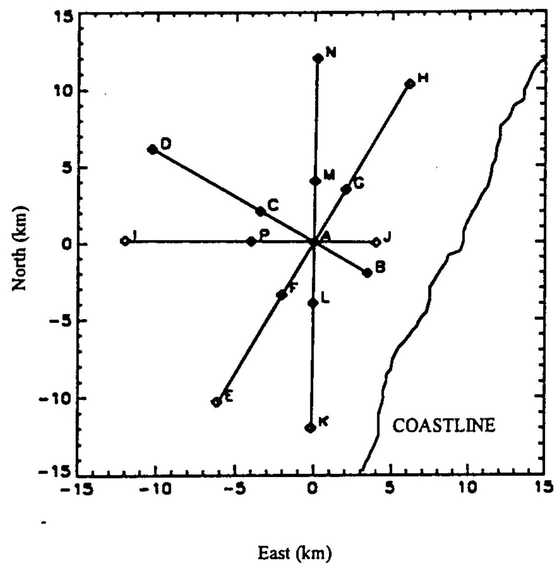

Figure 1. Waypoints and profile lines showing towed source traverse across receiver array. Receiver array located at waypoint A.

2. INSTRUMENTATION

Three bottom-mounted OMS recording instruments were deployed in a profile with a spatial separation of 46 meters and 143 meters. The autonomous receivers recorded three axis vector magnetic measurements plus two axis electric field measurements. Two of the receiver units recorded data in the band from near DC to 128 Hz. The other unit had a bandwidth from DC to 50 Hz for the magnetic and near DC to 100 Hz for the electric field components. The data analyzed to date and presented in this paper came from the lower bandwidth unit.

The vector magnetic measurements were recorded with a three-axis ring-core fluxgate magnetometer that has a sensor noise on the order of 0.01 $nT/Hz^{1/2}$. The electric potential measurements were recorded with two horizontal perpendicular electrode pairs composed of silver-silver chloride electrodes attached to the ends of the dipoles for a total length of 11 meters. The electrodes and the low noise pre-amplifiers were developed at Scripps Institute of Oceanography. Preamplifier and fluxgate data were recorded with 16-bit resolution along with a high accuracy synchronized clock.

The towed source consisted of a digitally controlled current source, a low electrical impedance underwater tow-cable, an 11-meter long fiberglass tow-fish with electrodes attached to each end, and a telemetry monitoring system. Incompressible foam floats were used to keep the tow cable near the surface. The tow-fish was maintained at a steady depth of 12 meters with a combination of a passive depressor and floats. A short-range acoustic positioning system was used to locate the tow-fish relative to the absolute location of the ship. Location of the ship was determined using a global positioning system (GPS) operated in a differential mode. The absolute position of the towed source was measured to an accuracy of 2 - 3 meters. Stationary tests of the GPS in differential mode indicate a standard deviation of less than 2 m. The short-range acoustic positioning system on the towed source has a standard deviation of less than 0.2-m range, and the depth of the source is resolved to less than 0.2 m.

A series of source tow traverses were conducted over the three OMS receiver units. Source tow tracks were arranged in a star pattern over the receiver units to investigate the bottom electrical properties from six azimuthal directions. The transmitted waveform was composed of 5 sinusoidal components at 1, 2, 5, 10 and 20 Hz and it was synchronized to the GPS time pulse. Transmitted current amplitudes were 25 amps on most traverses producing a source amplitude of 268 A-m for each frequency.

To reduce the complexity of the model interpretation, the water column properties were measured daily with a conductivity-temperature-depth (CTD) instrument. The conductivity profile showed a slightly higher conductivity upper layer approximately 9 m thick with a fairly uniform lower layer. Based on these measurements, a two-layer model was used to approximate the water column. Layer 1 assigned from surface to 9 m with conductivity 3.83 S/m and layer 2 beginning at 9 m to the bottom at 62 m with a conductivity of 3.60 S/m.

3. INTERPRETATION

To obtain estimates of the sub-bottom electrical properties, the measured field values from the receiver instruments must be transformed into electrical resistivities. This process which is referred to as "inversion" has been implemented as a parameterized least squares data fitting process to estimate the electrical properties of a predetermined model. Initially we have started with a simple layered one-dimensional earth, and will add complexity as permitted by the data quality. The initial results and the simplest model are for a two layered water column and a half-space for the bottom sediments.

The inversion routine uses an iterative approach to derive the best fit to the data. The approach computes the field values from a layered model and compares the computed values to the measured field data. The Levenberg-Marquardt technique is used to adjust the model parameters and minimize the sum of squares of the differences between the computed and measured field values.

A discrete Fourier transform is applied to the measured field values to resolve the complex components for each of the transmitted frequencies. A sliding 10 second long window is used to compute the complex spectral components at 5 second intervals. Corrections for amplifier and recording system characteristics are applied to the data prior to data inversion.

Four transmitted frequencies were used in the data inversion. The two axes of the electric field data with four complex frequencies each produces 16 independent measurements for each 5-second point. If data are interpreted with a layered model consisting of only the fixed water layers and a half-space of sediment, the large number of data per point produces an overdetermined problem. To minimize positional errors, source position and orientation were allowed to vary in some cases.

4. RESULTS

At this time only one of the eight primary source towlines has been analyzed. Data from a north-south line have been inverted for an initial estimate of bottom electrical properties. The track for the line is shown in Fig. 2 relative to the recording instrument. The closest point of approach (CPA) is marked along the profile. Since this line never approaches closer than 150 m to the receiver position, thin surficial layers are not resolvable.

The inversion model consists of a fixed two-layer water column and a half-space bottom. The inversion has been done for each point along the profile utilizing only the data for each source-receiver separation. Sediment electrical properties and source headings were permitted to vary until a satisfactory fit to the observation was achieved. Estimates for the half-space resistivity are shown in Fig. 3 for each point along the

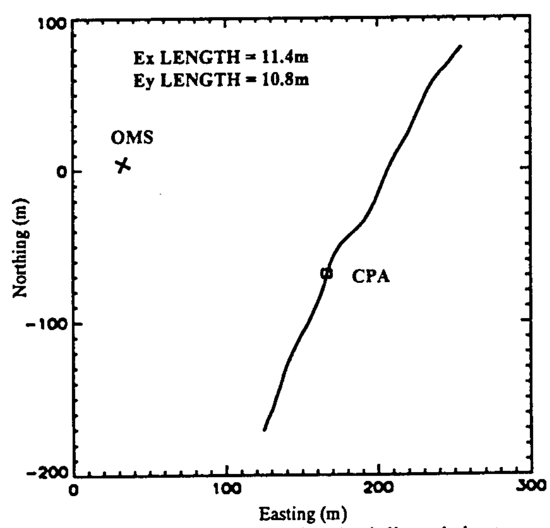

Figure 2. Analyzed profile. Track-line relative to OMS recording instrument. CPA marks the closest point of approach.

profile. The half-space resistivity varies from roughly 1.25 to 2.1 ohm-m. The variation in resistivity across the profile suggests the presence of lateral variations in the sub-bottom. Using the bottom water conductivity of (ρ_w) of 0.28 ohm-m we obtain an estimate of the formation factor ($f=\rho_s/\rho_w$) ranging from 4.5 to 7.5. From Archie's law [4] we can obtain a representative estimate of the bulk porosity to range from 0.36 to 0.26 using an exponent of 1.5 [5] in Archie's relation between porosity and the formation factor. Evans [6] conducted an active EM survey in the same area with a system developed by the Geological Survey of Canada. He identified the region of our site as having a high degree of spatial variability and some very high resistivities for a shallow sedimentary environment.

5. ACKNOWLEDGEMENTS

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7. BIOGRAPHIES

Will Avera received his Bachelors of Science at the University of Georgia and his Masters of Science in Geophysics at Oregon State University. He has worked in exploration for the oil and gas industry and is currently working with electromagnetic techniques to study

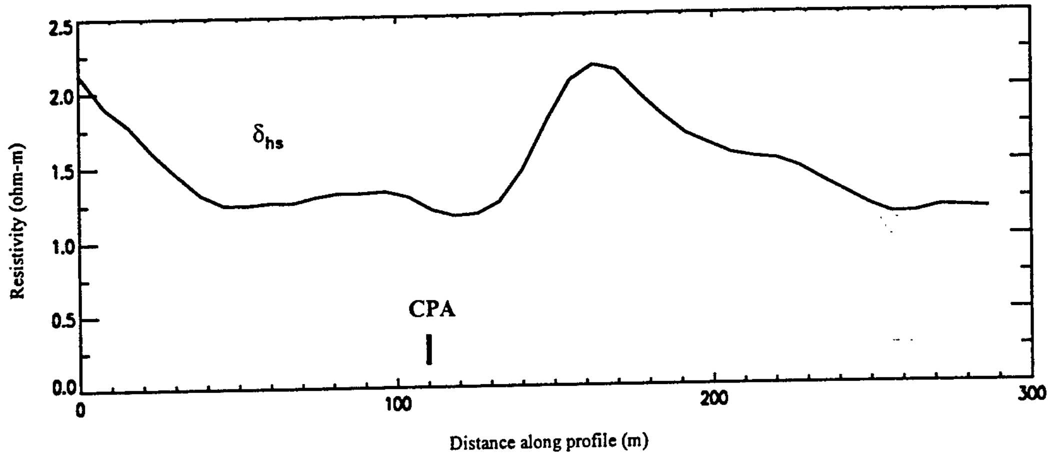

Figure 3. Inverted solution for half-space resistivity along profile.

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Dr. Edward C. Mozley received his PhD in geophysics/geological engineering from the University of California Berkeley in 1982. He worked as a geophysicist with Newmont Exploration Limited in mineral exploration from 1982-1985. He has worked for the U.S. Navy as a geophysicist with NORDA from 1986-1989 and as a research physicist for NOARL/NRL from 1990-1997 with primary interest in electromagnetic sensor/system development for shallow marine environments. He is currently a program manager for Oceanographer of the Navy involved with the development of marine environmental sensors.

Juan Reynaud received his Bachelor of Science in Electrical Engineering and his Master of Science in Engineering at the University of New Orleans. He is currently involved in the development and support of the Navy's Airborne and Underwater Electromagnetic Systems.